Bundesanstalt für
Geowissenschaften
und Rohstoffe

Cobalt

Sustainability Information

ECOLOGY ECONOMY GOVERNANCE SOCIAL

January 2021

AT A GLANCE

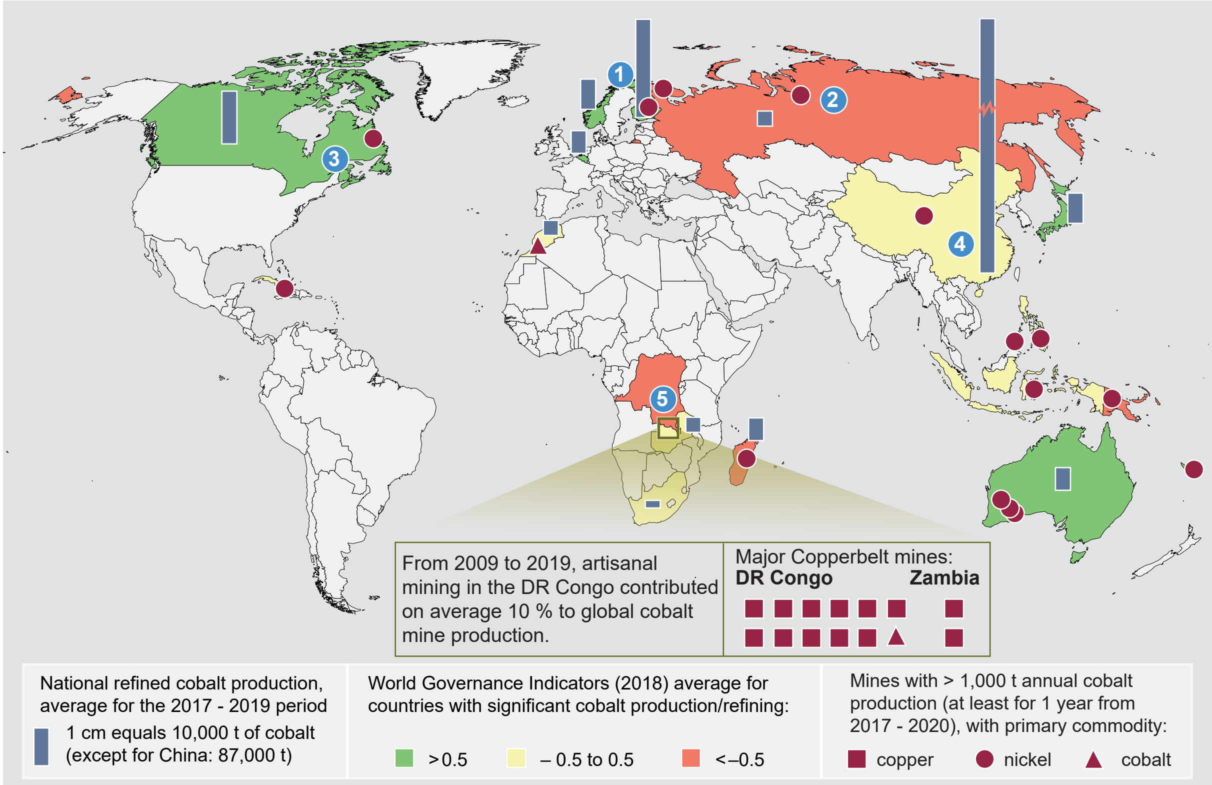

***Fig. 1:** Global distribution of cobalt production by major mine locations and refiner countries. See text below for selected sustainability aspects. World Governance Indicators (World Bank) displayed as average values.*

1. Scandinavia is currently Europe's centre for cobalt production. Finland hosts both significant refining capacities and the Terrafame project; the latter represents a bioleaching operation that produces cobalt and other metals. A plant in the Finnish town of Kokkola refines Russian intermediate products.

2. Norilsk has been called the dirtiest city in the world, due to the long-standing pollution caused by Nornickel's smelters and plants. In 2020, the widespread contamination of local ecosystems caused by diesel tank failure received international attention.

3. Voisey's Bay represents a good example for the social license to operate in mining. Initial project designs were scaled back to a smaller level based on negotiations with the local Inuit and Innu. Plans for the processing plant location were adjusted in order to respect protected watersheds.

4. The People's Republic of China is the world's most important producer of cobalt chemicals. At the same time, China represents the largest market for electric vehicles and plays a key role for expanding cobalt recycling. Chinese plants mostly process cobalt originating from the Democratic Republic of the Congo.

5. Historical smelting activities resulted in damages to the local ecosystems of the Copperbelt. Issuing industrial mining concessions is associated with corruption risks. Cobalt is partly produced by artisanal miners – often illegally, and associated with health and safety problems as well as child labour.

CONTENT

1 COBALT'S RELEVANCE

As an important element in the precursor material of cathodes, the relevance of cobalt is intricately linked to the increasing prevalence of lithium-ion batteries. The cobalt demand from this sector rose by an average of 16.5 % per year in the period from 2013 to 2018. Currently, 50 – 60 % of the cobalt produced globally is used in lithium-ion batteries [1]. Although public discussions on the use of cobalt in these batteries frequently focus on electric vehicles (EV), the market relevance of the electronics sector is currently almost twice as high as that of the automotive sector. However, demand from the EV sector will continue to rise and increasingly represent the most important field of application for cobalt. This reflects both the global EV market expansion and the fact that batteries employed in electric vehicles are many times larger compared to those in electronic devices. Table 1 shows the cobalt content of various products and battery cathode types.

Forecasts of EV market growth are associated with large uncertainties. Current estimates assume anything between 25 – 45 million electric vehicles in 2029 [2] implying significant uncertainties for the resulting demand in battery metals – in addition to cobalt, these include lithium, nickel, manganese and graphite. The uncertainties are due to a range of impact factors such as changes in the Chinese government's subsidy policy or the economic upheavals of the coronavirus pandemic. In addition, the chemical composition of battery cathodes is changing in the course of technological progress, possibly to the point of complete cobalt substitution. Although it is undisputed that the global demand for cobalt will increase significantly with the EV market expansion, demand forecasts, especially long-term forecasts beyond the year 2030, should therefore be treated with caution.

Substitution effects in the cathodes of lithium-ion batteries installed in electric vehicles lead to a progressive decrease in their average cobalt content. This substitution is mainly cost-driven, mirroring similar developments of the cobalt content in magnets since the 1980s – here, too, cobalt was substituted for pricing reasons, in this case by neodymium (a rare earth element). Moreover, technological factors also play a role in substitution trends. These relate to customer requirements with regard to the batteries' energy density (and thus their weight and driving range), operational reliability and the number and speed of charging cycles. In addition, manufacturers are concerned about possible reputational risks associated with the use of cobalt. These concerns are due to the circumstances surrounding the cobalt extraction in Central Africa. However, the negative impact on cobalt demand resulting from these substitution trends is more than offset by the expected overall market growth for lithium-ion batteries. Therefore, the demand for cobalt will continue to rise, at least in the medium term. In addition to electric vehicles, lithium-ion batteries will continue to be used in electronic devices such as smartphones and laptops. Moreover, their use in energy storage systems is relevant in the context of the global energy transition.

While lithium-ion batteries represent a key application for cobalt, the metal has a number of additional industrial applications. These are related to cobalt's specific material properties such as its heat resistance. Until the 1990s, these industrial applications were the main field of application; they currently still represent around 40 % of total cobalt use. The aerospace industry uses cobalt as a component of superalloys while the metal industry uses it as an alloying element in tool steels and advanced materials. Additional important fields of application are the pigment industry, the use of cobalt as a catalyst in the petrochemical industry and, because of its ferromagnetic properties, as a magnetic material. Almost all of these fields of application show significant growth rates, but the market for lithium-ion batteries is growing around twice as fast.

***Table 1**: Cobalt content of selected products or battery cathodes (based on [3], [4]).*

Product	Cobalt content
Smartphone	5 – 20 g
Tablet or laptop	20 – 50 g
Plug-in hybrid electric vehicle (PHEV)	1 – 4 kg
Electric vehicle (EV)	4.5 – 15 kg
Cathode type	**Cobalt content**
Lithium cobalt oxides (LCO; electronics)	60 %
Lithium nickel manganese cobalt oxides (NMC; passenger electric vehicles)	6 – 20 %
Lithium iron phosphate (LFP; electric vehicles, e.g. Chinese buses)	0 %

2 FROM DEPOSIT TO METAL

2.1 Geology

The majority of the cobalt ore mined today occurs in three deposit types: (1) primarily stratiform, sedimentary rock-hosted copper deposits of what is known as the Central African Copperbelt (in the Democratic Republic of the Congo, DRC, and Zambia), (2) lateritic nickel deposits (e.g. Philippines, Indonesia, Cuba) and (3) magmatic nickel-copper deposits (e.g. Canada, Russia, Australia). Lateritic ores comprise oxides and silicates while nickel-copper ores in magmatic deposits mainly comprise sulphides. Due to weathering effects, the ore type mined in the Copperbelt changes with depth: shallow sections of the deposits are mostly characterised by oxide ore whereas sulphides form the major ore type at depths below 250 m. These distinct domains are separated by a transition zone comprising both oxide and sulphide ore.

In addition, cobalt occurs in a number of other ore deposit types. Along with other non-ferrous metals, cobalt is extracted via bioleaching from black shale-hosted polymetallic deposits in Finland. In Morocco, the Bou-Azzer mine produces cobalt from vein-hosted arsenide ore, although the deposit's reserves are nearly depleted. Significant cobalt resources are contained in manganese nodules that formed as concretions on the ocean floor at depths of 4 – 6 km. Formal resources were defined for one of the potential mining zones in the Clarion-Clipperton Pacific Fault Zone (CCZ) in 2016, but there is currently no commercial production. The various deposit types are summarised in Table 2 with regard to their economic geology characteristics.

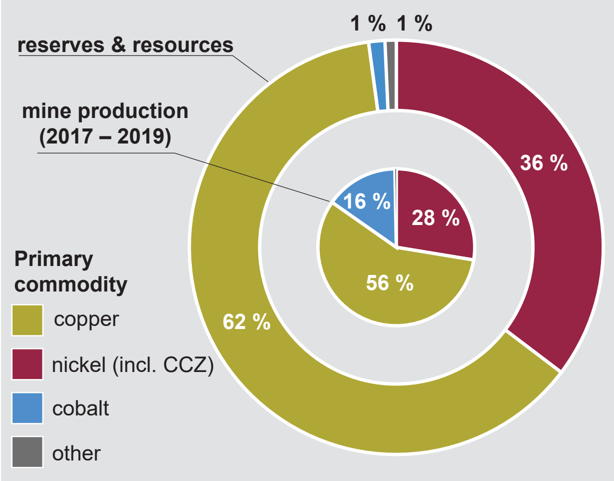

Fig. 2: *Cobalt production as well as reserves and resources grouped by primary commodity. Primary commodity shares were calculated from a sample of projects based on the selection criteria shown below Table 2. Artisanal production considers cobalt to be the primary commodity.*

This distribution of ore deposits implies that cobalt is predominantly mined as a by-product (Fig. 2). Currently, a good 60 % of the global cobalt reserves and resources are contained in copper deposits; nickel deposits (laterites, manganese nodules in the CCZ and black shales) account for around one third of reserves and resources. While the cobalt production share from artisanal and small-scale mining (ASM) in the DRC is

Table 2: *Key features of major cobalt ore deposit types*

Ore deposit	Mining method	Global share of production, reserves & resources (R&R)*	Ore grades (average / variation)*
Stratiform sedimentary rock-hosted copper deposits	Mostly open pit, partly underground	70 % (production) 60 % (R&R)	0.3 % Co (0.1 – 0.8 %), 2.2 % Cu (1 – 5 %); 1.5 – 5 % Co for artisanal mining
Lateritic nickel deposits	Open pit	16 % (production) 18 % (R&R)	0.08 % Co (0.02 – 0,13 %), 1.2 % Ni (0.5 – 2.5 %)
Magmatic Ni-Cu deposits	Mostly underground	11 % (production) 11 % (R&R)	0.04 % Co (0.01 – 0.13 %), 1.1 % Ni (0.1 – 3.3 %), 0.7 % Cu (0.1 – 1.9 %)
Black schists (Finland)	Open pit (bio-heap leaching)	0.8 % (production) 1.5 % (R&R)	0.02 % Co, 0.25 % Ni, 0.14 % Cu
Vein-hosted arsenide ore (Morocco)	Underground	1.4 % (production) 0.1 % (R&R)	1.3 % Co
Manganese nodules (CCZ*)	Ocean floor (4 – 6 km depht)	no active production 7 % (R&R)	0.2 % Co, 1.3 % Ni, 1.1 % Cu, 29 % Mn

* CCZ = Clarion-Clipperton Zone project, Nautilus Minerals, Tonga. Source for production, resources & reserves (R&R) and ore grades: Author's calculations based on evaluating project-specific data sourced from [5], supplemented by BGR data. The table only considers projects with active production in 2017 – 2019 or projects with combined reserves and resources > 100 kt cobalt.

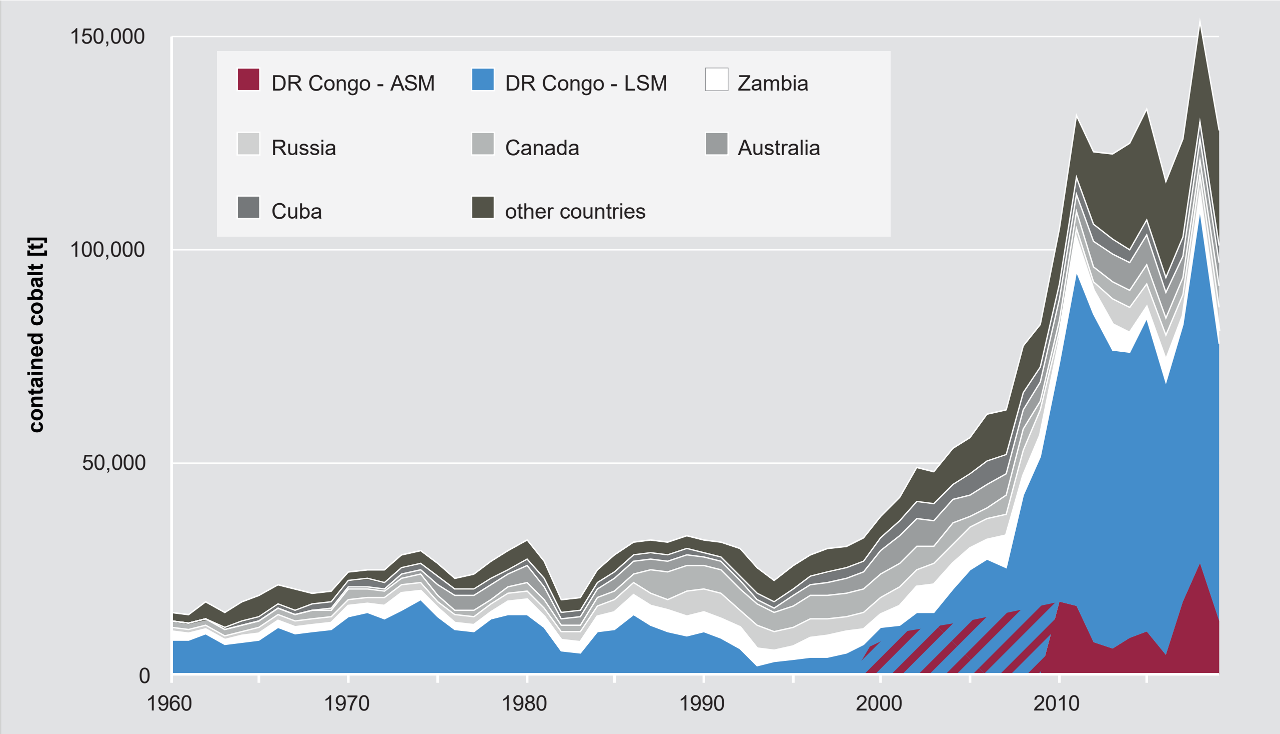

***Fig. 3:** Global cobalt mine production from 1960 – 2019. ASM refers to artisanal and small-scale mining, LSM corresponds to large-scale (industrial) mining. Data obtained from the BGR raw materials database; ASM production share estimate based on the author's research.*

globally relevant, these mining activities currently take place without exploration and formal resource definition. This may change in the future in case the Congolese government engages in the systematic designation of official artisanal mining zones, as provided for in national mining law.

The formation of cobalt-bearing ore deposits spans a long geological period and comprises diverse genetic processes. Secondary enrichment caused by weathering plays a key role for the profitability of mining in the Central African Copperbelt and in lateritic nickel deposits. Accordingly, most of these deposits are located relatively close to the surface. In contrast, mineralisation in magmatic deposits occurs at depths of up to 2 km. The ore bodies of cobalt-bearing nickel or copper deposits often contain several hundred million tonnes of ore. Few deposits have tonnages > 1 billion tonnes, for example the black shale-hosted cobalt mineralisation in Finland. The latter, however, is associated with extremely low ore grades (Table 2).

2.2 Mining and Beneficiation

Global cobalt production is critically influenced by market developments of the associated primary commodities, copper and nickel. In the period from 2017 to 2019, an average of 56 % of cobalt production was associated with copper and 28 % with nickel mining, respectively. Cobalt represented the primary mining commodity for about 16 % of total mine production during this period. The latter production component relates to the Bou-Azzer mine in Morocco and, in particular, to ASM production in the DRC. The intensity of local ASM activities varies with international commodity price developments. The ASM sector, therefore, plays an important role in buffering short-term peaks in commodity demand. This was most recently the case during the cobalt price peak in 2018 when artisanal mining expanded massively. At that time, the two largest artisanal mines, Kasulo and Mutoshi, achieved an annual output of several thousand tonnes of cobalt each. On an individual basis, this made them more important for global cobalt production than any large industrial mine outside of the DRC. The long-term ASM share in global cobalt mine production is around 10 % (average for the period 2009 – 2019).

Cobalt production from the Congolese copper mines has dominated the world market for around ten years (Fig. 3). Without this significant production share, it would be impossible to satisfy the anticipated growth in cobalt demand in the course of the global EV market expansion. Outside of Central Africa, nickel or nickel-copper mines are the main source of cobalt. In contrast, primary copper mines outside of the Copperbelt are currently largely insignificant for cobalt extraction. The platinum mines in southern Africa contribute to cobalt production to a minor extent.

In economic geology terms, and depending on the development of commodity prices and ore grades, cobalt is a co-product (rather than by-product) of copper mining in some cobalt-rich industrial mines in the Congolese Copperbelt. In these mines, the revenues generated from cobalt extraction affect the profitability of the entire mining operation. This situation is reflected in a recent decision made by the Swiss mining company Glencore, which has operations in the DRC. In times of falling cobalt prices, the company decided to temporarily place its Mutanda open-pit mine on care and maintenance. At that time, at the end of 2019, the Mutanda mine represented the world's largest cobalt producer. This case illustrates that industrial copper-cobalt mining in the DRC depends on both copper and cobalt market development. Additional factors need to be considered as well. In the case of the Mutanda mine, for example, the local availability of sulphuric acid for processing has recently presented a problem while the Congolese government has also significantly increased taxes on cobalt exports.

Lateritic ore deposits usually have low stripping ratios (e.g. Murrin Murrin 1.0, Ambatovy 0.6). Depending on the location and geometry of the ore bodies, mining therefore proceeds by open-pit methods. This is also the predominant production method in the Congolese-Zambian Copperbelt. In some Copperbelt mines, and in many magmatic nickel-copper deposits in the rest of the world, on the other hand, production comes from underground mining instead. Artisanal and small-scale mining, as a special form of mining, is widespread in the DRC: depending on the development of cobalt prices, 100,000 – 200,000 artisanal miners selectively mine high-grade cobalt ore in the upper layers of the ore bodies. The ore is extracted by means of manually dug drifts, at depths up to 80 m.

In the Congolese-Zambian Copperbelt, several 100 million tonnes of tailings and slags have been produced through decades of mining activities. This is symbolised by the "Big Hill" slag heap, a prominent landmark of the city of Lubumbashi. Heavy metal contamination of rivers and soils, which is frequently observed in the region, indicates that the storage and disposal of historical tailings often took place without adequate protective cover or sealing. As a result of the high residual cobalt content of tailings, secondary processing has become economically attractive; it is currently being planned or already ongoing in several industrial projects. Furthermore, artisanal miners perform manual reprocessing of tailings. The residual cobalt content of the tailings is in the range of 0.2 to > 2 %, although not all of this is economically recoverable.

The beneficiation process implemented at a given mine in response to the ore's metallurgical properties plays a key role for the profitability of the operation (Fig. 4). In particular, the construction of the processing plants for lateritic nickel projects is associated with significant capital expenditure on the order of several billion US dollars. In cases where these plants are designed to produce ferronickel by smelting, cobalt is usually not recovered, despite the significant cobalt content in many lateritic ores. On the other hand, cobalt is recovered from lateritic deposits along with nickel in plants where ore beneficiation involves a leaching process. The current standard in most of these mines is the HPAL process (high pressure acid leach). It is based on a thermal leaching process by means of sulphuric acid in an autoclave, with subsequent controlled intermediate-product precipitation from the pregnant solution. This produces the intermediate products nickel-cobalt sulphide (MSP) or hydroxide (MHP). Subsequent refining of these intermediates produces cobalt metal and, increasingly, cobalt chemicals. The cobalt recovery rates for the whole process are relatively high, amounting up to approximately 85 % (Fig. 4). In addition to the HPAL process, the Caron process is of historical relevance and continues to be used in a few processing plants. However, this process is inferior to the HPAL process in terms of output rates and energy consumption.

Cobalt recovery from processing mixed sulphide-oxide ore found in the Copperbelt is typically associated with recovery rates of 45 – 70 %; for pure oxide ores, recovery is slightly higher. Recovery rates are usually at the higher end of this range in case processing plants are modernised and optimized for cobalt recovery (in addition to copper). The hydrometallurgical processing of copper-cobalt oxide ores involves leaching and subsequent pH-controlled precipitation processes to separate impurities and recover cobalt as a hydroxide salt. Copper is separated off beforehand by means of solvent extraction (Fig. 4). The crude cobalt hydroxide obtained in this way, with a typical cobalt content of around 30 %, represents an intermediate product that is refined abroad into higher-purity intermediates and cobalt chemicals, mainly in China.

In order to effectively dissolve the cobalt contained in copper-cobalt oxides, the ore is leached using sulphuric acid in a reducing environment. Sulphur dioxide is predominantly used as a reducing agent. Compared to the historically widespread use of copper or sodium metabisulphite, this procedure is cheaper and also generates sulphuric acid as a useful processing reagent. Some deposits in the Copperbelt are associated with elevated uranium concentrations necessitating separate

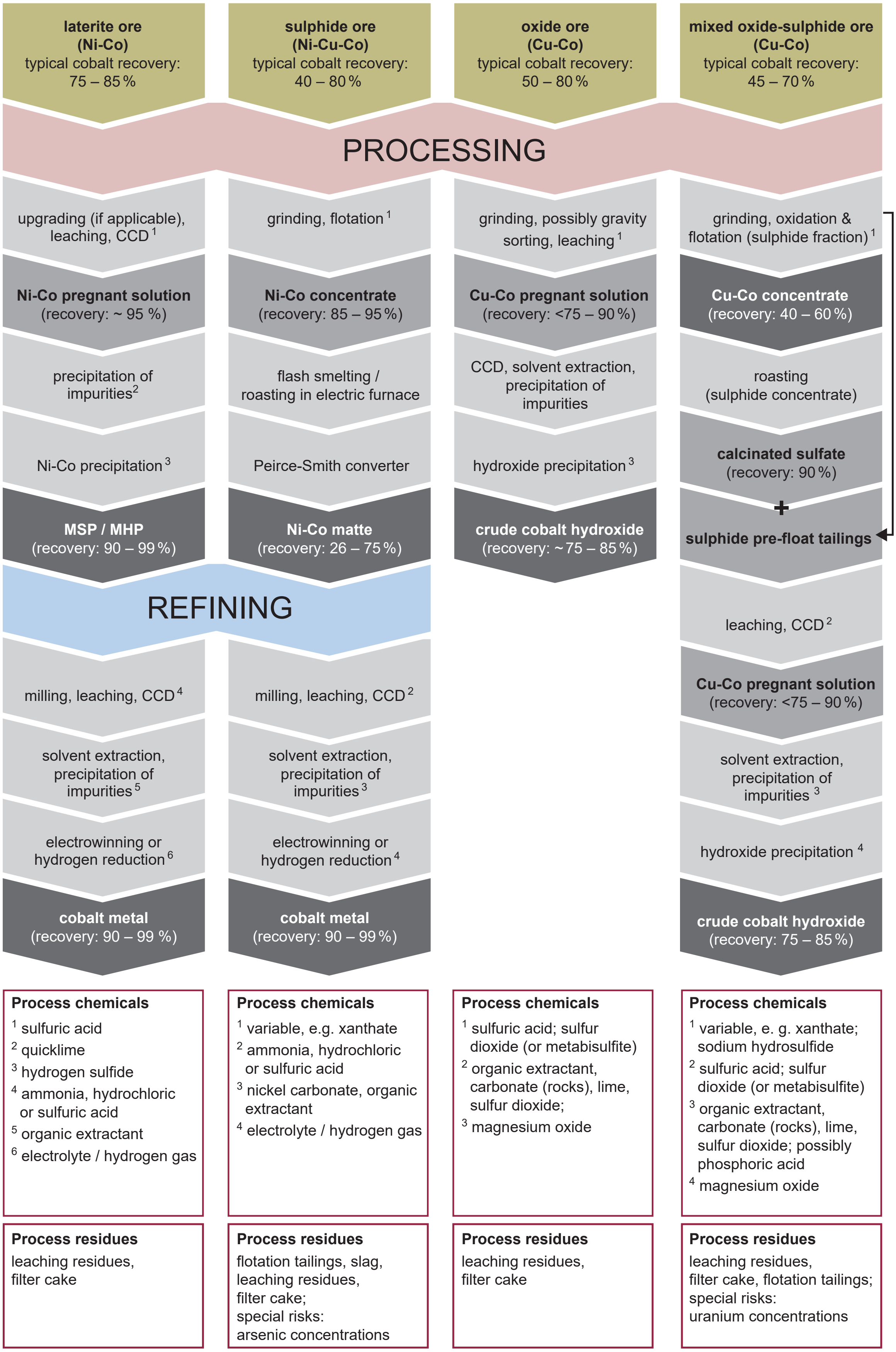

***Fig. 4:** Schematic flowsheets for the most widely used cobalt processing and refining procedures. Dark grey fields indicate intermediate and final cobalt products (that may be shipped internationally). Grey fields indicate additional process products. Light grey fields refer to processing procedures. All recovery figures refer to cobalt only, based on [6] and supplemented by BGR observations as well as [5], [27]. MSP / MHP = mixed sulphide / hydroxide product, CCD = counter current decantation.*

cleaning steps during beneficiation. Because its product exceeded the acceptable uranium concentration in cobalt hydroxide (75 g/t), exports from the Kamoto mine in the DRC were temporarily suspended in 2019. Since then, the mine operator has successfully tested two methods (ion exchange and phosphate precipitation) for reducing uranium concentrations in its cobalt hydroxide. It is currently not publicly known which of these processes was ultimately adopted and how the radioactive process residues are handled.

In the case of mixed oxide-sulphide ores, a combination of flotation, roasting and hydrometallurgical treatment is employed in the DRC; the flotation reject fraction is leached as well (Fig. 4). Individual processing plants are optimised for specific oxide-sulphide ore ratios. Compared to the pyrometallurgical treatment of sulphide ores, the hydrometallurgical production of crude cobalt hydroxide from oxide ores is economically advantageous for the operator. Artisanal miners mainly extract oxide ore and may employ gravity sorting. The artisanal ore is either bought locally and processed to obtain crude cobalt hydroxide or exported directly as a concentrate.

Cobalt recovery from magmatic sulphide deposits is somewhat inefficient at the smelter level. This reflects that the cobalt contained in the nickel-cobalt concentrates is difficult to separate from iron by pyrometallurgical means. The pyrometallurgical treatment of flotation products is optimised for nickel recovery. Therefore, the associated typical cobalt recovery rates are often relatively low (Fig. 4). Accordingly, the slag has a high cobalt content which may be recovered by secondary processing. As some nickel sulphide ores are associated with arsenic, the arsenic content of the process products and tailings must be carefully controlled.

In addition to the nickel, copper and cobalt mining and beneficiation methods discussed above, a number of other processes play a minor role in global cobalt extraction. These include the processing of arsenide ores in Morocco where cobalt is recovered from the concentrates using hydrometallurgy. Terrafame extracts nickel, copper, zinc and cobalt by means of bio-heap leaching from a large low-grade black shale deposit in Finland. Subsequent hydrometallurgical processing and refining produces cobalt and nickel sulphate for use in the cathodes of lithium-ion batteries. The synthetic production of radioactive cobalt-60 may be mentioned as a side note. This isotope is used for specialised applications in medical technology and is synthesized in nuclear power stations.

The mining of cobalt-containing manganese nodules and other deep-sea deposits is not yet commercially relevant. Although geological resources have already been quantified in a certain area, the technical and financial feasibility of production has not yet been clarified. Furthermore, open questions still exist with regards to the environmental impacts of mining as well as the regulations of the responsible International Seabed Authority.

While phytoremediation is not yet established as commercial practice, it is of potential interest in the context of mine closure and post-mining land use. For this process, hyper-accumulator plants, which selectively absorb particularly high concentrations of certain metals such as cobalt or nickel from the soil, can be deployed on tailings and other waste rock dumps. These plants are then incinerated and the resulting high-grade "bio-ore" ash is available for subsequent processing.

2.3 Refining and Processing

Intermediate cobalt processing products are refined to either cobalt metal or high-purity cobalt chemicals. Due to the growing importance of lithium-ion batteries, the proportion of produced chemicals, relative to metal, has risen continuously over time. In 2019, about 60 % of cobalt ore was refined into chemicals.

Refined cobalt chemicals in the form of oxides (especially tetroxide) and sulphates represent important intermediary products for producing cobalt-containing cathode precursor materials and, subsequently, lithium-ion batteries. They are also used for pigment production. Cobalt chemicals are produced from concentrates or crude hydroxides without requiring prior refinement to cobalt metal. A large proportion of the cobalt mined in the DRC is processed along this value chain. Cobalt chemicals are predominantly refined in the People's Republic of China where a large proportion of the global production of lithium-ion batteries takes place. In 2019, the Chinese market share in the production of lithium-ion batteries was around 75 % while the European share was around 5 % [7].

The local transport and international shipping of intermediate products is subject to special regulations as cobalt hydroxide is classified as toxic if inhaled. The refining process to obtain chemicals includes leaching with sulphuric acid with the addition of sodium disulphite, solution filtration and solvent extraction of copper and other impurities. Cobalt is then concentrated and crystallised from the solution as sulphate or chlorite. To produce cobalt oxide, the chlorite is reacted with caustic soda or ammonium salt, followed by subsequent calcination or pyrolysis. The precursor material for the cathodes of lithium-ion batteries is fabricated using either hydro- or pyrometallurgy. To this end, the metal chemicals are combined in certain proportions (e.g. nickel, manganese and cobalt in a ratio of 6 : 2 : 2), followed by lithiation of the material using lithium carbonate or hydroxide.

Cobalt metal can also be used for the manufacturing of cathodes for lithium-ion batteries. This may apply, for example, to the lithium cobalt oxide (LCO) cathode type used in the batteries of electronic products. It is also possible to transform cobalt metal into cobalt chemicals. Compared to the direct use of cobalt chemicals in order to obtain cathode precursor material, however, this plays a subordinate role. By contrast, other applications of cobalt metal are much more prevalent, for example as an admixture in nickel alloys, in tool steels and as a magnetic material. Cobalt refining plants are partly located in relative proximity to the mines. In other cases, the processing and refining facilities are connected to the mine sites via pipelines, with lengths up to 220 kilometres (cf. chapter 5.2). Moreover, refining is also carried out at globally scattered locations. For example, Glencore uses its facilities in Norway to refine the cobalt mined and processed in its Canadian mines and partly recovered from scrap. Overall, global cobalt metal refining is subject to a significantly lower market concentration than cobalt chemicals refining, which is dominated by China.

The refining process is based on a hydrometallurgical treatment with subsequent cobalt extraction through hydrogen reduction or electrolysis (Fig. 4). Cobalt recovery in the refining process is consistently high (> 90 %). The cobalt metal obtained in this way is sold on the market as powder, briquettes or cathodes in various specifications.

3 RECYCLING

Recycling currently plays a relatively minor role in the cobalt market. An average recycling volume of around 13,000 t cobalt per year was estimated for the years 2017 – 2019 [1]. The contribution of recycling to total cobalt supply is around 10 %. Market observers expect that integrated recycling systems may eventually have a significant financial impact on the price structure in EV value chains by contributing to reduced production costs for lithium-ion batteries. Even though only small quantities are currently made available to the market, the recycling sector will therefore play a stronger role in supplying cobalt and other battery metals in the long term.

Lithium-ion batteries contain a large number of valuable raw materials that can be recovered using suitable processes. These include copper, aluminium, iron, cobalt, lithium, nickel, manganese, graphite and plastics. The product lifespan of lithium-ion batteries is 2.5 – 8 years for batteries in electronic devices, and 8 – 10 years in electric vehicles. In addition, a secondary product use is widespread in developing and emerging countries and further extends the service life of these products. Accordingly, cobalt demand growth in the short to medium term will essentially have to be covered by expanding primary production. At the same time, integrated recycling concepts are increasingly ready for the market. In the long term, these recycling concepts are expected to make a significant contribution to cobalt supply and to company business models.

Today's cobalt recycling market is characterised by significant geographical differences. A number of recycling service providers in the EU are paid by the product manufacturers to recycle and dispose of their products at the end of their lifespan. This indicates that in many cases the recycling process in the EU is currently not economically viable on the basis of the contained value of the recoverable raw materials. The EU therefore seeks to support the expansion of the circular economy as part of its "Green Deal". In China, the world's largest EV market, the situation is somewhat different but the underlying challenges are comparable. All Chinese cobalt recycling companies operate additional business segments beyond recycling in order to ensure their operations remain overall profitable [1]. Only in periods of high commodity prices, as most recently during the cobalt price peak in 2017 – 2018, does the recycling process pay off based on the value of the contained raw materials alone.

Other business segments of Chinese recycling companies include either directly connected services (such as the packaging and distribution of secondary products) or refining and further processing of recycled materials into precursor material and cathodes for lithium-ion batteries. Therefore, recycling should not be regarded as a stand-alone business but forms part of an integrated business model of the company. From this perspective, the rising number of EV battery plants within the EU should be regarded as an important factor for strengthening the overall development towards a circular economy.

Traditionally, cobalt recycling mainly refers to alloys and scrap. The recycling rates are highly variable. Superalloys had a recycling rate of around 90 % in 2005. The rate was much lower for other products (catalysts, magnets, steels), occasionally as low as 10 % [1]. In many cases, these products were recycled in order to recover other metals while recovering their contained cobalt was not considered as economic. Lithium-ion batteries in consumer electronics were frequently not recycled at all but disposed of in landfills instead. This reflects the generally problematic handling of electronic waste ("e-waste"). Despite an estimated value of over USD 60 billion, only 20 % of the valuable materials contained in electronic waste were recovered through formal recycling in 2017 [8].

At a technical level, the recycling process for cobalt-bearing lithium-ion batteries comprises the following steps: after sorting the different batteries by type, the structural components of the battery – electrolyte, anode and cathode – are dismantled and separated in a mechanical pre-treatment stage. Safety is a particular concern at this stage as the batteries can combust due to lithium oxidation upon contact with the air. As part of this step, and in addition to the mechanical treatment, a thermal treatment is also employed to drive off binders, carbon and organic additives by means of pyrolysis.

In a subsequent step, the valuable materials are recovered from the cathode. This is mainly done via hydrometallurgical treatment, applying to 60 % of all Chinese cobalt recycling. The process allows for the recovery of cobalt, nickel and manganese, as well as lithium. Similar to the refining process of primary raw materials, the hydrometallurgical treatment comprises various steps including leaching, precipitation, ion exchange, solvent extraction and electrochemical separation. More than 80 % of the contained valuable substances are recoverable [1]. Cobalt is usually recovered as a sulphate, carbonate or tetroxide; as such, it is directly usable during the subsequent manufacturing of cathode precursor material.

Pyrometallurgical treatment and cathode-to-cathode processing represent alternative or complementary processing technologies to hydrometallurgical treatment. Pyrometallurgical treatment creates an alloy of copper, cobalt, nickel and iron, from which the valuable materials are then extracted via hydrometallurgy. The advantage of this process is its speed and reduced complexity, as it has lower requirements for mechanical pre-treatment; the disadvantage is its lower process efficiency. Moreover, lithium is not economically recoverable from the slag generated in the process. In cases where cathode-to-cathode treatment is employed, an old cathode is re-inserted into a new lithium-ion battery. The spent electrolyte is extracted, the cell components separated and the cathode material lithiated once again. However, it is unclear whether the performance of lithium-ion batteries produced in this way can match that of a new battery.

4 SUSTAINABILITY ASPECTS OF MINING

Cobalt is predominantly obtained as a by-product of copper and nickel mining; in some mines in the DRC, it represents a co-product of copper mining. Evaluating the sustainability of cobalt mining is therefore intricately linked to the extraction of these primary commodities. For this reason, water use, energy consumption and emission figures as discussed below refer to one tonne of ore and all its contained metals. From these data, the requirements of individual large mines can be inferred using the ore throughput rates shown in Table 3.

4.1 Environment

Land Use and Reclamation

Cobalt production associated with copper or nickel mining temporarily occupies areas for mining and processing infrastructure, as well as for storing mine waste including overburden, tailings and slags. In 2005, the global land use change due to nickel mining was estimated at almost 2 km². Between 1990 and 2010, a total area of 34 km² was newly occupied by nickel mining [9]. Copper mining's global land use change is much larger, with an estimated area of 66 km² in 2016 [10]. Recalculating these combined figures to apply only to those copper and nickel mines where cobalt is extracted as a by- or co-product yields an annual land use change of about 3 km². In practice, these aggregated global estimates are of limited informative value when viewed in isolation. Rather, the decisive factor is the extent to which a given area occupied by mining would otherwise fulfil important economic or ecosystem functions. For example, in some places in Southeast Asia nickel (-cobalt) mining is associated with clearing ecologically valuable rainforests.

Adequate and sustainable reclamation or renaturation efforts are a key concern for land no longer reserved for on-going mining activities. In fact, whenever possible, the operator should implement a progressive reclamation approach in parallel to the on-going mining activities. In the past, mine operators have often failed to meet this requirement. Historical liabilities pose a major problem on some mining concessions that are still active today.

***Table 3:** Average ore throughput and production of the ten largest industrial cobalt-producing mines in 2017 – 2019.*

Mine	Country	Operator (main owner)	Contained cobalt production [t]	Ore throughput p.a. [million t]
Mutanda	DR Congo	Glencore	25,400	6.3
Tenke Fungurume	DR Congo	China Molybdenum Co.	17,100	5.4
Kamoto	DR Congo	Katanga Mining (Glencore)	9,400	6.5
Etoile	DR Congo	Chemaf (Shalina Resources)	5,300	1.1
Ruashi	DR Congo	Jinchuan Group Int. Res. Co.	4,800	1.2
Taimyr district	Russia	Norilsk Nickel	3,500	17.7
Moa Bay	Cuba	Moa Nickel JV (Sherrit)	3,400	3.3
Ramu	Papua-New Guinea	Metallurgical Corp. of China	3,200	3.6
Taganito	Philippines	Taganito Mining Corp. (Nickel Asia Corp.)	3,100	3.1
Murrin Murrin	Australia	Minara Resources (Glencore)	3,000	3.0

All mines shown above produce cobalt as a by- or co-product of copper or nickel mining. The list only shows projects with at least two years of active production in the 2017 – 2019 period. Figures were rounded to 100 t (cobalt content) and 100,000 t (ore throughput). The Mutanda open-pit mine was placed on care and maintenance in late 2019. The Kamoto mine (pits and underground operations) has been in its ramp-up phase since 2018. Therefore, the 3-year average production shown above is significantly below its anticipated final production capacity (up to 30,000 t p.a. contained cobalt).

This is exemplified at a dramatic scale in the Congolese-Zambian Copperbelt, where the intensity of mining activities has been increasing since the beginning of the 20th century. The large number of abandoned open pits, tailings, slags and other waste dumps indicates that in many cases reclamation was unsuccessful or did not happen at all. The total inventory of tailings and slags stored on the surface in the Congolese part of the Copperbelt in 2018 is estimated at 416 million tonnes [11]. Similarly, there is no adequate reclamation of the areas affected by artisanal and small-scale mining in the DRC.

The high spatial concentration of deposits and mines along the prospective ore zones in major mining districts such as the Copperbelt poses a significant challenge with regards to sustainable reclamation. The interlocked mining activities of neighbouring concession holders result in complex impacts on their respective reclamation responsibilities. Figure 5 and the adjacent text box illustrate this problem using the example of the Kamoto mining district in the DRC, currently the world's most important cobalt mining district. A positive side effect of the rising demand for cobalt is the increasing economic interest in reprocessing historical Copperbelt tailings using modern methods in order to recover the residual cobalt content. In combination with increasing public scrutiny, this improves the chances that the affected areas will eventually be subject to a proper reclamation process.

Water

The extraction and beneficiation of Australian nickel-cobalt sulphide ores requires in the order of 1,100 – 1,400 litres of water per tonne of ore [13]. By comparison, the mining, hydrometallurgical processing and refining of laterite ores requires 1,000 – 4,500 l/t. The BGR estimates similar water requirements for the copper-cobalt mines in the DRC, including processing and local refining to crude cobalt hydroxide and cathode copper, respectively (e.g., around 1,000 l/t for the Mutanda and Kamoto mines controlled by Glencore). In the Russian polymetallic mines operated by Nornickel significantly higher values apply, around 30,000 l/t, up to the point of refining [13]. As these values may additionally reflect the impact of mining and processing platinum group elements (in conjunction with nickel, copper and cobalt), they may not be directly comparable in the above context.

A mine's total water use is covered to varying degrees by water abstraction and reuse of industrial water, either with or without reprocessing. The rates of water reuse and recycling are highly variable for different cobalt mines. For example, Glencore reports a reuse and recycling efficiency of 73 % for its two Congolese mines; accordingly, only 270 litres of new water abstraction is required to treat one tonne of ore. On the other hand, BHP reports a significantly lower water reuse and recycling rate of around 34 % for the Australian Nickel West Complex, located in an arid region.

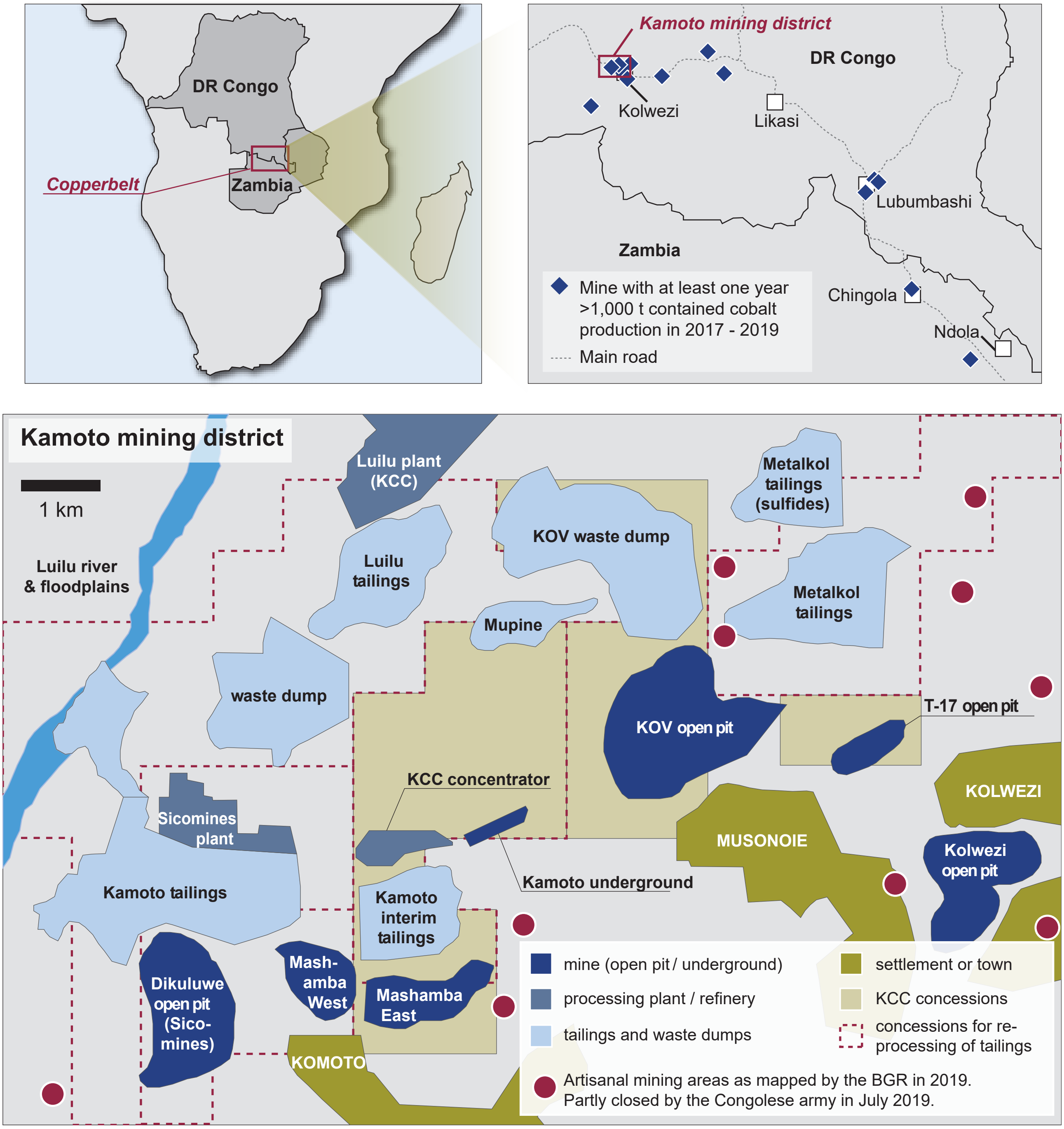

***Fig. 5:** Location of the Kamoto mining district, close to the provincial capital of Kolwezi (upper insets) and local distribution of mining areas and tailings (lower figure). Mining of copper-cobalt ore takes place both underground and in open pits. In addition, there is significant re-processing of historic and recent tailings. The figure is based on satellite images taken in 2019.*

Except for a few Australian mines, global cobalt production takes place in regions without pronounced water scarcity and with high precipitation rates. For example, the south-eastern DRC has an annual precipitation rate of around 1200 mm. Therefore, water management and drainage is a demanding task for the mine operators in order to control the inflow and outflow of water and keeping the mines dry. Compared to copper mines elsewhere (e.g., in Chile and Peru), water scarcity risks for the cobalt-producing copper and nickel mines are much less pronounced. On the other hand, different water-related challenges arise from the socio-economic context of the mining activities. In the DRC, for example, as a result of weak governance and state institutions, only 26 % of the population had direct access to drinking water in 2014, while the average in Africa is 60 % [14]. This fact, combined with the frequent public perception that mining is water-intensive, results in demands on industrial mine operators to provide local communities around the mines with improved access to drinking water.

The contamination of surface waters, groundwater and coastal waters in the vicinity of mines, processing and tailings storage facilities can be particularly problematic. This includes the effects of acid mine drainage associated with sulphide ores. Historically, the resulting environmental problems often went hand in hand with inadequate regulatory standards. These days, regulations have improved and accidents or negligence on the part of the operator play a major role for creating water quality problems, partly exacerbated by corruption risks. Even if these problems often occur as isolated incidents that are not representative of the mining sector as a whole, they nonetheless result in a negative public perception and challenge the social acceptance of mining at a broad scale. Ecosystems affected by heavy metal contamination or river siltation due to historical mining activities often require decades to regenerate. For example, river sediments and soils in the vicinity of the Congolese mining centre of Kolwezi show strong historical contamination with cobalt, copper, nickel, zinc, lead, thorium, and, locally, arsenic as well as uranium. In places, the observed concentrations of these metals exceed the limits as defined by applicable standards and guidelines by a factor of 100 – 1,000 [15]. Even though today's mine operators in the region are not directly responsible for causing these problems, some residents nonetheless perceive their current mining activities as being linked to these issues.

The pollution around the Norilsk processing centre on the Russian Taimyr Peninsula, north of the Arctic Circle, is currently of major public concern. After damage to a diesel tank at a coal-fired power station in May 2020, up to 21,000 m³ of diesel (i.e., 17,500 tonnes; the exact figure is subject to some controversy between the mining company and the regulator) leaked and contaminated soil and surface water bodies over an area of around 350 km². Partial thawing of the permafrost zone was cited as one of the possible causes for tank failure while other sources mentioned inadequate maintenance. The costs of the initial emergency remediation measures are estimated at almost USD 150 million, the total anticipated clean-up costs over a period of 5 – 10 years at around USD 1.5 billion [16]. In June 2020, another incident was reported at one of the Norilsk processing plants: 6,000 m³ of unfiltered process wastewater were illegally discharged into the environment in order to avoid flooding due to heavy rainfall. These incidents, as well as the extensive historical damage resulting from emissions around the Norilsk mining centre, are particularly critical because the regeneration of Arctic ecosystems is extremely slow.

Mining areas and reclamation – challenges in the Kamoto mining district in the Congolese Copperbelt

The Kamoto mining district comprises a number of copper-cobalt deposits discovered in the early 20th century. The district currently represents the world's most important cobalt production centre. With some temporary interruptions, many deposits have been mined as open-pit or underground operations since the 1950s. These historic mining activities and their tailings have resulted in large-scale emission problems that remain harmful to the environment and the health of residents to this day.

The largest local operator in the district is Katanga Mining Ltd. (KML), a subsidiary of Swiss mining group Glencore. In addition, Chinese and Kazakh mine operators are active in the district. The Congolese parastatal mining company, Gécamines, has stakes in several projects while also running its own mining operations in the surrounding areas. Artisanal and small-scale mining is widespread as well. Cobalt is currently produced from both mining the original deposits as well as re-processing of the large historical tailings of recent decades. The concession areas for primary ore mining and re-processing of tailings overlap (Fig. 5).

Glencore's local involvement in the district is based on a joint venture agreement concluded in 2005 and a subsequent merger of local operators in 2008. Based on these agreements, the company owns the mining rights on three concessions, as well as the rights to process the associated tailings, some of which are located outside of the concessions.

The close proximity of multiple mining operations in the district limits the space available for the storage of new mine tailings. At present, KML tailings are stored in the former Mupine open pit – however, the available storage space will reach its limit by the end of 2021. Storing tailings above ground level would create new risks of possible dam failures. For the time being, KML keeps negotiating with local land owners with regards to developing additional areas for storing the tailings generated during its on-going operations; these negotiations have not yet been successfully concluded.

KML puts the closure and reclamation costs for the Kamoto mine at USD 132 million [12]. These costs relate only to the mining legacies of the last few years for which the company is responsible. Given the close linkages between KML and Gécamines activities, however, the distribution of closure and reclamation responsibilities is complex. For instance, KML is responsible for the reclamation of historical tailings located within its concessions in case it has itself added material to these dumps. In return, Gécamines has undertaken to take responsibility for other tailings located on the concession. The sustainable reclamation of the entire historical mining district hence requires that all individual operators fully comply with their respective reclamation responsibilities.

Energy and Emissions

Processing either sulphide or laterite ore has a significant impact on the energy and emission profile of a given mine. An evaluation performed in 2010 estimated that Australian nickel-copper-cobalt mines producing sulphide ore required 0.4 – 1.1 GJ/t of ore for the mining and concentration process (figures converted from [13]). Similar values can be estimated for the copper-cobalt mines producing mixed oxide-sulphide ore with associated hydrometallurgical processing in the DRC. At Canadian mines with associated smelting and refining activities, the energy requirements increase to 1.7 – 2.4 GJ/t ore. In contrast, the mining, smelting and refining of lateritic ore requires around 4 – 8 GJ/t ore. The energy required for processing and producing metals from lateritic ore is thus significantly higher than that required for sulphide ore. However, a high energy demand of 2 – 9 GJ/t of ore is also reported for the mines on the Russian Taimyr and Kola Peninsulas, even though they mine sulphide ore [13]. One of the reasons for this is that these are underground mines, which are generally more energy-intensive. In addition, the mining facilities are in need of modernisation.

The carbon footprint of a mine is influenced by both its direct emissions as well as the location-specific energy mix. The mine's vehicle fleet accounts for around 30 – 50 % of the greenhouse gases produced in open-pit mining. Optimising and electrifying parts of the fleet (for example by means of trolley assist) allows for a significant reduction in fleet emissions. This is exemplified by the Kevitsa mine in Finland (producing nickel, copper and cobalt), which is planning to reduce emissions by 80 % in this way. The vehicle fleets in some of the underground mines in Canada's Sudbury district have also been increasingly electrified since 2018. Before such kind of measures commenced, the CO_2 emissions for mining and processing cobalt-bearing sulphide ore were in the range of 20 – 170 kg CO_2/t ore. For laterite ore, this increases to around 360 – 620 kg CO_2/t ore as a result of the greater energy intensity of the treatment process (figures converted from [13]). Consequently, mining and processing a tonne of cobalt-bearing ore generates roughly as much CO_2 as a short-haul or a short medium-haul flight per passenger.

The site-specific energy mix of the mines is highly variable. While copper-cobalt mining in the DRC is often associated with social and ecological risks, the energy mix of these mines is mostly climate-friendly. Almost all major mines are connected to the provincial power grid which mainly relies on hydropower. However, trucking of the ore and intermediate products to the ports of southern Africa generates significant emissions during the subsequent transport stage. In Canada's Sudbury district, electricity comes primarily from hydropower and nuclear power, but also from fossil fuels. Nornickel Group's Russian nickel, copper and cobalt mines and processing centres depend on fossil fuels, but the company pursues a strategy of increasing the use of hydropower. In 2016, 25 % of the company's energy requirements were met by renewable sources. Many cobalt-producing mines are dependent on reagents such as sulphuric acid and sulphur dioxide which may be produced in local plants (Fig. 4). This process releases energy (as heat) that is convertible into electricity via turbines and may thus contribute to the mines' power supply.

At a local scale, mining-related dust emissions are highly relevant. Although operators regularly sprinkle the mine roads for dust suppression, tailings may be inadequately maintained while mine-related traffic also occurs on dirt roads outside of the concession. This creates significant dust exposure for local communities in the Congolese-Zambian Copperbelt where mining activities are intimately associated with numerous settlements, located in the immediate vicinity of open-pit mines and tailings (Fig. 5). Respiratory diseases, including silicosis, as well as carcinogenic or other diseases resulting from daily exposure to the heavy metals in the dust, pose serious health risks for the local population.

The smelting of sulphide ore and the resulting sulphur dioxide emissions has created significant environmental impacts in many historic mining districts. Such emissions may further be associated with inadequately secured tailings. This aspect is discussed in Section 5.1.

4.2 Social and Economic Aspects

Occupational Health and Safety

From the perspective of occupational health and safety, ASM activities in the DRC should be regarded as especially critical. Cave-ins and other accidents in underground drifts and adits have led to numerous fatalities in recent years. In general, ASM activities are associated with higher risks if performed underground, rather than in open pits. In both cases, however, numerous accidents could be avoided if proper safety procedures were implemented.

For industrial mine operators, occupational health and safety is often a central aspect of their sustainability management. Notwithstanding this commitment, industrial cobalt extraction is also occasionally affected by occupational health and safety problems.

Operations at the Ramu open-pit mine in Papua New Guinea (producing nickel and cobalt), developed and operated by Chinese investors, have been repeatedly criticised and suspended by local authorities due to occupational health and safety concerns. In China, local media repeatedly reported accidents and fatalities in association with the Jinchuan nickel, copper and cobalt mines. In part, these were related to the tectonic and geotechnical complexities of local underground mining. As a result of these complexities, a 700 m deep ventilation shaft collapsed in 2005; in 2016 underground roof failure affected an area of 11,000 m².

The transport safety of mining products and processing reagents outside of the mining concessions is of high local relevance. In 2019, the cobalt hydroxide produced at the Kamoto mine exceeded the permissible transport limits with regard to radioactivity. The mine operator is therefore currently integrating a method to reduce the uranium content during processing [12]. In the same year, a truck carrying sulphuric acid for the nearby Mutanda open-pit mine collided with oncoming vehicles on a public road. Acid was spilled over a large area, 18 people died. This underlines the important role played by external contractors and service providers in mining. When evaluating sustainability management, these stakeholders need to be considered as well, in addition to the mine operators themselves.

Child Labour

Poverty-driven child labour is a widespread phenomenon in the Global South. Affecting many economic sectors, including artisanal and small-scale mining, child labour is especially critical in cases where it is associated with health risks or comes at the expense of school attendance and losing educational opportunities. The Congolese artisanal cobalt sector is associated with explicit risks for the occurrence of the worst forms of child labour, based on the definition of the International Labour Organization (ILO). In this context "worst forms" include activities that are harmful to the health, safety or morals of children, as well as forced labour. Situations involving the worst forms of child labour have been repeatedly observed in the Congolese ASM sector, albeit as incidents, rather than as a general phenomenon.

An inspection of 58 artisanal cobalt mines in 2019 found that a total of around 2,500 children were present at 29 % of the sites, including many young children under the age of 10 [17]. The children predominantly performed light work tasks such as ore sorting which do not necessarily fall under the ILO definition. Due to their poverty-driven nature, it is almost impossible to effectively prohibit child labour. Incentives to perform such tasks can be reduced by offering children free access to education (and if school attendance also includes a meal, for example) or by creating alternative, less problematic income opportunities. During the BGR-supported mine inspection survey conducted in the DRC in 2019, two out of 58 artisanal cobalt mines were found to be associated with the worst forms of child labour. These latter incidents fall under the risk definition employed in the context of supply chain due diligence.

Local Communities

The presence of children on artisanal cobalt mines in the DRC is not least due to the fact that mining activities often take place in, or in the immediate vicinity of, settlements. This is exemplified by the Kasulo site, an artisanal mining zone covering a 40-hectare area in the centre of the local city of Kolwezi. Starting in 2014, numerous residents began performing illegal ASM activities in their backyards and basements in order to benefit from the rich cobalt mineralisation. In 2017, the provincial government decided to evacuate the district and designated it as an official artisanal mining zone. The 600 houses were demolished, their residents relocated or compensated and a fence was constructed around the site. The Chinese Huayou Cobalt Corporation became involved as a buyer through a local subsidiary. The BGR estimates that up to 15,000 small-scale miners were active in Kasulo at the height of the cobalt price peak in 2018 (Fig. 6).

With the cobalt price collapse that followed in 2019, artisanal miners abandoned large parts of the Kasulo concession; fewer than 1,000 active miners remained and Huayou withdrew its engagement. In retrospect, this implies the question whether the formally desirable designation as an official artisanal mining zone – which in this case included the forced relocation of 600 households – represented a truly sustainable approach. This dynamic illustrates the difficulty in dealing with an artisanal mining rush, including its potential social upheavals. Conversely, artisanal mining may also be carried out over a long time period in a stable social environment, without significant internal migration. The latter scenario improves the chances for introducing responsible mining standards and developing viable alternatives to social problems such as child labour.

Commonly, the area claimed by exploration and mining concessions is much larger than the area actually occupied by the mining infrastructure and mine waste dumps. In the Congolese part of the Copperbelt alone, the concessions currently cover an area of around 70,000 km², corresponding to 28 % of the total area of the provinces of Haut-Katanga and

Fig. 6: *Impressions from the Congolese Copperbelt. A – Lubumbashi's „Big Hill" slag hill. B – Mutanda (central-northwest pit), the world's largest (copper-) cobalt mine in 2018. C – The artisanal mining area of Kasulo, located in the centre of Kolwezi, at the height of the cobalt price peak in April 2018. Photo reference: BGR.*

Lualaba. Given this situation, it is obvious that there will be frequent contacts between license holders and the local population, influencing the social acceptance of industrial mining activities. Even at the exploration stage, prior to mining, social conflicts may arise; this is further accentuated in the DRC by widespread ASM activities. The Canadian PDAC and other associations have developed principles for responsible exploration in order to address such problems [18].

Engaging and consulting with local communities at an early stage of project development, well before mining activities commence, is an important prerequisite for facilitating the social acceptance of mining among the local population ("social license to operate"). A positive example in this regard was set at the Voisey's Bay nickel-cobalt mine on the Canadian Labrador Sea.

Economic Relevance

Copper and cobalt mining is a significant source of tax revenue and export earnings for the Congolese state. From a financial perspective, the copper and cobalt subsector represents by far the most important branch of the national mining sector. Informal artisanal cobalt mining with up to 200,000 workers provides an additional economic stimulus at the local level, even though this is not directly reflected in official key metrics, such as GDP. Employment in the artisanal cobalt sector is currently on the decline, estimated at less than 100,000 miners. This is due to the negative cobalt price development since the peak in 2018. In other cobalt-producing countries, the economic relevance of cobalt mining is significantly lower because the economy and the mining sector are more diversified.

Based on typical ore grades, cobalt is usually a by-product of copper or nickel extraction. In the past decade, large nickel-cobalt mining projects have frequently faced profitability challenges, caused by both unfavourable commodity price developments and misassumptions during project planning. As illustrated in Figure 7, the development of large lateritic nickel-cobalt projects was characterised by massive budget overruns. The collapse in cobalt prices and the decision of the Congolese government in December 2018 to hike cobalt export royalties from 3.5 % to 10 % threatens the profitability of several DRC-based copper-cobalt mining operations. Against this backdrop, Glencore decided to place the globally important Mutanda copper-cobalt mine on care and maintenance, for an initial period of two years from the end of 2019.

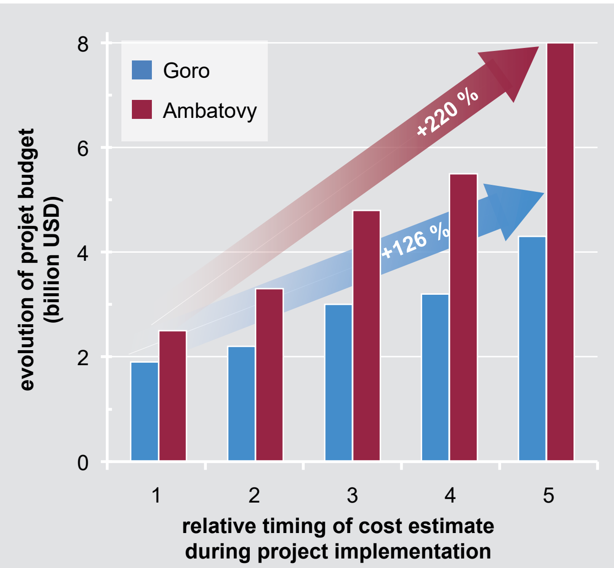

***Fig. 7:** Evolution of project budgets through time during the construction of the nickel-cobalt mines of Goro (New Caledonia) and Ambatovy (Madagascar). Cost estimates refer to different points in time throughout 2005 – 2010 (Goro) und 2007 – 2012 (Madagascar), based on figures quoted in [5].*

4.3 Governance

Corruption Risks

Only three of the large cobalt-producing countries – Australia and Canada, as well as New Caledonia, which is under French administration – are associated with low governance and corruption risks. All other producer countries tend to perform poorly in the corresponding rankings of the World Bank and other organisations. This is particularly evident in the DRC. The country participates in the Extractive Industries Transparency Initiative (EITI) and has established a national implementation process for this purpose. However, the national EITI process coordinator was arrested in April 2020 for embezzling USD 217,000. This example illustrates the extent of the corruption problems in the country.

Concerns have also been raised with regards to the activities of Glencore in the DRC. Glencore is one of the world's leading mining groups and indirect supplier of cobalt to multiple EV manufacturers. In the DRC, the company or its subsidiary entered into agreements with companies controlled by the Israeli businessman Dan Gertler in order to acquire the Kamoto and Mutanda concessions. Gertler is said to be close to the former Congolese President Kabila and allegedly forwarded some of the profits of his business deals to Kabila's entourage. In return, he benefited from financial advantages during the original partial acquisition of the above and other mining concessions in the DRC. For this reason, Gertler was declared a "specially designated national" by US authorities. As such, companies doing business with him are subject to possible sanctions. In 2015, for example, a Gertler-controlled company was due a royalty advance of USD 58 million. This amount was transferred from a Glencore subsidiary to the Gertler-controlled Africa Horizons Investment Ltd. [12]. Gécamines, a parastatal company, is also involved in these opaque financial transactions. To avoid potential US sanctions, Glencore makes the payments due to Gertler's companies in EURO instead of in US Dollars.

Supply Chain Due Diligence Risks

Due diligence risks, as defined by the OECD, include conflict financing, human rights violations, forced labour, the worst forms of child labour, corruption and fraud to conceal the origin of minerals. With the exception of conflict financing, all of the above risks are relevant in the DRC's cobalt sector [17]. This includes, but is not limited to child labour in the ASM sector. Human rights violations may, for example, result from the conduct of the mining operators' security forces towards artisanal miners. Similar risks pertain to the deployment of the Congolese army to industrial mining concessions in 2019, aimed at preventing illegal artisanal and small-scale mining.

Outside the DRC, such risks are significantly less pronounced but remain relevant nonetheless. Protests by local communities against mining projects and their impacts can lead to violence. This is exemplified by the conflict surrounding the Taganito open-pit mine in the Philippines. Some members of the indigenous population were dissatisfied with the distribution of mining profits as well as the resettlement associated with the nickel-cobalt mining activities. A local militarised group, the New People's Army, attacked the mine in 2011, destroying mining equipment, taking hostages and killing four guards in the process. As a consequence, the mine operator founded a private militia for protection, trained by the Philippine army. In the context of responsible supply chains, the question arises as to whether such militias contribute to the protection of the local population or whether there are risks that they will themselves get involved in human rights violations.

5 SUSTAINABILITY ASPECTS OF PROCESSING

5.1 Environment

Emissions

Historically, the most important environmental impact caused by processing cobalt-bearing copper and nickel ores relates to sulphur dioxide emissions. These emissions are generated through the oxidising smelting of sulphide ores or the roasting of concentrates for subsequent hydrometallurgical processing. Fugitive sulphur dioxide emissions form an acid mist that is incorporated into precipitation, thus contributing to the acidification of soils and surface water bodies. The resulting acidic environment increases the mobility of heavy metals, which – like sulphur dioxide itself – are toxic to flora and fauna in high concentrations. The historical damage caused by sulphur dioxide emissions is considerable. For example, 7,000 lakes in the Canadian Sudbury district suffered massive biological damage as a result of acidification [19]. Drastic environmental damage is observed in the catchment areas of the Russian processing centres Taimyr (Norilsk) and Kola, as well as in the Congolese-Zambian Copperbelt. In addition, acid rain caused corrosion and structural damage to buildings in mining districts.

These days, the majority of smelters have significantly reduced their sulphur dioxide emissions. As a rule, more than 90 % of the sulphur dioxide produced per tonne of metal is usually captured if filters are installed. Regulatory requirements play a key role in this development. The legal limit of total permissible sulphur dioxide emissions for the INO (Integrated Nickel Operations) facilities in Sudbury, Canada, has been successively reduced from 150,000 t SO_2 in the 1980s to currently below 30,000 t SO_2 – while at the same time doubling the output of smelted nickel [20]. In addition, local operators are obliged to report publicly on their emissions. In the EU and China, the emission limits for primary copper smelting in 2016 were 500 mg SO/Nm³ (standard cubic meters) or 600 mg SO/Nm³, respectively [21]. In practice, the effectiveness of emission capturing among different smelters is highly variable. The emissions by some smelters are significantly below the respective regulatory limits. This is motivated by multiple factors including regulatory requirements, social acceptance, company reputation as well as economic reasons. The latter reflects that captured sulphur dioxide can be used to produce sulphuric acid. This process releases heat that can be used to generate energy.

The high emissions associated with the processing plants of the Russian Nornickel group remain problematic. These involve both sulphur dioxide and airborne heavy metal contamination related to dust. In recent years, and in particular since 2015, Nornickel has begun modernising some of its facilities. It is worth noting that Norway offered financial support for this task in order to improve the emission profiles of the smelting plants located on the Kola Peninsula. The emissions associated with these plants also affect Scandinavia, leading to protests by Norwegian residents. In addition to addressing the issue politically, the Norwegian government therefore offered financial assistance to support Nornickel in modernising its plants. Although the SO_2 emissions on the Kola Peninsula remain significant, they were reduced by 21 % (to 132,900 t) in 2016, compared to the previous year [22].

Cradle-to-gate evaluations of raw materials and their emission profiles integrate multiple stages of the value chain, for instance mining, beneficiation and refining. Applying this approach through a life cycle assessment allows calculating the theoretical share of emissions attributable to cobalt, separately from nickel or copper. Based on 2012 data, a total of 38 kg CO_2 equivalents and 0.62 kg SO_2 equivalents were generated to produce 1 kg of cobalt metal [23]. The Cobalt Institute plans commissioning a study to calculate comparable values for cobalt chemicals, the main cobalt product used in the EV value chain.

5.2 Social and Economic Aspects

Social Acceptance

Pipelines are a critical aspect influencing the social acceptance of cobalt processing operations. The pipelines serve to connect mines with smelting or refining sites, supply certain process chemicals or facilitate wastewater disposal. Pipelines pumping ore slurry to distant processing sites reach a significant length at several large lateritic nickel-cobalt projects: 135 km in the case of the Ramu mine in Papua New Guinea, 220 km for the Ambatovy mine in Madagascar.

In both cases, local residents have expressed strong reservations about the pipelines, fearing leaks or other defects may cause emissions that negatively affect human health or local ecosystems. The European Investment Bank, one of the lenders of the Ambatovy project, examined these allegations. The bank found that leaks in a supply pipeline running through a residential area did in fact result in occasional sulphur dioxide emissions exceeding regulatory limits. While the bank's experts concluded that this did not cause any serious hazards to human health, they criticised the operator's emergency preparedness plans [24].

INCO, at that time the operator of the Voisey's Bay nickel-cobalt mine in Canada, set a positive example for social engagement when planning the construction of the mine's processing plant. Initially, in 2006, INCO planned constructing the facility in Argentia, but later on changed its plans and selected Long Harbour as the new location instead. This modification of the plan allowed the company to avoid routing an effluent pipeline through a protected watershed that was essential for the potable water supply of local communities.

Value Addition

Public information on the production costs and value addition along the individual supply chain segments for lithium-ion batteries – from the cathode manufacturers to the cobalt chemicals refiners and back to the mine – is relatively limited. Commercial platforms do provide price notations for individual products and value distribution models for the raw materials contained in battery cathodes. However, it is difficult to generalize these figures as the underlying economic supply chain arrangements and business models vary from one manufacturer to the next. Pricing mechanisms defined in supply contracts may not directly mirror published commodity and chemical product price notations. Notwithstanding these uncertainties, it is relatively safe to say that DRC exports of crude cobalt hydroxide fetch about 60 – 80 % of the contained metal value. In addition, a certain proportion of the country's cobalt mine production is exported as concentrate, rather than hydroxide; refined cobalt exports, on the other hand, are insignificant. Overall, cobalt is the DRC's second most important export product behind copper, with a typical annual export value of USD 1 – 2 billion.

There is a clear trend of cost-driven substitution of cobalt as a component in the cathodes of lithium-ion batteries. In 2019, cathodes – containing variable proportions of cobalt and other battery metals – contributed about one quarter to the total battery production costs. Against the backdrop of current commodity price developments, battery producers seek to reduce these costs, for instance by increasing the nickel content of the cathode relative to cobalt or by developing cobalt-free cathode types. Roskill, a commodity research service provider, estimates that the production costs of an electric vehicle (in this case a Tesla Model 3 with energy consumption of 55 or 54 kWh) significantly decrease when a cobalt-free battery is installed –around USD 20,000 instead of USD 25,000 [25]. While this price difference reflects multiple production factors, it is partly related to installing a cobalt-free LFP battery instead of a cobalt-containing NCA battery. Accordingly, cobalt substitution increases the EV manufacturer's profit margin. However, as implied in the introduction to this section, these model calculations should be treated with caution due to the uncertainties associated with resolving and generalizing production costs along the battery supply chain.

5.3 Governance

Responsible Supply Chains

The cobalt sector features an increasing number of initiatives aimed at improving risk management in the supply chain. Public discussions of child labour risks associated with artisanal cobalt supply from the DRC acted as an important catalyser for this development. The Cobalt Institute, a cobalt industry association, created the CIRAF (Cobalt Industry Responsible Assessment Framework) reference framework for reporting and risk management. Other initiatives serve as discussion platforms.

Monitoring the activities of smelters and refiners represents a key element for strengthening the transparency and control in mineral supply chains. This reflects that smelters and refiners occupy a central position at the interface of upstream and downstream supply chains while their total number is relatively limited at a global scale. At the time of writing, 92 cobalt smelters and refiners have been identified by the Responsible Minerals Initiative (RMI). Of these, eleven have successfully passed an audit against the RMI assurance standard while another 23 sites are either in the process of preparing for an audit or implementing corrective measures [26]. The audit process examines management system conformity with regard to the OECD recommendations on supply chain due diligence. The RMI initiative has been using a similar standard to audit smelters and refiners of so-called conflict minerals – tin, tantalum, tungsten and gold – since 2010. From 2021 onwards, an EU regulation requires importers of these commodities to demonstrate due diligence on any imports of the affected minerals or metals above certain volume thresholds. Cobalt is not included in this regulation; therefore, participating in cobalt supply chain audits is voluntary at this stage.

In 2019, an international law firm sued major US corporations such as Apple, Google and Tesla on behalf of 14 Congolese parents and children. The firm claims that in accepting cobalt from the DRC in their products, the defendants supported mining companies believed to have benefited from child labour. The outcome of this legal action is still pending. It cannot be ruled out that this process will lead to international corporations and their suppliers deliberately refraining from purchasing cobalt extracted by Congolese artisanal miners in order to not expose themselves to further legal risks. It is important to note, though, that pursuing such a strategy would not override the fundamental dynamics leading to child labour in the DRC. Furthermore, a strategy of disengagement may undermine the moderate transparency advances achieved in the artisanal cobalt sector in recent years.

6 CONCLUSIONS

Public discussions on cobalt supply chains, especially in the EV sector, frequently focus on child labour risks associated with artisanal cobalt supply from the DRC. While child labour represents an undisputed problem, limiting discussions to this subject does not do justice to the complexities influencing sustainability in the cobalt sector. As illustrated in the present factsheet, the sustainability of cobalt extraction, closely linked to the sustainability of copper and nickel mining, has long been associated with a wide variety of challenges on a global scale.

The experience of past decades and especially the last few years has shown that many of these sustainability challenges were successfully addressed; others continue to represent significant problems. Regulatory standards as well as the requirements imposed by investors, lenders and consumers play a key role in influencing the cobalt sector's sustainability dynamics. Moreover, the progress achieved in managing supply chain risks for so-called conflict minerals demonstrates that the engagement by downstream industries is a key factor for promoting legal and responsible artisanal supply chains. Adopting and building on these lessons learnt represents a significant opportunity for the cobalt sector.

7 BIBLIOGRAPHY

[1] Roskill (2019): Cobalt: Outlook to 2029. 15th Edition, Roskill, London.

[2] Roskill (2020): Nickel sulphate: Outlook to 2029. 3rd Edition, Roskill, London.

[3] Mbeingi Diluzolele, G. (2019): Supply and demand analysis of cobalt. MSc thesis, University of Geneva. https://archive-ouverte.unige.ch/unige:124753 [accessed: 7.7.2020].

[4] Al Barazi, S. (2018): Rohstoffrisikobewertung – Kobalt. DERA Rohstoffinformationen 36. Bundesanstalt für Geowissenschaften und Rohstoffe, ISBN 978-3-943566-49-9.

[5] S&P Global (2020): S&P Global Market Intelligence, New York. https://www.spglobal.com/en/ [accessed: 7.7.2020].

[6] Crundwell, F.K., Moats, M.S., Ramachandran, V., Robinson, T.G., Davenport, W.G. (2011): Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals. Elsevier, Oxford/Amsterdam, ISBN 978-0-08-096809-4.

[7] SMM News (2020): China will continue to be the global battery production center in the next few years. https://news.metal.com/ [Stand: 29.5.2020].

[8] World Economic Forum (2019): A new circular vision for electronics: Time for a global reboot. World Economic Forum, Geneva. http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf [accessed: 7.7.2020].

[9] Nakajima, K., Nansai, K., Matsubae, K. et al. (2017): Global land-use change hidden behind nickel consumption. http://dx.doi.org/10.1016/j.scitotenv.2017.02.049.

[10] Tost, M., Bayer, B., Hitch, M. et al. (2018): Metal mining's environmental pressures: A review and updated estimates on CO_2 emissions, water use, and land requirements. https://doi.org/10.3390/su10082881.

[11] Tshamala Kaniki, A. & Tumba, K. (2019): Management of mineral processing tailings and metallurgical slags of the Congolese copperbelt: Environmental stakes and perspectives. https://doi.org/10.1016/j.jclepro.2018.11.131.

[12] Kamoto Copper Company S.A. (2019): Katanga Mining Limited – NI 43-101 technical report on the

material assets of Katanga Mining Limited, Lualaba Province, Democratic Republic of Congo, 7.11.2019. www.sedar.com [accessed: 7.7.2020].

[13] Mudd, G.M. (2010): Global trends and environmental issues in nickel mining: Sulfides versus laterites. https://doi.org/10.1016/j.oregeorev.2010.05.003.

[14] KPMG (2014): Democratic Republic of Congo – Country mining guide. KPMG Global Mining Institute. https://assets.kpmg/content/dam/kpmg/pdf/2014/09/democratic-republic-congo-mining-guide.pdf [accessed: 7.7.2020].

[15] Atibu, E.K., Laxroix, P., Sivalingam, P. et al. (2018): High contamination in the areas surrounding abandoned mines and mining activities: An impact assessment of the Dilala, Luilu and Mpingiri Rivers, Democratic Republic of the Congo. https://doi.org/10.1016/j.chemosphere.2017.10.052.

[16] BBC (2020): Arctic circle oil spill prompts Putin to declare state of emergency. BBC, 4.6.2020. https://www.bbc.com/news/world-europe-52915807 [accessed: 7.7.2020].

[17] BGR (2019): Mapping of the artisanal copper-cobalt mining sector in the provinces of Haut-Katanga and Lualaba in the Democratic Republic of the Congo. Bundesanstalt für Geowissenschaften und Rohstoffe, ISBN 978-3-943566-68-9.

[18] PDAC (2014): e3 plus: A framework for responsible exploration – principles and guidance notes. Prospectors & Developers Association of Canada. https://www.pdac.ca/priorities/responsible-exploration/e3-plus/principles [accessed: 7.7.2020].

[19] Keller, W., Heneberry, J.H., Gunn, J.M. (1998): Effects of emission reductions from the Sudbury smelters on the recovery of acid- and metal-damaged lakes. https://doi.org/10.1023/A:1009975116685.

[20] Sudbury Integrated Nickel Operations (2020): Environmental management system & community engagement report 2019. https://www.sudburyino.ca/en/environment/EnvironmentalPerformance/2019%20Annual%20EMT%20Report.pdf [accessed: 7.7.2020].

[21] International Copper Study Group (2017): Regulatory trends affecting the processing, transport and disposal of copper industry impurities. https://www.ecometales.cl/ecometales/site/docs/20191113/20191113154836/1_don_smale_presentation.pdf [accessed: 7.7.2020].

[22] Bellona (2018): Nornickel and the Kola peninsulas. https://www.nornickel.com/files/en/investors/cmd/Nornickel-on-The-Kola-Peninsula.pdf [accessed: 7.7.2020].

[23] Environmental Resources Management Ltd. (2016): The environmental performance of refined cobalt: Life cycle inventory and life cycle assessment of refined cobalt – summary report. Cobalt Development Institute, Guildford.

[24] European Investment Bank (2018): Ambatovy nickel project, Madagascar. Conclusions report, complaint SG/E/2012/04. https://www.eib.org/attachments/complaints/2018-03-19-sg-e-2012-04-ambatovy-conclusions-report-en.pdf [accessed: 7.7.2020].

[25] Roskill (2020): White paper – the resurgence of LFP cathodes. Roskill, London.

[26] Responsible Minerals Initiative (2020): Cobalt refiners list. http://www.responsiblemineralsinitiative.org/cobalt-refiners-list/ [accessed: 25.12.2020].

[27] Dehaine, Q., Tijsseling, L.T., Glass, H.J et al. (2021): Geometallurgy of cobalt ores: a review. https://doi.org/10.1016/j.mineng.2020.106656. [accessed: 25.12.2020].

EDITORIAL

Editor:
© Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, BGR)
B 1.2 Geology of Mineral Resources Department
Mining and Sustainability Unit
Stilleweg 2
30655 Hannover

E-Mail: mineralische-rohstoffe@bgr.de
www.bgr.bund.de

Author:
Philip Schütte
Research supported by:
Sebastian Vetter, Siyamend al Barazi, Gudrun Franken
Layout:
Jolante Duba
Title photo:
© Wellnhofer Designs – stock.adobe.com

Date:
January 2021

DOI:
10.25928/argd-2w51