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Carbon Neutral European Battery Cell Production with Sustainable,
Innovative Processes and 3D Electrode Design to Manufacture

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HORIZON-CL5-2021-D2-01 - Environmentally sustainable processing techniques applied to large scale
electrode and cell component manufacturing for Li ion batteries

D2.2 – Report on sustainable raw materials supply chain



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Project Summary

BatWoMan aims to develop sustainable and cost-effective concepts for the production of Li-ion battery cells in the European Union. The project will exploit various technological improvements such as energy-efficient processing of 3D patterned electrodes, an innovative electrolyte filling process, and low-cost and energy-efficient cell conditioning. The implementation of these improvements will be digitally supported and controlled by an AI-driven manufacturing platform. In addition, a battery passport will be created that will contain all key information about the manufacturing process, including materials and their sources, carbon footprint, and efficiency of production steps. The project aims to reduce cell production costs by up to 70% and energy consumption by up to 60%, putting Europe at the forefront of sustainable and cost-effective battery production. The main objectives of the project are to achieve sustainable cell manufacturing with a low carbon footprint and no volatile organic solvents, cost-effectiveness, and verification of environmental improvements throughout the manufacturing process chain. The project will pave the way towards carbon neutral, sustainable Li-ion battery cell production in the European Union, in line with the European Green Deal Action Plan to achieve full carbon neutrality by 2050.

Executive Summary

This deliverable is a screening report on the upstream parts of the lithium-ion battery value-chains, i.e. extraction, processing, and refining of raw materials, needed for manufacturing of components and materials for the batteries. It sheds some light on the urgent need for secure and resilient supply chains, but also on the so far untapped potential within the EU. In line with the latter, suggestions on companies are given, where EU produced (including mining, processing, and refining) battery materials possibly can be procured. The report also gives some general background and overview for the later modelling of the BatWoMan sourcing value-chains, to be used in the life cycle assessment and life-cost assessments.

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Figure 3 Supply risks for different steps in the LIB supply chain. Assessments for Raw Materials and Processed materials in the upper figure (on previous page), assessments for Components and Assembly in the lower (this page). Supply risk (SR) is graded from 0 to 6, where $SR \geq 1$ means the supply-risk is critical (i.e., high risk). Accordingly, the supply risk is relatively high for most of the raw materials needed for LIBs, but the supply risk is even higher for processed materials, because of the poor domestic mining and processing in the EU. Also the component and cell level are critical (in terms of supply risks). Source: Carra S et al. (2023) 37

List of Abbreviations

Acronym / Short Name	Meaning
Al	Aluminium
Al ₂ O ₃	Aluminum Oxide; alumina.
BMI	Benchmark Mineral Intelligence
CML	Institute of Environmental Sciences (CML), which is an institute of the Faculty of Science of Leiden University in the Netherlands
CRM	Critical Raw Materials
Co	Cobalt
CoSO ₄	Cobalt sulphate
CO ₂	Carbon dioxide
Cu	Copper
DRC	Democratic Republic of Congo
IEA	International Energy Agency
EC	European Commission
EU	European Union
EOL-RIR	End-of-life recycling input rate
Fe	Iron
FeMn	Ferromanganese
FeSiMn	Ferrosilicomanganese
Gt	Giga tonne
HPAL	High pressure acid leaching
JRC	Joint Research Centre
HPEMM	High purity electrolytic manganese metal
HPMSM	High purity manganese sulphate monohydrate
LCA	Life cycle assessment
Li	Lithium
LIB	Lithium Ion Battery
Li ₂ CO ₃	Lithium carbonate
LiO ₂	Lithium superoxide
Mg	Magnesium
Mn	Manganese
MnO	Manganese Oxide
MSP	Minerals Security Partnership
Mt	Mega tonne
MWCNT	Multi Walled Carbon Nano Tube
NCA	Nickel, Cobalt, Aluminium

Acronym / Short Name	Meaning
Ni	Nickel
NMC	Nickel, Manganese, Cobalt
NiSO ₄	Nickel sulphate
O	Oxygen
P	Phosphorus
PVDF	Polyvinylidene fluoride; (C ₂ H ₂ F ₂) _n
PTFE	Polytetrafluoroethylene; trade name: Teflon
Si	Silicon
SR	Supply Risk
t, t/y	Tonne, Tonne per year
USGS	United States Geological Survey

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1 Introduction

This deliverable reports a screening study on the upstream part of the battery cell value chain, i.e., the extraction of raw materials (mining and beneficiation of ore to produce a concentrate), processing of these to intermediate and pure metal products (through metallurgy) and refining to compounds suitable for battery component production (electrochemical and/or chemical purification). There are two main end-purposes with this study. Firstly, to bring focus on the challenges for the EU industry and transition with the current raw material and refined material supply-chains, but also to shed light on the so far nonutilized potential to meet these. Secondly, to evaluate the positive (or negative) impact on social, environmental, and economic sustainability when changing the current supply-chain for a certain raw material to such with a stronger sourcing, processing, and refining within the EU (or other more diversified outside), the applied LCA, LCC, and Social-LCA calculations need a full understanding of the entire value-chain and the different steps.

The current report is a screening survey of some of the most important raw materials in this context and will be followed up by a more in-depth report for selected parameters, relevant for the BatWoMan project. In general, major *potential* environmental concerns raised with mining, processing, and refining are abiotic resource depletion, conflicting land-use interests, impact on biodiversity, excessive water use, energy consumption, carbon footprint, release of dangerous substances, and waste generation. In some nations or regions there are additional concerns regarding social sustainability issues such as corruption, ill treatment of indigenous people or other socially weak groups, poverty, labour rights, child labour, corruption, and prostitution. These potential impacts are of interest to evaluate when comparing potential new value chains with the current.

The materials that have been assessed are listed in Table 1. All these (or their battery-grade refined equivalent) are currently considered as critical raw materials by the EU (Table 2). Explanation of some terminology is given in Table 3. NMC is short for a class of lithium-ion cathodes with the general composition $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$. The cathode NMC622 has a good balance between important properties for use in EV. The composition of NMC622 is $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$.

Table 1 Raw materials and their function in LIBs

Raw material	Function in LIB	Comment
Nickel	Cathode	Part of NMC622 cell
Manganese	Cathode	Part of NMC622 cell
Cobalt	Cathode	Part of NMC622 cell
Lithium	Cathode, electrolyte	Part of NMC622 cell
Aluminum	Cathode, tabs, pouch foil	Part of NMC622 cell
Graphite – natural	Anode	
Graphite – synthetic	Anode	Part of NMC622 cell
Carbon black	Anode and Cathode	Part of NMC622 cell
Copper	Anode	Part of NMC622 cell
Fluorine	Electrolyte	Part of NMC622 cell
Phosphorous	Electrolyte	Part of NMC622 cell. Also in cathode of lithium ion phosphate batteries (LFP)
Sulfonyl	Electrolyte	Not assessed
Methane	Electrolyte	Not assessed
Polypropylene, polyethylene	Separator	Not assessed
PVDF, PTFE	Binders	Partly assessed, see fluorine above
Carbon nanotubes	Cathode	Not assessed. A NMC622 cell can contain 15-25% graphite and maybe 1% of MWCNT would be an optimal replacement; 1% of 15-25% is 0,15%-0,25% of cell.

Table 2 Selection of EU critical raw materials and strategic raw materials for LIBs

Critical Raw Materials					Strategic RM
EC 2011	EC 2014	EC 2017	EC 2020	EC 2023	EC 2023
			Bauxite*	Bauxite*	
Cobalt	Cobalt	Cobalt	Cobalt	Cobalt	Cobalt
				Copper	Copper
Fluorspar	Fluorspar	Fluorspar	Fluorspar	Fluorspar	
			Lithium	Lithium	Lithium**
				Manganese	Manganese**
Graphite	Natural Graphite	Natural Graphite	Natural Graphite	Natural Graphite	Natural Graphite**
				Nickel**	Nickel**
		Phosphorus	Phosphorus	Phosphorus	

*Aluminium ore, **Battery grade

Table 3 Nomenclature

Crustal abundance	In this report referring to the average concentration of the element in the <i>upper continental crust</i> , as calculated and reported by Rudnick & Gao (2014). Estimated from average concentration in different rock-types and the abundances of the respective rock-type. The baseline (CML) abiotic depletion measure in LCA (named “elements, ultimate reserve” is based on the amount in the upper continental crust, constituting 31.7% of the continental crust (Rudnick & Gao, 2014).
Conflict mineral	A raw material that is regulated by conflict mineral regulation. According to EU legislation, currently Tin, Tungsten, Gold, and Tantalum.
Gangue	In mining, gangue is the non-commercial material that surrounds, or is closely mixed with, a wanted mineral in an ore deposit. Note that the gangue at the point of extraction, with changing demands, technology and/or economic conditions, at a later point in time could be of interest for extraction or other utilization.
Matte	An intermediate product from a smelter, containing metal and some sulphur, which must be refined further to obtain pure metal.
Mineral resource	Concentration or occurrence of material of economic interest in or on the Earth crust, in such form, quality and quantity that there are reasonable prospects for economic extraction. With increasing confidence, subdivided in inferred, indicated and measured resource. The non-baseline (CML) abiotic depletion measure in LCA (named “elements, reserve base”) is probably based on this definition of resource.
Mineral reserve	The economically mineable part of an indicated or measured resource. With increasing confidence, subdivided in probable and proven reserve. The non-baseline (CML) abiotic depletion measure in LCA (named “elements, economic reserve”) is probably based on this definition of Reserve.
End of Life - Recycling Input Rate (EOL-RIR)	The share (%) of the demand that can be satisfied through secondary raw materials. The latter has been produced by post-consumer functional recycling of old scrap, sent to processing and manufacturing, and is replacing primary material input.

2 Nickel

Nickel (Ni) is a metal with a continental crustal abundance of 47 ppm (Rudnick & Gao, 2014). It is usually mined as a main product and the main global producers of ore and ore concentrates in the period 2012-2016 were Indonesia (18%), Philippines (17%), Australia (11%), Russian Federation (11%), and Canada (10%) (EC, 2020b). The EU accounted for 2% of the world production (Greece, Finland, Spain, and Poland).

The main producers of refined nickel in 2012-2016, were China (29%), Russian Federation (12%), and Japan (10%). The EU contributed 4% of the refined nickel on the global market.

Six companies produce 50% of the global nickel raw materials (Barman et al. 2023): Jinchuan Group (China), BHP Group (Australia), Vale SA (Brazil), Tsingshan (China), Nicel Asia Cooperation (Philippines), and Glencore (Switzerland).

The major end-uses in the EU in the period 2012-2016 were steel for Engineering (39%), Metal goods (21%), Transport (19%), Electrical and Electronics, including batteries (11%), and Building and construction (10%) (EC, 2020b).

From the 2023 revision, *battery-grade nickel* is listed as a critical raw material (and strategic raw material) by EU. *Battery grade nickel* is also considered a Strategic Raw Material by the EU (EC, 2023).

2.1 Ore deposits

Economic grade nickel is usually found in either magmatic sulphide deposits or laterite deposits. *Magmatic sulphide deposits* are mafic to ultramafic (Mg-/Fe-rich, relatively Si-poor) igneous rocks enriched in nickel sulphide minerals, of which the most abundant and important is pentlandite ($[(\text{Fe},\text{Ni})_9\text{S}_8]$). The nickel concentration may reach >20 wt.% in sulphide rich sections, but the overall deposit is generally in the range 0.2-3.5 wt.% (Evans, 1993; Barnes et al, 2017; EC, 2020b). The most important magmatic sulphide deposits are in Russia, South Africa, Canada, Australia, and China.

Laterite deposits are formed by tropical weathering of ultramafic rocks and are subdivided into three subtypes, depending on principal minerals hosting the nickel: Oxide (Limonitic), Hydrous Mg-silicate, and Clay silicate deposits. The average nickel concentration in these is 1.0-1.6, 2-5, and 1.0-1.5 wt.%, respectively (Butt & Cluzel, 2013). The subtype bears implications on the processing of the ore. Usually, a certain nickel laterite deposit contains horizons of both oxide type and one of the other. The most important deposits are in New Caledonia (France), Indonesia, Columbia, Greece, Russia, Kazakhstan, USA, and Cuba (Butt & Cluzel, 2013). An important byproduct from both types of nickel deposits is cobalt.

2.2 Extraction

The nickel extraction process depends on the deposit type. After mining operation, which can be underground or open pit, the *magmatic sulphide ore* is crushed and concentrated by flotation and magnetic separation. Magnetic separation removes unwanted sulphide minerals such as pyrrhotite (magnetic Fe-sulphide). The non-magnetic concentrate is subjected to a flotation process, in which a nickel-sulphide concentrate is produced. If also copper is to be extracted, the flotation process might be a two-step-one in which the first produces a nickel-poor copper concentrate.

Laterite (oxide) deposits are typically large, of low grade, and extracted through shallow mining. The nature of this ore does not allow beneficiation with the normal physical methods, so the entire ore needs to be treated in the processing. An exception are oxide deposits where abundant secondary silica is removed by crushing and screening (Butt & Cluzel, 2013).

2.3 Processing

In a typical modern extraction process, the nickel *sulphide* concentrate mixed with added silica (sand) is subjected to a series of roasting and smelting operations. This reduces the iron and sulfur content by converting the iron sulphide to oxides, which reacts with the added silica to form silicates, that is removed as a slag. The resulting *matte* (nickel-iron-sulphide alloy) is allowed to cool, whereupon different phases crystallize (Ni_3S_2 , Cu_2S , and Ni/Cu metal), that may be mechanically separated from each other. The use of the matte intermediate step is due to the extremely high temperature (>1,600 °C) required to turn pure Ni-sulphide directly to metal. The removal of sulfur is controlled to

produce a nickel-sulphide matte with a composition that balances the need to reduce the melting point (to c. 1350°C), with the negative effect of too high sulfur content that can contaminate the smelter. Extraction of nickel from *laterite deposit* is not associated with the same potential sulfur pollution problem as the magmatic sulphide ores, but instead requires substantial energy input in the drying and smelting processes. Laterite ores contain large amounts of water (35-40 wt.%), weakly bound as moisture and more strongly bound as part of the mineral crystal structures. The drying and removal of the chemically bound water is carried out in large rotary-kiln furnaces, 50-100 meters long and 5-6 meters in diameter, to allow handling of the large volumes and providing for the necessary retention time. To reduce the Ni-oxide to Ni-metal, electric furnaces operating at up to 1600 °C are standard in modern laterite nickel smelters. The high magnesia content in most laterite ores and the liquidus temperature of the furnace products necessitate these higher smelting temperatures, which in turn make necessary an extensive system of cooling blocks within the refractory lining of the furnace. In some plants, sufficient sulfur is added to produce a furnace matte that can be further processed like matte from a sulfide smelter. However, most laterite smelters produce a crude ferronickel, which, after refining to remove impurities such as silicon, carbon, and phosphorus, is marketed as an alloying agent in steel manufacture.

2.4 Refining

Primary nickel is produced in two main categories. Nickel Class I comprises products such as electrolytic nickel, powders and briquettes, sulphates and oxides. Nickel Class II comprises nickel pig iron and ferronickel. The Class II products have a lower nickel content and are used especially in stainless steel production. Most (but not all) Class I products (>99.8%) originate from refining of nickel matte from sulphide ores, by electrowinning or leaching using sulfuric acid, hydrochloric acid, or ammonia. From the Class I nickel, nickel sulphate hexahydrate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) is produced, through a dissolution-precipitation process in sulphuric acid.

Refining nickel from laterite operations to Class 1 nickel is usually done through high pressure acid leaching (HPAL), in which nickel and byproducts (e.g., cobalt) are leached in autoclave at temperatures up to 270°C and pressures up to 50 bar. Examples of laterite mining operations that are producing Class 1 nickel by HPAL are Coral Bay and Taganito in the Philippines, Moa in Cuba, and Ramu in Papua New Guinea.

2.5 Environmental and social imprint

The USGS estimates the global commercial resources to be at least 300 Mt nickel, where 60% is in laterite and 40% in sulphide deposits. The reported commercial reserves amount to over 100 Mt of which nearly 60% are in Indonesia, Australia, and Brazil (USGS, 2023). Nickel also occurs with Co, Cu, and Mn in manganese nodules on the ocean sea floors. According to the Nickel Institute, the recent estimated nickel resources in these are >300 Mt.

The global usage of refined nickel increased from 1.84 Mt in 2016 to 2.38 Mt in 2019 (EC, 2020b; Roskill, 2021). The main part of this is used in stainless steel. However, the share going to battery applications will increase. A forecast by Roskill states that the global nickel demand to battery applications only, will be 2.86 Mt in 2040 (Fraser et al, 2021).

The impact on the environment from nickel production rests heavily on the type of ore processed. As a consequence of the nature of laterite ores – generally lower grade, surficial, and located in subtropical to tropical areas – mining and processing of these often have larger negative impact on environmental issues such as land use, biodiversity, and water use, compared to production of the same nickel amount from a sulphide magmatic ore deposit. Furthermore, the carbon footprint is generally larger for laterite deposits, up to double or even triple that of sulphide processing, due to the high energy consumption in the drying and smelting processes, the HPAL process, and consumption of limestone (releasing chemically bound CO_2) as acid neutralizer (Norgate & Jahanshahi, 2011). The difference in carbon footprint is also to a large extent dependent on how the energy is produced at the location. On the other hand, mining and processing of sulphide ores need to take potential problems with acid drainage or sulfur contamination into account.

The Russia–Ukraine conflict has drastically affected the nickel supply chain globally, as Russia is the topmost supplier of class-1 battery-grade nickel (Barman et al. 2023). The EOL-RIR of nickel in the EU in the period 2016-2020 was 16% (EC, 2023).

2.6 Potential within EU

The annual average EU consumption of (processed) nickel metal between 2015 and 2018 was 300 kt/y, of which only a small share was used for battery applications (EC, 2020b). The amount of Ni to batteries will increase. Roskill prognoses that the demand from EU27 cathode producers will be 71 kt/y in 2030 and 76 kt/y by 2040 (Fraser et al, 2021).

In the period 2012-2016, the EU import of nickel ores and concentrates was 56 kt/y whereas the domestic production was 47 kt/y. Subtracting the export of 38 kt/y, gives an EU consumption of nickel ores and concentrates of 65 kt/y. In the same period, the EU import of processed nickel materials was 287 kt/y whereas the domestic production was 69 kt/y. Subtracting the export of 36 kt/y, gives a net consumption of processed nickel materials at 356 kt/y.

The major suppliers of nickel ores and concentrates to the EU market in 2012-2016 were South Africa (28%), Greece (21%), Finland (18%), Canada (14%), and Brazil (8%). The main suppliers of refined nickel to the EU market in the same period, were Russia (26%), Finland (14%), UK (10%), Norway (8%), and Ukraine (5%). EU countries other than Finland, contributing refined nickel to the EU market, were Greece (4%) and France (2%). In 2016-2020, the main suppliers of refined nickel to the EU had shifted to Russia (29%), Finland (17%), Norway (10%), Canada (6%), and Australia (6%) (EC, 2023).

The refinement of nickel within the EU has, until recently, been to intermediate products (e.g., nickel matte and nickel alloys) suitable for steel making, but not to battery grade products. However, in 2021 the Terrafame Oy plant in Finland started the transition from production of NiCo-sulfide (66% Ni content) to battery class Ni-sulphate (and Co-sulphate). Terrafame uses an industrial scale bioleaching process, which is unique in the world. The company claims 60% lower carbon footprint compared with global average, to large extent due to the much lower energy consumption associated with this method (90% lower than global average). The plant has the capacity to produce Ni-sulphate for 1 million electric cars annually (<https://www.terrafame.com>).

There are several enterprises in the EU active in the recycling of nickel, but dominantly for stainless steel and alloying purposes. On global average, only 0.2 wt% of the class 1 nickel is from recycling (reference to the Ecoinvent organization in EC, 2020b).

Known resources in Finland is 4.96 Mt, whereas the current mine production there is 0.041 Mt/y (Eilu et al, 2021). The same report states minimum resources in Norway at 0.11 Mt, and Sweden at 2.6 Mt. Above this, there are also estimated “undiscovered resources” at 5.9 Mt in Finland, at 3.8 Mt in Greenland, and also additional potential in Norway (magmatic deposits) and Sweden (particularly in shale-hosted deposits).

The current nickel refining from imported matte is 92 kt/y in Norway (EC, 2020b).

3 Cobalt

Cobalt (Co) is a metal that usually is mined as a by-product or co-product during copper and nickel operations, and only obtained as the main product from one (1) deposit (in Morocco). Its crustal abundance is 17 ppm (Rudnick & Gao, 2014).

In the period 2012-2016, the main global producers of ores and concentrates were DRC (59%) and China (7%). Finland, as sole producer of Co ores and concentrates within the EU, contributed with c. 1% of the global supply that period (EC, 2020a). The main global producers of refined cobalt in the same time period were China (49%), Finland (12%), and Canada (6%). The majority of the feed material for China's production of refined cobalt is sourced from the DRC; China is the dominant importer of cobalt ore and concentrates from DCR (EC, 2020a).

Three companies produce 70% of the global cobalt raw materials (Barman et al. 2023): Jinchuan Group (China), CN Molybdenum (China), and Chemaf (DRC).

The major end-uses in the EU in 2015 were in Superalloys and other alloys (36%), Hard materials (14%), Pigments and inks (13%), and Catalysts (12%). Batteries accounted for 3% of the cobalt used, which is in stark contrast with the end-use on a global scale, where 50% of Co is used for batteries (EC, 2020a). Cobalt was listed as a critical raw material by EU already in the first edition (2011) and has stayed on the list through all later revisions (2014, 2017, 2020, 2023). Cobalt is considered a Strategic Raw Material by the EU (EC, 2023).

3.1 Ore deposits

In the continental crust, Cobalt is found in economic concentrations in four main geological deposit types: *sediment hosted* (e.g., the Central African Copperbelt in Zambia and DRC), *hydrothermal and volcanogenic* (e.g., polymetallic deposits in Finland, Sweden, Norway, USA, Canada, and Australia), *magmatic sulphide* (e.g., the Noril'sk deposit in Russia, the Sudbury deposit in Canada, and the Kambalda deposit in Australia), and *laterite* (e.g., New Caledonia and Cuba).

Cobalt present at ore-grade levels usually exists in either of the minerals cobaltite (CoAsS), skutterudite ($[\text{Co,Ni}]\text{As}_{3-x}$), smaltite (CoAs_2), linnaeite (Co_3S_4) and erythrite ($\text{Co}_3[\text{AsO}_4]_2 \cdot 8\text{H}_2\text{O}$).

3.2 Extraction

As a by- or coproduct, cobalt extraction typically follows that of the main metal (nickel or copper). Mining takes place either from surface or underground mines, and the extraction processes involves crushing the primary ore, separating the ore minerals from gangue using physical and/or chemical techniques, such as flotation or gravimetry. Typical products from copper mines are Co concentrates and Co-Cu-concentrates, and from nickel mines Co-sulphide or Co-Ni-concentrates (Al Barazi 2018; EC, 2020a)

3.3 Processing

Traditional pyrometallurgical operations on cobalt minerals involves smelting and roasting processes, to drive off unwanted species as gases and with the slag (see nickel extraction). After smelting, cobalt is normally still combined with nickel, copper or other metals in intermediate products of varying Co-content, such as sulphide mattes, sinters or different crude salts. Further refinement demands processing by different electro- and hydrometallurgical methods. Hydrometallurgy typically involves leaching using hydrochloric or sulphuric acid, sometimes at high pressures and temperatures (HPAL). A newer method is bioleaching (see section on Nickel, subsection Potential within EU).

3.4 Refining

Cobalt is produced into different refined raw materials: pure metal, oxides, hydroxides, carbonates, sulphates, chlorides, and acetates. Battery grade Cobalt is usually in the form $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$ and of >98% purity (EC, 2020a).

3.5 Environmental and social imprint

The USGS estimates global cobalt resources to 25 Mt; the majority of these are found in sediment-hosted stratiform copper deposits in DRC and Zambia, laterite deposits in Australia (and nearby island

nations) and Cuba, and in mafic to ultramafic Ni-Cu sulphide deposits in Canada, Australia, Russia and US (USGS, 2023). The additional cobalt resource potential from nodules and crusts on the ocean sea floors is estimated to >120 Mt. The reported cobalt reserve amounts to 8.3 Mt, of which nearly half is in DCR (USGS, 2023). Between 1998 and 2017, the global annual mine production of Co increased from 32 to 135 kt/y; the world production of refined Co increased from 27 to 120 kt/y in the same period (EC, 2020a). The expansion of the EV market will increase the global Co demand further, with 7-13 % *annually* at least until 2030 (EC, 2020a). In 2022, the global cobalt production was 190 kt (USGS, 2023). There are some socio-economic issues related to the situation in the DCR, including poor governance, political instability, and trade restrictions. Some cobalt originates from artisanal and small-scale mining (<20% of global supply), raising concerns on human rights abuse (EC, 2020a). Of the 210 countries included in the Worldwide Governance Indicators, developed by the World Bank, DRC share the third place (together with North Korea and Sudan) of worst countries and is only better than Afghanistan and Somalia. DRC is considered one of the riskiest countries to do business in and a source of so-called conflict minerals. However, when it comes to cobalt it is mined as a by-product of copper in the southern province of Katanga, and this region is not associated with the well-published armed conflicts that have taken place in the North and South Kivu provinces of eastern DRC. Consequently, and similarly to copper, cobalt is not one of the defined conflict minerals. There have been reports on problems with child labour, but this is linked with illegal or poorly regulated artisanal mining, not with the large-scale mining industry (EC, 2020a).

When it comes to recycling cobalt containing products, some are difficult or even impossible to recycle, since their uses are dissipative (e.g., pigment in glass, ceramics, paint). However, cobalt used in applications such as superalloys, hard metals, batteries and even spent catalysts can be collected and either reused or recycled. The EOL-RIR of cobalt in the EU in the period 2016-2020 was 22% (EC, 2023).

3.6 Potential within EU

On average for the period 2012-2016, the EU imported 12.1 kt/y of cobalt ores, concentrates and intermediate cobalt products (e.g., cobalt matte), whereas the domestic production was 2 kt/y. Subtracting the export of 0.25 kt/y, yields a net EU consumption of 13.85 kt/y (EC, 2020a).

In 2012-2016, the main suppliers of cobalt ore, concentrates and intermediate products to the EU market were DCR (68%), Finland (14%), and New Caledonia, Russia, and Canada (5% each). The main supplier of refined cobalt in the same period, was Finland (54%), followed by Belgium, Norway, and the US (7% each). Other EU contribution came from France (1%) (EC, 2020a).

In the same period, the EU imported 7.85 kt/y processed (refined) cobalt, whereas the domestic production was 12.84 kt/y. Subtracting the export of 3.1 kt/y refined cobalt yields a net EU consumption of 17.6 kt/y (EC, 2020a).

Currently, the only EU member state mining Co is Finland, contributing ca. 2% of mined Co globally (Cobalt Market report 2022, Cobalt Institute 2023) from several mines, as byproduct of Ni or Cu mining. The amount mined in Finland in 2020 was 1.56 kt (Eilu et al., 2021). There are known resources in Finland at 454 kt, but also in Greece (79 kt resource and 50 kt reserve), Poland (7.3 kt resource and 75 kt reserve), Sweden (24.3 kt), and Norway (11.7 kt) (Eilu et al, 2021; EC, 2020a). There is also additional resource potential in Finland, Sweden, Norway, Greenland, and Spain (the Aguablanca mine closed down in 2016). In Greece and Poland, cobalt is extracted in operating mines of lateritic nickel and copper ores, respectively, but it is not recovered as a by-product (EC, 2020a). The H2020 project METGROW+ investigated different (bio-)hydrometallurgic methods to extract e.g., cobalt from such low grade rest flows, with interesting initial results (Mäkinen et al., 2018).

The EU is an important producer of refined cobalt accounting for almost 12% of the world's production (Cobalt market report 2022, Cobalt Institute 2023). Intermediate and refined cobalt are currently produced (EC, 2020a) in *the Terrafame Oy plant* in Finland (refining NiCo-sulfide to battery class Co and Ni sulphate, from intermediate Ni-Co-sulphide produced by bioleaching from domestic ore concentrates), the *Kokkola cobalt refinery* in Finland (producing powders and chemicals, including battery-grade cobalt compounds used as precursors for cathode materials, from intermediate Co products from DCR and Finland), *the Harjavalta nickel refinery* in Finland (operated by Norilsk Nickel, producing cobalt sulphate and cobalt solutions from Ni-concentrates from Russia), the *Olen refinery*

in Belgium (operated by Umicore, producing e.g., metal powder, cobalt salts, and cobalt oxide), and *the Sandouville* nickel refinery in France (operated by Sibanye-Stillwater, producing cobalt chloride as a by-product of refining nickel matte imported from New Caledonia).

There are estimates showing that 0.5 kt recycled cobalt from EV batteries deployed in the EU should be available in 2025 and may amount to 5.5 kt in 2030, accounting for around 10% of European cobalt consumption in the EVs sector (EC, 2020a; Patrícia Alves Dias et al. 2018).

4 Manganese

Manganese (Mn) is one of the most common elements in the Earth continental crust (12th in order) with a MnO concentration of 0.1% (Rudnick & Gao, 2014). It is usually mined as a main product and the three main global producers of ore concentrate in 2012-2016 were South Africa (28%), Australia (17%), and China (17%), whereas the EU contributed <1% to the global market (EC, 2020b). The main global producers of processed manganese in the same period were China (57%), India (12%), and South Africa and Ukraine (5% each).

The end-uses in the EU in 2012-2016 were Steel for e.g., construction, automotive, engineering and metalware (87%), Non-steel alloys (6%), Chemicals (5%), and Battery cathodes (2%) (EC, 2020b).

Manganese was listed as a critical raw material by EU in the last edition (2023). *Battery grade manganese* is also considered a Strategic Raw Material by the EU (EC, 2023).

4.1 Ore deposits

Economic grade manganese is usually found in four different deposit types, each with its particular associated rock-types, ore mineralogy, and gangue material: *Magmatic manganese deposits*, *Sedimentary manganese deposits*, *Structure-related manganese deposits*, and *Metamorphic manganese deposits*. Pyrolusite (MnO₂) is the most important ore mineral, whereas rhodochrosite (MnCO₃), braunite (Mn²⁺Mn³⁺₆SiO₁₂), and psilomelane (hydrous Ba-Mn-oxide), are subordinated.

4.2 Extraction

The mining method is by open-pit or underground mining depending on the deposit type and depth of the ore body. The extracted manganese ore is crushed and milled, before the ore minerals are separated by physical (e.g., gravity) and/or chemical (e.g., froth floatation) techniques.

4.3 Processing

Processing of manganese ore to products for steel applications is conducted by smelting the ore in blast furnace or electric arc furnace (generally, the latter when cheap electric energy is available), usually with coke (reductant) and lime (flux). The primary product from that process is ferromanganese, containing 76-80% Mn, 12-15% Fe, and up to 7% carbon. If the ore lacks bases such as magnesium or calcium or flux is not added in the process, the smelting results in a Mn-rich slag. By smelting this slag (or smelting original ore with coke and silica flux), at even higher temperatures, ferrosilica-manganese is produced (65-68% Mn, 16-21% Si, 2% C).

For processing to pure manganese metal, a thermal, hydrometallurgical and electrometallurgic route can be taken, in which the ore is roasted to produce MnO, which is dissolved in sulfuric acid. Additions of different chemicals precipitates unwanted metals and the purified solution is fed into the cathode of an electrolytic cell. The manganese deposited on the cathode is removed by hammering and the resulting flakes are heated to 500 °C to remove hydrogen. The purity of the powdered manganese is >99.9%.

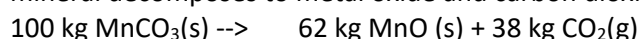
4.4 Refining

Further refining of ferromanganese to battery grade manganese is performed by electrowinning to flakes of high purity electrolytic manganese metal (HPEMM), that can be further refined by dissolution-precipitation in sulfuric acid to high purity manganese sulphate monohydrate (HPMSM).

4.5 Environmental and social imprint

The USGS estimates global manganese reserves to ca 1700 Mt, of which 38% are in South Africa (USGS, 2023). However, the manganese resource potential is much higher, e.g., from manganese nodules on the ocean sea floors. The global manganese production 2022 was 20 Mt (USGS, 2023).

Extraction of manganese from rhodochrosite (MnCO₃) or other carbonate minerals results in release of carbon dioxide, if the extraction is done through calcination (heating to temperature where the mineral decomposes to metal oxide and carbon dioxide gas):



However, if performed through hydrometallurgical methods, the carbonate is trapped in the solid residue.

The EOL-RIR of manganese in the EU in the period 2016-2020 was 9% (EC, 2023).

4.6 Potential within EU

In the period 2012-2016, the EU import of manganese ores and concentrates was 324 kt/y, whereas the domestic production was 32 kt/y. Subtracting the export of 43 kt/y yields a net EU consumption of 323 kt/y. In the same period, the EU imported 767 kt/y processed manganese materials (FeMn, FeSiMn, Mn metal) and domestically produced 387 kt/y. Subtracting the export of 673 kt/y, yields a net EU consumption at 481 kt/y (EC, 2020b).

In 2012-2016, the main suppliers of manganese ore and concentrate to the EU market were South Africa (36%), Gabon (29%), and Brazil (24%) (EC, 2020b). In 2016-2020, these had shifted to South Africa (41%), Gabon (39%), Brazil (8%), and Ukraine (3%) (EC, 2023). The main suppliers of processed manganese (FeMn, FeSiMn) in the period 2012-2016, were Norway (28%), South Africa (23%), India (16%), and Ukraine (12%) (EC, 2020b).

In the EU, manganese was until recently extracted as a primary product in Bulgaria, Romania and Hungary, although this accounted for less than 1 % of total global mine output (EC, 2017b). Since then, production has stopped in both Bulgaria and Hungary, with the result that import from outside EU has increased (EC, 2020b).

In EU, there are reported Mn resources in Bulgaria, Czeck Republic, Finland, Germany, Greece, Hungary, Kosovo, Portugal, Spain, Sweden. Potential resources in e.g., the Czeck Republic are 139 Mt at 11.3 % ore grade (equivalent to over 15 Mt manganese) and known resources in Finland and Sweden are 4.75 and 5.94 Mt, respectively (Eilu et al, 2021; EC, 2020b).

According to Euro Manganese, the Czeck Chvalětice Manganese Project east of Prague is the only sizeable manganese resource in the EU, with the potential to provide up to 20% of the projected EU demand for batteries in 2030. The extraction will be from three silt and clay tailings from historical pyrite mining. The resource estimate is 27 Mt tailing at 7.3 wt.% manganese, dominantly (80%) occurring as rhodochrosite (MnCO_3) and kutnohorit ($\text{Ca}[\text{Mn}^{2+}, \text{Mg}, \text{Fe}^{2+}][\text{CO}_3]_2$), and to lesser extent (20%) in Mn-silicates. If getting the permissions and necessary plants and infrastructure in place, the plan is to mine the tailings by shovels and haulers, concentrate ore minerals by magnetic separation, and recover manganese by acid leaching (in sulphuric acid at 90°C; slurry neutralized with lime), while removing iron, phosphorous, and magnesium. The manganese-rich solution will then be processed by electrowinning to high purity electrolytic manganese metal (HPEMM). Roughly two thirds of the HPEMM are further refined in high-purity sulfuric acid to high purity manganese sulphate monohydrate (HPMSM). Since working on tailings, the operation will avoid “traditional” energy intensive mining steps, i.e., drilling, blasting, crushing, and grinding.

In Europe, there is currently processing of manganese ore to FeMn for steel manufacturing in Spain, France, Slovakia, Italy, Romania, Norway and Poland (EC, 2020b). Norway also produces FeSiMn. Nevertheless, for utilization in batteries, further refining is needed.

5 Lithium

Lithium (Li) is a relatively rare metal with an upper continental crustal abundance of 24 ppm (Rudnick & Gao, 2014). It is usually extracted as a main product from saline brines or from hard rock (Li-bearing pegmatites and granites). In 2012-2016, the main lithium producers were Chile (39%; brines), Australia (36%; ore concentrates), and Argentina (12%; brines). In 2015, the world production of refined lithium compounds (lithium carbonate, Li_2CO_3 , and lithium hydroxide monohydrate, $\text{LiOH}\cdot\text{H}_2\text{O}$) was dominated by Chile (44%; from brines), China (39%; mostly from ore concentrates), and Argentina (13%; from brine) (EC, 2020a).

Five companies produce 50% of the global lithium raw materials (Barman et al. 2023): Pilbara Minerals (Australia), Allkem (Australia), Sociedad Quimica Y minera De Chile SA (Chile), Livent Corporation (USA), and Ganfeng Lithium Co. (China).

The major end-use in the EU in the period 2012-2016 was in Glass and ceramics (66%), Lubricating greases (9%), Cement production (9%), Steel casting (5%), Pharmaceuticals (4%), Rubber and plastics (4%), Al-Li alloys (2%), and Batteries (1%) (EC, 2020a). This can be compared with the *global* situation where the leading end-use at the same time was Batteries (37%), reflecting the on a global scale still very small EU battery industry.

Lithium was listed as a critical raw material by the EU in the 2020 version of the list and remains there in the latest revision (2023). *Battery grade lithium* is also considered a Strategic Raw Material by the EU (EC, 2023).

5.1 Ore deposits

Economic grade lithium is usually found in saline *brines* or *hard rock* (pegmatites and granites); in the former the average grade is 0.1% Li_2O , in the latter the grade is usually 1-3% Li_2O (Linnen et al, 2012). In hard rocks, the important ore minerals are spodumene ($\text{LiAlSi}_2\text{O}_6$), petalite ($\text{LiAlSi}_4\text{O}_{10}$), lepidolite ($\text{K}[\text{Li,Al}]_3(\text{Al,Si})_4\text{O}_{10}[\text{F,OH}]_2$), and amblygonite-montebrazite ($\text{LiAlPO}_4[\text{F,OH}]$). Earlier all lithium was produced from hard rocks, but today the lower production cost of brine extraction has shifted the operations more to brines. Of the eight countries producing lithium, Australia, Zimbabwe, Portugal and Brazil extract from hard rocks, whereas Chile, Argentina, and USA extract from brines. China extract from both sources (EC, 2020a).

5.2 Extraction, processing and refining of lithium from hard rock

Extraction from hard rock deposits is conducted by conventional open pit or underground methods, with e.g., drilling, blasting, tunneling, and beneficiation through crushing of ore and separation. The latter is performed by gravity, magnetic or electrostatic methods, followed by froth flotation or dense media separation, to produce Li-mineral concentrate suitable for further processing (at this stage usually 6-7% Li_2O , “chemical-grade concentrate”).

Lithium is usually recovered from the mineral concentrate through acid leaching, autoclave carbonate leaching, or lime leaching. The most common product is lithium carbonate, which can also be used as a precursor to other lithium compounds (e.g., lithium hydroxide, butyl-lithium, lithium chloride). The acid leaching process involves calcination of the concentrate at about 1100 °C to improve the acid solubility of spodumene (due to phase change to a more soluble polymorph), followed by acid digestion at 200-250 °C with sulphuric acid. The liberated lithium forms water soluble lithium sulphate. Impurities are removed from the solution by filtration, precipitation, and ion-exchange techniques. Finally, lithium is precipitated by adding sodium carbonate at 80-100 °C. The purity of the precipitated lithium carbonate can be improved up to 99.9%, by redissolution, precipitation, and ion exchange steps. Battery-grade lithium carbonate is >99.5%. Lithium hydroxide can be produced by acid leaching, but instead of adding sodium carbonate (and following steps), the solution is subjected to electrodialysis followed by precipitation. Lithium hydroxide can also be produced from lithium carbonate through chemical reaction with calcium hydroxide.

5.3 Extraction, processing and refining of lithium from brines

Extraction from brines is conducted by pumping the saline water from the underground aquifers through wells and boreholes (that of course need to be drilled and dug), to a series of ponds on the surface, where the brine is further concentrated through evaporation. Lime is added to precipitate impurities. It takes at least 9-12 months to achieve a concentrate sufficiently enriched in lithium (around 0.6%). The concentrated solution from the last pond is transferred to a processing plant. To produce lithium carbonate, the solution is treated with sodium carbonate, followed by filtering, washing, and drying. Potassium, magnesium and boron salts may be recovered as co-products.

5.4 Environmental and social imprint

Global known resources of lithium are 98 Mt, whereas the known reserves are estimated at 26 Mt. This is to be compared with the global production of lithium at 0.13 Mt in 2022 (USGS, 2023). The EOL-RIR of lithium in the EU in the period 2016-2020 was 0% (EC, 2023).

5.5 Potential within EU

In 2012-2016, the main suppliers of lithium concentrates to the EU market were Australia (89%) and Portugal (11%). In the same period, the main suppliers of refined lithium (lithium carbonate and hydroxide) were Chile (78%), USA (8%), and Russia (5%) (EC, 2020a). In 2016-2020, the main suppliers of refined lithium to the EU had shifted to Chile (79%), Switzerland (7%), Argentina (6%), and USA (5%) (EC, 2023). No processing of lithium concentrates to refined products is taken place in the EU, so EU is 100% reliant on import of battery grade lithium products (EC, 2023). However, chemical industry producing lithium chemicals from imported lithium carbonate exist (Albemarle, Germany).

On average in 2012-2016, the EU import of lithium ore concentrates was 868 t/y, whereas the export was nil. The domestic production of concentrates was 128 t/y. In the same period, the EU imported 3101 t/y processed lithium materials (1st stage materials such as carbonate and hydroxide), whereas the export was 873 t/y (2nd stage materials such as lithium chemicals and cathode materials and electrolytes for battery cells).

The known reserves in EU are in Czeck Republic (104 kt), Germany (94 kt), Portugal (60 kt), Finland (36 kt) and Austria (25 kt) (EC, 2020a; USGS, 2023). Additional lithium resources are in Germany, Czech Republic, Spain, Sweden, Portugal, Austria, Finland, Ireland, and France. In the EU, lithium is extracted from hard rock mining at several sites in Portugal, for use in the ceramics industry. The concentrate is marketed as “Li-rich feldspars” and is thus not processed further in the EU.

Some current exploration activities that have reached more advanced stages are summarized in Table 6 (information from EC, 2020a). Except for the Vulcan brine, they are all hard rock deposits.

Table 4 Selection of advanced lithium exploration projects in Europe

Member state	Deposit(s)	Reserve/Resource, ore amount (Mt)	Li ₂ O, average ore grade (%)	Company
Austria	Wolfsberg	Reserve: 7.5 Resource: 11	0.71 1.00	European Lithium Ltd
Czechia	Cinovec	Resource: 700	0.42	European Metals Ltd
Finland	Syväjärvi, Rapasaari, Länttä, Outovesi, Emmes, Leviäkangas	Reserve: 7.4 Resource: 9.5	1.04 1.16	Keliber Oy
Germany	Zinnwald	Reserve: 31.2 Resource: 40	0.65 0.76	Deutsche Lithium GmbH
	Sadisdorf	Resource: 25	0.45	Lithium Australia
	Vulcan	Resource:		Vulcan Energy Resources
Portugal	Mina Do Barroso	Resource: 27	1.06	Savannah Resources Plc
	Alvarrões	Resource: 5.9	0.87	Lepidico Ltd
	Sepeda	Resource: 10.3	1.0	Dakota Minerals
	Aregemela	Resource: 11.1	0.21	PANNN
Spain	San Jose	Resource: 111	0.61	Infinity Lithium Ltd

6 Graphite

Most of the battery anode materials are graphite-based, either natural graphite from mining and refining, or synthetic graphite manufactured through high temperature processing of amorphous carbon materials (e.g., petroleum coke). The benefits of natural graphite are the lower production cost and much lower energy consumption, whereas synthetic graphite has some technical advantages. Some manufacturers use mixtures of natural and synthetic graphite in the anode, to optimally benefit from the two materials' respective advantages. The annual use of synthetic and natural graphite is around 1.5 Mt and 1 Mt, respectively (EC, 2020a).

“Graphite” was listed as a critical raw material by the EU already in the first edition (2011), but in the later editions (2014, 2017, 2020, 2023) this has been specified to “natural graphite”. Natural graphite is also considered a Strategic Raw Material by the EU (EC, 2023).

Three companies produce 50% of the global anode materials (Barman et al. 2023): Ningbo Shanshan (China), Shanghai Putailai New Energy Technology (China), and BTR New Energy Materials (China).

6.1 Natural Graphite

Graphite is a mineral consisting solely of carbon (chemical formula: C) with traces and should also be crystalline (crystal structure of repeating ABAB layers). However, all natural graphite is not perfectly crystalline but could be low-crystalline and even amorphous, demanding more processing to be suitable for graphite anode production. Natural graphite thus encompasses graphite in the strict sense as well as amorphous or low-crystalline graphite-like varieties (Beysac & Rumble, 2014). Graphite is usually extracted from certain metamorphic rocks (where the protoliths are sedimentary rocks rich in carbonaceous).

The main global graphite *mining* countries in 2012-2016 were China (69%), India (12%), and Brazil (8%). In 2017, the main *exporting* countries of graphite ore concentrates were China (59%), Brazil (6%), Germany (6%), USA (5%), and Canada (4%) (EC, 2020a). Hence, both China and India are using much of the produced graphite for their own industry.

The end-uses for natural graphite in the EU in 2012-2016 were Refractories for e.g., steel making and foundries (54%), Miscellaneous (27%), Friction materials (8%), Lubricants (5%), Li-ion batteries (5%), and other batteries (1%).

6.1.1 Ore deposits

Economic grade graphite is mined from three types of deposits, generally formed when carbon-rich sedimentary rocks are reworked by metamorphic processes (Beysac & Rumble, 2014; EC 2020a):

- *Flake graphite* occurs in certain high-grade metamorphic rocks. Crystals are generally >100 µm and are disseminated in the rock. The carbon concentration is usually 5-40%.
- *Amorphous or microcrystalline graphite* occurs in certain metamorphic rocks. Graphite grains are generally <1 µm and not always crystalline. The carbon concentration is usually 15-80%.
- *Vein or lump graphite* occurs in hydrothermally deposited veins in high-grade metamorphic or magmatic rocks. Graphite is generally pure and forms perfect crystals. Rare ore-type that only accounts for 1% of the world production.

6.1.2 Mining, extraction and refining

The ore is quarried from open pit or shaft mined from underground, depending on the depth of the ore body from the earth surface. The ore is crushed, grinded in aqueous slurry, and subjected to flotation and screening, to create a graphite-rich concentrate (Beysac & Rumble, 2014).

Further purification and refining of the graphite concentrate is carried out by various processes (Beysac & Rumble, 2014; Buseck & Beysac, 2014; EC 2020a):

- *Chemical purification.* Acid leaching is the most common method, in which different impurities, especially silicates, are removed by using acids such as HCL, HF, H₂SO₄, and HNO₃ (or mixtures of these). Sulfur can be removed by combining acid leaching with roasting (oxidation at elevated temperature in oxygen rich atmosphere). Able to produce 99.99% pure graphite.

- *Thermal purification.* Heating to improve crystallinity from amorphous or poorly crystalline “graphite” and remove impurities such as hydrogen, oxygen, sulfur, and nitrogen. Temperatures of 1100 °C or more.
- *Expandable graphite.* Produced through chemical treatment on flake graphite at room temperature, in which the graphite crystalline layer-structure is exfoliated, which in effect expands the graphite volume by up to 300 times or more. This is achieved by intercalation of designed compounds in between the carbon layers, and washing, drying, and heating to remove impurities and the intercalation compounds.
- *Flexible graphite.* Produced by rolling and compressing expanded graphite into thin sheets.
- *Spherical graphite.* This is the battery-grade graphite that is used in Li-ion battery anodes. Generally produced from high-carbon flake graphite, by successive stages of mechanical milling, spheroidization, and purification to >99.95% carbon. The process increases the surface area and packing effectiveness of the graphite.

6.1.3 Environmental and social imprint

The USGS estimates global resources to be in excess of 800 Mt and world reserves at 330 Mt. Of the reserves, 27% are in Turkey (90 Mt), 22% in Brazil (74 Mt), and 16% in China (52 Mt). The global production of natural graphite in 2022 was 1.3 Mt (USGS, 2023).

The EOL-RIR of graphite in the EU in the period 2016-2020 was 3% (EC, 2023).

6.1.4 Potential within EU

In 2012-2016, the EU imported 88.6 kt/y of graphite ore concentrates while the domestic production (mining) was 2.1 kt/y. The main suppliers to the EU market were China (47%), Brazil (12%), Norway (8%), Zimbabwe (6%), Ukraine (4%), and Belarus (4%). In 2016-2020, these had shifted to China (40%), Brazil (13%), Mozambique (12%), Norway (8%), and Ukraine (7%) (EC, 2023). A small share in 2012-2016 came from within the EU, namely Romania (2%), and Austria, Germany, and Sweden (together 1%) (EC, 2020a). Since then, the graphite mining in Romania has closed down and the one in Sweden (Woxna Mine, Leading Edge Materials) only operated a few months in 2015 (EC, 2020a). The active mines in Austria and Germany are the Kaisersberg mine (Grafitbergbau Kaisersberg GmbH) and the Kropfmühl mine (Graphit Kropfmühl), respectively (EC, 2020a).

In Europe, the resource potential is particularly high in Czech Republic, Finland and Sweden (EC, 2020a; Eilu et al, 2021). A promising activity in Sweden is the Vittangi anode project, in which Talga Resources Ltd intend to mine the high quality Vittangi deposit and produce graphite anodes (ASX:TLG, 2021). If the permits come in place as planned, mining will commence in 2023 and anode production in 2024. The resource estimate is 19.5 Mt at average 24% graphite (i.e., in total, 4.7 Mt graphite). The reserve is currently estimated at 2.3 Mt ore of 24% graphite content. Standard open pit mining methods will be applied, i.e., drilling and blasting followed by loading and hauling. About 0.1 Mt ore will be extracted annually over a period of 24 years. Ore will be beneficiated through crushing, grinding, and flotation. The graphite concentrate will be refined to a final purity of $\geq 99.95\%$, through chemical and thermal processes. Metallurgical test results for low temperature alkali roasting with some stages of acid washing, was confirmed satisfactory to produce a >99.95% final anode product (ASX:TLG, 2021). Since the cumulative yield in the processes from ore to anode planned by Talga is relatively high (ca 80%), the footprint is consequently very small on a global basis, requiring only 5 t ore to produce 1 t of anode. This is due to the natural anode-sized flakes of Vittangi graphite, combined with the suggested processing and anode production technology. Talga is also participating in the CLIMB cooperation, a model developed by Swedish industry to calculate, evaluate, and compensate for impact on biodiversity. Talga is also exploring other deposits in Sweden, e.g., the Jalkunen and Raitajärvi projects. Some important natural graphite deposits in the EU are summarized in Table 7.

Table 5 Selection of advanced graphite exploration projects in Europe

Member state	Deposit(s)	Reserve/Resource, ore amount (Mt)	C graphitic	Company
Austria	Kaisersberg	Reserve: Resource:	0.16 Mt 1.5 Mt	Kaisersberg GmbH
Czechia	Eight deposits	Resource:		Czech Geological Survey
Finland	Aittolampi	Resource: 19.3	4.5 %	Beowulf Mining
Sweden	Woxna	Resource: 9.7	9.1 %	Leading Edge Materials
	Nunasvaara (Vittangi)	Resource: 12.3	25.5 %	Talga Resources Ltd
	Raitajärvi	Resource: 4.3	7.1 %	Talga Resources Ltd
	Jalkunen	Resource: 31.5	14.9 %	Talga Resources Ltd

When it comes to graphite refining to battery grade spherical graphite in the EU, there is currently no capacity. However, the companies exploring the Vittangi and Woxna deposits in Sweden (Talga Resources Ltd and Leading Edge Materials, respectively), are both including such graphite refining facilities as part of their graphite mining activities and feasibility studies.

6.2 Synthetic Graphite

Synthetic (also called artificial) graphite is produced through a complex process at very high temperatures. Synthetic graphite can have a purity of >99% carbon. Precursors to graphite are many, and can be derived from petroleum, coal, or natural and synthetic organic materials. The important thing is that they are “graphitizable”, which often means hydrogen-rich carbonaceous precursors, in contrast with “non-graphitizable” carbonaceous precursors, which are typically oxygen-rich (Buseck & Beyssac, 2014). In some cases, graphite can even be manufactured by the direct precipitation of graphitic carbon from pyrolysis of a carbonaceous gas such as acetylene (pyrolytic graphite).

6.2.1 Ore deposits

The carbon rich material used to produce graphite should be of a type (referred to as “graphitizable carbon”) that under reasonable temperature and time frame, allows movements and rearrangement of atoms, reconstructing the bonds and lattice to graphite (Buseck & Beyssac, 2014). Usually this is tar or coke produced either from petroleum or stone coal. From petroleum, it is produced from the residual after refinery processes retrieving the volatile low-density products. Petroleum coke usually contains 10-20% volatile components after the coking process, which need to be removed. This is done by calcining process, i.e., heating to a high enough temperature (at least in the range 1100-1300 °C) to volatilize, vaporize, or burn off volatile components. After this step, the coke is known as calcined petroleum coke.

Another precursor material is carbon black, a powdered form of carbon produced by pyrolysis of hydrocarbons, wood or other carbon containing materials. Carbon black may contain impurities of oxygen, hydrogen, nitrogen and sulfur.

6.2.2 Mining, extraction, and refining

The carbonaceous precursor is crushed, milled, graphitized, and demagnetized to produce synthetic graphite. At ambient pressure the temperature required to create graphite from amorphous graphitizable carbon in a reasonable time period range is close to 3000 °C in inert atmosphere (Beyssac & Rumble, 2014; Buseck & Beyssac, 2014). The first to occur during heating is *carbonization*, which removes impurities such as hydrogen, oxygen, sulfur, and nitrogen, as well as initiating the formation of aromatic carbon skeleton. Secondly, the aromatic carbon skeleton is rearranged and polymerized to the ideal graphite ABAB layer structure (*graphitization*). Synthetic graphite can be manufactured in any number of forms including solid articles of varied shape and size, granular materials, and powders.

7 Copper

Copper (Cu) has a crustal abundance of 28 ppm (Rudnick & Gao, 2014). In nature, copper exists in many different types of minerals, e.g., sulphides, oxides, and carbonates, but also as native element (copper metal). It is usually mined as a main product and the main global producers of ore concentrate in 2012-2016 were Chile (30%), China (9%), Peru (8%), USA (7%), Australia (5%), and DRC (5%). The main producers of refined copper in the same period, were China (33%), Chile (12%), Japan (7%), USA (5%), and Russian Federation (4%) (EC, 2020b).

Due to outstanding properties when it comes to electrical and thermal conductivity, corrosion resistance, ductility, and malleability, copper is one of the most important metals for the society and is used in energy-efficient circuits, wirings, and mechanical parts in a wide range of applications.

In 2012-2016, the apparent EU consumption of refined copper was 2.6 Mt/y. The major end-uses were components and household (22%), tubes, plates, wires (21%), machinery (15%), digital appliances (14%), and ships, trucks and armored vehicles (10%) (EC, 2020b).

Copper entered the EU critical raw materials list in the latest edition (2023). Copper is also considered a Strategic Raw Material by the EU (EC, 2023).

7.1 Ore deposits

Copper is found in many different types of deposits, but on a global scale the most important are Porphyry copper, Sediment hosted, and Volcanogenic Massive Sulphides (VMS). The principal ore minerals are chalcopyrite (CuFeS_2), bornite (Cu_5FeS_4), and chalcocite (Cu_2S), although a few other copper minerals also are economically important (Fontboté et al, 2017). Sediment hosted and VMS deposits are usually high-grade but low tonnage ores (2-3% Cu in 200-3000 Mt ore for the former, 1.0-1.8% Cu in 10-50 Mt ore for the later), whereas porphyry copper deposits are low-grade but high tonnage deposits (0.4-1.5% Cu, 500-5000 Mt ore) (Fontboté et al, 2017). In Europe, porphyry copper deposits are found in Sweden, Greece, and Bulgaria, whereas sediment-hosted deposits occur in Poland and Germany. An important VMS deposit in Europe is the Cobre Las Cruces deposit in Spain.

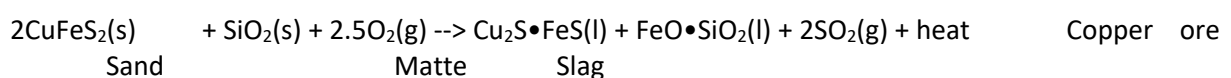
7.2 Extraction

The mining method will largely depend on the deposit type, its ore grade and how deep it is located. For copper, *open pit mining* is the most common and suitable when close to surface (<100 m). Examples on open pit copper mines are the Bingham copper mine (USA), and the Aitik (Sweden). For higher grade and deeper located copper ores, *underground mining* is more suitable. A third method, *in-situ leaching*, is applied in some areas where the ore grade is low. In this method, a diluted sulphuric acid is pumped through the ore body to dissolve and bring back copper in solution.

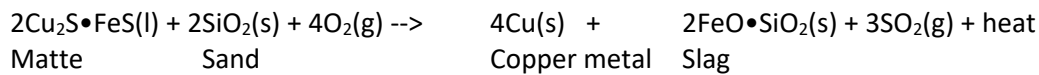
7.3 Processing and refining

The copper ore is crushed, grinded, and separated to produce a copper ore concentrate (usually increasing the grade from <3% to ca 30%). Beneficiation is carried out at the mine site, to reduce transport of huge amounts of gangue material. The separation methods could be chemical or physical or both, depending on e.g., ore-type.

The conversion into pure copper is done by pyrometallurgy or hydrometallurgy. *Pyrometallurgy* is dominant for sulphide ores and includes roasting, smelting and electrolytic refining. Initially the ore is fed into a flash furnace with oxygen-rich air and silica sand, to oxidate the ore, melt it, and separate into an intermediate copper product (matte) and slag (the sand is added to aid slag formation). Simplified chemical reaction for chalcopyrite:



The slag is lighter than the matte, floats atop and is physically removed. The sulfur dioxide can be retrieved and processed into sulphuric acid by-product. The intermediate copper product, the matte, is further processed in a converter oven, to produce copper metal:



The copper metal is further refined to high purity through electrolysis.

Hydrometallurgy is used for ores other than sulphide (due to poor solubility of chalcopyrite), e.g., copper carbonates, oxides or silicates, and involves leaching with sulphuric acid to bring copper into solution. The solution is purified by solvent extraction, a liquid-liquid extraction method in which the different solubility for e.g., a certain element in two immiscible liquids is utilized. Generally, organic chelators are used to selectively form copper complexes and when adding an organic (non-polar) solvent, these complexes are dissolved in the organic solvent, rather than in the original sulphuric acid solution (polar). The liquids are separated, and the organic solvent is evaporated, leaving a copper-complex residue. The copper is retrieved by dissolving this residue in sulphuric acid. Further purification is achieved through electrowinning.

A relatively novel method, at least on industrial scale where it has been implemented at several mine sites on a production scale up to 1 Mt/y, is bio-leaching, in which the copper leaching also from sulfides (e.g., chalcopyrite) is enhanced by aid of bacterial activity. This opens up for processing by solvent extraction and electrowinning also on sulfide ores (de Villiers, 2017).

7.4 Environmental and social imprint

The USGS has estimated the global copper resources at 5600 Mt, of which 2100 Mt are identified and 3500 Mt undiscovered. The known reserves amount to 890 Mt, where over 40% are in Chile, Australia, and Peru. The global copper ore and refined copper production in 2022, were 22 Mt and 26 Mt, respectively (USGS, 2023).

The EOL-RIR of copper in the EU in the period 2016-2020 was 55% (EC, 2023).

7.5 Potential within EU

The main suppliers of copper ore concentrate to the EU in 2012-2016 were Poland (27%), Chile (13%), Peru (10%), Spain (8%), Bulgaria (7%), and Brazil (7%). On average for this period, the EU import of copper ores and concentrates was 0.77 Mt/y, whereas the export was 0.4 Mt/y. The domestic production was 0.79 Mt/y, mainly from Poland, Bulgaria, Spain, Portugal, Finland, and Sweden, and with minor contributions from Romania, Cyprus, and Slovakia (EC, 2020b). In 2016-2020, the main suppliers of copper concentrates had shifted to Poland (19%), Chile (14%), Peru (10%), Spain (8%), Bulgaria (5%), Sweden (4%), Finland (2%), and Portugal (2%) (EC, 2023).

On average for 2012-2016, the EU import of refined copper was 0.33 Mt/y, whereas the domestic production was 2.71 Mt/y. Most of the imported copper came from Russian Federation (67%), Kazakhstan (10%), the UK (6%), and Serbia (4%), whereas the domestically refined copper came from Germany (25%), Poland (21%), Spain (15%), Belgium (14%), and other EU countries (25%).

The largest reported copper reserve in the EU is in Poland (30 Mt). Known resources exist in e.g., Finland (>4.8 Mt + additional resource potential of 10 Mt), Sweden (>11.7 Mt), and Norway (1.88 Mt) (Eilu et al, 2021; USGS, 2023). Copper resources are reported also from many EU member states, including Spain, Portugal, Ireland, Hungary, Slovakia, Albania, Romania, Serbia and Czech Republic.

8 Aluminium

Aluminium (Al) is the third most common element in the continental crust (after oxygen and silicon) with an Al_2O_3 crustal abundance of 15.4 % (Rudnick & Gao, 2014). It is usually mined as a main product and in 2015, the main global exporters of *ore (bauxite)* were Malaysia (30%), Australia (23%), Guinea (20%), Brazil (10%), India (8%), and Jamaica (5%). China is the largest importer of bauxite on the global market (62% of bauxite in 2015) and has become the largest producer of alumina (EC, 2020a). In 2016, the main exporting countries of *alumina (Al_2O_3)* were Australia (36%), Brazil (20%), Germany (5%), and USA (5%), i.e., China is using most of the alumina they produce (EC, 2020a). The main exporters of *aluminium (metal)* in 2016 were Canada (12%), Russian Federation (12%), United Arab Emirates (11%), Norway (6%), and Australia (6%) (EC, 2020a).

The bauxite end-uses in the EU in 2012-2016 were Refining to alumina (90%), Refractories (3%), Cement (3%), Abrasives (2%), and Chemicals (2%). The end-uses for refined aluminum in the same period were Mobility (42%), Construction (23%), Packaging (17%), High Tech Engineering (12%), and Consumer Durables (6%) (EC, 2020a).

Bauxite was listed as a critical raw material by EU in fourth edition (2020) and remains on the list in the latest revision (2023).

8.1 Ore deposits

Aluminium is extracted from bauxite, a heterogenous soil or soft rock remaining after intense lateritic weathering of precursor materials such as granite, basalt, volcanic ash or shale, occurring in tropic and subtropic climate (Reich & Vasconcelos, 2015). The primary ore minerals are Al-oxide-hydroxides (e.g., gibbsite, boehmite and diaspore), coexisting with varying amounts of silica, iron oxide, and aluminosilicate minerals. The Al_2O_3 concentration in bauxite is usually >40%.

Although aluminium is abundant and available in a wide range of silicate and other minerals, bauxite is currently the only reasonable source, due to economical issues and high energy consumption needed to liberate the metal from its mineral structure in other sources.

8.2 Extraction, Processing and refining

Bauxite deposits are usually surficial to shallow and are therefore mined with open pit techniques; ripping using bulldozer when the deposit is less consolidated or drilling and blasting when it is more consolidated. Except for possible washing and screening to remove clay, more complex beneficiation processes are generally not applied.

To produce alumina in a refinery facility, the thermo-chemical Bayer process is used (World Aluminium, 2017). The ore is treated with caustic soda at 140-280 °C in a digester, dissolving the aluminium-oxide-hydroxides. The Al saturated slurry is rapidly cooled in a series of flash tanks to 100 °C, and the solid residue is removed by sedimentation (adding a chemical flocculant to aid settling). The solution is cooled and $\text{Al}(\text{OH})_3$ crystals precipitates. These are separated by vacuum filtration and calcined at 1100 °C, to remove H_2O and form alumina (Al_2O_3).

To produce pure aluminium metal in a smelter facility, alumina is melted using the Hall-Héroult process (World Aluminium, 2017). This is conducted by dissolving the alumina powder in an electrolytic bath of molten cryolite (Na_3AlF_6) at ca 970 °C. As a direct current of 600 kA is passed from the anode to the cathode through the cryolite melt, the dissolved alumina splits to oxygen and molten aluminium. The aluminium melt sinks to the bottom, where it is siphoned.

Approximately 90% of mined bauxite is converted to alumina using the Bayer Process, and 80–90% of the alumina is smelted to aluminium using the Hall-Heroult Process.

8.3 Environmental and social imprint

The USGS estimates global bauxite resources to 55-75,000 Mt, distributed in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%), and elsewhere (6%). The reserves are estimated to 31 000 Mt, of which almost 60% are in Guinea, Vietnam, and Australia (USGS, 2023). In 2022, the global bauxite production was 380 Mt (USGS, 2023).

Cryolite is used as a flux to dissolve alumina in the Hall-Heroult process, since this reduces the energy needed to liberate aluminium from the oxide. Earlier cryolite was mined at the Ivvituu deposit in

Greenland, but since the closure of this mine in the late 1980's, cryolite synthesized from the mineral fluorite is used (see section on fluorine).

Bauxite deposits are generally located in tropical to subtropical regions, where there could be a potential conflict with nature of high conservation value (i.e., biodiversity and land-use issues). Mining requires access to large zones of land and water resources that sustain local communities (EC, 2020a). The EOL-RIR of aluminium in the EU in the period 2016-2020 was 32% (EC, 2023).

8.4 Potential within EU

The main suppliers of bauxite to the EU in 2012-2016 were Guinea (63%), Greece (12%), Brazil (10%), and Sierra Leone (7%). On average for the period 2012-2016, the EU import of aluminum ore (bauxite) was 13.6 Mt/y, whereas the export was 0.26 Mt/y. The domestic extraction was 2 Mt/y (EC, 2020a). In 2016-2020, the main suppliers had shifted to Guinea (62%), Brazil (12%), and Greece (10%) (EC, 2023). In 2012-2016, the EU imported 3.17 Mt/y processed materials (aluminum metal and alumina, Al_2O_3), whereas the export was 0.056 Mt/y. The domestic refinement was 2.1 Mt/t (EC, 2020a). The main suppliers of refined aluminium to the EU market in this period were various EU member states (46%; including Germany, France, and Iceland), the Russian Federation (17%), Mozambique (9%), and Norway (6%) (EC, 2020a).

Three EU member states mine bauxite, with Greece contributing 0.7% of the global production and Hungary, France and Croatia less than 0.1% each. The average domestic bauxite production in the EU in the period 2012-2016 was 2 Mt/y (EC, 2020a). Bauxite deposits of the karst type also exists in Albania, Serbia, Montenegro, Bosnia and Herzegovina, Italy, Spain and Austria.

Within the EU, there are *alumina refineries* in France, Germany, Greece, Ireland, Romania and Spain, with a combined total production amounting to 5% of the global total in 2012-2016 (EC, 2020a). Within the EU, there are *aluminium smelters* in Germany, France, Spain, Romania, Slovakia, Greece, Netherlands, Sweden, and Slovenia; these contributed ca 4% of the global aluminium metal production in the period 2012–2016 (EC, 2020a).

9 Fluorine (fluorspar)

Fluorine (F) is a relatively abundant element with a crustal concentration of 557 ppm (Rudnick and Gao, 2014). It is usually mined as by product and the three main global producers in 2012-2016 were China (64%), Mexico (15%), and Mongolia (5%) (EC, 2020a). The three main producers of processed fluorspar in the same period were China (34%), Mexico (16%), and Singapore (8%). EU member states contributing to the global figures on processed fluorspar were Italy (7%), Germany (6%), Spain (2%), Sweden (1%), and France (1%) (EC, 2020a).

The end-use in the EU in 2012-2016 was in Steel and iron making (36%), Refrigeration and air conditioning (18%), Aluminium making and metallurgy (15%), Solid fluoropolymers (11%), Fluorochemicals (10%), Nuclear uranium fuel (6%), and Alkylation process for oil refining (3%) (EC, 2020a).

Fluorspar was listed as a critical raw material by EU already in the first edition (2011) and has stayed on the list through all later revisions (2014, 2017, 2020, 2023).

9.1 Ore deposits

The mineral fluorspar (or fluorite; CaF_2) is the only commercial source for fluorine. Economic grade fluorite is usually found as vein fillings resulting from hydrothermal activity, often accompanied by sulfides of e.g., tin, silver, and copper. It is also found in certain types of granite and pegmatite, alkaline rocks, greisen, and as filling or grains in sedimentary rocks such as limestone, sandstone, and phosphorite.

9.2 Extraction, processing, and refining

The fluorspar ore is mined through open pit or underground operation. The ore is crushed, grinded, and beneficiated (through flotation), to remove gangue minerals and concentrate the fluorspar. Fluorspar concentrates are usually produced in two quality classes: metallurgic grade ($\leq 97\% \text{CaF}_2$) and acid grade ($>97\% \text{CaF}_2$) (USGS, 2023).

Acid grade fluorspar is further processed into hydrogen fluoride (HF), cryolite (Na_3AlF_6), or aluminum fluoride (AlF_3), whereas metallurgic grade fluorspar is mainly used in iron and steel making, but also e.g., cement production. HF is a precursor to other fluorine chemicals, such as fluorocarbons, fluoropolymers, fluoroaromatics and uranium hexafluoride.

9.3 Environmental and social imprint

Fluorspar deposits are abundant on all continents and the USGS estimates global fluorspar resources to at least 5000 Mt of 100% CaF_2 equivalent. The known reserves amount to 260 Mt (100% CaF_2), with the largest reserves in Mexico, China, South Africa, Mongolia, and Spain. In 2022, the global fluorspar production was 8.3 Mt (USGS, 2023).

The EOL-RIR of fluorspar in the EU in the period 2016-2020 was 1% (EC, 2023).

9.4 Potential within EU

In 2012-2016, the suppliers of acid and metallurgical grade fluorspar to the EU market were Mexico (25%), Spain (14%), South Africa (12%), Bulgaria (10%), China (8%), Germany (7%), UK (6%), Kenya (6%), and Namibia (5%) (EC, 2020a). In 2016-2020, the three main suppliers were Spain (62%), Germany (22%), and Italy (14%) (EC, 2023). On average for the period 2012-2016, the EU import of raw material (fluorspar) was 588 kt/y, whereas the export was 88 kt/y. The annual extraction in the EU in the same period was 254 kt/y. In the same period, the EU imported 12 kt/y processed materials (hydrogen fluoride, cryolite, and aluminium fluoride), whereas the export of these was 25 kt/y, i.e., the EU was a net exporter of processed fluorspar (EC, 2020a).

In the EU, fluorspar is produced entirely in the acid grade and takes place in the UK, Spain, and Germany. There was recent fluorspar production in France, Italy, and Bulgaria, but these operations have been closed. In the period 2012-2016, Spain contributed to 2% of the global fluorspar production, whereas UK and Bulgaria contributed 1% each (EC, 2020a). For the EU sourcing in the period 2012-2016, Spain (14%), Bulgaria (10%), Germany (7%), and the UK (6%) together contributed with over a

third of the EU need. However, the Bulgaria operation close-down will of course affect these figures negatively.

There are fluorite resources in Spain, France, Italy, UK, Sweden, Norway, Poland, Hungary, Czech Republic, and Serbia (EC, 2020a). When it comes to reserves, Spain has the largest in the EU at 6 Mt CaF₂.

The Swedish iron-ore company LKAB is planning to start extraction of *fluorine*, phosphorous, and rare earth elements, from apatite associated with the iron oxides. Historically, apatite has not been recovered when beneficiating the iron ore (it has stayed with the other gangue minerals in the tailings). However, the plan is to start production of apatite concentrate as by-product to the iron-oxide concentrates. The tailings from the iron ore concentrate production will go through a floatation step, in which the apatite will be recovered. Thereafter, fluorine, phosphorous acid, and mixed rare earth oxides will be extracted through acid leaching processes. A pilot plant is already in place, and full-scale operation is planned to 2027 (Source: <https://ree-map.com/>).

10 Phosphorous

Phosphorus (P) is a relatively common element with a P_2O_5 crustal abundance of 0.15 % (Rudnick & Gao, 2014). The pure phosphorous (“white phosphorous”), P_4 , needed for production of chemicals, electronics, or batteries, is refined from phosphate rocks through an energy intensive thermal reduction process. Phosphate rocks are mined as main product, and the three main global producers of ore concentrate in the period 2012-2016 were China (48%), Morocco (11%), and the USA (10%). In the same period, the main global producers of white phosphorous were China (74%), Vietnam (9%), Kazakhstan (9%), and the USA (8%) (EC, 2020a).

In 2012-2016, the end-use for phosphate rock in the EU was as Mineral fertilizer (86%), Animal feed (10%), and Detergents, chemicals, and food additives (4%). In the same period, the end-use for white phosphorous was in Chemical industry (90%), Electronics (5%), Agrochemicals (4%), and Metal products (1%) (EC, 2020a).

Phosphorus was introduced on the EU critical raw material list already in the second revision (2017) and has stayed there through the later revisions (2020, 2023).

10.1 Ore deposits

Economic grade phosphorous is found in phosphate rocks, i.e., rocks dominated by one or more of the hundreds of different phosphate minerals. Around 80% of the phosphate mining is from marine sedimentary rocks, 17% from igneous rocks, and 3% from residual sedimentary and guano deposits (Oelkers & Valsami-Jones, 2008). The most common phosphate mineral in the sedimentary deposit type is microcrystalline carbonate-fluorapatite and in igneous rocks it is apatite ($Ca_5[PO_4]_3[OH,F,Cl]$). Typically, the ore grade is 20-30% P_2O_5 (Oelkers & Valsami-Jones, 2008).

10.2 Extraction, processing and refining

Most phosphate rocks are extracted in open pit or opencast, including operational steps such as drilling, blasting and transportation of overburden and subsequently the ore by large draglines, shovels, bulldozers and trucks. Intercalated limestone layers are drilled, blasted, and removed, to exposure the continued phosphate rock body. When working deposits of relatively lower grade, e.g., apatite rich igneous intrusions, the ore needs to be concentrated through e.g., floatation processes. Most of the phosphate rock is processed to less pure phosphoric acid for production of fertilisers or other inorganic phosphate chemicals, whereas a smaller part (1% or less of phosphate rock production; EC, 2020a) is processed to pure phosphoric acid for production of elemental (white) phosphorus.

Reduction of phosphate to white phosphorous is conducted through heating in the presence of coke and silica, in electric or fuel-fired furnaces. Elementary phosphorus is liberated as vapor and collected under phosphoric acid.

10.3 Environmental and social imprint

The USGS estimates global phosphate rocks resources to at least 300 000 Mt. The USGS estimates global phosphate rock reserves to 72 000 Mt, of which 70% are found in Morocco. Relatively large reserves are also in the US, Algeria, Australia, Brazil, China, Egypt, Finland, Jordan, Saudi Arabia, South Africa, and Tunisia (USGS, 2023). The global phosphate rock production in 2022 was 220 Mt (USGS, 2023).

In theory, white phosphorus could be produced from phosphorus-rich waste, such as sewage sludge, manure, food waste, incineration ash or meat and bone meal ash. However, as far as we are aware only pilot scale facilities are yet in operation (<https://phosphorusplatform.eu/home2>; checked 2023-10-06).

The EOL-RIR of phosphorous in the EU in the period 2016-2020 was 0% (EC, 2023).

10.4 Potential within EU

In 2012-2016, the EU imported 1708 kt/y of phosphate rock, whereas the domestic extraction was 330 kt/y. The main suppliers to the EU were Morocco (24%), Russian Federation (20%), Finland (16%), Algeria (11%), and Israel (7%) (EC, 2020a). In 2016-2020, the figures had shifted to Morocco (27%), Russia (24%), Finland (17%), and Algeria (10%) (EC, 2023).

In 2012-2016, the import of white phosphorus to the EU was 49 kt/y and the main suppliers were Kazakhstan (71%), Vietnam (18%), and China (9%). There is no production of white phosphorus in the EU (EC, 2020a). In 2016-2020, this had shifted to Kazakhstan (62%), Vietnam (22%), and China (13%) (EC, 2023).

In Europe, phosphate resources are documented in Spain, UK, Finland, Norway, Estonia, Greece, Serbia, Denmark (Greenland), and Sweden (EC, 2020a; Eilu et al., 2021).

The only EU domestic extraction of phosphate rock is from the Siilinjärvi open pit mine in Finland (operated by Yara International). The deposit is associated with a carbonatite complex and the mine has been in operation since 1979, with annual extraction of more than 10 Mt ore at average grade 3.8% P₂O₅. The expected mine life is to 2035. The produced concentrate is processed to phosphoric acid and fertilizer in an adjacent plant ().

The Swedish iron-ore company LKAB is planning to start extraction of *phosphorous*, fluorine, and rare earth elements, from apatite associated with the iron oxides (the REEmap initiative). Historically, apatite has not been recovered when beneficiating the iron ore (it has stayed with the other gangue minerals in the tailings). However, the plan is to start production of apatite concentrate as by-product to the iron-oxide concentrates. The tailings from the iron ore concentrate production will go through a floatation step, in which the apatite will be recovered. Thereafter, *phosphorous acid*, fluorine, and mixed rare earth oxides will be extracted through acid leaching processes. A pilot plant is already in place, and full-scale operation is planned to 2027 (Source: <https://ree-map.com/>).

11 Conclusions

There are several challenges for the EU when it comes to a resilient and sustainable sourcing of raw materials to LIBs. One is the low degree of domestic mining of raw materials which are crucial for LIBs, where one or few external countries dominate the global market supply of ores and ore concentrates, with potentially large negative effect from supply-chain disturbances (Figure 1). Currently, over 50% of the global lithium supply currently comes from Australia, whereas 79% of the refined phosphorus is produced by China. For some raw materials, the EU sourcing is somewhat more diversified and even includes domestic production (Figure 2), e.g., nickel mining in Finland, and fluorspar (fluorine source) and phosphate rocks (raw material for white phosphorus production) also sourced from Mexico and Morocco, respectively, although China dominates the global supply of these (cf. Figure 1 and Figure 2). However, to a large extent Europe still relies heavily on sourcing outside the EU, often from countries with weaker social and environmental legislation, raising many concerns when it comes to environmental, social, and economic sustainability issues (Table 2).

Also, on the sourcing of processed raw material (i.e., production and refinement of intermediate to pure metals and compounds from the mining products, e.g., ore concentrates), the EU is highly dependent on import to the EU (Figure 2). For example, although the sourcing of phosphate mining products is somewhat more diversified, the refinement to white phosphorus needed for chemicals and battery manufacturing, is highly dominated by Kazakhstan (71% of the EU supply). The main suppliers to the EU market for raw materials crucial for LIBs, both on mining/extraction stage and the processing stage, are summarized in Table 6. Even though the figures for processed raw materials consumed within the EU in some cases looks reasonably good, these are calculated for the bulk processed raw materials, where intermediate products aimed at use in large-volume industries, e.g., steel, ceramics and glass, make a huge impact. For example, high-purity chemicals of battery grade class such as nickel or cobalt sulphate constitute a small share of all processed nickel and cobalt, where nickel and cobalt matte and other intermediate products for steel production dominates. Of the refined lithium, cobalt, and natural graphite used in the EU in 2012-2016, only 1, 3, and 5%, respectively, were used for battery production (and thereby of that refinement quality). For global comparison, 37, 50, and 8 %, respectively, of the raw material available were used in batteries (EC, 2020a; EC, 2020b). Therefore, the figures for the sourcing of processed raw materials in Table 6 could be misleading and give a false impression of a situation for LIB's better than it is, since the EU is even more reliable on few suppliers when it comes to the further refinement of specific battery-grade compounds.

In 2020, China accounted for 60% of refined cobalt, 93% of graphite active materials, 69% of refined lithium, 79% of battery-grade manganese (electrolytic and high-purity sulphate) and 63% of nickel sulphate production capacity (Carrara et al, 2023). This situation is graphically illustrated in Figure 3, where the different steps of the LIB value-chain is shown in context of supply risk (SR from 0 to 6, where a raw material, processed material, component, or assembled product with $SR > 1$ is considered *critical*, from an EU perspective). In Figure 3 the supply risk for the processed battery materials/compounds (second "column") is higher than that for the individual raw materials (first "column"), although the SR also for the individual raw materials is high enough to rank them as critical. Phosphorus, lithium, natural graphite, and cobalt are the most critical raw materials from a supply risk perspective, whereas the refined battery materials such as lithium cobalt oxide, lithium manganese oxide, and lithium iron phosphate active materials, and natural and synthetic graphite anode materials, have much higher supply risk. Phosphorus has such high SR mostly due to the concentration of processing plants that extract and purify the white phosphorus from phosphate rocks to a few locations, with almost 75% of the capacity in China and the rest in Vietnam, Kazakhstan, and USA (EC, 2020a). Most of the phosphor production in China stays there, to be incorporated in their own battery component and products manufacturing.

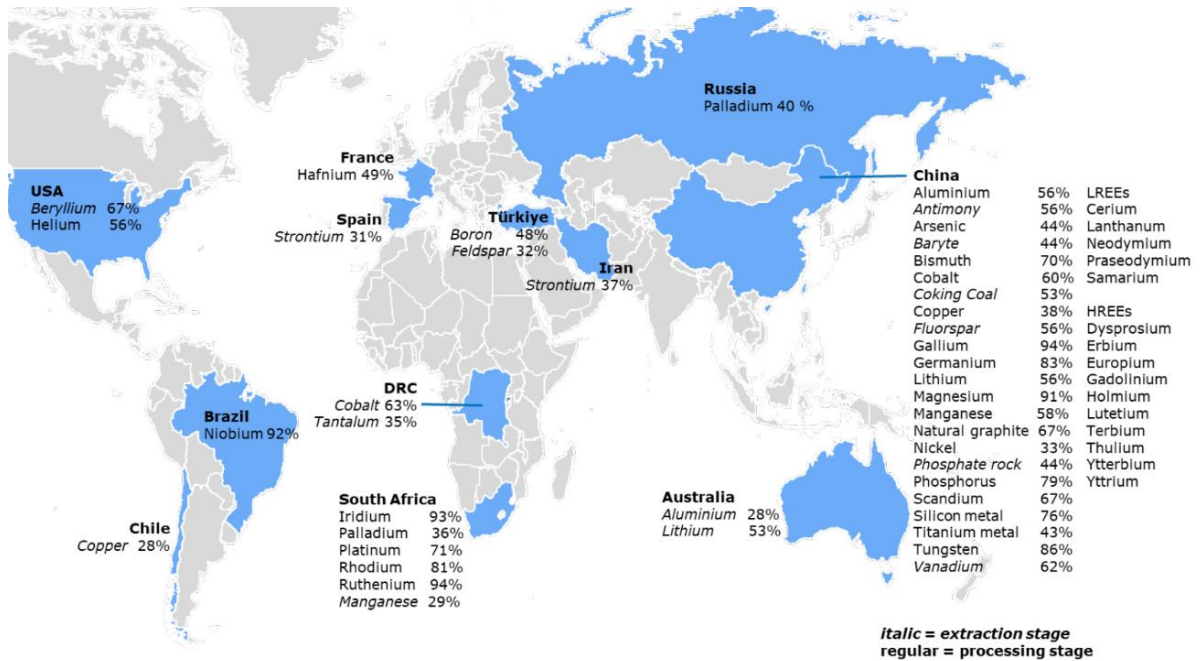


Figure 1 Main global suppliers of different Critical Raw Materials (European Commission, 2023). Raw material and percentage in *italics* refers to extraction stage. Normal style refers to processing stage.

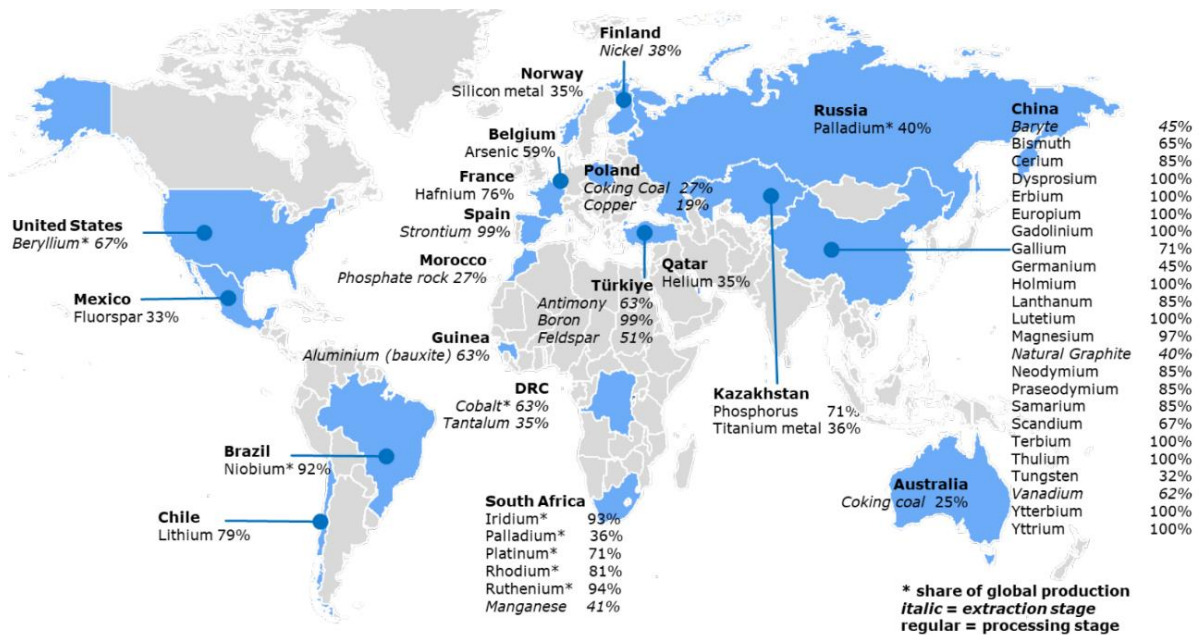
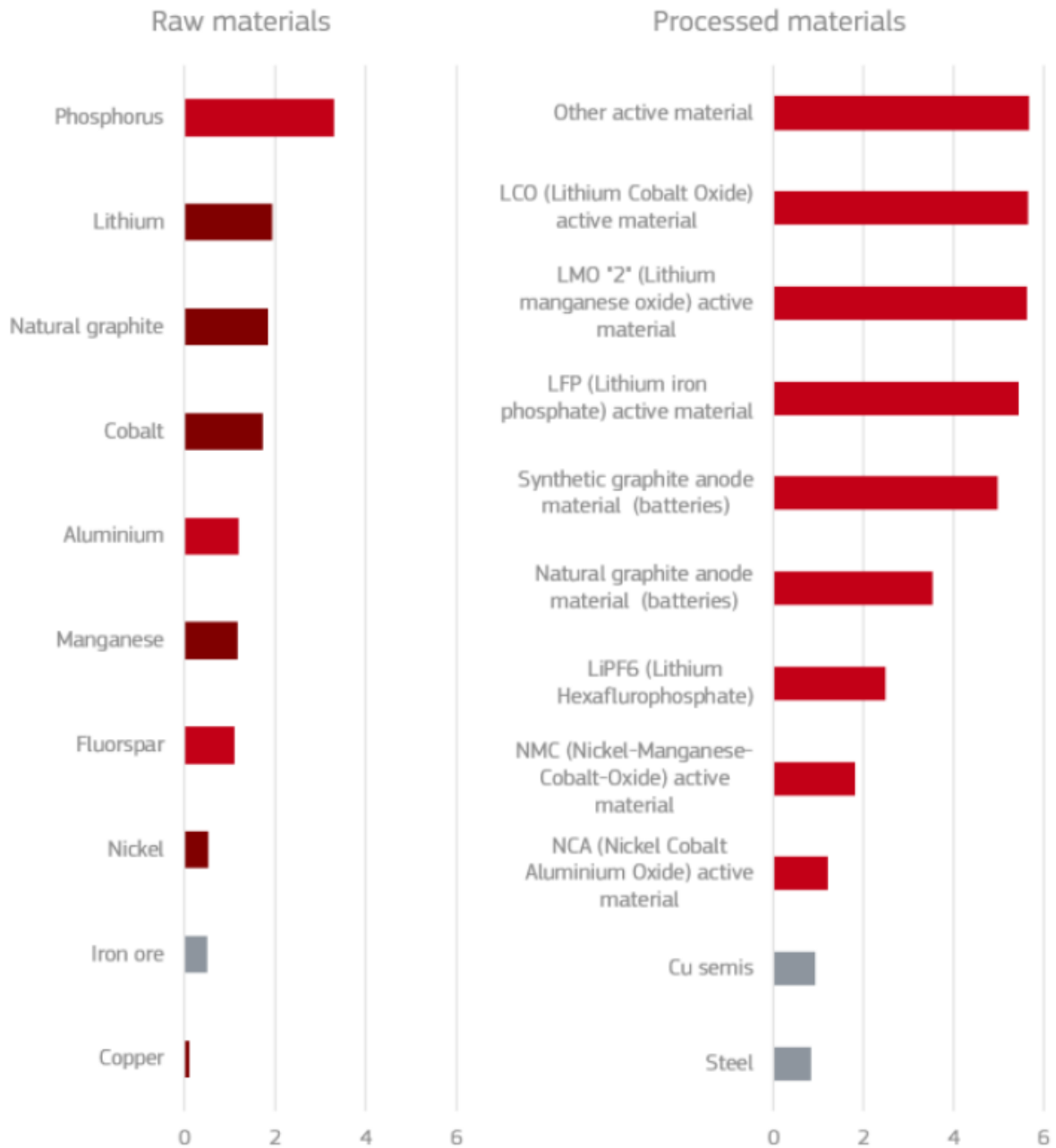


Figure 2 Main supplier of each individual Critical Raw Material to the EU (European Commission, 2023). Raw material and percentage in *italics* refers to extraction stage. Normal style refers to processing stage.

Table 6 Main producers for the EU market in 2012-2020 (EC, 2020a; EC 2020b; EC, 2023)

Raw material	Main producers for the EU market					
	Ore concentrate/mining products			Processed raw materials		
	1st	2nd	3rd	1st	2nd	3rd
Lithium 2012-2016:	Australia 89%	Portugal 11%		Chile 78%	USA 8%	Russia 5%
2016-2020:	n/a	n/a	n/a	Chile 79%	Switzerland 7%	Argentina 6%
Nickel 2012-2016:	South Africa 28%	Greece 21%	Finland 18%	Russia 26%	Finland 14%	UK 10%
2016-2020:	n/a	n/a	n/a	Russia 29%	Finland 17%	Norway 10%
Cobalt 2012-2016:	DCR 68%	Finland 14%	Russia 5% Canada 5% N Caledonia 5%	Finland 54%	Belgium 7% Norway 7% USA 7%	
Manganese 2012-2016:	South Africa 36%	Gabon 29%	Brazil 24%	Norway 28%	S Africa 23%	India 16%
2016-2020:	South Africa 41%	Gabon 39%	Brazil 8%	n/a	n/a	n/a
Natural graphite 2012-2016:	China 47%	Brazil 12%	Norway 8%	n/a	n/a	n/a
2016-2020:	China 40%	Brazil 13%	Mozambique 12%	n/a	n/a	n/a
Copper 2012-2016:	Poland 27%	Chile 13%	Peru 10%	Russia 67%	Kazakhstan 10%	UK 6%
2016-2020:	Poland 19%	Chile 14%	Peru 10%	n/a	n/a	n/a
Aluminium 2012-2016:	Guinea 63%	Greece 12%	Brazil 10%	EU 46%	Russia 17%	Mozambique 9%
2016-2020:	Guinea 62%	Brazil 12%	Greece 10%	n/a	n/a	n/a
Fluorspar 2012-2016:	Mexico 25%	Spain 14%	S Africa 12%			
2016-2020:	Spain 62%	Germany 22%	Italy 14%			
Phosphate 2012-2016:	Morocco 24%	Russia 20%	Finland 16%			
2016-2020:	Morocco 27%	Russia 24%	Finland 17%			
Phosphorous 2012-2016:				Kazakhstan 71%	Vietnam 18%	China 9%
2016-2020:				Kazakhstan 62%	Vietnam 22%	China 13%



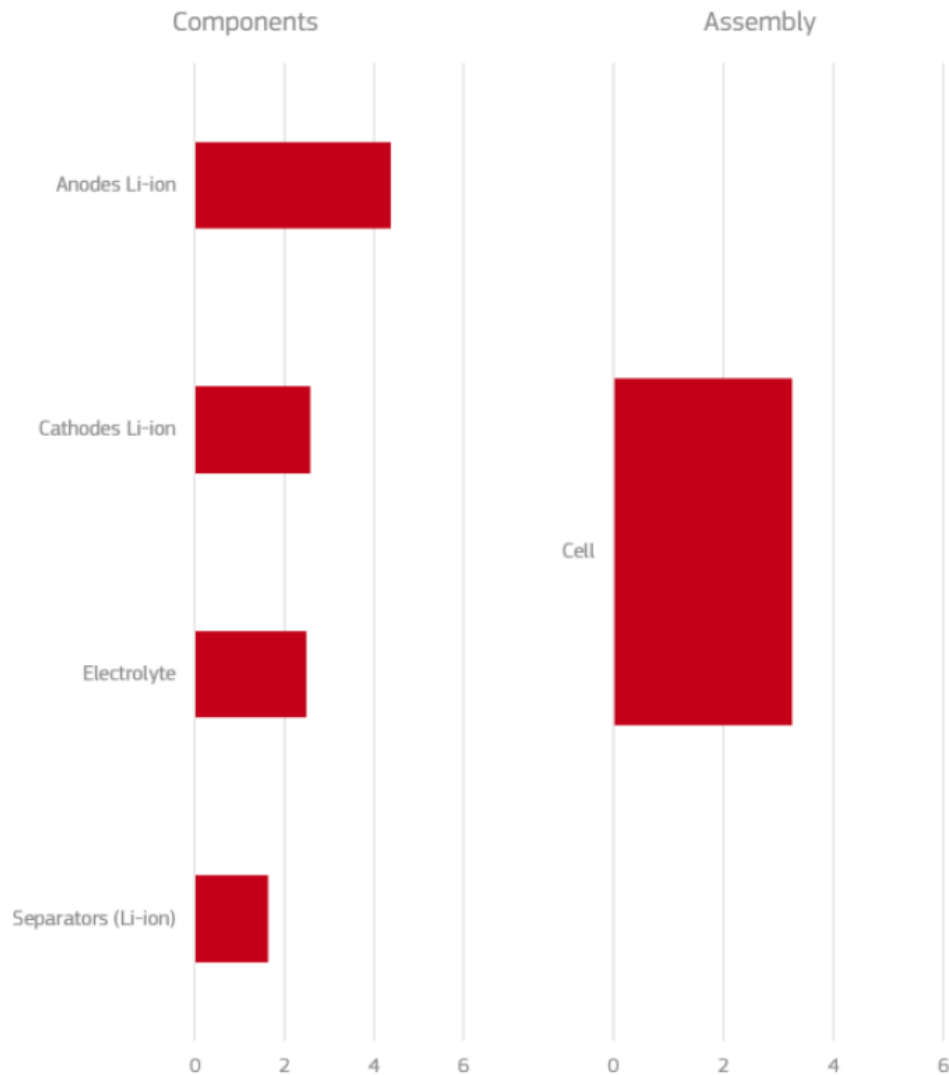


Figure 3 Supply risks for different steps in the LIB supply chain. Assessments for Raw Materials and Processed materials in the upper figure (on previous page), assessments for Components and Assembly in the lower (this page). Supply risk (SR) is graded from 0 to 6, where $SR \geq 1$ means the supply-risk is critical (i.e., high risk). Accordingly, the supply risk is relatively high for most of the raw materials needed for LIBs, but the supply risk is even higher for processed materials, because of the poor domestic mining and processing in the EU. Also the component and cell level are critical (in terms of supply risks). Source: Carra S et al. (2023)

However, the EU is increasing its capacity when it comes to the raw material sourcing and battery-grade compound refining industry. In 2020-2021, the EU contributed 8 and 10% of the global battery-grade cobalt and nickel sulfate capacity (Carrara, 2023), from new refining process plants in Finland. When it comes to battery-grade manganese, the Czeck Chvaletice Manganese Project could potentially provide up to 20% of the projected EU demand for batteries in 2030. Graphite mining, processing, and anode production is under development at different sites, and in Sweden will start already in 2024, where the company Talga will produce 19500 t/y anode material annually for at least 24 years; if investigations and permitting processes works out also for their other deposits, this will be upscaled to 100 000 t/y, making Talga the largest anode manufacturer outside China.

More untapped potential will probably be utilized the coming years, and it will be of importance to compare these new supply-chains with the conventional ones, in terms of effect on sustainability parameters such as global warming potential, biodiversity, land and water use, labour working conditions, and geopolitical stability. Some suggestions of companies for sourcing of active battery materials to small-scale testing, are given in Table 7.

Table 7 Potential suppliers of battery materials produced from EU raw materials

Material	Use	Company	Commercial status
Battery-grade nickel sulphate hexahydrate	NMC622 cathode	Terrafame Oy, Finland	Already operating on industrial scale.
Battery-grade cobalt sulphate hexahydrate		Terrafame Oy, Finland	Already operating on industrial scale.
Cathode material		Umicore	Recycled material
Battery-grade manganese sulphate monohydrate		Euro Manganese, Czech republic	Not yet operating, but materials from lab and pilot testing might already be available.
Battery-grade lithium hydroxide monohydrate	NMC622 cathode, electrolyte	Albemarle, Germany	Producing lithium chemicals from imported lithium carbonate-
		Sibanye-Stillwater, Finland	Plans to refine lithium from own deposits in Finland. Not yet operating, but materials from lab and pilot testing might already be available.
Graphite anode material	Anode	Talga AB, Sweden	Operation on industrial scale will start 2024. Materials from lab and pilot testing might already be available.
Hydrofluoric acid, precursor to other fluorine compounds	Electrolyte	Eurofluor	This organization lists European companies that produce HF from acid-grade fluorspar. Check if any is using domestically mined fluorspar as raw material.
Phosphoric acid, precursor to iron phosphate	Lithium iron phosphate cathode	ReeMAP, LKAB, Sweden	Planned production of pure phosphorus acid from apatite concentrate. Unclear if measures will be taken to refine to white phosphorus (elemental). Material might be available from pilot plant.
Copper, metallic (Grade A copper cathode)	Anode, wires,	KGHM Polska Miedz, Poland	Already operating on industrial scale
		Boliden, Sweden and Finland	Already operating on industrial scale
		Arubis, Germany, Belgium, and Bulgaria	Already operating on industrial scale
Aluminium, metallic	Tabs, foils	European Aluminium	This organization lists many alumina refining plants and aluminium smelters in the EU. Check if any is using domestically mined bauxite as raw material.

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#	PARTICIPANT SHORT NAME	PARTNER ORGANISATION NAME	COUNTRY
1	AIT	AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	AT
2	CIDETEC	FUNDACION CIDETEC	ES
3	KIT	KARLSRUHER INSTITUT FUER TECHNOLOGIE	DE
4	UDE	UNIVERSITAET DUISBURG-ESSEN	DE
5	SOV	SOVEMA SPA	IT
6	SAUERESSIG	MATTHEWS INTERNATIONAL GMBH	DE
7	RISE AB	RISE RESEARCH INSTITUTES OF SWEDEN AB	SE

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