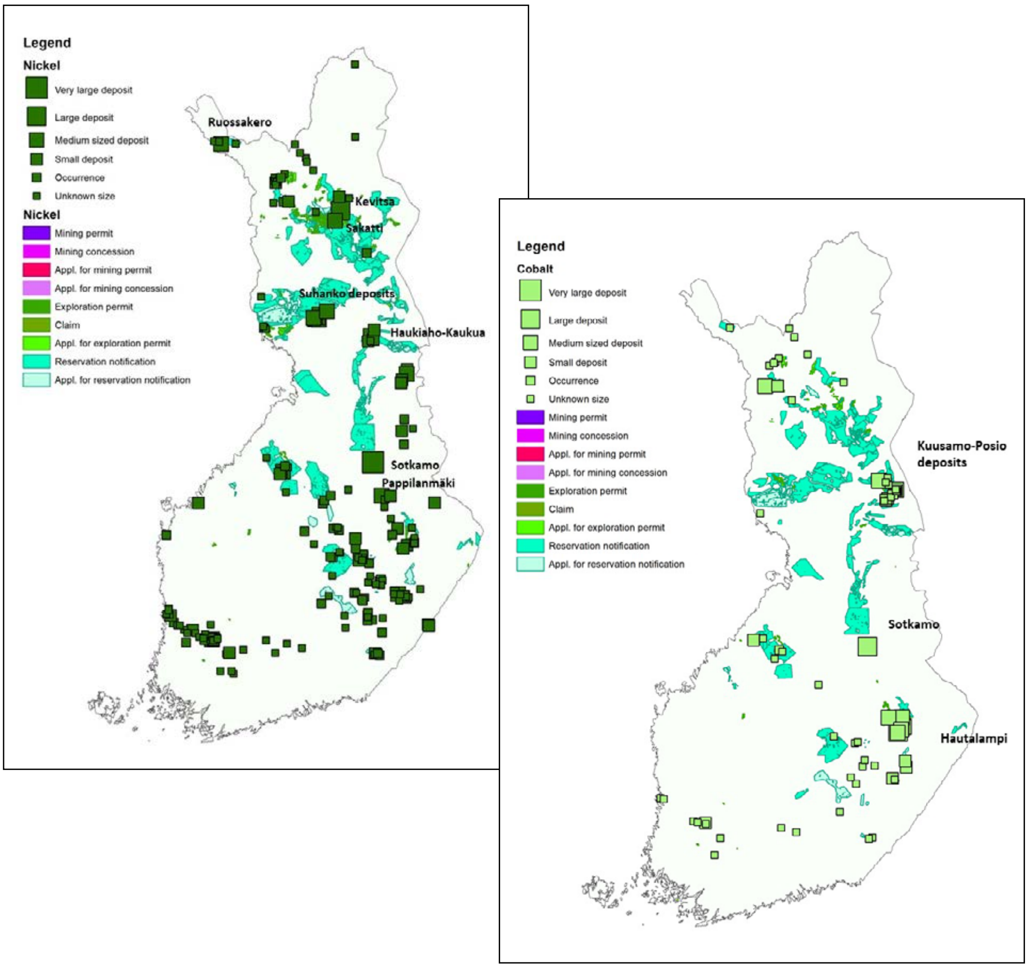
Geological Survey of Finland

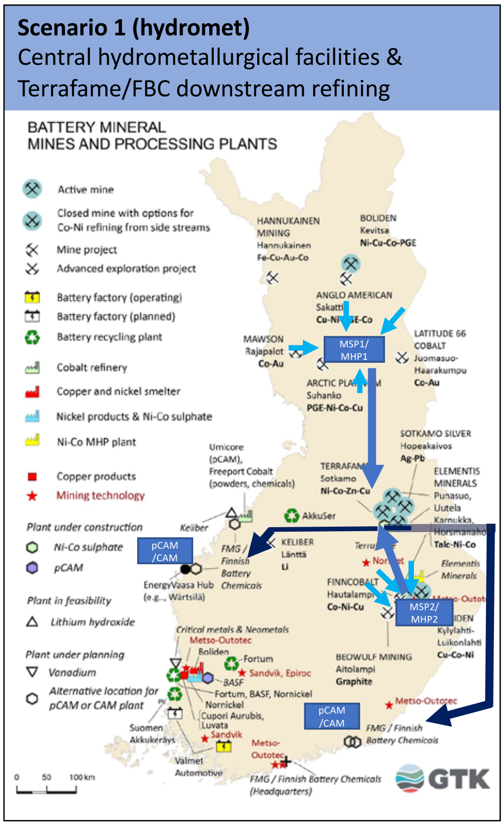
2021

Strategic roadmap for the development of Finnish battery mineral resources

Pekka Tuomela, Tuomo Törmänen and Simon Michaux

GTK Open File Research Report 31/2021





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Unless otherwise indicated, the figures have been prepared by the author of the publication.

Front cover: Exploration activity for nickel and cobalt during fall 2020. Maps include also known deposits for these commodities with some of the most notable specified by name. Note that cobalt map does not show the deposits, where Co is listed as other commodity of secondary importance. Maps are based on GTK mineral databases and Tukes mining registry. Third map shows one possible scenario of Finnish battery value chain development utilizing the resources in these deposits. Maps prepared by the authors.

Layout: Elvi Turtiainen Oy

Espoo 2021

Tuomela, P., Törmänen, T. & Michaux, S. 2021. Strategic roadmap for the development of Finnish battery mineral resources. *Geological Survey of Finland, Open File Research Report 31/2021*, 78 pages, 21 figures and 18 tables.

Nickel and cobalt are among the most essential battery commodities. DRC produces 70% of world cobalt as copper mining byproduct. Nearly third of cobalt is produced elsewhere as by-product from lateritic and sulphidic nickel mines. Southeast Asian countries produce over 50% of world nickel. The nickel deposits in these countries are predominantly lateritic ores. Main sulphidic nickel deposits and mines are located at higher latitudes (Russia, Canada, Finland). Traditionally the sulphidic deposits have been exploited for the battery applications but lateritic nickel and cobalt is being increasingly utilized due to limited supply from sulphidic deposits. Intermediate feedstocks like mixed hydroxide precipitate (MHP) and mixed sulphide precipitate (MSP) are preferred feedstocks for the battery chemical manufacturers, these in turn refined into precursor and cathode active materials to feed the cell and battery factories.

Utilization of lateritic nickel deposits is in practice crucial for adequate supply of nickel and cobalt, considering soaring demand. For nickel, the global supply was 1.5 Mtpa in 2000 but has grown to 2.5 Mtpa in 2020. The demand could exceed 3.5 Mtpa by 2030 and 4.5 Mtpa by 2040 whereas projected supply does not exceed 3.5 Mtpa even in the 2030s. It seems like investments into new mines and production capacity cannot match the increasing demand for nickel or cobalt either. Furthermore utilization of lateritic deposits has several drawbacks against sulphidic deposits. For example typically much higher CO_2 and biodiversity footprint amongst many other sustainability indicators as well as societal challenges in these countries.

The Finnish battery ecosystem is one of the most developed in Europe. Finland is the predominant producer of primary nickel and cobalt in European comparison, also being the most important producer of refined products for these commodities, as well as feedstocks for the battery industry although partly operating based on imported raw materials. Currently the Finnish battery ecosystem contains five basically separate streams for nickel and cobalt refining, to big extent operating on imported raw materials.

Future roadmap (2020–2050) for new battery metal and mineral mines is presented in this report. It is estimated that Finnish nickel production could increase to the level 50 000 tpa (41 400 t 2020) and cobalt production to the level of 2 500 tpa (1 560 t 2020) during the following decades. Even higher production figures are possible if the major mine projects advance as planned. On the other hand, the worst-case option is that domestic production of these commodities will be nearly zero from mid-2030s onwards in case new mines are not opened or the life of mine for the current mines is not extended. Three downstream value chain scenarios are presented, how the raw materials could be refined to most effectively feed the Finnish battery ecosystem. It is estimated that roughly 40 GWh cell factory could be sourced (cathodes) mostly from domestic raw materials, equaling the size of Northvolt Skellefteå plant after the planned expansions. For anode production (graphite) there are domestic production opportunities as well.

Keywords: nickel, cobalt, supply, demand, value chain, strategy, roadmap, scenario, Finland

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CONTENTS

1 NICKEL AND COBALT OVERVIEW

1.1 Introduction

Nickel and cobalt are essential commodities for lithium ion battery (LIB) production and also important commodities for the Finnish mining industry.

This paper presents an overview of the current nickel and cobalt primary production and connection to the battery production value chain globally and especially in Finland. Also, downstream refining for battery industry raw material sourcing is discussed, with emphasis on the Finnish value chain. Significant part of world cobalt is produced as a by-product of nickel production although copper associated by-products (DRC and Zambia) make up the biggest share of the market. In Finland, the association with nickel is practically always the case and hence it is necessary to consider the coincident nickel (and copper) production that are so typical with cobalt in Finnish deposits as well as other associated commodities. In principle, these other commodities (Ni, Cu and also Zn, PGE, Fe or Au depending on the particular deposit type) may be the main commodities and products regarding current and potential future mines in Finland, with minor or more substantial Co credits. More detailed review on the features of Finnish battery mineral deposits and their processing options is presented in separate GTK report (Törmänen & Tuomela 2021).

Nickel is generally thought to increase its relative importance in respect of cobalt in future battery applications, but cobalt demand also grows on absolute basis, despite the relative decreasing share in LIB applications.

Mining is necessary for raw material sourcing for society's needs and provides many benefits for the areas of operations, mainly in the form of economic and employment benefits. On the other hand, mining faces globally several challenges as adverse environmental and societal effects may not be always prevented. Permitting in general has become more challenging all over the world that is partly causing long lead times for ramping up new mines. Public awareness of the industry's environmental performance has increased but still some important aspects are not extensively discussed currently. These are namely the greenhouse gas (GHG) emission intensity and biodiversity consequences, together with many societal effects that current and upcoming sustainability and traceability systems aim to govern and mitigate. These items are briefly discussed in this paper.

The focus of this paper, is to study the Finnish raw material sourcing and processing options at the ecosystem scale, covering the whole LIB value chain up to cathode and anode materials production. The current Finnish production and material streams are examined, also considering the necessary and widely used imported raw materials. Global commodity markets and respective supply/demand developments significantly effect also the Finnish primary raw material production. Therefore, this report presents an overview of the current market situation and forecasted future scenarios.

Certain raw material sourcing aspects important to the execution of recently published Finnish Battery Strategy are discussed. Finally, a Strategic roadmap for the holistic ecosystem or cluster development of Finnish battery mineral resources is presented. This roadmap is definitely not a comprehensive presentation on topic but rather an initiative for hopefully active future discussion and development measures for this field, both on national level and amongst individual companies or consortiums. It is emphasized that the ideas and conclusions presented in chapters 2, 3 and 4 (including the roadmap and strategic development plan) are purely by GTK and do not necessarily represent plans or thoughts of individual companies.

1.2 Nickel and cobalt Supply/Demand scenarios

There are countless supply/demand scenarios regarding metals and mineral commodities in general and especially in the case of battery raw materials. For LIB applications the following five commodities: cobalt, nickel, manganese, lithium and graphite are generally considered as most essential ones due to their importance in manufacturing of battery cathodes and anodes.

It can be plausibly said that the on-going Energy Transformation and associated switch from internal combustion engine vehicles into Electric Vehicles (EVs, including all type of hybrid variations as well) is the most disruptive demand side factor for the mining & metals industry (including recycling) of the past century. Only the tremendous, and still continuing, growth development of China since late 1970s can be compared with energy transformation. Energy transformation needs to be taken into consideration together with China and other developing economies that also constantly require increasingly bigger metal tonnages for numerous purposes. Counting all the other needs of the Energy Transformation some other commodities, like aluminum, copper and several REEs will play a significant role also besides the mentioned five important LIB commodities.

Many of the supply/demand scenarios are prepared by companies like McKinsey, S&P Global, Roskill etc. and are not necessarily public documents. For the purposes of this study the following public analyses have been utilized: Fraser et al. 2021, IEA 2020, Alves Dias et al. 2018 and Hund et al. 2020. The outcomes of these studies have been summarized in the following section with notes on primary raw material production. Only nickel and cobalt are discussed here as they are so closely connected considering Finnish nickel-cobalt production. The market development for these commodities will be an important external factor for any future plans in Finland. This chapter mainly discusses the overall market situation. More detailed information regarding individual countries and mines is presented in chapter 1.3.

1.2.1 Market balance in short and long term

Nickel

Roskill sees that global primary nickel balance would remain slightly positive for most of the 2020s, until the market will turn to deepening deficit starting in 2028. This deficit deepens throughout the 2030s reaching estimated 1.4 Mtpa Ni by 2040 vs. the projected supply of 3.5 Mtpa Ni (equaling 30+% deficit). In case of nickel sulphate, the most important intermediate product for LIB precursor manufacturing, the market is forecasted to balance at slight deficit or at times surplus until 2028 with respective deepening deficit developing towards 2040 (close to 1 Mtpa $NiSO_4$). For details see Figures 1 and 2. A number of uncertainty factors need to be accounted in these analyses: for example, the actual market share development of EVs, respective cathode chemistries, steel industry share of Class 1 nickel, development of metal and energy prices as well as actual ramp up of new expansions for existing operations or completely new mines. It is important to note that Roskill clearly predicts that EU27 nickel supply will enter a structural and deepening deficit period after 2025, much earlier than similar global phenomena. To fill the gap new domestic nickel supply investments are needed and/or significant sourcing abroad as well as efficient recycling. (Fraser et al. 2021)

Currently (2020) the global primary nickel supply is roughly 2.5 Mtpa whereas it was only ca. 1.5 Mtpa in 2000. The bulk of this huge growth has taken place in laterite nickel mining and refining (to big extent nickel pig iron (NPI) used by the stainless-steel industry), especially in Indonesia and Philippines. These two countries are expected to dominate the future production increase as well, with sulphide deposits constituting only a minor share in the future growth. The vast majority of Chinese imported nickel is currently sourced from Philippines, following the recent developments of Indonesian export bans for unprocessed raw materials. (Fraser et al. 2021)

Still the Chinese companies operating in Indonesia produce vast quantities of nickel raw materials and NPI further transported to China.

Important conclusion in the Roskill study (Fraser et al. 2021) is that the availability of suitable feedstock rather than processing capacity is the biggest bottleneck in the nickel sulphate supply chain, which is the cause for the market potentially going into a structural deficit position post-2027. Also, it is stated that Class 1 nickel metal is a significantly higher cost feedstock than that of intermediates such as mixed hydroxide precipitate (MHP). Nickel sulphate production from MHP is expected to increase from 24% currently to over 42% in 2030 but again dropping in 2030s as recycling from battery scrap is thought to increase in volumes. If mixed sulphide precipitate (MSP) is counted, their combined share is estimated to be close to 50% in 2030 and remains at 40% or bigger for most of the 2030s. It is apparent that MHP/MSP production is the preferred nickel feedstock for battery raw material sourcing for the next 10–15 years.

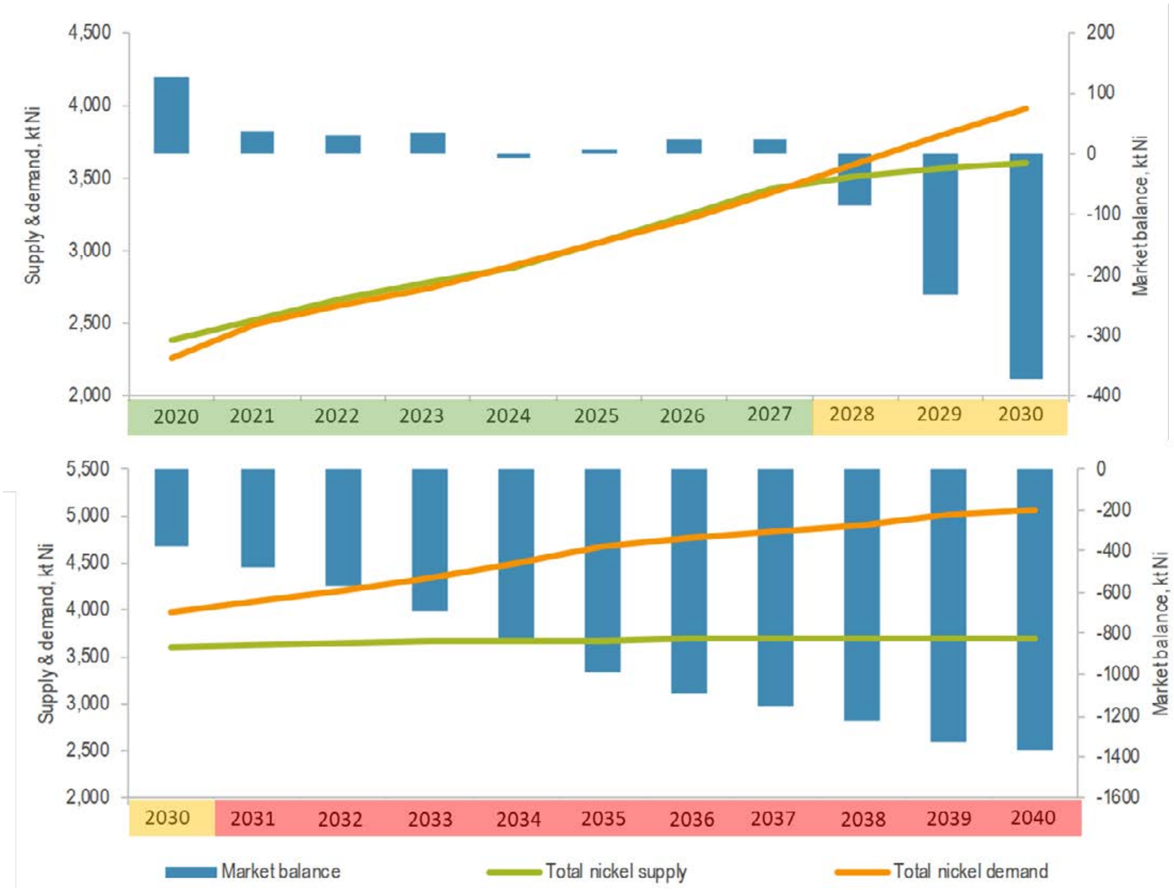


Fig. 1. Predicted nickel supply-demand 2020–2040. Modified after Fraser et al. 2021.

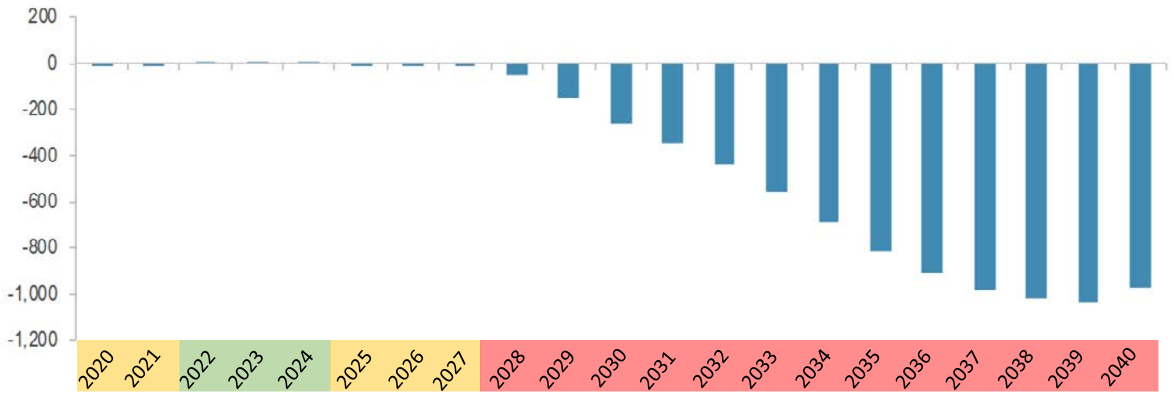


Fig. 2. Predicted nickel sulphate market balance 2020–2040. Modified after Fraser et al. 2021.

Cobalt

There are numerous cobalt demand/supply scenarios also available. Although most likely the relative importance of cobalt against nickel will decrease in the future battery chemistries the absolute demand anyhow will be growing for foreseeable future. The estimated demand for battery applications mostly range from 0.2 Mtpa to 0.4 Mtpa by 2030 and counting the conventional applications could exceed 0.5 Mtpa (Alves Dias et al. 2018, IEA 2020). Cobalt demand may increase up to 0.64 Mtpa by 2050, including all Energy transformation applications (Hund et al. 2020). The latter estimate doesn't include conventional cobalt applications. If maximum scenarios become reality it means more than fourfold cobalt production by 2030 and over fivefold production by 2050 (0.14 Mtpa in 2020).

JRC (Alves Dias et al. 2018) has estimated cobalt market deficit to happen around 2024, increasing strongly towards 2030 (Fig. 3). By 2030 the deficit is estimated to exceed 175 000 tpa that is 1.25 times the current cobalt production in 2020. As the forecast is few years old (released in 2018) the actual production and surplus/deficit situation for recent years is also presented in Figure 3, based on USGS (2021a) and Statista (2021) statistics as well as S&P Global forecast for years 2021–2025 (S&P Global 2021a). For the past few years, the JRC forecast has

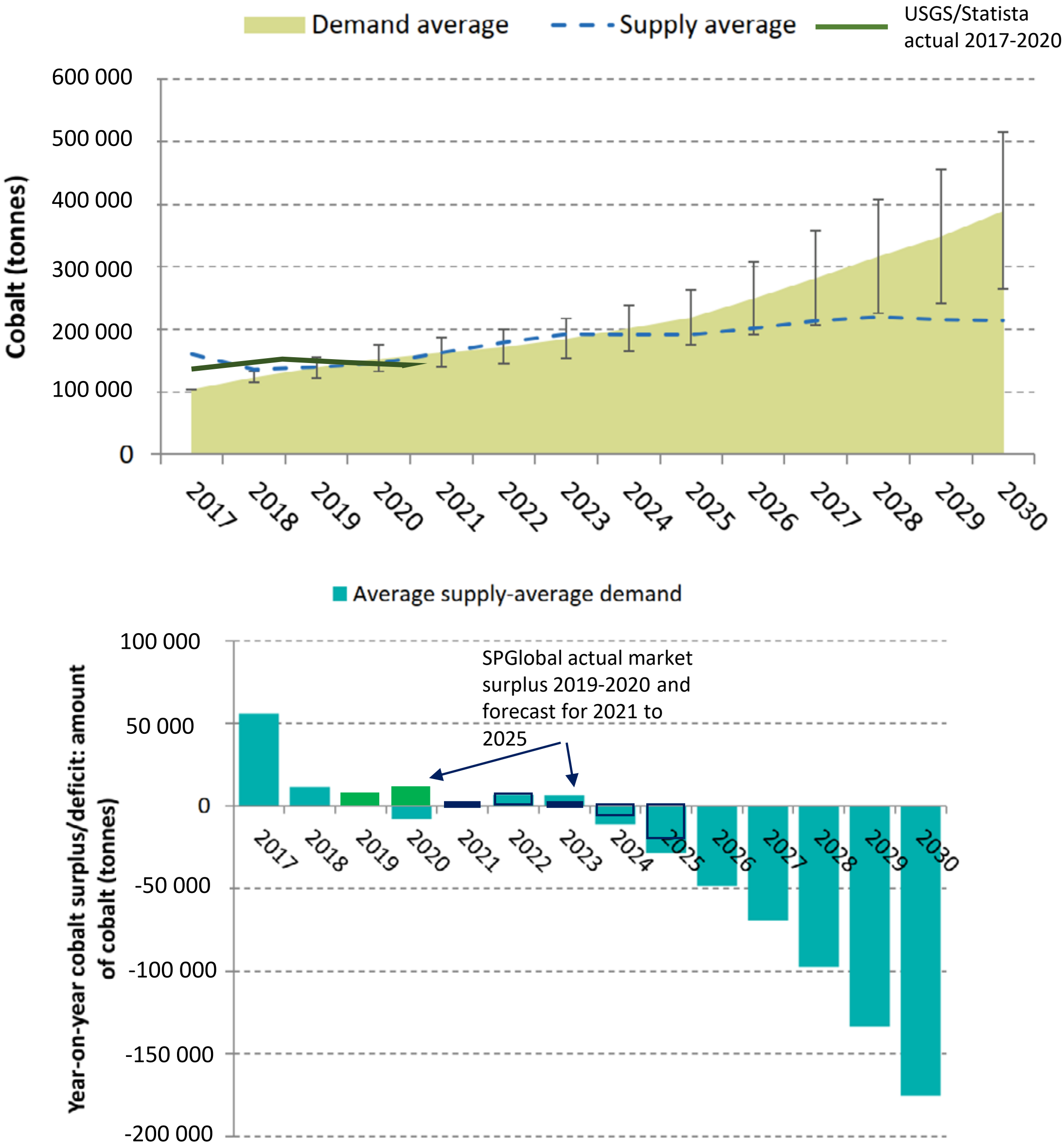


Fig. 3. Forecasted global cobalt supply/demand for years 2019–2030 and forecasted market surplus deficit for respective years not counting increased recycling measures. Modified after Alves Dias et al. 2018, USGS 2021a, Statista 2021 and S&P Global 2021a.

slightly underestimated the actual cobalt production and respective slight market surplus situation. However, the estimate is pretty similar towards 2025 as the more recent S&P Global estimate. Hence the statement about the looming market deficit seems to be still valid. According to JRC forecast if much higher recycling rates would be applied after 2025, the market deficit could potentially be lower but still clearly exceed 60 000 tpa by 2030. It is remarkable that increased recycling after 2025 is totally dependent on the available stock for the purpose (spent LIBs) and also the development of more efficient recycling techniques. The forecast has used 8 years lifetime for the EV batteries but the lifetime may be much longer with direct effects to the stock availability. On the other hand, the EV penetration may also be higher than estimated, increasing the absolute demand for cobalt. Conservative estimate for market deficit therefore would be much higher, ranging between 60 000–175 000 tpa, the order of magnitude being roughly the size of current global primary cobalt production.

Cobalt market balance estimates beyond 2030s has not been available for this study. But considering the demand forecast until 2050, it is easy to prognose that market deficit likely remains well into 2030s despite potentially more efficient cobalt recycling in the future.

Similar to the case for nickel feedstocks also in case of cobalt various Intermediate cobalt products are mainly used in the downstream processing for different applications, including battery grade chemicals. These intermediate 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 (Alves Dias et al. 2018). For example,-Finnish cobalt refining is mainly based on imported raw materials, the main feedstocks are mixed hydroxide precipitates (Umicore) and cobalt containing mattes (Nornickel).

1.2.2 Nickel-cobalt discoveries and mine development timeframe

GTK sees that Roskill has taken rather optimistic view for their analysis regarding new nickel producers (mines). Commonly the mine ramp-up timeframe has been estimated to be 13 years and 6 years in fast track projects. These seem to be far lower figures than global materialized averages (see chapter 3.2). On the other hand, individual projects are not defined in the study and many of the projects in Indonesia and Philippines are expansions of current mines that may be completed in much shorter timeframe. Still the timeframe for a typical mine project is significant, globally close to 17 years on average, from the discovery of the deposit. Preceding exploration efforts may take years or even decades before the actual mine development can even start.

Furthermore, major nickel discoveries have become more and more rare lately. Since 1990 there have been 50 major discoveries globally (containing over 500 000 tonnes of nickel in reserves, resources and past production, in which nickel accounts for at least 30% of the nominal value of all contained metals). Of these only three have been discovered during the past decade and only one of these is currently in production. The preceding decade recorded 16 discoveries of which two are currently in production. However, none of these three producing mines are truly significant producers nowadays. Back in 1990s four of the discoveries out of 30+ in total have developed to be truly major producers, currently being in Top-30 nickel mines globally. Hence it can be concluded that it takes easily 20–30 years to produce substantial metal supply from new discoveries. (S&P Global 2020a). It can be expected that some of the new deposits found during the past few decades will be successfully brought into production phase. Still the biggest potential regarding nickel supply increase is with the expansion of the existing mines.

In Roskill expected mine production analysis the share of new deposits (sulphide or laterite) is rather low which makes sense based on the decreasing discovery rates. However, should the development of these projects be delayed, it would increase the already heavy deficits in the 2030s (Fraser et al. 2021). Considering the long lead times and the fact that global major nickel discoveries have been practically negligible since 2000, the long-term supply security does not seem to be particularly well established as depleting reserves should be continuously replaced.

Cobalt will be produced in minor amounts together with certain nickel deposits. In 2017 roughly 1/3 of cobalt was produced from magmatic or lateritic nickel deposits but over 60% was produced in connection to copper production (Törmänen & Tuomela 2021). Therefore future cobalt supply is strongly dependent of the development of copper mining in DRC and Zambia. Like is the case with new nickel mines, the amount of new cobalt producing copper or nickel mines is limited. There are some 60 mines globally that produce cobalt at least on occasional basis and there are further 30+ projects aiming for cobalt production, most of them being quite minor by planned production. However just a few of these seem to be advancing to production by 2025. Short term supply increase from new mines appears to be rather limited. See chapter 1.3 for more details on individual mines and project developments.

1.2.3 Automotive stock development and electrification

Roskill analysis assumes roughly 20–30 million electrified vehicles sold annually by 2025 depending on the scenario and respectively 25–40 million units sold annually by 2030. Similar prognosis by IEA (2020) predicts roughly 15–25 million electric vehicles sold annually by 2025 and 25–45 million units sold annually by 2030. Numerous forecasts assume 110–120 million vehicles in total manufactured by 2030 so the EV penetration, counting annual manufacturing and sales would be 20–40% by that time. Both IEA and Roskill estimates fall within that range. In Roskill analysis the EV percentage is assumed to be significantly higher by 2040. Still even in Europe the conventional ICE vehicles are predicted to make over 20% of the annual stock at that time. This seems to be in contradiction with the many recent very ambitious all-EV plans released by numerous automotive manufacturers. It is a well justified question if the raw material sourcing allows even the figures predicted by Roskill and IEA to be manufactured in the 2030s, considering the predicted market deficiencies for nickel and cobalt. Not to say anything about fully electrified global automotive manufacturing.

Roskill estimates nearly 2.9 Mt nickel demand across all battery applications by 2040 of which 95% is constituted by automotive sector. By 2030 the battery demand is estimated to be roughly 1 Mtpa nickel. Cobalt demand by automotive sector is estimated to range from 0.3 to 0.4 Mtpa by 2030 (Alves dias et al. 2018).

World Bank estimates that the planned Energy transformation measures require nearly 2.7 Mt Ni and 0.64 Mt Co on annual basis by 2050 (2DS or 2–degree scenario as defined by IEA). More sustainable scenarios would require much higher tonnages, especially for metals like aluminum, copper and zinc but also for nickel (and cobalt). (Hund et al. 2020). Third estimate is by IEA, prognosing nickel demand of 1–2 Mtpa by 2030, depending on the scenario (IEA 2020).

Conclusion is that actual future nickel demand very much depends on the realized scenario. The only clear thing is that the battery applications will require 1–3 Mtpa nickel in the future, the order of magnitude of current primary nickel production. Cobalt range is similarly 0.3–0.6 Mtpa.

Comparing these figures with the current production for these commodities, it is more than obvious that to meet the demand, the supply side requires significant investments in the future.

1.2.4 Recent NPI developments

Until 2021 it has been thought that sulphide deposits and respective Class 1 nickel will dominate the battery chemicals supply side, due to simpler, cheaper and more environmentally friendly processing into nickel sulphate. Although it is possible to process laterite feedstocks into battery chemicals, for example with so called HPAL process. Typically, laterites and NPI production in general cause multiple times higher CO_2 emissions compared with sulphide nickel processing, depending on the process and energy source. On average the multiplier is at least 3.5 but may be significantly higher, even tenfold in some cases. This naturally has significant LCA effects not even counting many other aspects like biodiversity.

Tsingshan, the world’s largest nickel producer, announced in March 2021 that it will supply nickel matte based on converted nickel pig iron (NPI) from its operations at Indonesia Morowali Industrial Park (IMIP) to Chinese companies Huayou and CNGR Advanced Materials, which will be further processed to produce battery-grade nickel sulphate. At the same time the company plans to significantly expand their nickel production with over 0.5 Mtpa Ni by 2023 and furthermore planning for major investments in renewable energy to mitigate the CO_2 footprint of their production processes. S&P Global estimates that if Tsingshan’s plans are successful, and can be scaled up to increase the availability of feedstock for nickel sulphate production, they would trigger the most significant structural supply-side change to the global nickel market since the company brought NPI to the wider market in the early 2000s. NPI share of world primary nickel production was mere 2% back in 2006 but has grown to exceed 40% by 2019. These latest NPI developments likely are not fully considered in the above discussed Roskill analysis. (S&P Global 2021a)

It is good to note that without the said NPI development during the past 15 years, the planned Energy transformation measures would simply not be possible from nickel supply point of view. If the NPI production can be successfully converted to feed the battery industry, it would relieve the supply side bottlenecks for nickel and to lesser extent for cobalt, however at considerable environmental cost (CO_2, biodiversity etc.). At this point it is too early to estimate if the planned NPI developments will be successful.

Considering the early 2021 development in nickel supply side, it seems likely that the earlier nickel deficit scenarios may be delayed at least few years, especially in case of Class 1 nickel and associated nickel chemical supply scenarios. Obviously, this is to big extent subject to successful Tsingshsan (and possibly other companies) NPI utilization for battery grade nickel sulphate production. Even if the pure supply challenge could be solved at least for the short term, the long term deficit seems to be inevitable. As roughly 20% of global cobalt production is tied with laterite nickel production, this new NPI innovation may somewhat ~~relief~~ relieve the forecasted cobalt market deficit as well, subject to successful large scale implementation of the technique.

Thinking short term, cost effectiveness and environmental and responsibility concerns may become the crucial items, especially the latter from OEM/Manufacturer and end the user point of views, possibly limiting at least European companies to utilize nickel and cobalt sourced from laterite nickel deposits (regardless of the processing technique).

Supply risk considerations are also evolving due to big changes in Southeast Asia production. Nickel production in Philippines has been falling in recent years. Alternatively, the production is surging in Indonesia which may be producing 50% of global primary nickel by 2025 (S&P Global 2021a). These two countries would the count for over 60% of global production by 2025 and this ratio is forecasted to remain in Roskill analysis (Fraser et al. 2021). Majority of this production is feeding Chinese production (steel, batteries etc.) so despite growing nickel production, rest of the world needs to source their nickel as well and keep the sourcing in pace of the growing demand.

1.2.5 Environmental and societal considerations

Typically, mining industry, like any other industry or human activity, causes environmental consequences and degradation of the environment. With proper protocols, management and mitigation measures these consequences can be minimized. During the past few decades, the environmental performance of the mining industry has vastly developed, especially regarding water and waste management (acid rock drainage management etc.) although there still is much room for future improvements on that front. Numerous environmental and sustainability systems and standards have evolved and are currently in active use by the mining companies, or at least with the public companies, responsible for their shareholders also regarding the environmental and social performance. Despite the many positive developments, it has become evident that the so-called social license to operate (SOL) is becoming more and more difficult to achieve, regardless of the country or mine location. This is caused by many factors, for example conflicting land use interests or other societal challenges. These well-known environmental aspects need not further description in this report. Instead a few other aspects not so often discussed, especially in Finnish context, are briefly described in the following section. As efforts against climate change and biodiversity losses are nowadays seen as global phenomena that require global actions it would appear natural to apply this approach for resource extraction as well. Also, societal aspects are gaining more and more importance due to increasing interest for responsible and traceable raw material sourcing.

CO_2 *emission intensity*

Greenhouse gas (GHG) emissions are widely discussed nowadays but not that much in connection to mining. However, mining industry is one of the major energy consumers globally. Actual energy consumption and respective emissions depend on the deposit type, applied processes, energy sourcing etc. Depending on the source and extent of the sectors covered, the industry is generally thought to consume 2–11% of the global primary energy. Recent estimate by McKinsey points out that mining is currently responsible for 4 to 7 percent of GHG emissions globally. Scope 1 and Scope 2 CO_2 emissions from the sector (those incurred through mining operations and power consumption, respectively) amount to 1 percent, and fugitive-methane emissions from coal mining are estimated at 3 to 6 percent. A significant share of global emissions (28 percent) would be considered Scope 3 (indirect) emissions, including the combustion of coal. (McKinsey 2020).

Regardless of the exact figures it is clear that the share of global energy consumption is significant. Considering the global tendency to mine ever lower grade deposits and increasing tonnages to meet the growing demand combined with associated more complex process flowsheets, the energy issue is apparently even more crucial in the future and cannot be ignored when evaluating the environmental performance of an individual mine or mining company.

It is widely regarded that sulphide nickel deposits enable much more environmentally friendly processing, especially considering CO_2 emissions. Terrafame has recently made an independent review of the CO_2 emission intensity of their product and the conclusion is that Terrafame's nickel sulphate production offers the lowest carbon footprint in the industry, 60% lower than existing conventional processes Figure 4, (Terrafame 2020a): roughly 5 t CO_2e/t for saleable product. Most laterite deposits easily exceed tenfold emissions. Also other notable Finnish producers belong to first quartile in this respect. Nornickel emissions are clearly below 10 t CO_2e/t of saleable product, for nickel sulphate specifically 6 t CO_2e/t of saleable product (Nornickel 2019). Boliden Kevitsa-Harjavalta integrated operations belong to the same peer group with ongoing investments into smelter processes and mine electrification further lowering the emissions (Boliden 2021a). All industrial and human activities should target for minimum CO_2 emission intensity so this argument strongly encourages to produce commodities from deposits having low emission intensity, in this case providing the Finnish operators a competitive advantage. When considering mining industry overall climate effects also carbon handprint should be considered besides the footprint but this topic is not discussed further here.

Emission intensity comparisons for cobalt producing companies are not readily available in public. However indirectly using the statistics for nickel compared with similar data for copper producers, at least indicative understanding of cobalt production emission intensity can be acquired. Glencore is clearly the largest cobalt producer in the world, having had 20–30% market share during the recent years. Majority of Glencore cobalt, roughly 90%, is produced in DRC as copper mining by-product (Glencore 2021a). This represents nearly half of all the cobalt produced in connection to copper mining.

Glencore reports their copper production emission intensity demonstrating that both the African

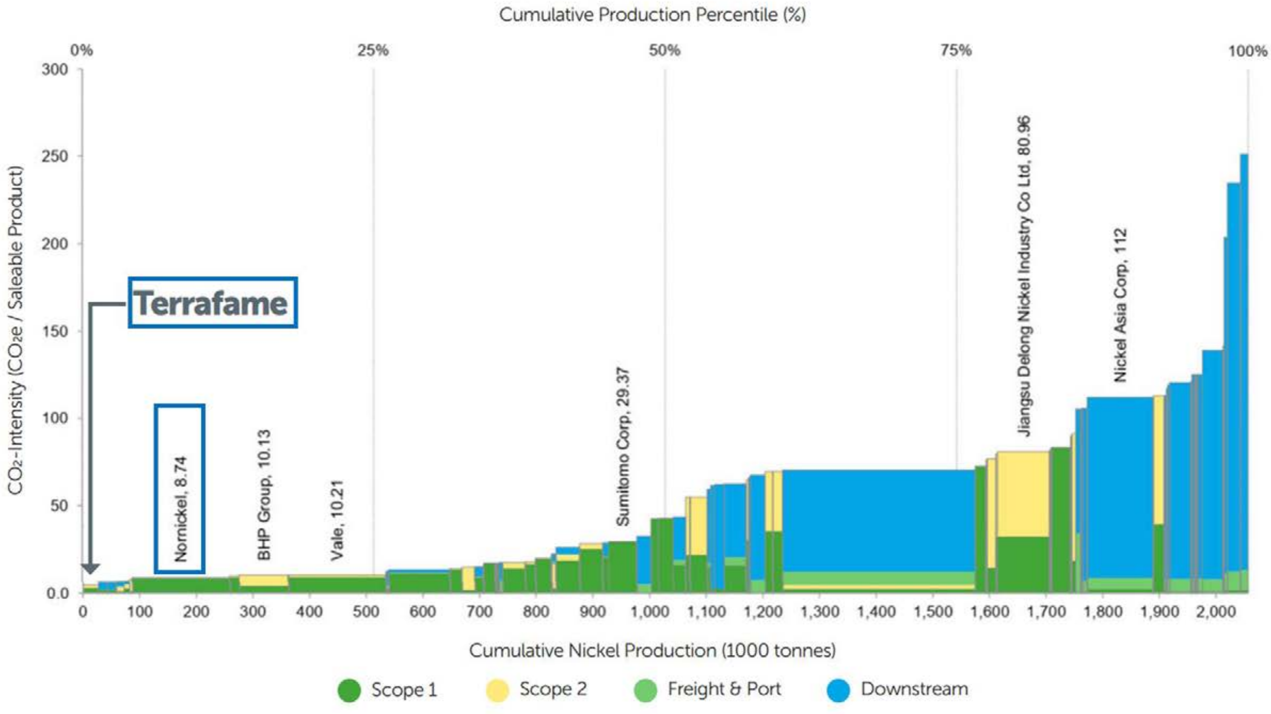


Fig. 4. Global nickel producers ranked by 2019 CO_2-equivalent-intensity. Modified after Terrafame 2020a.

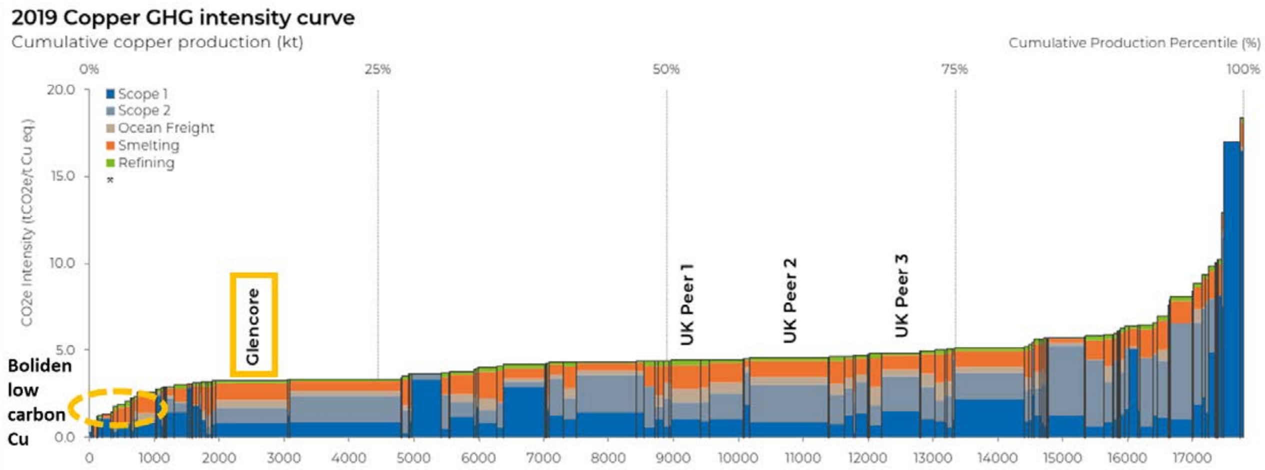


Fig. 5. World copper producers greenhouse gas intensity curve (t CO_2/t Cu produced). Modified after Glencore 2021b.

operations (Cu-Co) and the Canadian nickel-cobalt assets are low carbon operations, belonging to first quartile in comparison. The company emission intensity is roughly 3 t CO_2/t Cu (Fig. 5). The intensity is partly affected by electricity sourcing from hydro power (Glencore 2021b).

This demonstrates that copper ore associated cobalt production can be undertaken with rather low energy intensity. In general copper production is much less energy intensive than nickel production. Boliden has recently communicated being able to produce very low carbon copper, based on company's own concentrates (including Kevitsa), the intensity being <1.5 t CO_2/t Cu demonstrating the Finnish competitive edge on that front as well. (Boliden 2021b)

Biodiversity

Global biodiversity loss has been a much-discussed topic during the past few years, partly due to several extensive studies undertaken on the subject, for example by Díaz et al. (2019) and Dasgupta (2021). Mining together with other resource extraction sectors and other human activities contributes to deforestation and other deteriorating consequences causing respective biodiversity losses. Mining and potential biodiversity loss is a fairly recent field of study.

Mining specifically has been studied for example by Murguía et al. 2016. They studied mines and deposits for five commodities (Fe, Al, Cu, Au and Ag) and their locations in respect to global biodiversity zones (DZ1 to 10) by using vascular plants' diversity as a proxy to quantify overall biodiversity. Considering the five metals together, 63% and 61% of available mines and deposits, respectively, are located in intermediate diversity zones (DZ 4 to 6), comprising 52% of the global land terrestrial surface. 23% of the mines and 20% of the ore deposits are located in areas of high plant diversity (DZ 7 to 10), covering 17% of the land. 13% of the mines and 19% of the deposits are in areas of low plant diversity (DZ1 to 3), comprising 31% of the land surface. In the used categorization Finland mainly belongs to the diversity zone 3 with some parts on the coast belonging to the zone 4.

Unfortunately, the study did not include key battery metals with the exception of copper. It was concluded that 21.2% of the copper mines and 27.6% of the copper deposits are located in low plant diversity zones, 53.4% of mines and 53.1% of deposits in the intermediate diversity zones and 25.4% of mines and 19.3% of deposits in the high plant diversity zones. It is to be noted, that the study only concentrated on mine and deposit locations. not the actual production tonnages at these sites. It is clear that the actual production volumes and respective footprints much effect to the biodiversity losses.

These diversity zones are illustrated in the Figure 6, showing also the world major areas for nickel and cobalt production. Based on latest 2019 production figures (Brown et al. 2021) the countries located in Southeast Asia, Australia and New Caledonia produced over 65% of global primary nickel. For cobalt the production share is even higher, close to 80%, mainly from Africa. Similar spatial analysis on the exact location of these mines is not available for comparison but in general it can be concluded that vast majority of these mines are located in diversity zone 6 or higher. Mainly in Australia also diversity zones 4 and 5 are well represented. However low diversity zones do have substantial production for both commodities, especially in Canadian and Russian Arctic.

Therefore, the qualitative estimate is that production of these two commodities tend to be concentrated on higher diversity zone areas than the studied five commodities, consequently placing higher substantial biodiversity pressure on these production regions.

Similar type of analysis was undertaken by Sonter et al. 2018. In their study the reserves (including both operating and non-operating assets) for lead-zinc, copper and nickel have been mapped against the Earths terrestrial biomes (14 biome classes). The outcome of the study is that main tonnage for nickel is located in biome 12 (tropical and subtropical grasslands, savannahs and shrublands) and biome 13 (tropical and subtropical moist broadleaf forests), see Figure 7. Also biomes 1 (boreal forests/taiga) and 14 (tundra) possess significant reserves and production. Considering nickel production cobalt credits and copper mining associated cobalt production mainly in DRC and Zambia (mostly on biome 12), the most heavily effected biome by nickel and cobalt mining seems to be biome 12, tropical and subtropical grasslands, savannahs and shrublands.

Combining the outcomes of these two studies, the conclusion is that majority of world nickel and

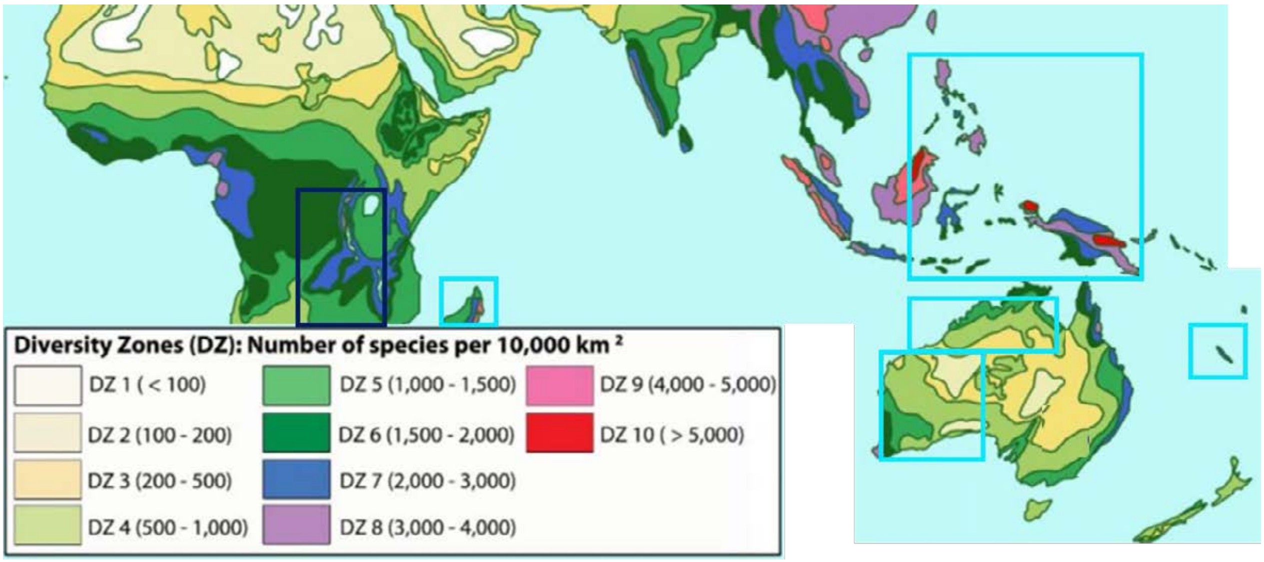


Fig. 6. Areas of major global cobalt and nickel mines and deposits. Main cobalt production area is shown with dark blue square and nickel (cobalt) production areas with light blue squares. Modified after Murguía et al. 2016.

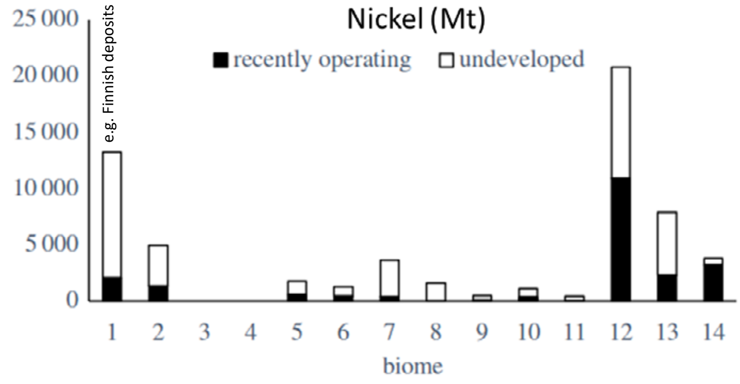


Fig. 7. Global nickel reserves and their location within 14 biomes: 1. boreal forest/taiga, 2. deserts and xeric shrubland, 3. flooded grasslands and savannahs, 4. mangroves, 5. Mediterranean forests, woodlands and scrub, 6. montane grasslands and shrublands, 7. temperate broadleaf and mixed forests, 8. temperate conifer forests, 9. temperate grasslands, savannahs and shrublands, 10. tropical and subtropical coniferous forests, 11. tropical and subtropical dry broadleaf forests, 12. of tropical and subtropical grasslands, savannahs and shrublands, 13. tropical and subtropical moist broadleaf forests, 14. Tundra. Modified after Sonter et al. 2018.

cobalt is produced in the areas of high or very high biodiversity. More specifically in the areas having mostly biomes of tropical and subtropical grasslands, savannahs and shrublands and to lesser extent tropical and subtropical moist broadleaf forests, including rainforests.

Third analysis of the nickel mines and their respective location vs. biodiversity has been undertaken by Verisk Maplecroft (2018, Fig. 8). The study compared the relative location of nickel reserves by ore type (laterite or sulphide). It was found that vast majority of the laterite deposits are located in areas with high biodiversity (and many protected areas as well). The study concludes: 39% of global nickel reserves – made up entirely of laterites – are found in locations exposed to high or extreme biodiversity risks. Verisk Biodiversity and Protected Areas (Terrestrial) Index captures the risk to business based on the level of species richness and the presence of protected areas. Operations in Indonesia and the Philippines are some of the worst-performing countries. Conversely, sulphide ores are almost entirely low risk, since deposits are mostly found in higher latitude and less biodiverse areas, like Russia, Australia and Canada.

Verisk also points out the water risks associated with mining. The large scale of laterite deposits means that extracting the ore produces more wastewater than when mining sulphides. Laterite production also requires acid leaching, consuming

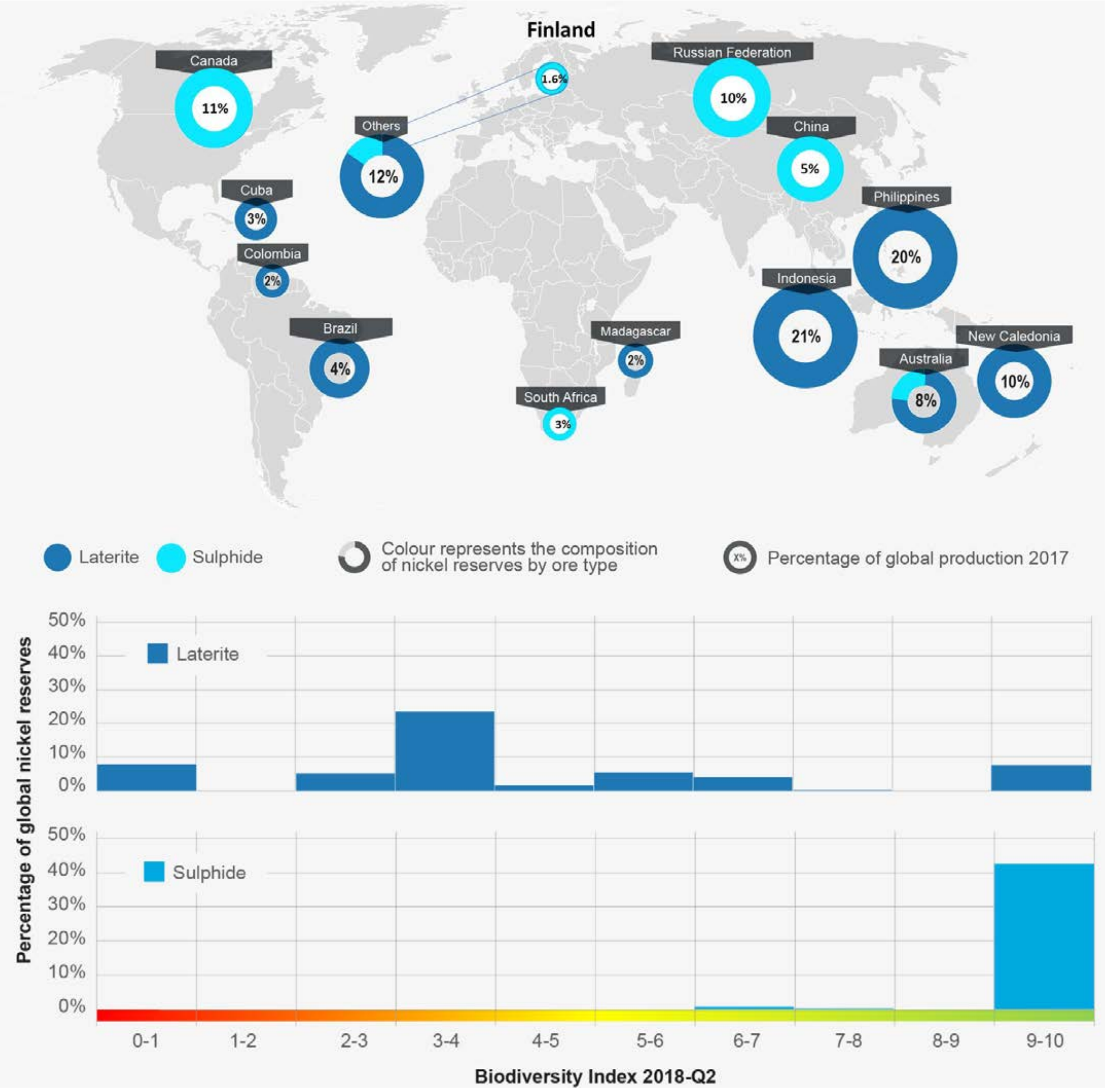


Fig. 8. Global nickel production by ore type (laterite, sulphide) breakdown of reserves by ore type against the biodiversity. Besides Finland, only South Africa, China, Australia, Russia and Canada produce substantial amounts of sulphide based nickel. Nickel laterite deposits are located almost entirely in biodiverse and protected areas whereas mostly higher latitude sulphide deposits are located on less biodiverse areas. Note that the biodiversity scale is different than in the other reference studies. Modified from graphs by Verisk Maplecroft 2018.

chemicals and increasing the threat to surrounding water quality. The Verisk subnational Water Stress Index quantifies risk by calculating the ratio of water supply to demand. Verisk data shows that 35% of nickel reserves (26% of which are laterites) are at locations exposed to high or extreme levels of water stress. This finding is driven by the impact of large operations in the Philippines, Indonesia and Australia – multiplying the existing water risks posed by the mining sector in these regions. This same water stress risk is confirmed by many other studies, for example by McKinsey (2020). The most important mining influenced water-stress hot-spots by 2040 are estimated to be Southeast and West Australia, Southern Africa, Eastern and mid China, Central Asia, Southwest USA and Mexico and Middle South America Pacific coast. Finland is defined to be an area with very low water stress risk, that can be seen as positive aspect for the Finnish mines when considering their environmental performance.

Yet another study was undertaken by Sonter et al. 2020, the study outcome is summarized in this section. The study analyzed 62 381 pre-operational, operational, and closed mining properties globally targeting 40 commodities. Also 28 409 Protected areas, 13 320 Key Biodiversity Areas and Earth's Remaining Wilderness—areas free from the industrial-scale activities and human pressure. For the purposes of this study identified as the top 10% of intact habitats (2009 Last of the Wild indicator) for each of Earth's 60 biogeographic realms (12.12 million km^2). Specific results for nickel and cobalt properties was not disclosed but the study included 1 917 properties for nickel and 1 012 properties for cobalt.

Assuming 50 km influence radius (direct and indirect effects) mining potentially influences 50 million km^2 of Earth's land surface. This can be thought as extremely conservative estimate, considering the influence area being bigger than Americas combined. Of the defined influence areas 8% coinciding with Protected Areas, 7% with Key Biodiversity Areas, and 16% with Remaining Wilderness. Using more conservative 10 km influence radius the total influence area was defined being 6.6 million km^2 (85% of Australia area). However, mining area proportional overlap with specified conservation/wilderness areas changed only slightly using these parameters. Reason for this is not completely interpreted but may be caused by the fact that majority of the mines with potential to overlap these sensitive areas are located relatively close to the borders of them, hence resulting nearly same overlapping ratios with 10 km or 50 km influence sphere.

Furthermore, it needs to be considered that majority of the properties analyzed are defined as being pre-operational (mines) of which apparently big majority are actually exploration sites. These pre-operational properties make up 85% of the 50 km influence radius assessment and 78% of the 10 km influence radius assessment with respective influence areas for remaining operational and closed mines being ca. 26 million km^2 and 2 million km^2. These should be considered as true influence areas for mining properties, especially the latter one. Real environmental influences are largely caused by these properties, with pre-operational properties posing mostly theoretical influences in case of advancement into operational phase. Despite this deficit the study is comprehensive, first of a kind, analysis of the number and extent of exploration and mining properties.

Most mining areas (82%) target-commodities needed for renewable energy production, and areas that overlap with Protected Areas and Remaining Wilderness contain a greater density of mines (the indicator of threat severity) compared to the overlapping mining areas that target other materials. The study concluded that mining threats to biodiversity will increase as more mines target commodities for renewable energy production and, without strategic planning, these new threats to biodiversity may surpass those averted by climate change mitigation. The outcome of this study confirms that mining in general tends to coincide with nature conservation areas or otherwise high biodiversity value areas as well as wilderness areas. Specific coincidence rates by individual commodities is subject to future research. (Sonter et al. 2020)

As summary of these mining-biodiversity studies it is concluded that purely from biodiversity point of view the unfortunate fact seems to be that these commodities (Ni and Co) imperative for Energy Transformation, are mostly sourced from the areas with high or very high biodiversity and respective biomes, potentially effecting large surface areas at least counting also potential indirect effects. From global perspective this favors any deposit or mines located on lower biodiversity zone or biome, such is the case with the Finnish peers. This is not to say that these current or future Finnish mines would not affect the local environment or biodiversity but the effect is definitely lower than by similar mine(s) located in higher diversity zone or biome. Obviously, this kind of comparisons are not undertaken or required by permitting procedures that only tend to focus on local, national and at most regional criteria, for example EU Natura2000 regulations. If global initiatives similar to climate regulation take place in the future, biodiversity issues are definitely worth to consider.

Societal aspects

Various responsibility aspects have become increasingly important over the past decades. Numerous initiatives and systems have been launched to improve stakeholder rights and verify the performance of the companies on responsibility issues, in many cases for example to convince the potential investors for project funding. Most of these initiatives and systems are implemented globally and therefore are not directly dependent on national regulation. However, all the official permits necessary for the operations will be typically granted based on national legislation and authorities. If the national governance structures and democracy in general is poorly developed, it may severely constraint the actual influence potential by the local stakeholders. Various governance and democracy aspects influence many other disciplines besides the permitting and appeal procedures. Occupational and public safety, child labour, human right violations as well as taxation transparency are just a few examples associated with this subject. Especially in projects where project operator is not public company and/or funding is not provided by lenders following Equator Principle or similar responsible financing guidelines in their funding decisions, there is a big risk for societal drawbacks if the country regime is not democratic enough. This may be the case in many Chinese operations and investments into Philippines, Indonesia or DRC for example that are predominant producers in these countries.

It is not a simple task to compare countries in that regard but various democracy indexes may provide one way to undertake a rough evaluation on topic, as democracy index can be thought as being a proxy for the overall governance for the institutions, authorities and government in general. In this study we refer to the Democracy Index compiled by the Economist Intelligence Unit (EIU 2021) as well as Fragile state index 2020 by Fund for Peace institution (2021).

When comparing Ni and Co producing countries discussed above in connection to CO_2 emissions and biodiversity effects, the following simplified conclusions can be done based on latest 2020 Democracy Index:

Canada (5.), Finland (6.) and Australia (9.) are among the most democratic countries in the world with respective ranks in the assessment, the actual scores ranging from 9 to 9.2. Their regime type is classified as full democracy indicating, according to Wikipedia definition, nations where civil liberties and fundamental political freedoms are not only respected but also reinforced by a political culture conducive to the thriving of democratic principles. These nations have a valid system of governmental checks and balances, an independent judiciary whose decisions are enforced, governments that function adequately, and diverse and independent media, having only limited problems in democratic functioning.

Philippines (55.), Indonesia (64.) and Papua New Guinea (70.) are classified as flawed democracies. Actual scores for these countries range from 6.1 to 6.6. Flawed democracies are nations where elections are fair and free and basic civil liberties are honored but may have issues (e.g. media freedom infringement and minor suppression of political opposition and critics). These nations have significant faults in other democratic aspects, including underdeveloped political culture, low levels of participation in politics, and issues in the functioning of governance.

Russia (124.) and DRC (166.) are classified as authoritarian regimes, where political pluralism is nonexistent or severely limited. The actual scores for these countries range from 1.1 to 3.3. These nations may have some conventional institutions of democracy but with meagre significance, infringements and abuses of civil liberties are commonplace, elections (if they take place) are not fair and free, the media is often state-owned or controlled by groups associated with the ruling regime, the judiciary is not independent, and censorship and suppression of governmental criticism are commonplace.

Zambia is ranked for position 99 and classified as hybrid regime between the flawed democracies and authoritarian regimes. As stated above, together these countries produce over 65% of global primary nickel and close to 80% of cobalt.

Fragile state index confirms the relative position of these countries. Finland is positioned as least fragile of all studied countries (178., note the inverse rank) with score 14.6. Canada is ranked 171. position with score 18.7. Australia having rank 169. and score 19.7. Indonesia rank is 96. and score 67.8. Russia rank is 76. and score 72.6. Philippines rank is 54. and score 81. Papua New Guinea being ranked yet slightly worse at 50. and score 82.3. Finally DRC rank is 5. with associated score 109.4 (with maximum score for worst performer being 120).

In many mining projects the indigenous people are among the most important stakeholders. The indigenous people question is much more diverse and complicated in many countries than in Finland. For example, considering the important nickel producing countries Philippines and Indonesia. It is estimated that in Philippines there are approximately 6.5 million indigenous peoples, composing about 10 percent of the total Philippine population and belonging to over 40 distinct ethnolinguistic groups. Similarly, it has been estimated that the number of indigenous peoples in Indonesia is between 50 and 70 million people, that makes 20–30% of the total population. With 1 072 different ethnic groups, including 11 ethnic groups with a population of over one million people, Indonesia is considered one of the world's most culturally diverse nations. (IWGIA, ECTF 2020)

Indigenous people questions and many other land use conflicts are closely associated with the population density. Both of these countries are much more densely populated than Finland for example. Philippines population density is ca. 370 people/km^2. In Indonesia the density is 150 people/km^2 on average with clearly higher densities on some of the islands. These can be compared with average population density in Finland, being 18 persons/km^2 and much lower in the northern and eastern parts of Finland that are the main interest areas for exploration and mining industry. (Worldometer 2021)

These figures and facts clearly emphasize the societal challenges in these and many other countries with heavy mining industry. This brief assessment unveils the position of Finland and mining companies operating in Finland as well as relative position for the local stakeholders, including indigenous people. Obviously thorough analysis should be much more detailed but such is beyond the scope of this study.

Many of the societal challenges are easier to manage in full democratic countries. In the future, when societal responsibility and traceability are gaining increasing importance, this will likely provide one more competitive edge for the Finnish industry, possible even potential price premiums depending on the developments on metal markets. For example, London Metal Exchange has disclosed initiatives that constrain or may even block trading of non-responsible sourced metal products in the future (LME 2021). The counterweight for full democracies is that NGOs and stakeholders have much stronger relative position than in less developed democracies. This typically lengthens the permitting and appealing procedures and makes them more complex, on the other hand eventually benefitting the environmental performance of the mines.

1.2.6 Finland's contribution to EU nickel and cobalt value chain

Finland is clearly the dominant country in all nickel production value chain steps among EU countries (Fig. 9). According to Fraser et al. (2021) Finland would produce over 75% of EU primary nickel during period 2020–2040, at most some 50 kt Ni annually. This is somewhat conservative estimate if certain Finnish mine projects advance as planned and especially regarding the recent news by the Finnish downstream refining sector, see chapter 3.

When it comes to nickel intermediates, the preferred option for nickel sulphate production, Finnish contribution is even more highlighted at 95% over the outlook period, see chapter 4 for respective GTK prognosis. The same applies for Class 1 refined nickel production dominated by Finland, also sourcing raw material for nickel production in France, these together being close to 100% of production. In addition, some of the Finnish Ni matte is exported outside of EU not contributing to the tonnage here. There are a few non-EU major producers in Europe (mainly in UK and Norway) as well as ferronickel producers in Balkan area. (Fraser et al. 2021)

From EU perspective it seems that without fundamental changes in processing or refining facilities, Finland will remain the European powerhouse for these value chain steps for the foreseeable future. This clearly provides competitive advantages for the Finnish companies that mostly rely on domestic raw materials or imported from nearby sources with substantial benefits e.g. from CO_2 emissions and biodiversity point of view as discussed earlier.

Finnish contribution on EU cobalt value chain is even more dominant than in the case of nickel, especially in primary production. When it comes to cobalt primary production (mining), Finland is the only producer in EU area. Finland is also the biggest cobalt refiner in Europe and EU. The only other notable production country is Belgium in addition to Norway. France has also produced minor cobalt quantities in the past but in 2019 did not produce cobalt at all. Finland, Belgium and Norway production tonnages were 12 526 t (66% of EU production), 6 500 t and 4 354 t respectively (Alves Dias et al. 2018, Brown et al. 2021). However, basically all refined cobalt in Finland is sourced from abroad. More details of Finnish value chains for both commodities is presented in chapter 2.1.

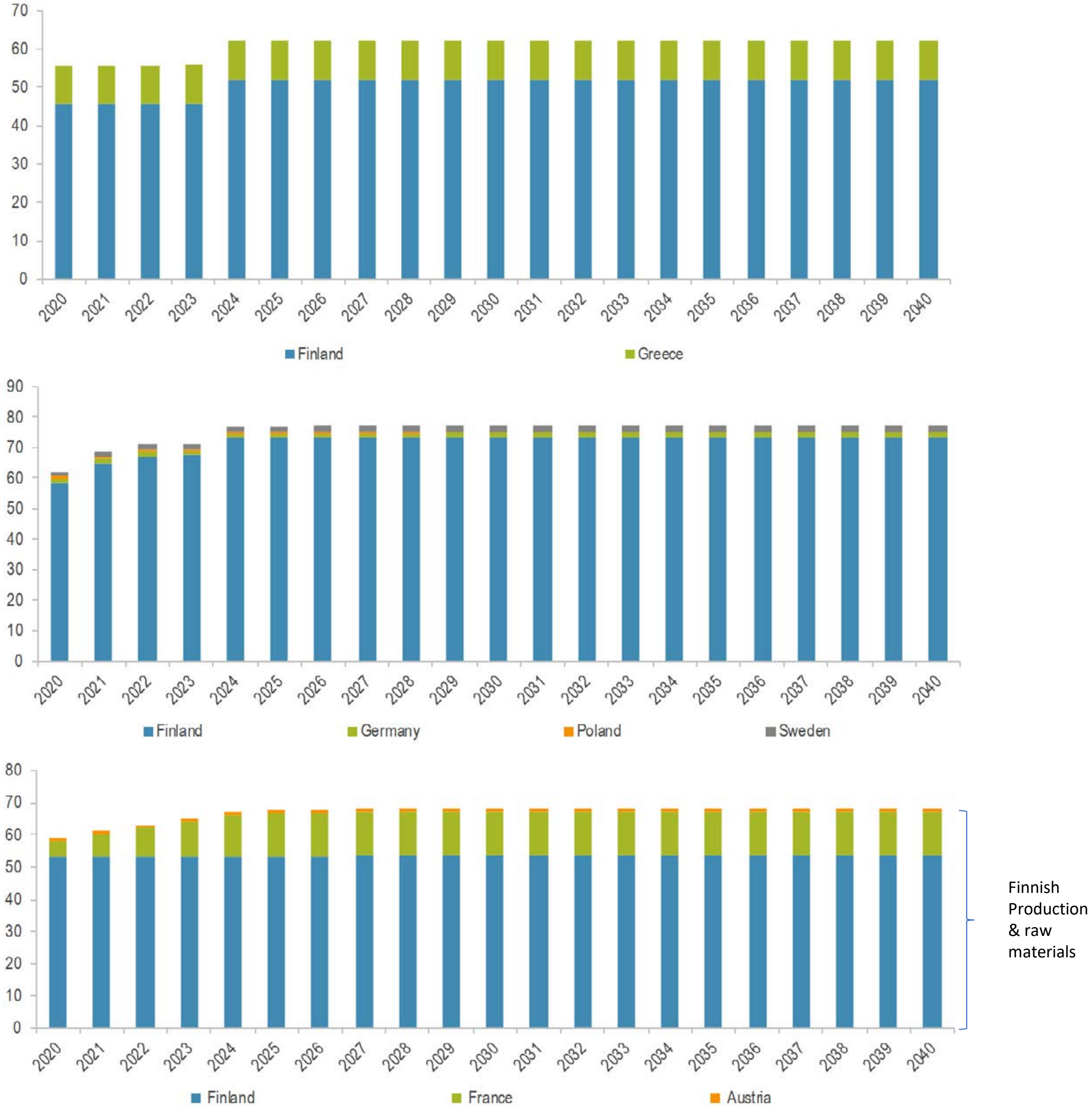


Fig. 9. Roskill prognosis for expected EU mine supply for primary nickel 2020…2040 (topmost graph), intermediate production (middle graph) and Class 1 nickel production (bottom graph). Note that the estimated Class 1 nickel production in France relies on nickel matte sourced from Finland. Modified after Fraser et al. 2021.

1.3 Nickel and cobalt primary production

This chapter provides a generic breakdown of the current nickel and cobalt production globally. Resources or reserves and other geological aspects are not discussed here. An overview regarding cobalt can be obtained from the report by Törmänen and Tuomela 2021. For nickel and other commodities there are numerous sources for resource estimates available, for example USGS statistics.

The aim here is to get basic understanding of the primary nickel and cobalt production on country basis and also to present similar information about the mine size distribution that provides better comparison for the consequent analyses of the Finnish deposits, mines and their future development. Typically, the production rates are only presented on country wide aggregated numbers that do not enable similar comparison.

Global mine production of nickel was 2.6 million tonnes in 2019 and is estimated to be 2.5 million tonnes of nickel in 2020 (USGS 2021b). Indonesia is the biggest producer with the global share of 30%, and the two Asian countries Indonesia and Philippines together produce nearly half of the world's nickel (Table 1). While Russia holds the third position on the list, Finland is the biggest producer among European countries.

Table 1. Top countries in mine production of nickel in 2020 and 2019 (USGS 2021b, Tukes 2021). Figures and percentages do not necessarily sum up to the sharp figures due to rounding.

Country	Mine production in 2020^e (t Ni)	Global share (%)	Mine production in 2019 (t Ni)	Global share (%)
Indonesia	760 000	30.4	853 000	32.7
Philippines	320 000	12.8	323 000	12.4
Russia	280 000	11.2	279 000	10.7
New Caledonia	200 000	8.0	208 000	8.0
Australia	170 000	6.8	159 000	6.1
Canada	150 000	6.0	181 000	6.9
China	120 000	4.8	120 000	4.6
Brazil	73 000	2.9	60 600	2.3
Cuba	49 000	2.0	49 200	1.9
Dominican Republic	47 000	1.9	56 900	2.2
Finland	**41 430**	**1.7**	**38 530**	**1.5**
United States	16 000	0.6	13 500	0.5
Other countries	248 570	9.9	271 470	10.4
TOTAL	**2 500 000**		**2 610 000**	

^{e} Estimation

Global mine production of cobalt was 148 000 t Co in 2018 and it is estimated to be 140 000 t Co in 2020 (USGS 2021a). Nearly ¾ of the cobalt in the world originates from the DRC, and the shares of each of the next highest producing countries (Russia, Australia, Philippines) are less than 5% each (Table 2). The DRC produced 95 000 t Co and all other countries together <45 000 t Co. While Russia holds the second position on the list, Finland is the only European country producing cobalt in mines, its global share being 1%. The DRC's share in production of world's refined cobalt is diminutive (0.05% in 2018) (Brown et al. 2021), because it exports most of the cobalt as intermediate cobalt products, for example cobalt hydroxide, for further refining elsewhere.

Table 2. Top countries in mine production of cobalt in 2020 and 2019 (USGS 2021a, Tukes 2021). Estimate for 2020 totals for 135 000 t cobalt but is for some reason reported to be 140 000 t Co.

Country	Mine production in 2020^e (t Co)	Global share (%)	Mine production in 2019 (t Co)	Global share (%)
DRC	95 000	68.0	100 000	69.4
Russia	6 300	4.5	6 300	4.4
Australia	5 700	4.1	5 740	4.0
Philippines	4 700	3.4	5 100	3.5
Cuba	3 600	2.6	3 800	2.6
Canada	3 200	2.3	3 340	2.3
Papua New Guinea	2 800	2.0	2 910	2.0
China	2 000	1.4	2 500	1.7
Morocco	1 900	1.4	2 300	1.6
South Africa	1 800	1.3	2 100	1.5
New Caledonia	[1]		1 700[2]	1.2
Finland	**1 560**	**1.1**	**1 450**	**1.0**
Madagascar	700	0.5	3 400	2.4
United States	600	0.5	500	0.4
Other countries	4 840	3.5	4 870	3.4
TOTAL	**140 000**		**144 000**	

^{e} Estimation, [1] included in the other countries (in addition at least Zambia, Zimbabwe, Indonesia), [2] Brown et al. 2021.

Cobalt production figures are not as reliable as similar figures for many other commodities. This is partly dependent on the producing countries statistical reporting and non-uniform reporting specifications. For example, there is frequently disparity between the cobalt content of the ore and cobalt actually recovered. In addition, significant artisanal mining contribution adds up the confusion and uncertainties.

Special feature associated with the cobalt production is the strong artisanal and small-scale mining (ASM) contribution in the DRC. ASM contributes a considerable amount to the primary supply of cobalt (Mancini et al. 2020). As a counter-measure several large industrial giants (e.g., Glencore and Umicore) have developed procedures to verify that ASM cobalt and any form of child labour are excluded from the supply chain (Umicore 2019a). The number of artisanal copper-cobalt miners in the DRC is estimated to be about 200 000. They commonly extract cobalt from small sites located alongside large-scale industrial operations. The relative proportion of ASM in the DRC fluctuates greatly depending on the development of large-scale mining. In 2018, the ASM production is reported to 18 000 tonnes (BGR 2019). However, ASM production is expected to decrease in 2019 compared to production in 2016 to 2018 due to the lower global cobalt prices. It is estimated to continue to amount to 15-20% of total production in the DRC due to the expected decline in industrial cobalt production (BGR 2019).

Some other statistical bodies like British Geological Survey (BGS) report significantly lower cobalt production figures. BGS reports 2019 production figures being 123 000 t cobalt in total that is clearly less than USGS figures. Biggest difference is in DRC production that is estimated to be roughly 78 000 t by BGS and 100 000 t by USGS. For some other countries like Australia, Canada and Cuba, BGS reports somewhat higher figures than USGS. (Brown et al. 2021). One can also compare the production figures with those reported by S&P Global, see table 9 and breakdown into mines by size.

It has been estimated that the Chinese companies could be controlling up to 50% of the total production in DRC (hence over 1/3 of global total supply) and some minority stakes in Zambia. Counting both of these, Chinese control is thought not to exceed 50% of total African production. Considering the dominant position of DRC, the Chinese control of cobalt production is significant, especially when considering the other commodities. In total it has been estimated that out of total African mine production value (2018) the Chinese control less than 7%. Globally the respective share of the total value is estimated to be around 3%. The Chinese investors have been particularly interested in iron ore, gold and copper, in case of DRC and Zambia copper mines also produce cobalt as well. Cobalt is definitely the commodity, where Chinese control is the strongest. This study however misses the Chinese control of Southeast Asian (Indonesia, Philippines) nickel mines although they supply bulk of Chinese nickel. The study mentions Ramu mine (Papua New Guinea), one of the big Southeast Asian producers, that is majority controlled by the Chinese. (Ericsson et al. 2020)

During early the 2000s Chinese companies started big investments into Indonesia, the biggest company being Tshingshan, currently the world biggest stainless steel producer. The company operates several mines in Indonesia of which Morowali Industrial Park is notable as being the world first fully integrated stainless steel industrial chain, including nickel mining, NPI and ferrochrome smelting, stainless steel production, hot rolling and cold rolling. Besides stainless steel the company is also strongly contributing to the EV value chain with nickel and cobalt, especially with the latest innovation of producing nickel matte from laterite ore and subsequent battery chemicals from this new kind of feedstock. (S&P Global 2021a)

Despite the statistical irregularities it is clear which countries are the most prominent producers. The top 10 producing countries supply over 90% of the world cobalt. The Chinese controlled mines in Southeast Asia have much more profound impact on nickel supply than cobalt supply.

Individual mines producing nickel

In order to be able to get more detailed overview of global nickel production, it is necessary to evaluate the production on individual mine basis. According to S&P Global nickel production statistics (S&P Global 2021b) the 10 biggest mines produce nearly 35% of global total output (Table 3). Considering the top 17 mines, the total output is nearly 45% of world total. Three Finnish nickel producing mines total together some 1.4% of world output. Terrafame Sotkamo is actually a significant mine even on global scale, having position 22 in global comparison. Overall, 36 mines were producing over 20 000 t nickel in 2019. Finnish Kevitsa mine was ranked on position 52 and Kylylahti 83 respectively production-wise.

Altogether there were 95 mines in 22 countries with registered nickel production in 2019. Of these only 22 belong to OECD countries (Australia, Canada, Colombia, Finland, Greece, Norway and USA) and of these only seven mines are in the top producing category. Greece, Norway and USA are rather minor producers.

Further 16 mines did not register nickel production during the year. The number of producing mines is therefore quite limited if compared with many other base metal mines typically having hundreds of operating mines globally. In the case of nickel, supply risk is not insignificant but still much more modest when compared with cobalt supply.

The cumulative mine production data by S&P Global totals 1 958 538 t nickel leaving considerable gap vs. estimated global production. As Indonesia and Philippines together register only some 176 000 t nickel summing up the individual mines and on the other hand China share is nearly 560 000 t nickel, it can be estimated that this gap is mostly explained by Indonesian/Philippines production being registered for Chinese companies. This is evident for example in case of Shandong Xinhai and Jiangsu Delong that are known to be operating with imported nickel feedstock. (S&P Global 2021b)

Overall, the Chinese and Indonesian/Philippines nickel mines production is rather opaque topic and reliable figures are hard to acquire.

When further examining the size of producing mines by dividing these 111 mines (of which some have been recently in care & maintenance) into size classes with roughly equal production shares (% of global total production) it is found that top four classes contribute 83% of the total with approximately equal shares by each class, ranging from 18 to 26% (Table 4). If the fifth class is counted, the production share exceeds 96%. These five classes include 58 mines in total. Hence the rest 53 mines are fairly small or currently non-producing. As described earlier, the production in Indonesia and Philippines is hard to quantify and therefore this mine size assessment is incomplete for that part. Likely many of the mines in these countries are quite large and would be classified in the top four categories.

Of the Finnish mines, Terrafame Sotkamo and Boliden Kevitsa can be classified as medium size producers and both belong to the group of 58 biggest mines globally (Table 5). Even though the Finnish mines are not currently among the biggest global producers, their significance cannot be underestimated. All mines belonging to top five categories are extremely important for the current nickel supply and especially when considering the growing global demand for nickel.

Country specific size breakdown reveals that top three class mines are distributed in 12 countries (altogether 20 mines). Terrafame Sotkamo mine is closing in on this group and with full planned production would easily be included in this majors category. All the other nickel producing countries do have similar size or smaller mines in operation than Finland. Relative significance of the Finnish mines (and deposits) is highlighted by the fact that they are sulphide ores providing easier and more environmentally friendly processing, especially for battery applications, as discussed earlier.

Table 3. Top ranking nickel mines in 2018 and 2019 (S&P Global 2021b). Mines highlighted grey, also are among top cobalt producers globally, see table 7.

Rank	Mine	Country	Current Controlling Company(s) Note	Production (tonnes) 2019	Production (tonnes) 2018	Global Production Share–(%) 2019	Cumulative Global Production (%) 2019
1	Kola Division[2]	Russia	PJSC MMC Norilsk Nickel	166 265	158 000	6.4	6.4
3	Shandong Xinhai	China	Shandong Xinhai Technology Co Operates based on imported laterite ores	155 743	NA	6.0	12.4
2	Sudbury Operations[2]	Canada	Glencore Plc	92 700	91 400	3.6	16.0
4	Polar Division[2]	Russia	PJSC MMC Norilsk Nickel	^{e}92 265	NA	3.6	19.5
5	Jiangsu Delong	China	Jiangsu Delong Nickel Industry Operates based on imported laterite ores	77 241	NA	3.0	22.5
6	Jinchuan[2]	China	Jinchuan Group Co. Ltd.	^{e}75 557	NA	2.9	25.4
7	Sorowako[1]	Indonesia	PT Vale Indonesia Tbk.	71 025	74 800	2.7	28.2
8	Nickel West[2]	Australia	BHP Group	^{e}66 000	90 600	2.5	30.7
9	SLN	New Caledonia	ERAMET S.A., Société Territoriale, Nippon Steel Nisshin Co.	54 300	NA	2.1	32.8
10	Ontario Division[2]	Canada	Vale S.A.	50 800	50 600	2.0	34.8
11	Murrin Murrin[1]	Australia	Glencore Plc	40 700	39 700	1.6	36.3
12	Cerro Matoso[1]	Colombia	South32 Ltd.	^{e}40 600	43 800	1.6	37.9
12	Raglan[2]	Canada	Glencore Plc	^{e}39 835	NA	1.5	39.4
14	Voisey's Bay[2]	Canada	Vale S.A.	35 400	38 600	1.4	40.8
15	Barro Alto[1]	Brazil	Anglo American Plc	33 900	33 500	1.3	42.1
16	Ambatovy[1]	Madagascar	Sumitomo Corp., Korea Resources Corp., Private Interest, POSCO, STX	33 733	33 200	1.3	43.4
17	Moa Bay[1]	Cuba	Sherritt International Corp., General Nickel Co SA	33 108	30 700	1.3	44.7
22	Terrafame[2]	Finland	Terrafame Oy	27 468	27 377	1.1	45.8
52	Kevitsa[2]	Finland	Boliden AB	9 021	13 948	0.3	46.1
83	Kylylahti[2]	Finland	Boliden AB	731	518	0.03	46.1

Deposit types: [1] Laterite Ni-Co and [2]polymetallic sulphide deposit.

Table 4. Segmenting of world nickel mines by production 2019. Cumulative shares are calculated from total figures of individual mines that is lower than total production globally, see explanation in text. Data source S&P Global 2021b.

Nickel production (t)	Number of mines	Production share %	Finnish mines, in production & planned	Notes
90 000+	4	25.9		
< 90 000	6	20.1		
< 50 000	10	18.0		50% of the producing mines are placed on these segments contributing over 50% of global production
< 30 000	16	19.4	Terrafame Sotkamo	
< 20 000	22	12.8	Kevitsa	
< 5 000	17	3.1		
< 2 000	20	0.7	Kylylahti	
0	16			
Total	**111**			

Table 5. World nickel production by countries 2019 and size of individual mines (S&P Global 2021b). OECD countries shown as bold. Note that several Chinese producers actually rely on imported raw materials (mainly from Indonesia and Philippines), see further explanation in text.

Country	Production	No. of mines	No prod.	Prod. < 2 kt	Prod. 2–5 kt	Prod. 5–20 kt	Prod. 20–30 kt	Prod. 30–50 kt	Prod. 50–90 kt	Prod. > 90 kt
			Minors			Medium		Majors		Giants
China	559 833	34	6	3	8	9	5		2	1
Russia	258 530	2								2
Canada	**231 535**	**7**		**2**		**1**		**2**	**1**	**1**
Australia	**188 808**	**10**	**4**	**1**			**2**	**2**	**1**	
New Caledonia	101 400	4	1				2		1	
Indonesia	99 846	3			1		1		1	
Philippines	76 000	3					2	1		
Brazil	60 200	4				3		1		
Cuba	52 800	2				1		1		
South Africa	51 714	20	2	11	4	3				
Guatemala	41 000	2				1	1			
Colombia	**40 600**	**1**						**1**		
Finland	**37 220**	**3**		**1**		**1**	**1**			
Madagascar	33 733	1						1		
Papua New Guinea	32 722	1						1		
Dominican republic	22 313	1					1			
Myanmar	22 200	1					1			
Zimbabwe	17 621	4			3	1				
USA	**14 273**	**2**		**1**		**1**				
Greece	**13 700**	**1**				**1**				
Zambia	2 250	1			1					
Norway	**240**	**1**		**1**						
other countries	0	3	3							
Total	**1 958 538**	**111**	**15**	**20**	**17**	**22**	**16**	**10**	**6**	**4**

Table 6 outlines the planned nickel mines globally according to S&P Global database, counting the active projects since 2018. There are number of other projects also in the database but the projects having been inactive since 2018 are not considered being progressing for the moment. In addition, there likely are several development projects operated by the Chinese project owners in Southeast Asia (Indonesia/Philippines), these are typically not, for the most part, disclosed in public. The database does not include any active projects for these countries since 2018 which is not true in reality. Instead the biggest nickel mine developments in the world are actively on-going on the region.

In addition to the S&P Global listed projects, three Finnish mine projects are included in the table. Of these Sakatti is considered as a major project globally as being one of only 23 projects with potential to produce over 10 000 tpa nickel. Sakatti being a sulphide deposit emphasizes the potential of the project. Further details on these Finnish projects is presented in chapters 3.3.

Using afore mentioned criteria, the database lists altogether 39 projects of which nine have not disclosed their production targets. Cumulative production for the listed products totals nearly 460 000 tpa nickel. This figure is far from estimated 1 Mtpa new supply required as estimated by Roskill (Fraser et al. 2021). However, this figure completely lacks on-going developments in Indonesia and Philippines which likely are the biggest contributors to the future new supply.

It is noteworthy that the biggest single project aims for 45 000 tpa production, altogether only 6 projects being in the major category according to the classification used in this study. The 16 projects in the next two smaller categories count for over 50% of the planned new production. Anglo American Sakatti project is included in this category. Most of the projects included in the list are far from becoming operational, mainly preliminary technical-economical studies are being undertaken, likely delaying their ramp-up to the 2030s.

Only some 10 projects have advanced into or beyond feasibility study phase. It can be estimated that at best within next five years or by the 2030 the latest these mines could potentially supply up to 160 000 tpa nickel assuming all the projects would

Table 6. Segmenting of world planned new nickel mines by envisaged production (S&P Global 2021b). In addition to S&P Global database the table lists the planned new Finnish mines (in italics) and current mines with their possible envisaged maximum production. See further details for the Finnish projects in chapters 3.3.

Nickel production (t)	Number of mines under development	Combined total planned production	Countries	Finnish mines planned production[1]	Notes
90 000+					
< 90 000					
< 50 000	6	190 000	Canada (3) Australia, Zambia	Terrafame Sotkamo[2]	
< 30 000	4	100 000	Brazil (2) Russia Australia		These 16 project count over 50% of the planned production
< 20 000	13	150 000	Russia (4) Australia (6) USA, Vietnam, Finland	*Sakatti* Kevitsa[2]	
< 5 000	3	15 000	Australia, USA, Cote d'Ivoire		
< 2 000	4	4 000	Finland (2) Australia, Brazil	*Hautalampi, Suhanko,* Elementis talc-mines[2]	
0	9		Australia (5) Canada (2) USA, South Africa		Planned nickel production not released
Total	**39**	**459 000**			

[1] Future planned maximum production considering potential or ongoing expansions. [2] Not counting to the number of mines under development or combined planned production.

become operational. Nornickel aims to substantially expand their Russian operations in Norilsk area with several new mines in Talnakh, South Cluster and Skalisty areas. Many of these investments are already being implemented so Nornickel production increase is estimated to be on reliable basis compared with many other companies and their respective plans. On the basis of this assessment it is evident that to meet the growing global demand, the new supply is definitely needed but big part of it is likely coming from Southeast Asia. Any details on that front are hard to estimate. Supply security is a big issue also as it is mostly the Chinese companies who are doing the development in that region.

Individual mines producing cobalt

According to S&P Global cobalt production statistics (S&P Global 2021c) the 10 biggest mines produce nearly 65% of global total output (Table 7). Considering the top 15 mines the total output is nearly 74% of world total. Adding the three Finnish cobalt producing mines, these mines cover 75% of world total production. Overall, there were 47 mines in 18 countries with registered cobalt production in 2019. Of these only 17 belong to OECD countries (Canada, Australia, Finland, USA and Mexico). Only two of these mines are included in the top producing category.

Further 13 mines did not register cobalt production during the year. Number of producing mines is therefore quite limited. Finnish mines Terrafame Sotkamo and Boliden Kevitsa & Kylylahti take positions 25, 36 and 37 respectively. S&P Global presents clearly higher cobalt production tonnage for Terrafame than national production statistics indicate (Tukes 2021). For example, comparing with global copper production the production distribution is the following:

To reach 62% cumulative production 55 mines are needed and 93 mines to reach 75% production level. In 2019 there were 455 mines in production and further 53 not registering copper production during the year. Also in comparison with nickel, cobalt production seems to be very centralized. Both considering few countries and individual mines producing significant share of global tonnage. Further considering Chinese strong grip on cobalt production chains, the supply risk is to be taken seriously.

When further examining the size of producing mines by dividing these 60 mines into size classes based on produced tonnage, the extreme concentration of the primary production is revealed (Table 8). Top two classes make up over 60% of global production, including only 7 mines of which three are giant scale in comparison to the others. All of these biggest mines are located in DRC. The next three classes contain 30 mines with much more widespread geography, 13 countries having at least one mine in these categories and DRC having only 3 mines out of the total (Table 9). Together these mines produce substantial cobalt tonnage, nearly 40% of the world total. DRC mines produce some 10% of the total for these categories so the share for the rest of the world is very important. Remaining 20+ mines in three smallest classes produce mere 1.5% of world total. Considering obscure production statistics (and strong ASM sector) for DRC and further the largely Chinese controlled production chains in the country, the importance of the country for cobalt supply cannot be underestimated.

Of the Finnish mines, Terrafame Sotkamo can be classified as major producer and Boliden Kevitsa and Kylylahti as medium size producers. From battery raw material sourcing perspective, the relative importance of Finnish mines is highlighted by the fact that the deposits are sulphide ores with parallel nickel production and many benefits e.g. for processing.

Crude cobalt hydroxide

In 2020 ca. 124 280 t of Crude Co hydroxide was produced. This is forecasted to grow into 195 000 tpa by 2026. Globally there are some 15 major producers of crude Co hydroxide. Glencore is by far the biggest one of these, having over 30% market share in 2019. Last year (2020) Glencore market share was smaller due to temporary shutdown of Katanga mine and production. China Molybdenum is the second biggest producer having ca. 11% market share. Dubai headquartered Shalina Resources is third biggest producers having been steadily increasing its production during the past decade. Shalina market share was 5% in 2019 and ca. 6.5% in 2020. Chinese Jinchuan Group held 4.5% market share in 2019 and ca. 6.5% in 2020. All these companies source their cobalt mainly or only from DRC. Basically, only Glencore has other significant sourcing countries (Canada, Australia).

All other companies have market share less than 5% (ie <6 200 tpa Co hydroxide), these being, in the order of size, Sherritt International (Canada, Cuba, Madagascar), Vale (Indonesia, Brazil and Canada) and Nornickel (Russia), country of cobalt raw material shown in brackets. Also Trafigura (New Caledonia), Nickel 28 (PNG, Canada, Australia) and Managem (Morocco) source and produce cobalt elsewhere than DRC but all the remaining producers (Huaoy Cobalt, Eurasian Resources Group, Nanjing Hanrui, Wanbao Mining, Guangdong Jiana and Chengtun Mining) basically operate with DRC cobalt. These 15 companies produce nearly 80% of world total crude cobalt hydroxide, the remaining 20% produced by number of smaller companies. Nornickel Harjavalta in Finland is the most important crude cobalt hydroxide producer in Europe. This interim product is further refined into final cobalt products. (QY Research 2021)

Table 7. Top ranking cobalt mines in 2018 and 2019 (S&P Global 2021c). Mines highlighted grey, also are among top nickel producers globally, see table 3. S&P Global presents clearly higher cobalt production tonnage for Terrafame than national production statistics indicate (Tukes 2021).

Rank	**Mine**	**Country**	**Current Controlling Company(s) Note**	**Production – Cobalt (tonnes) 2019**	**Production – Cobalt (tonnes) 2018**	**Global Production Share – Cobalt (%) 2019**	**Cumulative Global Production Cobalt (%) 2019**
1	Mutanda[1]	DRC	Glencore Plc	25 100	27 300	16.9	16.9
3	Kamoto[1]	DRC	Katanga Mining Ltd., Gécamines SA	17 054	11 112	11.1	28.3
2	Tenke Fungurume[1]	DRC	China Molybdenum Co. Ltd., Gécamines SA	16 098	18 747	10.8	39.1
4	Mutoshi[1]	DRC	Chemaf-Trafigura (Responsible ASM)	^{e}8 000	-	5.4	44.5
5	Etoile[1]	DRC	Shalina Resources Ltd	^{e}7 000	e7 000	4.7	49.1
6	Metalkol RTR[1]	DRC	Eurasian Group LLP (Tailings re-treatment)	^{e}6 000	-	4.0	53.2
7	Ruashi[1]	DRC	Jinchuan Grp Intl Rsrc Co. Ltd, Gécamines SA	5 070	4 752	3.4	56.6
8	Sudbury Operations[3]	Canada	Glencore Plc	4 400	4 200	3.0	59.6
9	Murrin Murrin[2]	Australia	Glencore Plc	3 700	3 200	2.5	62.0
10	Moa Bay[2]	Cuba	Sherritt International Corp., General Nickel Co SA	3 376	3 234	2.3	64.3
11	Taganito[2]	Philippines	Nickel Asia Corp., Pacific Metals Co., Sojitz Corp.	3 100	NA	2.1	66.4
12	Ramu[2]	Papua New Guinea	Metallurgical Corp. of CN Ltd.	2 911	3 275	2.0	68.3
12	Ambatovy[2]	Madagascar	Sumitomo Corp., Korea Resources Corp., Private Interest, POSCO, STX	2 900	2 852	1.9	70.3
14	Lubumbashi slag hill[1]	DRC	Groupe Forrest Intl S.A., Gécamines SA (Tailings re-treatment)	^{e}2 500	NA	1.7	72.0
15	Polar Division[3]	Russia	PJSC MMC Norilsk Nickel	2 433	^{e}3 520	1.6	73.6
25	Terrafame[3]	Finland	Terrafame Oy	1 203	-	0.8	74.4
36	Kevitsa[3]	Finland	Boliden AB	445	591	0.3	74.7
37	Kylylahti[3]	Finland	Boliden AB	425	278	0.3	75.0

Deposit types: [1] stratiform sediment hosted Cu-Co, [2] Laterite Ni-Co and [3] polymetallic sulphide deposit.

With iron ore, the corresponding figures are: 38 mines for 62% production and 67 mines for 75%. In total 438 mines registered production during the year.

Hence copper and iron ore production is much more less centralized and takes place on much wider geographical area and mining jurisdictions. This significantly decreases the potential supply risks for these commodities.

Table 8. Segmenting of world cobalt mines by production 2019. Cumulative shares are calculated from total figures of individual mines that is lower than total production globally, see explanation in text. Data source S&P Global 2021c.

Cobalt production (t)	Number of mines	Production share %	Finnish mines, in production & planned	Notes
15 000–25 100	3	43.0		All in DRC
< 15 000	4	19.2		All in DRC
< 5 000	9	20.5		60+% of the producing mines are placed on these segments contributing over 36% of global production
< 2 000	10	11.0	Terrafame Sotkamo	
< 1 000	11	4.9	Kevitsa, Kylylahti	
< 400	7	1.3		
< 100	3	0.2		
0	13			
Total	**60**			

Table 9. World cobalt production by countries 2019 and size of individual mines (S&P Global). OECD countries shown as bold. Data source S&P Global 2021c.

Country	Production	No. of mines	No prod.	Prod. < 99 t	Prod. 100–399 t	Prod. 400–999 t	Prod. 1 000–1 999 t	Prod. 2 000–4 999 t	Prod. 5 000–14 999 t	Prod. 15 000–25 100 t
			Minors		**Medium**		**Majors**		**Giants**	
DRC	89 142	12	2			1	1	1	4	3
Canada	7 368	7	1	1	1	2	1	1[1]		
Australia	6 203	9	3		3	1	1	1		
Philippines	4 600	3	1				1	1		
Cuba	4 028	2				1		1		
Russia	3 686	2					1[2]	1[2]		
Zambia	3 026	4	2				2			
Papua New Guinea	2 911	1						1		
Madagascar	2 900	1						1		
Morocco	2 397	1						1[3]		
Finland	2 073	3				2	1			
New Caledonia	2 003	2			1		1			
China	2002	3		2			1			
Indonesia	911	1				1				
South Africa	737	2	1			1				
USA	607	2	1			1				
Mexico	503	1				1				
Zimbabwe	468	3		1	2					
other countries	0	2	2							
Total	**135 565**	**61**	**13**	**4**	**7**	**11**	**10**	**9**	**4**	**3**

[1] Glencore Sudbury operations is the biggest Co producer in Canada. It consists of two separate mines.

[2] Nornickel operations consist of several separate mines within the same geological complex.

[3] Morocco Bou Azzer complex consists of several separate mines (4–5) in production.

Table 10. Segmenting of world planned new cobalt mines by envisaged production. (S&P Global 2021c). In addition to S&P Global database the table lists the planned new Finnish mines (in italics) and current mines with their possible envisaged maximum production. See further details for the Finnish projects in chapters 3.3.

Cobalt production (t)	**Number of mines under development**	**Combined total planned production**	**Countries**	**Finnish mines planned production[1]**	**Notes**
15 000–25 100	0	-			
< 15 000	2	10 000+	Canada (5 000+), Indonesia (5 000+)		The Canadian company, First Cobalt initially relying on third party feed (DRC) for the refinery
< 5 000	5	15 700	Australia (4), Chile		Nearly 25 000 t or over 70% of planned production
< 2 000	5	7 700	Canada (2), USA, Brazil, DRC	Terrafame Sotkamo[2]	
< 1 000	3	1 800	Australia (2) Finland	*Sakatti, Kevitsa*[2]	
< 400	5	1 000	Finland (4) USA	*Hautalampi* *Hannukainen* *Kuusamo* *Suhanko*	
< 100	2	150	Brazil, Finland	*Rajapalot* Elementis talc-mines[2]	
0	11		Australia (6), Canada (3), Zambia, USA		Planned cobalt production not released
Total	**33**	**36 000+**			

[1] Future planned maximum production considering potential or ongoing expansions. [2] Not counting to the number of mines under development or combined planned production.

Table 10 lists the most advanced projects planning to produce cobalt in significant quantities. The list is based on S&P Global database, counting the active projects since 2018. There are number of other projects also in the database but the projects having been inactive since 2018 are not considered being progressing for the moment. In addition, there likely are several development projects with Chinese project owners in Southeast Asia and/or DRC, these are typically not much disclosed in public. Of these only one is listed in the table.

In addition to the S&P Global listed projects, several Finnish mine projects are included in the table. The new Finnish projects make up almost 20% of the listed projects. When comparing planned production tonnages, the share is much smaller though, less than 4% of the total. Further details on these Finnish projects is presented in chapters 3.3 and 3.4.

Of the top-7 projects listed in the table above, only one is at the moment progressing into production (plant construction in process), Chinese QMB New Energy Joint Venture in Indonesia. The company lists the following production targets for the near future: the initial goal is to achieve a production capacity not less than 50 000 tons of nickel through metal wet-process smelting, 4 000 tons of cobalt through metal wet-process smelting, 50 000 tons of nickel hydroxide intermediate, 150 000 tons of battery-grade nickel sulfate crystal, 20 000 tons of battery-grade cobaltous sulfate crystals and 30 000 tons of battery grade manganese sulfate crystals.

By 2025 also First Cobalt Canada refinery may be in production but initially relying on imported feedstocks (DRC). Of the other five top projects Chilean Capstone Mining Santo Domingo and Australian Cleanteq Sunrise are planning to advance into production phase but these plans are not confirmed for the moment being. Most of the other projects listed are also in the development phase with no confirmation on actual production. It is notable that the list contains only one project from DRC and Zambia. Most likely, potential new supply can be developed in these two countries either in the form of new mines, expansion of the current ones or reprocessing of the old mine feedstocks. Also Australia and Canada will contribute significantly to the potential new supply.

The same conclusion is stated by the JRC study 2018 (Alves Dias et al. 2018), estimating that 60% of the global cobalt supply in 2026 comes from current operations or their expansions. For some reason the capacity development in Indonesia is largely neglected in the study. On the other hand, the Finnish cobalt production in the late 2010s and the scenario up to 2030 is overly optimistic. The study likely counts the Boliden Kylylahti cobalt-nickel concentrate stockpiling as primary production that is not true strictly considering. Naturally, this stockpiled feedstock can be utilized for cobalt and nickel production in the future.

The study lists 37 projects in preproduction or feasibility phases with potential cobalt supply up to 61 000 tpa and further 92 projects (pre-feasibility and reserves development) with potential supply over 40 000 tpa. Estimated breakdown of cobalt mine capacities in 2030 is presented in Figure 10. These should however be considered as rather immature projects that may easily require at least a decade or in many cases 10–20 years to proceed into production (if ever).

It is rather obvious that considering the global mine development timeframes, the expected cobalt supply deficit by 2030 is not easily filled with the planned new mines or existing mines expansions. Considering only pure resources, the tonnage most likely is available but converting resources into reserves and commercially viable operations is dependent on many factors, not least the metal prices. Most likely, effective reserve converting and especially increasing production requires positive development of metal prices, which is totally opposite direction that most OEMs/Manufacturers and downstream refiners are relying on their future scenarios to be able to provide more affordable EVs to the mass market.

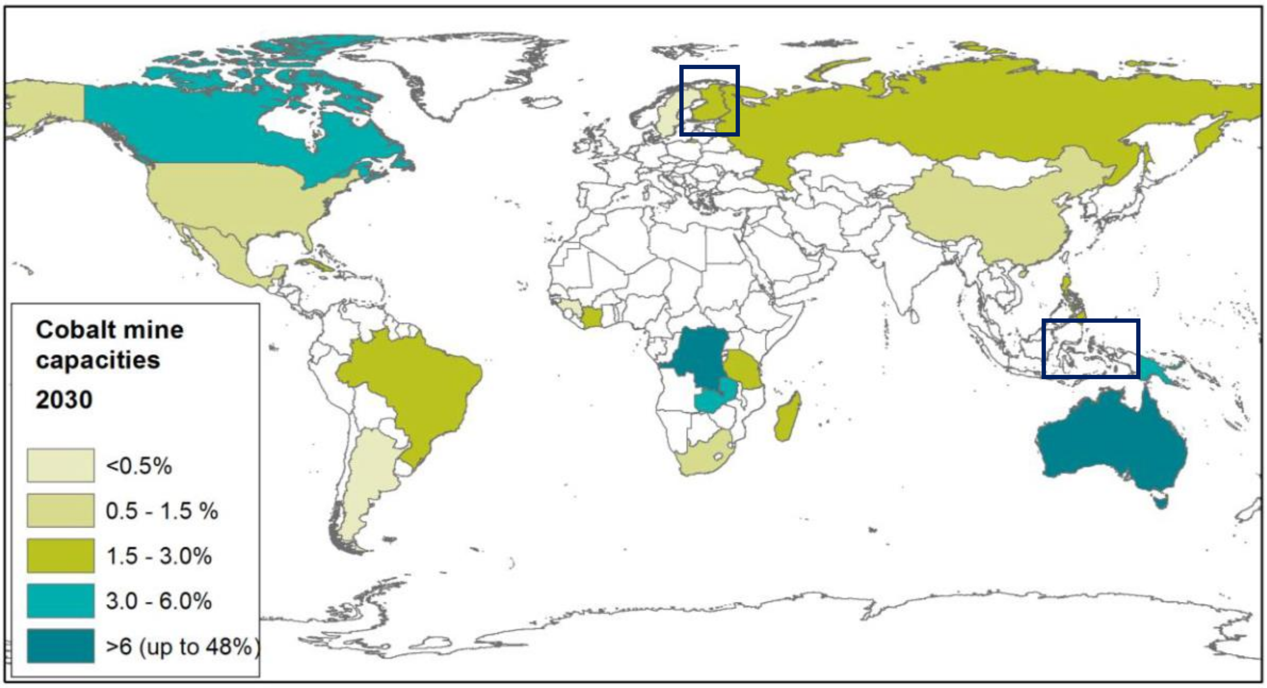


Fig. 10. Estimate and distribution of mine supply in 2030 according to scenario 1 of JRC supply/demand study. In this scenario mine supply is prognosed to produce nearly 193 kt cobalt in 2030. The study largely neglects Indonesian production and overestimates the Finnish production shown with cobalt blue squares (modified after Alves Dias et al. 2018).

1.4 Finnish mine production and reserves

Finnish mine production in 2018–2020 is presented in table 11. Unlike earlier, all this cobalt enters further refining, and therefore the production numbers from the earlier years are not directly comparable to these. Back in 2017 Boliden Kylylahti mine did not produce saleable nickel-cobalt concentrate but the material was instead stored at the site tailings storage facility. This stockpile together with the high sulphur tailings may form a significant future reserve for nickel and cobalt recovery assuming a feasible process can be innovated for the purpose. Active development for the utilization of these streams is currently on-going.

In Finland, cobalt is produced as a by-product from three mines: Kevitsa (Boliden), Kylylahti (Boliden) and Sotkamo (Terrafame). Here, mine production of cobalt is closely connected with nickel mining, because both cobalt and nickel occur in the same ore mineral(s). The Kevitsa sulphide deposit is hosted by mafic to ultramafic rocks, and Talvivaara deposit (Sotkamo mine) is hosted by black schists. Kylylahti mine represents Outokumpu type ore, in which the main products are typically copper and zinc. More detailed geological and mineralogical information is presented in a separate GTK report (Törmänen & Tuomela 2021).

Terrafame does not publish the figures for mine production of cobalt in the **Sotkamo mine**, however, national Mining authority production statistics indicate that the annual production has been within the range of 500 to 600 t Co during recent years (Tukes 2021). Nickel production has exceeded 27 000 tpa. At the moment the company produces nickel-cobalt sulphide, zinc sulphide and copper sulphide. The final products are currently sold for refining abroad.

Terrafame is about to become an industrial giant of global scale in the manufacture of battery chemicals. In 2018 Terrafame decided to construct a **battery chemicals plant**, one of the largest in the world, at the mine site. According to plans, production of battery chemicals in the plant will start in spring 2021. The current main product, nickel-cobalt sulphide, will be used as a raw material to produce nickel sulphate and cobalt sulphate. Ammonium sulphate will be produced as a by-product of nickel and cobalt sulphate production in the battery chemicals plant. Production of zinc sulphide will continue as currently. This unique integrated production process from open pit to battery chemicals expands Terrafame's coverage a step forward in the downstream value chain. The production chain is short, 'traceable' (in the sense that the exact origin is known), responsible and transparent. The target for year 2024 is to annually produce 170 000 t of nickel sulphate and 7 400 t of cobalt sulphate. These are sufficient for about one million and 300 000 electric cars, respectively. (Terrafame 2021)

Terrafame has the largest nickel ore reserves in the Europe, and due to its huge size, the utilization of the deposit may still continue for several decades (Terrafame 2020b). However, the ore reserves have not been publicly disclosed unlike the resources. Terrafame's mineral resource and ore reserve estimates were updated in accordance with the JORC code (2012) in November 2020. Its measured, indicated and inferred mineral resources amount to 1 499 million tonnes, with a metal content of 3.9 million tonnes of nickel and 0.3 million tonnes of cobalt. The amount of nickel had increased by 19.4% from the previous estimate (2018). (Terrafame 2020a). Ongoing Kolmisoppi EIA states that unless Kolmisoppi deposit is taken into use, the life of mine cannot be extended beyond 2035 (Terrafame 2020b).

Kevitsa mine produced 9 000–14 000 tpa nickel and 450–600 tpa Co in 2018–2020 (Table 11) (Boliden 2021c). The main products of the mine are nickel concentrate and copper concentrate, which are supplied to Boliden's Harjavalta smelter in Finland and Boliden's Rönnskär smelter in Sweden (Boliden 2020a). Kevitsa nickel concentrate is transported to Harjavalta smelter to produce nickel matte. This intermediate product (nickel matte containing cobalt) is exported abroad for further refining. Based on the current ore reserves and production rates, the life of mine is expected to continue around 2034, obviously depending on the actual production. Reported mineral reserves are 128 Mt @ 0.21% sulphidic nickel, 0.01% sulphidic cobalt and 0.32% Cu (Boliden 2021d).

Kylylahti mine produced 500–990 tpa nickel and 280–450 tpa Co in 2018 and 2020 (Table 11) (Boliden 2021c). The production ended, at least temporarily, late 2020 due to mine closure. Four types of concentrates were produced in the at the Boliden Luikonlahti concentrator: 1) gravity gold concentrate, 2) copper concentrate and 3) zinc concentrate and 4) nickel-cobalt concentrate. (Boliden 2020b). The production of nickel-cobalt concentrate was not started until late 2017. In addition, ores processed to produce a zinc concentrate generate a sulphur concentrate containing also some cobalt and nickel that is stockpiled together with produced sulphur concentrate into so called CoNi -tailings facility. There is an ongoing project to find an economically feasible process to recover refractory cobalt and nickel from these tailings (Boliden 2020b). GTK roughly estimates that this stockpile contains over 10 000 t, Co in addition to substantial amounts of nickel but there are no official (CRIRSCO -compliant) public figures available.

Elementis talc mines produce minor amounts of nickel and cobalt. Talc reserves of these mines are substantial but not publicly disclosed. Still it seems probable that production on these sites can continue for several decades at current production rates.

The LOM estimates above are used in the Roadmap and Strategy work in the latter part of this study. Naturally the LOM of any given mine may vary in the future. For example, due to variation in the actual mining rates or successful conversion or resources into reserves or by the effect of metal prices. For some of the mines the LOM may be longer than expected and also shorter in some cases. These cannot be predicted accurately in advance.

Table 11. Mine production of cobalt in Finland in 2018 and 2019. Data is based on Mining authority (Tukes) production statistics and annual reports by the companies.

Mine	Company	2018 (t)	2019 (t)	2020 (t)	Ni-Co-containing product	Reserves (end of 2020) and Life of Mine (LOM)
Kevitsa	Boliden	Ni: 13 948 Co: 591	Ni: 9 021 Co: 445	Ni: 11 074 Co: 495	Ni-PGE-Co concentrate	128.2 Mt. LOM until 2034 depending on annual mining
Kylylahti	Boliden	Ni: 518 Co: 278	Ni: 731 Co: 425	Ni: 989 Co: 447	Ni-Co concentrate	Closed at the end of 2020
Sotkamo	Terrafame	Ni: 27 377 Co: ca. 5001	Ni: 27 468 Co: 500–600[1]	Ni: 28 740 Co: 500–600[1]	Ni-Co sulphide, starting from early 2021 it will be refined onsite to Ni sulphate and Co sulphate	Terrafame only reports mineral resources not reserves. Based on ongoing Kolmisoppi EIA, LOM extension beyond 2035 requires expansion of mining operations into Kolmisoppi area during the 2030s.
Talc mines	Elementis	Ni: 1 729 Co: ca. 20[1]	Ni: 1 310 Co: ca. 20[1]	Ni: 626 Co: ca. 10[1]	Ni-Co concentrate or MHP	LOM several decades[1]
Total		**Ni: 43 572 Co: 1 377**	**Ni: 38 530 Co: 1 454**	**Ni: 41 429 Co: 1 559**		

[1] Estimate

2 COBALT AND NICKEL VALUE CHAIN AND MATERIAL STREAMS IN FINLAND

2.1 Production breakdown for the current mines and refineries

This is an introduction to the current battery material ecosystem in Finland (Fig. 11) as well as associated value chains and material streams. Five (5) such streams have been identified as described hereafter. This chapter also presents an overview of the planned developments into the material streams, based on publicly disclosed information regarding each stream. Possible future scenarios associated with the planned new primary production and further downstream refining are discussed in chapter 4. These scenarios have been outlined based on 1) the currently existing or planned refining infrastructure and on the other hand 2) potential primary raw material sources under development in Finland. GTK has had discussions with the companies involved in this assessment to gain understanding and ideas of possible developments but all the conclusions and proposed scenarios are purely drafted by GTK and as such do not represent plans of any individual company.

Based on Tukes/GTK annual production statistics follow-up (Tukes 2021), the mine production of nickel has been strongly increasing in Finland since early 2010s, when the production was less than 20 000 tpa. Since 2018 the production has been close to 40 000 tpa or even more, the top production being 43 570 t in 2018. Majority of this figure comes from Terrafame Sotkamo mine. During the past few years, the cobalt production has varied from 1 380 tpa to 1 560 tpa, again the big majority produced by Terrafame Sotkamo.

Company specific figures have been estimated using the publicly announced figures for nickel and cobalt (Boliden) and nickel (Terrafame), then subtracting the known figures from the reported total amount. This way the nickel production breakdown for the last three years has been on average the following (Figs. rounded): Terrafame Sotkamo 27 900 tpa, Boliden Kevitsa 11 350 tpa, Elementis talc mines 1 200 tpa, Boliden Kylylahti 750 tpa, altogether 41 200 tpa.

Similarly, average cobalt production for the same period is estimated to be: Terrafame Sotkamo 550 tpa, Boliden Kevitsa 510 tpa, Boliden Kylylahti 380 tpa and Elementis talc mines 20 tpa, altogether 1 460 tpa. As mentioned earlier the Kylylahti mine has been closed, at least temporarily, by the end of 2020.

Similarly, according to Tukes/GTK annual production statistics (Tukes 2021), the annual nickel refinery production in Finland has ranged from 85 000 tpa to nearly 93 000 tpa during the recent years (2016–2020). The raw materials for the refineries have been partly sourced from Finland but mostly the production has taken place using imported raw materials. This is especially the case for Nornickel Harjavalta and Umicore/Freeport Kokkola.

Based on the company announcements Nornickel Harjavalta is the biggest nickel producer, exceeding 60 000+ tpa in recent years (Nornickel 2021a). Boliden Harjavalta produces 25 000–30 000+ tpa (Boliden 2021c). The smallest producer is Freeport/Umicore in Kokkola with production of 500–1 500 tpa maximum. Kokkola refinery has not publicly disclosed the production figures but this estimate is calculated based on overall figures less production announced by Nornickel and Boliden.

The same companies and refineries also produce cobalt, the production being 12 000–15 000 in recent years (since 2017). However, the breakdown is somewhat difficult to estimate as the companies have not in general published their cobalt production. It is generally known though that the biggest producer is with a great margin Umicore/Freeport Kokkola, that is responsible for the majority of Finnish total production. For the purposes of this study we assume the Kokkola production being 90% of the Finnish production on annual basis, hence on average 12 900 tpa. Nornickel cobalt production is likely ≤10% of Kokkola refinery production, on average ≤1 400 tpa. Matte contained cobalt in Boliden Harjavalta is likely 30% of Nornickel figures the most.

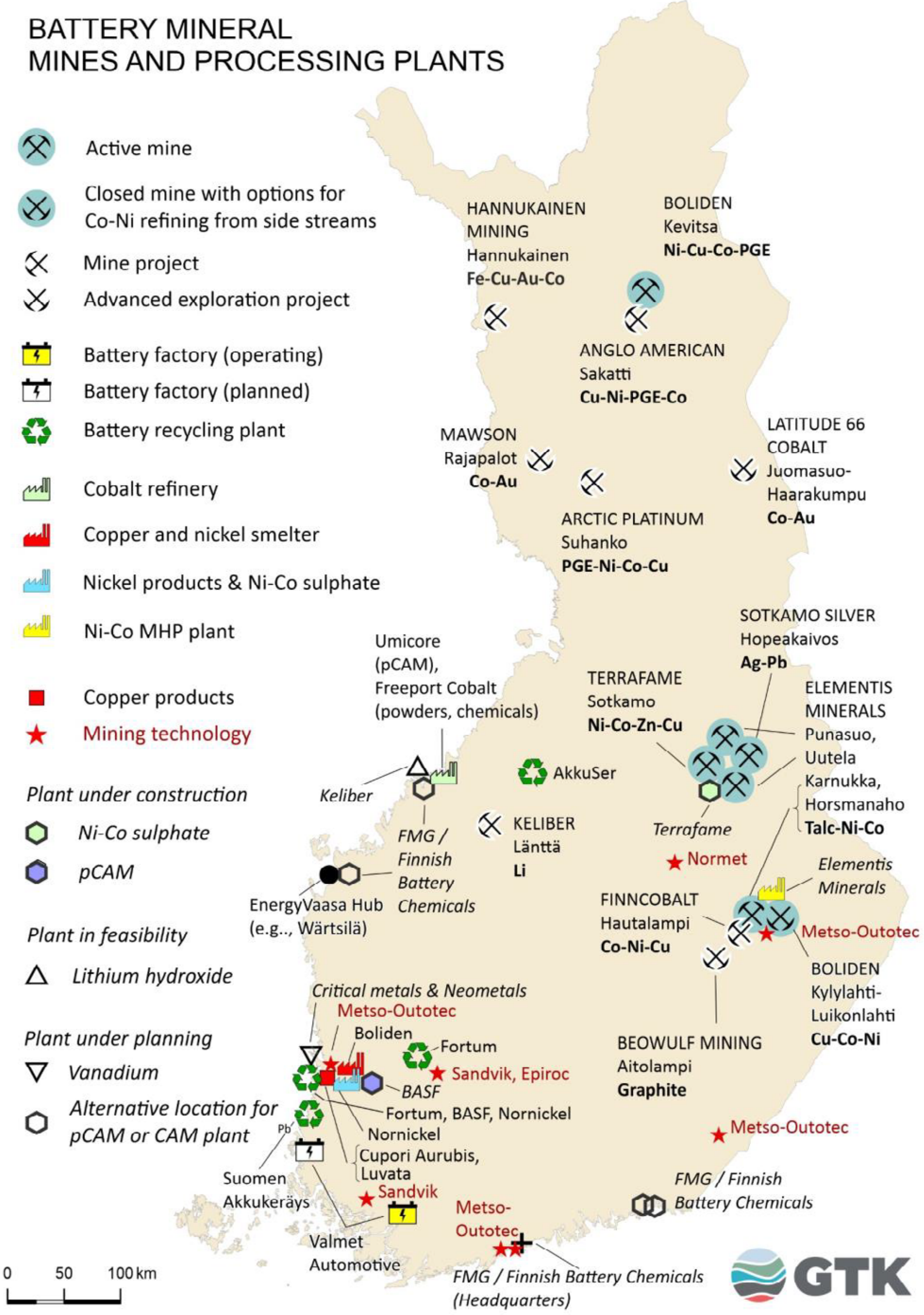


Fig. 11. Finnish battery mineral mines, battery material refineries and technology providers. Also planned future production facilities for battery value chain are presented in the map. Primary nickel-cobalt has recently been produced at Kevitsa, Sotkamo, Kylylahti and Elementis mines. These commodities have been refined further at Harjavalta (Boliden, Nornickel) and Kokkola (Umicore-Freeport), mostly based on imported raw materials. See text for further details.

2.2 Finnish Ni-Co refining streams

Figure 12 presents simplified refining streams for the Finnish nickel-cobalt refineries. The figure also shows the refineries and plants that are under construction or being planned, as well as the raw material sourcing and ultimate material flows where known. The following brief descriptions of each stream (chapters 2.2.1 to 2.2.5) are based on publicly available information on topic, e.g. environmental permits.

The figure tries to summarize each successive value chain step: mine-intermediate product-chemicals, pCAM (precursor cathode active material) and CAM (cathode active material) by feedstock and tonnage where possible. Further explanations and details for the planned production are presented in the subchapters for each stream.

The streams are presented in the order of nickel sulphate annual tonnage, since this chemical is the most important chemical needed for further value chain steps. This makes Terrafame Sotkamo-FMG to be stream 1, Nornickel-BASF Harjavalta stream 2, Umicore-Freeport Kokkola stream 3 and Boliden Harjavalta smelter stream 4 (Boliden mines plus external/imported concentrates). As the production figures in chapter 2.1 indicate, the amounts are partly estimated as detailed quantities are not reported by all the parties. Also, the interaction between the streams has been taken into account in the stream order. Currently all of the streams operate pretty much independently of each other although in the past there was a strong link for example with streams 4 and 2. Also other links have been in existence and can still be nowadays but to much smaller extent than historically.

Considering the future plans for each of the stream, there will most likely be some sort of link between streams 1 and 2, counting the recent press releases by FMG, Johnson Matthey and Nornickel (pCAM plant in Hamina/Kotka and CAM plant in Vaasa). These are described with more detail in the following chapters. Also stream 5 that consists of recycling of various feeds based on co-operation by Fortum, BASF and Nornickel is closely connected with stream 2.

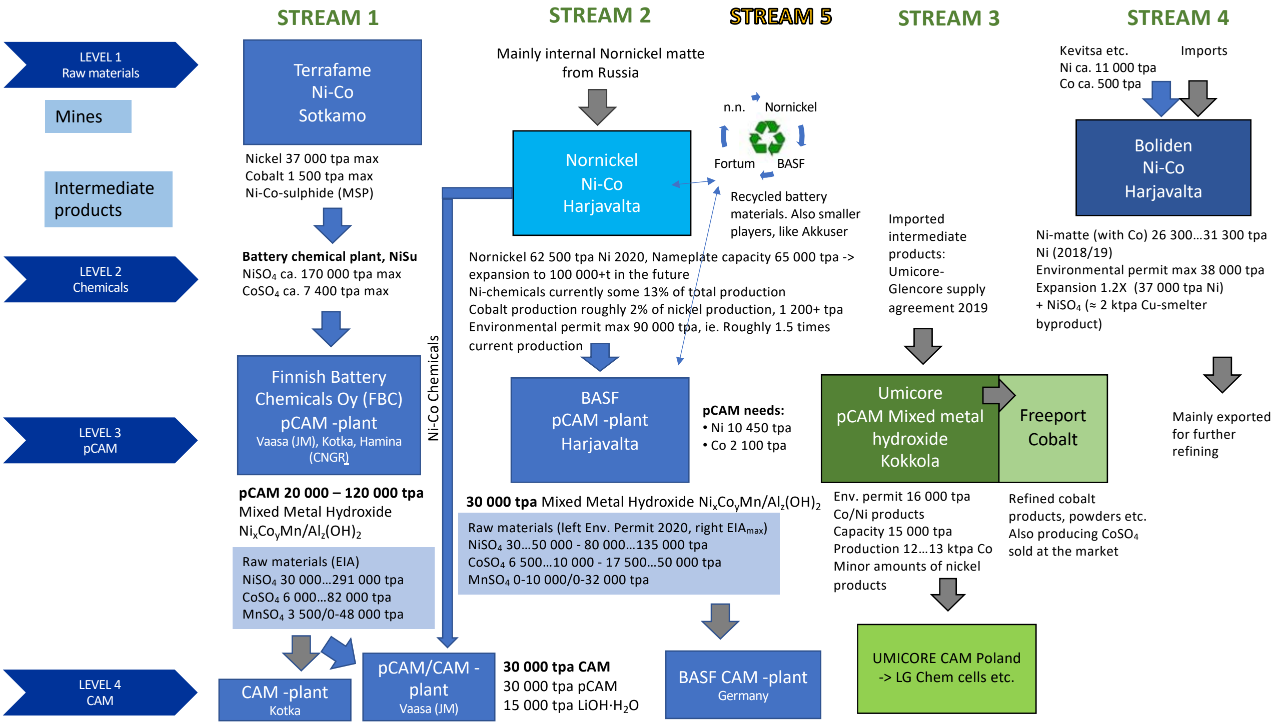


Fig. 12. Simplified presentation of the current main nickel and cobalt refining streams in Finland. There are five major mostly separate streams in place of which one is recycling based. Domestic material streams are marked with blue arrow and international ones with grey arrow. Note, that the figures presented for Kokkola cobalt refinery (Umicore-Freeport) represent the whole refinery complex.

2.2.1 Stream 1

Overview

This stream consists of Terrafame Sotkamo mine and the associated products of which most important considering the batteries are nickel and cobalt (planned production maximum 37 000 tpa and 1 500 tpa respectively). These will be fully processed in the nearby battery chemical plant that starts operations in spring 2021. Initially the products $NiSO_4$ (170 000 tpa max) and $CoSO_4$ (7 400 tpa max) will be sold on the market, possibly partly to the companies operating Finland. It is to be noted that during the history of Terrafame Sotkamo operations, the planned maximum production targets have not yet been accomplished. In case of nickel, the maximum output so far has been nearly 80% of the target. Similarly, for cobalt, the maximum output has been some 40% although detailed cobalt production figures have not been published. This study assumes that presented maximum production rates will be eventually achieved.

Eventually however, these chemicals will be at least partly utilized in pCAM production that subsidiary of FMG, i.e. Finnish Battery Chemicals (FBC) is planning at several locations in Finland, the most advanced plan being with recently announced joint venture partner CNGR Advanced Materials at Hamina/Kotka. Produced precursor material could possibly be upgraded into CAM material using lithium hydroxide produced by Keliber. So far however, there has not been further information on the planned Kotka CAM plant. (FMG 2021a)

Second path in FMG's plans is to invest in the planned CAM plant in Vaasa, together with Johnson Matthey (JM). FMG would be responsible for the development of selected auxiliary processes required in the production of battery materials. The contribution into the auxiliary processes is twofold: firstly, to develop and deploy novel technological solutions to treat sodium sulphate-rich effluent at industrial scale, and secondly to implement production of selected metallic raw materials. The work also includes auxiliary process integration to the main process of battery materials production. The public press releases have not been very detailed with the process descriptions. Raw materials for the Vaasa CAM plants have been instructed to be sourced from Nornickel (Harjavalta, nickel and cobalt) and Chilean SQL (lithium). However, Nornickel does not produce pCAM currently and has not published having such plans for the future. This means that pCAM production necessarily takes place in Vaasa to feed the CAM plant (FMG 2021b, Johnson Matthey 2021).

If these plans will become actual, this stream would be clearly the most extensive in Finland, to a large extent relying on domestic mining and raw materials, extending to the production of cathode active materials. No other company (or joint venture) currently produces or plans to produce CAM in Finland.

South Coast pCAM/CAM

FMG subsidiary FBC is planning pCAM/CAM plants in a couple of locations. One option is south coast (Hamina/Kotka) and the second one west coast (Kokkola/Vaasa). Hereafter these projects are referred as South coast project and West coast project. The plants are to be constructed together with external investor(s). It may even be possible that there would be plants in both of the proposed locations, depending the pCAM/CAM demand and associated investor interest and available funding. As described above, the investment parties for both of the locations have been recently disclosed but there still are not final or complete plans for either of the locations about the technical project implementation. The current status for both of the subprojects is briefly described in the following sections.

South coast project is for the moment being bit more advanced. Joint venture partner CNGR Advanced Materials, regarding the planned pCAM plan, was disclosed at the end of February 2021. The project EIA has been completed although the authority approval has not yet been received. Meanwhile project technical engineering and feasibility study are ongoing by both joint venture parties. The study should be completed by Q3/2021 and subject to following investment decision, the plant construction could be started in 2022. The partner for the planned CAM project has not been released but FBC is actively developing the project on that front as well. In principle the pCAM and CAM projects can be thought as separate projects although they may be operated on an integrated manner. (FMG 2021b, FBC 2021)

Signed letters of intent with the cities of Kotka and Hamina are available for industrial areas, enabling construction of the plants in case of positive investment decision. Project permitting is on-going but likely the process takes at least a year after application submission that could happen during the latter part of 2021. Appealing process is more than likely adding at least another year before valid permit is available. Hence the start-up of the pCAM plant could happen in 2024 at the earliest.

Public EIA document is rather generic on plant specifications. The production capacity alternatives for pCAM/CAM plants range from 20 000 tpa to 120 000 tpa. Presented raw material requirements also range widely, being in minimum: $NiSO_4$ 30 000 tpa, $CoSO_4$ 6 000 tpa and $MnSO_4$ 3 500 tpa. Respective metal tonnages are roughly 6 500 tpa Ni, 1 000 tpa Co and 1 000 tpa Mn.

In case of maximum scenario the following raw material feeds are required: $NiSO_4$ 291 000 tpa, $CoSO_4$ 81 000 tpa and $MnSO_4$ 48 000 tpa. Respective metal tonnages are roughly 66 000 tpa Ni, 18 000 tpa Co and 18 000 tpa Mn.

Proposed raw material mix range enables production on various pCAM/CAM types, but likely the plan is to produce NMC811 type of chemistries based on raw material quantities. Specific recipe has not been disclosed.

The current Terrafame Sotkamo nickel production (and future $NiSO_4$ production) would enable 60 000+ tpa pCAM/CAM production, depending on the chemistry. But for the highest production options external sourcing would be definitely necessary unless a significant mine expansion would take place.

Depending on the plant capacity cobalt sourcing may be problematic if proceeding solely of Terrafame internal raw materials. Sotkamo cobalt production will be adequate for the smallest capacity scenario. But at 60 000 tpa production Terrafame cobalt production only covers 40–50% on feedstock demand if producing NMC811 type of material. With ≤ 50 000 tpa pCAM production the announced Sotkamo $CoSO_4$ production capacity would be much closer to required supply for pCAM production although low cobalt pCAM chemistries possibly enable higher tonnages. Manganese feedstock source has not been disclosed so far but could be external and likely will be initially at least. However, Sotkamo ore contains plenty of manganese that could possibly be refined for this purpose. The question is the economical feasibility. Domestic sourcing of manganese is therefore subject for further studies.

Considering the BASF pCAM example (see section on Nornickel and BASF) and associated permitting challenges, it can be estimated that most likely initial production capacity will be something between 20 000–60 000 tpa pCAM with option for expansion later on. Plant having capacity of 30 000 tpa pCAM would be a good tradeoff, also considering the Terrafame Sotkamo feedstock volumes as well as planned Keliber lithium hydroxide production.

Keliber Oy, which is part of FMG portfolio, plans to produce initially 12 500 tpa lithium hydroxide, possibly increasing the production into level of 15 000 tpa later on. The latter figure is used in this study for hereafter. If assuming approximation of 30% lithium hydroxide input of CAM total material input, rough estimate of 38 000–50 000 CAM production capacity is possible with the planned Keliber production. (Keliber 2021a)

Depending on the ultimate chemistries, the proposed 30 000 tpa pCAM/CAM production could be entirely sourced from the FMG subsidiary companies feedstock, from Terrafame and Keliber, with the possible exception of manganese. This capacity would still allow half of the nickel sulphate produced by Terrafame to be used elsewhere, likewise up to one third of Keliber lithium hydroxide production.

Naturally with some CAM chemistries the lithium and cobalt demand may vary and therefore CAM production capacity varies too. At this point of time it is not possible to estimate in detail the possible CAM quality.

If it turned out to be that both south and west coast projects were to proceed, this would naturally constrain the capacity of each individual plant if the raw material feed was mainly sourced from Terrafame Sotkamo and Keliber. It has been disclosed however that the Johnson Matthey CAM plant at west coast will rely on Nornickel feedstock (nickel and cobalt, Chilean SQM for lithium) so this leaves other options South coast project capacity and/or Terrafame and Keliber for the possibly remaining “surplus” production, that is highly sought after on the market.

West Coast pCAM/CAM with Johnson Matthey

The project on the west coast has changed from the original plans released in 2020. The EIA procedure has not been completed and needs to be completed according to the new plans with the announced partner Johnson Matthey. The plant at Vaasa adds to JM’s first commercial 10 000 tpa eLNO (nickel-rich advanced cathode materials) plant located in Konin, Poland, set to commence operations from 2022. Originally Kokkola was also one location option for the pCAM plant. But now following the recent news on joint venture with Johnson Matthey, both pCAM and CAM production will be done at Vaasa, where the industrial area property has been already reserved for the plants.

Based on the original EIA program (to be revised) the project specifications are pretty much the same as for the South coast project. Obviously, these will be fine-tuned to fit JM product specification. It has been announced that they plan to produce high nickel cathode materials, called with commercial name eLNO. According to the company description, eLNO is an advanced NMC 811 product featuring a layered nickel rich oxide structure with a proprietary stabiliser package and advanced surface modifications that allow the use of high nickel contents whilst moving to increasingly lower levels of cobalt to deliver superior energy density whilst sustaining excellent cycle life.

There is a raw material source agreement in place with Nornickel regarding the nickel and cobalt raw materials for the plant and with SQL for lithium feedstock (Johnson Matthey 2021). FMG is responsible for the necessary auxiliary processes as described earlier. It is not excluded though that other feedstocks could not be used in the production, enabling also Terrafame and Keliber feedstocks to be used if necessary.

The construction of the JM CAM plant could be started by the end of this year the earliest, subject to positive investment decision, based on on-going technical studies. Still the project needs to complete the EIA and permitting procedures and proper technical studies prior to final decisions or at least prior to plant production ramp-up. Considering the described time schedules for FMG South coast project and BASF Harjavalta project, it is unlikely that the production could ramp up prior 2025 although JM has estimated that the plant could be ready in 2024. Regarding European cathode production, Roskill has estimated that JM would be supplying roughly 25% of the cathodes produced in Europe during the 2030s, after initially smaller market shares when ramping up the production in mid-2020s (Fraser et al. 2021).

Depending on the final specifications and raw material needs for these projects, there may be “surplus” production regarding FMG subsidiaries FMG and Keliber. Assuming both South and West coast projects nameplate capacity would be 30 000 tpa CAM, and Terrafame chemical products would be used for both plants, there still would be 20 000+ tpa nickel sulphate available for external sales. In case there was no need for Terrafame nickel sulphate at West coast project, there could be nearly 100 000 tpa nickel sulphate for external sales. Terrafame cobalt sulphate would be adequate only for the South coast project. If Keliber lithium hydroxide production would be used in the south coast project for the given nameplate capacity, there would be at maximum 5 000 tpa available to be used at the West coast project or sales on the market.

In addition to nickel and cobalt production, Terrafame Sotkamo also is planning to ramp up the uranium recovery plant in the near future. The government (TEM 2020) has granted the necessary Nuclear act 21 § permit (6 February 2020) for this purpose but the permit has been applied to the supreme court with two years estimated processing time. The company has estimated that the plant commissioning would require at least one year before commercial production could be started. Taking into account both on-going supreme court procedure and commissioning time, it is unlikely then that the uranium recovery would be started prior to 2023. The uranium recovery plant has a connection to the Nornickel Harjavalta plant, see respective chapter and also the discussion in Chapter 4.

Figure 13 summarizes the plans described in this chapter.

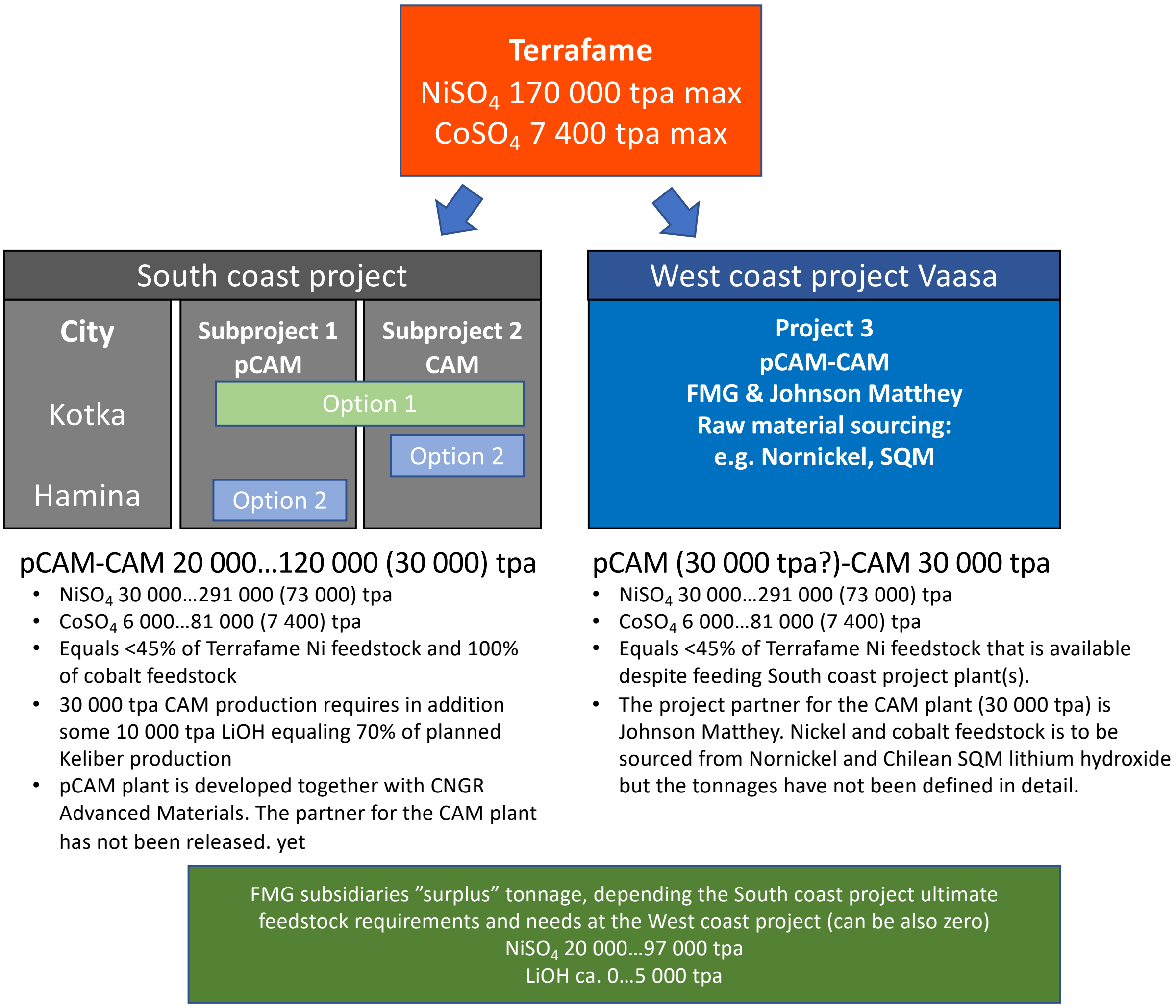


Fig. 13. Simplified material flowsheet for the projects being part of FMG plans. The volumes and shares are just indicative as detailed plans have not been released in public.

2.2.2 Stream 2

The stream is made up by Nornickel Harjavalta and nearby BASF pCAM plant that is currently under construction. Nornickel plant refines mostly imported raw materials (so called nickel stone, a type of matte) produced by the company other units in Russia. Annual production has exceeded 60 000 tpa in several recent years. Nornickel has investments plans to further develop Harjavalta production and recently the company announced big investment plan to raise the nameplate capacity 100 000+ tpa (Nornickel 2021b). In addition, the Nornickel parent company plans to boost company production in total by 20–30% by 2030 (Nornickel 2020). Also, the recent Johnson Matthey CAM plant news will affect Nornickel Harjavalta production in the future (Nornickel 2021c).

Production raw materials

Although Kola nickel matte is the main raw material feed at Harjavalta, the plant refines other streams as well (3^{rd} party feeds, <10% of total feed). These mainly include various secondary streams like nickel containing materials from copper refineries. Based on annual report 2020 databook, the Russian feed has been 92–98% of the total in the recent years (Nornickel 2021a). This leaves some capacity for the external producers also. Future share of external supply is an obviously question mark and the planned capacity increase may also have certain effects to this share.

Considering the current plant process flowsheet, various Ni-Co sulphides (like Terrafame Sotkamo) are the easiest to process. Mixed hydroxide precipitates (MHP) can also be refined but typically are more challenging due to impurities etc. One option is also to refine mattes from other producers than Nornickel but GTK assumes that this is not the preferred option for Nornickel. However, any potential 3rd party stream should be studied considering both material metal contents, impurities and especially volume.

Production and products

In 2020 Nornickel Harjavalta made a new production record, fourth year in a row. Production has exceeded 60 000 tpa Ni during the past few years, whereas the nameplate capacity for the plant is 65 000 tpa. Nameplate capacity is significantly lower than permitted capacity 60 000–90 000 tpa nickel according to environmental permit (Nro 240/2014/1; Dnro ESAVI/148/04.08/2011).

The plant produces nickel briquettes, cathodes and chemicals as well as cobalt sulphate. Refined cobalt tonnage is typically estimated to be some 2% of refined nickel tonnage, i.e. 1 200–1 400 tpa during the recent years. Nornickel 2020 annual report databook states the cobalt production having been 1–2 ktpa in years 2018–2020 so the estimated production fits this range. (Nornickel 2021a)

Various nickel chemicals are one of the Nornickel strengths, i.e. nickel sulphate, nickel hydroxide and nickel hydroxide carbonate – making up 13 percent of the plant's total production. With current production levels this means 8 000+ tpa nickel.

All Nornickel nickel products are currently refined at Kola and Harjavalta. In Kola, mainly nickel cathodes are produced. Harjavalta is the main production facility for cobalt chemicals within Nornickel group. In Kola there is a process line to produce cobalt powders, but these are mainly for metallurgical applications. Tonnage-wise Kola is bigger producer still as Harjavalta cobalt production has counted maximum 33% of the company total production during the recent years, for nickel the Harjavalta share has been 26…28% (Nornickel 2021a).

Produced nickel sulphate will be mainly utilized by nearby BASF pCAM plant, when the plant ramps up production. Initially BASF needs in terms of nickel is some 10 500 tpa, meaning that $NiSO_4$ production needs to be higher than it has been in the recent years. However, there still is capacity to deliver nickel chemicals to other customers also, for example Johnson Matthey in the future. Especially when the production capacity is increased beyond 100 000 tpa nickel. There has not been public news release about the need to revise the environmental permit due to planned expansion. However as current permit limit will be exceeded, it can be assumed that some adjustments to the permit are necessary.

BASF pCAM production will initially be 30 000 tpa. This production facility is currently under construction with aim to ramp up the plant in 2022. See further details in the next chapter.

BASF Harjavalta

BASF is planning to initially produce 30 000 tpa pCAM material. The project was granted environmental permit during fall 2020 (Nro 291/2020 Dnro ESAVI/36534/2019) although for the moment being the environmental permit is not valid due to appeals to the administrative environmental court (VaHO) which has given so called interim order that prevents start-up of the production prior to court decision on certain issues under appeal. Company plans to ramp up the production in 2022, naturally depending on the court proceedings.

Precursor plants typically produce pCAM tailored for the end user needs, hence the chemistry can vary according to application. Based on the BASF permit documentation the permitting has been done for NMC622 base case but the pCAM chemistry can naturally be modified as need be. In the permit the raw material consumptions are the following: $NiSO_4$ 50 000 tpa, $CoSO_4$ 10 000 tpa and $MnSO_4$ 10 000 tpa. Respective metal tonnages are roughly 10 500 tpa Ni, 2 100 tpa Co and 3 250 tpa Mn. Real tonnages based on stochiometric ratios may somehow vary but preceding tonnages are correct order of magnitude. If the pCAM chemistry was adjusted to NMC811 or other high nickel chemistries, the tonnage for nickel would respectively be higher and for other metals lower.

According to current plans, the pCAM production would require 15–20% of Nornickel Harjavalta annual nickel production, indicating significant upscaling opportunities in terms of nickel if so desired. Any production expansions are however subject to respective permit revisions and associated procedures.

However cobalt demand is apparently higher than Nornickel Harjavalta annual production. Hence the deficit and manganese feedstock need to be sourced externally.

Produced pCAM will be transported to Germany, where further processing into CAM is made closer to potential battery factories and OEM/Manufacturing companies (BASF 2020a). Latest news is that BASF and Umicore are co-operating to certain extent with their pCAM and CAM development (BASF 2021). Regarding European cathode production, Roskill has estimated that BASF would be supplying roughly 10% of the cathodes produced in Europe during the 2030s, having initially higher market share during the 2020s (Fraser et al. 2021).

Nornickel uranium sidestream

According to the environmental permit 2014 (Nro 240/2014/1, Dnro ESAVI/148/04.08/2011) the raw material intermediates may contain small amounts of uranium that is not removed in the cobalt and calcium extraction but instead cumulates on the course of time to the leach solution. If not removed, this would eventually decrease the leach capacity. For this reason, Nornickel has made the necessary investments for uranium recovery to the intermediate product (storage and management) permit which has been granted by STUK, up to 10 tpa (nro 7/Y42214/2009 (31.12.2009). The further refining would require treatment of this material for example at the Terrafame Sotkamo uranium plant.

Nornickel Harjavalta has processed Talvivaara Ni-Co sulphide precipitate in the past. In this process small amounts of uranium containing side stream has been generated. There are plans to return this material to Terrafame Sotkamo, once Terrafame ramps up the uranium recovery there. The permit includes processing of Harjavalta side stream up to 10 t. This stream may also contain small amounts of uranium from other raw material streams as it may be impossible to separate these from each other. Based on the government permit, the amount would be for the maximum tonnage but annual quantities are not defined.

Based on the permitting documentation it seems evident that Harjavalta uranium intermediate product can be processed at Sotkamo uranium plant, once it is operational. However, the tonnage appears to be limited although likely the past Talvivaara uranium and some other stored materials can be processed but not exceeding 10 t maximum. Any leftovers and potential future uranium intermediate products could not be processed at Sotkamo, unless the permits are revised.

The uranium extraction and downstream refining process is not fully operational yet until Terrafame Sotkamo uranium plant is ramped up. Considering the battery ecosystem future developments, especially regarding primary production, it is important to have such stream in place though. Even if further studies and permit revisions were required to fully utilize the opportunities provided by this stream. See further discussion in Chapter 4.

2.2.3 Stream 3

This stream consists of Kokkola cobalt refinery and associated facilities operated by Umicore Finland Oy and Freeport Cobalt Oy. Current operations and work distribution are based on Umicore acquisition of the cobalt refining and cathode precursor activities from Freeport in 2019 (Umicore 2019b). Based on the released materials the current operations are as follows:

Umicore sources cobalt containing raw materials for the refinery. Currently the company has long term sourcing agreement with Glencore established in 2019 (Umicore 2019c). Glencore provides Umicore sustainable and traceable cobalt hydroxide (MHP) from its operations in DRC. Glencore feed is the main raw material source for Umicore, but the refinery may also utilize other smaller external streams. Minor cobalt streams are acquired elsewhere, e.g. from Akkuser Nivala. Since the refinery currently mainly uses MHP type of intermediate feedstock in their production, it is assumed that it would be technically possible to use other suitable MHP or MSP feedstocks as well, naturally subject to number of technical and commercial requirements.

The sourced raw materials are leached in Umicore process and copper & nickel are separated before final cobalt refining. Leached cobalt is distributed partly for Freeport refining needs in addition to Umicore precursor production. Leaching takes place in continuously operating pressure leaching followed by various precipitation processes to recover the desired metals from the leached liquor. Process information is sourced from the environmental permits (Nro 56/2009/1, Dnro LSY-2007–Y-60 and Nro 194/2014/1, Dnro LSSAVI/72/04.08/2013) as well as publication by Heikkinen & Heino (2002).

Freeport produces cobalt powders (main product) as well as various cobalt chemicals, for example $CoSO_4$. Umicore only produces various precursor materials according to client requirements.

Umicore/Freeport Kokkola are assumed to produce 12 000–13 000 tpa cobalt, in various products. On annual basis 12 900 tpa production on average is assumed. Production breakdown between the companies has not been disclosed but based on press release information, it is assumed that bigger percentage of the production is controlled by Umicore. Production estimate for this study is 7 000 tpa cobalt on average and < 6 000 tpa for Freeport respectively.

Umicore estimated cobalt production enables 33 000+tpa cobalt sulphate production. This would enable ca. 60 000–120 000 tpa pCAM production, depending on precursor chemistry, assuming adequate nickel and manganese sulphate feedstock was available. This amount would be multiple times bigger compared with the BASF and Johnson Matthey announced capacities. However, there are no official public figures on the Kokkola refinery pCAM capacity. Finnish custom statistics do not indicate large scale nickel and/or manganese sulphate imports to Finland during recent years (Uljas 2021). Therefore, it is unclear how the pCAM plant raw material sourcing is arranged, unless some intermediate feedstocks are used to refine these metals in-house for chemicals, instead of buying pure chemicals from the market. At least for nickel such production process is in place. Therefore any estimates of Umicore pCAM production tonnage are rather inaccurate.

In the future bulk of the production is further refined at Umicore other plants, e.g. CAM plant in Nysa Poland, starting operations in mid-2021. The plant is the first largescale CAM plant operating in Europe together with BASF Schwarzheide plant. Produced CAM is delivered to customers, e.g. LG Chem with whom Umicore has multiyear supply deal in place. Nysa production capacity has not been disclosed but together with Jiangmen (China) and Cheonan (South Korea) production lines, Umicore aims to reach CAM production capacity of 175 000 metric tonnes by 2021. GTK estimates that likely Nysa (Poland) capacity is less than 1/3 of the total. (Umicore 2018)

It is reasonable to assume that the Kokkola refinery would be sourcing 30–40% at most of necessary Umicore global pCAM material production. Regarding European cathode production, Roskill has estimated that Umicore would be supplying roughly 33% of the cathodes produced in Europe during the 2030s, whereas Umicore share is currently nearly 100% but decreasing as Northvolt production is ramped up (Fraser et al. 2021). Latest news is that BASF and Umicore are co-operating to certain extent with their pCAM and CAM development (BASF 2021).

2.2.4 Stream 4

Boliden Harjavalta operates nickel smelter in Harjavalta, the only such facility in western Europe. The smelter sources raw materials from domestic and imported concentrates. One significant source is Boliden Kevitsa mine. Nickel and cobalt containing concentrates are processed into nickel matte (and EF matter) further refined abroad. Slag is produced as by-product.

Based on Boliden production statistics the nickel production of the smelter has been 30 000+ tpa in recent years (Boliden 2021c). Environmental permit (Nro 239/2014/1, Dnro ESAVI/147/04.08/2011) enables 38 000 tpa production which is more than the current nameplate capacity. In 2020 it was announced that during 2021 Boliden executes expansion investment to increase the feed and production capacity from the current 310 000 tpa feed to 370 000 tpa. In practice the production capacity will therefore be close to current permit limit. (Boliden 2020)

Based on Boliden production statistics the share of domestic nickel feed (Kevitsa and Kylylahti) has ranged from ca. 40 to 50% of the Harjavalta production. Boliden also operates copper smelter in Harjavalta, producing e.g. nickel sulphate as minor by-product.

Currently this stream does not contribute to the Finnish battery raw material stream as nickel smelter mattes are further refined abroad. Export countries or refineries have not been disclosed by the company or its customers, with the exception of French Eramet (EIT 2017, Eramet 2017). Based on BGS (Brown et al. 2021) nickel statistics the French nickel production in 2017–2019 has been 2 300–6 900 tpa and is estimated to be solely Eramet production at the Sandouville refinery (S&P Global 2020b). It seems like the envisaged production figures totalling 15 000+tpa nickel products and 400 tpa cobalt (using 25 000 t matte, Eramet 2017) have not been achieved so far.

Indirectly this French feed may contribute to the European battery cluster development though. Eramet and BASF have signed a partnership agreement to assess the development of a nickel-cobalt refining complex to supply growing electric vehicle market. Part of the plan is to construct a base metal refinery (BMR) that would supply nickel and cobalt to produce precursor cathode active materials (pCAM) and cathode active materials (CAM) respectively by mid 2020s. (BASF 2020b) Further details and the location of the BMR have not been disclosed but it can be estimated that Sandouville products could very well be used for this purpose in the future.

Rest of the Boliden Harjavalta matte is sold elsewhere (>70% of the total according to BGS figures, Harjavalta total production less French share/ Eramet). Based on statistics from the Finnish Customs office (Uljas 2021), the main export countries for nickel matte since 2017 have been Canada, China, Japan and Norway, in addition to France. Based on the statistics it seems likely that Glencore Nikkelverk in Norway refines up to one third of the produced nickel matte. Nikkelverk produces mainly various high purity metallic nickel, cobalt and copper products (around 50 product variances) that can be used for as feedstock for battery applications but are generally thought as secondary source vs. the chemicals produced from intermediates. There are expansion plans at Nikkelverk for cathode production and also development for recycling and battery material business (Glencore 2021c).

2.2.5 Stream 5

The latest addition into the Finnish battery metal ecosystem is the recycling co-operation between Fortum, BASF and Nornickel in Harjavalta and associated Ikaalinen mechanical recycling plant (Fortum 2020 and 2021).

Recycling plant in Ikaalinen has started operations in February 2021. The plant is operated in synergy with the Fortum Harjavalta plant so that initial mechanical recycling (crushing and sorting) takes place at Ikaalinen and further hydrometallurgical processing at Harjavalta. Mechanical treatment produces metal stream (e.g. copper and aluminum) to be further recycled by conventional methods, plastics and so-called black mass, typically a sludgy mixture of lithium, manganese, cobalt and nickel that is transported to Harjavalta for hydrometallurgical processing.

With the novel hydrometallurgical process, the metals contained in black mass are separated and recovered with 80–95% recovery rate that is significantly higher than in conventional methods whilst having very high energy efficiency and as consequence low carbon footprint. Many current operators that recycle battery metals often do so by smelting, which results in lower material recovery rates and higher emissions.

Fortum has capacity to recycle ca. 3 000 t of batteries. Currently LIB recycling is not big volume business but it has been estimated that by 2030 global recycling business revenue could be 18–20 billion euros and some two million tons (2 Mtpa) of old batteries would be recycled annually. This provides plenty of opportunities for upscaling in the future.

Recovered metals are utilized by the partner companies (Nornickel and BASF) as feed for new battery materials. All three companies operate within the same industrial park, providing upsides for logistics and energy efficiency for example. Hydrometallurgical process is not limited to the decommissioned batteries but also e.g. other industrial side streams and household appliance batteries can be recycled in the plant.

As indicated by the current recycling figures the share of recycled material is yet fairly low but will likely increase significantly in the absolute figures recycled. Also, the relative share of recycled material will likely increase in long term perspective during the 2030s when there are adequate amounts of decommissioned batteries available, initially produced from the primary raw materials.

2.2.6 Conclusion

These five described streams are all significant nickel and cobalt streams currently (streams 1–4) or in the future (stream 5), especially in European and EU context. As described earlier, Finland is practically only primary producer of nickel in Europe and the sole producer of cobalt. Harjavalta smelter is the only nickel smelter in western Europe. Altogether nickel and cobalt refineries are in production in a few European countries only. There are nickel refineries in Austria, Finland, France, Greece, Kosovo, North Macedonia, Norway, Poland and UK. Of these the Balkan countries, Norway and UK are not part of European Union, the last two being the biggest production countries besides Finland. However, Finland is clearly the leading producer in nickel chemicals. In cobalt refining Finland is one of the few producing countries besides Belgium, Norway and France. Of these the production in France has been nearly negligible in recent years. Planned Finnish pCAM and CAM projects strengthen the country important position in the European battery value chain.

These five parallel streams also enable many synergy opportunities in the future, especially when thinking the raw material sourcing for each stream. This topic is discussed in the coming chapters of this report.

2.3 Geometallurgy and applicable products for finnish primary streams

GTK BATCircle studies involved extensive geometallurgical study program for two Finnish case studies, namely Suhanko Arctic Platinum Konttijärvi deposit and Mawson Rajapalot deposit. In the case studies the ore types were first defined and sample selection procedure for the geometallurgical studies presented. Secondly detailed geochemical and mineralogical characterization for these ore types was undertaken. Finally, geometallurgical orientation study testwork was undertaken for both deposits with the objectives shown below:

- Rajapalot: Geometallurgical orientation study to refine the metallurgical process response and maximize recovery of gold and cobalt minerals into two separate concentrates
- Suhanko: Geometallurgical studies to refine the metallurgical process response to maximize recovery of minerals into separate Cu/PGE and Ni/PGE/Co concentrates

Geometallurgical studies are presented in detail in the following reports: Dehaine et al. 2021 and Michaux et al. 2021.

Mawson case study represents Kuusamo type supracrustal or atypical orogenic gold deposits with substantial cobalt and/or copper grades. Suhanko case study in turn represents Finnish orthomagmatic Ni-Cu-Co-PGE deposits, more precisely their layered intrusion subtype. (Törmänen & Tuomela 2021).

One object of the geometallurgical studies was to study certain processing related aspects for this kind of deposits, possibly beneficial for the development of the other similar deposits elsewhere and as an input for this strategic study, as the presented roadmap includes several projects categorized for these deposit types. In addition, there are several more similar deposits under development, with potential to contribute to the nickel-cobalt supply in the long run.

Unfortunately, due to the reasons beyond GTK control, all of the originally planned testworks could not be completed for the case studies and therefore the outcome applicability for this study was eventually limited. Short summary of the studies completed below.

Rajapalot

Three ore-types (MP, Ay and PAL1) were determined with distinct mineralogical properties with most of cobalt hosted by cobaltite except PAL1 where linnaeite is the main host. The ore types were tested using various mineral processing methods, including magnetic separation, gravity concentration and cyanide leaching (for gold only) with a view to investigating their processing behaviour, as well as evaluating the potential of each technique. Overall, flotation appeared to be the most efficient technique both for gold and cobalt recovery. Leaching also produced very good results. Magnetic and gravity concentration only yielded very low recoveries for gold below 50% for all ore types, but cobalt recovery as high as 71% was obtained during the magnetic separation of the PAL1 ore type. This is a result of a mineralogical control over cobalt recovery which is dictated by the cobalt deportment in linnaeite (PAL1) or cobaltite (AY or MP). Indeed, cobalt recovery in the magnetic fraction can be accounted for by linnaeite locked in pyrrhotite, while flotation is selectively floating cobaltite with mineral recoveries between 78%-93%. For the penalty elements, arsenic is almost exclusively hosted in cobaltite, and it will therefore follow the latter in the flotation concentrate, while uranium tends to follow the same pattern as gold during magnetic and gravity concentration, but is not recovered during flotation, making flotation the ideal method to selectively recover gold and cobaltite against uraninite.

The study highlighted that the three selected ore types can be considered as individual geometallurgical ore types with distinct process behaviour when submitted to the same process. This is partly due to a clear mineralogical control over cobalt recovery which is constrained by cobalt deportment in cobaltite or linnaeite. The rest of the deposit was made up of a combination of these three rock textures.

Based on the current results, a possible process path for the Rajapalot Au-Co project would include the following stages:

- Crushing & grinding to liberate gold and cobaltite,
- (Optional) Magnetic separation to recover pyrrhotite and linnaeite in a separate concentrate,

- Bulk Au-Co flotation with at least a roughing and cleaning stages to recover gold and cobaltite in a single concentrate.

The design and choice of the following stages are beyond the scope of the initial geometallurgical study and will depend on the decision whether or not the refining stages will happen on-site, if gold and cobalt are to be sold in a single or separate product, etc. Each possibility will lead to different products:

- After thickening, filtering and bagging, the Au-Co concentrate could be sold as a Au-Co mixed product,
- After an additional gold-cobalt separation stage, possibly by flotation, to obtain separate gold and cobalt concentrates to be sold as such or further refined,
- The thus obtained gold concentrate could then go through cyanidation and smelting to produce gold doré while the cobalt concentrate could as well undergo further hydrometallurgical treatment (leaching, solvent extraction, purification) to produce cobalt sulphate.

Also, it may be of interest to remove most of pyrrhotite early in the process in a separate pyrrhotite concentrate to improve flotation efficiency and reduce reagents consumption as well as improve the environmental quality of the final tailings. By doing so, the amount of sulphide in the ore will be significantly reduced prior to flotation as pyrrhotite can make up to 12 wt.% of the ore. In addition, it would allow to recover most of the linnaeite which is locked in pyrrhotite in a separate stream that could potentially be further processed to recover the cobalt or stored on site in addition to other tailings stream.

Not studied in connection to geometallurgical study but still an important issue regarding the project viability is the mine environmental performance and especially uranium. Since uranium appears to be reporting to the final tailings, it might be beneficial to study the options to separate uranium rich fraction from the regular tailings and further study the options for downstream refining or treatment for this higher uranium content material. This separation could possibly be done for example with gravity separation that has been tested by Dragon Mining 2011–2013 for Kuusamo ore (the project currently developed by Lat66 Cobalt). Dragon Mining estimated that this treatment would produce tailings with higher uranium content, ranging from 0.05–0.1%, hence not exceeding the limit set for the materials interpreted as uranium ore in the legislation (Dragon Mining 2013). The uranium issue is definitely subject to further studies to mitigate the environmental consequences of Mawson operations or similarly any Kuusamo type of ores containing anomalous uranium grades.

These options provide several opportunities for eventual process design and downstream processing to generate feedstock for the described Finnish nickel-cobalt refining streams. This topic is further discussed in chapter 4.

Suhanko

Suhanko case study confirmed the benefits of flotation in comparison to associated gravity or magnetic separation processes as primary recovery process. However, these (secondary) methods could be used to clean the feed to the flotation circuit, or they could be used to clean the tailings to mitigate acid mine drainage risk.

Flotation was the most effective separation process to recover Cu, Pd, Pt, Au and Ag while less effective for Ni and Co. Each of these metals had different flotation kinetics. Copper floats relatively quickly compared to other metals, where different orientation samples have slightly different signatures. As the Konttijärvi deposit is a lens structure with each of the ore types in a known layered form, this difference could be exploited. Sorting based on XRF scanning was also tested showing that heterogeneity of palladium grade does exist in this deposit. Theoretically it seems possible to reduce the amount of gangue to upgrade the head grades in the mill feed but this is subject to further bigger scale studies in the future. Leaching tests could not be undertaken so the fundamental experimental question for this deposit still remains, i.e. a comparison between flotation recovery and leaching recovery.

The former project owner (Gold Fields Arctic Platinum) undertook extensive studies in 2009–2013 to explore the options to produce precious metal concentrate (PMC), cathode copper and mixed hydroxide precipitate (MHP, containing nickel and cobalt) with consequential bulk flotation and Platsol pressure leaching -hydrometallurgical process combination (GFAP 2013). Cathode copper would have been readily marketable product to the end customers but PMC and MHP would have been sold to be further refining elsewhere. Commercial products could be produced with this approach but

Gold Fields never made the investment decision due to non-justified investment costs and associated technical risks. Eventually Gold Fields divested the project from their portfolio and the current project owner CD Capital is investigating other project implementation options of which one is the production of separate concentrates as studied in the GTK geometallurgical study. This is pretty close to the process and operations currently in use at Boliden Kevitsa mine.

Both options or some combination (e.g. flotation-leaching) could be feasible depending on the various factors including market situation (supply/demand, prices etc.) and possibly associated other feeds and downstream processing ecosystem in Finland. This is further discussed in chapter 4.

3 FINNISH BATTERY STRATEGY AND ASSOCIATED FUTURE PRIMARY PRODUCTION ROADMAP

3.1 Finnish Battery Strategy

Finnish Battery Strategy was launched in January 2021. Figure 14 summarizes the focus areas of the strategy. Some of the key elements in the strategy are Production of Battery Minerals and on the other hand further downstream Advanced Battery Materials. Both of these need to be undertaken on sustainable and responsible manner. Regarding these two areas Finland is currently the leading European country, especially in case of primary raw materials. There are significant business opportunities to increase the value added if the domestic (and imported) raw materials would be refined further downstream, e.g. for Cathode Active Materials or CAM. Finnish operating environment and aspects associated with sustainability/responsibility are at good international level. Still there are number of topical challenges that may constrain new investments to the industry. Social license to operate is certainly one of the biggest associated challenges. These elements are reflected also in the defined strategic objectives, see Figure 15. (TEM 2021)

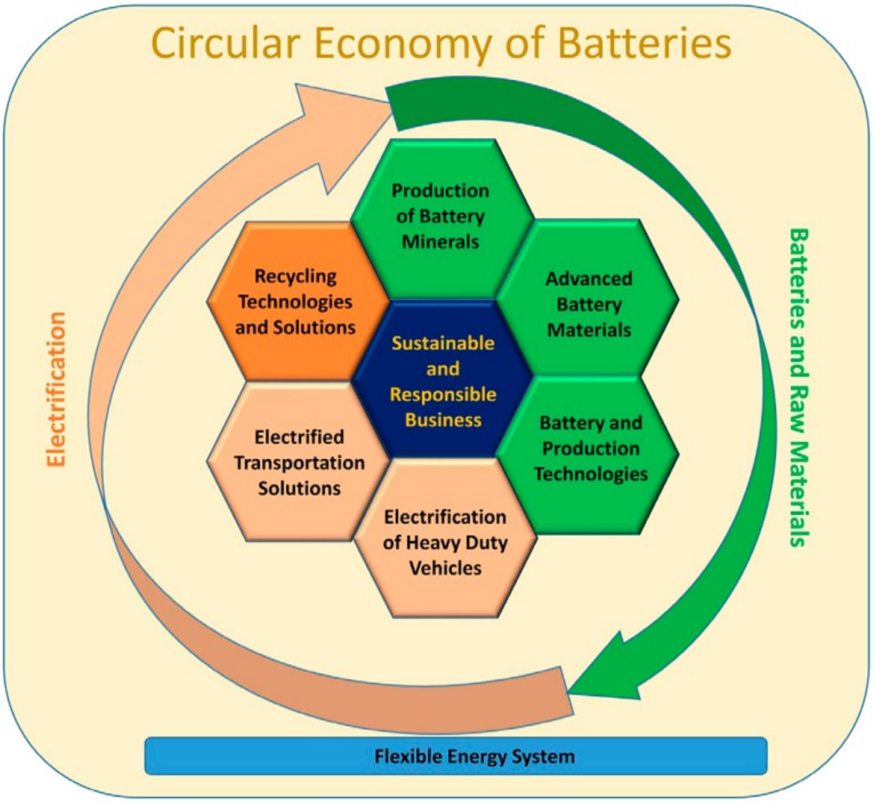


Fig. 14. Focus areas of the national battery strategy. Modified after TEM 2021.

The strategy includes seven strategic objectives (Fig. 15) of which four can be seen especially important regarding raw material sourcing. These are growing and renewal of the sector, including new companies, investments and their diversification covering the whole value chain to the extent possible. Co-operation of the battery sector is also seen more and more important. Responsibility is seen as sort of disruption factor that may enable sustainable growth of the sector. This requires new more advanced Traceability protocols and other sustainability indicators to be in place in the future. (TEM 2021)

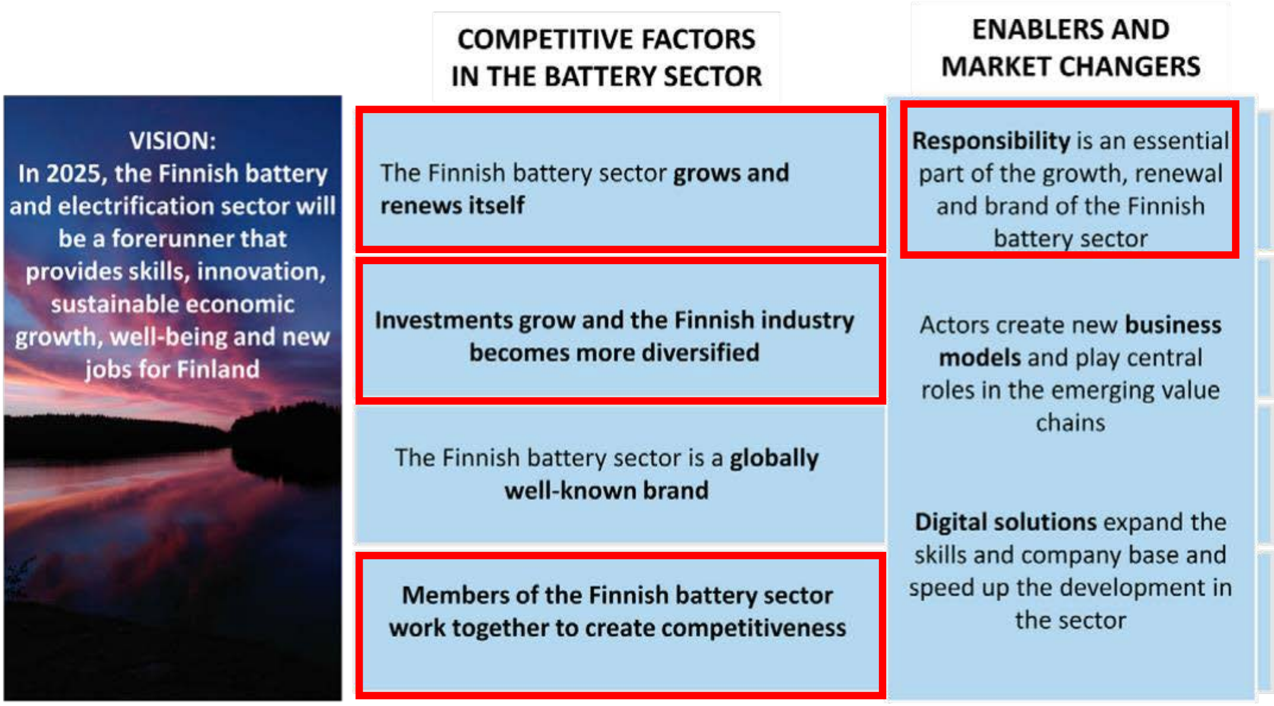


Fig. 15. Summary of the seven strategic objectives. Modified after TEM 2021.

Seven strategic actions have been identified to accomplish the said objectives:

Strategic actions

1. Enhancing national cooperation
2. Scaling up the skills of the battery and electrification cluster
3. Expanding EU and international cooperation
4. Establishing an operating environment that attracts investments to Finland
5. Making Finland a forerunner in sustainable and responsible battery production
6. Developing the brand of the Finnish battery and electrification cluster
7. Developing bigger and more agile funding

Of these actions 4 and 5 as well as 7 can be seen as especially important from raw material sourcing point of view.

Our known battery mineral resources enable this position to be retained or even strengthened in the future, not to underestimate the importance of recycling and other circular economy measures that will also strongly develop in the future. However, the prognosed long term supply-demand scenarios for the battery raw materials definitely require both of these streams, even then the ability to source enough materials for the industry is a big challenge.

Long term competitive battery sector necessarily requires growing and renewing primary production. Since the mines are always finite operations with depleting resources, unless exploration measures enable resource conversion into mineable reserves. Still all the mines are closed down at some point even though the life cycle or life of mine (LOM) may be several decades, even centuries in some cases. Successful exploration and project development after deposit discovery are crucial steps needed in generation of new primary resources and reserves. This study presents a future roadmap for the most advanced Finnish mine projects (battery commodities) at the moment. This roadmap is based on typical project development timeframes, known resources and theoretical LOM. The roadmap is presented in chapter 3.3 but first it is necessary to have a brief overview to the timeframes required to ramp up a new mine following successful exploration and project development phases. Unlike many other industrial investments, like battery chemical, pCAM or CAM plants for example, a typical mine may require decades of active development. This causes big uncertainties in all supply/demand scenarios for example. Considering the Battery Strategy implementation this fundamental fact is to be noted seriously enough.

3.2 Mine development lead time

3.2.1 Global perspective

Mine development from a prospect to deposit to mine project to an operating mine is a long process. SP Global has made a global assessment about the mines lead times from discovery to production (Table 12), studying 35 successful global mine projects during years 2010–2019 (S&P Global 2020c). The study outcome was that global average for a mine lead time is 16.9 years with 20 projects ramping up production in less than average lead time (average lead time of this group 12 years) and 15 projects clearly exceeding the average lead time, average lead time being 23.5 years. Less than average group included only 4 projects from OECD countries, whereas the more than average group included 8 projects from OECD countries, one of these a Finnish Kevitsa project. Lead time of Kevitsa mine was 25 years, since the deposit discovery in 1987. In other words even higher than the average of the latter group, 4th longest amongst all studied projects.

There were 15 mines with longer than average lead times commissioned during the period. Considering the number of mines commissioned, Chile topped the list with all three of its mines commissioned during the period posting longer lead times, averaging 23.7 years. Mexico followed with two mines averaging 17.5 years. Canada and Russia both commissioned four mines during the period, with two in each country having longer than average lead times: two Canadian mines averaged 23.5 years and two Russian mines averaged 27.5 years. The Bystrinskoye copper mine in Russia posted the longest lead time of 32 years, having been discovered in 1986 and only starting operations in 2018. In some cases, very fast development from discovery to mine has been achieved, such as the IGO Nova Ni-Cu-Co mine in Australia, which took just five years from discovery (2012) to production (2017) (IGO 2021).

Like in Australia, Canada uses a streamlined permitting process and timeline. Still the permitting process can involve extensive community engagement and environmental requirements that can cause significant delays. The Rainy River and Dublin Gulch mines in Canada took 22 and 25 years, respectively, to be completed.

Table 12. Top new mines average lead time per country, 2010–2019 (S&P Global 2020).

Below average lead time			Above average lead time		
Country	**No. of new mines**	**Average lead time (years)**	**Country**	**No. of new mines**	**Average lead time (years)**
Russia	2	8	Mexico	2	17.5
Zambia	1	8	Peru	1	21
Turkey	1	9	Ghana	2	22
Australia	2	10	Canada	2	23.5
China	1	11	Chile	3	23.7
Suriname	1	11	**Finland**	**1**	**25**
Egypt	1	12	Kazakhstan	1	26
Mongolia	1	12	Russia	2	27.5
Peru	4	13	New Caledonia	1	28
Canada	2	13.5			
DRC	1	15			
Indonesia	1	15			
Burkina Faso	2	16			
Total average	**20**	**12**		**15**	**23.5**

3.2.2 Finnish perspective

For Finnish perspective the following projects that are included in the following roadmap, can be used as further examples:

First mineralizations in Suhanko area were discovered in 1960s. Juomasuo deposit in Kuusamo was discovered mid-1980s. Rompas and Sakatti deposits were discovered in 2008–2009. None of these deposits are yet in production. Considering latest plans by Anglo American (Sakatti) and possible opening of the mine in late 2020s as well as Rompas & Kuusamo mines possibly opening thereabouts, the average lead time would be well over 35 years. These figures do not even count the time period that was used for initial exploration efforts (and years) prior to deposit discovery. **Hence it can be said that in Finnish operating environment it takes at least 20 years (absolute minimum) to commission a mine following the deposit discovery, likely much longer, close to 30 years or beyond.** In an extremely fortunate case, where the discovered deposit would be located on an area with no conflicting land use interests and high enough grades & tonnage to streamline the feasibility studies and project financing, it could maybe be possible to shorten the lead time, but still the lead time can be estimated to be between 10–20 years minimum with high likelihood closer to 20 years.

It is well known that most of the exploration projects or even mine projects never actually advance to the operational phase due to e.g. low grades or technical difficulties in processing. This emphasizes the fact that there needs to be big enough project portfolio for an individual company to be able to develop at least one the projects into production. Obviously, this portfolio may be spread over in several countries or even continents. The few successful projects on a way finance all the unsuccessful projects if considering the industry as a whole. This principle can be expanded to cover the national interests as well. A country with plenty of high-quality exploration projects is likely able to have at least of one or more projects advancing into production. Preferably this project portfolio should have enough projects in different maturity phases. The following Roadmap plan is based on this portfolio approach. The roadmap contains several advanced battery metal and mineral projects with varying maturity levels, in addition to a few operational mines. Besides to the chosen projects, there are many more much less advanced exploration projects. Such early phase projects cannot be similarly evaluated due to numerous associated uncertainties and hence they are not included in this assessment. Adequate exploration measures may still produce many other promising projects in the long run. For this very reason it is extremely important to have active exploration on-going to safeguard adequate domestic primary raw material supply also for the decades beyond this Roadmap assessment.

3.3 Roadmap

GKT BATCircle report (Törmänen & Tuomela 2021) provides detailed review of Finnish battery metal deposits, their geology and mineralogy as well basic information regarding the processing options of the ores in question. Using this information as source material in addition to the expert opinion on current mine project situation in Finland, GTK has prepared the following roadmap and development plan (Chapter 4) for potential Finnish battery metal/mineral mines in operation during 2020s to 2040s. Based on the mines and projects included, it is possible to evaluate approximate production tonnages of nickel, cobalt, copper and lithium for five (5) years intervals during the prognosis period. This in turn makes possible to build up scenarios on potential downstream refining, see chapter 4.

Projects and preconditions of the roadmap

The roadmap includes currently operating battery metal mines and their estimated life of mines (LOM) based on company reports. Furthermore the projects listed in Table 13 are included.

Table 13. Basic information of the projects included in the Roadmap. Commodity listing after the project name only indicates the battery metals/minerals relevant for this study. Most of the mines are also producing other commodities, in many cases being the main products. Sakatti, Hautalampi, Kaustinen and Aitolampi projects are shown as bold, since battery commodities would be the main products for these planned mines.

Mine project Battery commodities	Company, parent company or main owner	More information
Sakatti (Cu-Ni-Co)	**AA Sakatti Mining Oy, Anglo American Plc.**	https://finland.angloamerican.com/fi-fi/about-sakatti
Suhanko (Cu-Ni-Co)	Suhanko Arctic Platinum Oy, CD Capital	https://www.suhanko.com/
Hautalampi (Co-Ni-Cu)	**FinnCobalt Oy, Eurobattery Minerals1**	www.finncobalt.com https://eurobatteryminerals.com/en/projects/hautalampi/
Rajapalot (Co)	Mawson Oy, Mawson Gold Ltd.	https://www.mawsongold.com/projects/finland/rompas-rajapalot-overview
Kuusamo (Co-Cu)	Latitude 66 Cobalt Oy, Latitude 66 Cobalt Ltd	https://lat66.com/
Hannukainen (Cu-Co?)	Hannukainen Mining Oy	https://www.hannukainenmining.fi/
Kaustinen (Li)	**Keliber, SMJ Oy**	https://www.keliber.fi
Aitolampi (graphite)	**Fennoscandian Resources Oy, Beowulf Mining Plc.**	https://beowulfmining.com/projects/fennoscandian-finland-graphite/

[1] Project is funded by Eurobattery. The company has option to increase their shareholding in the project according to the valid investment and shareholders agreement.

These are projects that are in advanced exploration or project development phase with potential to ramp up production within next 10–15 years, assuming project development can be successfully completed and project funding arranged. Naturally there are numerous other less advanced projects that might proceed similarly by mid 2030s. But considering the typical timeframe it takes for an exploration project to develop to an operating mine, the probability for other projects be in production within next 10–15 years is very low. Uncertainties in any prognosis extending beyond 15+ years are rather big. Especially considering the lack of knowledge on battery chemistries and demand scenarios towards

2040, we have therefore only included these eight (8) projects in the roadmap assessment. Whenever possible the official company figures have been used for evaluation of mine LOM and production figures (for example EIA, permitting or other company documentation). For all of the projects such plans are not available and in those cases, GTK has undertaken a professional estimate for possible LOM and annual production. This is not necessarily the same as the companies in question may be planning for.

All the rest of the recognized projects are yet in study phase with varying maturities. GTK has undertaken a professional estimate for each of the project and estimated LOM for each planned mine is scheduled to start at earliest reasonable year, considering all the necessary aspects and constraints associated with typical mine and specific issues for each mine in question. It needs to be noted that most likely some of these projects will not proceed at estimated schedule, some of them may be much delayed or will never advance to an operating mine. The aim is to provide a reasonable estimate about the schedule that could happen, assuming the projects advance, permits are granted and the investment financing can be arranged. Hence the roadmap does not provide a best-case estimate for accelerated ramp-up, nor it forecasts which projects could advance and which could not. No probability for successful ramp-up is therefore presented, simply the timeline when and how long the mine could operate assuming realistic development time from the current status in the project. Based on the outcome it is possible to forecast possible total tonnages for each commodity during the prognosis period.

It needs to be remembered that the tonnages in the roadmap are aggregate figures. If some of the projects will be delayed or dismantled, the tonnage varies accordingly. The tonnage estimated for time period 2025 to 2030 can be used as average tonnage for the prognosis period. The tonnages are higher than 2020 actual production, hence requiring existing mine production increase or expansion (production and/or LOM) and/or new mines but not necessarily all included ones. Estimated production increase is moderate but still reflects the battery strategy objectives for the battery sector growth and renewal.

Nickel, cobalt and copper production

The roadmap is presented in Figure 16. Each project is shown with an estimated timeline. For the existing operations the timeline continues as long as the official LOM figures allow production to be undertaken with current production levels. Kevitsa mine contains the shortest LOM of the existing operations. Terrafame Sotkamo has pretty much similar LOM but assuming the mine can be expanded to the Kolmisoppi area, the LOM will be significantly extended to cover the whole prognosis period. On the other hand, if the permit is not granted, at worst the production could be dismantled mid-2030s. Elementis talc mines supposedly have big reserves and respective long LOMs justifying the estimated production over the whole prognosis period.

Sakatti mine is located topmost of these potential new primary metal suppliers. This is justified based on the planned production tonnages. Sakatti mine would be pretty much comparable to the Kevitsa mine with fairly similar products and volumes as well. Moreover, thinking of the known Kevitsa mine LOM and realistic ramp up year for Sakatti, these two mines could in a way substitute each other around mid-2030s to keep up the current production levels by Kevitsa mine, until 2050 or even longer. Technically Sakatti mine is extremely promising project, considering for example the tonnage and grades. However, from permitting point of view the project is extremely challenging, due to nature protection aspects. (Anglo American 2021)

Suhanko and Hautalampi mines are presented next. Both of these would produce nickel and cobalt, the former at roughly similar quantities, the latter clearly higher at Hautalampi. However, Suhanko mine would have significantly longer LOM. Suhanko area includes several deposits that allow LOM of several decades depending of the annual production volumes. Hautalampi LOM would be less than decade unless the mine reserves can be considerably upscaled. Both of these mines could be in production mid-2020s if proceeding smoothly. The main challenge for both of these projects is the technical feasibility rather than the constraints due to conflicting land use interests.

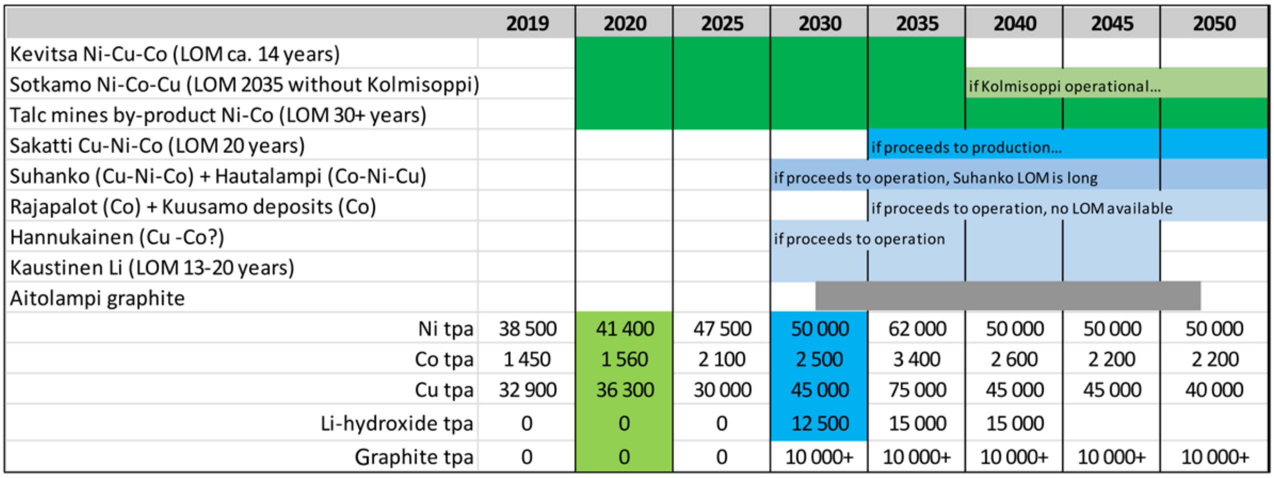
Mawson Rajapalot and Lat66 Cobalt Kuusamo projects are grouped into the same category, both producing cobalt together with gold (main product), also containing uranium in the ore. These projects share the major challenge with the permitting issues, due to nature protection aspects and other land use issues not to underestimate potential technical and feasibility challenges. There are no official LOM estimates for these mines, hence LOM has been estimated based on current resource and respective decent production rates. These projects are under active exploration that can also significantly increase the resource and possibly also the reserve that could affect to the LOM and/or production rates in the future.

Hannukainen mine currently plans to produce only copper and gold together with the main product iron concentrate. The deposit however contains cobalt and due to substantial production volumes, cobalt could possibly also be recovered in notable quantities. This is subject for further development in the future. Still it is justified to include the mine in this prognosis, especially since it would add up significant amount of domestic copper into the downstream value chain.

More detailed breakdown of the estimated production development is presented in tables 14 (nickel) and 15 (cobalt). The production rates shown in these tables are based on official company plans or GTK professional estimates that are based on company plans published at some point in project history or purely on GTK estimate based on the deposit tonnage and characteristics.

Terrafame Sotkamo will remain as biggest individual producer for nickel in the foreseeable future, assuming the LOM can be extended beyond 2035. For Terrafame Sotkamo the future production estimates are based on the tonnage requirements by nickel and cobalt sulphate production. These figures are clearly bigger than the actual production amounts realized to date.

Terrafame share of total production varies between 60–75% annually. Kevitsa and Sakatti mines could both be contributing some 20% of the annual total. The rest of the mines would be minor producers in all cases although Suhanko mine could potentially produce roughly double the estimated tonnage with 10 Mtpa mining (GFAP 2013). The tonnage for this study is estimated with 5 Mtpa mining rate as the company is developing the project at smaller capacity initially (details not disclosed). Production expansion could very well take place at some point, which is the case for all of the mines listed.



	2019	2020	2025	2030	2035	2040	2045	2050
Kevitsa Ni-Cu-Co (LOM ca. 14 years)								
Sotkamo Ni-Co-Cu (LOM 2035 without Kolmisoppi)						if Kolmisoppi operational...		
Talc mines by-product Ni-Co (LOM 30+ years)								
Sakatti Cu-Ni-Co (LOM 20 years)					if proceeds to production...			
Suhanko (Cu-Ni-Co) + Hautalampi (Co-Ni-Cu)				if proceeds to operation, Suhanko LOM is long				
Rajapalot (Co) + Kuusamo deposits (Co)					if proceeds to operation, no LOM available			
Hannukainen (Cu -Co?)				if proceeds to operation				
Kaustinen Li (LOM 13-20 years)								
Aitolampi graphite								
Ni tpa	38 500	41 400	47 500	50 000	62 000	50 000	50 000	50 000
Co tpa	1 450	1 560	2 100	2 500	3 400	2 600	2 200	2 200
Cu tpa	32 900	36 300	30 000	45 000	75 000	45 000	45 000	40 000
Li-hydroxide tpa	0	0	0	12 500	15 000	15 000		
Graphite tpa	0	0	0	10 000+	10 000+	10 000+	10 000+	10 000+

Fig. 16. Roadmap for Finnish primary production (Ni, Co, Cu, Li and graphite) for the time period 2020–2050. The figures shown on blue background may be taken as conservative mean estimate for the coming decades.

Table 14. Estimated mine production of nickel in Finland in 2020–2050. The aggregate figures are estimated based on cumulative production by each mine. Luikonlahti CoNi-stockpile reprocessing might be producing reasonable amounts of nickel but as the share would likely be just few percents of the total production, it is not counted in the total figure. Mines with tonnage estimated by GTK are shown with suffix E after the tonnage.

Mine	Company	2020s tpa	2030s tpa	2040s tpa
North Finland producers				
Kevitsa[1]	Boliden	11 500+	11 500+, ends by 2034	-
Suhanko	SAP	1 200E, mid 2020s	1 200E	1 200E
Sakatti	AA Sakatti	-	11 500E	11 500E
North Finland total		**11 500…12 700**	**24 200**	**12 700**
South Finland producers				
Sotkamo and other talc mines[1]	Elementis	1 200E	1 200E	1 200E
Hautalampi	Finncobalt	1 000, LOM 7+ years[2]. Mid 2020s the earliest	-	-
Sotkamo[1]	Terrafame	37 000[3] max	37 000[3] max If production continues to late 2030s	37 000[3] max If production continues to 2040s
South Finland total		**37 000…39 000**	**37 000…38 200**	**37 000…38 000**
Projects possibly producing Ni containing sidestreams				
Luikonlahti	Boliden	potential not disclosed. Subject to further studies	could be several hundreds tpa if reprocessing feasible	could be several hundreds tpa if re-processing feasible
Total		**48 500…51 700**	**61 200…62 400 early 2030s** **50 000 late 2030s**	**49 700…50 700**

[1] Operating mine as of 2021. [2] Depending on production rate and resources 2021 (being revised). The company has communicated LOM being 7 years minimum. [3] Production from 2021 onwards has been estimated based on production estimates for $CoSO_4$.

It is assumed that nickel supply/demand will develop increasingly tight at the 2030s the latest. This is likely reflected in the commodity prices and also promotes recycling in the future. Based on these potential trends, it is estimated that CoNi-stockpile at Boliden Luikonlahti site will be reprocessed at some point in the future, if not 2030s the latest in the next decade. The tonnage is not estimated here as there are no official public plans for recycling at any scale and anyhow the contribution for nickel would likely be just a few percents compared with annual total production. Regarding cobalt the share could be much more significant. There are also other possible sidestreams in the Finnish mines that could be studied for reprocessing purposes. One of these could be the Kevitsa high sulphur tailings that contains elevated nickel and cobalt concentrations, which is however not included in this analysis.

Table 15. Estimated mine production of cobalt in Finland in 2020–2050. The aggregate figures are estimated based on cumulative production by each mine. Luikonlahti CoNi-stockpile reprocessing might be producing significant amounts of cobalt (vs. the total production) that has been counted in the maximum figure for 2030s and 2040s cobalt production. Mines with tonnage estimated by GTK are shown with suffix E after the tonnage.

Mine	Company	2020s tpa	2030s tpa	2040s tpa
North Finland producers				
Kevitsa[1]	Boliden	500	500, ends by 2034	-
Suhanko	SAP	125E, mid 2020s	125E	125E
Kuusamo	Lat66		300E	-
Rajapalot	Mawson		100E	-
Sakatti	AA Sakatti		500E	500E
North Finland total		**500…625**	**1 525 max**	**625**
South Finland producers				
Sotkamo and other talc mines[1]	Elementis	20E	20E	20E
Hautalampi	Finncobalt	300, LOM 7+ years[2]. Mid 2020s the earliest	-	-
Sotkamo[1]	Terrafame	1 5003 max	1 500[3] max If production continues to late 2030s	1 500[3] max If production continues to 2040s
South Finland total		**1 820 max**	**1 520 max**	**1 520 max**
Projects possibly producing Co containing sidestreams				
Hannukainen	Hannukainen Mining Oy	200+E, late 2020s?	200+E?	-
Luikonlahti	Boliden	potential not disclosed. Subject to further studies	could be several hundreds tpa if reprocessing feasible	could be several hundreds tpa if re-processing feasible
Total		**2 300…2 650 max**	**2 700…3 400 max**	**2 100…2 200 max**

[1] Operating mine as of 2021. [2] Depending on production rate and resources 2021 (being revised). The company has communicated LOM being 7 years minimum. [3] Production from 2021 onwards has been estimated based on production estimates for $CoSO_4$.

In the case of cobalt there may be more producing mines but still most of them are rather small by tonnage. Sotkamo mine will be clearly the biggest producer with share of 45 to nearly 70% of the production. Kevitsa and Sakatti may contribute 15 to 20+% of total. Hautalampi, Kuusamo, Suhanko and Rajapalot projects will all be clearly smaller as individual producers but together they could produce over 800 tpa annually if operating at the same time. Their cumulative production would not be insignificant by any means.

In addition, Hannukainen and Luikonlahti side stream processing could produce several hundred tons cobalt annually. Since cobalt total production is way smaller than nickel production (and respective weight for these sidestreams therefore much bigger), a conservative share for these projects has been included in the total figures for cobalt.

Regarding copper production the most important mines would be Kevitsa and Sakatti, both of which could be producing some 30 000 tpa copper. Suhanko could produce third of that maximum with 5 Mtpa mining and Hannukainen mine almost the same tonnage. Hautalampi and Kuusamo projects would also produce smaller amounts copper, assuming Haarakumpu deposit was in production at Kuusamo. In addition, Terrafame Sotkamo produces copper precipitate currently but the tonnage is not disclosed. However, it is clear that Kevitsa and Sakatti mines are the key producers for the coming decades.

Alternative production outlooks

Finnish copper production has been constantly decreasing during the past five years and will be even lower in the near future, due to mine closures (Kylylahti mine in 2020 and Pyhäsalmi during 2021). During 2020s the copper production will therefore be roughly 50% of the 2017 peak.

If Kevitsa LOM is not extended and Hannukainen and/or Sakatti mine would not be opened, the Finnish copper production would drop down to practically zero during the next decade. This would leave Terrafame the only producer of copper in Finland with modest amounts that have not been released in public. This would be a huge drop from the production record year (2017) with 53 000+ t production, in less than two decades. On the other hand, if Sakatti is successfully brought into production and there are also other producers, like Hannukainen, the production may increase up to 75 000 tpa level by mid 2030s and later on stabilize around 40 000 tpa level after Kevitsa is closed. This would be pretty much the same production level as during the past decade.

Practically the same could happen for nickel and cobalt if Kevitsa is closed as planned, Terrafame Sotkamo operations could not be extended beyond 2035 and Sakatti mine would not be opened. Production in late 2030s would be nearly zero, two decades after the record nickel production year (so far), 43 600 t Ni in 2018. Even though all the rest mines included in the prognosis would be in operation by then, the tonnages would still be fairly modest compared with these big nickel-cobalt-copper mines. Likewise, the copper scenario, domestic nickel and cobalt production can be maintained at current levels or even increased if new production can be developed to substitute the discontinued production.

If either one or both of these worst-case scenarios would become true, the share of domestic production for all three commodities would be fairly small. This would not be beneficial for the Finnish battery cluster and metal refining value chain in general.

Both of these worst-case scenarios emphasize the importance of capability to generate new mines and undertake successful exploration to discover new deposits for further project development and eventually production ramp-up. Still even with highly feasible project the other constraints like permitting challenges may eventually prevent mining emphasizing the risk business nature of this industry.

Lithium production

Keliber is developing mining project at the so-called Central Ostrobothnia lithium province and also downstream processing refinery at Kokkola to produce battery quality lithium hydroxide. The mine project contains several deposits that are planned to be exploited in certain sequence, initially starting production at Syväjärvi and Rapasaari deposits. Current life of mine estimate is 16 years but active exploration on the area continues. The project plan is based on JORC 2012 compliant proven and probable ore reserves, using a cut-off grade of 0.40% Li_2O for the open pit ore reserves and a cut-off grade of 0.40 – 0.70% Li_2O for the underground ore reserves, amount to 9.372 Mt with an average grade of 0.98% Li_2O. The reserves contain several individual deposits. (Keliber 2021a)

The resources of Keliber deposits have recently been revised. The total Measured and Indicated Mineral Resources of Keliber now total 13.69 Mt (previously 11.77). Including the Inferred Mineral Resources, the total Mineral Resources are 15.62 Mt (previously 14.19). The average Li_2O grade of the Company's combined Mineral Resources is 1.05% (Keliber 2021a).

Produced spodumene concentrate would be transported to the Kokkola refinery for further processing. Initially the target is to produce 12 500 tpa lithium hydroxide and eventually 15 000 tpa. (Keliber 2021a)

If recently announced larger resources can be converted into reserves, even higher production in the future may be justified subject to positive feasibility studies.

EIA procedure has been recently completed for the revised mining plans as well as the chemical plant at Kokkola although a minor revision for the latter one is on-going. Also, the environmental permit application for the chemical plant has been recently announced. For the mines the environmental permit is in place but since the plans have been adjusted according to the new EIA, the permit needs yet to be reprocessed accordingly. This revised permit application has not yet been submitted (end of April 2021). The company plans to ramp up mine production by the end of 2024 and chemical plant after the mine is operational. These plans are naturally subject to successful permitting and likely appealing procedures as well as project financing. Considering two-year construction period for both operations (mine and chemical plant), the schedule is ambitious but can be implemented if permitting procedure does not contain major setbacks. Most likely, the mine permitting will be the critical path. In any case it is reasonable to estimate that the mine and chemical plant complex would be operational during the latter half of 2020s. (Keliber 2021b, Keliber 2021c)

In general, the Finnish mineral potential for lithium is good (Rasilainen et al. 2018) and there are other known lithium deposits in Finland but none of these is nearly as advanced as Keliber project. Therefore, these projects are not taken into account in this roadmap. In the long run Finland could be even more significant lithium producer than estimated in this roadmap. This could happen either due to new lithium mines or production expansion by Keliber if the on-going exploration activities would justify even bigger production in the future.

Graphite production

Beowulf Mining and its 100% owned Finnish subsidiary Company, Fennoscandian Resources Ab Oy are developing the Aitolampi graphite project in Eastern Finland close to Outokumpu (Beowulf 2021).

During 2019, the company produced an upgraded Mineral Resource Estimate for the Aitolampi project, with a global Indicated and Inferred Mineral Resource of 26.7 million tonnes at 4.8%. Total Graphitic Carbon is 1 275 000 tonnes of contained graphite, reported in accordance with the JORC Code, 2012 edition. Of this the indicated resources are 11.1 Mt at 5.8% graphitic carbon for 542 000 tonnes of contained graphite. Aitolampi contained graphite tonnage is close to Top 30 deposits worldwide so the deposit is significant even in global comparison.

As has been demonstrated in associated BATCircle studies and other studies, it seems to be possible to produce good quality graphite concentrates and purified products in limited quantities from Aitolampi feed. Obviously commercial scale saleable product is subject to the successful outcome of extensive future technical studies and production upscaling. However purely from technical point of view it is reasonable to assume that Aitolampi could be producing mine in the future.

The company is currently working with Scoping study of the project, aimed to be completed by the end of Q2/2021. Considering the typical project development pipeline for mining projects, it can be estimated that if the project proves to be economic and is successfully financed and permitted, production could start around 2025 at the earliest. For the purposes of this forecast, it has been estimated by GTK that the production would be started around 2027 and would continue roughly the following 20 years. Actual LOM is fully dependent on the annual production figures. Known resources would enable even much longer operations subject to successful resource conversion into reserves.

At this point the company has not disclosed any envisaged production figures. Considering the market forecast, known resources and compared with other graphite projects or operations worldwide, GTK professional estimate is that Skaland (Norway) size (or bigger) production is justified initially. Skaland currently produces roughly 10 000 tpa graphite concentrate that is ca. 2% of global annual natural flake graphite production.

Hence this would mean 10 000+ tpa graphite concentrate production. The eventual production figures are subject to proper feasibility studies, predicted project economics and respective funding arrangements as well as commercial agreements for the product. These in turn are strongly dependent on realistic achievable market share in the growing market. Graphite demand is generally estimated to multiply during the next 10 to 15 years so even higher production tonnages may be realistic assuming high enough product quality and respective commercial agreements can be put into place.

Other deposits

There are numerous battery mineral deposits potentially contributing to the Finnish primary production in the future but required development time scale may be rather long, even decades. Detailed review of these deposits is beyond the scope of this study but in the following just a few of these are briefly listed.

Läntinen Koillismaa project (Haukiaho-Kaukua) is a Suhanko type of deposit with rather similar characteristics (PGE-Cu-Ni). The project is being developed by Palladium One Mining Inc. Suhanko project entity also contains several other deposits not currently under active development, for example deposits at Narkaus and Penikat.

Ruossakero komatiite deposit (Ni-Cu-Co-PGE) is one of the most underexplored deposits in Finland, to large extent due to location at Enontekiö and associated land use challenges. There are also several other komatiite type of deposits elsewhere.

Pappilanmäki black shale deposit, similar to Terrafame Sotkamo Talvivaara deposit is being studied by Bluejay Mining Finnish subsidiary, FinnAust Mining.

Areas of active exploration for nickel and cobalt are presented in Figure 17, indicating the most interesting exploration areas for these commodities. Further details on undiscovered deposits regarding nickel, copper and cobalt are presented in respective GTK reports (Rasilainen et al. 2010, 2014, 2016, 2020).

In case of lithium also Somero-Tammela in Southern Finland area contains several interesting deposits being explored currently. Regarding graphite there are several known deposits for example around Aitolampi in South-Eastern Finland.

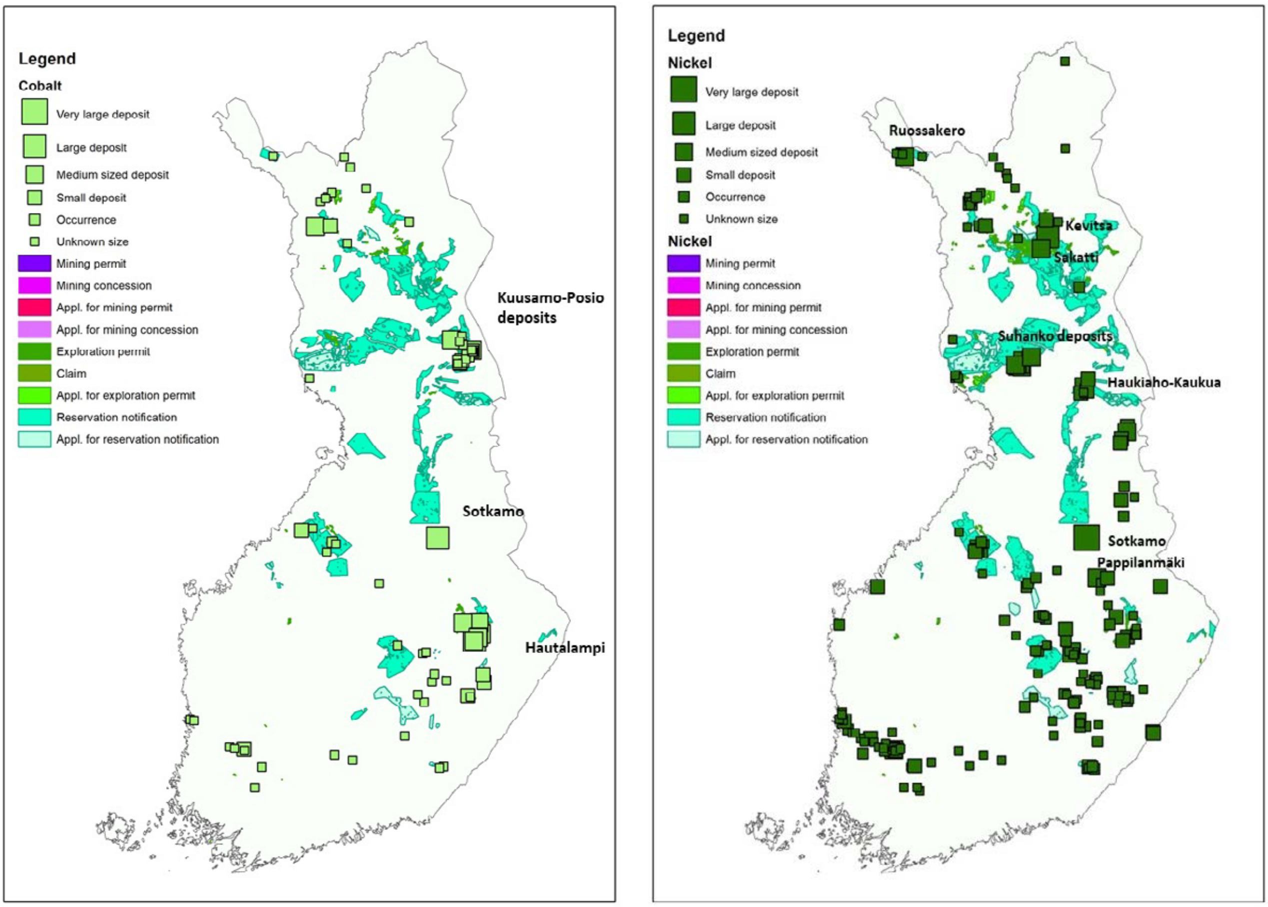


Fig. 17. Exploration activity for cobalt and nickel during fall 2020. Tenements of various classes shown in the legend. Maps include also known deposits for these commodities with some of the most notable specified by name. Note that cobalt map does not show the deposits, where Co is listed as other commodity of secondary importance. Size of the box indicates the tonnage of the main commodity that typically is other than cobalt. Hence e.g. Kevitsa and Sakatti are not shown. The map gives an overview of cobalt relative importance in various deposits, emphasizing Kuusamo-Posio area deposits, Sotkamo and Outokumpu area deposits. Maps are based on GTK mineral databases and Tukes mining registry.

3.3.1 Potential feedstocks

Any investment project is planned based on the outcome of economic modelling. Typically, such analysis includes various implementation options that are compared against each other and proper sensitivity analyses are carried out to test the project economics response to the applied parameters. Net present value (NPV) is typically used in these economic models, NPV being the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is commonly used in capital budgeting and investment planning to analyze the profitability of a projected investment or project.

These implementation options may include production of various alternative products, i.e. variable feedstock for the downstream refiners. The ultimate product is decided based on number of factors: for example ore characteristics and optimum process flowsheet suitable for the feed, process risks (especially in case of novel or uncommon industrial scale processes), market supply/demand and respective prices. In principle the only fixed parameter is the ore itself but basically all the other factors may change over time and drastically effect to the economics of optimum product.

It is impossible to perfectly forecast the future feedstock demand but based on the best estimates presented earlier in this study, it seems probable that intermediate products like MHP and MSP will be highly sought after in the foreseeable future. In general, these can be produced from the Finnish battery mineral deposits, likewise the regular sulphide concentrates, suitable for hydrometallurgical or conventional pyrometallurgical processes. Big upside of the Finnish Battery ecosystem is that it is able to use broad mix of feedstock providing true options for the primary producers trying to optimize their process flowsheets and respective products. These options are assessed at high level in chapter 4, also including certain centralized operations options that could be beneficial especially for the smaller mines and companies. The following sections briefly introduce the main product alternatives for a typical sulphide ore mine. More details on specific products are presented in report Törmänen & Tuomela 2021.

Conventional sulphide concentrates

Various types of concentrates can typically be produced from the sulphidic deposits, the main types being bulk concentrate containing all the economically important metals in one product or separate concentrates, like the copper and nickel concentrates produced at the Kevitsa mine. Nowadays selective flotation to produce separate concentrates is favored due to better options in downstream refining.

Finnish deposits typically contain both copper and nickel-cobalt at such quantities that bulk concentrate production would cause challenges at the smelters if pyrometallurgical treatment was planned. Typically nickel smelters cannot handle the amount of copper in the bulk concentrate, owing to the downstream nickel refining process feed specification requirements. And the same applies for the copper smelters and nickel correspondingly. Also, the pure quantity of bulk concentrate may limit the smelting options even though the quality of the concentrate would be treatable as such.

Separate concentrates therefore enable easier downstream refining if proceeding for pyrometallurgical treatment and matte production but can also typically be used as feedstock for direct hydrometallurgical processing. Pyrometallurgical process path and products also typically feed hydrometallurgical downstream refining.

Hydrometallurgy

Bulk concentrate production could be an option if hydrometallurgical process path is envisaged. Although a common way to process e.g. copper and zinc ores, it is fairly uncommon for Ni-Cu-Co sulphides currently. Still hydrometallurgical processing may provide several advantages compared to smelting: first of all, ability to use bulk concentrate and process lower grades with high recoveries. Capital costs may be significant, especially for large scale operation. However, a centralized hydrometallurgical plant could be a feasible option for several mines on same geographical area, producing concentrates that could be processed together or mixed to gain optimal feed for the hydrometallurgical process. These could be bulk concentrates or separate concentrates, depending on the chosen technology and approach.

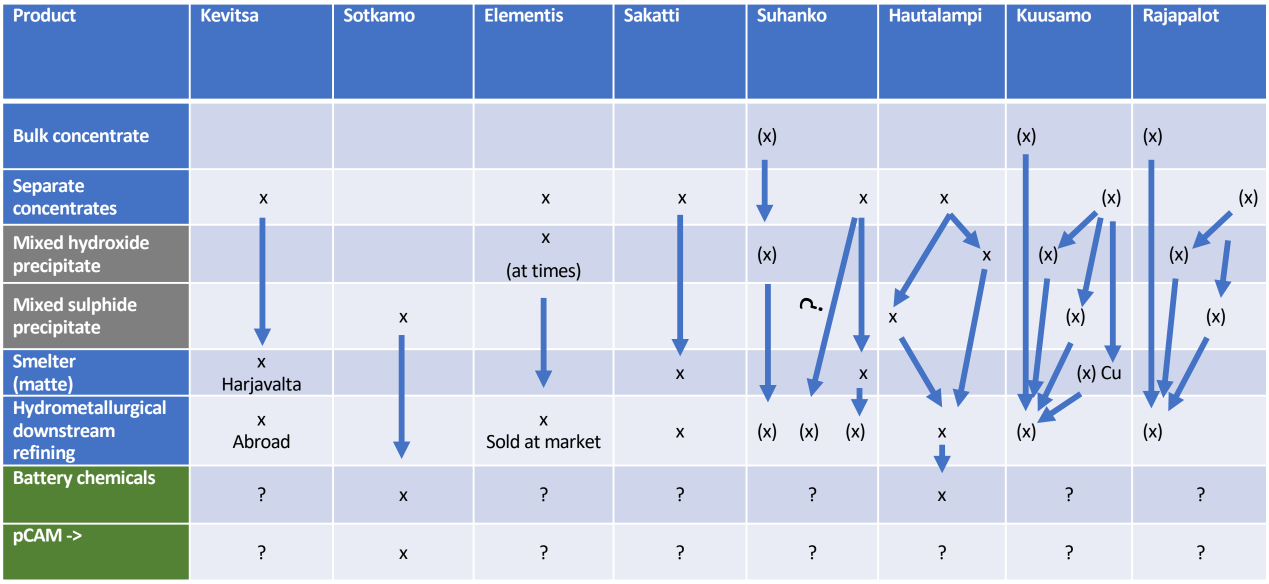
Hydrometallurgy itself is a broad process concept with several technologies on market available. Most importantly these can be classified e.g. based on initial oxidation method, pressure oxidation (POX), atmospheric -leach processes (with various sub-techniques) or by the eventual downstream process route i.e. intermediate or end products produced (most importantly MHP, MSP or pure metal products). Canadian Voisey’s Bay mine, operated by Vale being is the leading example for sulphide mines and direct hydrometallurgical process path. The Voisey’s Bay nickel sulphide deposit utilizes patented chloride-assisted acid oxidative pressure leaching process involving SX for copper, nickel and cobalt recovery. After treating the fine-ground nickel concentrate in an atmospheric acid-chlorine leach stage and an oxidative pressure leach stage, copper is removed either by sulphide precipitation or SX-EW from the solution. Iron is precipitated by limestone and lime and Ca, Zn, Pb and residual Cu and Fe are separated by SX. Cobalt is separated from the raffinate by SX and nickel is electrowon. Most of the nickel spent electrolyte is recycled for leaching and a small portion of the spent electrolyte is treated to remove impurities and maintain water balance. Oxygen and chlorine from nickel electrowinning are used for leaching. (Cheng & Urbani 2005, Kerfoot et al. 2002)

Voisey's Bay is not producing intermediate products but these can be produced from sulphidic deposits also if so preferred. Examples where this takes place or has been/is being considered are Terrafame Sotkamo, Elementis talc mines, Suhanko and Hautalampi projects.

In the following scenario analysis (Chapter 4) mainly the concentrate and intermediate products are included for the mines as it is supposed that further refining takes place in the other battery ecosystem facilities, either in place or planned.

Table 16 summarizes the currently known product portfolio for the current and planned Finnish Ni-Co-Cu producing mines (the ones included in the Roadmap). Basically, it seems like the biggest potential future producer Sakatti has pretty much established the pyrometallurgical process route. For the smaller producers the process options are being studied currently and many alternative options remain, possibly enabling potential synergies between the companies. This is discussed further in chapter 4.

Table 16. Current and planned Ni-Co-Cu producing mines in Finland and their products. Kevitsa, Sotkamo and Elementis products are known to be in production. Sakatti has indicated the pyrometallurgical process route in their EIA. Several process routes have been investigated for Suhanko during the project history. Hautalampi EIA includes both shown process routes. Studies for Kuusamo and Rajapalot projects are in early phases leaving basically all process routes open, process routes estimated by GTK.



Product	Kevitsa	Sotkamo	Elementis	Sakatti	Suhanko	Hautalampi	Kuusamo	Rajapalot
Bulk concentrate					(x)		(x)	(x)
Separate concentrates	x		x	x	x	x	(x)	(x)
Mixed hydroxide precipitate			x (at times)		(x)	x	(x)	(x)
Mixed sulphide precipitate		x			?	x	(x)	(x)
Smelter (matte)	x Harjavalta			x	x		(x) Cu	
Hydrometallurgical downstream refining	x Abroad		x Sold at market	x	(x) (x) (x)	x	(x)	(x)
Battery chemicals	?	x	?	?	?	x	?	?
pCAM ->	?	x	?	?	?	?	?	?

Most existing process plants for nickel laterite ores use intermediate precipitation processes to recover nickel and cobalt from the leach solution. The precipitation produces an intermediate product of nickel and cobalt, either as mixed sulfide precipitate (MSP) or mixed hydroxide precipitate (MHP), at the same time largely separating these metals from impurities such as manganese, calcium and magnesium. Also, direct solvent extraction (DSX) is being used as third main downstream process route as well as other hybrid flowsheets. (Willis 2007)

To get basic understanding of these flowsheets MHP and MSP processes are briefly presented in the following sections (based on Willis 2007) as applied to laterite operations where these processes are most often used. With proper adjustments these may be applied to sulphidic ore treatment also.

MHP

MHP is not highly selective for nickel and cobalt over manganese. It is therefore best performed in two stages in order to control the extent of manganese deportment to the mixed hydroxide product. In the first stage MHP the solution is typically adjusted to pH 7.2–7.5 in order to obtain the maximum practical nickel and cobalt precipitation achievable while limiting the manganese content of the product solids to <5%. This is somewhat dependent upon the nickel to manganese ratio in the feed stream. Approximately 90–95% of the nickel, cobalt, copper and zinc are precipitated along with any residual iron, aluminium and chromium present. An operating temperature of >60°C is favoured to facilitate fast reaction kinetics. Operation at ambient temperature is possible however the kinetics are slow. The co-precipitation of manganese is typically in the range 15–35%. When magnesia is used for pH adjustment, some magnesium reports to the MHP product, generally in the form of unreacted magnesium oxide.

The MHP product is washed to remove soluble impurities and dewatered for onward shipment. Magnesia may be substituted with caustic soda (sodium hydroxide), hydrated lime (calcium hydroxide) or soda ash (sodium carbonate). Caustic soda eliminates the magnesium content of the MHP product that is associated with unreacted magnesia offering slightly improved selectivity for nickel over manganese through faster mixing and more precise pH control, yielding a higher quality product. However, it is generally very expensive. Lime introduces calcium which results in gypsum precipitation and therefore contamination of the MHP product. The use of soda ash results in the precipitation of basic carbonates along with hydroxides, however the solubility of manganese carbonate is lower than that of nickel carbonate, thus the selectivity for nickel over manganese is further reduced. The depleted solution is forwarded to second stage MHP where residual nickel and cobalt are recovered by adjusting the pH to 7.5–8.0. Nearly all of the residual nickel and cobalt are precipitated, along with 20–30% of the remaining manganese. The precipitates typically contain 10–20% manganese. Terminal nickel and cobalt concentrations in solution are reduced to <5 mg/L.

The nickel and cobalt hydroxides contained in the precipitates can be re-dissolved by contact with acidic leach liquor (PLS). Manganese hydroxide also re-dissolves, establishing a recirculating load of manganese in the flowsheet. A low-grade mixed hydroxide product can be produced by employing single stage precipitation at pH 7.5–8.0. This approach will lower the project capital expenditure however the product may contain >10% manganese, limiting marketing options.

HPAL processes using pressure oxidation typically produce higher temperature and higher nickel as well as iron containing liquor, also containing higher solids content. These factors can have a significant impact on the downstream recovery of nickel and the quality of the desired intermediate product. High Pressure Acid Leach (HPAL) remains the process of choice for treating limonite type of laterite ores, especially for large scale developments. It has the advantages of high nickel and cobalt recoveries and is applicable to a wide range of ores.

MHP process is also widely utilized for high-purity cobalt hydroxide production at Central African Copperbelt region (DRC/Zambia).

If applied to sulphide concentrates the process could for example be the following: initially pressure oxidation followed by iron precipitation and filtration steps, precipitation of other metals like copper. Then after filtering the final hydroxide precipitation and filtering to precipitate the MHP product. Further technical details are beyond the scope of this study and subject to project specific requirements and studies anyhow.

MSP

In MSP process the mixed nickel-cobalt precipitate is produced by contacting purified pregnant leach solution with hydrogen sulfide gas at temperatures of 80–120°C and partial pressures of between 2 and 10 bar. MSP processes have a higher selectivity for nickel and cobalt over manganese and magnesium, resulting in a lower level of impurities compared with MHP. Also, the metal content of the precipitate is much higher compared with MHP, thereby enabling lower logistical costs. Another upside of the MSP product is that, MSP can also be treated similarly to a sulphide concentrate as a smelter feed. MSP flowsheet benefits if the project includes a sulphuric acid plant (synergistic with process plant sulphur and energy requirements).

Disadvantage of MSP is that the operation of the process is relatively expensive and complex as the process requires use of hazardous hydrogen sulfide gas at high temperatures and pressures. Hydroxide precipitation process is more simple and easier to operate. However, it is unsuitable for treating feed liquor with high manganese content.

Examples of MSP process include Coral Bay (Philippines) and several of world top20 nickel mines: Murrin Murrin (Australia), Moa Bay (Cuba), Ambatovy (Madagascar) and Taganito (Philippines). Respectively MHP route has been used for example at Cawse (Australia), Ravenstorphe (Australia) and Ramu (Papua New Guinea). Finally, as domestic case, Terrafame Sotkamo is an excellent example of this process. There the ore is stacked for heap leaching following crushing and agglomeration.

Heap leach PLS or pregnant leach solution is further processed in the metal plant with sequential metal precipitation (Cu->Zn->Ni-Co) as sulphides.

Terrafame process is tailored for the type of black schist. In general, for the more common sulphide concentrates the process could in general be processed initially pretty similar to sulphide MHP flowsheet presented earlier. However following the iron removal the rest of the metals would be precipitated with sulphide precipitation with the disadvantages described above also. Sulphide precipitation produces MSP that can be transported elsewhere for further refining or refined on-site with proper solvent extraction and precipitation processes to produce battery chemicals. Depending on the quality of the feed, new leaching process may be required, like in case of Terrafame Sotkamo battery chemical plant. Further technical details are beyond the scope of this study and subject to project specific requirements and studies anyhow

The direct solvent extraction (DSX) route is the newest addition among the three and has now been used in two commercial operations: Bulong (Australia) and Goro (New Caledonia). This process circumvents the need of intermediate precipitation of the nickel and cobalt. Therefore, this route offers a potential economic advantage over the two intermediate precipitation processes.

In addition to abovementioned process routes there are several other options available called hybrid flowsheets that typically are fine-tuned variations of MSP route. Potential upside of these flowsheets is even higher quality product than MSP route whereas providing better tailoring options for different ore types. Commercial industrial scale applications for the hybrid route are few though. Table 17 presents typical compositions for MSP and MHP products from heap leach operations. (Willis 2007) Based on unpublished technical studies by number of companies, it can be said that roughly similar products can be produced from sulphide feeds also.

Table 17. Typical compositions of MSP and MHP intermediate products at heap leach (atmospheric leaching) operations (Willis 2007). Public information on Terrafame MSP composition is not readily available and hence cannot be presented here.

Component	Unit	MSP	MHP
Nickel	wt% (dry)	55–61	30–39
Cobalt	wt% (dry)	3–6	2–5
Zinc	wt% (dry)	2–6	1–4
Copper	wt% (dry)	1–5	1–4
Manganese	wt% (dry)	< 0.1	4–9
Magnesium	wt% (dry)	< 0.1	3–5
Iron	wt% (dry)	< 0.8	< 0.5
Aluminium	wt% (dry)	< 0.1	< 0.5
Sulphur	wt% (dry)	34–36	3–5
Moisture	wt%	10–15	35–45
wet tonnes to be transported for 1 t Ni	t	2	4.5

Although typically applied for laterite ores, these processes can be used with sulphide ores as well. An example of Finnish MHP process is Elementis plant at Vuonos. Production of MHP has also been tested at Suhanko project in connection to Platsol process for precious metals in the ore. Large scale example of MSP process is Terrafame Sotkamo mine.

Considering the Finnish metal refinery infrastructure, the MSP route has clear advantage since it can be used as feed in all four refineries: Terrafame Sotkamo, Boliden Harjavalta smelter, Nornickel Harjavalta and Umicore Kokkola. MHP route products cannot be utilized at Harjavalta smelter and in general they are less preferred by Nornickel and

Terrafame. However, in general both of these process routes and respective intermediate products enable downstream processing at several places. Figure 18 summarizes the various nickel (and cobalt) processing options currently in use. The summary reveals the numerous process flowsheets that can be applied depending on raw material characteristics.

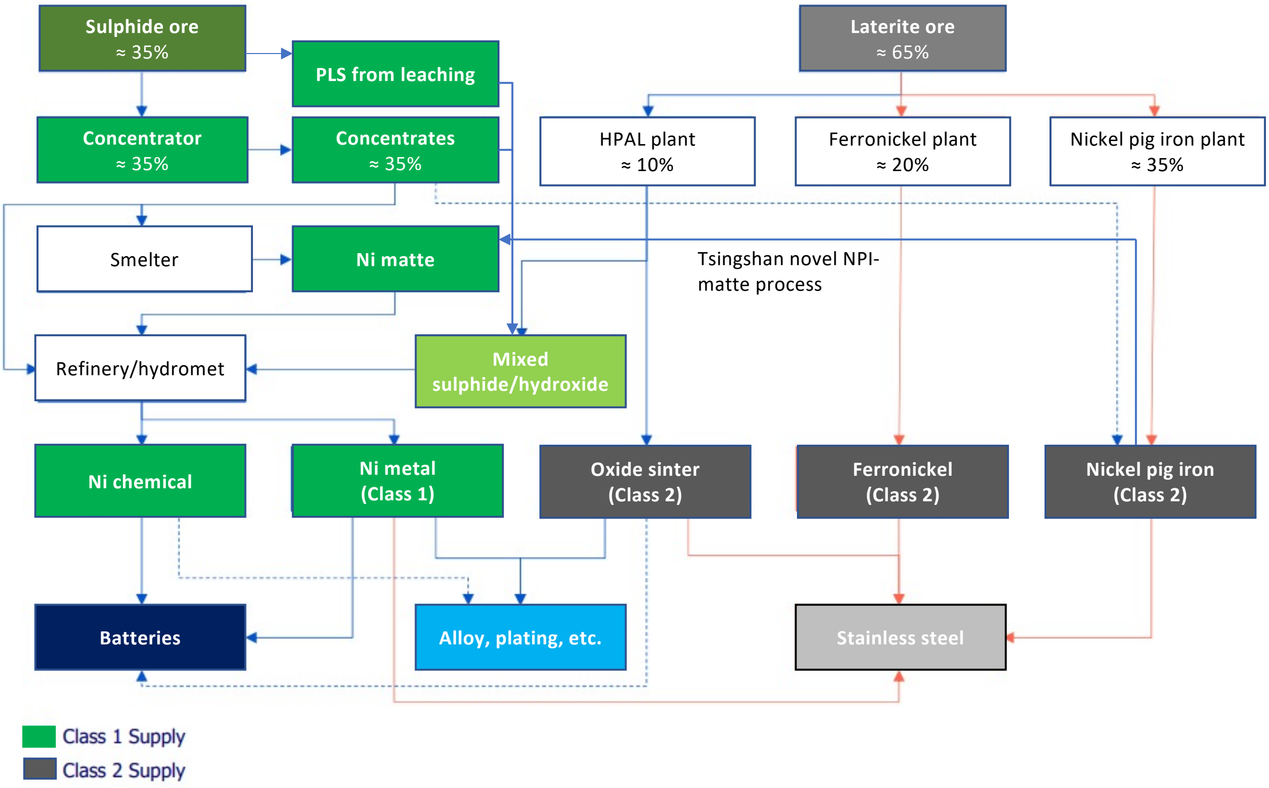


Fig. 18. Summary of the available nickel and cobalt processing options in use currently. For the sulphide ores PLS from leaching may refer to various technical implementations to recover the PLS (or pregrant leach solution for downstream metal precipitation), for example Terrafame Sotkamo type of heap leach or Voisey's Bay type of atmospheric-pressure leaching. The summary is compiled based on various sources used in this study, including Heikkinen & Heino 2002, Kerfoot et al. 2002, Cheng & Urbani 2005, Willis 2007 and Törmänen & Tuomela 2021.

4 FUTURE SCENARIOS

Based on the project Roadmap presented in the preceding chapters, the following high-level future scenarios have been constructed in order to study the maximal value chain benefits from Battery raw materials point of view.

These scenarios provide possible holistic development paths that may take place to some extent or may not happen, or the actual outcome is combination of the scenarios. The purpose of these scenarios is to present overview of possible alternatives that could be actively promoted for example by the Government parties as part of implementation of Finnish Battery Strategy. Or by the industry players together when studying further the battery ecosystem, trying to maximize the production and benefits for all parties. All scenarios presented hereafter are solely generated by GTK based on the information and input from the preceding chapters. The companies that have been interviewed during the work have not contributed to this scenario work and therefore these scenarios do not represent company visions or objectives as such.

An important starting point is that many of the deposits and respective mines are rather small (in global comparison) by the potential tonnage they could be producing. To attain benefits of bigger scale an idea of centralized concentrate downstream processing plant is included in several of the scenarios. Most likely this could be a hydrometallurgical facility producing MHP or MSP type of products, possibly refining them to even battery chemicals.

4.1 Scenario Zero

This scenario refers to situation, where all players develop their projects on standalone basis and sell their products on the market (Finland/exported) purely on commercial basis without any coordination or systemic value chain maximization efforts by the Government and Industry Platform. This is the most probable scenario and basically describes business as usual.

In this scenario the Roadmap presented earlier is executed to some extent. Even though the Finnish metal refining industry and battery cluster may operate based on imported raw materials, it is envisaged that domestic production would contribute at least the tonnages produced during 2015–2020 also in the long term, up to 2040s. Domestic production has several significant advantages in global comparison against the peers abroad as described earlier in this report. To keep up the production at current level, or any upscaling, requires new mines ramping up into production according to Battery Strategy objectives. The scenario is not analyzed further here.

4.2 Scenario 1

This scenario can be shortly described as Terrafame-FBC value chain based on the two main companies in upstream and downstream value chains (Stream 1 chapter 2). This visionary scenario would integrate other upstream producers into Terrafame battery chemical plant as external feedstock sources in addition to Terrafame internal Sotkamo mining operations-heap leach-metal plant -operations. In that sense the battery chemical plant can be seen as mid-stream production.

External upstream feedstocks

To enable external feedstock production for Sotkamo battery chemical plant, this scenario includes two centralized hydrometallurgical facilities (Fig. 19). One in northern Finland and the other one in south-eastern Finland. Alternatively, there could be only one such facility but from logistical point of view two facilities likely could enable more cost-effective processing as transportation most likely would take place by trucks. The location of such facility or facilities should be optimized based on available raw material feedstocks (tonnage, quality) and timing of individual projects. The idea is that centralized processing facility could process concentrates from several individual, possibly small mines. Construction of dedicated hydrometallurgical plant is not easily justified for a mine, even a larger one, like indicated by Suhanko Platsol-project having not been executed to date.

The owner and operator of such facilities is subject to separate studies with proper tradeoffs between the various options. Possibly the company could be a joint venture of all individual companies providing raw materials for refinement:

Practical aspects might favour the biggest (and longest operating) feedstock producer or otherwise logistically central location to host such a facility. In north Finland this could be for example Rovaniemi or Suhanko mine site, assuming Sodankylä raw materials will feed pyrometallurgical production stream. In south Finland the location could be for example Outokumpu or even Terrafame Sotkamo. One option could also be to place just one facility into Terrafame Sotkamo and utilize railroad transportation for all the other streams. This could require interim storage and loading facilities for example in Rovaniemi and Outokumpu.

Regardless of the hydrometallurgical plant location the purpose would be to produce suitable intermediate product to feed the Terrafame Sotkamo battery chemical plant. Basically, the facility would contain pressure leaching and respective hydrometallurgical process, producing mixed hydroxide precipitate (MHP containing Ni-Co etc.) or alternatively mixed sulphide precipitate (MSP) similar to current Terrafame Sotkamo current feedstock. MHP plant would likely be a cheaper investment and similarly cheaper and easier to operate. But on the other hand would require bigger investments in Sotkamo. Engineering of the hydrometallurgical plant should take into consideration all potential concentrate feedstocks to optimize the process for each one of these to be processed individually in batches or continuously in proper mix.

An important aspect that should be studied further in connection to this scenario, is the side stream potentially produced by Kuusamo type of deposits (Latitude 66 Kuusamo project, Mawson Rajapalot project and other similar projects), namely uranium containing tailings. If such stream would be produced at adequate quality, it might be possible to refine the stream at Terrafame Sotkamo uranium extraction plant. Obviously, this would require detailed technical studies and especially it would be subject to most stringent permitting procedures. Still this kind of centralized uranium refining stream would be environmentally the most optimal solution instead of several parallel facilities or solutions. Especially if the uranium issue would otherwise prevent the granting of environmental permit for these mines, this could be an option for detailed future studies.

Midstream

It is evident that this kind of external feedstocks would require investments also at Sotkamo as well as proper permitting procedures. Likely at least a parallel pressure leaching process line next to current one as well as more capacity to the subsequent process phases or complete separate process line.

Whichever way the practical project execution would happen, to subsequent nickel and cobalt chemicals would feed the FBC downstream process facilities on the coast or alternatively sold on the market.

Alternatively, this midstream refining step could be done at the upstream hydrometallurgical facility with proper leaching-extraction-precipitation processes requiring extra investments at these sites. Without proper technical studies the feasibility of either option is impossible to estimate. Intuitively modest upscaling of existing big scale plant would be more feasible option though than construction of stand-alone new facility.

Downstream

Produced chemicals could be utilized by the planned Finnish Battery Chemical (FBC) pCAM/CAM plants on the coast either in Vaasa or Hamina/Kotka or both, depending the ultimate production capacity.

Eventually produced CAM material could possibly be exported if there was no Finnish cell or battery factories in operation. Currently there are no known actual battery plant projects in Finland, besides Valmet Automotive plants in Salo and Uusikaupunki. However potential integration into these value chains could be studied separately in the future.

Potential benefits

Regardless of the ultimate technical solutions, business model and ownership, the proposed utilization of external upstream feedstocks would provide opportunity for further production expansion or increase of domestic raw material share for the Finnish Minerals Group portfolio companies. Assuming the FBC plans will become actual, the upside of this scenario would also be the maximal domestic value addition to the primary raw materials.

Further details should be carefully studied having better knowledge on the concentrates of the mines in question (tonnage, quality, timeline etc.). Proper technical-economical studies would shed light on the feasibility of any of these options and mines possibly involved in the system. Even though the individual projects are developed and run by individual companies, it might have beneficial to have some sort of national coordination platform to better enable the integration of the projects, to the extent seen beneficial by the companies. From Government side this platform could for example be the recently established National Battery co-operation body (Akkualan kansallinen yhteistyöelin) that was launched to do follow-up of National Battery Strategy. For the Industry Platform the suggestion should become from the industry.

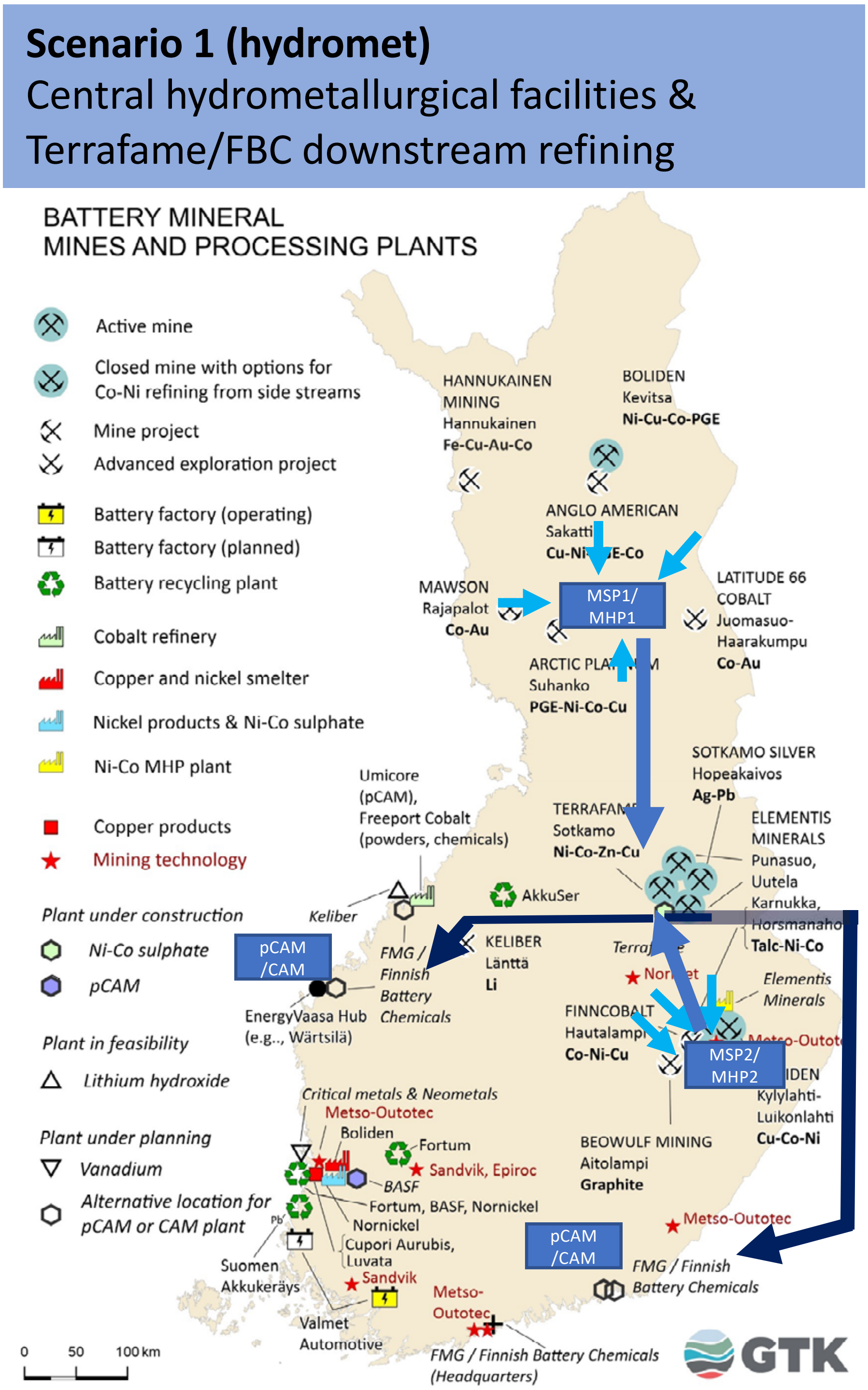


Fig. 19. Scenario 1 includes one or two centralized hydrometallurgical plants producing proper feedstock (MSP/MHP) for Terrafame Sotkamo battery chemical plant feeding the pCAM/CAM plants on the coast.

4.3 Scenario 2

This scenario is in principle pretty similar to the scenario 1, having similar centralized hydrometallurgical facilities or facility that could process the concentrate streams from the individual mines. The main difference is that instead of using Terrafame/FBC facilities for intermediate products refining, the materials would be channeled to the existing refineries on the west coast (Fig. 20), effectively utilizing the existing Stream 2 and 3 facilities (see chapter 2).

Utilization of existing refineries provides several potential upsides in terms of capacity and schedules. Both Nornickel Harjavalta and Umicore/Freeport Kokkola have at current production levels capacity reserve available for increased production if needed. Moreover, Nornickel Harjavalta is planning to significantly upscale their production. Both of these companies also are willing and capable to treat external material streams assuming commercial and technical criteria are satisfactory. Obviously, these need to mutually agreed in each individual case between the parties. In this scenario, the assumption is that proper intermediate feedstock could be produced at adequate tonnage. Most likely MSP would be the preferred feedstock for Nornickel Harjavalta and could also be processed in a smelter process (Boliden Harjavalta, scenario 3) if so preferred. On the other hand, Umicore Kokkola mostly utilizes MHP feedstocks currently, possibly better suiting them also in case of domestic feedstocks.

Existing capacity reserve provides in theory fast option to produce e.g. cobalt and nickel sulphates to be further used in pCAM production. These chemicals could feed the extension of BASF pCAM plant in Harjavalta (as indicated in plant EIA) or Umicore pCAM production in Kokkola as well as recently announced Johnson Matthey-FBC pCAM/CAM plant in Vaasa, having raw material agreement in place with Nornickel.

Biggest downside of this scenario is that at least in case of Kokkola and BASF refining the produced pCAM would be further refined abroad. This is because both BASF and Umicore production chains include CAM plants located outside of Finland. Likely any pCAM feed that the Finnish plants of these companies are able to produce in the future, will be needed in these CAM plants elsewhere in Europe.

Anyhow at Harjavalta the produced battery chemicals could enable BASF Harjavalta expansion or feed the planned Johnson Matthey-FMG CAM plant operations in Vaasa. At Kokkola the domestic feedstock could partly replace imported raw materials or alternatively enable further production expansion

Importantly Nornickel Harjavalta process also enables treatment of feedstocks containing low grades of uranium. This sidestream is currently stored on site but in the future may be further refined at Terrafame Sotkamo, however limited to the tonnage.

Namely the tonnage produced in connection to past Talvivaara MSP refining (and streams precipitated parallel to that). Any other new streams would require proper permits in place but technically this option is in place. Any further plans would require dedicated detailed studies on the subject.

Potential benefits

This option provides certain benefits for the number of upstream producers possibly involved in the centralized MSP/MHP production as there would be two options for the sales of intermediate feedstock. Naturally it can be thought that Terrafame Sotkamo would be the third in both options (Option 1 and 2). However, option 1 would require significant new investments in Sotkamo to enable the enlarged battery chemical production based on external feedstocks. Such investment likely would not be justified without long term off-take agreement or similar arrangement, effectively constraining the amount of potential customer. Option 2 could be quite easily applied for the existing flowsheets, in any case the potential investment needs being way smaller than in Option 1. Also the market demand for MSP/MHP intermediate feedstock is estimated to be high in the future, leaving an option for feedstock exports as well. Not to forget the opportunity to sell MSP product for Scenario 3 type of pyrometallurgical processing. In a way this Scenario 2 is the most flexible of all three main scenarios providing plenty of options for the upstream and midstream producers.

Fig. 20. Scenario 2 includes one or two centralized hydrometallurgical plants producing proper feedstock (MSP/MHP) for existing downstream refineries on the coast producing battery chemicals for the pCAM/CAM plants on the market domestically and abroad.

4.4 Scenario 3 Pyrometallurgical route

This option is fundamentally different in terms of process path and logistics compared with Options 1 and 2. Basically the concentrates produced by each individual mine would be transported to Boliden Harjavalta smelter for production of Nickel (Co) matte and no intermediate production would take place (Fig. 21), that corresponds to Stream 4 as presented in chapter 2. Also the copper concentrates could in principle processed by Boliden Harjavalta producing minor nickel (and possibly cobalt) sulphate side stream(s). This scenario has connection to scenario 2 as MSP intermediate could also be pyrometallurgically processed in a smelter.

Domestic nickel-cobalt concentrates make up some 40–50% of the current Harjavalta feed. The rest is made by imported concentrates. Hence, the export concentrates could be 1) partly replaced by new domestic concentrates or 2) provide feed increase overall as during most of the recent years the plant has not been running at full capacity or 3) enable capacity increase even higher than current expansion plans envisage.

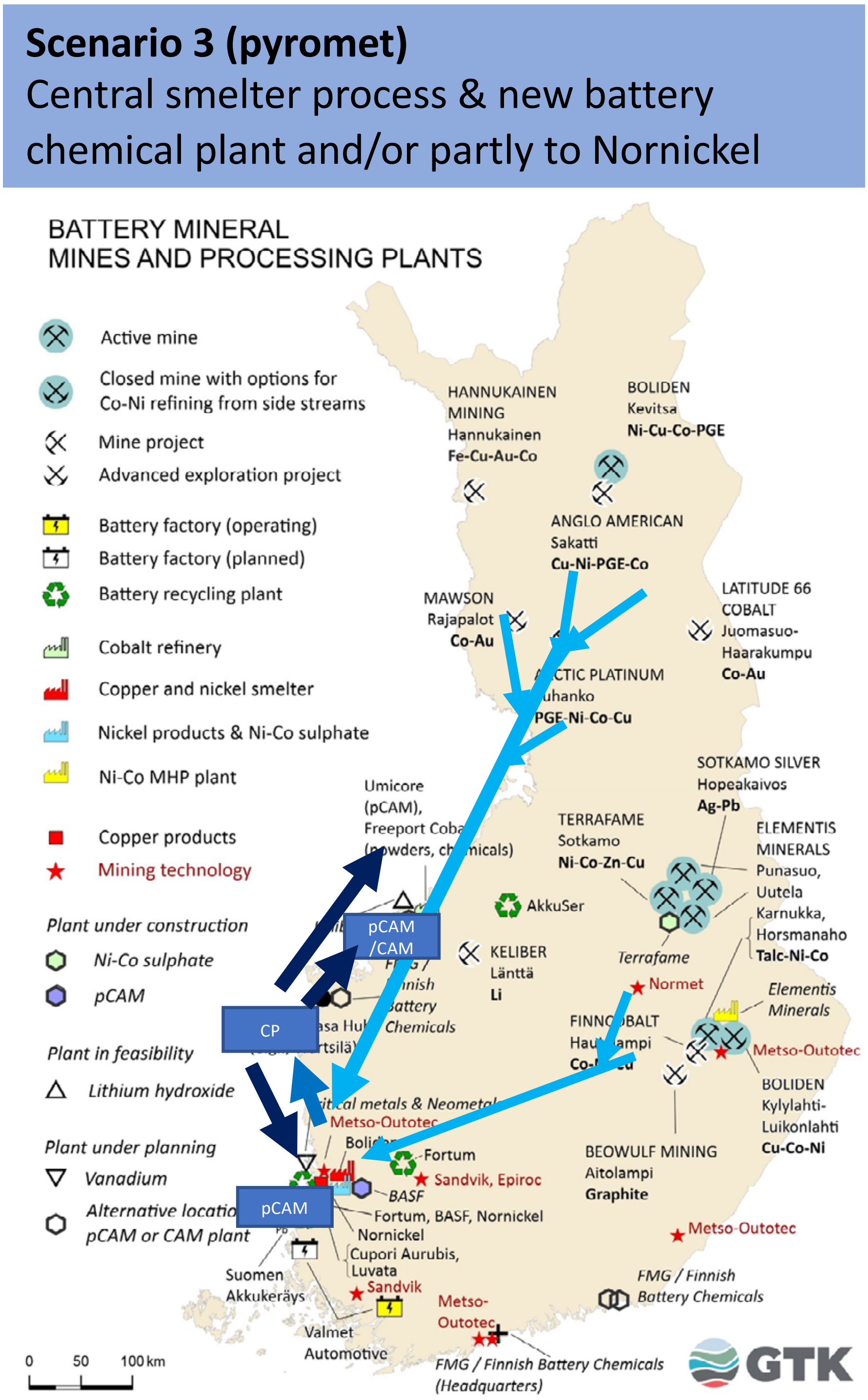


Fig. 21. Option 3 includes production of sulphide concentrates with pyrometallurgical processing at Boliden Harjavalta smelter. This nickel matte could be further refined at nearby Nornickel refinery or dedicated new facility could be constructed for the purpose. Battery chemicals from this downstream refining could feed Johnson Matthey-FBC pCAM/CAM plant or other similar plants in Finland or abroad.

From capacity increase point of view, the expansion of current facility is much easier than permitting and construction of completely new smelter elsewhere, no matter the location. Therefore, if pyrometallurgical process route is envisaged, Boliden Harjavalta is definitely the most likely option for the execution of this scenario. Investment and successful permitting of stand-alone new smelter is rather unlikely in any OECD country recently.

In case of pyrometallurgical process path the interim product would be the matte and slag that needs to be further refined into metal products or chemicals to benefit the domestic battery ecosystem. This could happen at nearby Nornickel facility that optionally uses external feedstocks or alternatively would require a new plant with process similar to Nornickel Harjavalta, capable of leaching the matte and producing nickel and cobalt chemicals in order to further refine them to pCAM materials. The latter option would be a significant investment. Johnson Matthey-FBC or other FBC plants could be an option or then sales on the market.

Potential benefits

This would be pretty close to Scenario Zero, where most of the individual mine projects likely undertake negotiations with Boliden Harjavalta regarding their respective products. Clear upside is that there would be no need for extra investment for the centralized hydrometallurgical processing plant, even though the investment would be somehow jointly funded by the companies. On the other hand, some of the upstream producers may find that their concentrate is not suitable or preferred by Boliden Harjavalta for various reasons, for example either due to quality or inadequate tonnage or both. Most likely at least some of the new projects will anyhow proceed according to this scenario.

If the smelter products were refined in the new refining facility or would be refined by Nornickel existing (and expanding) facility, this would be a big change to the current situation where the end products are basically all exported to be further refined abroad. This would likely be the biggest change and benefit from value chain and national economy point of view.

4.5 Other potential future streams

There are numerous other potential feedstocks available as discussed earlier. These include for example: Hannukainen pyrite concentrate, Luikonlahti CoNi-concentrate, other Boliden Harjavalta side streams, slags etc. and Boliden Kevitsa high sulphur tailings as well as numerous recycling streams.

These cannot be grouped into any stand-alone scenario with the potential exception of recycling stream. It is obvious that the recycling stream under development by Nornickel, BASF and Fortum will be strengthened and the tonnage treated and produced will evidently grow significantly in the future. Perhaps other similar initiatives will also be developed by other industry players. This stream will develop in parallel to all other scenarios or their combination, regardless of the actual outcome.

The utilization of the other side streams is a more challenging question and mostly beyond the scope of this study. It is evident though that most likely the ultimate processing of these streams takes place with some advanced or novel hydrometallurgical techniques rather than with pyrometallurgical processing initially. This seems to emphasize the opportunities possibly generated by the Scenarios 1 and 2 that could possibly also enable or promote the utilization of one or several of the mentioned side streams.

Further details should be carefully studied from technical, economical and permitting point of view. Basically, nothing can be said on the feasibility of any of these streams for the moment being.

4.6 Production opportunities

Table 18 summarizes the potential cobalt and nickel production by the mines included in the Roadmap and also the associated maximum chemical, pCAM/CAM production from domestic raw material sourcing. Mine and chemical production is estimated for five-year timespan periods. Production of refined products (pCAM/CAM) is estimated from 2025 onwards. In brief the table summarizes the maximum pCAM/CAM production based on domestic raw materials and feedstock, not including the side streams described earlier in the report. It is emphasized that it is unrealistic assumption that all domestic primary mine production would be channeled to battery chemicals production. Still it is important to evaluate the overall potential of the domestic battery value chain.

Further regarding the mine production, it is to be considered that the estimated quantities are in the higher end of potential production range. Most likely some of the mines will not become operational eventually or the products will not contribute to the battery value chain at all.

Maximum total cobalt sulphate production could be around 9 500–15 000 tpa depending on the operating mines at each period. Similarly nickel sulphate production could be 220 000–280 000 tpa at maximum. The chemical demand by the pCAM-CAM plants is not known in detail. But assuming the published 30 000 tpa pCAM production by BASF and estimated 30 000 tpa production by FMG-FBC and their joint venture partners in the pCAM-CAM production, it is assumed that total pCAM production around mid-2020s onwards would be roughly 90 000 tpa. This is not including Umicore pCAM production that is not publicly disclosed. Depending on the Umicore pCAM chemistry their production could be roughly similar, hence total production could be around 150 000–200 000 tpa.

Not accounting the Umicore pCAM production further but simply considering their cobalt sulphate production in addition to BASF and FMG-FBC plants, the total cobalt sulphate demand would exceed 70 000 tpa.

Nickel sulphate demand would be around 200 000 tpa counting only BASF and FMG-FBC plants. Depending on the Umicore pCAM chemistry the total demand could be even double. Manganese sulphate demand would be roughly 10% of nickel sulphate demand.

Considering the estimated maximum domestic nickel and cobalt sulphate production, it is evident that domestic nickel supply is much higher than for cobalt. If not accounting Umicore nickel demand, the domestic nickel supply could in principle meet the raw material supply for now planned pCAM-CAM plants. Obviously not all domestic nickel production is directed to this value chain but at theoretical level this shows the potential of domestic feedstock. In case of cobalt, maximum 20% of the demand could be supplied domestically, emphasizing the constant need for large scale cobalt imports the future as well. If the cobalt containing side streams could be utilized in the future, the domestic cobalt supply could be even higher than the estimated 20%.

Precursor materials from BASF and Umicore are to be exported and will not feed the Finnish value chain any further in the future either. There are only two Finnish CAM plants being planned for the moment being. Assuming their combined production being 60 000 tpa, the nickel supply could be sourced domestically also in practice as Terrafame nickel sulphate production could be adequate for this CAM production volume. Regarding cobalt 70–100% could be sourced domestically, depending the mines operating and if all primary production was refined into cobalt sulphate. In practice the share would likely be 50–60% maximum. Some 50% of lithium could be supplied by Keliber according to current production plans.

With these CAM production assumptions roughly 40 GWh cell factory could be sourced, equaling the size of Northvolt Skellefteå plant after the planned expansions. Naturally this would require adequate anode raw material supply, basically graphite of which Beowulf could produce certain percentage. Depending on the project size, possibly most or even all the needed supply. Cell factory of this size could hence at best operate mostly with Finnish raw materials, still needing imported manganese feedstock if domestic production cannot be ramped up, and up to 50% of cobalt and lithium supply unless the domestic side streams are utilized and Keliber production expanded. In addition, there could be significant amount of nickel sulphate and/or other nickel products still exported for other applications.

Currently there are no public Cell factories disclosed anywhere in Finland. Although there are battery factories operated by Valmet Automotive for example, they rely on imported raw materials/cells and concentrate to the very downstream end of the battery manufacturing. Chapter 4.7 presents few generic thoughts on this last value chain step in the battery production.

Table 18. This table summarizes the outcome of potential mine production scenarios presented in the text and associated maximum possible domestic battery chemical and material production. All figures are tpa. Figures are rounded for clarity and uncertainties in the estimates. Note that all figures are estimates by GTK and have not been disclosed us such by the companies. It is noted also that this scenario does not take a stand for materialization probability for any individual project. Potential metal tonnages are presented separately for North and South Finland. Cobalt tonnages and associated chemicals are shaded with dark blue and nickel with light blue respectively. Table section 1 (mines) shows estimated production by time periods. Section 2 (refineries) shows estimated production from 2022–2025 onwards. CAM production estimate from 2025 onwards is based on estimated FMG-FBC pCAM/CAM plants capacity.

MINES: Finnish Co-Ni mines potentially in production from 2020 onwards

Period	**2021–2025 Co/Ni**	**2026–2030 Co/Ni**	**2031–2035 Co/Ni**	**2036–2040 Co/Ni**	**2041–2050 Co/Ni**	**Note**
North Finland projects						
Kevitsa	500/11 500	500/11 500	500/11 500	-	-	
Suhanko	-	125/1 200	125/1 200	125/1 200	125/1 200	
Sakatti	-	-	500/11 500	500/11 500	500/11 500	
Rajapalot/Kuusamo	-	-	400/-	400/-	NA	LOM estimated
Sub-total	**500/11 500**	**625/12 700**	**1 525/24 200**	**1 025/12 700**	**625/12 700**	
$CoSO_4$	2 400	3 000	7 300	4 900	3 000	
$NiSO_4$	52 000	57 000	109 000	57 000	57 000	
South Finland projects						
Sotkamo	1 500/37 000	1 500/37 000	1 500/37 000	1 500/37 000	1 500/37 000	Terrafame
Talc mines	20/1 200	20/1 200	20/1 200	20/1 200	20/1 200	Elementis
Hautalampi	-	300/1 000	-	-	-	
Sub-total	**1 520/38 200**	**1 820/39 200**	**1 520/38 200**	**1 520/38 200**	**1 520/38 200**	
$CoSO_4$	7 300	8 700	7 300	7 300	7 300	
$NiSO_4$	172 000	176 000	172 000	172 000	172 000	
TOT $CoSO_4$	**9 700**	**11 700**	**14 600**	**9 700**	**9 700**	**North+South**
TOT $NiSO_4$	**224 000**	**233 000**	**281 000**	**229 000**	**229 000**	**North+South**

REFINERIES: Upcoming and potential pCAM/CAM plants from 2025 onwards

Feed		**$NiSO_4$**	**$CoSO_4$**	**$MnSO_4$**	**LiOH**	
BASF		50 000	10 000	10 000[3]	-	30 kt pCAM
Umicore[1]		NA	33 600	NA		in production
Freeport[1]		-	14 400	-		in production
FMG-FBC pCAM-CAM plants being planned (west and south coasts)		150 000	15 000[2]	15 000[3]max		FMG JVs **á 30 kt pCAM/ CAM**
Total battery chemicals		200 000[4]	73 000	25 000[4]max		
Domestic share maximum		100+%	20%	-		
pCAM 2025 –>			**≈90 000+[4]**			Coast
CAM 2025 –>			**≈60 000**	≈ 40 GWh	30 000[5]	Coast

[1] Currently use mostly imported raw materials only. Share of cobalt production is assumed to be ca. 55% for Umicore and rest for Freeport. All Umicore cobalt production is estimated to be refined into $CoSO_4$ and 50% of Freeport production respectively.

[2] Terrafame Sotkamo produces only ca. 50% maximum of this amount.

[3] Not currently produced in Harjavalta or Sotkamo.

[4] This figure does not include Umicore pCAM production and associated $NiSO_4$ and $MnSO_4$ demand.

[5] Keliber plans to produce roughly 50% of this tonnage maximum.

4.7 Cell factories and downstream applications

There are currently a few major companies that operate with the downstream applications, i.e. at the end of the battery value-chain. These are Valmet Automotive and Sandvik as well as few other mining machinery manufacturers and Celltech to name a few.

Valmet Automotive is partly owned by CATL and is in strategic partnership with the company. CATL in turn is one of the leading global companies in the development and manufacturing of lithium-ion batteries. CATL business covers R&D, manufacturing and sales in battery systems for new electric vehicles and energy storage systems. CATL has internal raw material sourcing and production networks and is one of the battery cell/modules providers for Valmet Automotive.

Valmet Automotive in turn manufactures battery systems for electric vehicles. There is an existing battery factory in Salo (48 V systems) with an option to later expand to batteries of industrial applications. In battery contract manufacturing, Valmet Automotive is already one of the globally leading providers, with a capacity of hundreds of thousands of battery systems annually. Another factory is under construction in Uusikaupunki. This plant will be focusing on high-voltage automotive battery systems and modules, also for full electric vehicles. (Valmet 2021)

Although currently both factories operate with imported cells/modules, in the future it would be worthwhile to study in detail the options to utilize Finnish pCAM/CAM products in Valmet Automotive production chain, on a way or another. This production chain has not been studied further in connection to this study.

Similarly, the battery material sourcing for Finnish & Nordic working machinery manufacturers, especially the ones providing machines for the mining industry could be potential end users for the battery materials produced. After all these companies are leading global players on their field and electrification is rapidly increasing in mining industry also. Finland is not and never will be the country of major automotive manufacturing. Instead we are and aim to maintain our leadership in these selected niche sectors, like mining machinery, especially in the underground mining applications. Of the companies operating in this sector Normet, Sandvik and Epiroc are good examples of globally competitive manufacturers. Completion of the EV-value chain in this kind of special applications could very well be a big future opportunity for Finland and Nordics. This special value chain should be one of the targets for future research and business development.

It is to be noted though that the battery systems for these applications may be different compared with common EV applications. For example, Sandvik uses Artisan™ battery systems that are based on litium-phosphate-iron-chemistry (LFP/$LiFePO_4$). (Sandvik 2021). These are at least partly used also by Epiroc (Epiroc 2021). In addition to heavy duty applications LFP batteries have also experienced resurgence for electric vehicle applications, especially in Asia. Finland has geological potential for these LFP commodities as well and production currently (phosphate) or planned production (lithium, iron) for example from Sokli deposit that is currently owned and developed by FMG subsidiary Sokli Oy.

Finnish battery value chain includes all the value chain steps despite the production of cells and modules. These abovementioned companies operate in the very last value chain step manufacturing tailor-made battery systems into their vehicles.

5 SUMMARY AND CONCLUSIONS

5.1 Global nickel and cobalt supply and demand

Nickel and cobalt are among the most essential commodities for the cathodes of lithium ion batteries. Significance of nickel is increasing due to new cathode chemistries. DRC is well known centre of global cobalt production (70% of total production as copper mining byproduct) but nearly third of cobalt is produced elsewhere as by-product from lateritic and sulphidic nickel mines. In terms of nickel production South-East Asian Indonesia and Philippines are the global heavyweights totaling nearly 50% of world production, followed by Russia and New Caledonia. In South East Asia nickel production has experience a tremendous growth during since 2000, mainly due to Chinese companies investing heavily into nickel pig iron (NPI) production.

The mines operating in these countries are predominantly lateritic ores. Main sulphidic nickel deposits and mines are located in Russia, Canada, Australia and Finland, hence mostly at higher latitudes. Traditionally the sulphidic deposits have been exploited for the battery value chain purposes but lateritic nickel and cobalt is being increasingly utilized due to limited supply from sulphidic deposits and new processing techniques like HPAL. Most recently the Chinese have developed technique to apply NPI production of intermediate feedstocks for battery industry purposes. These intermediate feedstocks like mixed hydroxide precipitate (MHP) and mixed sulphide precipitate (MSP) are most typical and preferred feedstocks for the battery chemical manufacturers, producing precursor and cathode active materials for the next value chain steps. Similarly, MHP is the most typical export product in DRC.

Utilization of lateritic nickel deposits is in practice crucial for adequate supply of nickel and cobalt, especially when considering the constantly increasing demand for these commodities. For example, in case of nickel, the global supply was 1.5 Mtpa in 2000 but has grown to 2.5 Mtpa in 2020. The demand could exceed 3.5 Mtpa by 2030 and 4.5 Mtpa by 2040 whereas projected supply does not exceed 3.5 Mtpa even in the 2030s. It seems like investments into new mines and production capacity cannot match the increasing demand for nickel or cobalt either. This is due to many reasons, such as insufficient exploration during the past decades and scarcity of new discoveries. Also, the timeframe to ramp up a mine is increasing all over the world, the global average being 17 years since deposit discovery and exceeding 20 years in many developed countries like Finland. Therefore, the mining industry capacity for rapid new supply is severely constrained.

Moreover, there are many challenges and even deficiencies associated with environmental performance, sustainability and traceability regarding many mines located in DRC and South East Asia for example. When CO_2 footprint and effects to biodiversity are considered, these mines located close to Equator or low latitudes in general, the detrimental effects are much more pronounced than for the mines located at higher latitudes, the latter being typically sulphide ore mines and the former laterite ore mines. Most sustainability indicators therefore heavily favor sulphidic ore mines over laterite ore mines.

Compared with the base metal or gold mining, it is remarkable how few nickel and cobalt mines there are globally. There are less than 100 active nickel mines currently and less than 50 for cobalt. Moreover only 22 nickel mines operate in OECD countries and 17 mines in case of cobalt. In case of cobalt it is to be remembered that only one mine in Morocco produces cobalt as a major commodity. Supply risk is further emphasized by the fact that out of these few mines, few giant mines dominate the production. For nickel the Top10 mines account nearly 35% of total output and Top17 mines nearly half of total output whereas for cobalt Top10 mines produce nearly 65% of total output and Top15 nearly 75% of total. In comparison to copper for example, there are over 450 mines in production globally of which 55 mines produce 62% of total output and 93 mines 75% of total output. In other words, production is much less centralized or more disperse.

Finnish mines and deposits are mainly small in comparison with global giants. Still Terrafame Sotkamo has position 22 regarding global nickel production and position 25 for cobalt. Kevitsa has positions 52 and 36 respectively. Mines of this size are not insignificant, especially in European context and when evaluating the environmental and sustainability performance of the production. There are numerous small mines in operation globally also. Some 45% of the global nickel mines are smaller than Kevitsa and 23% of the cobalt mines. Many of these produce less than 5 000 tpa nickel and/or less than 400 tpa cobalt, still adding their share into the much needed demand. New planned mines are not very numerous for either commodity, some 20+ projects with disclosed nickel production exceeding 5 000 tpa and 15 projects exceeding 400 tpa cobalt. Typically, many of the projects in development never mature into operational phase. Clearly there is demand for new producers, especially considering the projected demand scenarios for both commodities.

5.2 Finnish battery ecosystem and future roadmap

The Finnish battery ecosystem is one of the most developed in Europe. Finland is the predominant producer of primary nickel and cobalt in European comparison, also being the most important producer of refined products for these commodities as well as feedstocks for the battery industry although partly operating based on imported raw materials.

Primary nickel production has exceeded 40 000 tpa at times and cobalt production 1 500 tpa. Refined nickel production has exceeded 90 000 tpa and cobalt production 15 000 tpa, i.e. more than double (nickel) and ten times (cobalt) the domestic primary production. There are plans to further increase the refining capacity, both by Nornickel and Boliden Harjavalta.

Battery material refining streams

This study identified five separate refining streams for these commodities in Finland.

Stream 1 being the Terrafame-Finnish Minerals Group stream, majority owned by the state. The stream consists of Terrafame Sotkamo mine, associated battery chemical plant and planned pCAM-CAM facilities on the coast. In the future the Sotkamo mine production will be fully utilized by the battery industry.

Stream 2 consists of Nornickel Harjavalta nickel refinery and associated BASF pCAM plant exporting their product abroad. Nornickel mostly operates based on company internal feedstock imported from Russia but also uses other external feedstocks. The production is only partially directed to BASF with rather extensive product portfolio for various industry applications being produced.

Stream 3 includes the Kokkola cobalt refinery operated jointly by Umicore and Freeport, the former being in charge for raw material sourcing and initial processing. Umicore produces pCAM materials for the company CAM plants abroad. Freeport produces cobalt chemicals, partly feeding the battery industry but main products are e.g. various cobalt powders.

Stream 4 is operated by Boliden, including company mines in Finland as well as Harjavalta nickel smelter. The smelter treats internal concentrate feedstocks but also uses external streams. The produced nickel matte is exported abroad and may only partially feed battery industry.

Stream 5 is currently minor one compared with the other streams. It includes the recycling companies of which most important is the conglomerate operated by Fortum and Nornickel-BASF in Harjavalta. Together with the Ikaalinen recycling plant they are capable to effectively recycle LIB batteries returning these commodities back into industry feedstock, for example to the battery industry. This stream will grow its importance in the future when there will be more recycled material available.

Primary production Roadmap 2020–2050

One of the Finnish battery strategy objectives is to grow and renew the Finnish battery sector. This includes also the development of the first value chain step, namely the mines. This study identifies the most advanced Finnish battery mineral mine projects and a Roadmap 2020–2050 has been prepared in order to evaluate the potential tonnage and timeframe of the planned production.

Altogether there are five mine projects aiming to produce nickel and/or cobalt and one project each aiming to produce lithium and graphite. These projects have been selected based on their maturity and opportunity to ramp up production by early 2030. In addition, there are a few projects that could contribute on nickel-cobalt production assuming the existing side streams could be economically processed. Obviously, there are many other less mature projects but their production would most likely ramp up towards late 2030s or 2040s, hence they are excluded from more detailed evaluation.

Most likely all of these planned mines will not become operational but still it is estimated that Finnish nickel production could increase to the level 50 000 tpa (41 400 t 2020) and cobalt production to the level of 2 500 tpa (1 560 t 2020) during the following decades. Even higher production figures are possible if the major mine projects advance as planned. On the other hand, the worst case option is that domestic production of these commodities will be nearly zero from mid-2030s onwards, when the Kevitsa and Sotkamo operations life of mine is thought to end and if new mines are not substituting their production. Current investment climate is not very favourable for new mines so this option should be taken seriously enough.

Even though the Finnish nickel-cobalt deposits are sulphidic, enabling conventional smelter processing, they can typically also be processed hydrometallurgically. This approach enables even production of battery chemicals, like Terrafame, or possibly production of intermediate products like MHP and MSP. The latter of these may also be used as smelter feedstock providing numerous opportunities for the product sales. Common problem with hydrometallurgical processing is the high investment cost for the hydrometallurgical plant. This could possibly be tackled with one or more centralized hydrometallurgical plants in logistical locations. With proper ownership arrangements, this could possibly provide feasible way to utilize the feedstocks from several smaller mines. Combined intermediate product or battery chemical stream from this kind of facility could be significant, even when comparing the smaller or mid-tier producers globally.

Battery ecosystem development scenarios

Similar to current refining streams, several future scenarios have been built up to study alternative value chain options.

Scenario 1 consists of Terrafame and FMG portfolio companies. This scenario would integrate other upstream producers into Terrafame battery chemical plant as external feedstock sources in addition to Terrafame internal Sotkamo mine feedstock. There could be one or more centralized hydrometallurgical facilities in proper places, producing MHP or MSP intermediate products to be further processed at Sotkamo. Battery chemicals produced in Sotkamo could in turn feed to pCAM-CAM plants on the coast.

Scenario 2 is to some extent similar to previous one, but instead battery chemical production in Sotkamo, the other existing facilities on the coast could be used, namely Nornickel Harjavalta and/or Kokkola cobalt refinery. At Harjavalta the produced battery chemicals could enable BASF Harjavalta expansion or feed the planned Johnson Matthey-FMG CAM plant operations in Vaasa. At Kokkola the domestic feedstock could partly replace imported raw materials or alternatively enable further production expansion.

Scenario 3 includes use of Boliden Harjavalta smelter and pyrometallurgical processing to produce nickel-cobalt matte. In practice this would be pretty close to current situation where most companies study the suitability of their concentrate into Harjavalta process. It may not be only the technical constraints preventing their treatment but also matter of tonnage and price. Domestic nickel-cobalt concentrates make up some 40…50% of the current Harjavalta feed. The rest is made up by imported concentrates. Hence, the export concentrates could be 1) partly replaced by new domestic concentrates or 2) provide feed increase overall as during most of the recent years the plant has not been running at full capacity or 3) enable capacity increase even higher than current expansion plans envisage. Most likely this will be the route that at least some of the new mines follow. To convert this stream into the benefit of domestic battery ecosystem, the produced interim products should be further refined into metal products or chemicals. This could happen at nearby Nornickel facility that optionally uses external feedstocks or alternatively would require a new plant with process similar to Nornickel Harjavalta, capable of leaching the matte and producing nickel and cobalt chemicals in order to further refine them to pCAM materials. Especially the latter would be a significant investment.

If all the mines envisaged in the Roadmap would contribute to the battery ecosystem, the maximum total cobalt sulphate production could be around 9 500…15 000 tpa depending on the operating mines at each period. Similarly nickel sulphate production could be 220 000…280 000 tpa at maximum. It is assumed that total pCAM production around mid-2020s onwards would be roughly 90 000 tpa. This is not including Umicore pCAM production that is not publicly disclosed. Not accounting the Umicore pCAM production further but simply considering their cobalt sulphate production (based on cobalt refining tonnage) in addition to BASF and FMG-FBC plants, the total cobalt sulphate demand would exceed 70 000 tpa. Nickel sulphate demand would be around 200 000 tpa counting only BASF and FMG-FBC plants.

Considering the estimated maximum domestic nickel and cobalt sulphate production, it is evident that domestic nickel supply is much higher than for cobalt. If not accounting Umicore nickel demand, the domestic nickel supply could in principle meet the raw material supply for now planned pCAM-CAM plants. Obviously not all domestic nickel production is directed to this value chain but at theoretical level this shows the potential of domestic feedstock. In case of cobalt, maximum 20% of the demand could be supplied domestically, emphasizing the constant need for large scale cobalt imports in the future as well. If the cobalt containing side streams could be utilized in the future, the domestic cobalt supply could be even higher than the estimated 20%.

Precursor materials from BASF and Umicore are to be exported and will not feed the Finnish value chain any further in the future either. There are only two Finnish CAM plants being planned for the moment by FMG and their JV partners. Assuming their combined production being 60 000 tpa, the nickel supply could be sourced domestically as Terrafame nickel sulphate production could be adequate for this CAM production volume. Regarding cobalt 70–100% could be sourced domestically, depending the mines operating and if all primary production was refined into cobalt sulphate. In practice the share would likely be 50–60% maximum. Some 50% of lithium could be supplied by Keliber according to current production plans.

With these CAM production assumptions roughly 40 GWh cell factory could be sourced, equaling the size of Northvolt Skellefteå plant after the planned expansions. Naturally this would require adequate anode raw material supply, basically graphite of which domestic production could cover certain percentage at best of the total need. Cell factory of this size could hence at best operate mostly with Finnish raw materials, still needing imported manganese feedstock if domestic production cannot be ramped up, and up to 50% of cobalt and lithium supply unless the domestic side streams are utilized and Keliber production expanded. In addition, there could be significant amount of nickel sulphate and/or other nickel products still exported for other applications.

Although cell production is the lacking component in the current Finnish Battery ecosystem, also the integration of domestic battery raw material sourcing into the value chain of existing downstream application producers, like Valmet Automotive and Sandvik, could be studied in the future.

These figures emphasize the current significance as well as future potential of the Finnish mining industry and associated battery ecosystem. Finland has a well developed metal refining sector, hence the pure existence of current Finnish battery ecosystem being a huge upside for the upstream value chain producers providing several optional downstream processing options. With proper coordinated development efforts and practical implementation of the Battery Strategy, the battery ecosystem could be promoted in the future, simultaneously benefitting the whole mining and metal refining industry.

Expansion and development of this Finnish battery ecosystem is also well justified from many sustainability indicator point of views, not least the traceability. Demand for more sustainable, traceable production is growing continuously and could therefore be one of the biggest competitive factors for the Finnish battery products.

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