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Cobalt: demand-supply balances in the transition to electric mobility

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Abstract

The expansion of the electric vehicle market globally and in the EU will increase exponentially the demand for cobalt in the next decade. Cobalt supply has issues of concentration and risk of disruption, as it is mainly produced in Democratic Republic of Congo and China. According to our assessment these risks will persist in the future, likely increasing in the near term until 2020. Minerals exploration and EV batteries recycling can make for an improvement in the stability of cobalt supply from 2020 on, which together with the expected reduction in the use of cobalt, driven by substitution efforts, should help bridge the gap between supply and demand. Despite this, worldwide, demand is already perceived to exceed supply in 2020 and such a loss making trend is expected to become more consistent from 2025 on. In the EU, although the capacity to meet rising demand is projected to increase through mining and recycling activities, there is an increasing gap between endogenous supply and demand. The EU's supplies of cobalt will increasingly depend on imports from third countries, which underscores the need for deploying the Raw Materials Initiative and the Battery Alliance frameworks.

Executive Summary

As a result of the accelerated introduction of electric vehicles (EVs), the demand for lithium-ion batteries (LIB) is expected to increase significantly in the future. However, a potential limiting factor in the deployment of LIBs may be the supply of cobalt, largely used in a number of conventional battery chemistries.

Potential disruptions in cobalt supply can arise from the near-monopolistic supply structures for both mined and refined cobalt, unethical practices in producing countries, the long lead-time for developing new mining projects, and the fact that cobalt is mainly mined and recovered as a co- or by-product of copper and nickel.

In 2016, 126 000 tonnes of cobalt were mined in 20 countries around the world, with the largest supply coming from the Democratic Republic of the Congo (55 % of global cobalt production). In turn, EU production of cobalt was estimated at 2 300 tonnes, all sourced from Finland.

Considering various levels of uptake of LIB and other cobalt uses, we estimate that global cobalt demand will increase at a compound annual growth rate of between 7 % and 13 % from 2017 to 2030. On average, annual global cobalt consumption is expected to reach about 220 000 tonnes in 2025, increasing to 390 000 tonnes in 2030, if not alleviated by substitution mechanisms with the adoption of alternative battery chemistries requiring less cobalt. In the EU, overall cobalt demand may amount on average to 53 500 tonnes in 2025, increasing to 108 000 tonnes in 2030.

The production capacity of cobalt from operating mines worldwide is currently estimated at 160 000 tonnes. In 2030, considering additional exploration projects under late stage development, cobalt mining may provide for around 193 000 – 237 000 tonnes. Whilst some projects are expected to bring significant cobalt into the market by 2025, additional supply will most likely come from the expansion of existing producers, led by DRC. In the future, countries such as Australia and Canada are expected to gain additional importance as cobalt producing countries, helping to reduce the concentration of supply and the risk of disruption by 29 % in 2030. In the EU, future mine production might be of 2 700 tonnes in 2020, increasing to 3 200 tonnes in 2030. By then, this amount could provide for around 6 % of European cobalt consumption in the EVs sector.

Substitution of cobalt in Li-ion batteries, although possible, has not taken place. Lately, it has even gone in the opposite direction, as the majority of automakers switch to cobalt-intensive chemistries, drawing on its comparative advantages in terms of energy density and range. Although the present trend is expected to continue until 2020, leading to further increases in cobalt demand of up to 6 %, there is broad consensus over the reduction of cobalt consumption in batteries from 2020 onwards. Until 2025, cobalt can be reduced by 17 %, and by another 12 % between 2025 and 2030, on account of changes in the EV battery chemistry mix. Nickel is likely to be the main substitute in such applications.

Significant opportunities to recycle cobalt may also be anticipated over the coming years. In the EV batteries sector the recycling potential is significant, as these batteries will be easier to collect. However, given the recent introduction of EVs in global and European markets, large-scale recycling can only be more effectively accomplished beyond 2025. In 2030, recycling of EV batteries can provide for around 10 % of the European cobalt consumption in the EVs sector, if established to the extent of the assumptions used to develop the forecasts.

Considering annual supply and demand balances in global average scenarios, including the effects of substitution over demand, and of EV batteries recycling over projected mine supply, demand is already perceived to exceed supply in 2020. By then, around 8 000 tonnes of additional cobalt would be needed to cover global demand. This deficit is expected to increase to 64 000 tonnes in 2030.

Bridging gaps between supply and demand in the EU may require specific actions along the three pillars of the European Raw Materials Initiative.

In the mining sector, the promotion of specific brownfield projects merits further action, along with the attraction of investment to reactivate inactive projects and promote efficient greenfield exploration in highly prospective areas. Private investment in minerals exploration may come in line with improvements in the regulatory context, as many EU countries do not currently ensure the right to exploit a new deposit provided other regulatory conditions are met.

As the EU will continue to depend on imports in the future, consolidating trade agreements with countries such as Australia and Canada, projected to gain additional importance as cobalt producing countries, can also be beneficial as a means of ensuring responsible sourcing practices.

Cobalt recycling is likely to be boosted by higher collection rates of EV batteries from 2025 on. Nonetheless, the high share of PHEV in Europe may entail additional uncertainties as to whether relevant collection rates are met in the future. Ensuring that such targets are met is of particular importance to the optimisation of future balances between supply and demand.

On the use of cobalt in EV batteries, an overall reduction of 29 % per unit is expected by 2030. However, the deployment on a mass scale of such low-cobalt chemistries will still be needed. As nickel is likely to bear the load of the substitution strategy, these developments should come in line with close monitoring exercises of the nickel supply and demand situation. In the longer term, additional reductions in the use of cobalt in the automotive sector might also come in line with the market uptake of fuel cell vehicles and other cobalt-free chemistries.

Finally, the raw materials sector plays an important role in the value-chain of battery and automotive industries. Increasing the industries' manufacturing capacities, which now represent only 2 % of the global capacities, besides preventing a technological dependency on competitors, should also have positive spill-over effects on private investment along all segments of the value-chain. If properly developed, it should promote the responsiveness and competitiveness of the European raw materials sector whilst ensuring cobalt supplies through domestic mining and recycling.

1 Introduction

1.1 Setting the scene: the importance of cobalt and pressing challenges of supply security

Some analysts believe that cobalt can be a limiting factor in the deployment of lithium-ion batteries (LIB) [e.g. (MIT, 2017), (Bloomberg, 2017), (Greentech Media, 2016)]. Emphasis has been put on the ability to secure relevant supply streams to fast-growing markets, the prevalence of near-monopolistic supply structures and the fact that cobalt is usually mined as a co- or by-product of copper and nickel.

Cobalt is needed for LIB in the market for electric vehicles (EVs) and stationary energy storage, both with increasing global relevance in the transition to a low-carbon economy. Globally, EVs demand is expected to grow considerably as parity price is achieved with internal combustion engine vehicles (ICE)[1]. Also, it will be pushed up by pollution prevention legislation, for example in China, or efforts to decarbonise road transport, as in the case of Europe.

As long as the expansion of the use of these technologies is certain, and subject to significant growth rates, supplementary cobalt supply will be needed, creating additional pressure upon traditional and emerging supply sources. Thus, substantial increases in mining and recycling are expected to move in line with market expectations. However, limitations to supply, resulting in production lagging behind demand or price increases, may arise for several reasons.

Constrains to mineral supply may arise, for example, with cutbacks on copper and nickel production or lack of capacity at existing mine facilities. Although it is acknowledged that mineral resources and reserves are dynamically changing over time as the costs of extraction and price of metal change, giving mining companies some flexibility to re-adjust production as appropriate, the ability to manage new supply and demand balances is likely to be achieved at the expense of increased prices to downstream users (e.g. (Bloodworth & Gunn, 2014), (SEI, 2012).

On the other hand, while a continued price increase could galvanise efforts to open new mines, the long lead-time for their development could give rise to shortfalls in future provision. Although high market prices remain the driving force behind innovation, assisting the search for substitution chemistries, supply-demand imbalances can persist and be amplified by the long development time of successful substitutes.

Limitations to supply can also arise due to geopolitical constraints. This is particularly relevant in the case of cobalt, whose gross production is concentrated in a small number of countries, including politically insecure suppliers. Around 55 % of cobalt is mined in the Democratic Republic of the Congo (DRC) (WMD, 2018), viewed as politically unstable (WGI, 2018), thereby reducing the certainty of access to supply. Moreover, according to (Bloomberg, 2018), DRC declares cobalt to be strategic and intends to more than double the taxes applied to cobalt exports, which could lead to an aggressive increase in the commodity price.

Adding to DRC's instability and weak governance, the country is under pressure to restrict artisanal mining, in which a prevalent and unethical use of child labour has been identified (Amnesty International, 2017). According to Roskill, around 7 000 tonnes resulted in 2012 from artisanal mining, whilst SMRE argues that presently approximately 20 % (or ≈ 14 000 tonnes) of DRC's cobalt production comes from artisanal based operations (Roskill Information Services, 2014), (SMRE, 2017), (Darton Commodities, 2016).

At the same time as analysts believe DRC will continue to be a main source of cobalt in the future, car makers and technology companies such as Apple, Microsoft and Tesla are looking to secure future cobalt supply and to ensure the metal used in rechargeable

[1] According to (Bloomberg, 2017), beyond 2025 falling battery costs will push EVs to price parity.

batteries is sourced ethically (Cobalt Investing News, 2018), (Bloomberg, 2018). To this end, companies' strategies have included closing long-term supply deals directly with mining companies (Bloomberg, 2018) or engaging actively in promoting and implementing traceability mechanisms throughout the supply chain (e.g. The Better Cobalt pilot project).

In the longer term, demand levels for the strategic raw materials will also depend to a large extent on the level at which present technologies will be employed in the future. Factors such as efficiency improvements or the uptake of alternative materials and/or technologies, within the concept of substitution, are likely to affect global demand.

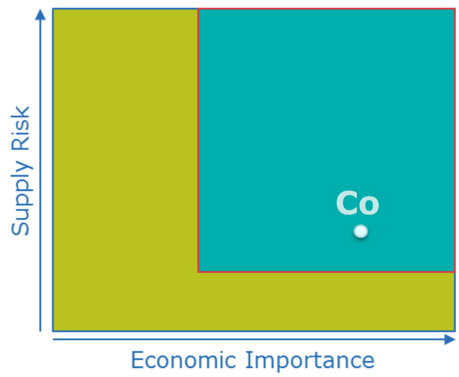


Figure 1. Cobalt position within the European Commission criticality matrix, as of 2017.

In the European context, cobalt has been identified as a critical raw material on the basis of its economic importance and high supply risk, in the 2011, 2014 and 2017 assessments carried out by the European Commission (European Commission, 2018) (Figure 1).

This status and the context described call for regular monitoring exercises of supply and demand developments.

1.2 The European Commission's initiatives concerning batteries

Recognising the importance of batteries for the clean energy transition, the European Commission established sectoral policy priorities and actions expressed in the following initiatives[2]:

- The European Battery Alliance, launched in October 2017, whereby key strategic objectives were laid down. These involved the creation in the short term of a competitive manufacturing value chain in Europe to prevent the technological dependence on competitors in third countries and ultimately capitalise on the jobs, growth and investment potential of batteries.

- The Strategic Battery Action Plan, adopted in May 2018, whereby a set of 'concrete measures to develop an innovative, sustainable and competitive battery 'ecosystem' in Europe' were adopted. The plan is structured around six priority actions to promote the production and use of high-performing batteries and to set sustainability targets throughout the batteries value chain. Securing the sustainable supply of raw materials for battery applications is one strategic action area.

In May 2018, the European Commission published a Staff Working Document Report on Raw Materials for Battery Applications (EC, 2018), to detail the implementation of the Battery Action Plan in this strategic action area.

1.3 Cobalt prices – fluctuation and causes

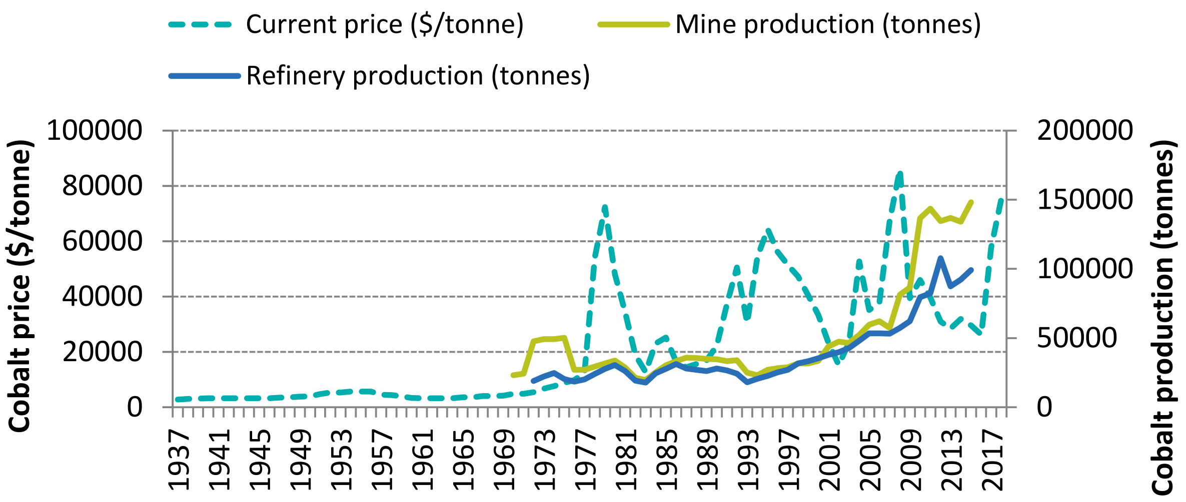
International cobalt prices have fluctuated significantly over the past decades (Figure 2).

Since 2000, cobalt demand has begun to rise progressively. Strong demand for rechargeable batteries, initially used in electronic equipment, was the main driver of growth. Cobalt mine production increased by around 270 %, from 34 000 tonnes in

[2] https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en

2000 to around 126 000 tonnes in 2016 (WMD, 2018)[3]. While prices have remained relatively stable and low since 2012 (on average 24 000 EUR/tonne), these nearly doubled to values around 50 000 EUR/tonne in 2017, reaching 65 000 EUR/tonne[4] in February 2018 (S&P Global Market Intelligence, 2018).

Figure 2. Historical mine production and prices of cobalt.

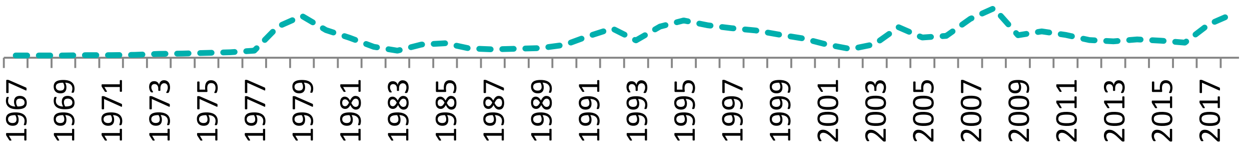


Data sources: (BGS, 2017), (USGS, 1999), (USGS, 2015), (S&P Global Market Intelligence, 2018).

Various events that have affected cobalt prices are noted in Figure 3. These range from de-stocking, geopolitical unrest, the setting of a joint price and recession.

[3] To be noted that (WMD, 2018) and (USGS, 2018) have calculated different figures for cobalt mine production.
[4] Official 3-month prices per tonne according to London Metal Exchange (LME), adjusted to euro-dollar exchange rates as of February 2018 (0.80).

Figure 3. Significant events affecting cobalt prices in the past.



=>**1967-1976** Sales of significant quantities of cobalt from U.S. Government stockpile

=>**1978** Strong cobalt demand, invasion of Zaire's copper-cobalt mining region, and free market developed

=>**1981-1982** Sharp recession

=>**1984** Zaire and Zambia announce a joint producer price

=>**1990** Strikes in Zaire and political unrest in Zambia, cave-in at Zaire's Kamoto copper-cobalt mine, Russia began exporting cobalt to western markets

=>**1991** Unrest in Zaire and dissolution of the Soviet Union

=>**1991-1993** Economic downturn and decrease in U.S. defence spending

=>**1993-1998** Sales of cobalt from the U.S. Government stockpile

=> > **2000** Steady demand increase owing to Li-ion powered electronics (including cell phones & computers)

=> **2008** Cobalt deficit, DRC instability

=> **2012** Cobalt surplus, China de-stocking

Data sources: (USGS, 1999), (GGC, 2011), (SEI, 2012).

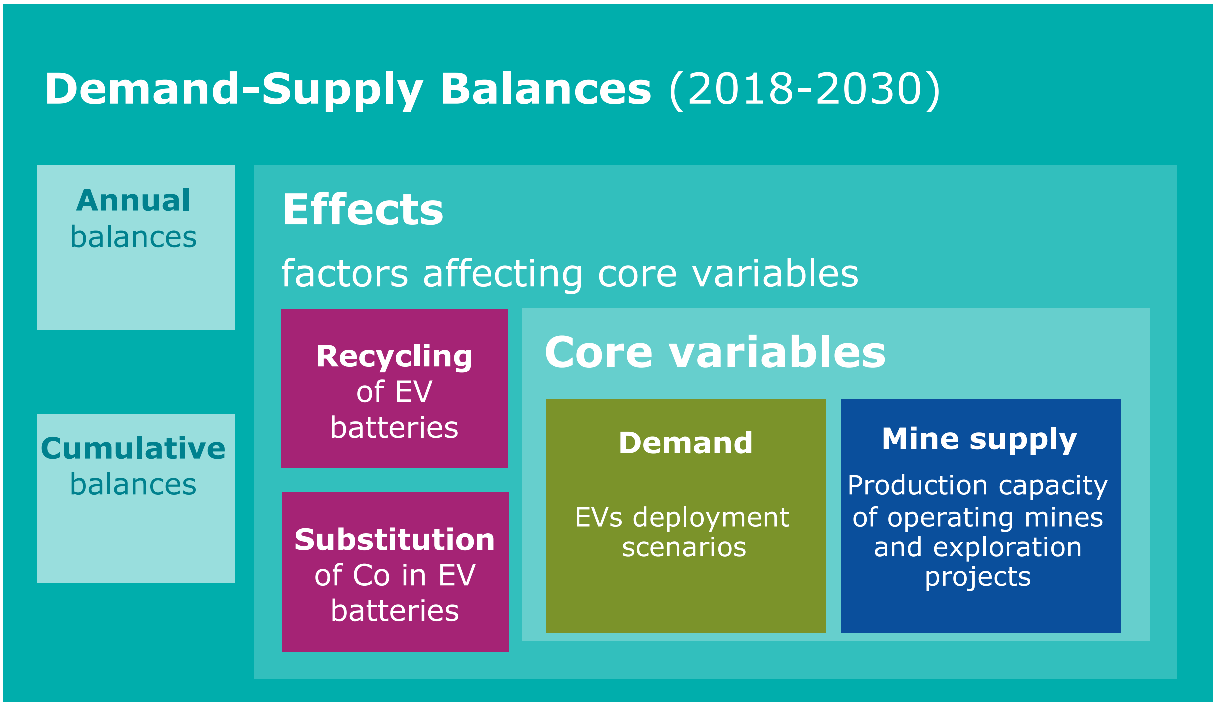
Since 2017, concerns over cobalt supply in the context of soaring demand for batteries for transport, together with concerns over long-term access to cobalt resources following instability in DRC, appear to have pushed prices up [e.g. (Roskill (PR), 2018)]. This could be transitory, with the industry returning to the lower prices of the recent past, or alternatively, further price increases may occur due to limited cobalt output, as discussed above.

Considering the historical volatility of cobalt prices over time, it is also reasonable to assume that the present context can be prone to stockpiling, which in the past triggered sudden sharp increases in cobalt prices. For example sales from US stocks would have resulted in increased cobalt prices in 1995 (Figure 3).

1.4 Objectives, approach and layout of the study

The present analysis aims to assess the increased need for cobalt in the transition to electric mobility while comparing it with projected supply over an equivalent period. The overall approach is summarised in Figure 4 and details are given in Table 1. The analysis is global in scope but focuses on a number of elements specific to the EU. Its timeframe extends to 2030.

Figure 4 Summary of the study's phased approach.



The demand situation is presented in section 2. Demand forecasts incorporate expected levels for various intensities of uptake of electric vehicles. Several scenarios based on the International Energy Agency (IEA) targets for EVs deployment were used to estimate market growth. In those scenarios the scale and size of the EV market and Li-ion demand vary with deep decarbonisation, market expectations and business as usual considerations.

The third section deals with mine supply. Future supply estimations were assessed against the reported and estimated production capacities of operating mines and ongoing late-stage exploration projects. The analysis took into account the magnitude of current mining operations, the time taken to start new operations, the availability of resources at operating facilities and ongoing late-stage exploration projects. Although the analysis is set against a general market context of continuing high prices, as a precondition for making all inventoried projects profitable, it offers an indication of the relative potential to increase production in the future, therefore providing a reasonable basis for the analysis carried out in this study.

The effects of substitution over demand patterns and of EV battery recycling as a means of increasing supply are also assessed in the same timeframe. The analysis is presented in sections 4 and 5, respectively. The analysis of substitution focused on the increased uptake of those battery chemistries with a reduced cobalt content until 2030. The quantification of additional cobalt supply available to the market from recycling EV batteries relied on certain product life-times, collection rates and efficiency assumptions.

The balances between production and consumption are then used to assess shortages and surpluses, in the timeframe 2018 to 2030. The results are provided on a yearly basis (non-cumulative approach), comparing directly the production potentially available from mining and recycling activities with the annual overall demand, seen as dependent on the scale and size of the EV market and substitution efforts. The analysis is also carried out on a cumulative basis, for each 5 year period.

Partial analysis of gaps between supply and demand in each sub-system, constructed with the conditions gradually laid down, is provided at the end of each main chapter. In the concluding chapter (section 6), future scenarios are related to each other in one consistent forecasting approach.

The European demand and endogenous supply of cobalt are also evaluated in this report. Cobalt mine production and recycling capacities within EU Member States are examined alongside, with the extent to which they may contribute in the future to the effective management of supply and demand balances. As in the global context, cobalt demand will be influenced mainly by the expansion of the EVs market, evolving according to the projections made by the European Road Transport Research Advisory Council (ERTRAC).

Table 1 Key elements considered in the analysis of gaps between supply and demand.

A. Demand (2010-2030)	
Rational: Co is needed for LIB in the market for EVs. In the future Co demand will be influenced mainly by the expansion of the EV market, pushed by price parity with ICE, legislation and decarbonisation efforts.	
EVs deployment scenarios	
World	**EU**
1. Reference Technology Scenario. 2. Paris Declaration on Electro-Mobility and Climate Change Scenario (100 million EVs in 2030).	1. ERTRAC – low scenario: CO_2 targets are achieved by more efficient and hybridised internal combustion engine vehicles.
3. Deep decarbonisation scenario - IEA 2DS (160 million EVs in 2030) 4. Deep decarbonisation scenario - IEA B2DS (200 million EVs by 2030)	2. ERTRAC – high scenario: expected mass production of EVs in the context of deep decarbonisation.
Methodological aspects	
Cobalt demand in the EVs market Factors influencing the calculation: 1. Type of vehicle (BEV/PHEV shares) 2. Battery storage capacity 3. LIB preferred cathode chemistry in 2017 4. Co consumption per KWh 5. Replacement of end-of-life batteries 6. Population growth in the EU	**Cobalt demand in other sectors** 1. Assumed to grow moderately at an annual growth rate of 2.5 %

B. Mine supply (2018-2030)

Rational. In the transition to electric mobility, supplementary cobalt supply will be needed, creating additional pressure upon mining activities. Exploration efforts to increase production through successful mineral discoveries are underway. These projects will add capacities and new actors to the current list of suppliers while contributing to diversification in the market.

Mine supply scenarios

Low-case: Life-of-mine production profiles were simulated using a declining resources method. Reported resources were used to estimate the no. of production years that could theoretically be supported at full capacity.

High-case: All operating mines with reported production capacities are considered including those for which resources are not reported.

Low-case intermediate: A recovery rate of 90 % is assumed throughout the reference period to allow for technological improvements in refining operations (adding on the low-case scenario).

High-case intermediate: throughout the reference period, 20 % of current total production will become unavailable due to unethical practices, geo-political risks or unforeseeable production stoppages (subtracted from the high-case scenario).

Methodological aspects

Projects reviewed fall into the following stages:

1. Operating mines
2. Mine-stage projects: Preproduction and commissioning stages (assumed to come online in 2019)
3. Feasibility-stage exploration projects (assumed to start up in 2021)
4. Prefeasibility and reserves development exploration projects (expected to start up in 2026).

Assumption. The analysis is set against a general market context of continuing high prices as a precondition for making all inventoried projects profitable. The start-up dates of late-exploration projects were assumed to be fixed and established on the basis of the current development stage, irrespective of the project economics.

C. Recycling and substitution effects (2017-2030)

Rational. The full or partial replacement of cobalt in EV batteries can affect demand patterns by triggering a potential reduction in demand. The potential for cobalt substitution in batteries is extensive. Until 2030, other cathode chemistries requiring less cobalt and with higher nickel and aluminium contents will be used increasingly. The recycling of EV batteries will create an alternative cobalt supply, thereby increasing its availability and supply security.

Recycling of EV batteries (2010-2030)	Substitution of Co in EV batteries (2018-2030)
Methodological aspects	
Cobalt available through recycling of EV batteries calculated with the following assumptions: 1. Global EOL-RIR (72 %) 2. Global collection rate (90 %) 3. EU EOL-RIR (variable over time depending on the number of BEV and PHEV units deployed): EU BEV collection rate (90 %); EU PHEV collection rate (50 %) 4. Recovery efficiency (80 %) 5. EV battery life-time (8 years)	% of reduction of cobalt use motivated by the deployment of optimised chemistries between 2017 and 2030, calculated assuming: 1. Potentially prevalent EV cathode chemistry mixes in 2017, 2020, 2025 and 2030 – examples from the literature.
Assumption. A potential second use for EV batteries, with the effect of delaying their recycling potential, is not considered.	Assumption. Disruptive technologies beyond those which are market-ready or with short-term maturity were discarded.

D. Supply-demand Balances (2018-2030)

Rational The deployment of LIB for EVs can be limited by constraints in the supply of cobalt, resulting in production lagging behind demand or causing subsequent price increases. Constraints to mineral supply may arise, for example, because of a lack of capacity at existing facilities and the long lead-time for the development of a mining programme from exploration to extraction. Although it is reasonable to assume that, to some extent, mining companies enjoy the flexibility to adjust production through investments in higher capacities together with mineral reserves replacement strategies, these are likely to be achieved at the expense of increased prices to downstream users. In resilient scenarios, shortages, surpluses and respective price fluctuations should be short-lived if backed by adequate mining capabilities and mineral discoveries in a number of countries characterised by political stability, if demand is alleviated by substitution mechanisms, and recycling outputs are able to compensate for potential gaps.

Annual demand-supply balances	Cumulative demand-supply balances
Each year cobalt will be produced to the extent of the demand. The extent to which supply exceeds demand and vice-versa is assessed yearly.	Each year cobalt will be produced to the extent of the capacity of available mines and EVs recycling output; the amounts that are not consumed will be stockpiled and stored for use in the following years. The analysis is conducted for each 5-year period on a cumulative basis.

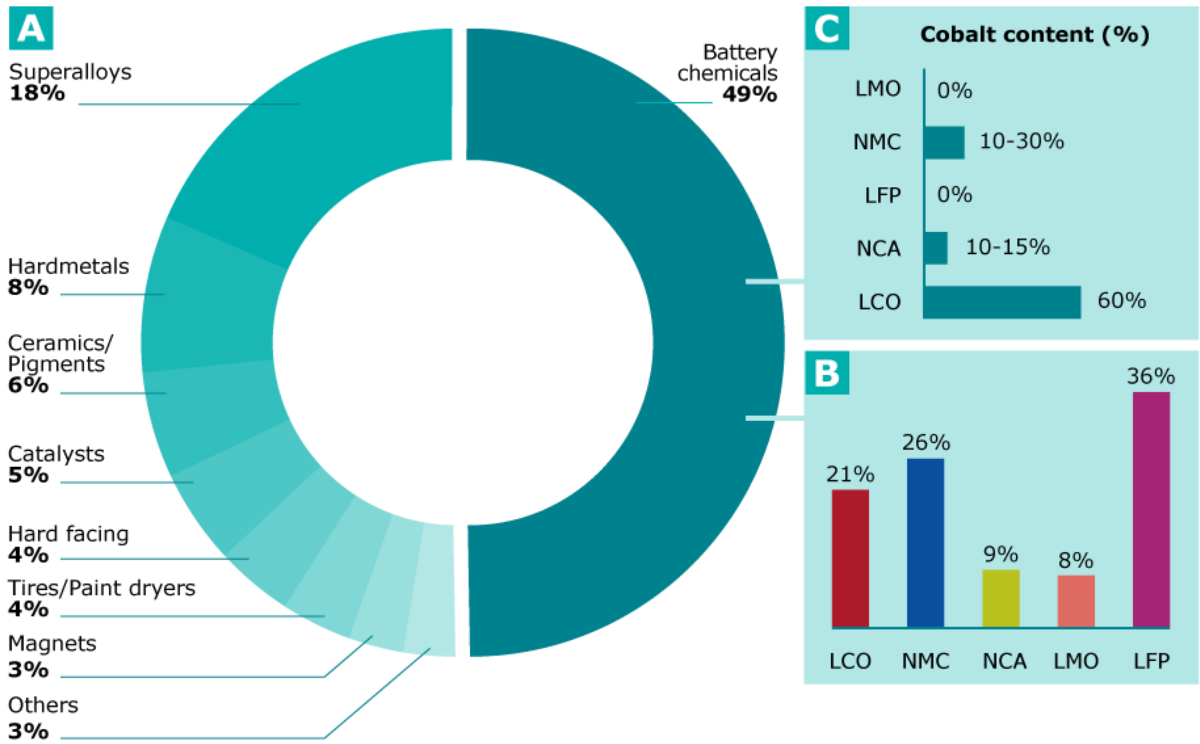
2 Cobalt demand

2.1 The current global situation

2.1.1 Cobalt uses and the rechargeable battery market

In 2016, the global demand for refined cobalt was around 98 000 tonnes (BGS, 2017), an amount which had almost tripled since 2000. The current consumption of the metal is apportioned as shown in Figure 5 below.

Figure 5. Refined cobalt demand by end-use and end-use specifications in 2015 (Darton Commodities, 2016) (A); market shares of cathode active materials used in Li-ion batteries in 2016 according to (Avicenne Energy, 2017) (B); cobalt content in each type of cathode (Avicenne Energy, 2017) (C).



=> Battery chemicals: Li-ion (LCO, NCM, NCA cathode) and NiMH/NiCd (anode/cathode).

=> Superalloys: Aerospace; Land based turbines/IGT; Medical (prosthetics); Others

=> Hardmetals: Cutting tools, mining, oil & gas drilling, etc

=> Ceramics/Pigments: Ceramics, glass and colouring applications

=> Catalysts: Oxidation (thermoplastic polymers production); Hydrotreating/desulfurisation (gas, oil, refining, petrochemicals); Fischer Tropsch process to convert carbon monoxide and hydrogen into liquid hydrocarbons

=> Hard Facing: Satellites; Triballoy, etc

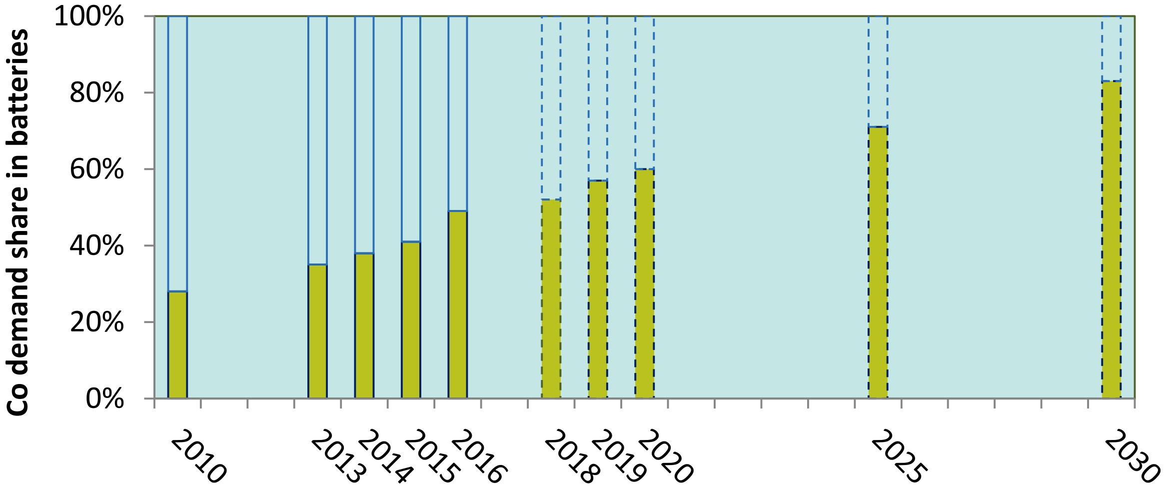
=> Magnets: AlNiCo; SmCo; NdFeB; CoFe

=> Others: Electroplating; high speed steels; agriculture/animal feed; synthetic diamonds

The rechargeable battery market is the largest and fastest growing for cobalt demand. Demand from this industry grew by nearly 12 % in 2015, driving consumption in this sector close to 45 000 tonnes (Darton Commodities, 2016). While cobalt is still used in nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries, over 90 % of current consumption in the battery industry is bound to the production of LIB (Darton Commodities, 2016). In 2015, rechargeable batteries accounted for 49 % of total cobalt consumption, while this usage represented merely around 28 % of total cobalt demand in 2010 (Figure 6).

The remaining end sectors consist of nickel alloys, including superalloys, which accounted for 18 % of total consumption in 2015, tool materials, catalysts, pigments and decolourisers, magnets, soaps and dryers and a number of other minor end-uses (Figure 5).

Figure 6. Cobalt demand share in rechargeable batteries.



Own compilation based on (BRGM, 2014), (Roskill Information Services, 2014), (Darton Commodities, 2016), (Bloomberg, 2018).

Although consumer electronics has traditionally driven demand for LIB, within the rechargeable batteries market, the greater demand growth is currently driven by the automotive industry. In the electric vehicles market, cobalt consumption is boosted by the usage of NMC (nickel-manganese-cobalt) cathode materials. According to (Darton Commodities, 2016), while until recently the cathode chemistry of choice for the majority of electric and plug-in hybrid vehicles (BEV and PHEV) producers was a combination of NMC with a non-cobalt chemistry material, mainly LMO (lithium-manganese), an increasing number of automakers are choosing full NMC chemistry to achieve higher energy density, and thus longer distances per charge.

In addition, Electrical Storage Systems (ESS), both for residential (smaller systems below 10 KWh) and professional or utility use, are increasingly using Li-ion batteries, because of inherent advantages such as dynamic charge acceptance, longer shelf life, reliability and total cost of ownership (Darton Commodities, 2016). As with the EVs market, a growing number of producers are developing ESS batteries based on NMC chemistries.

In 2016, the demand for cathode active materials in rechargeable batteries was above 180 000 tonnes (Avicenne Energy, 2017), with 26 % of the LIB market comprised of NMC (Figure 5B). In such chemistries, cobalt contents are in the range of 10-30 %, representing around 4 % by weight of the individual battery cell[5]. According to (Avicenne Energy, 2018), cathode materials account for around 27 % of battery costs.

Table 2 Types of lithium ion battery chemistries [Sources: (Cobalt Institute, 2018), (Benchmark Minerals, 2016) quoting information from Battery University], (Avicenne Energy, 2017).

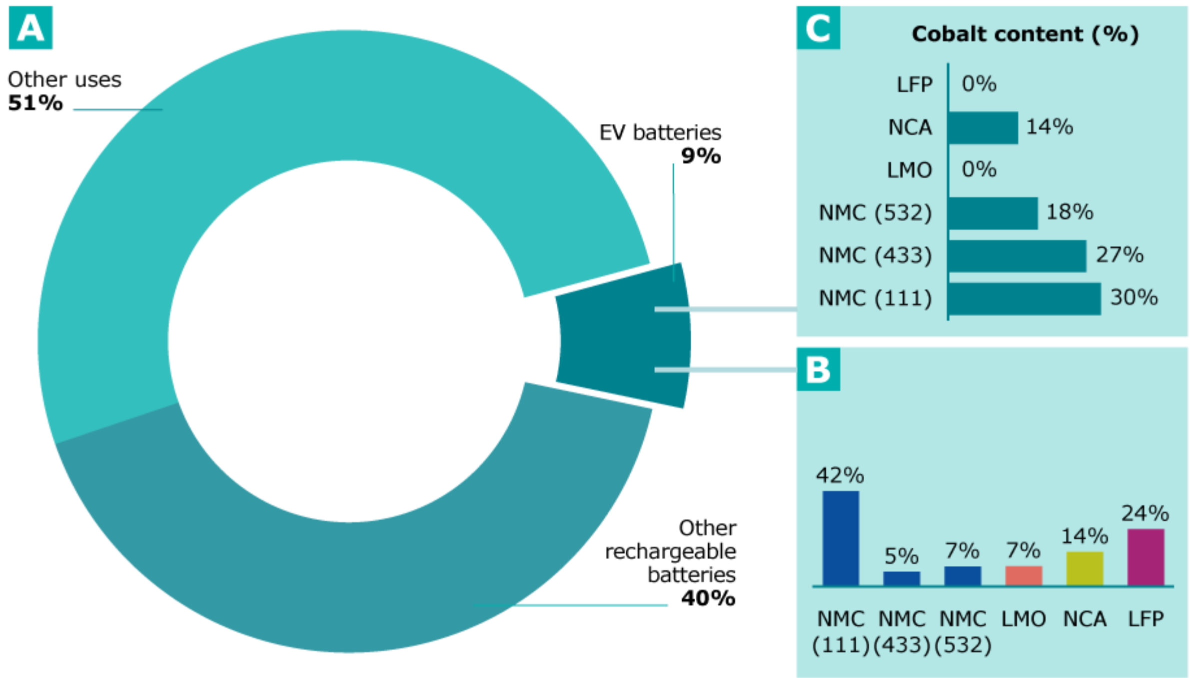
Name	Abb.	Chemical formula	Cobalt content	Properties and applications
Lithium Cobalt Oxide	LCO	$LiCoO_2$	60 %	High capacity. Mobile phones, tablets, laptops, cameras
Lithium Manganese Oxide	LMO	$LiMn_2O_4$	no Co	Safest; lower capacity than LCO but high specific power and long life. Power tools, e-bikes, EVs, medical devices.
Lithium Iron Phosphate	LFP	$LiFePO_4$	no Co	
Lithium Nickel Manganese Cobalt Oxide	NMC	$LiNiMnCoO_2$	10–30 %	
Lithium Nickel Cobalt Aluminium Oxide	NCA	$LiNiCoAlO_2$	10 -15 %	High capacity; gaining importance in electric powertrain and grid storage; industrial applications, medical devices

In EV batteries, cathode active materials accounted for 18 % of cobalt consumption in 2017 (or 9 % in comparison with overall uses) (Figure 7A). Several configurations with different cobalt contents are currently employed, at the rates shown in Figure 7: NMC (111) (42 %), NMC (433) (5 %), and NMC (532) (7 %), LMO (7 %), LFP (24 %) and NCA (14 %).

While cobalt represents around 30 % of the mass fraction of the preferentially used configuration (NMC 111), other chemistries, requiring less cobalt, are being used increasingly, amongst them the NCA with 14 % of cobalt (Figure 7C)[6].

[5] On average, 10Kg of cobalt are used to produce a battery weighting 250 Kg.
[6] In the future, different cathode mixes are expected. The respective evolution in 2030, and the proportional reduction in the use of cobalt over time, will be given in chapter 5.

Figure 7. Cobalt demand in EV batteries (A), preferred cathode chemistries used in EV batteries (B) and respective cobalt contents (C) in 2017.

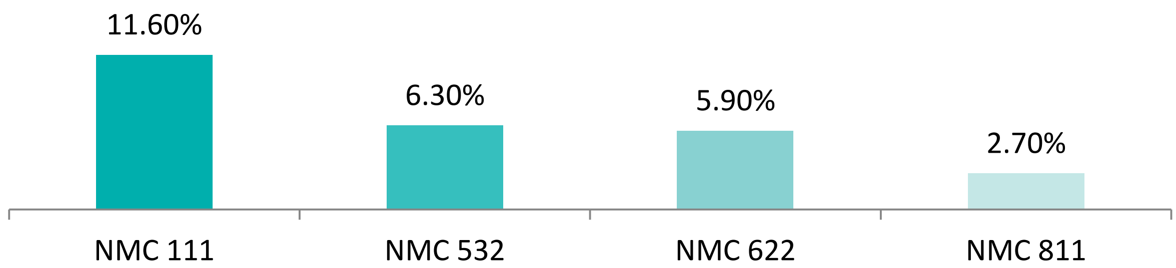


Data source: (Bloomberg, 2018).

Notes: LCO is not used in large format cells where NMC is preferred. LMO is mostly used as a blend with NMC in EVs; NCA is used in Panasonic cells in Tesla cars and as a blend with LMO in other EVs (Avicenne Energy, 2018).

According to (Avicenne Energy, 2018) cobalt price can account for a fraction between 3 % and 12 % of the total cell cost, depending on the chosen chemistry, as given in Figure 8. These are highest in NMC 111. In such compositions, the impact of current high prices and of any further increases in the future is even greater.

Figure 8 Impact of the cobalt price on the total cell cost.



Data source: (Avicenne Energy, 2018)

2.1.2 Global EVs market and present cobalt demand

Electric cars can mean partially electrified vehicles and full EV's (see Box 1). Although the latest category additionally includes fuel cell vehicles (FCEV), their deployment has been lagging as sales of battery electric vehicles consolidate. Though FCEVs are currently on the road, cost competitiveness in relation to conventional alternatives is pointed out as a key challenge for their short-term deployment (IEAHEV, 2018). Hence, for the present assessment, further segmentations of the EVs market beyond Battery electric vehicles (BEV) and Plug-in hybrid electric vehicles (PHEV) were not implemented.

Globally, sales of BEV and PHEV surged during 2015, as the total number of electric vehicles registered, sold or entered into service increased to around 1.3 million units (IEA, 2017). From 2015 until the end of 2017, the cumulative number of vehicles sold globally amounted to 3.0 million. In this period, sales of EVs increased by around 60 % on a yearly basis (approximation based on (IEA, 2017)).

Annual sales of EVs were estimated at 550 000 in 2015, and 1.2 million in 2017 (Figure 9). The proportion of BEV sales was higher than that of PHEV, at 66 % against 34 % (IRENA, 2017).

Box 1. EVs market – types of vehicles

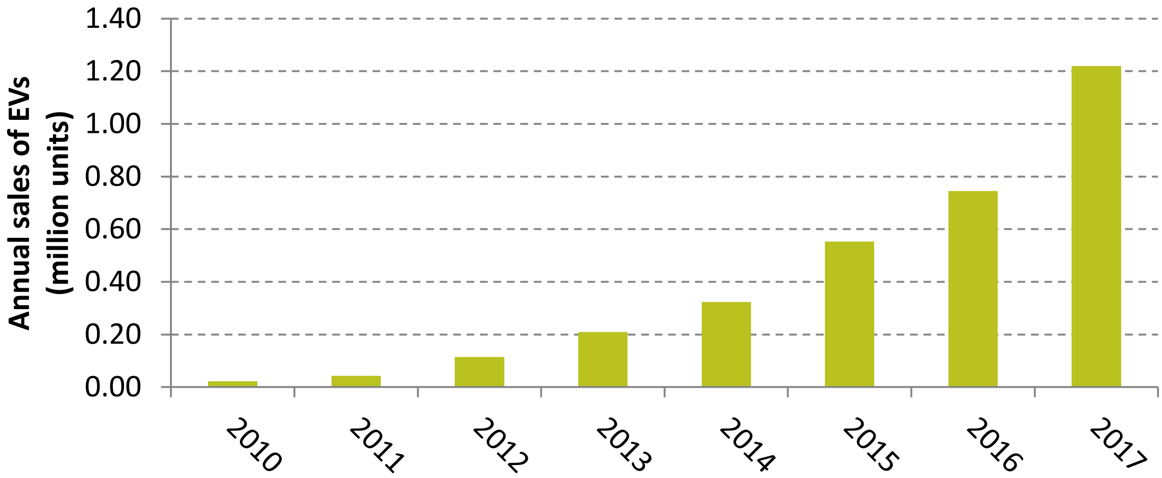
Electric cars comprise partially electrified vehicles and full EV's. The following systems are marketed:

Battery electric vehicles (BEVs) – propelled by an electric motor (or motors) and powered by rechargeable battery packs.

Plug-in hybrid electric vehicles (PHEVs) - have both an internal combustion engine and electric motor; are powered by conventional fuel and a battery, which is charged up by plugging into an electrical outlet or charging station.

Fuel-cell vehicles (FCEVs) - propelled by an electric motor and powered by hydrogen.

Figure 9. Past annual EV sales.



Data source: (IEA, 2017)

While until 2014, preferential countries for EVs deployment were the United States and Japan, the Chinese market has grown consistently since then. In 2016, China became the country with the largest electric car stock (IEA, 2017).

Assuming that an average cobalt amount of 5.5 Kg[7] was used per vehicle until 2017, the cumulative consumption of cobalt in the EVs sector would have been about 17 600 tonnes.

[7] Details concerning the amount of cobalt used per vehicle globally and in the EU are given next in the discussion of projected demand levels until 2030.

2.2 The European cobalt demand

2.2.1 Current perspective in the EVs market

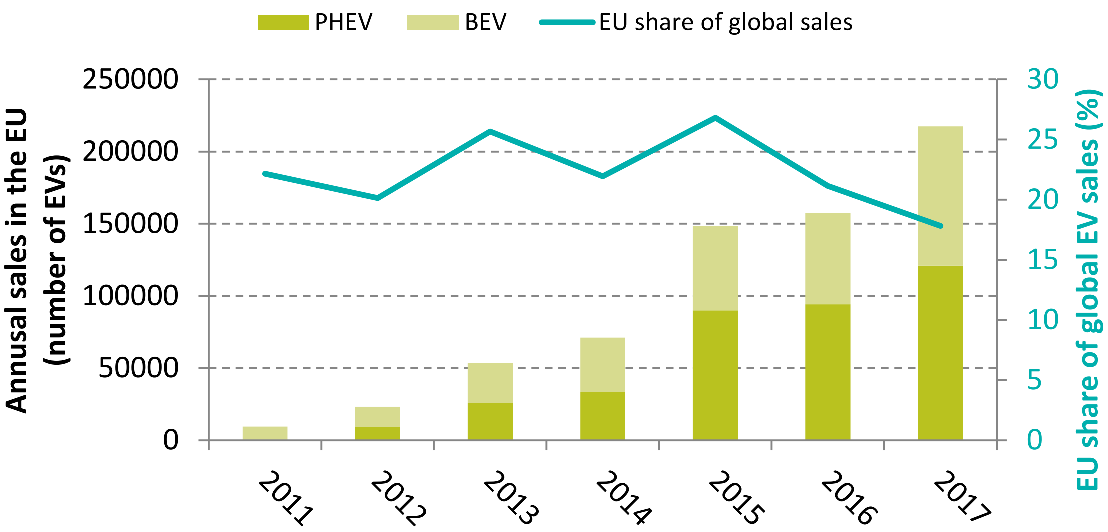
In the EU between 2010 and 2017, EV sales amounted to around 681 000 units[8] (EAFO, 2018).

In 2017, approximately 217 500 vehicles were sold, which represents a market share in new car sales of approximately 1.5 % (estimate based on (ICCT, 2017)).

Out of this volume, around 56 % was accounted for by PHEVs and the remainder by BEVs (EAFO, 2018). This contrasts with the global trend, in which the uptake of BEV has been consistently ahead of that of PHEV.

As of 2017, Europe had an estimated market share of 21 % of worldwide sales of EVs throughout the period in question. While this varies on an annual basis, the EU fraction of global sales appears to have decreased slightly in 2017, to around 18 % (Figure 10).

Figure 10. EV sales in the EU.



Data sources: based on (EAFO, 2018) and (IEA, 2017)

Assuming that an average cobalt amount of 4.5 Kg[9] was used per vehicle, the total amount of cobalt consumed on the European EV market to date can be estimated at around 3 000 tonnes. In 2017 alone, levels attained by the EV market in the EU have created a demand of nearly 1000 tonnes of cobalt.

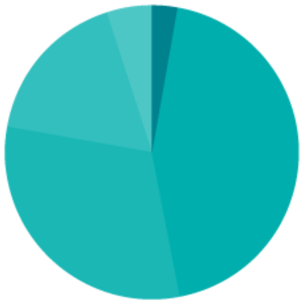
2.2.2 Cobalt demand from EU manufacturers

According to (Deloitte Sustainability, 2015), the amount of cobalt contained in several finished products used in the EU amounted to nearly 20 000 tonnes in 2012 (Table 3). Although this represents around 20 % of the world cobalt consumption in 2015, only 55 % was used by European manufacturing industries (nearly 11 000 tonnes) in the production of finished products.

[8] 373,000 PHEV and 307,000 BEV have been sold in the EU between 2010 and 2017 (EAFO, 2018).

[9] Details concerning the calculation of the amount of cobalt used per vehicle are given next in the discussion of projected demand levels until 2030. Differences between the EU and world regions in terms of cobalt amount per unit are related to higher shares of PHEV sales in the EU.

Table 3 EU demand for cobalt (in tonnes) per end-use sector in 2012.

End use sector	Finished products manufactured in the EU		Finished products used in the EU	
Batteries	327		10 099	
Superalloys	4 791		3 578	
Hard metals	3 376		4 065	
Pigments	1 851		1 476	
Catalysts	544		599	
Total	10 889		19 818	

Data Source: (Deloitte Sustainability, 2015).

Similarly, while cobalt usage in batteries that entered the EU market in 2012 ascended to 10 100 tonnes, only 3 % of the demand was met by European manufacturing processes (Table 3).

Currently, Li-ion battery cells for EVs and storage are produced mainly in Asian countries & companies (~85 % of global manufacturing capacity) with the EU having a limited share of about 2 % (or 3 GWh of global cell manufacturing capacities) (BNEF, 2018).

2.3 Global demand projections in the EVs sector

Meeting the Paris Declaration targets on climate change, thereby limiting the global temperature increase to below 2 degrees Celsius, shall entail a consistent reduction of greenhouse gas emissions across the full range of transport modes (passenger cars, two and three wheelers, light commercial vans, trucks, etc). For achieving these targets, an expansion of the global EVs fleet to around 20 % electric vehicles in use by 2030 is essential. This translates into 110 million electric cars in 2030 and entails that annual sales must account for at least 35 % of global vehicle sales in 2030 (UNCC, 2015).

In addition to the Paris Declaration, other projections on the uptake of EVs have been put forward by the International Energy Agency (IEA) (see Box 2). These scenarios reflect the effects of announced policy actions (IEA-RTS) or are aligned with different levels of ambition to combat climate change (IEA – 2DS and IEA-B2DS).

Box 2. EVs deployment – IEA scenarios, deployment targets and assumptions

The following scenarios and targets on global EVs deployment are put forward by (IEA, 2017):

• **Reference Technology Scenario (RTS)** - reflects projections that respond to policies on energy efficiency, energy diversification, air quality and decarbonisation that have been announced or are under consideration.

• **2DS Scenario (2DS)** - reflects the ambition for 160 million electric cars in 2030 in a context consistent with a 50 % probability of limiting the expected global average temperature increase to 2°C.

• **B2DS Scenario (B2DS)** - projects around 200 million electric cars in 2030, targeting the achievement of net-zero GHG emissions from the energy sector shortly after 2060.

• **Paris Declaration on Electro-Mobility and Climate Change** (announced at COP21) - expresses the ambition to exceed the global threshold of 100 million electric cars and

400 million electric two-wheelers by 2030 – about a third below the number of electric cars projected in the 2DS and half the EV stock of the B2DS.

The following assumptions were adopted in the present study:

The envisaged world EV fleet may include partially electrified vehicles (PHEV) and full EV's (BEV, FCEV). For the present assessment it is assumed that until 2030, new EV sales will rely on battery technologies and basic car system configurations (either BEV or PHEV). Throughout the relevant period, no relevant deployment of FCEVs will occur to the extent necessary to affect the future consumption of cobalt by reducing the market share of battery vehicles.

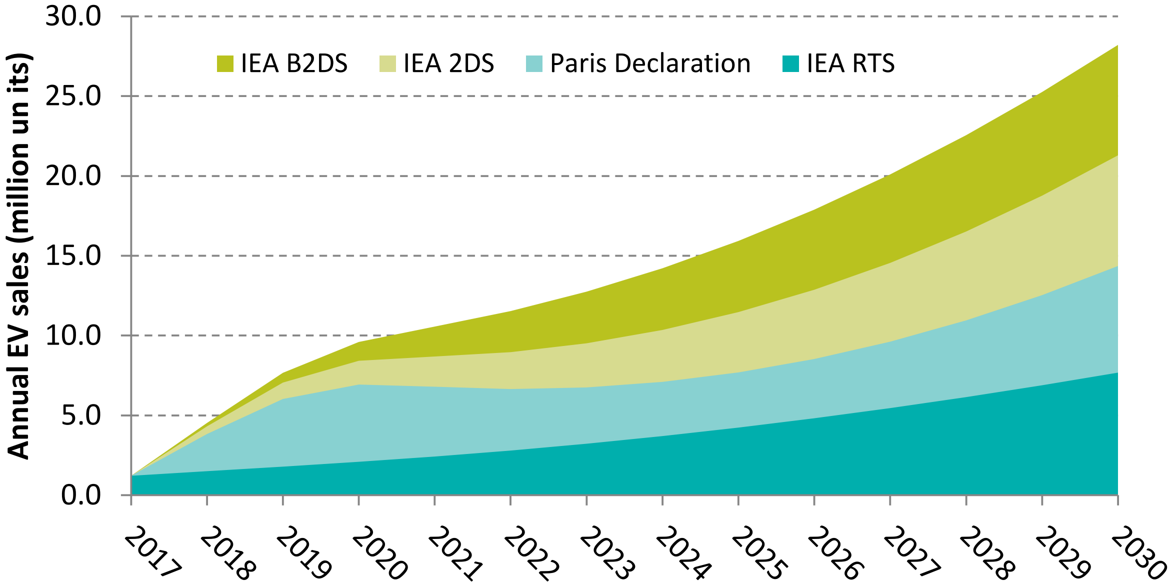
To meet the most stringent emission targets set out in the 2DS and B2DS scenarios, the global electric car stock would need to increase from an estimated 3.2 million in 2017 to 23-25 million by 2020, and 156-204 million in 2030, with annual sales growing by a compound annual rate of 25 % to 27 %.

More conservative projections can be inferred from the IEA-RTS scenario. Under the assumptions made in this scenario, the size of the EV fleet is estimated to be around 9 million electric cars in 2020, increasing to 56 million in 2030. Albeit more moderate, a significant scale-up by 2030 would also arise under this scenario, for which a CAGR of 15 % between 2017 and 2030 may be inferred from annual sales.

Annual EV sales, calculated on the basis of deconstruction of cumulative figures given by IEA using an interpolation procedure[10], are given in Figure 11.

[10] A spline interpolation method was applied.

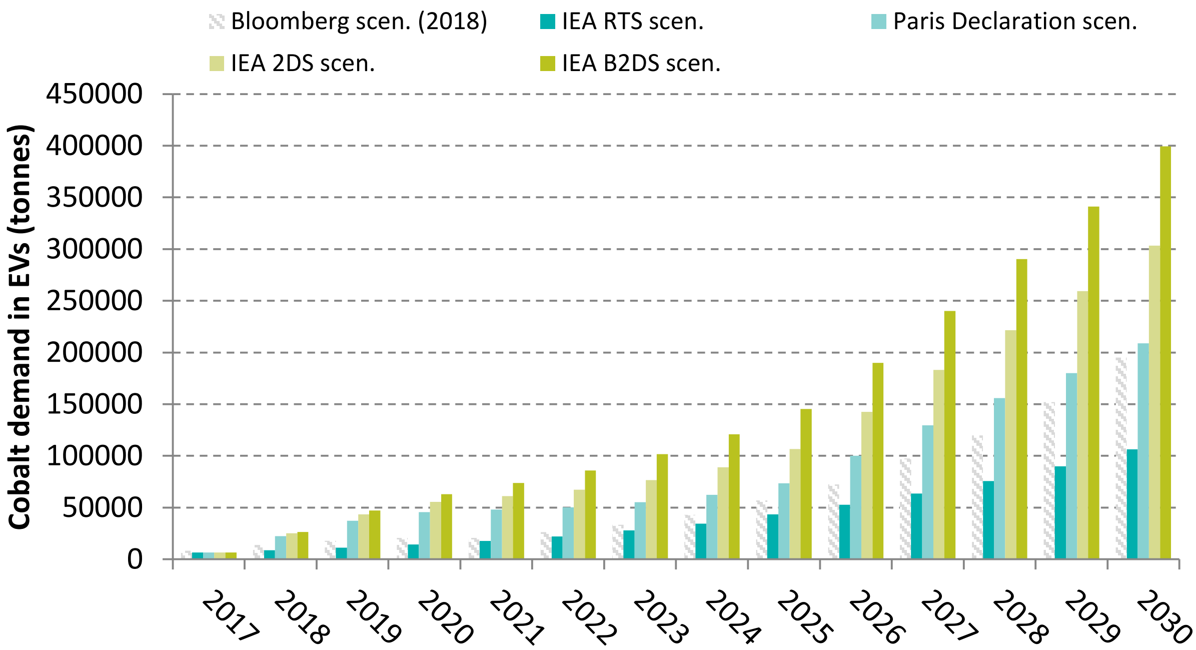
Figure 11. Global deployment projections of electric cars until 2030.



Note: annual EV sales were interpolated based on cumulative data from IEA scenarios.

The graph in Figure 12 depicts annual cobalt consumption figures calculated for each deployment scenario using the assumptions in Box 3. Values therein also take into account additional sales over the same period to compensate for those batteries that reach end of life after approximately 8 years of use.

Figure 12. Annual global cobalt demand in EVs between 2017 and 2030.



Assuming that an increasing average amount of between 5.5Kg and 11Kg of cobalt is used per vehicle from today until 2030, on account of projected growths in the storage capacity of EV batteries and the continued increase of BEV systems, the cumulative usage of cobalt in the automotive sector at the end of 2030 would be in the range of 1.6 to 2.1 million tonnes in high-case scenarios (IEA 2DS and IEA B2DS)[11]. In both scenarios the annual cobalt demand would increase from 6 650 tonnes in 2017 to 300 000 - 400 000 tonnes in 2030.

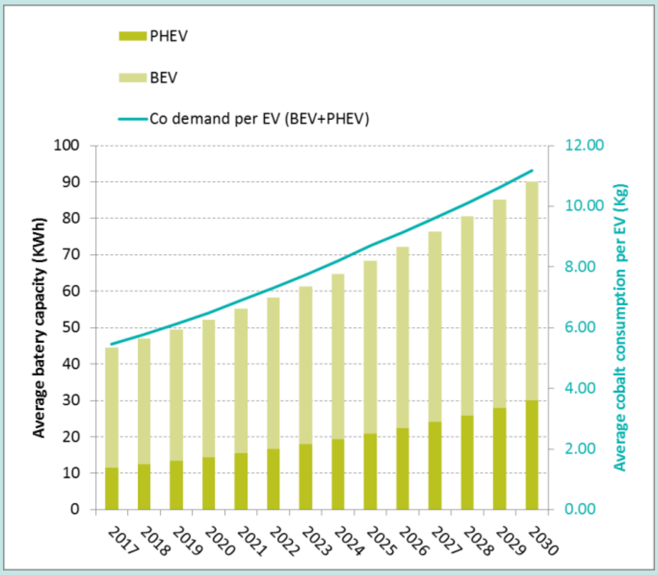
Box 3. Cobalt consumption per EV – assumptions underlying global demand calculations

The following assumptions underpin the estimation of the average cobalt consumption per electric car and its evolution until 2030:

- Average cobalt content per KWh: it is assumed to be 0.2 kg/kWh, estimated taking into account the 2017 EVs cathode chemistry mix proposed by (Bloomberg, 2018) (see

Figure **7**) and the cobalt contents per chemistry given by (Olivetti, Ceder, Gaustad, & Fu, 2017) as follows; NMC (111) = 0.394 Kg/KWh; NMC (433)= 0.36 Kg/KWh; NMC (532)= 0.23 Kg/KWh; LMO = 0 Kg/KWh; NCA = 0.143 Kg/KWh; LFP = 0 Kg/KWh).

- Average battery storage capacity: in addition to contrasts in cathode chemistries, the storage capacity of the battery is a fundamental aspect conditioning the consumption of cobalt. This is higher amongst BEVs with an average capacity of 30 kWh, than PHEVs with an average capacity of 10 kWh. Moreover, until 2030, the BEV's battery storage capacity is expected to increase to 60 kWh and that of PHEVs to 30 kWh (IRENA, 2017).
- Market shares of BEV and PHEV: at global level, the BEV market share is expected to increase from 66 % in 2017 to 75 % in 2030, while the share of PHEV sales is expected to decrease from 34 % to 25 % in 2030 [(IEA, 2017), (Bloomberg, 2017)].



On the basis of these assumptions, the average cobalt content was estimated to be 5.5 kg per EV in 2017. This amount is expected to increase to 11 kg in 2030 on account of projected growths in the storage capacity of EV batteries and the continued increase of BEV systems[12].

Under the RTS scenario, cumulative demand for cobalt in the EV market shall not exceed 575 000 tonnes at the end of 2030, with consumption in 2030 just exceeding 100 000

[11] In the future, a reduction in the use of cobalt from the optimisation of chosen cathode chemistries is expected. This effect will be assessed in chapter 5.
[12] We acknowledge however that it is unlikely that the cobalt content will increase linearly with the batteries' capacity on account of improvements in the material efficiency.

tonnes. As for the Paris Declaration, it is estimated that a cumulative amount of 1.2 million tonnes of cobalt is necessary to reach the respective 2030 targets.

For reference purposes, the same graph includes the yield of the Bloomberg analysis over the same period (Bloomberg, 2018), which is found to be comparable to the IEA-RTS projections until 2025, and from then onwards to the Paris Declaration targets.

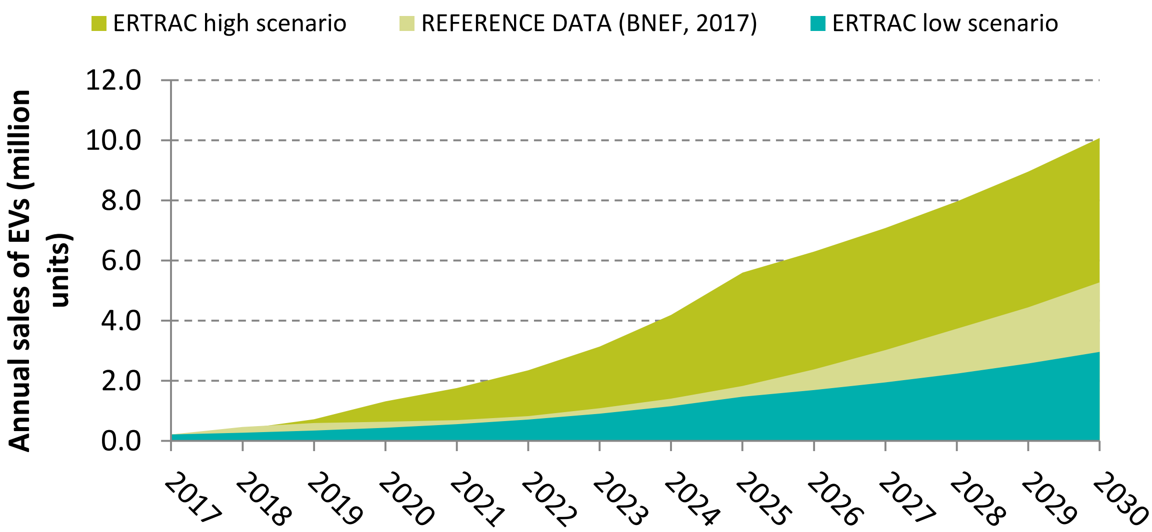
Although it is beyond the scope of the present study, the Li-ion market for ESS is expected to grow an average of 30 % per year until 2030 (Darton Commodities, 2016). From data made available by (Bloomberg, 2018) one can estimate that the consumption of cobalt in such technologies can represent an average fraction of 8 % of the global EVs market until 2025, and 7 % from then onwards until 2030. At the end of the period, around 55 000 tonnes of cobalt would have been used globally to fulfil ESS demand.

2.4 European demand projections in the EVs sector

In the EU, projections derived from ERTRAC scenarios (ERTRAC, 2017), suggest that the cumulative number of electrified passenger cars will range from 1.7 to 3.1 million in the year 2020, rising to 7-20 million in 2025 and 18-61 million in 2030 (see Box 4 for details on ERTRAC scenarios).

The more conservative scenario presents a compound annual growth rate of 22 % in 2017-2030, whilst in the high scenario, a growth rate of 34 % is expected.

Figure 13 European deployment projections of electric vehicles – annual EV sales forecast in the EU until 2030, based on ERTRAC scenarios.



Box 4. EVs deployment in the EU – ERTRAC scenarios and annual sales estimation

Projections for the deployment of electric vehicles in Europe until 2030 are presented by ERTRAC. Forecasts are made for electrified passenger cars and based on a multitude of factors and their interplay. These include, as stated: technological developments and breakthroughs, policy support, deployment of charging infrastructure, production capacity, future customer needs for mobility and their acceptance of new technologies, and economic parameters such as vehicle production cost, vehicle TCO and energy prices (ERTRAC, 2017).

Two scenarios – hereafter referred to as LOW and HIGH – result from an ERTRAC forecasting exercise, describing the introduction of electric vehicles in 2020, 2025 and 2030. Projections for EVs are given as market shares of new car sales.

LOW scenario: foresees that electric vehicles will constitute 4-5 % of market share in 2020, based on current policies. Additionally, this scenario anticipates a market penetration of 10 % for BEVs and PHEVs by 2025, increasing to 20 % by 2030. Under this scenario, CO_2 targets are achieved by more efficient and hybridised ICE (internal combustion engine) vehicles.

HIGH scenario: foresees a market share of 8-10 % in 2020, developed in the context of appropriate political support. In 2025, the number of vehicles will increase in line with major innovation, leading to a revised EV system and new mobility models. In 2030, market shares may be up to 70 %, with technical breakthroughs resulting in competitive products and mass production of EVs.

Annual EV sales were subsequently estimated taking into account projections of demographic growth from Eurostat (2018) and a constant ratio of new car registrations per inhabitant. This was estimated to be 0.028, calculated assuming that against a universe of 512 million inhabitants, 14.6 million cars were sold in 2016 (ICCT, 2017).

Until 2030, the cumulative amount of cobalt consumed in the European automotive sector may be of 170 000 tonnes in the low demand scenario or up to 570 000 tonnes in the high scenario (Figure 14). This represents between 27 % and 29 % of the amounts used globally in electric vehicle batteries to fulfil projected high and low demand scenarios, respectively (IEA B2DS and RTS) [13].

On an annual basis, the demand for cobalt may increase from 970 tonnes in 2017 to 36 370 – 123 200 tonnes in 2030 (Figure 14).

[13] See Box 5 for details on procedures to estimate the cobalt demand.

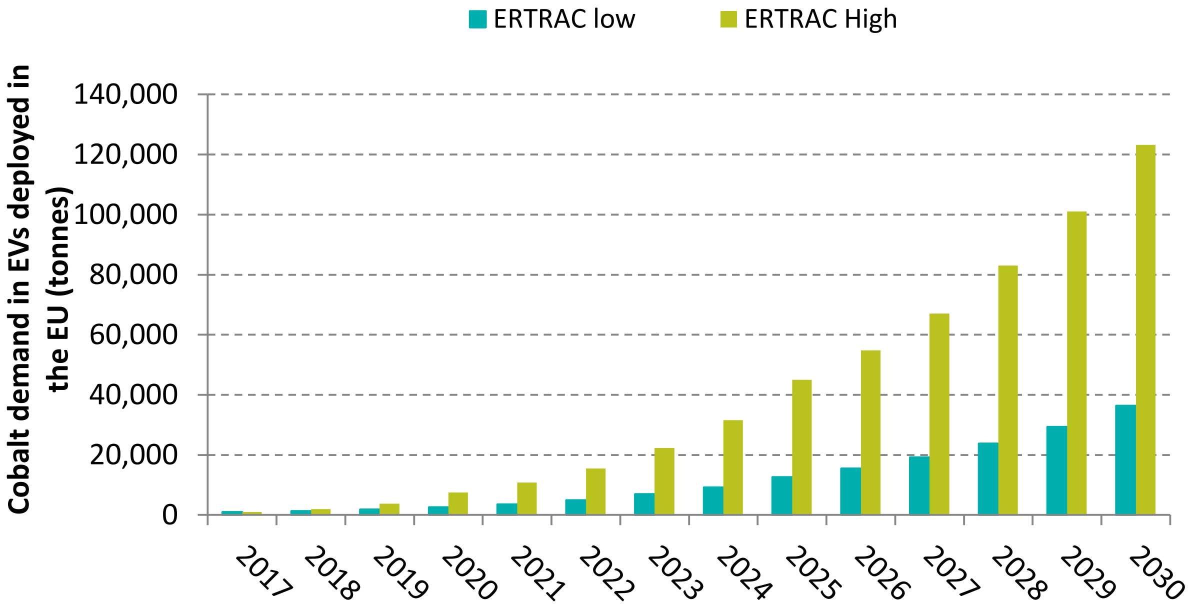
Box 5. Cobalt consumption per EV – assumptions underlying European demand calculations

While assumptions relating to the battery storage capacity and cathode chemistry mix are identical to those discussed for the global context (see Box 3), the relative shares of BEV and PHEV reflect European specificities.

In the EU, unlike the situation globally, the share of PHEV sales is higher than that of BEVs. In 2017, PHEV accounted for 56 % of EV registrations in the EU with the remaining 44 % held by BEV (EAFO, 2018). These relative shares have changed over the past years. In 2015, PHEVs held 60 % of the market share, experiencing a reduction of -4 % until 2017. Applying a similar reduction rate in the PHEV fleet until 2030, it can be assumed that by then, 32 % of European EVs will tend to be PHEV and the remaining 68 % shall consist of full electric vehicles.

In the light of this, the average cobalt content per EV in the EU market can be estimated as 4.5 kg in 2017 and is anticipated to increase to 10.7 kg in 2030.

Figure 14 Annual cobalt demand in the European EV sector, estimated based on ERTRAC deployment scenarios.



2.5 Demand from announced LIB mega-factories

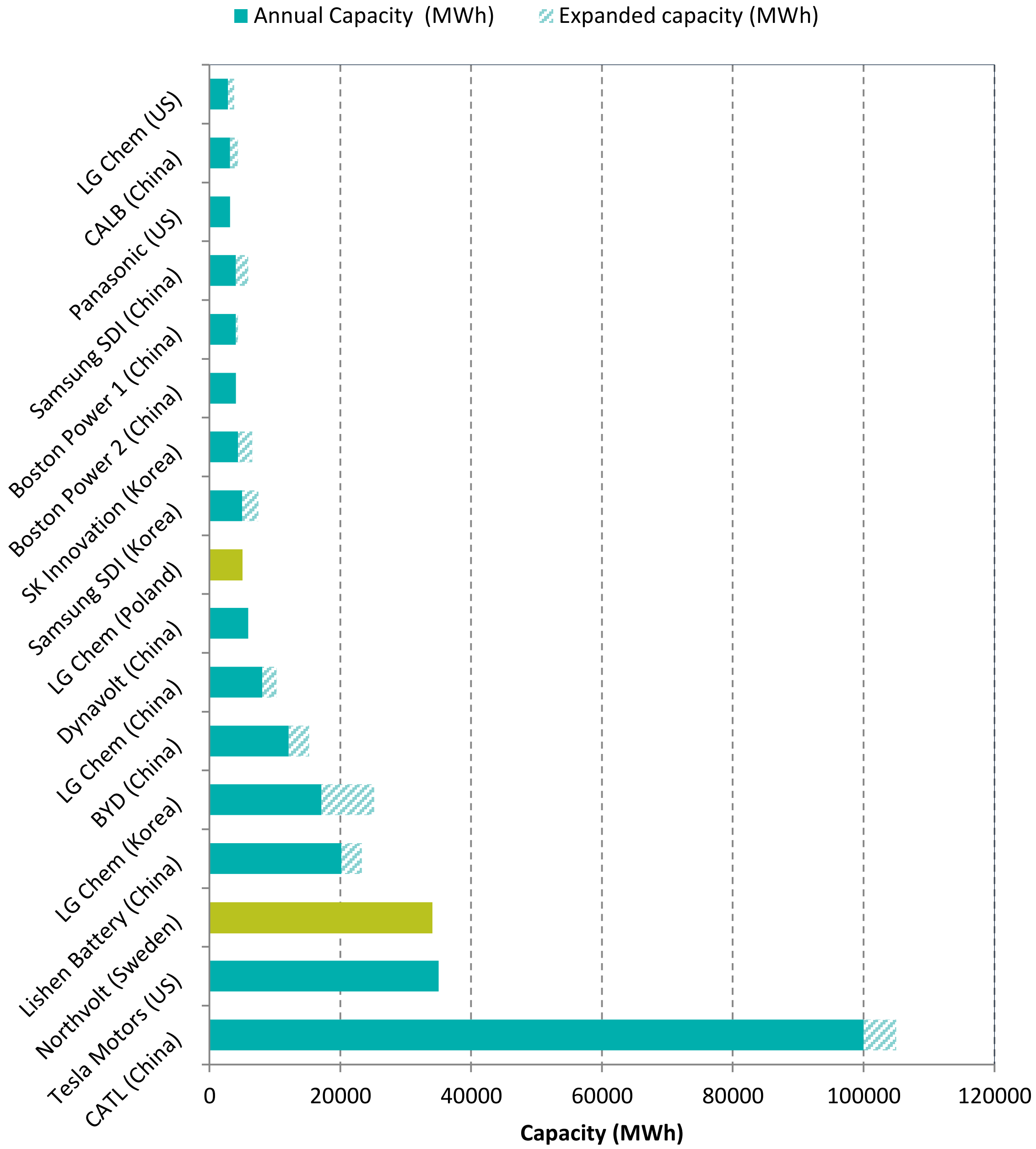
The changing characteristics of mobility and the prevalent use of lithium ion batteries are drivers to surging LIB mega-factories.

According to Benchmark Mineral Intelligence (quoted by (Sienna Resources, 2017)), more than 20 facilities with a capacity of above 1GWh have been announced, 10 of which are located in China (Figure 15).

Amongst these investments, the Tesla Gigafactory (projected capacity of 35 GWh, in the United States) and CATL (expanded capacity of 100 GWh, in China) will likely consume around 7 000 t/yr and 23 000 t/yr of cobalt, respectively.

By 2021, the LIB manufacturing capacity is expected to be around 400 GWh, with more than 70 % capacity installed in China (BNEF, 2018). Cobalt supply to these factories can be estimated at some 80 000 tonnes/yr.

Figure 15 LIB mega-factories with information on annual and expanded capacities by 2021.



Data source: Benchmark Mineral Intelligence (quoted by (Sienna Resources, 2017).

In Europe, the capacity expected to be available in 2021-2023 will ascend to 40 GWh, increasing from 3 GWh currently in place (Benchmark Mineral Intelligence (quoted by (Sienna Resources, 2017), (BNEF, 2018). Announced capacities will be developed mainly in Sweden and Poland (the Northvolt LIB mega-factory in Sweden, with a production capacity of 32 GWh[14] and the LG Chem in Poland with a production capacity of 5 GWh). This represents around 9 % of the global estimated capacity and entails an estimated cobalt consumption of around 7 400 tonnes/year.

[14] NorthVolt plans to expand its capacity to 8 GWh by 2021, and up to 32 GWh by 2023. http://www.eib.org/stories/northvolt-lithium-ion-battery

2.6 Demand projections for the assessment of supply-demand balances

To establish balances between supply and demand, annual projections of global cobalt consumption in the EVs sector were further added to the amounts consumed in other end-sectors beyond the EVs. These amounts were estimated to increase at a Compound Annual Growth Rate (CAGR) of 2.5 %, from 97 600 tonnes in 2017 to 135 300 tonnes in 2030 (Bloomberg, 2018).

In the four IEA scenarios, the following overall consumption levels are implied:

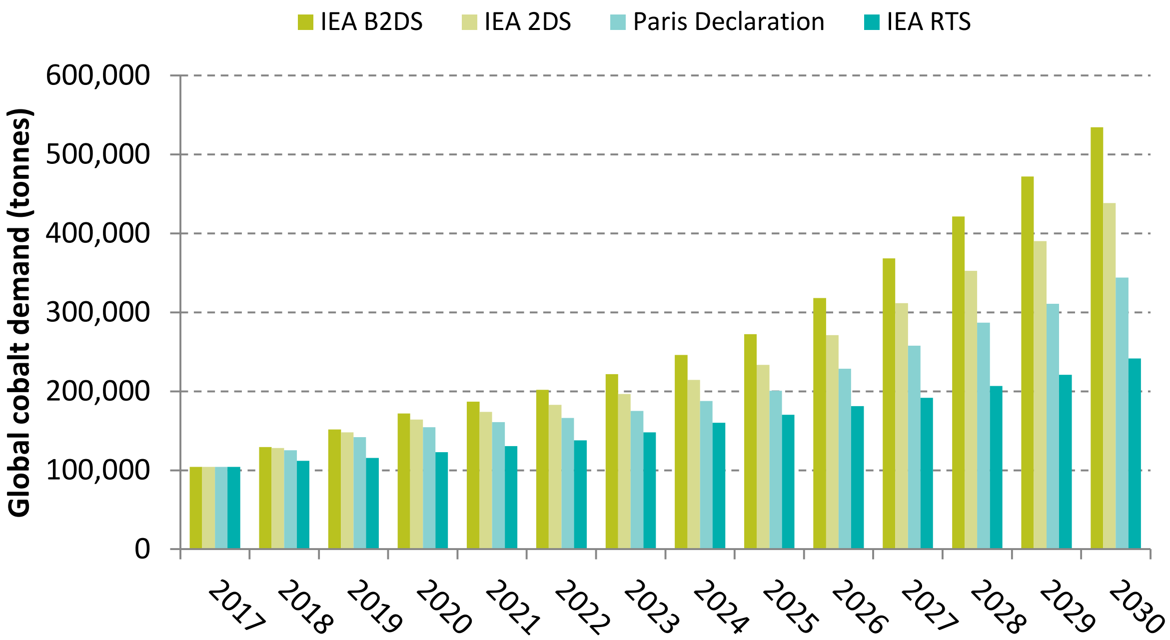
1- IEA B2DS: against the backdrop of a more widespread uptake of EVs, a compound annual growth rate of 13.4 % is estimated for the annual global consumption of cobalt in the period between 2017 and 2030; the potential cobalt demand is projected to increase from 104 300 today to 534 500 in 2030.

2- IEA 2DS: the potential global demand for cobalt is expected to more than quadruple in 2030, reaching 438 500 tonnes by then.

4- Paris declaration: global consumption of refined cobalt may amount to 200 500 tonnes in 2025 and 344 000 tonnes in 2030, increasing by 9.6 % between 2017 and 2030.

5- IEA RTS: cobalt demand shall not exceed 241 500 tonnes in 2030. This represents an annual growth rate of 6.7 % for the period between 2017 and 2030.

Figure 16 Overall global demand of cobalt simulated according to the four scenarios discussed in the text.



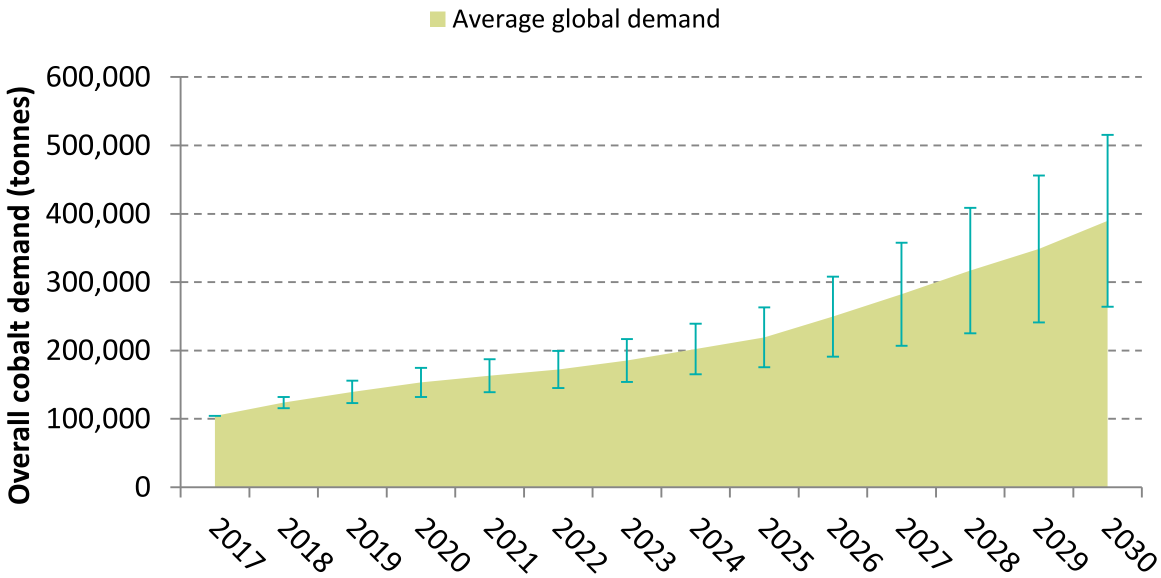
Forecast amounts in each relevant timeframe are given in Table 4.

Table 4 Annual demand projections of refined cobalt (tonnes) in reference years – overall uses in the global context.

Data source	[1] IEA B2DS	[2] IEA 2DS	[3] Paris Declaration	[4] IEA RTS
CAG-R	13.4 %	11.7 %	9.6 %	6.7 %
Reference period	2017-2030	2017-2030	2017-2030	2017-2030
Scenario	High	Medium-high	Medium-low	Low
2020	171 778	164 132	154 442	123 016
2025	272 212	233 414	200 530	170 452
2030	534 523	438 517	344 205	241 498

Figure 16 provides the evolution of cobalt consumption until 2030 calculated as an average of the four scenarios presented above.

Figure 17 Annual average global demand of cobalt until 2030 – overall uses in the global context.



Note: Error bars show the standard deviation of forecasted demand taking into account the various EV deployment scenarios.

In the EU, taking into consideration the deployment of EVs until 2030 put forward by ERTRAC, and the amounts of cobalt consumed in the remaining end-use sectors[15], the total cobalt demand for various uses could be 24 400 - 29 300 tonnes in 2020, 37 300 - 69 700 tonnes in 2025, and 64 300 - 151 100 tonnes in 2030, increasing by 9 % and 16.3 % in low and high demand scenarios respectively (Table 5).

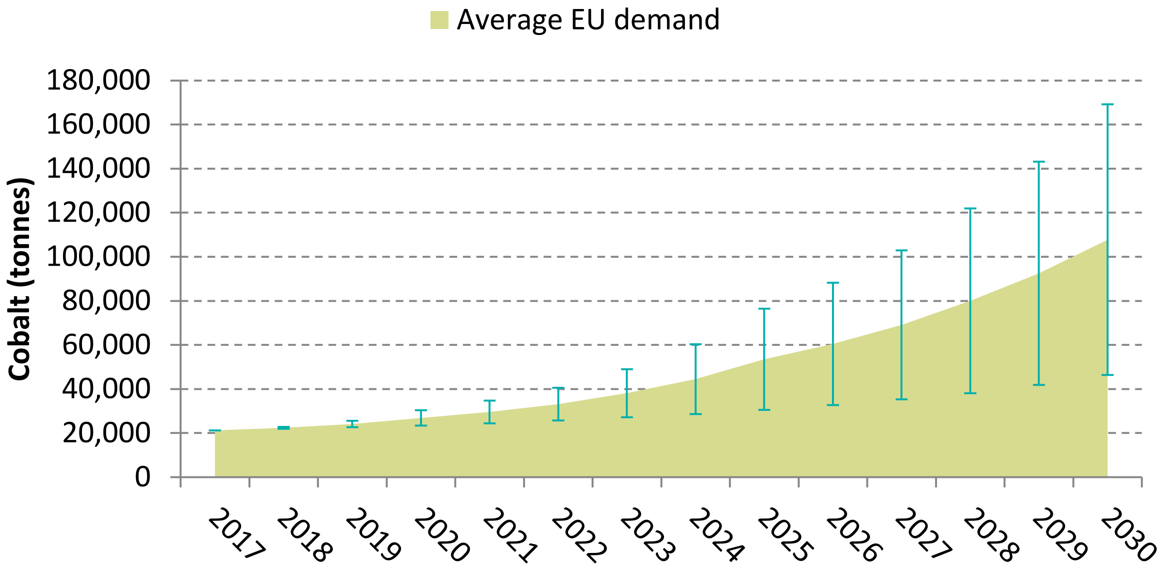
Until 2030, between 503 000 and 903 400 tonnes will be needed to fulfil expected demand levels within the EU.

[15] In 2017, it is estimated that 20,256 tonnes were consumed in the EU in other sectors beyond EVs. This is estimated assuming that 19,280 tonnes were used in 2015 (Statista, 2018), increasing since then with a constant growth rate of 2.5%.

Table 5. Annual demand projections of refined cobalt (tonnes) in reference years – overall uses in the European context.

Data source	[1] ERTRAC High	[2] ERTRAC low
CAG-R	16.3 %	8.9 %
Reference period	2017-2030	2017-2030
Scenario	High	Low
2020	29 311	24 381
2025	69 736	37 254
2030	151 131	64 300

Figure 18. Average demand of cobalt until 2030 – overall uses in the European context.



Note: Error bars show the standard deviation of forecasted demand in the various scenarios.

3 Cobalt mine supply

3.1 Recent trends in cobalt supply - global outlook

Most cobalt is obtained as a co- and by-product of copper (46 %) and nickel (39 %) mining[16]. In 2016, 16 % of world cobalt production came from primary producers, of which the only significant operation outside DRC is the Bou Azzer mine in Morocco, and 0.2 % from mines targeting PGMs as primary product.

The largest resources of cobalt occur in sediment-hosted stratiform and stratabound copper deposits such as those mined in DRC and Zambia (Table 6). DRC is the main mining producer, accounting for 55 % of global production in 2016. Other producers include China (accounting for 8 % of total supply), Canada (6 %) and New Caledonia (5 %) (WMD, 2018). In total, cobalt is mined in 20 countries (Figure 19).

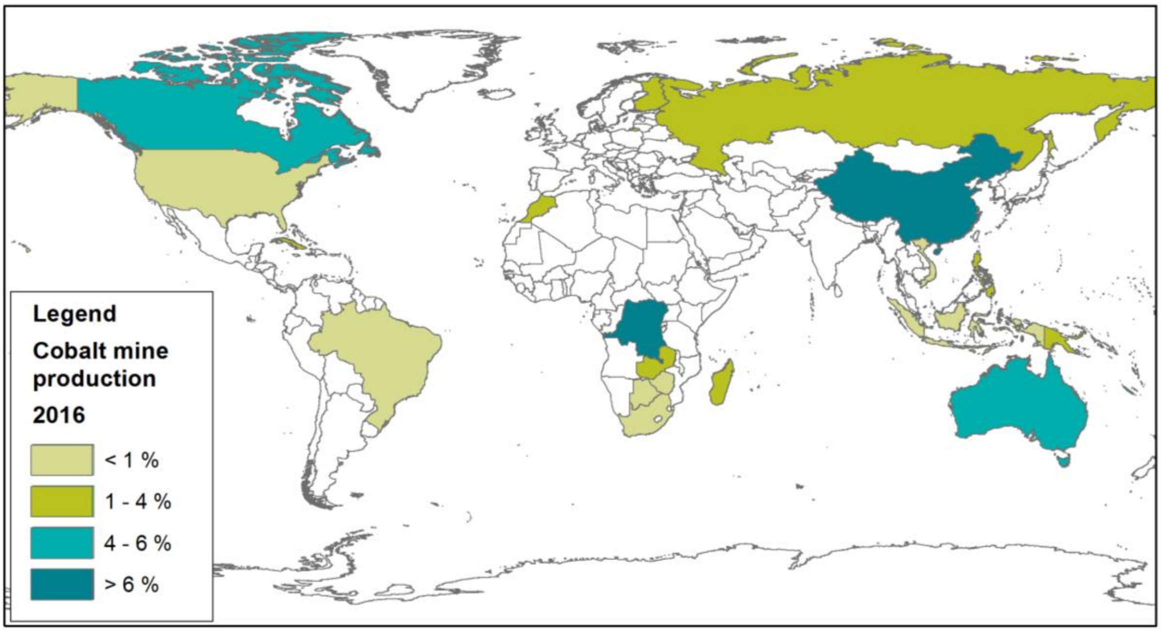
Table 6 Types of mineral deposits and respective average cobalt contents.

Types of deposits	Commodities and terms of reference	Average grades %
Sediment hosted copper deposits	Typically worked for copper with cobalt as a by-product. Examples are found in the Central African Copperbelt which spans the Democratic Republic of the Congo (DRC) and the north-west part of Zambia.	0.1 to 0.4
Magmatic nickel-copper-cobalt sulphide deposits	Primarily mined for nickel, copper and PGMs, such as those found in Russia and Canada	0.1
Nickel laterites	Primarily mined for nickel, such as those found in Cuba and New Caledonia	0.05 to 0.15
Hydrothermal cobalt deposits	Ultramafic-rock hosted deposits with cobalt as primary commodity are comparatively rare, such as those in Bou Azzer in Morocco	0.1
Manganese nodules and cobalt rich crusts	The feasibility of such projects has still to be demonstrated	Up to 2.5

Data sources: (Roskill Information Services, 2014), (Cobalt Institute, 2018).

[16] Own calculation based on (S&P Global Market Intelligence, 2018) taking into account production amounts at operating mines in 2016, representing 90% of overall production in that year. Other organisations have calculated different figures for this division. The Cobalt Development Institute states that approximately 50% of global supplies of cobalt come from the nickel mining industry, whilst 44% is sourced from copper mining and only 6% from mining operations where cobalt is the primary product (Cobalt Factsheet, 2017).

Figure 19 Distribution of cobalt supply amongst world countries.



Data source: (based on (WMD, 2018).

The largest cobalt project is the Mutanda mine, followed by Tenke Fungurume, Luiswishi and Lubumbashi, all located in DRC (Table 7). In 2016, these operations were responsible for 43 % of the world's cobalt production.

The ranking provided in Table 7 also includes significant facilities in Zambia, Cuba, Canada, Russia and Madagascar, which account for another 15 % of global cobalt production.

Table 7. Largest mining projects by production (Top-10) in 2016.

Mine name	Country Commodity	Primary Production	Cobalt - production (tonnes)	Global capacity share (%)	Production (tonnes/yr)	Capacity utilisation (%)
Mutanda	DRC	Cu	24 500	20	23 000	107
Tenke Fungurume	DRC	Cu	16 054	13	16 783	96
Luiswishi	DRC	Co	7 000	6	3 100	226
Lubumbashi Slag Hill	DRC	Co	5 000	4	5 500	91
Konkola	Zambia	Cu	3 888	3	NA	NA
Moa Bay	Cuba	Ni	3 694	3	3 400	109
Sudbury Operations	Canada	Ni, Cu, PGM	3 500	3	600	583
Ruashi	DRC	Cu	3 391	3	4 500	75
Polar Division	Russia	Ni, Cu, PGM	3 368	3	NA	NA
Ambatovy	Madagascar	Ni	3 273	3	5 600	58
Total	**-**	**-**	**73 668**	**61**	**62 483**	

Data source: (S&P Global Market Intelligence, 2018)[17]

In total, (S&P Global Market Intelligence, 2018) identifies 54 active mines, accounting for 110 350 tonnes of cobalt mine production in 2016[18].

In 2016, refinery production amounted to 98 000 tonnes (BGS, 2017). China is the largest producer of refined cobalt, accounting for 46 % of global production in 2016. Other significant producers include Finland (13 %), Belgium and Canada (6.5 % each) (Table 8).

Although cobalt is mainly mined in DRC, the country is only responsible for 0.4 % of global refinery production, despite the high level of unutilised capacity (Table 8). DRC is perceived to provide the majority of the feed material for China's production of refined cobalt (Cobalt Factsheet, 2017). In 2013 it was announced that DRC intended to ban exports of copper and cobalt concentrates to encourage refining within the country. To date, this has been put on hold and its implementation is not foreseen at any point over the coming years (Roskill, 2017). The importance of raw material exports to national GDP and a lack of electricity for such an energy-intensive sector[19], are pointed out as the main reasons. Nevertheless, according to (Cobalt Factsheet, 2017) based on OECD, the country has imposed export taxes of up to 25 % on cobalt ores and concentrates over the period 2010-2014.

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[17] Recent expansions at the mine site are thought to explain the situations in which production is higher than the known capacity (capacity utilisation > 100%).

[18] S&P Global Market Intelligence figures may not align with production totals from other sources due to a lack of reliable mine information for some countries.

[19] According to (USGS, 2011), electricity requirements for the recovery of cobalt cathode from intermediate products by electrowinning in chloride and sulfate media are on average 3400 KWh/tonne and 5300 KWh/tonne for operations in China, Japan, Norway, Zambia, DRC and Canada. In DRC these requirements are said to vary between 5000 and 6000 KWh/tonne. The same study also mentions that the DRC plants were undergoing major renovations to reduce the electricity requirements per unit of cobalt cathode produced.

Table 8 Cobalt refinery production in 2016.

Country	Production in 2016 (tonnes) (a)	Global production share in 2016 (%)	Refinery Capacity in 2015 (tonnes/yr)(b)	Form (b)
Australia	3 200	3.3	6 700	metal powder & oxide hydroxide
Belgium	6 329	6.5	1 500	metal powder, oxide, hydroxide
Brazil	400	0.4	3 000	metal
Canada	6 355	6.5	6 520	metal, metal powder, oxide
China	45 046	46.0	50 000	metal, metal powder, oxide, salts
DRC	400	0.4	9 050	metal
Finland	12 393	12.6	13 000	metal powder and salts
France	119	0.1	500	chloride
India	100	0.1	2 060	metal and salts
Japan	4 305	4.4	4 500	metal
Madagascar	3 273	3.3	5 600	metal powder
Morocco	2 081	2.1	2 250	metal and oxide
New Caledonia	2 531	2.6	NA	carbonate
Norway	3 541	3.6	5 200	metal
Russia	2 100	2.1	10 000	metal
South Africa	1 101	1.1	1 500	metal powder and sulfate
Zambia	4 725	4.8	9 600	metal
Uganda	0	0	720	metal
Total	**97 999**	**-**	**132 000**	**-**

Data sources; (a) (BGS, 2017), (b) (USGS, 2015).

Prior to refining, cobalt ores/concentrates are further processed into intermediate products (see Box 6). Although the majority of mining producers undertake processing to intermediate products domestically to lower the high costs of shipping bulky, low value ores/concentrates, the following exceptions were identified by (Roskill Information Services, 2014) in 2012: Ni-Cu-Co concentrates from Australia, Finland, Spain and Zimbabwe shipped to Canada, China and South Africa; Co and Cu-Co concentrates from DRC to China, Finland, India and South Korea; Laterite ores from Indonesia to Australia; Co concentrate from Russia to Finland; PGM-Ni-Cu-Co concentrates from Zimbabwe to South Africa.

Box 6. Stages of the cobalt production chain

Cobalt is traded in the following forms:

Cobalt ores and concentrates: common cobalt-bearing minerals found in economic deposits outlined in Table 6 include erythrite, skutterudite, cobaltite, carrollite, linnaeite and asbolite, belonging to the arsenates, arsenides, sulphosalts, sulphides and oxides mineral groups. Whilst these can form a valuable minor component of copper and nickel sulphide or oxide ore deposits, cobalt is mostly associated with, or contained in, Ni and Cu sulphide minerals, such as pyrrhotite, pentlandite and chalcopyrite, replacing other metals or forming inclusions.

Intermediate cobalt products: include cobalt salts (hydroxide, carbonate and sulphate), accounting for 56 % of capacity and production, crude cobalt oxide, cobalt alliage blanc, and cobalt containing mattes.

Refined products: can be split into chemical products and metal products (such as cathodes, briquettes, ingots, granules and powder). The metallurgical process that can be used, individually or in combination, for the production of pure cobalt metal can be classified broadly into hydrometallurgy or pyrometallurgy. Hydrometallurgical operations are mainly employed in the recovery of cobalt from copper products.

Sources: based on (Roskill Information Services, 2014) and (Cobalt Institute, 2018), (Cobalt Factsheet, 2017).

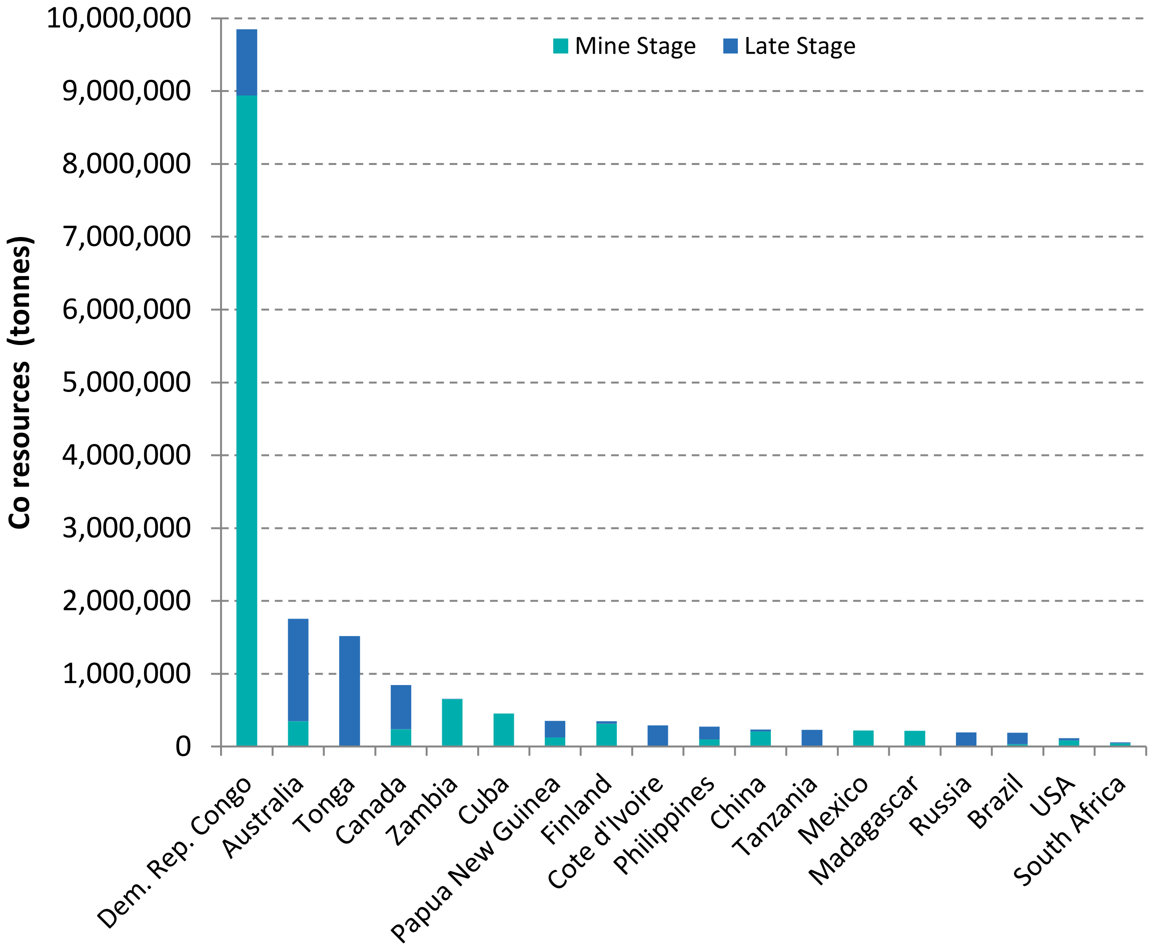
3.2 Cobalt reserves and resources

Globally, the largest cobalt resources are located in DRC and identified in connection with active mines. In DRC, these amount to almost 10 million tonnes of cobalt and represent 55 % of worldwide resources (Figure 20).

The amount of cobalt resources at mine-stage operations worldwide amounts to 12 million tonnes, while around 5.9 million tonnes have been identified at late-stage exploration projects (see Box 7).

The countries with the highest number of mine and late-stage exploration projects are Australia (49), followed by Canada (33) and DRC (17). Most projects in Australia and Canada consist of late-stage exploration ventures (see Annex 1).

Figure 20 Cobalt resources (inclusive of reserves) available at operating mines and late-stage exploration projects.



Data source: (S&P Global Market Intelligence, 2018)[20].

[20] Only active projects with declared resources are considered. Resource estimates are, in general, compliant with the Joint Ores Reserve Committee (JORC) reporting standard. Resources are inclusive of reserves and include inferred, indicated and measures volumes.

Box 7. Development stage of projects considered in the assessment

Projects reviewed fall into the following stages:

- Mine-stage (includes pre-production, further breakdown into construction planned and started, and production stage including operating, satellite, expansion, limited production and residual production phases): a project that has made a decision to move forward with production or is actively producing.

- Late-stage exploration (split into reserves development, pre-feasibility and feasibility, started or completed): a project with a defined resource that has not yet reached a production decision.

Projects without a defined resource estimate (in general all early-stage and some late-stage projects) were excluded from the analysis. As for the activity status, both active projects and on-hold were considered. Inactive projects were excluded from the assessment.

Most currently operating mines focus on copper as primary product of the mine output (Table 9). However, future cobalt production from late-stage exploration projects is likely to have nickel as primary product.

Table 9. Cobalt mine production capacity shares based on the typologies of the primary product.

	Copper (%)	Cobalt (%)	Nickel (%)
Operating*	54	12	34
Preproduction/commissioning	47	17	36
Late-stage	20	12	68

* Lack of uniformity between this assessment and the figures presented in section 3.1 reflect differences between actual production and existing production capacities.

3.3 Potential barriers to cobalt supply

Cobalt has, in general, high recovery efficiency, typically of 75-90 %, and it represents an important source of refinery revenue of approximately 15 %[21] (Oakdene Hollins and Fraunhofer ISI, 2013). Thus, there are large incentives for its recovery, both at existing refineries, and for developing poly-metallic deposits.

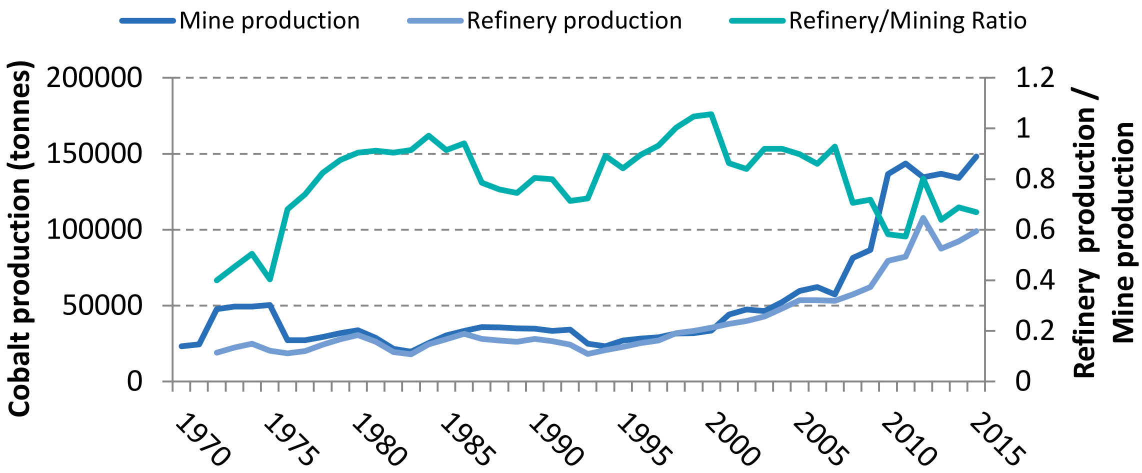
However, although cobalt may be mined, it is not always recovered during processing of copper or nickel concentrates and was, in the past at least, often lost to mine tailings or stored pending further processing. According to (Roskill Information Services, 2014) this decision seems to depend heavily on the price of cobalt in comparison to extraction costs, and the process routes used in individual operations[22].

A decrease in cobalt recovery is seen when comparing mine and refinery production on a year-on-year basis, as given in Figure 21. From this, the annual average amount of cobalt recovered can be estimated at 79 %, falling below known average efficiency values. Moreover this ratio appears to have declined significantly over recent years, and was on average 66 % between 2010 and 2015.

[21] To be noted that since 2012, cobalt prices almost doubled to the current amount of 65,000 EUR/tonne.

[22] According to (Roskill Information Services, 2014), numerous nickel operations in Philippines and New Caledonia, although implementing cobalt extraction, do not recover it.

Figure 21 Cobalt mine and refinery production and ratio on a year-on-year basis.



Data source: (BGS, 2015)

Several barriers can limit cobalt production from mining activities (Box 8). These factors include reserves depletion or unforeseeable production stoppages at active mines, the slow speed of developing mining projects from exploration to production, and economic and socio-environmental determinants.

Box 8. Mine supply - barriers to accessibility

The rate of cobalt production from mining is affected by a number of factors:

- Exhaustion of mineral reserves at operating mines;
- High costs of production restricting extraction at certain prices;
- Unfavourable economic environment, restricting investment in the exploration of new reserves;
- A retreat into resources protectionism in producing countries;
- Socio-environmental determinants whereby economic extraction also implies developing a social license to operate.
- Events such as strikes, plant failures and other factors that can lead to unforeseeable production stoppages;
- Expansions at the mine site aimed at increasing production and/or extending mine-life are likely to occur throughout the mine's life, if market conditions are favourable. Other factors that can be expected to increase production are technical developments and improvements in mining configuration, processing and metallurgical performance;

On the other hand, structural adjustments to meet changes in demand patterns while maintaining a stable price level might not be possible:

- Bringing new supply or capacity on stream is lengthy; it takes on average 10-15 years from discovery to production, thus supply shortages can persist and lead to significant price rises. These time frames can be further constrained by delays during the development period, which can be expected, especially in less favourable market conditions. Uncertainties and challenges in raising investment for mine development – due to generally increasing mining costs combined with uncertainties associated with market prices – are a major source of delays in setting up new operations. Developments are normally brought into line with material prices picking up, while some delayed projects may be reactivated by the appropriate market signals.
- Unexpected factors, such as geopolitical events, labour disruptions, permit issues and various technical challenges (e.g. mining engineering and metallurgical problems) can stall or put the development of planned and prospective mines on hold.
- Once capacity is in place and fixed costs are paid, producers are reluctant to limit output in response to lower prices (SEI, 2012).

Another frequently highlighted risk relates to what is referred to as by-products market dynamics, whereby cobalt production is largely driven by demand for the primary metal/s, hence it will not be increased if it is not cost-effective to increase the production of the primary metal/s.

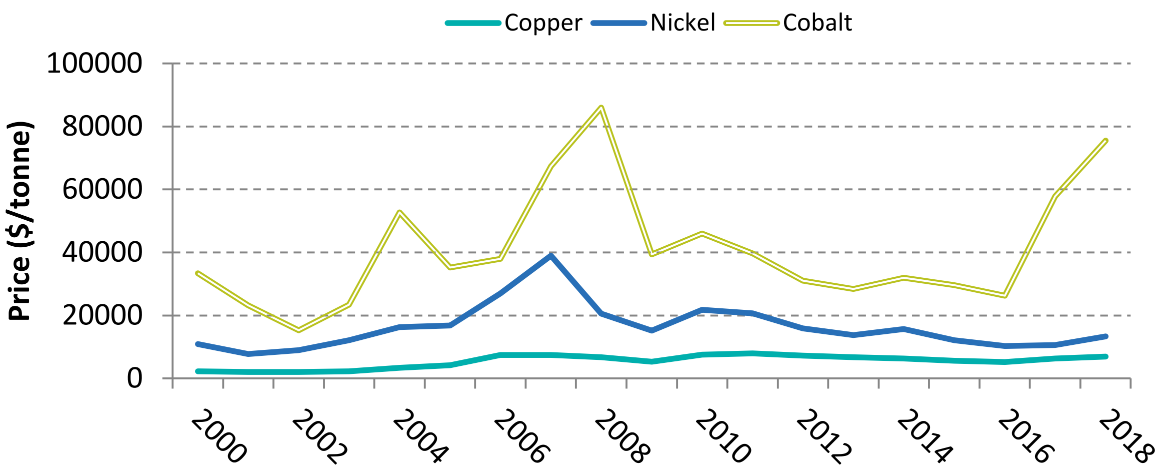
This makes uncertain whether existing cobalt contents in potentially available resources can be produced. For example, global cobalt mine production decreased from 141 000 tonnes in 2015 to 126 000 tonnes in 2016, mainly owing to lower production from nickel operations (WMD, 2018), (USGS, 2017).

The prices of copper and nickel contribute decisively to this dynamic, affecting the quantity of cobalt that is produced, and consequently the amount of cobalt that is recovered from these sources. Disruptions may occur as a result of low prices, yet in cases of high revenues, a by-product may also influence the supply of the primary metals.

Figure 22 provides an overview of nickel and copper prices since 2000. Here it is observed that the price of nickel is significantly higher than that of copper, and that in general both nickel and copper prices show a slight decrease since 2010, a trend which is more pronounced in the case of nickel. Moreover, with the exception of the last two years when cobalt prices surged, generally since 2000, these have followed the same trends as nickel prices.

The current situation with nickel prices threatening to decrease, might pose additional risks to cobalt production, potentially rendering around 39 % of its production, thought to come from nickel operations, more vulnerable to disruption.

Figure 22 Evolution of cobalt and nickel prices and comparison with cobalt prices.



Data sources: [based on USGS and (S&P Global Market Intelligence, 2018) data].

Note: Copper and nickel prices respectively refer to: LME, grade A, min. 99.9935 % purity, cathodes and wire bar (copper); LME, cathodes, minimum 99.8 % purity (nickel).

3.4 Cobalt supply in the European context

In the EU, production of cobalt ores and concentrates was estimated at 2 300 tonnes in 2016 (WMD, 2018), all sourced from Finland (around 1.8 % of global primary cobalt supply).

Refined cobalt, on the other hand, comes from a wider spectrum of countries. It is produced in Finland (13 % of the global total), Belgium (6.5 %) and France (0.1 %) (BGS, 2017). Norway also hosts refining capacities which represent around 3.6 % of the global supply.

According to (Cobalt Factsheet, 2017) the EU reliance on imports of cobalt ores and concentrates was estimated at 32 %, whilst the import reliance of refined cobalt amounted to 52 %[23].

Imports of ores and concentrates originate mainly from Russia (approximately 589 tonnes per year) and are intended for refining in Finland. Refined cobalt, on the other hand, is mainly imported from DRC. On average, over 2010-2014, the EU has imported about 19 700 tonnes of refined cobalt-bearing materials, 48 % of which originated from DRC[24]. Moreover, despite its high market share in the production landscape, the volume of European imports of refined cobalt from China is relatively small, at around 5 % (Cobalt Factsheet, 2017).

[23] The EU import reliance of cobalt ores and concentrates, as given in the EC raw materials factsheets (2017), does not include intermediate cobalt products, which were considered as part of bulk refinery imports.

[24] Imports from DRC most likely refer to intermediate cobalt products.

In Finland, cobalt is currently produced in four mines, Talvivaara (see Box 9), Kylylahti, Kevitsa and Hitura (S&P Global Market Intelligence, 2018), where it is a by-product of nickel or copper.

The Talvivaara open-pit mine started production in 2009 with a capacity of 30 000 tonnes/y Ni and 65 000 tonnes/y Zn[25]. In 2016, Talvivaara reported a production of 193 tonnes of cobalt from a low-grade cobalt-nickel concentrate, an amount which has fallen from 942 tonnes produced in 2014. By then, the expectation was that from 2018 onwards the mine would produce 1200 tonnes of cobalt annually. At full scale, cobalt production capacity is estimated at 1800 tonnes/y. Talvivaara's measured, indicated and inferred JORC resources[26], inclusive of reserves, ascend to 1 458 million tonnes, averaging 0.02 wt% Co, which represents around 300 000 tonnes of contained cobalt.

Kylylahti is an underground mine operated by Boliden Mining. Production from this mine started in 2012. The amount of cobalt contained in resources and reserves was calculated at 12 200 tonnes. Although recent production estimates are not known, a feasibility study completed in 2009 anticipated a production capacity of 800 tonnes of cobalt per year.

The Kevitsa open-pit mine, also operated by Boliden Mining, started-up in 2012 and was reported to have 21 years of production remaining. Although recent cobalt resources and reserves estimates are unknown, cobalt production from this mine is thought to have been 400 tonnes in 2016[27].

Even though Finland is the sole mine producer, within the EU, resources of cobalt are also known to exist in Sweden and Spain (Table 10). To date, around 58 000 tonnes of cobalt have been identified in projects undergoing reserves development and advanced exploration stages in these countries and Finland. The deposits concerned are in general low-grade, averaging 0.08 wt% Co. In total, 24 late-stage exploration projects[28] are listed by (S&P Global Market Intelligence, 2018), many of which (a total of 13 projects) appear to be inactive (Table 10). The amount of cobalt in resources from inactive projects is estimated at 19 000 tonnes.

Sakatti, operated by Anglo American Plc and located in Finland, is the largest project in reserves development stage. It targets copper, nickel, PGMs and gold, and presents around 19 900 tonnes of cobalt, of which 16 000 tonnes are contained in JORC inferred resources, grading on average 0.05 wt% Co.

Other projects at an early stage of exploration or development[29], without a defined resource estimate, can be found in Finland, Sweden, Cyprus, Slovakia, Austria, Czech Republic, Germany, Italy and Poland. In total, 20 projects are listed by (S&P Global Market Intelligence, 2018) in these countries, of which 4 appear to be inactive (Figure 23). During the Minerals4EU project it was identified that in 2013, exploration projects having cobalt in their portfolio were also undertaken in Portugal (Cobalt Factsheet, 2017).

[25] In 2013, the mine was targeting a production of 50,000 tonnes/y Ni and 90,000 tonnes/y Zn which was expected to be realised in 2018.

[26] JORC stands for Joint Ores Reserve Committee. It is a common reporting standard for mineral reserves and resources.

[27] In 2016, the mine produced around 11,000 tonnes of nickel, 20,500 tonnes of copper and 15,600 oz of gold. As of December 2016, Kevitsa was undergoing expansion.

[28] Late-stage exploration projects include those undergoing reserves development, feasibility, prefeasibility/scoping and advanced exploration.

[29] Early-stage exploration projects include the following developments: target outline, grassroots and exploration.

Box 9. The Talvivaara Black Shale-Hosted Ni-Zn-Cu-Co Deposit in Eastern Finland

Talvivaara is one of the largest known nickel sulphide deposits in Europe. It is located in Sotkamo in Eastern Finland, approximately 35 km southeast of the town of Kajaani. The Ni-Cu-Co-Zn mineralisations at Kuusilampi and Kolmisoppi are hosted almost entirely by high grade metamorphosed and intensively folded black shales of the Talvivaara formation in the Kainuu schist belt (central part of the Fennoscandian Shield). The main sulphides are pyrrhotite, pyrite, chalcopyrite, sphalerite and pentlandite. The sulphide content in the ore ranges typically from 15 % to 25 %. Roughly 90 % of the ore is hosted by black schist and the remaining 10 % by metacarbonate rocks, micaschists, quartzites and graywackes.

Sources: (S&P Global Market Intelligence, 2018), (Kontinen & Hanski, 2015)

Table 10 Cobalt resources in mine and late-stage projects undertaken in EU Member States.

Country	No. projects			Cobalt contained in resources & reserves (tonnes)	Grade (weighted average)
	Operating	Late-stage	Inactive		
Finland	2	15	10	359 166	0.08 %
Sweden	0	7	1	1 676	0.043 %
Spain	0	1	1	5 700	0.13 %
Germany	0	1	1	NA	NA

Data source: (S&P Global Market Intelligence, 2018).

Table 11. Cobalt reserves in the EU.

Country	Reserves (Mt)	Cobalt contained (tonnes)	Grade (% Co)	Reserve type/ Reporting code
Finland	1.51	2 416	0.16 %	Proved/ JORC
	75	10 500	0.014 %	Proven/NI43-101

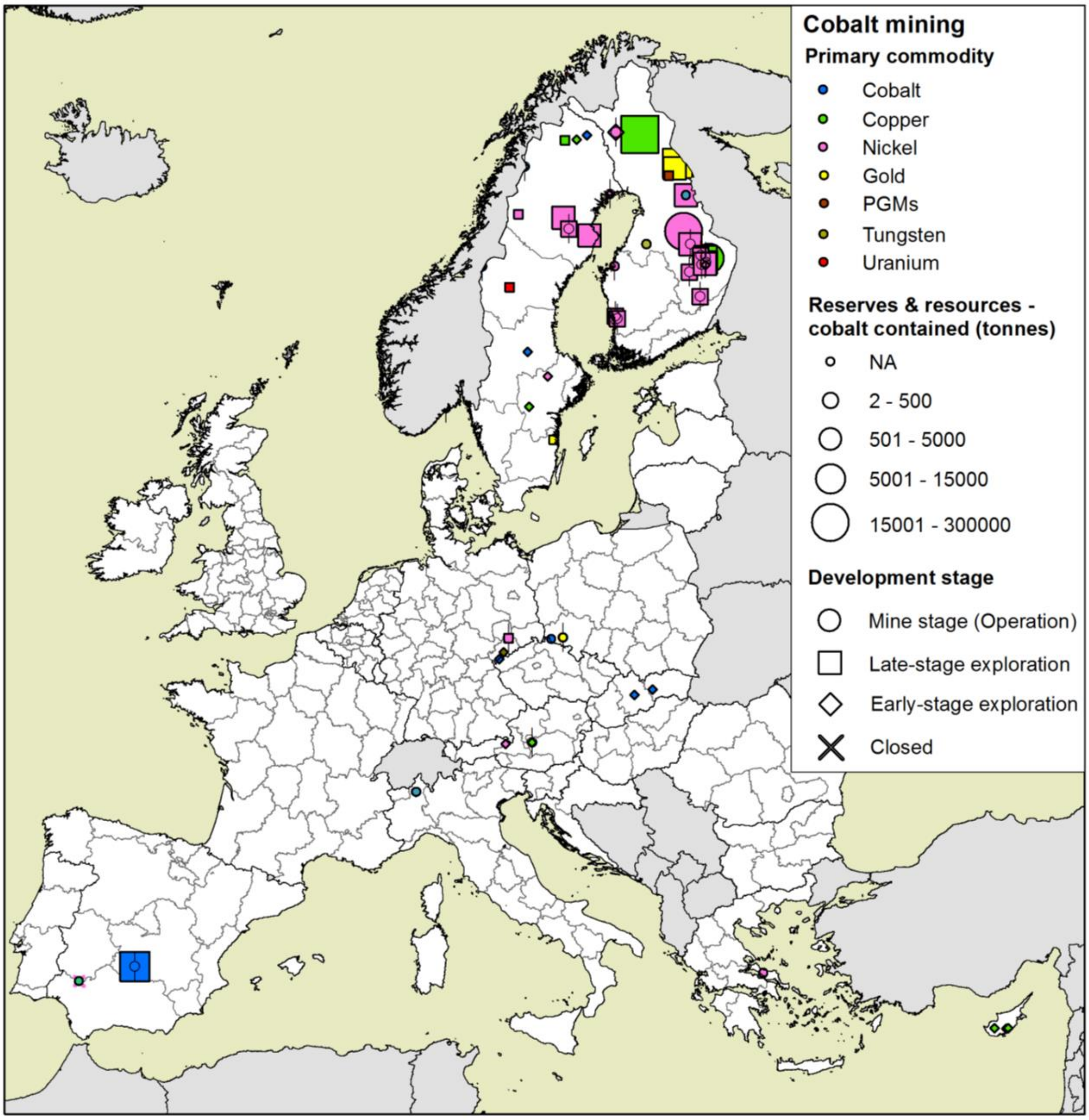
Data source: (Minerals4EU, 2014).

In addition to the Member States, in Europe, cobalt resources and/or the potential for polymetallic deposits possibly containing cobalt are also known in Albania, Greenland, the former Yugoslav Republic of Macedonia, Norway, Serbia and Turkey (S&P Global Market Intelligence, 2018)[30]. Prospective areas in such countries are identified in Figure 24 (Box 10).

Comparing Figure 23 and Figure 24, within and across EU Member States, it is clear that recent exploration activity has focused on some of the favourable areas delimited in the Promine study. Nevertheless, this comparison additionally shows that many other prospective areas have remained relatively under-explored.

[30] See also the outputs of the EU-funded project Promine (Promine, 2015) for details on mineralisation systems, metallogenic belts and predictive maps of mineral potential for certain commodity associations.

Figure 23 Distribution of cobalt resources and projects in different development stages within the EU-28.



Note: Properties additionally identified with the symbol ⚲ are considered to be inactive.

Box 10. Favourability for cobalt mineralisation within the EU – types of deposits and mineralisation styles - insights from the Promine project.

The ProMine MD database identifies a relatively large number of showings, occurrences and ore deposits which contain cobalt – 239 in total.

The following deposit types, in descending order of importance, are more significantly enriched in cobalt: mafic/ultramafic, volcanogenic massive sulphides (VMS) and residual deposits developed above ophiolitic basements.

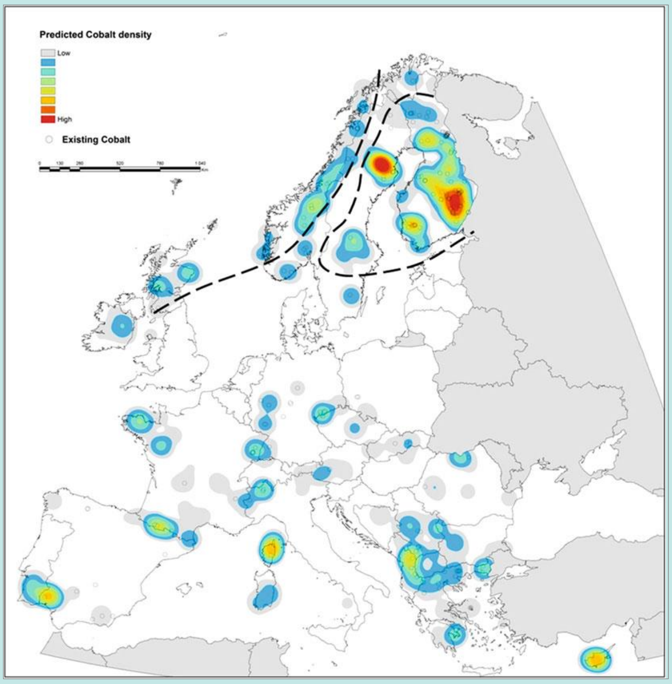


Figure 24 Predictive map of cobalt mineral potential reproduced from (Promine, 2015).

Favourability for cobalt deposits is most significant in the Fennoscandian Shield (Finland and Sweden), where it is mostly related to mafic and ultramafic complexes emplaced during the Paleoproterozoic and the early stages of the Caledonian orogeny.

In other regions, favourable cobalt enrichments occur in relation to Mesozoic-Cenozoic ophiolites (especially lateritic nickel mineralisation in the Balkans), to Bi–Co–Ni–Ag–U veins in the Bohemian Massif, and to VMS-type Cu mineralisation, in Cyprus, Spain and Portugal.

3.5 Competitiveness of the European mining sector

The Fraser Institute's Annual Survey of Mining Companies is commonly used to assess the performance of a country in terms of their policies and investments in the raw materials sector e.g. (Raw Materials Scoreboard, 2016).

The Policy Perception Index[31] evaluates the perceptions of various countries based on policy factors such as onerous regulations, taxation levels and the quality of infrastructure. Meanwhile, the ranking from the Best Practices Mineral Potential is used to provide data on the geological potential. The 'Investment Attractiveness' index, in turn, results from the combination of the above indexes, thereby measuring both policy as well as the mineral potential of a country (Fraser Institute, 2017).

Within the EU, Finland was in the top five of the most attractive jurisdictions in 2016, out of a total of 104 examined; Sweden also ranked highest in its ability to attract mining investment (Table 12). A relatively high Policy Perception Index was assigned to Ireland, Sweden and Finland, listed amongst the top five countries in terms of operating environment and policy practices; Portugal, Spain and Poland were also ranked in the top thirty of this index. As for the Best Practices Mineral Potential Index, a relatively low

[31] 'Policy Perception Index' ranks jurisdictions on factors such as administration of current regulations, environmental regulations, the legal system and taxation regime, dispute settlements, socioeconomic and community development conditions, amongst others.

perception of mineral potential in EU countries resulting from an apparent lack of large-scale resources can be inferred, with only Finland, Sweden and Ireland appearing in the top 30 country ranking (Table 12).

Table 12. Fraser Institute's Annual Survey of Mining Companies – Indexes of performance in the EU in 2016.

Country	Investment attractiveness index - Score	Rank (out of 104)	Policy perception index - Score	Rank (out of 104)	Best practices Mineral Potential Index	Rank (out of 104)
Finland	85.6	5	97.6	4	77.5	12
Sweden	84.3	8	98.2	3	75.0	21
Ireland	83.1	9	100.0	1	71.9	30
Northern Ireland	72.4	32	93.0	10	58.7	60
Poland	71.3	34	84.6	27	62.5	52
Portugal	70.9	36	90.3	16	57.9	65
Spain	70.4	38	85.2	24	60.5	55
Romania	56.6	69	55.7	75	57.1	70
Bulgaria	51.3	75	69.3	56	39.3	92
France	50.1	79	65.3	62	40.0	91
Greece	48.8	82	38.6	91	55.6	72
Hungary	47.4	85	73.5	45	30.0	101

The EU-funded project STRADE, whilst looking at the competiveness of EU mines in comparison to those in other countries, reached the following conclusions[32] (STRADE, 2016) (STRADE, 2017):

- Mining operations in the EU-28 exhibit competitive cost structures for all minerals considered in the assessment.

- The less competitive component of operating costs at mines within the EU is the labour cost, which results from multiple factors including higher wage rates in EU Member States, smaller and lower ore grade mines preventing greater metal production per employee and the prevalence of underground operations far more resource and labour intensive than open pit operations. However, these compare, often favourably, with those in other developed countries such as Australia, Canada, Chile and USA.

- Royalty and tax costs within the EU-28 are generally more competitive than other countries.

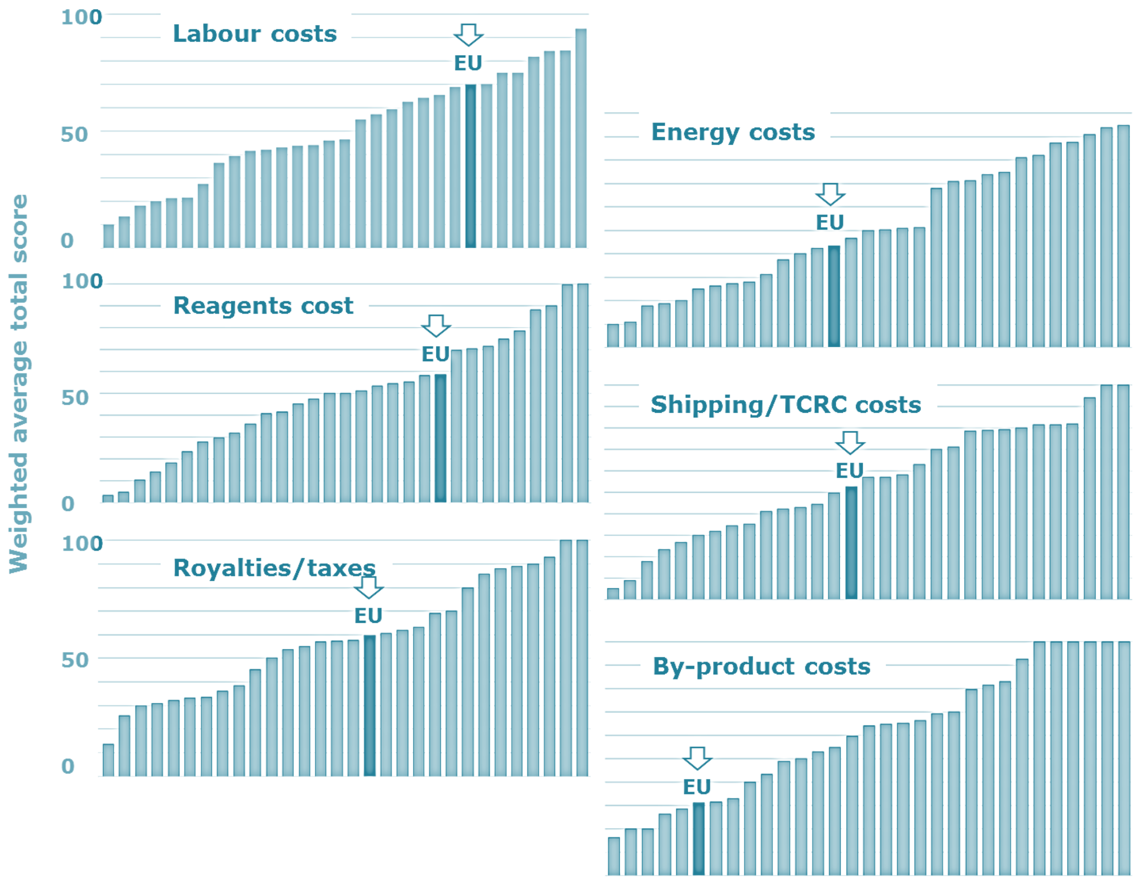
- Other cost elements are generally similar to the average costs from other regions, with mines operating within the EU benefiting from good access and infrastructure.

[32] The purpose of the STRADE study was to map the mining cost and regulatory framework performance of the EU Member States, relative to other mining jurisdictions. How the jurisdiction compares to others will influence the ability of a country to attract international mining investment. The methodology pursued considered the quality and size of the ore body, the operational costs of extracting the metal (onsite costs such as labour, energy and reagents), offsite costs such as royalties and taxes and the costs for shipping the concentrate and by-product revenues. The study focused on the following metals that are significant for the EU: copper, nickel, lead, zinc, gold and iron ore.

- By-product credits/additional revenue within the EU28 are generally above the global average.

STRADE concludes that operating costs for mining in the EU are competitive and these do not appear to hinder or inhibit operations (Figure 25). A disappointing performance in terms of increasing exploration budgets and mining investments is more bound to a poor regulatory context in which the fundamental determinants are the security of tenure and the right to mine. The second may be seen to have the greatest impact on the ability of companies to commit to investments, as many EU countries do not ensure the right to exploit a new deposit provided other regulatory conditions are met. This is also seen as the most influential measure available to strengthen the EU's competitiveness in mining and is in line with the Fraser survey, which comes to the conclusion that 40 % of a company's investment decision is determined by policy factors.

Figure 25. Competitiveness position of operating mines in the EU-28.



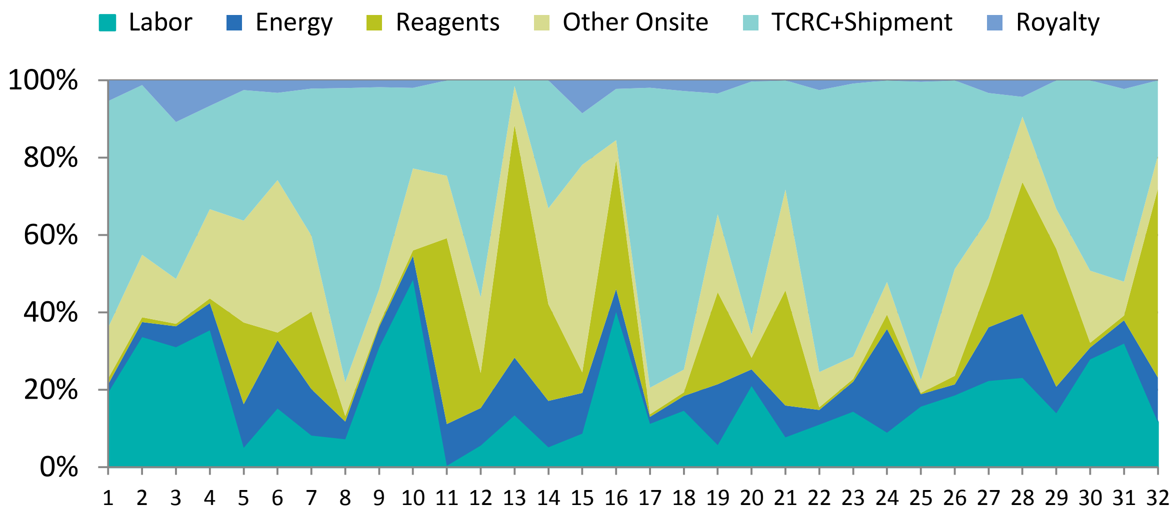
Source: (STRADE, 2017).

3.6 Costs of cobalt mining and competitiveness of European cobalt mines

With regard to cobalt mining, the highest ranked EU countries in the Fraser Institute's Survey – Finland and Sweden (Table 12) – also contain the highest number of projects having cobalt as subject of mine-, early- and late-stage activities (see also Figure 23).

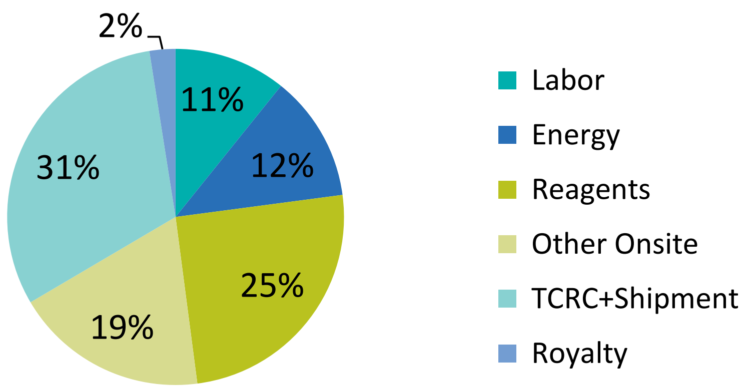
In 2017, operating costs of several cobalt producing mines worldwide were very variable. The highest value of 33 500 $/tonne was estimated in New Caledonia whilst the lowest value of 12 300 $/tonne was achieved at Norilsk, Russia. Average costs for the group of 32 mining operations assessed by (S&P Global Market Intelligence, 2018) can be estimated at 20 600 $/tonnes. The cost profile is given in Figure 26, which also shows that, on average, the highest cost category is related to transportation (31 %), followed by the cost of reagents (25 %) (Figure 27).

Figure 26. Distribution of costs in cobalt mines.



Data source: (S&P Global Market Intelligence, 2018) referent to 2017.

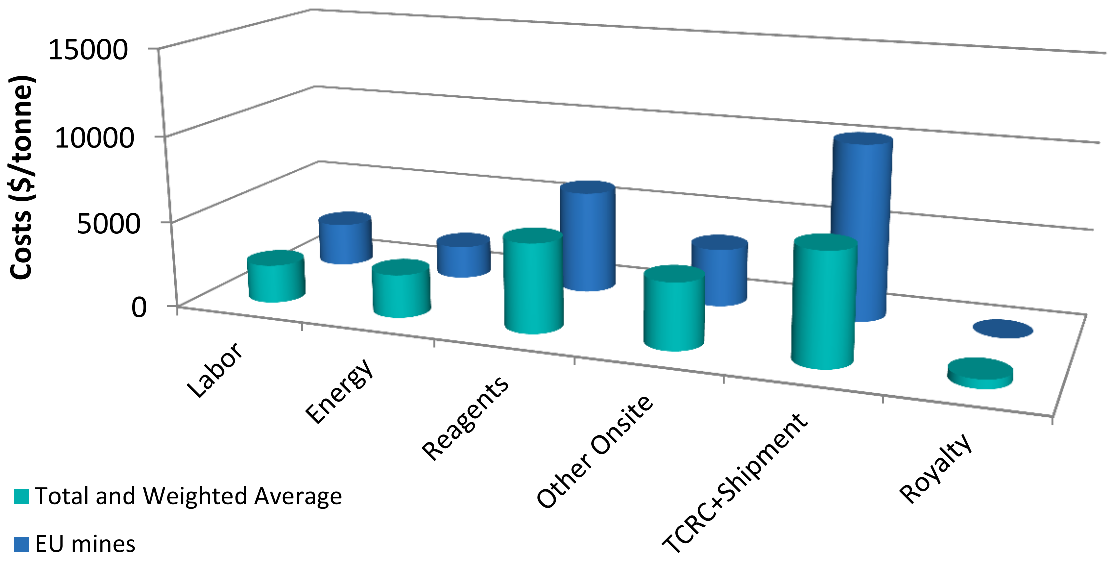
Figure 27. Cost structure of cobalt production - contribution of each cost component to the overall cost, weighted based on production amounts.



Data source: (S&P Global Market Intelligence, 2018) referent to 2017.

In Europe, shipping costs also contribute to the largest share of total costs, while other cost categories remain competitive in comparison to global averages (Figure 28). Total average costs at EU mines are estimated at 24 000 $/tonne.

Figure 28. Costs in European cobalt mines in comparison to the world weighted average.



Data source: (S&P Global Market Intelligence, 2018).

Decreasing the costs of transport (via the close proximity of consumer industries to the mines) could improve the competitiveness of European cobalt mines. This would also compensate for potentially higher costs related to lower productivity.

3.7 Mine supply projections

Mine production capacities - the nominal level of output based on mine design - are the underlying data used to develop projections of future mine supply, used as inputs to estimate cobalt supply-demand balances.

Both operating mines and ongoing exploration projects were assessed, using information largely obtained from S&P Global Market Intelligence in 2018. The evolution of supply sources and capacities over time has been estimated, assuming that all current late-stage development projects will reach production, adding capacities and new actors to the current list of suppliers. Given the nature of the mining industry and lead time for exploration/mining projects (10-15 years from discovery to production), the list of potential new suppliers is deterministic in that only the listed suppliers may be in the market e.g. (Poulizac, 2011). While this assumption is legitimate, thereby allowing for a predictive analysis to be carried out, market conditions are the primary driver of decisions to further develop exploration projects or move forward with committed and planned production centres: projects must meet increasingly severe production-cost criteria in order to obtain financing for development. Therefore, estimates of potential future production are only reasonable under certain preconditions of growth in demand and rising prices.

To capture the considerable uncertainty about long-term mine production, the assessment of supply trends through to 2030 relied on four assumptions:

Scenario 1 – Low Case. Mine supply projections were calculated by simulating idealised, life-of-mine, production profiles. This was done by using a declining resources method to estimate the number of production years reported resources could theoretically support at full capacity[33]. Since no distinction is made between reserves and resources (resources are inclusive of reserves), to calculate the remaining years of production, resource figures were adjusted by a factor of 75 %. Most information on production capacities was retrieved from (S&P Global Market Intelligence), however some statistical assumptions based on log-linear regressions between cobalt resources and production capacities were made to overcome data gaps in regards to production potential whenever information on resources was available (see Annex 2). The start-up dates for developing projects were established based on the development stage: mines under construction were assumed to come on-line in 2019; projects at feasibility stage were expected to come on-stream in 2021; supply from pre-feasibility and reserves development-stage projects was expected to be available at the project site in 2026 (see Annex 3). Moreover, as planned production capacities are rarely attained quickly after start-up, capacity profiles of mines expected to come online in the future were calculated assuming a ramp up trajectory over the first two years (30 % in the first year and 70 % in the second year), each mine reaching full capacity in the third year. Projects for which information on resources and reserves are not available, as a result, for instance, of the company involved not having or not releasing the data, were excluded from the analysis from 2018 on. This is likely to render estimates conservative and the resulting supply scenario is considered Low Case. On the other hand, depending on the project's economics, it is reasonable to expect that at least some projects with less challenging economics will take fewer years than the fixed timeframes to come into production.

To ensure the conversion of mine output to refined production, and thereby the comparability between supply and demand figures, an average recovery rate of 83 % in the subsequent refining was assumed[34].

Scenario 2 – High-Case. Supply projections were calculated assuming that current available capacities will include an amount of 53 700 tonnes until 2030, currently deriving from operations for which information on remaining resources is not available. In addition to these, capacity outputs resulting from pre-productive mines and late-stage exploration projects are added in different time horizons, as described in scenario 1. This gives an indication of how much additional supply could be available in the short-to-medium term. Again, a recovery rate of 83 % is assumed. Such a scenario is considered high case.

Scenario 3 – Low-Case Intermediate. To make allowance for technological improvements in refining operations, an average recovery rate of 90 % was assumed in this scenario and used to adjust the mine output estimated in scenario 1. This assumption allows for an increase in the percentage of cobalt potentially available for consumption (low-case intermediate scenario).

Scenario 4 – High-Case Intermediate. The deterrent effect on supply created by unethical practices in cobalt-producing countries, together with the potential for geo-political risks and unforeseeable production stoppages (e.g. labour disruptions and technical challenges), were considered in this scenario. It is assumed that 20 000 tonnes of cobalt will become unavailable in the future. This amount is subtracted from the mine output included in scenario 2, giving rise to a high-case intermediate scenario.

Figure **29** shows supply projections until 2030, estimated on the basis of the scenarios described above. Table 13 includes the projected amounts in relevant timeframes.

[33] Resources from S&P Global Market Intelligence correspond to measured, indicated and inferred quantities reported by companies, normally following common reporting standards (mainly JORC).

[34] The assumed recovery rate of 83% represents an average efficiency level obtained from the recovery range of 75-90% provided by (Oakdene Hollins and Fraunhofer ISI, 2013).

Figure 29 Mine supply projections until 2030.

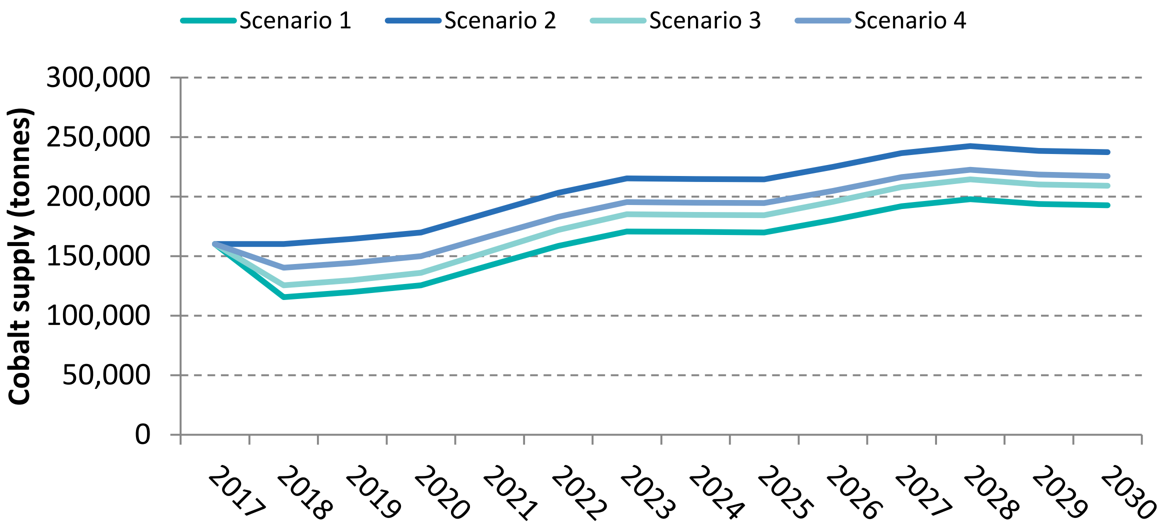


Table 13 Mine supply projections until 2030 in the relevant timeframes[35].

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
(tonnes of Co)	Low	High	Low-case intermediate	High-case intermediate
2017	160 200	160 200	160 200	160 200
2020	125 400	169 950	136 000	149 950
2025	170 000	214 600	184 400	194 600
2030	192 800	237 400	209 100	217 400

Starting from a capacity of approximately 160 000 tonnes of potentially recovered cobalt in 2017, projects on the horizon may make provision for limit values of around 170 000 tonnes in 2020, 215 000 tonnes in 2025, and 237 000 in 2030 in the high-case scenario (scenario 2). In the low-case scenario (scenario 1), the fact that numerous mine operations do not have allocated resources in the database consulted, and therefore have not been further considered, result in the indicative decrease of mine capacities from 160 200 in 2017 to 125 000 tonnes of potentially recovered cobalt in 2020. In 2030, around 193 000 tonnes are likely to be available under this scenario.

It can be noted in Table 14 that some projects are expected to bring additional material into the market by 2030, however the greatest potential is bound to operating mines. These account for almost 60 % of total capacity (current and future). The ramping up of new projects can increase cobalt production by 12 % until 2020, by 23 % in 2021 and by 20 % in 2026 (Table 14).

35 The mine output in different scenarios was adjusted to average recovery rates as described in the text, to ensure comparability between supply and demand figures.

Table 14 Additional cobalt output from mining projects at different development stages.

Development stage	No. Mines/ Projects	Potential cobalt supply (tonnes) from ongoing projects	Capacity share (%)	% change to global supply
Operating and expansion	70	160 000	60 %	-
Pre-production and Construction *(potentially available from 2019 on)*	8	19 000	7 %	12 %
Feasibility *(potentially available from 2021 on)*	29	42 000	16 %	23 %
Pre-feasibility and reserves development *(potentially available from 2026 on)*	92	44 000	17 %	20 %

Note: current and projected capacities are either consulted from S&P Global and (Roskill Information Services, 2014) or inferred based on a correlation between available resources and production capacity described in Annex 2. The mine output was adjusted to average recovery rates of 83 %. The % of growth in each timeframe, coinciding with the start-up of projects in different development stages, does not take into account the closure of operations in the same time horizons and the progressive increase in production during the ramp-up of operations. For this reason the results in this table will not match mine supply projections given in Table 13.

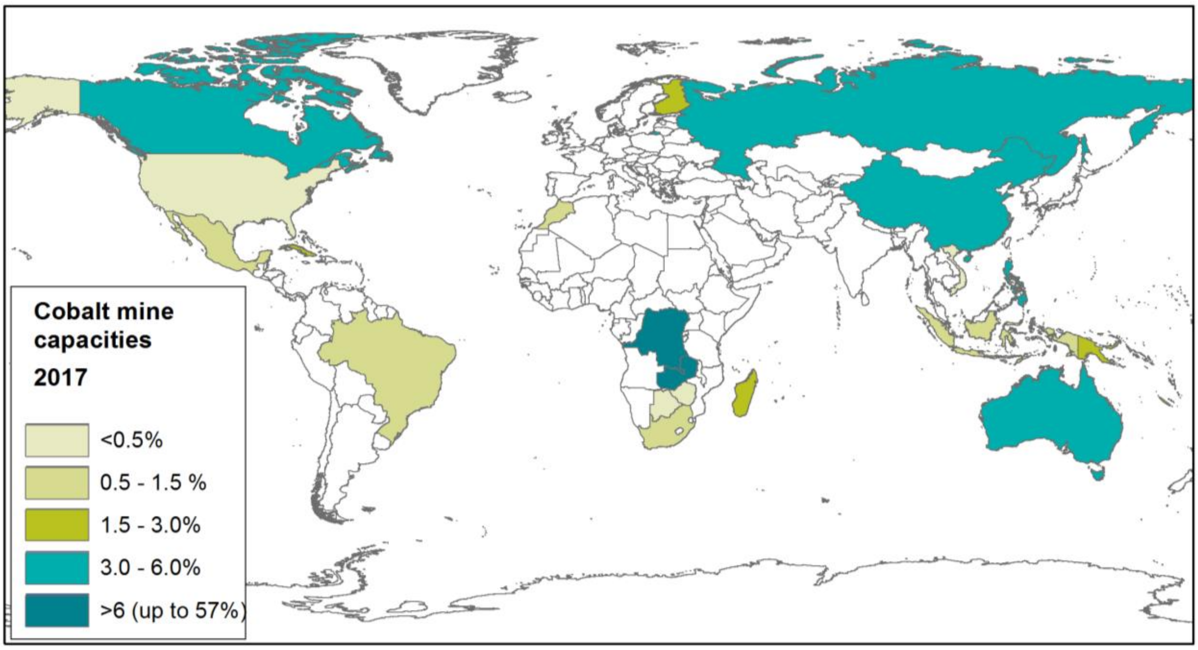
Figure 30 offers information on the distribution of cobalt mine production capacities per country in different timeframes, calculated on the basis of supply forecasts arising from scenario 1. It shows that in 2017, the largest mine capacity was located in DRC and Zambia. Additionally, in countries such as Australia and Canada, a pipeline of projects is being developed. These countries are likely to gain additional importance in the future, helping to reduce dependency on the supply from DRC. In 2030, the contribution of DRC to cobalt supply can be reduced to less than 50 %, with the potential increase in Australia's share to around 14 %.

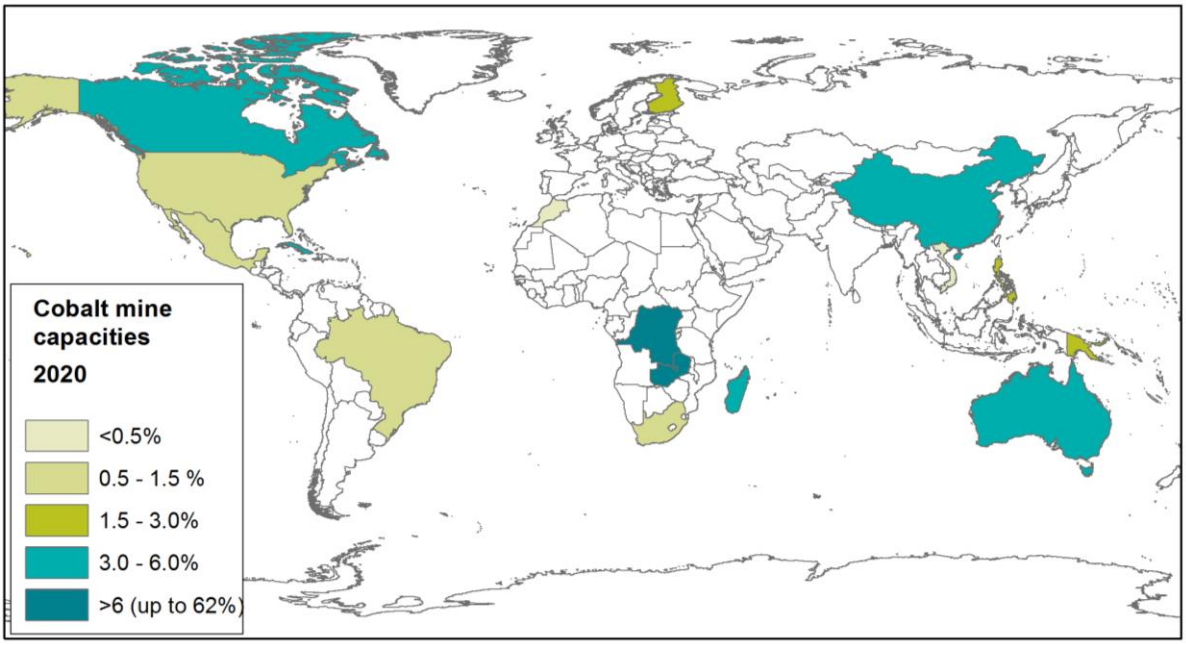
After 2025, cobalt extraction from deep-sea-mining projects currently at reserves development stage, such as those located in Tonga[36], can potentially provide for around 6 % share. These would account for nearly 21 % of the additional cobalt capacity that may come on stream by 2026.

In the EU, Finland accommodates around 1.65 % of the world's cobalt production capacity (around 3000 tonnes/yr). This share can be adjusted slightly upwards in the short-term to around 2 % in 2020.

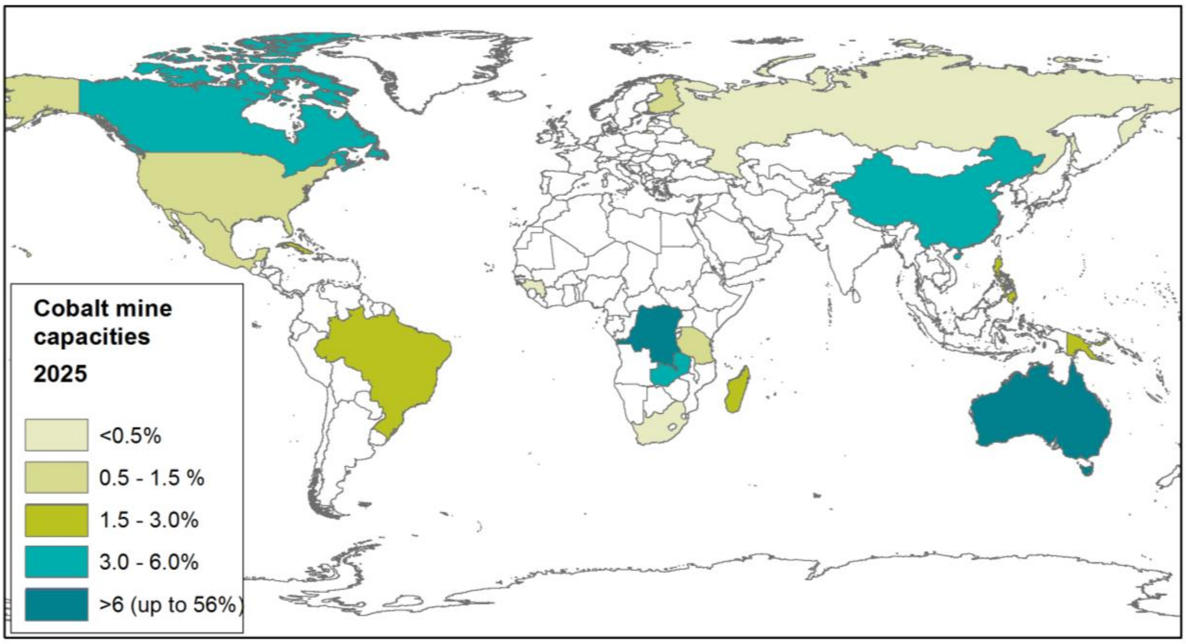
[36] The feasibility of such projects has still to be demonstrated. According to (USGS, 2018) and (Cobalt Institute, 2018), significant resources of cobalt are present in deep-sea nodules and crusts which occur in the Mid-Pacific, Atlantic and Indian Oceans; here, speculative and hypothetical resources of ~120 million tonnes of cobalt have been identified. The amount of proved and inferred cobalt resources in Tonga amounts to 1.5 million tonnes (S&P Global Market Intelligence, 2018).

Figure 30 Distribution of mine supply in 2017, 2020, 2025, 2030 according to projections in scenario 1[37].





[37] The data underpinning the map projection can be found in Annex.4.



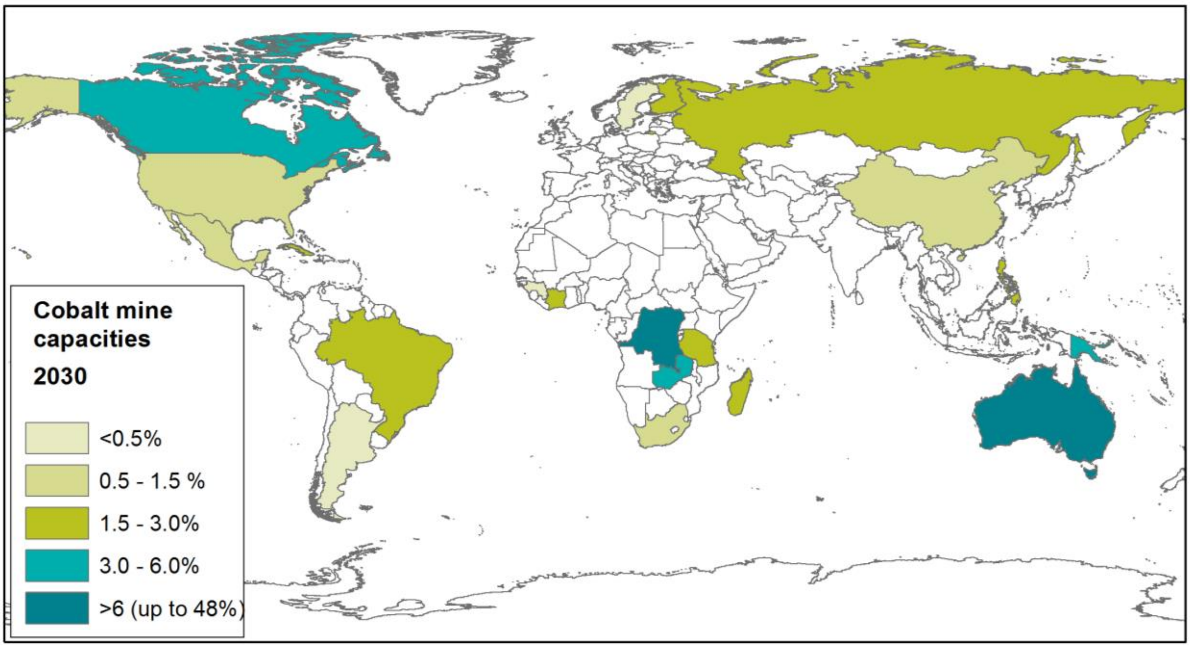
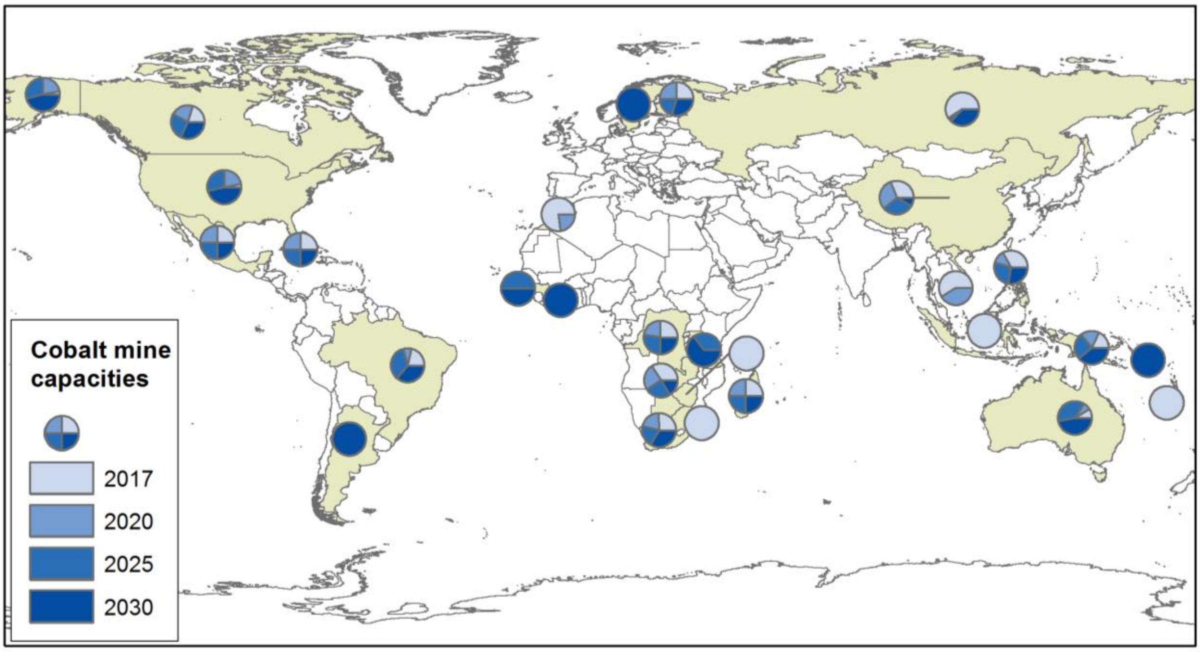


Figure 31 provides an insight into the evolution of supply shares within each producing country in reference years. It is clear that whilst cobalt supply may emerge in 2030 from new producers such as Argentina, Côte d'Ivoire, Solomon Islands, Sweden and Tonga, several other countries with current production capacities such as Botswana, New Caledonia and Zimbabwe might cease their cobalt mining activities if mineral resources are exhausted and not replaced through exploration.

Figure 31 Mine capacities and shares over time per producing country (based on scenario 1).



3.8 Perspectives on the evolution of mine supply concentration

It is widely taken as a proxy and accepted that supply for a specific material is constrained if the production is concentrated in a limited number of countries lacking adequate political stability (e.g. (JRC, 2017(b)). Such circumstance may lead to disruptive events such as supply shortages or high price volatility.

The issues of supply concentration as well as the geopolitical risks of producing countries can be established using commonly accepted metrics such as the Herfindahl-Hirschman Index (HHI) and the Worldwide Governance Indicators (WGI).

HHI is a measure of the relative concentration of the supply. It is defined as,

$$HHIyear\ x\ =\ \sum_i\ (si^2),$$

where si is the fraction of the total supply the i-th supplier is responsible for, and N the number of suppliers on the market. Higher values of this index (up to 10000) indicate a higher market concentration.

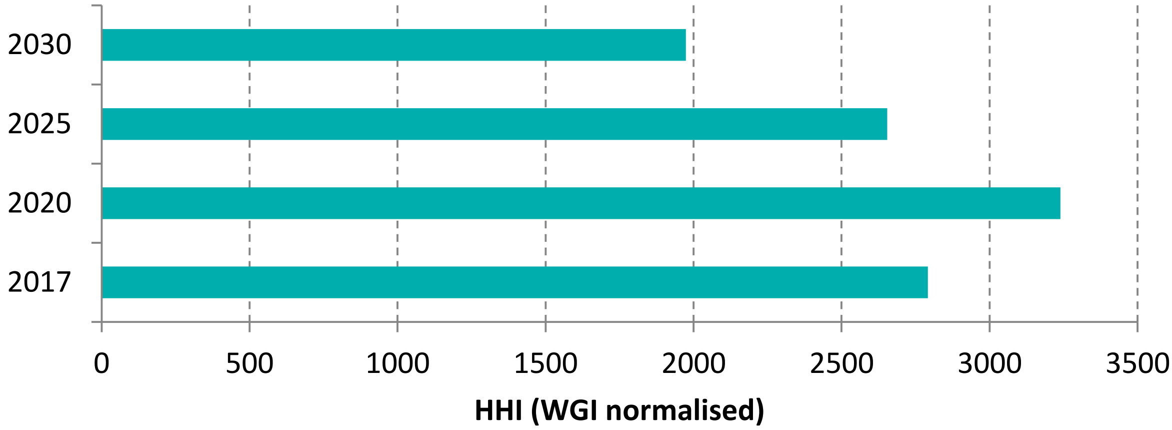
WGI, in turn, is used as a proxy for the political stability of the supplier countries. All six indicators that make up this parameter were used to derive average values which were then scaled linearly to fit between 0 and 1. Since WGI can alleviate the negative impact of concentration of supply, the following relationship is implemented:

$$HHI\ WGI_{year\ x} = \sum_i \left((si)^2{}_{year\ x} * (1 - WGI_i) \right)$$

Applying these metrics to the previous data, showing the potential evolution of mine supply sources and respective market shares over time, one can conclude that beyond 2020 and until 2030, the concentration of supply and risk of disruptions are expected to decrease (Figure 32).

The extent of this reduction can be 18 % from 2020 to 2025, and 26 % from 2025 to 2030, leading to an overall improvement of 29 % in the considered timeframe (2017-2030).

Figure 32 Estimated HHI-WGI values reflecting the market concentration of cobalt mine supply until 2030, based on production capacity estimates implied in scenario 1.



3.9 Mine supply-demand balances

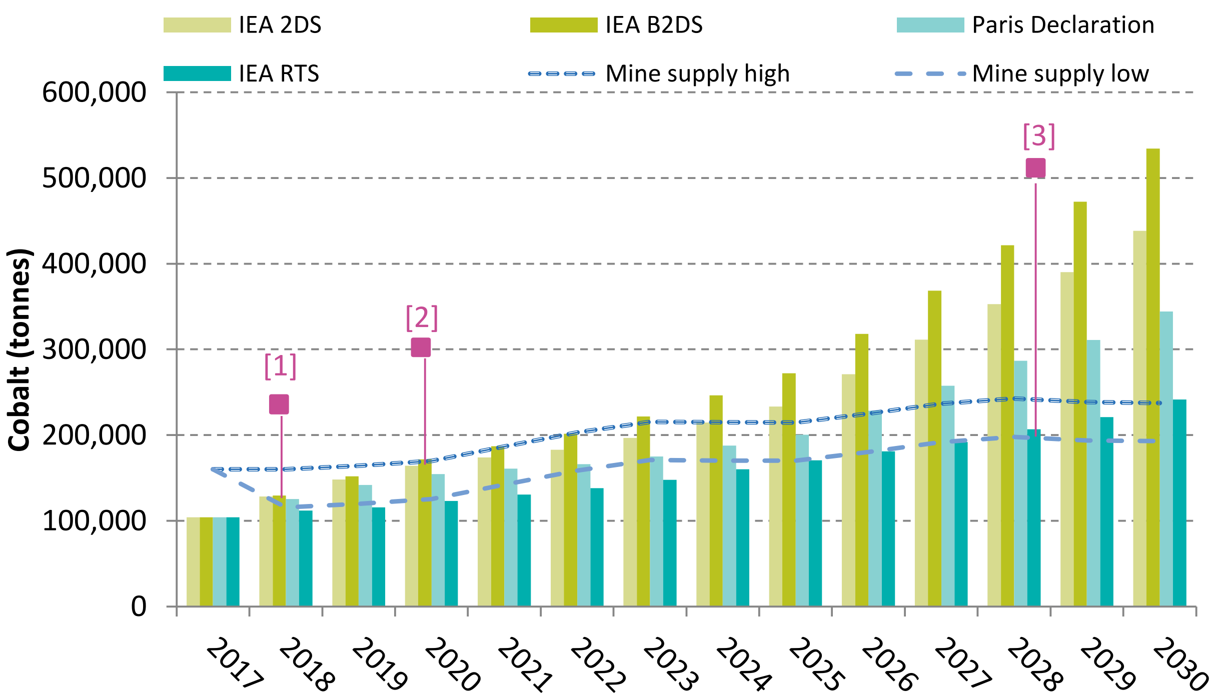
Potential deficits and surplus of supply over demand are given in Figure 33.

Considering simply the annual balances between supply and demand, existing mine capacities might already become constrained in 2018 in low supply/high demand scenarios (situation [1]). Additional capacities of about 14 000 tonnes would be required to meet demand in 2018, which would amount to around 102 000 tonnes in 2025.

Demand also exceeds supply in 2020 by 1 900 tonnes in high supply/high demand scenarios (situation [2]) and this is estimated to increase to 297 000 tonnes in 2030.

In low supply/low demand scenarios, supply and demand will likely be broadly in balance until 2027, before demand exceeds supply (situation [3]).

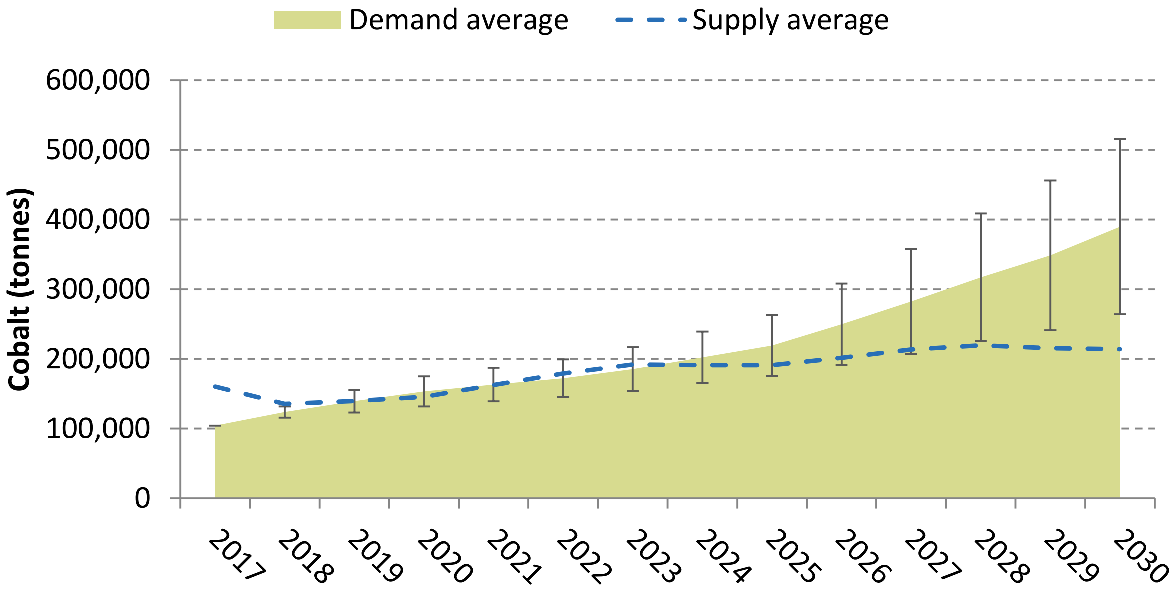
Figure 33 Comparison between potential supply and demand of cobalt until 2030.

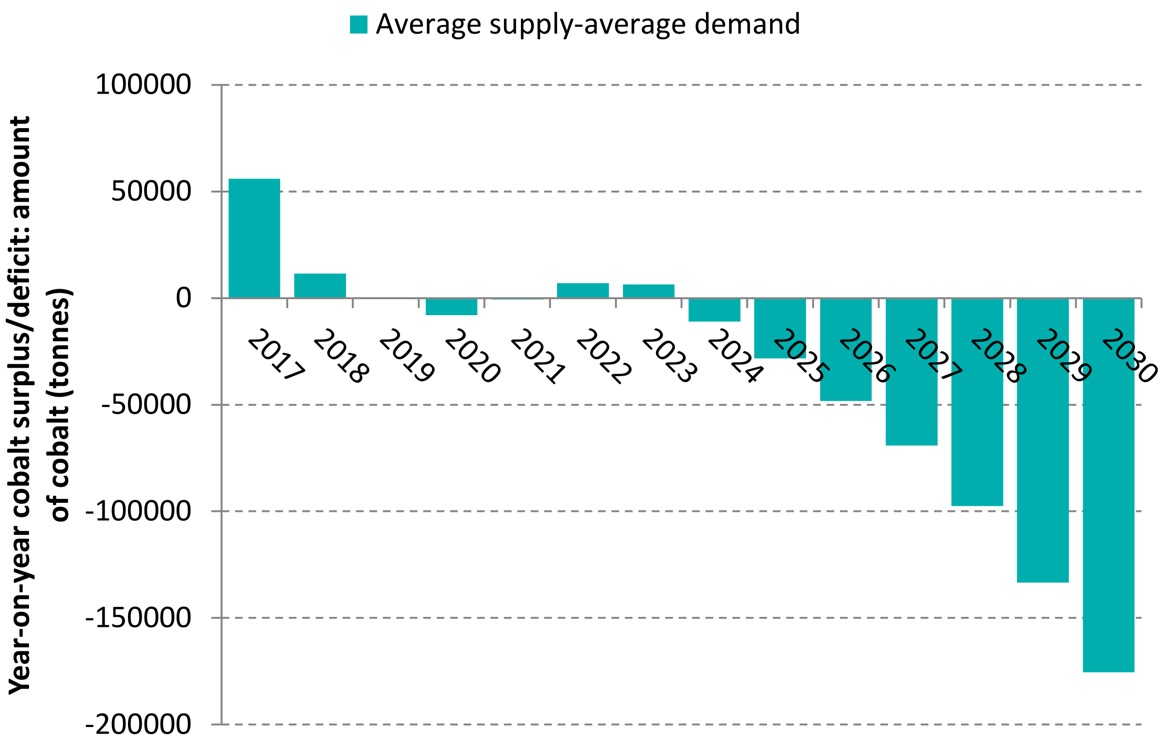


To facilitate the visualisation of data provided under various sets of supply and demand scenarios, and carry out the final balancing exercise, supply and demand averages were calculated over the reference period. When presenting them, the range for the demand is indicated by error bars. The same approach was followed in the next sections dealing with the recycling and substitution effects.

In average scenarios, existing capacity begins to become constrained in 2020. Additional capacities of about 8 000 tonnes would be required to meet demand in 2020, which would then amount to around 11 000 tonnes in 2024, increasing to 175 500 tonnes in 2030 (Figure 34).

Figure 34. Year on year cobalt surplus/deficit in average mine supply and demand scenarios.



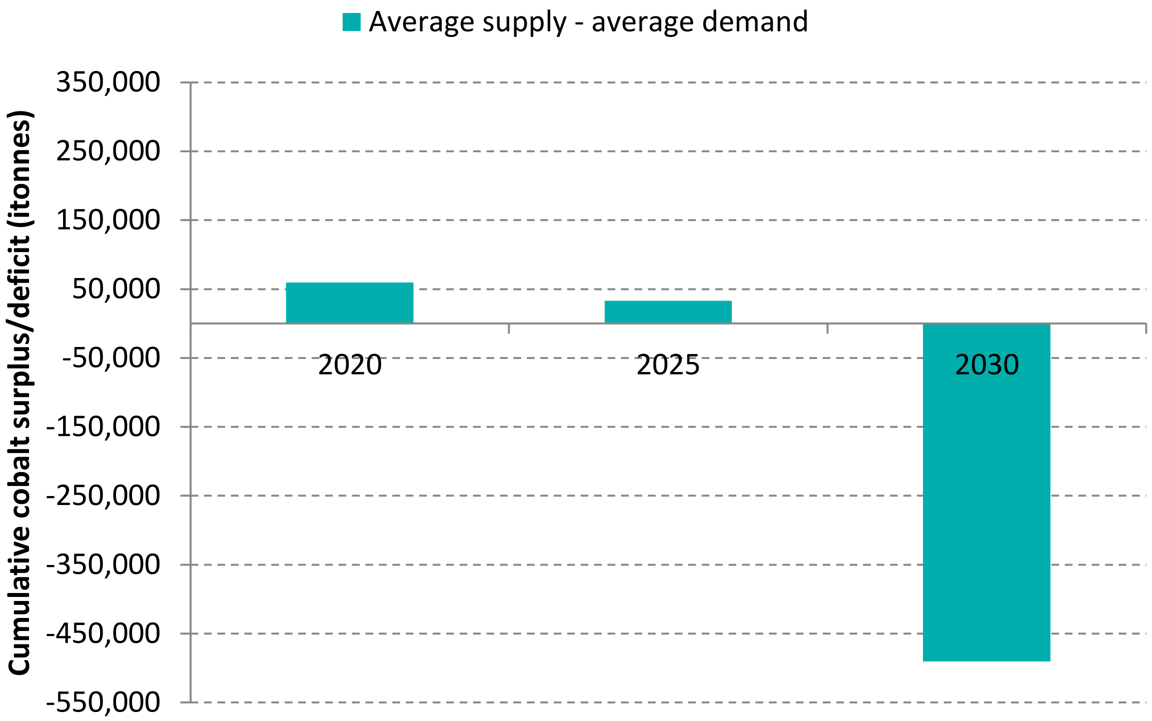


Note: 'demand average' was calculated as a simple average of the four demand scenarios, over the reference period (see section 2.3). Error bars show the standard deviation of demand forecasts in the various scenarios. 'Supply average' refers to the average amount of cobalt calculated from the four supply scenarios discussed in section 3.7.

The available data also indicate that cobalt supply had a net surplus of around 56 000 tonnes in 2017. Global demand was accommodated by approximately 65 % of mine capacity. Assuming that these extra amounts are produced each year and stored or stockpiled for use in the following years, in the assessment of average demand-supply scenarios, mine supply is expected to ensure that demand is satisfied to a reasonable extent until 2025 (Figure 35). At the end of 2025, a cumulative surplus of 33 200 tonnes can be inferred. However, in 2030, a deficit of 490 000 tonnes may occur.

In such conditions, against an exponential growth in cobalt demand for EVs not countered by the adoption of substitutes or optimised battery chemistries, mining projects in the pipeline are not expected to compound the current oversupply situation, and additional supply would be necessary to satisfy future cobalt demand. Although it is reasonable to assume that, to some extent, mining companies enjoy flexibility to adjust production through investments in higher capacities together with mineral reserves replacement strategies, these are likely to be achieved at the expense of increased prices to downstream users.

Figure 35 Cumulative cobalt surplus/deficits in reference years.



3.10 European supply-demand gaps

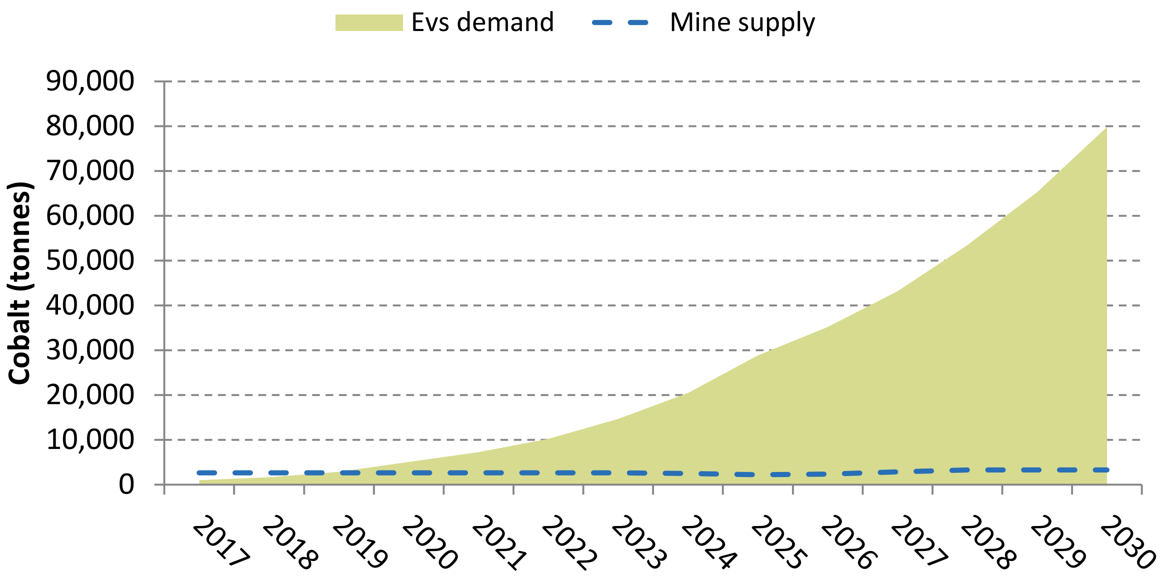
The current mining infrastructure in the EU is limited, despite the high potential for its development (Figure 23 and Figure 24).

Based on the latest S&P Global data (S&P Global Market Intelligence, 2018) concerning production capacities and resources in active European projects, both at operating mines and exploration projects, and taking into account the evaluation methods here implemented, future cobalt production capacity might be approximately 2 645 tonnes per year in 2020, increasing to 3 200 tonnes per year in 2028, if projects currently undergoing reserves development are carried over into a productive situation[38] (Figure 36).

Nonetheless, such levels of indigenous production fall far short of what will be required in 2030 to meet internal European demand in the EVs sector, and are also below the projected consumption of European LIB mega-factories thus far announced, estimated to be around 7 400 tonnes/year.

[38] It is unlikely that a project will maintain the same resources quantitative during its development. This will tend to increase and hence also the project/mine's production capacity.

Figure 36. Cobalt production capacity forecast in the EU in comparison with potential cobalt demand in the European EVs sector.



4 Substitution effects

The extent to which a material can be fully or partially replaced in its overall uses may arise if technological or design changes take place in one demand sector. For example the implementation of more efficient product designs can reduce the demand for a certain material. Likewise, alternative technologies that achieve comparable functionality using different materials can drive the abandonment of a material for a substitute.

Substitution can trigger a potential reduction in demand for a certain material in a given application, which leads to increased supply reliability, provided that the substitute has a more stable supply stream and increased available supply in the market, ultimately benefiting sectors lacking adequate substitutes.

4.1 Cobalt substitution – trends and overview

While in some applications the substitution of cobalt would result in a loss in product performance, there are a few examples where its use can be removed from the production process (Table 15).

On a scale of 0 to 100, cobalt has a substitute performance of 54[39] (Graedel, Harper, Nassar, & Reck, 2015). Details about the substitution potential and substitutes´ performance may be found in Box 11.

As shown in Table 15, nickel is the primary substitute for cobalt in most applications.

Table 15. Potential substitutes for cobalt and their performance.

Application	Application details	Primary substitute	Substitute performance
Batteries	Used in lithium-ion, nickel-metal hydride, and nickel-cadmium batteries in portable electronic devices, energy storage systems and electric vehicles.	Manganese and nickel	Good
Superalloys	Used primarily in turbine engine components	Nickel	Adequate
Magnets	Used primarily in Alnico magnets (in electric motors and loudspeakers) and in samarium- cobalt magnets (in turbomachinery and spectrometers)	Neodymium magnets	Good
Hard metal and surface treatment	Used in metal cutting and metal forming tools (e.g. dies), in construction and mining equipment	Nickel with chromium	Adequate
Pigments	Used in colouring glass and in paints	-	Very good
Catalysts	Used in petroleum refining, products for plastics and detergent manufacture, and polyester precursors	Nickel	Good

Sources: (Graedel, Harper, Nassar, & Reck, 2015), (USGS, 2015), (CRM InnoNet, 2015)

[39] 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.

Box 11. Substitution potential of cobalt – compilation based on (CRM InnoNet, 2015), (USGS, 2018).

Batteries – $LiFePO_4$ (LFP) and $LiMn_2O_4$ (LMO) without cobalt can be used instead of $LiCoO_2$ (LCO), $LiNiMnCoO_2$ (NMC) and $LiNiCoAlO_2$ (NCA) in Li-Ion batteries. Amongst cobalt-bearing cathodes, several configurations with different cobalt contents are available.

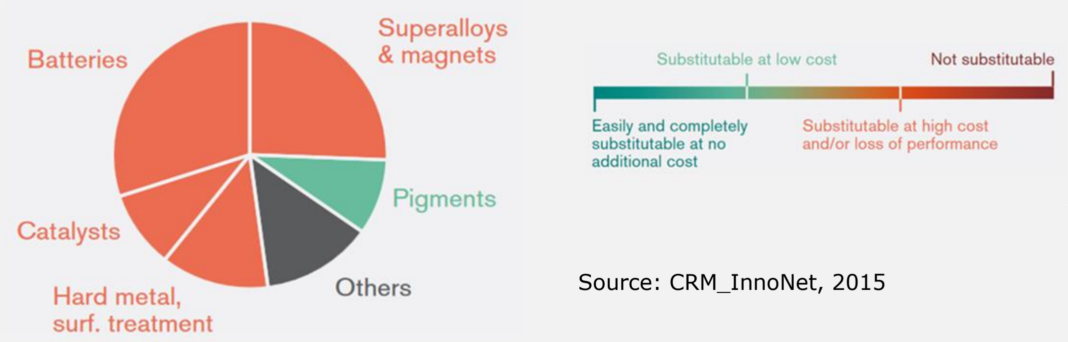
Superalloys - Fibre-reinforced metal matrix composites (MMC), ceramic-ceramic and carbon-carbon composites, titanium aluminides, nickel-based single crystal alloys or iron-based super-alloys may substitute to some extent cobalt-based ones in these applications. Loss of performance at high temperatures can be expected in some cases.

Magnets - There is some potential for substitution of cobalt-alloyed magnets by nickel-iron alloys or neodymium-iron-boron ones. The substitution seems to be difficult though, especially in high temperature applications. Other potential substitutes include barium and strontium ferrites.

Hard metal and surface treatment - There is potential for substitution of cobalt-iron-copper or iron-copper in diamond tools. However, there is a certain loss of performance.

Pigments - Cerium, acetate, iron, lead, manganese, and vanadium can all be used as substitutes for cobalt.

Catalysts - Ruthenium, molybdenum, nickel and tungsten can be used instead of cobalt, for instance in hydro-desulfurisation. An alternative ultrasonic process can also dispense with the use of cobalt, and rhodium can serve as a substitute for hydro-formylation catalysts. Cobalt may be substituted to some extent without major performance loss.



Source: CRM_InnoNet, 2015

4.2 Substitution of cobalt in Li-ion batteries – present and future developments

A number of risk factors, including price volatility and industry concerns over supply shortages, have brought about shifts in the chemistries of rechargeable batteries, leading to a decrease in the consumption of cobalt while favouring the use of substitutes. For example, LCO containing 60 % cobalt, applied specially in electronics, has been gradually replaced by NMC, with a cobalt content of 10-30 %, NCA with 14 % cobalt and LFP with no cobalt.

On the contrary, in the EVs market, the elimination of cobalt in Li-ion batteries, although possible, has not been the preferred option, insofar as it allows for optimal performance. In EV batteries, the usage of cobalt has increased in recent years: on the one hand, structural changes at the technology level have initiated the widespread use of Li-ion batteries in the hybrid vehicles segment, traditionally reliant on NiMH batteries; on the other hand, an increasing number of automakers are choosing full NMC chemistry to achieve higher energy density, and thus longer autonomy ranges, abandoning combinations of this chemistry with cobalt-free Li-ion battery technologies, namely LFP (Darton Commodities, 2016). Also (Benchmark Minerals, 2016) reinforce this idea by assigning overriding importance to cobalt-bearing NMC and NCA chemistries in the automotive sector.

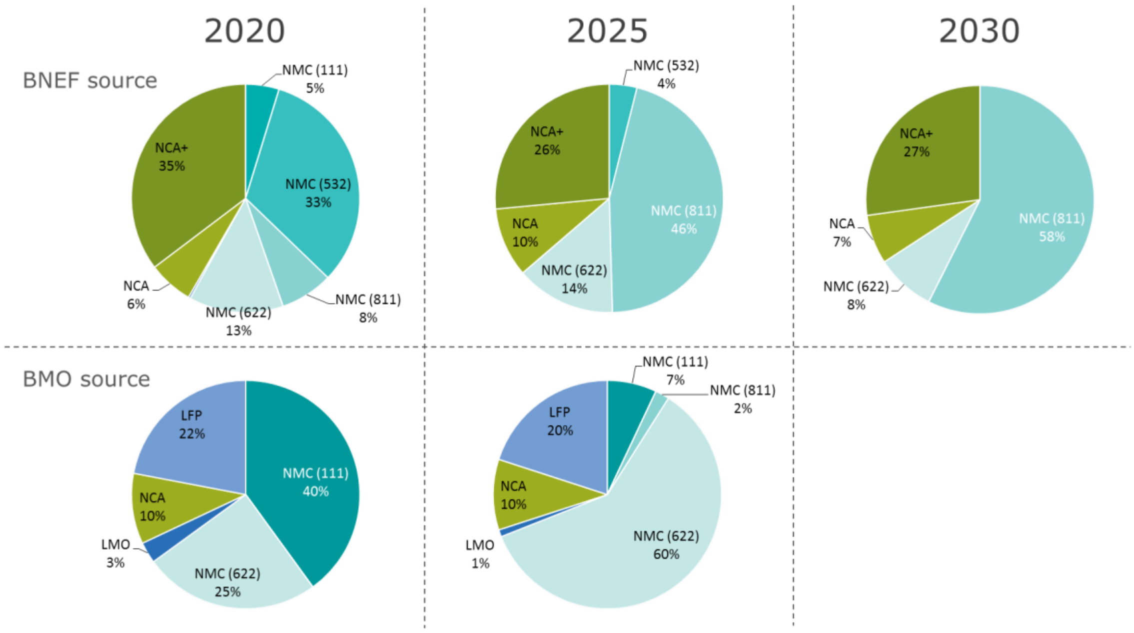
In the context of EV batteries, several NMC configurations with different cobalt contents are currently employed. Recalling Figure 7, it is noted that today, NMC 111 (with nickel-cobalt-manganese in the proportion of 1:1:1) is the most commonly used, with a market share of 42 %. In this configuration, cobalt represents around 30 % of the mass fraction.

Until 2020, either NMC (111) or NMC (532) are thought to remain the first choice for EVs (Figure 37). Such a trend, combined with a reduced use of cobalt-free cathodes (e.g. LFP), is likely to push up cobalt demand before it starts to decline after 2020, driven by substitution efforts.

In 2025 and 2030, other chemistries, requiring less cobalt and with higher nickel and aluminium contents, are likely to be used increasingly (e.g. (EC, 2018). Amongst them, NMC (811) with 9 % of cobalt[40] may be used at a rate of 46 % in 2025 and of 58 % in 2030, according to (BNEF, 2018) (Figure 37).

Although there is broad consensus over the reduction of cobalt consumption in batteries (e.g. less cobalt per kWh), at least from 2020 on, there is no general agreement on which cathodes will be prevalent in the future. In relation to the above-mentioned NMC 811, (BMO, 2018) argue that it will only be deployed to a limited extent in 2025 (up to 2 %), as shown in Figure 37. Additionally, while BNEF forecasts point to the disappearance of NMC (111) by 2025, BMO analysis concludes that NMC (111) will remain important (Figure 37). The same source anticipates that cars equipped with NMC (622) will be prevalent, and LFP will still be used up to a level of 20 %, in 2025.

Figure 37. Cathode chemistry mix in EVs.



Data sources: (Bloomberg, 2018), (BMO, 2018)

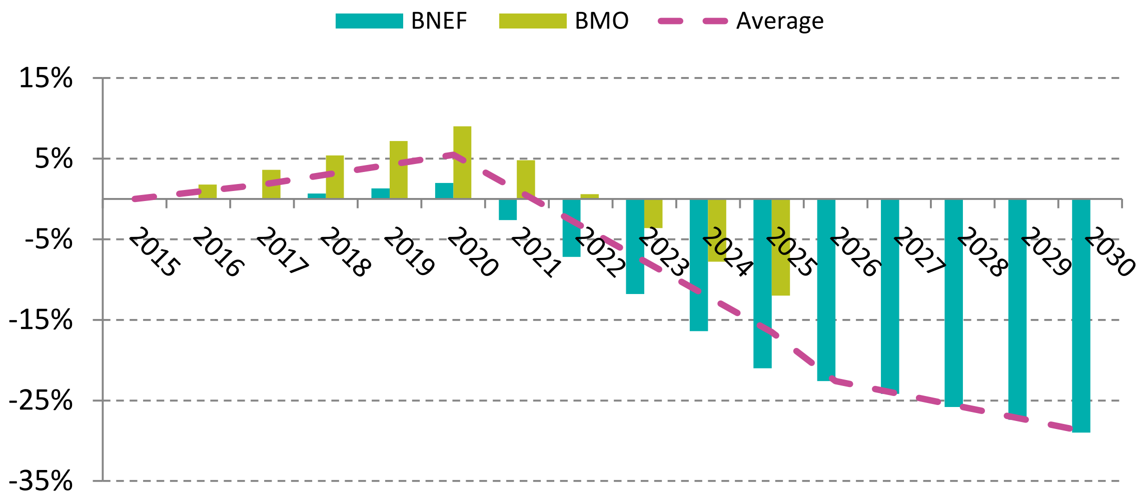
Irrespective of the mix of technologies adopted, changes on the horizon will contribute to the achievement of a substantial reduction in the use of cobalt in EV batteries until 2030. In the present analysis, the extent of this reduction was estimated over time, taking into

[40] According to (Business Insider, 2017), despite incentives to move towards NCM 811, the technology still needs to be developed and rigorously tested to be deployed on a mass scale.

account the cobalt loading in the various cathodes and the cathode mixes potentially adopted in 2020, 2025 and 2030. For the scenarios assessed, the results are given in (Figure 38). The graph shows that until 2025, cobalt can be reduced by 17 %, and between 2025 and 2030 by another 12 %[41]. These trends are likely to follow a period of average increase in consumption of up to 6 %, possibly lasting until 2020 (Figure 38).

The overall percentage of reduction between 2017 and 2030 was estimated to be 29 %.

Figure 38. Percentage of variation in cobalt use based on potentially prevalent LIB cathode chemistries by 2030.



Data sources: own calculation based on (BNEF, 2018) and (BMO, 2018) EV cathode mix forecasts.

Some analysts argue that this reduction might be of larger magnitude, reaching 60 % in 2025 (Cobalt Investing News, 2018). Cobalt-free materials for LIB are in the sights of many battery producers and automakers determined to abandon mainstream technologies while moving towards non-cobalt cathodes (e.g. (Tesla, 2018).

4.3 Disruptive technologies on the horizon

The strongest performing EV segment seems currently to rely on standard battery chemistries, not allowing for the anticipation of any disruptive technological or design changes beyond those mentioned above.

Although, with potentially limited market uptake in the next decade, still further depending on major innovative steps, the following technologies are thought to merit closer examination:

- Advanced cell generations such as lithium air and lithium sulphur, the two most promising at present for use in EVs (Benchmark Minerals, 2016). According to (EC, 2018), such batteries could be relevant beyond 2025.

- Technologies such as solid-state batteries.

- The market uptake of fuel cell vehicles leading to a revised EV system, thereby decreasing the use of battery vehicles to accomplish decarbonisation targets.

4.4 Substitution – resizing supply-demand balances

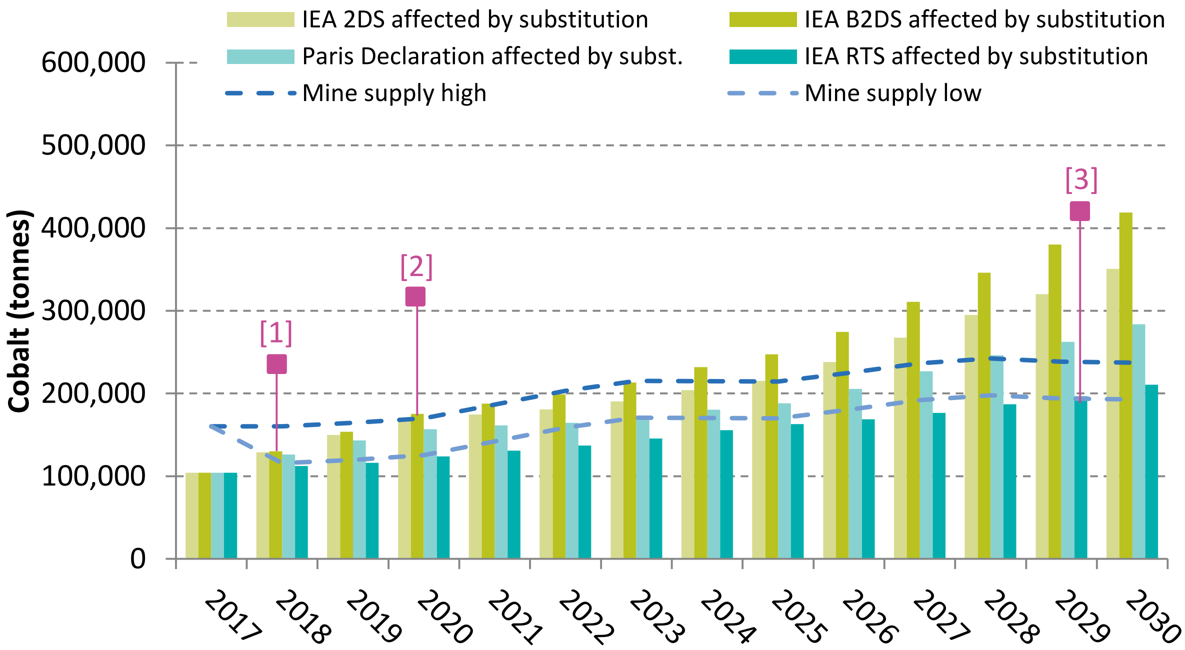
Figure 39 shows revised cobalt demand/supply balances obtained assuming a 6 % increase in the amount of cobalt used in automotive batteries until 2020, followed by a progressive reduction throughout the considered period, up to 29 % in 2030.

[41] Intermediate values of the forecast horizons (2020, 2025 and 2030) were determined by linear interpolation.

The following conclusions can be drawn:

- Demand exceeds supply in 2018 by 15 000 tonnes in high demand/low supply scenarios (situation [1]).
- 5000 tonnes of additional supply are required to meet demand levels in 2020 in high demand/high supply scenarios (situation [2]), increasing to 180 000 tonnes in 2030.
- In the intersection of baseline scenarios, no major deficits are expected in the period to 2029 (situation [3]).

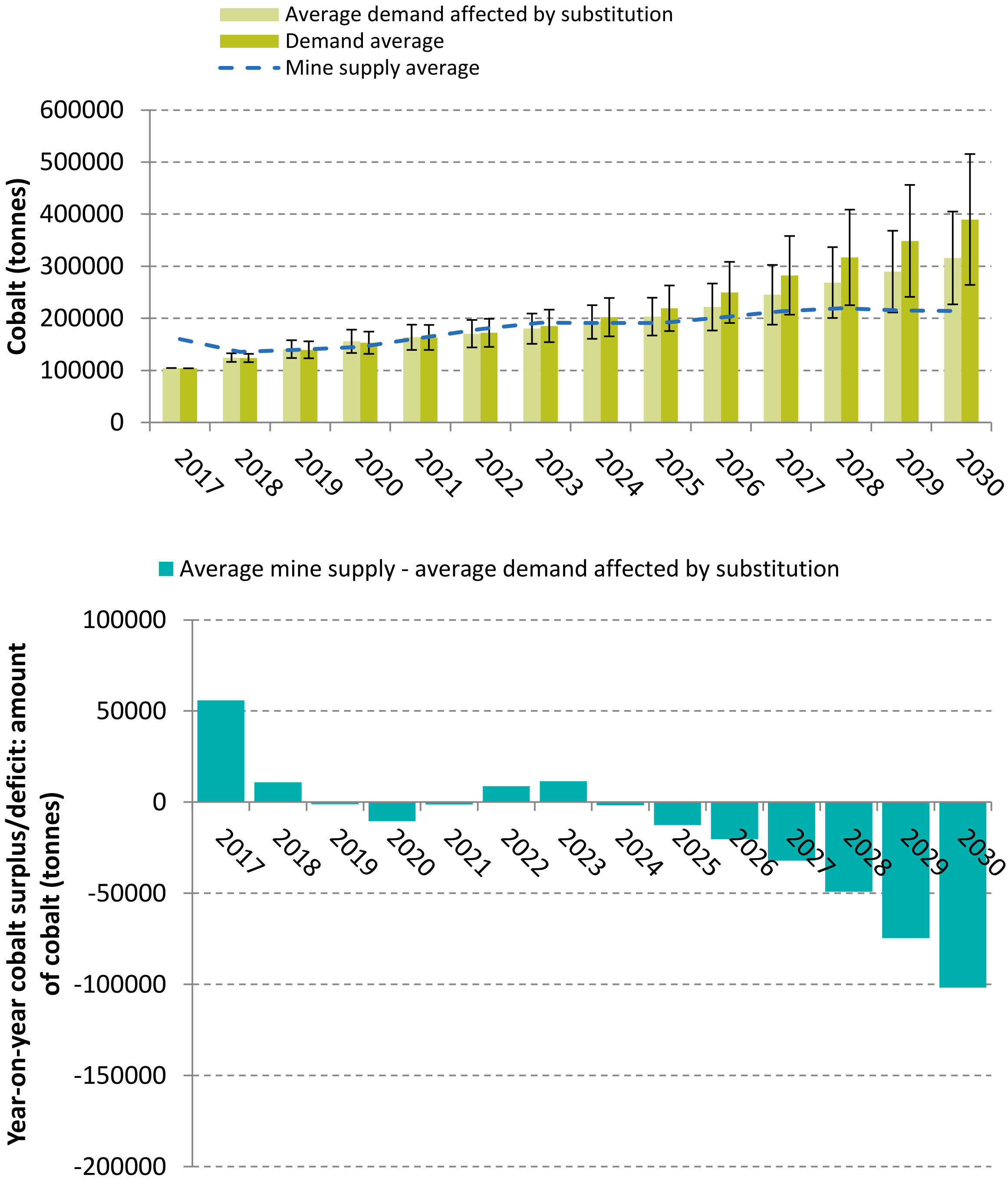
Figure 39. Revised demand/supply balances following cobalt substitution in EV batteries.



In average scenarios, demand exceeds supply in 2020 by 10 500 tonnes (Figure 40A). This trend is expected to become more consistent from 2025, with demand outpacing supply by a projected amount of 12 600 tonnes, increasing to 101 700 tonnes in 2030 Figure 40B).

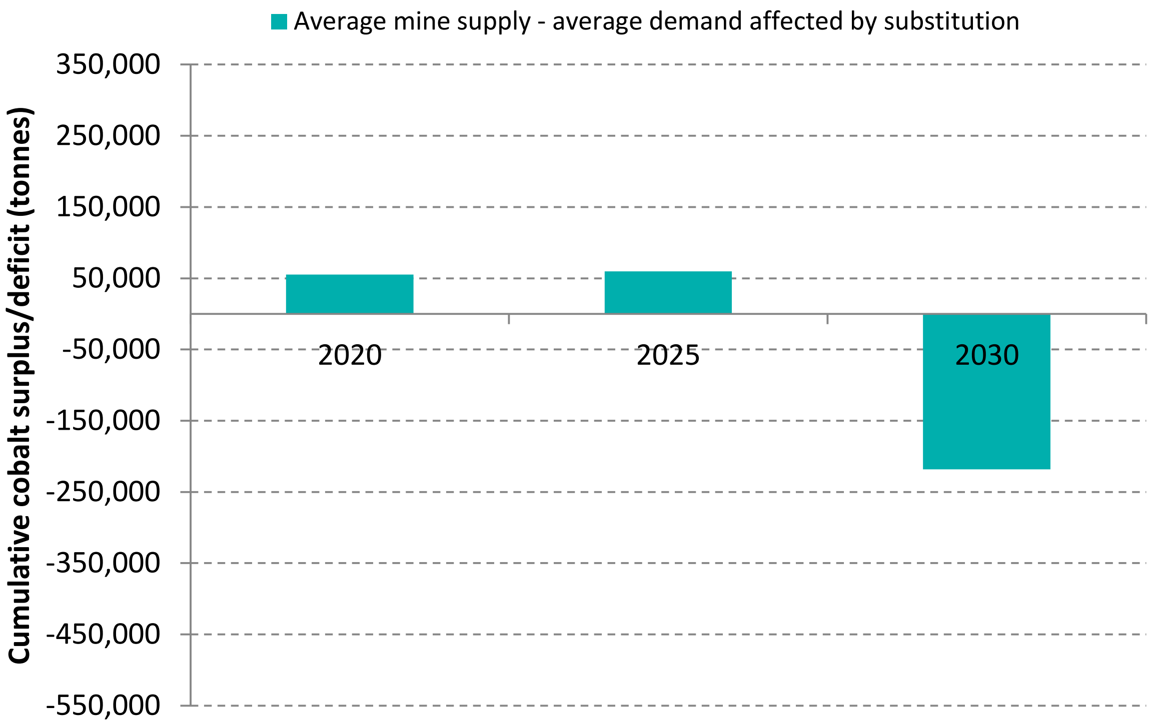
In the assessment of cumulative average scenarios, cobalt is expected to remain in surplus until 2025. However, between 2025 and 2030, exceeding amounts might not be enough to cover year-on-year shortfalls, resulting in a sizeable cumulative deficit of around 218 000 tonnes in 2030 (Figure 41).

Figure 40. Average demand/supply balances following cobalt substitution in EV batteries (top figure) and year-on-year cobalt deficit/surplus (bottom figure).



Note: 'average demand affected by substitution' was calculated as a simple average of the four demand scenarios (see section 2.3), each adjusted by the reduction factors set out above (see section 5.2) to reflect the uptake of different cathode chemistries in the EVs sector over the reference period. 'Demand average' refers to demand levels calculated as a simple average of the four demand scenarios, in which cobalt use in EVs was assumed to remain constant throughout the period – the same cathodes used today will be deployed until 2030. Error bars show the extent of variation of demand in the various EV deployment scenarios. 'Supply average' refers to the average amount of cobalt calculated from the four mine supply scenarios discussed in section 3.7.

Figure 41. Cumulative cobalt surplus/deficits in reference years, in average scenarios assuming revised demand levels resulting from cobalt substitution in EV batteries.



5 Recycling effects

The global supply of cobalt will also be affected by the degree to which recycling occurs. To the extent that it creates an alternative supply stream, recycling can contribute to an increase in the security of cobalt supply.

However, recycling developments will primarily depend on the economics and viability of the recycling businesses, linked to the costs of the process, the need to achieve economies of scale and materials prices e.g. (JRC, 2017(a)) (European Parliament, 2015). Recycling will also depend on the effective collection of batteries and battery-containing products (e.g. (Huisman et al., 2017).

5.1 Recycling trends and overview

Recovery of metals from new and 'post-consumer' scrap[42] is a rapidly moving topic in the political agenda, in the context of the circular economy[43].

While certain cobalt uses are dissipative such as pigments, ceramics, paints, etc, making the metal not available for recycling, cobalt used in applications such as superalloys, hard metals, batteries or even spent catalysts can be collected and either reused or recycled (Cobalt Factsheet, 2017).

Currently, cobalt post-consumer recycling is widely common. Globally, according to (UNEP, 2011), the end-of-life recycling rate (EOL-RR) of cobalt is estimated at 16 %, assuming that the fraction of old scrap to the overall scrap market is around 50 % and the fraction of secondary metal produced in comparison with the total metal input is 32 %. The same source (UNEP, 2011) considers realistic an increase of the EOL-RR to at least 30 % by 2020, depending on applications with long-term lifetime. In the EU this amount is already estimated at 35 % (Deloitte Sustainability, 2015).

The average lifetime of cobalt bearing products is given in Table 16.

Table 16 Lifetimes and recycling rates for cobalt bearing products in 2005.

Application	Lifetime (years)	Recycling rate (%)
Superalloys	5	90
Catalysts	2-8	0-89
Batteries	2.5-8	10-90
Magnets	5	10
Hard materials	1	15-75
Chemical & other	1	_

Source: (Roskill Information Services, 2014).

Focusing on rechargeable batteries, cobalt is the material of most interest to LIB recyclers, and is currently mainly recovered from electronic waste. Although the efficiency of the recovery procedure is high, the overall recycling rate is limited due to poor collection rates not exceeding 9 % (JRC, 2016 (a)). Improvements are, however, anticipated over the coming years. Specifically in the EV batteries sphere, the recycling potential is significant, as these batteries may be easier to collect if a dedicated system of return is established (JRC, 2017(a)).

To increase the efficiency of waste collection and raw materials recovery from EVs, several regulatory instruments are already applicable. In the EU, end-of-life vehicles are

[42] 'New scrap' is commonly used for e.g. production waste and 'old scrap' for consumer goods at end of life.
[43] http://ec.europa.eu/environment/circular-economy/index_en.htm

subject to EC Directive 2000/53/EC (End-of-Life Vehicles Directive)[44]. This Directive aims at reducing waste from end-of-life cars by ensuring that their constituent parts can be recycled. Under this Directive, Member States shall take the necessary measures to ensure that economic operators set up systems for the collection of all end-of life vehicles and the adequate availability of collection facilities. Batteries, in turn, are subject to EC Directive 2006/66/EC (Batteries Directive)[45] and Regulation No 493/2012[46]. These regulate the end-of-life management and set detailed rules and targets regarding the recycling efficiencies of waste batteries. Under the Batteries Directive, Member States are obliged to collect a minimum of 45 % of all portable batteries by 2016 and achieve a recycling efficiency of 50 %. The Battery Directive is currently under review. At the moment there is no separate collection target for industrial and automotive batteries, for which the easily removable and valuable lead-acid and NiCd batteries are collected to a high degree[47].

Given the recent introduction of EVs in global and European markets, with sales only reaching higher values in 2015, and taking into account the average lifetime of EV components, estimated to be approximately 8 years, a significant number of EVs have not reached yet end-of-life. Thus, large-scale recycling is not expected before 2020 and should only be more effectively realised beyond 2025 (JRC, 2017(a)).

5.2 Recycling of Li-ion batteries – available infrastructure

Future recycling will additionally depend on the existence of adequate treatment infrastructure. An overview of Li-ion recycling plants is given in Annex 5, based on data compiled by (JRC, 2016 (b)) and (CM Solutions, 2015).

Worldwide, the recycling infrastructure is thought to range between 79 000 and 96 000 tonnes of batteries per year. Taken together, the EU Member States have the highest installed capacity, accounting for a market share of 40-48 % (Table 17). China also holds a large percentage, ranging between 30 % and 42 %[48].

In the EU, recycling of Li-ion batteries is carried out by 10 specialised companies, with a collective processing capacity of 38 000 tonnes/y. Valdi, an ERAMET Group subsidiary in France, has the largest capacity, at 20 000 tonnes/year[49]. It is followed by Umicore in Belgium with a capacity of 7 000 tonnes/y, which enables the treatment of around 250 000 000 mobile phone batteries, 2 000 000 E-bike batteries, 200 000 HEV batteries and 35 000 EV batteries (Umicore, 2017). The recycling process employed by UMICORE is presented in Box 12.

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[44] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN

[45] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006L0066-20131230&rid=1

[46] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32012R0493&from=EN

[47] European Commission, 2014, Frequently Asked Questions on Directive 2006/66/EU on Batteries and Accumulators and Waste Batteries and Accumulators

[48] Currently, the Chinese share is believed to be higher, on the back of policies to promote the development of this emerging industry e.g. (Roskill, 2018).

[49] A capacity of 20,000 t/y was expected at the plant from 2017 onwards. It was not possible to verify, however, whether the company has reached the expected level.

Table 17 World and European present recycling infrastructure.

Country	Capacity (tonnes of batteries per year)	Share* (%)
North America	11 500	14.5
Japan	6 100	7.7
China	23 600 - 40 000	29.8
Belgium	7 000	0.3
France	20 610	8.8
Finland	4 000	26.0
Switzerland	200	5.1
Germany	6 000	7.6
UK	145	0.2

Based on data compiled by (JRC, 2016 (b)) and (CM Solutions, 2015)

* Battery types recycled in each facility include NiCd, NiMH, Li-ion (see Annex 5 for details). Shares were calculated taking into account the lower Chinese capacity.

Box 12. UMICORE recycling process

Umicore combines a pyro-metallurgical treatment and a hydro-metallurgical process to recycle Li-ion and NiMH batteries.

The pyro-metallurgical process deploys Umicore's patented Ultra-High Tmperature (UHT) technology, to convert the batteries into 3 fractions:

- An alloy phase, containing the valuable metals, cobalt and nickel, to be treated in a downstream hydro-metallurgical process for the production of $CoCl_2$ and $Ni(OH)_2$.

- A slag fraction which can be used in the construction industry (formed into concrete blocks) or further processed for lithium recovery using standard Li recovery flowsheets. In addition to lithium oxide, the slag phase contains oxides of other metals, including aluminium, silicon, calcium and iron.

- A fine dust fraction.

Although lighter batteries (mobile phones, laptops, etc) do not require pre-treatment prior to smelting, EV batteries must be previously dismantled to module/cell level. Temperatures achieved in the pyro-metallurgical process exceed 3000ºC and the average efficiency of the recycling process is above 50 %.

Sources: (UMICORE, 2012), (UMICORE, 2016)

5.3 EV battery stocks at the end of 1st life

The transmission of end-of-life discarded EV batteries to the recycling market depends largely on effective collection levels and the possibilities of battery re-use, for example in stationary storage.

Although the implicit assumption, that most EV batteries, due to their size, shall be subject to higher collection rates at the end of 1st life, seems valid, this situation may not apply to the EU for the quantification of domestic supply developed around the recycling of EVs deployed internally.

In the EU, collection levels of vehicles present in the European market (all fuel types) are undocumented, and a significant part of this is exported to third countries. In particular, the collection levels of EEE products with high battery content are even further under-represented in the reported collection channels due to scavenging of product and components and substantial export outside the EU of reusable equipment (Huisman et al., 2017) (see Box 13).

For the purposes of the present analysis, the possibilities of battery re-use were ruled-out and a collection rate of 90 % was anticipated at global level. With these assumptions, the number of LIB batteries from EVs deployed worldwide potentially available for recycling today was estimated to be on average 20 250 units (90 % of the current vehicle fleet). In 2025, this number might slightly exceed 1 million, reaching nearly 7 million in 2030 (Table 18).

Table 18 Number of EV batteries at the end of 1st use potentially available for recycling until 2030 (expected end-of-life stocks).

Number of EV batteries available for recycling	**Worldwide** (90 % of the average number of batteries deployed under IEA scenarios)	**EU** (collection rates estimated based on the number of BEV and PHEV deployed under average ERTRAC scenarios)
2018	20 250	900
2019	38 250	8 346
2020	103 500	17 226
2021	188 100	37 944
2022	291 600	50 639
2023	497 700	97 520
2024	670 500	104 178
2025	1 098 000	147 272
2026	3 192 683	230 552
2027	5 074 538	372 489
2028	6 087 780	619 274
2029	6 408 248	826 840
2030	6 739 313	1 103 764

Note: Batteries are assumed to reach end of life after 8 years, then becoming available for recycling. In this study, lifespans were considered to be distributed discretely. It is assumed that 90 % of all batteries deployed worldwide will be collected and subsequently recycled. In the EU, up to 90 % of BEV are assumed to be collected, while the PHEV collection rate is assumed to be 50 %. The possibilities of battery re-use are ruled out in the present analysis. The number of batteries available for recycling is estimated based on the average number of batteries deployed in each of the IEA scenarios discussed before. EV batteries deployed in the EU represent an average of the high and low ERTRAC scenarios.

In the EU, given current uncertainties and lack of data regarding unknown whereabouts of vehicles, a 90 % collection rate is assumed for BEV, while for PHEV this figure is considered lower, at 50 % (box 13).

Based on these premises, it is expected that around 150 000 EV batteries may enter European recycling channels in 2025, and that this number will progressively increase to around 1.1 million in 2030 (Table 18).

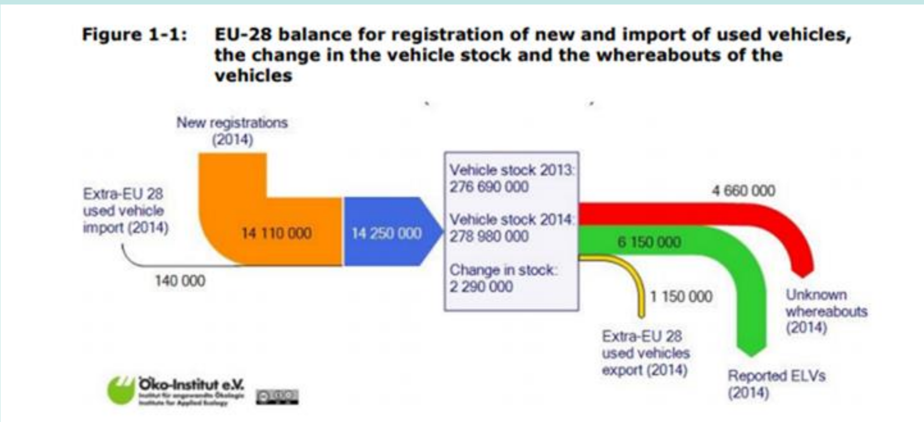
Box 13. The influence of vehicle (battery) collection rates on recycling potential in the EU

Two important factors regarding the amounts of batteries available for recycling in the EU are the lifespan of vehicles and their batteries, and the expected (future) collection rate of EV. According to the stock and flow modelling from the ProSUM project, the lifespan of an average vehicle present in the EU market (all fuel types) is 18 years (Huisman et al., 2017). However, specific and consistent information on the lifespan of electric vehicles and separately on the (distribution) of lifespan of EV batteries at the end of first use is not yet available. More work will be necessary to adapt this model to electric vehicles and batteries, and also, in particular, to incorporate the potential of a second use, for which a number of recent reuse and remanufacturing examples are observed (Bloomberg, 2018), possibly even leading to an entirely new industry sector. The consequence may be a significantly delayed recycling potential due to these second uses.

Regarding collection, a recent report by the Öko-Institut for DG Environment examined the unknown whereabouts of vehicles supposedly reported under the ELV Directive. Here, for 2013-2014, about 50 % of the vehicles leaving the EU fleet are collected and reported. Another 10 % is reported as being exported outside the EU and a significant value of 40 % is classified as having unknown whereabouts (Öko-Institut, 2018). The question for the future is what will happen with EV in comparison with the average drivetrain type. Here, for BEV, it can be imagined that they will stay mainly in Europe initially, as typical export countries may not yet have a charging infrastructure. However, for the EU-specific high share of PHEV, this assumption may not be valid, since home-charging may also occur sooner or later in typical export markets. The whereabouts of EV will hence need to be investigated in the future to determine more precisely the collection rate time series.

The Öko-Institut report also contains a number of suggestions to improve the reporting system. However, no recommendations are made to improve the reporting procedures regarding EV-specific data. The ProSUM project report recommends the amendment of vehicle statistics with a specification of the main drivetrain types as reported by Eurostat (Downes et al., 2017).

Figure 42 Unknown whereabouts of vehicles in the EU



Source: (Öko-Institut, 2018)

Assuming that the average weight of an EV battery is around 250 Kg e.g. (BCG, 2010), the currently available infrastructure worldwide is expected to suffice for the recycling of at least 317 000 units just above the total EOL batteries in 2022[50].

In the EU, the current recycling infrastructure should enable the recycling of around 160 000 units, well above the number of EV batteries forecast to be available for recycling within the EU until 2025.

With a large share of recycling capacity located in Europe, it is likely that in the future, EU facilities expand their processing capacities and also attract significant volumes from abroad. Additional recycling capacities can easily be added, depending on market requirements.

5.4 Potential additional cobalt supply from EV batteries recycling

Considering that 90 % of all batteries deployed will be collected and subsequently recycled at end of life, significant opportunities to recapture and recycle cobalt can be anticipated.

Potential cobalt flows resulting from the recycling of EVs deployed worldwide are given in Figure 44. Estimations therein assume an average lifetime of 8 years for each vehicle battery placed on the market, and a constant EOL recycling rate of 72 %, derived from a combination of collection and recovery efficiency rates of 90 % and 80 % respectively[51].

At global level, the amount of cobalt potentially recovered from old scrap EV stocks may amount to 452 tonnes in 2020 and 4 800 tonnes in 2025. Beyond 2025, available amounts will depend on the level of EV deployment. On average, this could be 38 000 tonnes in 2030.

Figure 45 shows potential additional cobalt supply estimates from EV battery recycling within the EU. These estimates were carried out assuming different collection rates for BEVs and PHEVs introduced in the European market (see Figure 10 and Box 5). Assuming an overall collection rate of 50 % for PHEV and 90 % for BEV, at constant efficiency rates of 80 %, potential recycling rates are considered to evolve over time as shown in (Figure 43). The resulting EOL-RR per unit deployed may vary between 53 % and 71 % between now and 2030.

The potential amounts of recycled cobalt generated from EOL vehicles deployed in the EU are estimated at 500 tonnes in 2025 and may amount, on average, to 5 500 tonnes in 2030 (Figure 45). In 2030, recycling can provide for around 10 % of European cobalt consumption in the EVs sector.

[50] Although the calculation assumes that the capacity of each recycling facility is entirely used for the recycling of LIB batteries from EVs, this is not a realistic assumption. We acknowledge, however, that one facility will additionally treat other products beyond EVs, such as batteries used in consumer electronics and e-bike batteries, among others.

[51] According to (EPA, 2013), the range of cobalt recovery from recycling is between 60% and 99.9% (80% on average).

Figure 43 Potential end-of-life recycling rates per EV deployed in the EU.

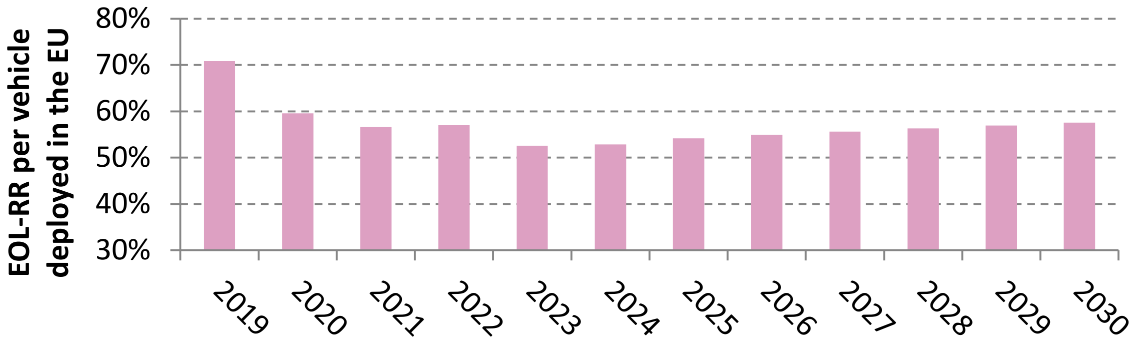


Figure 44 Additional cobalt supply generated by recycling of EV batteries deployed worldwide (tonnes of potentially recovered cobalt from Li-ion batteries).

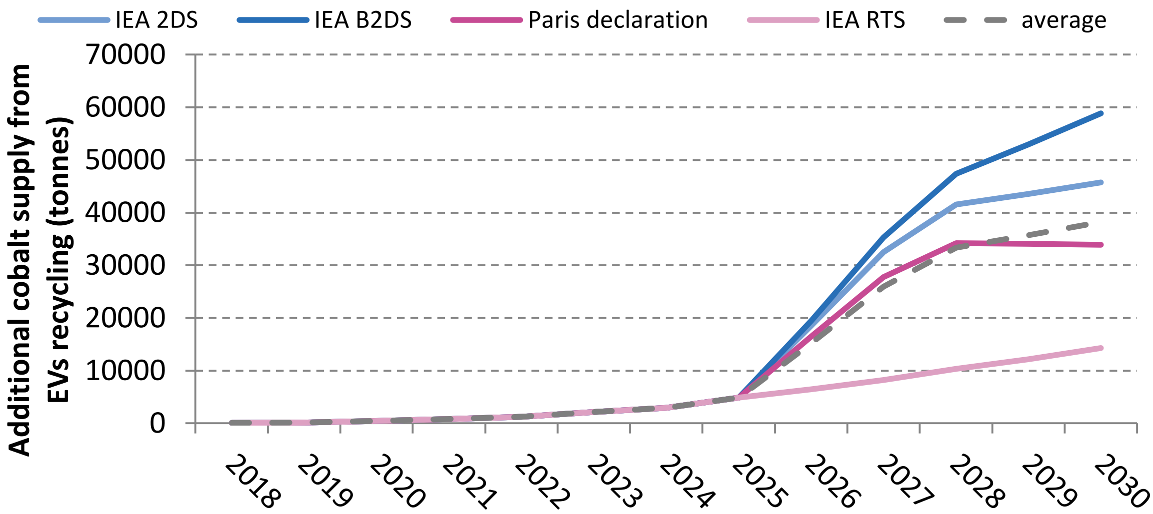
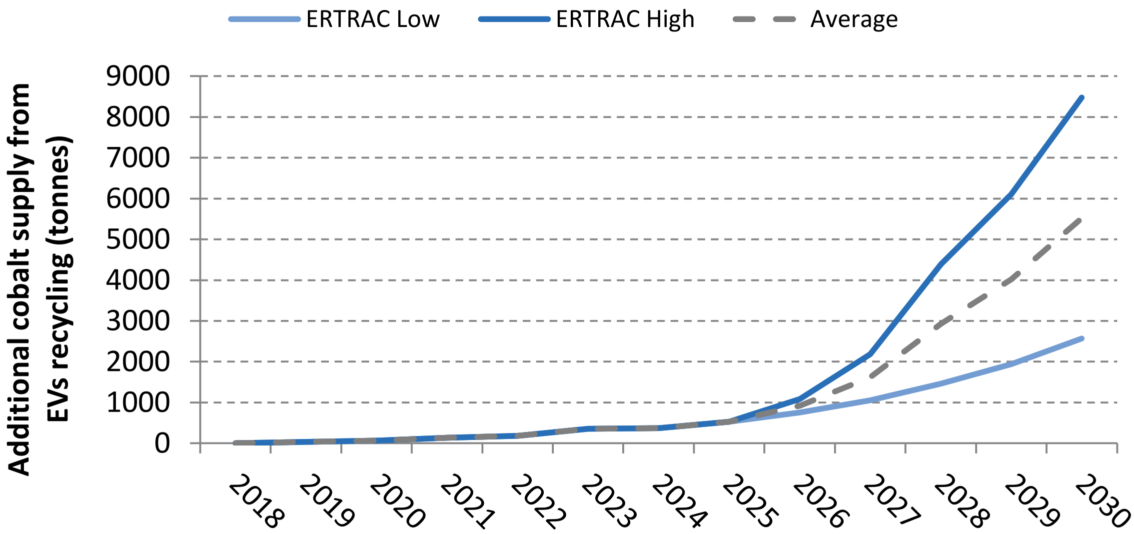


Figure 45. Recycling potential generated by EOL EVs deployed in the EU.



5.5 Recycling – resizing supply-demand balances

Revised supply/demand balances were obtained by adding together the amounts of cobalt recovered through EV battery recycling to the amounts forecast to proceed from mining activities throughout 2030. Demand estimations used in the revised assessment consider the effect of cobalt substitution in EV batteries. The effects of recycling over supply only reflect additional amounts originated from EV battery recycling, notwithstanding the fact that cobalt recycling has a wider context, extending to other end-use sectors.

Results are presented in Figure 46 and Figure 47. The assessment indicates that under average circumstances, almost 7 000 tonnes extra would still be needed to cover global demand in 2025. This deficit is expected to increase to 64 000 tonnes in 2030.

On a cumulative basis, a deficit of 43 000 tonnes can be expected to occur in 2030 (**Figure 48**).

Figure 46. Revised supply/demand balances taking into consideration the effects of recycling over mine supply for each considered demand scenario affected by substitution.

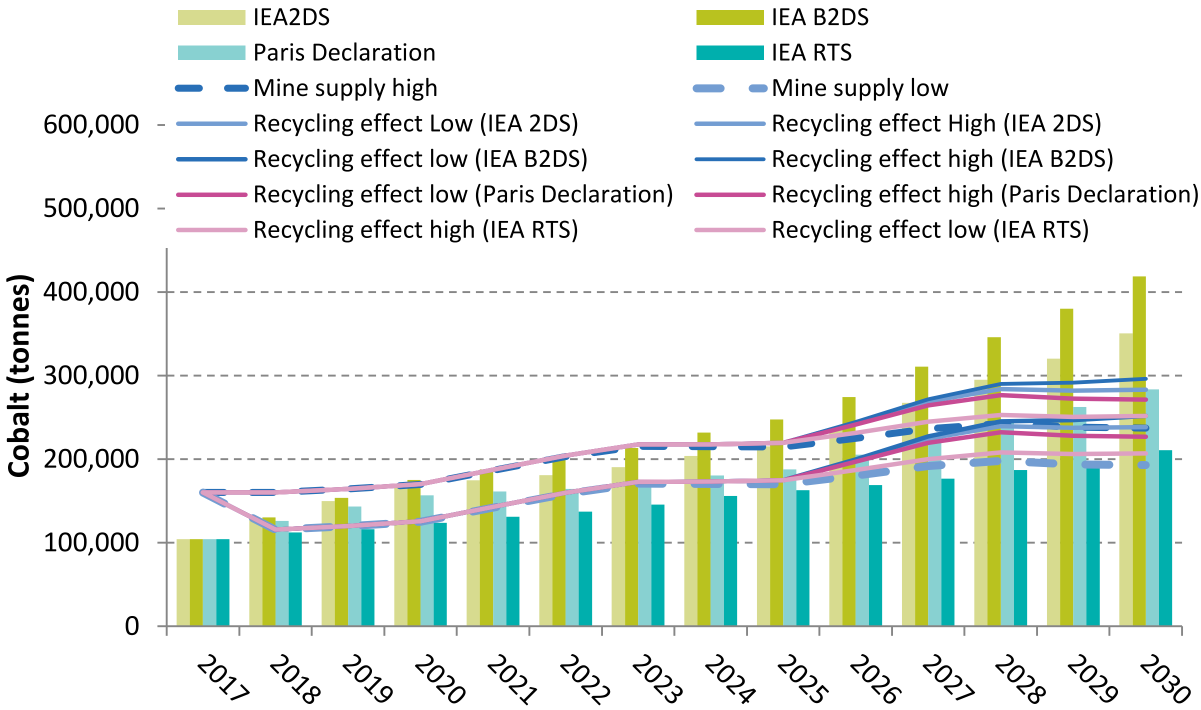
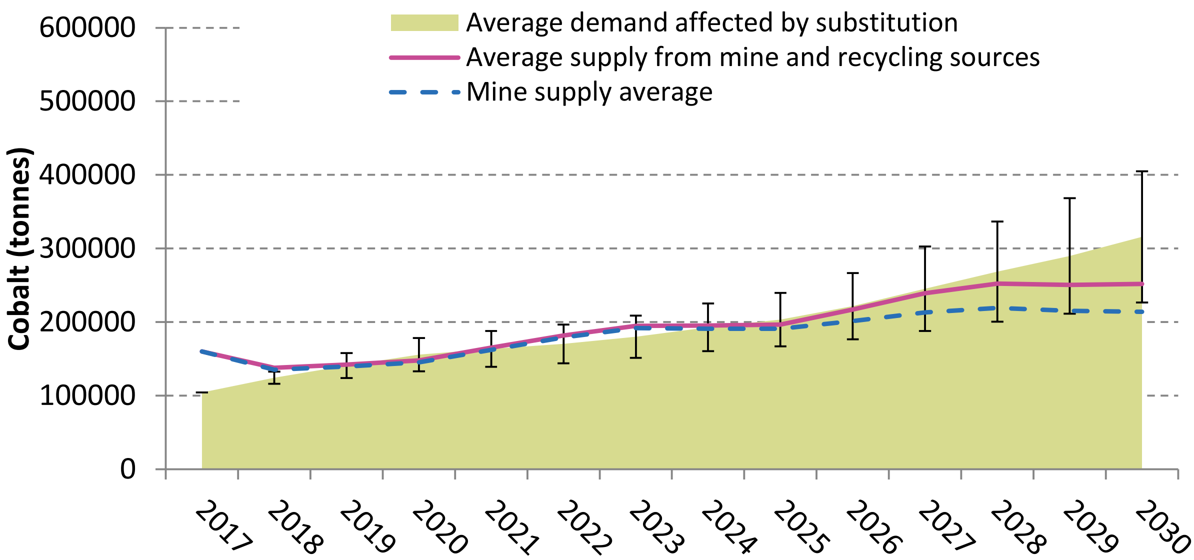


Figure 47 Average global demand/supply balances including the effects of substitution over demand and of EV batteries recycling over supply.



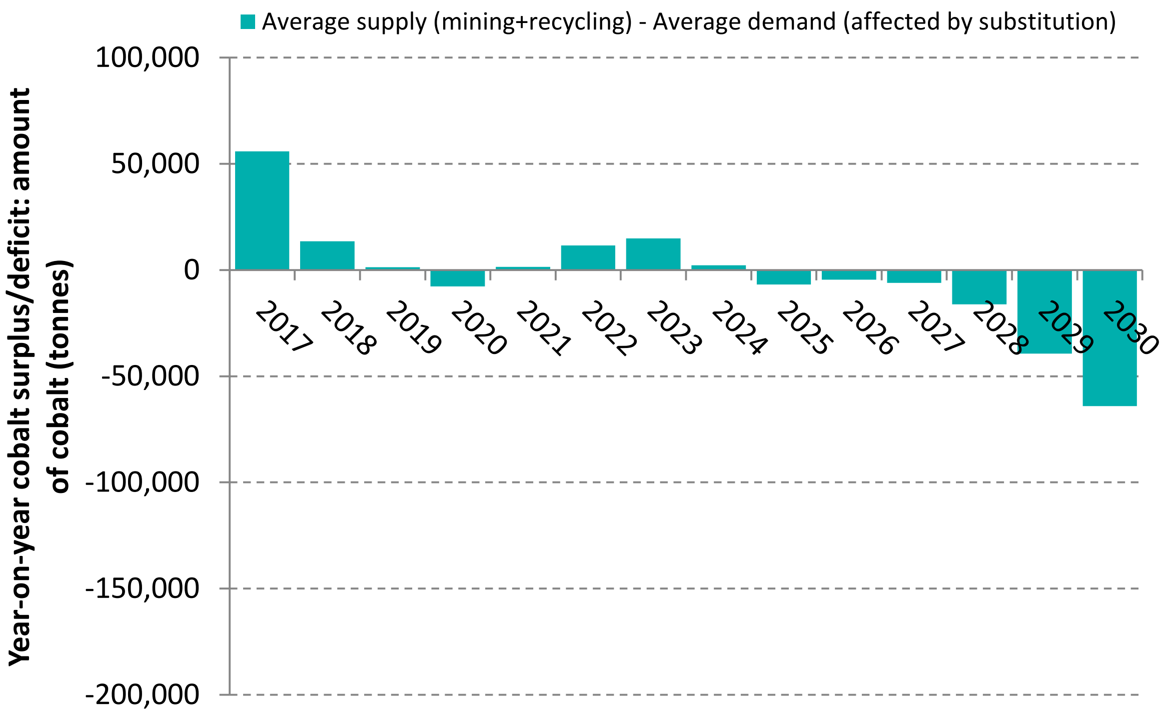
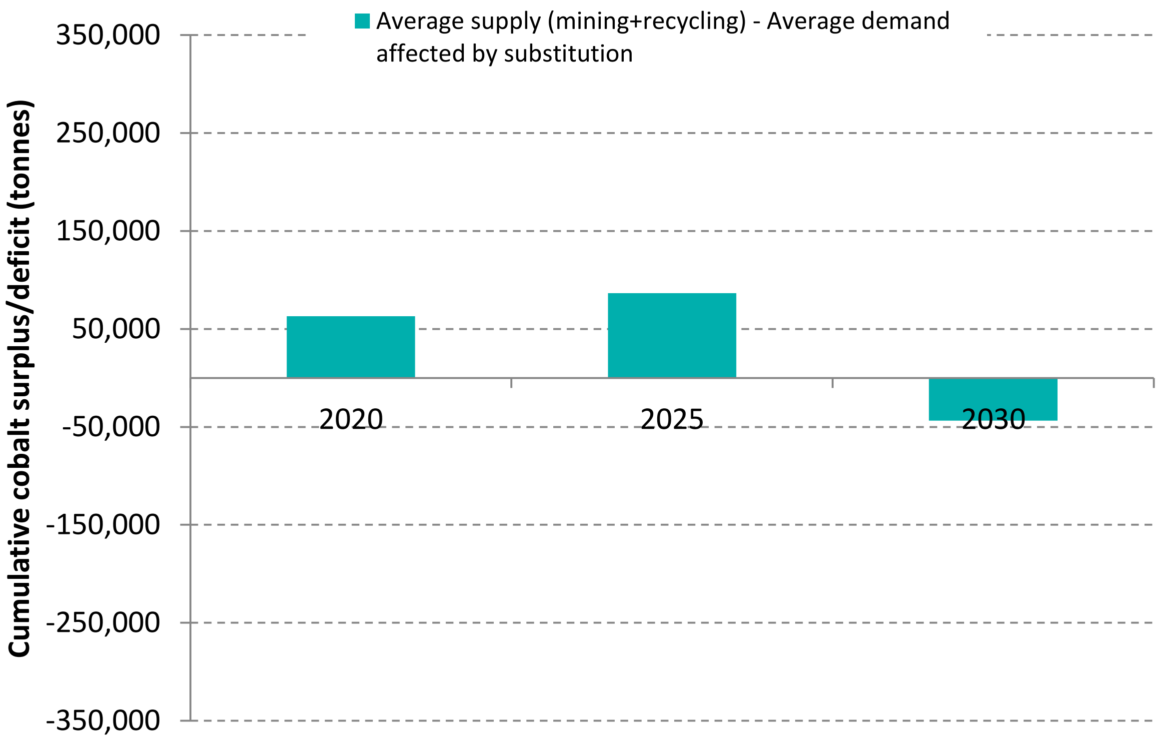


Figure 48 Cumulative cobalt surplus/deficits in reference years in average scenarios, assuming revised demand levels resulting from cobalt substitution in EV batteries, and revised supply resulting from EV batteries recycling.



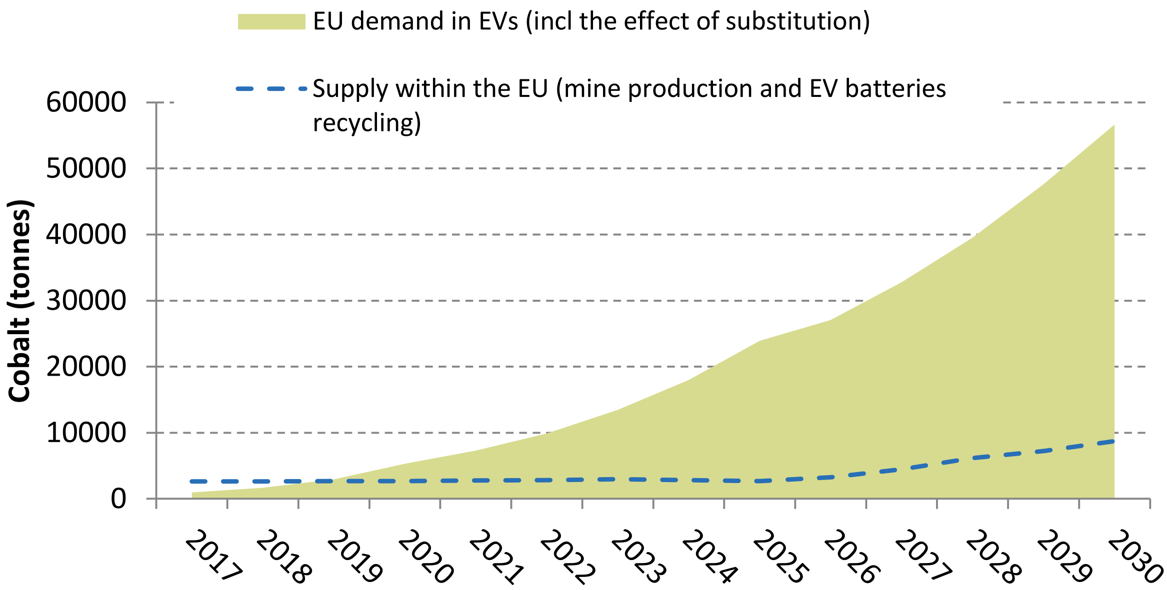
5.6 European supply-demand revised gaps

Comparing European demand levels in the EVs sector with the potential supply originated jointly from mine and recycling activities within the EU, the following aspects are highlighted (Figure 49):

- In 2030, around 8 700 tonnes of cobalt can proceed from mining and recycling activities within the EU.
- By 2030, endogenous supply can meet around 15 % of European demand in the EVs sector.

Although the capacity to meet rising demand is projected to increase over time, there is an increasing gap between endogenous supply and demand. The EU's supplies of cobalt will continue to depend largely on imports from third countries, which underscores the need for activation policies.

Figure 49 Potential cobalt supply from European sources in comparison with potential cobalt demand in the European EVs sector.



6 Conclusions

In the transition to a low carbon economy, increasing penetration of electric vehicles and energy storage systems is expected. In these markets, cobalt consumption will be boosted by the usage of Li-ion batteries, in particular Nickel-Manganese-Cobalt (NMC) and Nickel-Cobalt-Aluminium (NCA) chemistries, both of which use cobalt as cathode material, thereby making potential constraints in its supply a limiting factor in the deployment of lithium-ion batteries.

The ability to secure relevant supply cobalt streams to fast-growing markets, the prevalence of near-monopolistic supply structures, including the introduction of export taxes and the fact that cobalt is usually mined as a by-product of copper and nickel, have been put forward as particular causes for concern.

Various risks have been recognised in relation to the supply structure of cobalt, which is also rated as critical for the EU: the Democratic Republic of the Congo (DRC) is the main mining producer, accounting for 55 % of global production; approximately 20 % of DRC's cobalt production comes from artisanal-based operations in which a prevalent and unethical use of child labour has been identified; China is the largest producer of refined cobalt, accounting for 50 % of global production; and discretionary efforts to increase mining production in the short to medium term are limited by the time taken to fully develop a mining programme. All these factors can contribute to growing uncertainties over global supply growth and give rise to shortfalls in the provision of cobalt in the future. These trends may increase the risk of disruption, either through supply shortages or price escalation.

The analysis herein yielded a number of insights:

6.1 The demand situation

The rechargeable battery market is the largest and fastest growing demand for cobalt. In 2015, rechargeable batteries accounted for 49 % of total cobalt consumption and in 2020, a projected share of 60 % is expected. In the EU, while cobalt usage in batteries that entered the market in 2012 rose to 51 %, only 3 % of demand was provided for by European battery manufacturers. Currently, large format Li-ion battery cells for EVs and stationary storage are produced mainly in Asian countries and companies, with the EU having a limited share of about 2 %, or 3 GWh cell manufacturing capacity. Nonetheless, the EU is amongst the leaders in global car manufacturing.

Meeting stringent climate targets will entail an increase in the global electric vehicle stock to 156-204 million in 2030, with annual sales growing by a compound annual rate of 25-27 %. In the EU, available projections suggest that the number of electric vehicles will exceed 2 million in the year 2020, rising to 7-20 million in 2025 and 18-61 million in 2030, which represents a compound annual growth rate of 22 % to 34 %.

The changing characteristics of mobility and the prevalent use of lithium ion batteries are drivers to surging lithium ion battery mega-factories which will depend on the availability of an adequate supply of cobalt. The demand for cobalt intended for these facilities worldwide can be estimated at some 80 000 tonnes per year in 2021.

Considering various levels of electric vehicle uptake and other cobalt uses, world cobalt demand may be subject to a growth rate of between 7 % and 13 % in the period from 2017 to 2030, bringing average cobalt consumption to around 220 000 tonnes in 2025 and 390 000 tonnes in 2030. In the EU, cobalt demand will amount to 53 500 tonnes in 2025, increasing in 2030 to 108 000 tonnes in average circumstances.

6.2 The supply context

Cobalt is currently mined in 20 countries. In 2016, just four mines in DRC were responsible for 43 % of the world's cobalt production, currently estimated at around 126 000 tonnes.

In the EU, production of cobalt ores and concentrates was estimated at 2 300 tonnes in 2016, all sourced from Finland, where cobalt is produced in four mines.

Even though Finland is the sole mine producer within the EU, resources of cobalt are also known to exist in Sweden and Spain. Besides Talvivaara's large cobalt resource, estimated at 300 000 tonnes of cobalt, around 58 000 additional tonnes of cobalt have been identified to date, in projects undergoing reserves development and advanced exploration stages. However, many of these projects (13 out of 24) appear to be inactive. Other projects at an early stage of exploration or development, without a defined resource estimate, can be found in Cyprus, Slovakia, Austria, Czech Republic, Germany, Italy and Poland.

Worldwide, starting from a capacity of approximately 160 000 tonnes of potentially recovered cobalt in 2017, mining projects may make provision for around 193 000-237 000 tonnes in 2030. Some projects currently under development are expected to bring significant additional material into the market until 2025, however, additional supply is most likely to come from the expansion of existing producers, which currently hold the largest amount of resources. The ramping up of new projects can increase cobalt production by 21 % to 48 % in 2030.

Whilst mine capacities are currently concentrated in DRC, a pipeline of projects is being developed in countries such as Australia and Canada. These countries are likely to gain additional importance in the future, helping to reduce dependency on the supply from DRC. By 2030, the concentration of supply and risk of disruption might be reduced by 29 %. Nevertheless, DRC will still be responsible for around 48 % of the cobalt supply in this timeframe.

In the EU, the current mining infrastructure is limited, despite the high potential for its development. On account of capacities and available resources in operating mines, and projects undergoing late-stage exploration, future cobalt production was estimated to be 2 700 tonnes in 2020, increasing to 3 200 tonnes in 2030. By then, this amount could provide for around 6 % of the European cobalt consumption in the EVs sector.

Several barriers that can limit cobalt production from mining activities are recognised in the broad global landscape, making supply forecasts complex and largely uncertain. Projects must meet severe cost criteria prior to reaching a productive situation, which can involve longer delays than envisioned in starting up production. Moreover, recent decreases in global cobalt mine production are bound to lower production from nickel operations, which seem to accompany a more or less persistent decrease trend in nickel prices since 2010.

While currently operating mines focus mainly on copper as primary product of the mine output, future cobalt production from late-stage exploration projects will likely have nickel as primary product.

6.3 Substitution effects over demand

Substitution of cobalt in Li-ion batteries, although possible, has not been the preferred option in EVs. Currently, the strongest performing segment seems to rely on cobalt cathodes, and an increasing number of automakers are choosing full NMC chemistry, abandoning combinations of this chemistry with cobalt-free materials, to achieve higher energy density and thus longer autonomy ranges.

Until 2020, either NMC (111) or NMC (532) are expected to remain the first choice for EVs. Such a trend, combined with a reduced use of cobalt free cathodes (e.g. LFP), is likely to push up cobalt demand by up to 6 % before it starts to decline after 2020, driven by substitution efforts.

Until 2025, cobalt could be reduced by 17 %, and between 2025 and 2030 by another 12 %, on account of changes in the EV battery chemistry mix. Nickel will preferentially substitute cobalt in battery applications in the transition towards a potentially prevalent use of NMC 811 configurations.

Throughout the relevant period, cobalt usage in EV batteries might be reduced by 29 %.

As nickel is also the primary substitute of cobalt in most other applications, additional pressures will be put on its secure supply.

6.4 Recycling effects over supply

Significant opportunities to recapture and recycle cobalt may be anticipated over the coming years. The recycling potential of EV batteries is significant, as these batteries may be easier to collect if a dedicated system of return is established. However, given the recent introduction of EVs in global and European markets, and taking into account the average lifetime of EV components, estimated to be approximately 8 years, large-scale recycling is not expected before 2020, and should only be more effectively realised beyond 2025.

Globally, the amount of cobalt potentially recovered from old scrap EV stocks may amount to 452 tonnes in 2020, increasing to 38 000 tonnes in 2030.

The potential amounts of recycled cobalt generated by end-of-life vehicles deployed in the EU is estimated at 500 tonnes in 2025, and may amount to 5 500 tonnes in 2030. In 2030, recycling could provide for around 10 % of European consumption in the EVs sector.

The EU already holds sufficient relevant recycling infrastructure to enable the recycling of around 160 000 EV battery units, well above the number of EV batteries forecast to be available for recycling internally until 2025.

With a large share of recycling capacity located in Europe, it is likely that in the future EU facilities expand their processing capacities and also attract significant volumes from abroad.

In addition, at least at global level, substantial opportunities may also exist for the recovery of secondary products (new scrap) that in the past were often lost to mine tailings.

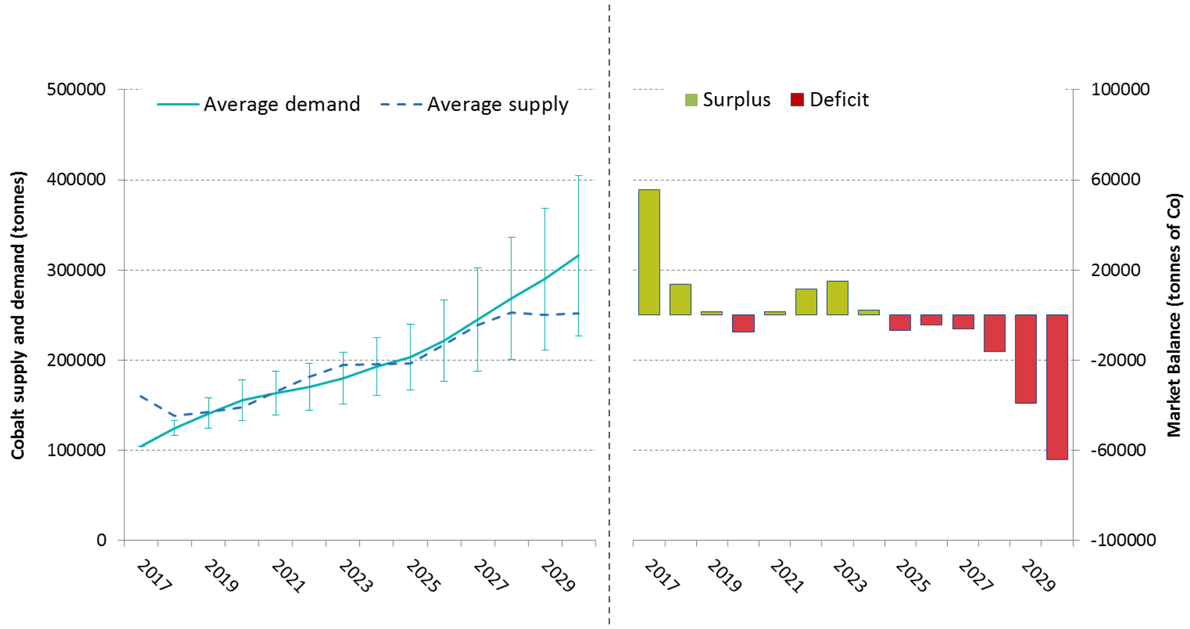
6.5 Supply-demand balances

Considering annual supply and demand balances in average scenarios, including the effects of substitution over demand and of EV battery recycling over the projected mine supply, demand is already expected to exceed supply by 2020. By then, around 8 000 additional tonnes of cobalt would be needed to cover global demand. Such a loss-making trend is resumed and expected to become more consistent from 2025, with demand outpacing supply by a projected amount of 7 000 tonnes. This deficit is projected to increase to 64 000 tonnes in 2030.

In 2017 cobalt supply had a net surplus of around 55 800 tonnes. Global demand was accommodated by approximately 65 % of mine capacity. Assuming that these extra amounts are produced each year and stored or stockpiled for use in the following years, cobalt is expected to remain in surplus until 2025, after which a cumulative deficit of 43 000 tonnes could occur.

Although very significant cumulative deficits are not expected to occur until 2030, the possibility that cobalt supply might depend highly on relevant stockpiles is not beneficial and might result in unstable and increased prices in the future.

Figure 50 Average global supply-demand balances between 2017 and 2030.



6.6 Bridging the gaps in the EU

In the EU, bridging gaps between supply and demand may require specific actions along the three pillars of the European Raw Materials Initiative (RMI).

In the mining sector, the promotion of specific brownfield projects merits further action, along with the attraction of investment to reactivate inactive projects and promote efficient greenfield exploration in highly prospective areas. Private investment in minerals exploration may come in line with improvements in the regulatory context, as many EU countries do not currently ensure the right to exploit a new deposit provided other regulatory conditions are met. Improving the competitiveness of European mines may also involve a concomitant decrease in the costs of transport, possibly through the reinforcement of endogenous battery manufacturing capacities.

As the EU continues to depend on imports in the future, consolidating trade agreements with countries such as Australia and Canada, expected to gain additional importance as future cobalt producing countries, can be beneficial as a means of ensuring responsible sourcing practices.

Cobalt recycling is likely to be boosted by higher recycling rates of EV batteries from 2025 on, predetermined by the product profile and characteristics (large format cells). Nonetheless, the high share of PHEV in Europe may entail additional uncertainties as to whether relevant collection rates are met in the future. Ensuring high targets seems to be of particular importance to optimise future balances between supply and demand. Room for improvement in recycling businesses may also exist in relation to efficiency rates as well as the recycling of other cobalt products (not assessed in this study).

Additionally, EU LIB recyclers already have a fair share in current global recycling capacity, which can act as a stimulus to attract additional scrap volumes from third countries, rather than just from the EU itself.

On the use of cobalt in EV batteries, a reduction of 29 % is expected by 2030. However, the deployment on a mass scale of such low-cobalt chemistries will still be needed. As nickel is likely to bear the load of the substitution strategy, these developments should come in line with close monitoring exercises of the nickel supply and demand situation. In the longer term, additional reductions in the use of cobalt in the automotive sector might also come in line with the market uptake of cobalt-free batteries such as lithium-air, lithium sulphur or solid-state, and of fuel cell vehicles.

Finally, the raw materials sector plays an important role in the value-chain of battery and automotive industries. Increasing the industries' manufacturing capacities, besides preventing a technological dependency on competitors, should also have positive spill-over effects on private investment along all segments of the value-chain. If properly developed, it should promote the responsiveness and competitiveness of the European raw materials sector whilst ensuring cobalt supplies through domestic mining and recycling.

6.7 Recommendations for improved analysis

The present report provides future scenarios on cobalt supply and demand, including substitution and recycling, related to each other in one consistent forecasting approach. In its conclusions, the report shows the necessity of deploying the RMI pillars to make this important EU sector more resilient in the long run.

Nonetheless, there are obviously many unknowns when doing a forward-looking study like this, some of which are explicitly given in Table 19.

In particular, for the areas where data is not really available or is uncertain, transposing improvements to the analysis may not be possible. In others, reducing the inevitable forecasting limitations may entail that:

- The forecasting of demand can be improved and updated by consolidating information on other cobalt uses beyond EVs.
- The forecasting of mine supply can be improved by incorporating economic factors influencing the success of exploration projects. This would allow setting the analysis against a dynamic market with premises of decreasing prices and flexibly adjusting the projects' start-up dates.
- The substitution scenarios can be improved by assessing the technologies landscape beyond those that are market-ready or with near-term maturities.
- The recycling scenarios can be improved by including additional information on stocks, lifespan distribution and the role of reuse and remanufacturing. In the EU, exports for reuse and EU imports for recycling need further substantiation in the future.

In spite of such limitations, the study enables a usable assessment of the raw materials sector's resilience, both worldwide and in the EU. Yet, the sector is dynamically changing over time, which requires regular monitoring, reviewing and updating of its variables for an effective evaluation. Despite the need to maintain a certain level of consistency in order to facilitate the tracking of changes over time, the approach is also flexible enough to allow for these revisions as needed.

Table 19 Uncertainties of the forecasting exercise - limitations to the present analysis.

A. Demand
EVs deployment scenarios
The scale and size of the global and European EV market and Li-ion demand varies substantially between scenarios, based on premises for deep decarbonisation, market expectations and business as usual considerations. Other sectors beyond EVs can be as influential in cobalt demand patterns in the future, growing more rapidly than expected.
Cobalt demand in the European EVs market
The EU currently lags in EV batteries manufacturing, with very limited share in global Li-ion manufacturing capacity. The EU market for cobalt will thus depend on the extent to which this sector will answer a real need in Europe.
B. Mine supply
Mine supply scenarios and estimations
The amounts supplied to the market from mineral and metal producers depend on multiple economic factors, making forecasts complex and largely unreliable. Setting the analysis against a dynamic market with premises of decreasing prices would be beneficial, allowing, for example, the consolidation of start-up dates for exploration projects, and insights into the costs of production restricting extraction at certain prices. Assessing reserves instead of resources by looking into the amounts that may be currently extracted in an economically viable manner would provide a more robust basis for evaluation and monitoring. Quantifying the influence of the extraction of primary products such as copper and nickel on the production of cobalt, and monitoring the respective markets, would also make the dynamics of supply restrictions arising from a by-product status more visible.
C. Recycling and substitution
The % of reduction of cobalt use in EV batteries is rather uncertain. Although there is broad consensus on the reduction of cobalt consumption in EV batteries, at least from 2020 on, there is no general agreement on which cathodes will be prevalent in the future, even for options that are market-ready or with near-term maturities. The quantification of the ability of disruptive technologies to influence the conditions of the batteries market should also be taken on board. The recycling potential of EV batteries is also rather uncertain. On one hand, a delayed recycling potential can be expected due to second use affecting lifespan distributions. On the other hand, at least in the EU, overall collection rates may be lower than expected. Another effect on the availability for recycling in the EU, which is difficult to forecast, is the relatively high share of cobalt recyclers in the EU and their ability to source end-of-use EV batteries from the global market in the future.

References

Amnesty International. (2017, November 15). *Industry giants fail to tackle child labour allegations in cobalt battery supply chains*. Retrieved December 2017, from https://www.amnesty.org/en/latest/news/2017/11/industry-giants-fail-to-tackle-child-labour-allegations-in-cobalt-battery-supply-chains/

Avicenne Energy. (2017). Lithium ion battery raw material supply & demand 2016-2025.

Avicenne Energy. (2018). *The rechargeable Battery Market and Main Trends 2017-2025.*

BCG. (2010). *Batteries for electric vehicles - challenges, opportunities and the outlook to 2020.* The Boston Consulting Group.

Benchmark Minerals. (2016). The lithium ion supply chain. *BENCHMARK september 2016, 45*.

Benchmark Minerals. (2018, May). *PANASONIC REDUCES TESLA'S COBALT CONSUMPTION BY 60% IN 6 YEARS*. Retrieved from http://benchmarkminerals.com/panasonic-reduces-teslas-cobalt-consumption-by-60-in-6-years/

BGS. (2017). *World Mineral Production 2016*. Retrieved December 2017, from http://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html

Bloodworth, A., & Gunn, G. (2014). Metal supply security and sustainability: understanding the whole system. *European Geologist, 27*.

Bloomberg. (2017, June 23). *Electric Cars to Reach Price Parity by 2025*. Retrieved August 2018, from https://about.bnef.com/blog/electric-cars-reach-price-parity-2025/

Bloomberg. (2017). *Electric Vehicle Outlook 2017.* Bloomberg New Energy Finance's annual long-term forecast of the world's electric vehicle market.

Bloomberg. (2017, June 8). *Race Is on to Mine Metal Powering Electric Vehicles*. Retrieved December 2017, from https://www.bloomberg.com/news/articles/2017-06-08/cobalt-upstarts-eye-glencore-s-turf-for-244-billion-ev-spoils

Bloomberg. (2018, March 26). *Apple Cobalt Supplier Seeking Ethical Supply With Industry Pilot*. Retrieved August 2018, from https://www.bloomberg.com/news/articles/2018-03-26/apple-cobalt-supplier-seeking-ethical-supply-with-industry-pilot

Bloomberg. (2018, February 21). *Apple in Talks to Buy Cobalt Directly From Miners*. Retrieved August 2018, from https://www.bloomberg.com/news/articles/2018-02-21/apple-is-said-to-negotiate-buying-cobalt-direct-from-miners

Bloomberg. (2018, January 10). *Congo May More Than Double Tax on Critical Cobalt Supply*. Retrieved January 2018, from https://www.bloomberg.com/news/articles/2018-01-10/congo-may-more-than-double-tax-on-critical-global-cobalt-supply

Bloomberg. (2018, March 08). Impacts from the surge in lithium and cobalt prices . *Webinar delievered in 08 March 2018*.

Bloomberg. (2018, June 27). *Where 3 Million Electric Vehicle Batteries Will Go When They Retire*. Retrieved August 2018

BMO. (2018). *The Lithium Ion Battery and the EV Market: The Science Behind What You Can't See.*

BNEF. (2018). Equipment Manufacturers - Battery cells. Retrieved June 29.

BNEF. (2018). *Long-term Electric Vehicle Outlook 2018.* Bloomberg New Energy Finance, Retrieved 21 May 2018.

BRGM. (2014). *Panorama 2013 du marché du cobalt.*

Business Insider. (2017, Oct 31). *Electric cars are going to mean a lot of demand for nickel*. Retrieved Feb 2018, from http://www.businessinsider.com/electric-car-batteries-are-going-to-drive-a-lot-of-demand-for-nickel-2017-10?IR=T

CM Solutions. (2015). *LITHIUM BATTERY RECYCLING PROCESS - Desktop Study - Prepared for DEPARTMENT OF ENVIRONMENTAL AFFAIRS DEVELOPMENT BANK OF SOUTH AFRICA.*

Cobalt Factsheet. (2017). *Cobalt factsheet. Critical raw materials factsheets 2017.* European Commission.

Cobalt Institute. (2018). *Lithium-ion*. Retrieved Feb 2018, from https://www.cobaltinstitute.org/lithium-ion-batteries.html

Cobalt Investing News. (2018, Feb 27). *Cobalt Critical to Lithium-ion Battery Chemical Mix*. Retrieved from https://investingnews.com/daily/resource-investing/critical-metals-investing/cobalt-investing/cobalt-critical-lithium-ion-battery-electric-vehicles/

Cobalt Investing News. (2018, March 26). *Pilot Project Aims to Produce "Ethical Cobalt" from DRC Artisanal Mines*. Retrieved August 2018, from https://investingnews.com/daily/resource-investing/critical-metals-investing/cobalt-investing/pilot-project-produce-ethical-cobalt-drc/

Cox, D., Wright, N., & Coakley, G. (1981). The nature and use of copper reserve amd resource data. In *United States Geological Survey Professional Paper 907-F.*

CRM InnoNet. (2015). *Critical Raw Materials Innovation Network.*

Darton Commodities. (2016). *Cobalt market review.*

Deloitte Sustainability. (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. *Prepared for the European Commission, DG GROW.* .

Downes et al. (2017). *ProSUM Recommendations Report.* Brussels, Belgium.

EAFO. (2018). *Vehicle Statistics*. Retrieved 05 2018, from EUROPEAN ALTERNATIVE FUELS OBSERVATORY: http://www.eafo.eu/eu

EC. (2018). *SWD Report on Raw Materials for battery Applications.* Brussels: European Commission.

EPA. (2013). *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles.*

ERTRAC. (2017). *European Roadmap Electrification of Road Transport.*

European Commission. (2017). *Study on the review of the list of critical raw materials. Critical raw materials factsheets.*

European Commission. (2018, 02). *DG Growth - Critical Raw Materials*. Retrieved from http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

European Parliament. (2015). *Recovery of Rare Earths from Electronic wastes: An opportunity for High-Tech SMEs.*

Fraser Institute. (2017). *Annual Survey of Mining Companies 2016.*

GGC. (2011). *Supply & Demand of the Strategic Metal - COBALT. Presentation by Global Cobalt Corporation*. (G. C. Corporation, Producer) Retrieved January 2018

Graedel, T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. *vol. 112, n. 20*.

Greentech Media. (2016, June 9). *Can Cobalt Supplies Scale With Massive EV Market Growth?* Retrieved December 2017, from https://www.greentechmedia.com/articles/read/can-cobalt-supplies-scale-with-massive-ev-market-growth

Huisman et al. (2017). *Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report.* Brussels, Belgium.

ICCT. (2017). *EUROPEAN VEHICLE MARKET STATISTICS - Pocketbook 2017/18.*

IEA. (2017). *Global EV outlook 2017.*

IEAHEV. (2018). *Fuel Cell Vehicles*. Retrieved from http://www.ieahev.org/about-the-technologies/fuel-cell-vehicles/

IRENA. (2017). *Electric vehicles technology brief.*

JRC. (2016 (a)). *Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU.*

JRC. (2016 (b)). Lithium ion battery value chain and related opportunities for Europe.

JRC. (2017(a)). *Critical Raw Materials and the Circular Economy - background report.*

JRC. (2017(b)). *Assessment of the Methodology for Establishing the EU List of Critical Raw Materials.*

Kontinen, & Hanski. (2015). The Talvivaara Black Shale-Hosted Ni-Zn-Cu-Co Deposit in Eastern Finland. *Mineral Deposits of Finland*, 557–612.

Minerals4EU. (2014). *European Minerals Knowledge Data Platform*. Retrieved from http://minerals4eu.brgm-rec.fr/

MIT. (2017, Oct 11). *Will metal supplies limit battery expansion?* Retrieved December 2017, from http://news.mit.edu/2017/will-metal-supplies-limit-battery-expansion-1011

Oakdene Hollins and Fraunhofer ISI. (2013). *Study on Critical Raw Materials at EU Level - Final Report.* A report for DG Enterprise and Industry.

Öko-Institut. (2018). *Assessment of the implementation of Directive 2000/53/EU on end-of-life vehicles (the ELV Directive) with emphasis on the end of life vehicles of unknown whereabouts, European Commission, DG Environment.* European Commission, DG Environment.

Olivetti, E., Ceder, G., Gaustad, G., & Fu, X. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule, 1*, 229-243.

Poulizac. (2011). *Modeling Mining Economics and Materials Markets to Inform Criticality Assessment and Mitigation.* Master thesis of the Massachusetts Institute of Technology.

Promine. (2015). ProMine Mineral Databases: New Tools to Assess Primary and Secondary Mineral Resources in Europe. *Mineral Resource Reviews*.

Raw Materials Scoreboard. (2016). *Raw Materials Scoreboard - European Commission.*

Roskill (PR). (2018, June 12). *Cobalt Global Industry, Markets & Outlook 2018*. Retrieved July 2018, from https://roskill.com/market-report/cobalt/

Roskill. (2017). *Cobalt: DRC delays ban on exports…again*. Retrieved from https://roskill.com/news/cobalt-drc-delays-ban-exportsagain/

Roskill. (2018, June 04). *Batteries: China EV battery recycling faces challenges.* Retrieved 09 2018, from https://roskill.com/news/batteries-china-ev-battery-recycling-faces-challenges/

Roskill Information Services. (2014). *Cobalt: Market Outlook to 2018*.

S&P Global Market Intelligence. (2015). *Permitting, Economic Value and Mining in the United States. Report Prepared for The National Mining Association.*

S&P Global Market Intelligence. (2018). SNL Metals & Mining database. Retrieved Jan 2018.

SEI. (2012). *Metals in a Low-Carbon Economy: Resource Scarcity,Climate Change and Business in a Finite World.* Stockholm Environment Institute.

Sienna Resources. (2017). At the Forefront of the Battery Metals Revolution. *Sienna Corporate Presentation*.

SMRE. (2017, July). *Lithium and cobalt metals markets booming*. Retrieved December 2017, from Strategic Metals & Rare Earths Letter.

Statista. (2018). *Cobalt demand annual growth rate worldwide from 2008 to 2018*. Retrieved May 2018, from https://www.statista.com/statistics/655946/annual-growth-rate-of-global-cobalt-demand/

STRADE. (2016). *Strategic Dialogue on Sustainable Raw Materials for Europe (STRADE) - The Cost Competitiveness of Mining Operations in the European Union - European Policy Brief.*

STRADE. (2017). *Strategic Dialogue on Sustainable Raw Materials for Europe (STRADE) - The Competitiveness of the European Union's Mining Sector.*

Sykes, J. (2012). Seven strategies for rare earths hopefuls: navifgating the uncertainties of the rare earth industry.

Tesla. (2018, May 7). *Tesla is leading electric car batteries away from cobalt mining industry*. Retrieved August 2018, from https://www.teslarati.com/tesla-battery-tech-cobalt-mining-industry/

UMICORE. (2012, September). *Hoboken site visit Hoboken site visit.* Retrieved May 2018, from http://www.umicore.com/storage/migrate/2012SeptHobokenSiteVisitEN.pdf

UMICORE. (2016, September). Recycling of EOL (X)EV Batteries. *Presentation at Putting Science into Standards Workshop*.

Umicore. (2017). Retrieved from http://pmr.umicore.com/en/batteries/our-recycling-process

UNCC. (2015). *United Nations Climate Change* . Retrieved from The Paris Declaration on Electro-Mobility and Climate Change and Call to Action: https://unfccc.int/news/the-paris-declaration-on-electro-mobility-and-climate-change-and-call-to-action

UNEP. (2011). *RECYCLING RATES OF METALS: A STATUS REPORT.*

USGS. (1999). Metals Prices in the United States through 1998--Cobalt. In K. B. Shedd.

USGS. (2011). *Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa.*

USGS. (2015). Minerals Yearbook: cobalt.

USGS. (2018). *Mineral commodities Summary - Cobalt.*

Weyhe, R. (2013). *Recycling von Lithium-Ion-Batterien.*

WGI. (2018). *Worldwide Governance Indicators (WGI) (1996–2016)*. Retrieved April 2018, from http://info.worldbank.org/governance/wgi/index.aspx#home

WMD. (2018). World Mining Data.

List of abbreviations and definitions

BEV	Battery electric vehicle
EOL-RR	End-of-life recycling rate
ERTRAC	European Road Transport Research Advisory Council
ESS	Stationary energy storage
EV	Electric vehicle
FCEV	Fuel cell vehicles
ICE	Internal Combustion Engine
IEA	International Energy Agency
KWh	kilowatt hour
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LMO	Lithium manganese oxide
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
NiCd	Nickel cadmium battery
NiMH	Nickel-metal battery
PHEV	Plug-in hybrid electric vehicle
RMI	Raw Materials Initiative

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Annex 1. Country ranking by cobalt reserves & resources identified in active mines and exploration projects

Country	Resources & reserves (cobalt contained, tonnes)		Number of projects (with reported cobalt resources)		
	Mine stage	Late-stage	Mine stage	Late-stage	Total
Dem. Rep. Congo	8 938 253	910 902	9	8	17
Australia	350 760	1 405 598	4	45	49
Tonga	0	1 519 000	0	1	1
Canada	238 189	609 094	7	26	33
Zambia	653 538	4 300	5	1	6
Cuba	454 000	0	2	0	2
Papua New Guinea	124 000	228 300	1	2	3
Finland	312 200	37 521	2	4	6
Cote d'Ivoire	0	290 480	0	2	2
Philippines	100 550	174 897	4	5	9
China	206 141	29 785	5	4	9
Tanzania	0	229 620	0	5	5
Mexico	223 000	0	1	0	1
Madagascar	215 000	0	1	0	1
Russia	0	197 124	0	5	5
Brazil	34 700	157 625	1	3	4
USA	85 479	28 488	3	3	6
South Africa	45 186	15 600	1	1	2
Guinea	0	34 610	0	1	1
Morocco	17 956	0	1	0	1
Solomon Islands	0	11 090	0	1	1
Uganda	9 400	0	1	0	1
Sweden	0	1 446	0	2	2
Argentina	0	1 381	0	1	1
Vietnam	1 100	0	1	0	1

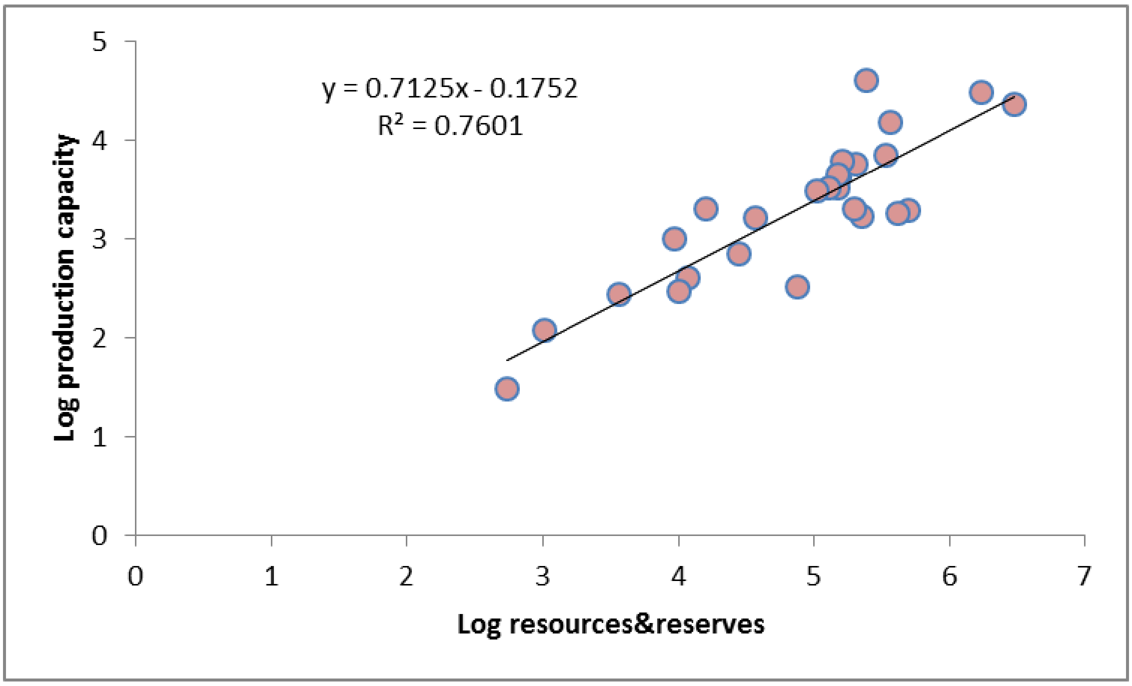
Data source: (S&P Global Market Intelligence, 2018).

Annex 2. Statistical correlations used to handle missing data in the estimation of mine supply forecasts

As a result of data availability issues, some data on production capacities was derived statistically.

The approach described in (Cox, Wright, & Coakley, 1981) was used to fill gaps in the data. The procedure invoked is based on the assumption that the total metal contained in deposits, and their annual production, is log-normally distributed – large deposits produce relatively less metal per tonne of metal contained annually than medium and small deposits – and a high correlation between the two can be observed. This correlation was used by the authors for a rough prediction of the potential copper production from undeveloped deposits in the US.

For the purposes of this analysis, annual production capacities of properties for which information is available were compared with the amount of resources and reserves. Both variables were first transformed by taking the natural logarithms and a regression equation relating them was obtained. This was used in the prediction of missing capacities data. Different improvements in the correlation coefficients were tested by eliminating outliers in the data.



Annex 3. Development timeframes over the lifecycle of a mine project

The stages in the lifecycle of a mine have different development timeframes.

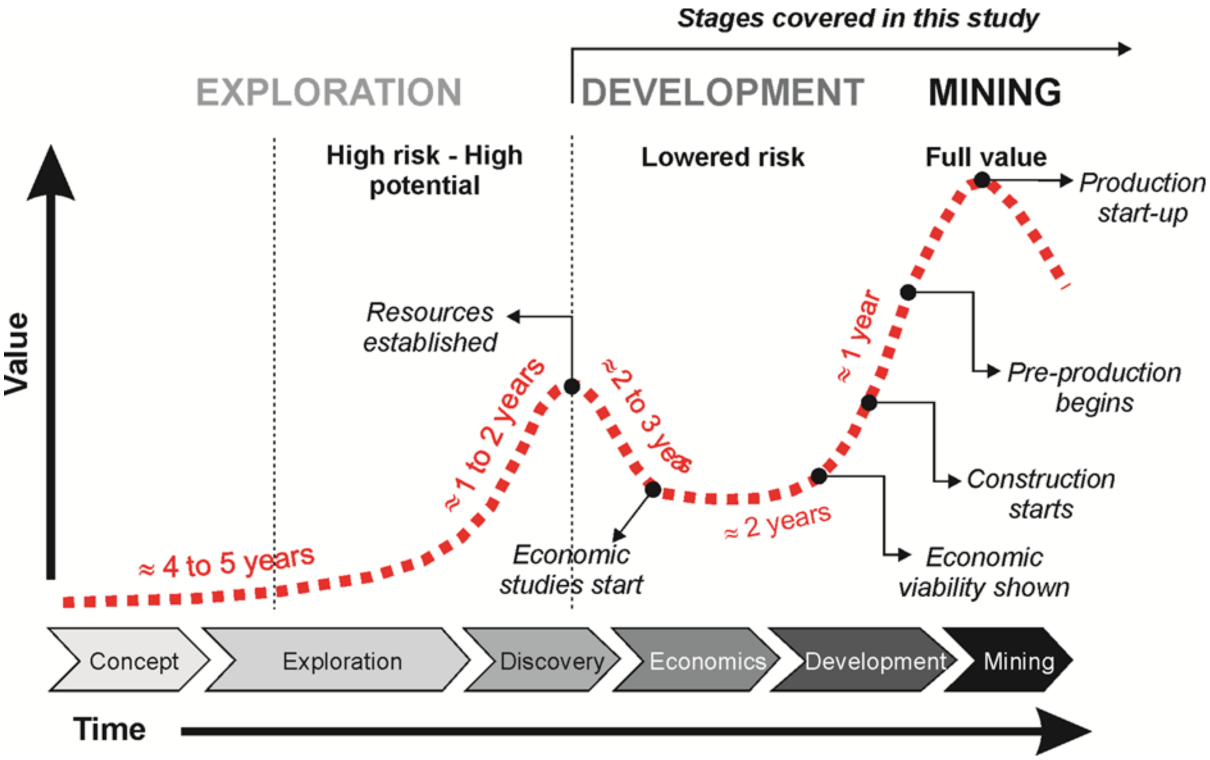
For the pre-production stage, typical development timeframes will be around one year. For developments prior to the decision to build a mine, the best-case scenario will be four years.

According to (S&P Global Market Intelligence, 2015), a pre-feasibility study prepared with suitable resources identified (after around six years of initial and advanced exploration), can take two years to produce. When reflecting a positive outcome for the project, a pre-feasibility study will then be developed further into a feasibility study, which takes an average of two years to prepare.

The permit and financing stage should take about three years while construction of a mine is likely to take at least two years.

These timeframes can be further constrained by delays during the development period, which can be expected, especially in less favourable market conditions.

On the other hand, it is reasonable to expect that at least some projects with less challenging economics will take fewer years than the fixed timeframes to come into production.



Source: adapted from (Sykes J. , 2012), presented in (JRC, 2016 (a)).

Annex 4. Mine production capacities per country until 2030.

Country	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Dem. Rep. Congo	110 025	81 185	86 285	93 085	103 036	109 504	114 355	114 355	114 355	113 428	112 193	111 266	111 266	111 250
Cuba	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408	5 408
Finland	3 187	3 187	3 187	3 187	3 187	3 187	3 187	2 947	2 627	2 801	3 353	3 767	3 767	3 767
Mexico	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 000
Madagascar	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600	5 600
China	6 866	6 679	6 679	6 679	6 679	6 679	6 679	6 679	6 679	5 230	3 298	1 848	1 848	1 848
Papua New Guinea	3 308	3 308	3 308	3 308	3 698	4 218	4 608	4 608	4 608	5 386	6 423	7 202	7 202	7 202
South Africa	1 033	813	813	813	813	813	813	813	813	972	1 183	1 342	1 342	1 342
Canada	7 257	6 419	7 003	7 782	8 667	9 067	9 367	9 367	9 360	11 088	13 398	13 893	12 410	11 358
Zambia	17 160	13 760	13 310	12 710	12 260	12 260	12 260	12 260	12 260	12 323	11 148	9 531	8 271	8 271
Australia	6 035	4 999	4 999	4 999	11 314	19 464	25 419	25 148	25 146	29 090	32 550	34 095	32 280	32 261
Morocco	2 100	2 100	1 470	630	0	0	0	0	0	0	0	0	0	0
USA	163	163	589	1 157	1 582	1 582	1 582	1 582	1 582	1 901	2 326	2 596	2 530	2 481
Vietnam	80	80	80	56	24	0	0	0	0	0	0	0	0	0

Philippines	7 321	2 721	2 721	2 721	3 801	5 154	6 118	6 031	6 031	6 242	6 524	6 557	6 320	6 142
Brazil	2 635	935	935	935	1 930	3 256	4 251	4 251	4 251	4 299	4 364	4 412	4 412	4 412
Guinea	0	0	0	0	280	653	933	933	933	933	933	933	933	933
Tanzania	0	0	0	0	833	1 943	2 775	2 775	2 775	3 471	4 398	5 094	5 094	5 094
Russia	6 520	0	0	0	130	302	432	432	432	1 519	2 968	4 055	4 055	4 055
Solomon Islands	0	0	0	0	0	0	0	0	0	124	290	415	415	415
Tonga	0	0	0	0	0	0	0	0	0	4 142	9 666	13 808	13 808	13 808
Cote d'Ivoire	0	0	0	0	0	0	0	0	0	1 333	3 110	4 442	4 442	4 442
Argentina	0	0	0	0	0	0	0	0	0	28	66	94	94	94
Sweden	0	0	0	0	0	0	0	0	0	37	87	124	124	124
Zimbabwe	153	0	0	0	0	0	0	0	0	0	0	0	0	0
Botswana	350	0	0	0	0	0	0	0	0	0	0	0	0	0
New Caledonia	4 800	0	0	0	0	0	0	0	0	0	0	0	0	0
Indonesia	1 045	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	193 046	139 357	144 387	151 070	171 241	191 091	205 788	205 190	204 862	217 357	231 285	238 481	233 622	232 308

* Data results from scenario 1 projections. It includes mine capacities in tonnes of Co per year, not adjusted to any specific recovery in the refining process.

Annex 5. Overview of world and European Li-ion recycling plants

Company	Location	Process	Battery type	Capacity (tonnes of batteries per year)
Glencore (former XSTRATA Nickel Ltd)	Canada (Sudbury)	Calcination> EAF> Hydrometallurgy	Co-based LIB	7000
Retriev Technologies Inc. (incl. former Toxco Inc.)	Canada (BC, Trail), US (Baltimore, OH; Anaheim, CA)	Hydrometallurgical	Li metal, Li-ion	4500
AERC Recycling solutions	US (Allentown, PA; West Melbourne, FL; Richmond, VA)	Pyrometallurgical	All types including Li-ion and Li-metal	
Sony Electronics Inc. – Sumitomo Metals and Mining Co.	Japan	Pyrometallurgical	Li-ion	120-150
Nippon Recycle Center Corp.	Japan (Osaka; Aichi; Myagi)	Pyrometallurgical	Ni-Cd, NiMH, Li-ion, alkaline	
Dowa Eco-System Co. Ltd.	Japan	Pyrometallurgical	Various including Li-ion	1000
JX Nippon Mining and Metals Co.	Japan	Pyrometallurgical	Various including Li-ion	5000
Shenzhen Green Eco-Manufacturer Hi-Tech Co.	China (Jingmen, Hubei)	Hydrometallurgical	NiMH, Li-ion	20000-30000
Hunan BRUNP	China (Ningxiang, Changsha, Hunhan)	Hydrometallurgical	Various including Li-ion	3600-10000
BATREC AG	Switzerland (Wimmis)	Pyrometallurgy> mechanical treatment	Li-ion	200
UMICORE S.A.	Belgium (Hoboken)	UHT pyrometallurgy followed by hydrometallurgy	Li-ion, NiMH	7000

RECUPYL S.A.	France (Grenoble)	Hydrometallurgy	Li-ion	110
SNAM	France (Saint Quentin Fallavier)	Pyrometallurgy> mechanical separation>Hydro metallurgy	NiCd, NiMH, L-ion	300
Euro Dieuze/SARP	France (Dieuze)	Hydrometallurgy	Li-ion	200
ERAMET (Valdi)	France (Commentry)	Pyrometallurgy	Various including Li-ion	20000
AKKUSER Ltd.	Finland (Nivala)	Mechanical treatment (output sold to hydrometallurgical plant)	NiCd, NiMH, Li-ion, Zn alkaline	4000
ACCUREC GmbH	Germany (Mulheim, Krefeld)	Pyrolysis> mechanical treatment> hydro or Pyrometallurgy	NiCd, NiMH, Li-ion	6000
G&P Batteries	UK (Darlaston)	NA	Various including Li-ion	145
AEA Technology	UK (Sutherland)	Hydrometallury	Li-ion	NA

Note: Some capacities given in the table might refer to tons/year instead of tonnes/year. Data sources: (Weyhe, 2013), (CM Solutions, 2015) and (JRC, 2016 (b)).

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