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IEA Hybrid and Electric Vehicles (HEV) Task 40: Critical Raw Materials for Electric Vehicles

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IEA Hybrid and Electric Vehicles (HEV) Task 40: Critical Raw Materials for Electric Vehicles

Martin Beermann, Christian Aichberger, Gerfried Jungmeier, Michael Brenner-Fließer
JOANNEUM RESEARCH Forschungsgesellschaft

Wien, Mai 2023

Ein Projektbericht im Rahmen des Programms

IEA Forschungskooperation
im Rahmen von open4innovation

des Bundesministeriums für Klimaschutz, Umwelt, Energie,
Mobilität, Innovation und Technologie (BMK)

Vorbemerkung

Der vorliegende Bericht dokumentiert die Ergebnisse eines Projekts aus dem Programm FORSCHUNGSKOOPERATION INTERNATIONALE ENERGIEAGENTUR. Es wurde vom Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (BMK) initiiert, um Österreichische Forschungsbeiträge zu den Projekten der Internationalen Energieagentur (IEA) zu finanzieren.

Seit dem Beitritt Österreichs zur IEA im Jahre 1975 beteiligt sich Österreich aktiv mit Forschungsbeiträgen zu verschiedenen Themen in den Bereichen erneuerbare Energieträger, Endverbrauchstechnologien und fossile Energieträger. Für die Österreichische Energieforschung ergeben sich durch die Beteiligung an den Forschungsaktivitäten der IEA viele Vorteile: Viele Entwicklungen können durch internationale Kooperationen effizienter bearbeitet werden, neue Arbeitsbereiche können mit internationaler Unterstützung aufgebaut sowie internationale Entwicklungen rascher und besser wahrgenommen werden.

Dank des überdurchschnittlichen Engagements der beteiligten Forschungseinrichtungen ist Österreich erfolgreich in der IEA verankert. Durch viele IEA Projekte entstanden bereits wertvolle Inputs für europäische und nationale Energieinnovationen und auch in der Marktumsetzung konnten bereits richtungsweisende Ergebnisse erzielt werden.

Ein wichtiges Anliegen des Programms ist es, die Projektergebnisse einer interessierten Fachöffentlichkeit zugänglich zu machen, was durch die Publikationsreihe und die entsprechende Homepage www.nachhaltigwirtschaften.at gewährleistet wird.

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Zusammenfassung

Batterieelektrische Fahrzeuge stellen in Kombination mit erneuerbarem Strom für den Fahrzeugbetrieb eine wesentliche Säule in den politischen Strategien der EU und in Österreich für den Übergang des Verkehrssektors zur Klimaneutralität bis 2050 in der EU und 2040 in Österreich dar. Der zukünftige Bedarf an benötigten kritischen Rohstoffen in Batterien und Elektromotoren wird weltweit um ein Vielfaches des heutigen Bedarfs steigen. Dem gegenüber stehen Beschränkungen bei zusätzlich bereitstellbaren Rohstoffmengen, aufgrund von heute noch zurückhaltenden Investitionen in der Rohstofferschließung, der durchschnittlich langen Vorlaufzeit für neue Bergbauprojekte und der geographischen Konzentration der heute bekannten Reserven und Ressourcen meist außerhalb Europas.

Der IEA HEV TCP Task 40 "Critical Raw Materials for Electric Vehicles" greift die vielschichtige Nachfrage nach aktuellen Informationen zur Entscheidungsunterstützung in diesem Bereich auf. Ziel und Mehrwert von Task 40 ist eine integrierte Analyse aller relevanten Aspekte der zukünftigen Versorgung mit kritischen Rohstoffen für Elektrofahrzeuge, die die zukünftige Entwicklung in Form von Szenarien von Elektrofahrzeugflotten in Regionen und weltweit berücksichtigt, ebenso Technologieentwicklungen im Bereich von Batteriesystemen, primäre und sekundäre Rohstoffquellen und die Entwicklung von Recyclingtechnologien für Elektrofahrzeuge. Potentielle gesamthafte ökologische und soziale Auswirkungen der Rohstoff- und Batterieproduktion werden bewertet.

Elf Länder mit Institutionen der öffentlichen Hand, Forschung, Unternehmen und Interessenvertretungen beteiligten sich von 2018 bis 2022 an dieser internationalen Zusammenarbeit, mit JOANNEUM RESEARCH, Institut LIFE als österreichischem Vertreter. In einer Reihe von acht internationalen Expert:innen-Workshops sowie über Desktop Research wurden aktuelle Informationen und Daten zu kritischen Rohstoffen für Batterien erarbeitet.

Die wichtigsten Ergebnisse sind:

Der erforderliche steile Anstieg der weltweiten Elektrofahrzeugzahlen zur Erreichung der Klimaziele im Verkehrssektor im Jahr 2030 stellt hohe Anforderungen an das Angebot von Batterien und kritischen Rohstoffen, die in Task 40 bewertet wurden für: Nickel, Kobalt, Lithium, Graphit, Phosphat sowie Seltene Erden für Elektromotoren.

Bei den Batterietechnologien wird erwartet, dass Nickel-Kobalt- und Lithium-Eisen-Phosphat-Batterietechnologien bis 2030 vorherrschend bleiben werden. Neue Technologien wie Natrium-Ionen- oder Festkörperbatterien werden erst nach 2030 größere Marktanteile gewinnen. Lithium-Eisen-Phosphat-Batterien bieten einen Ausweg aus möglichen Defiziten bei der Versorgung mit Nickel und Kobalt.

Die Szenarien für die Entwicklung der globalen Elektrofahrzeugflotte ergeben den Bedarf einer Gesamt-Batteriekapazität von 3.000 bis 4.300 GWh im Jahr 2030, was dem 5- bis 8-fachen des Batterieabsatzes im Jahr 2022 entspricht. Die globalen Batterieproduktionskapazitäten lagen

2022 bei 1.500 GWh (die aber nur zu ca. 35% genutzt wurden), die bis 2030 um das Zwei- bis Dreifache steigen müssten. In Europa müssten die Produktionskapazitäten um das 30-fache von heute ca. 35 auf 1.300 GWh steigen, was eine echte Herausforderung für die Skalierung darstellt. In der EU wird die erste LFP-Batterieproduktion im Jahr 2023 in Betrieb genommen.

Die Nachfrage nach kritischen Rohstoffen für Elektrofahrzeuge wird bis 2030 stark ansteigen, abhängig von den Marktanteilen der Nickel-Kobalt- bzw. der Null-Nickel-Kobalt-Technologien. In einem Szenario mit einem hohen Anteil von Nickel-Kobalt-Batterien würde es zu einem Versorgungsdefizit bei Nickel und Kobalt kommen. Unabhängig von der Kathodenchemie sind Versorgungsdefizite bei Lithium und Graphit wahrscheinlich. Graphit könnte durch synthetisches Graphit ersetzt werden, allerdings um den Preis eines steigenden Energiebedarfs für die Herstellung und damit verbundener Treibhausgasemissionen. Der Phosphatbedarf in Lithium-Eisen-Phosphat-Batterien wird aus globaler Sicht nicht zu einem Versorgungsdefizit führen. Seltene Erden als magnetische Metalle können durch den Einsatz von induktiven Elektromotoren mit Nicht-Permanent-Magneten, die nicht auf seltene Erden angewiesen sind, ersetzt werden.

Das Batterierecycling ist ein zentrales Element der Versorgung mit kritischen Rohstoffen, insbesondere in Europa. Die Hydrometallurgie ist die Technologie, die am ehesten eine Kreislaufwirtschaft in diesem Bereich ermöglicht. Großtechnische Recyclinganlagen für Nickel-Cobalt-Batterien werden voraussichtlich Ende der 2020er Jahre zur Verfügung stehen. Großtechnische Recyclinganlagen für Lithium-Eisen-Phosphat-Batterien werden aus wirtschaftlichen Gründen erst nach 2030 zur Verfügung stehen, da wirtschaftlich weniger wertvolle Materialien zurückgewonnen werden können.

Die Ökobilanz von Batterien identifiziert die wichtigsten Lebenszyklusphasen und Prozesse, welche die Treibhausgasemissionen im Lebenszyklus von Batterien beeinflussen. Dabei handelt es sich um die Herstellung von Kathoden- und Anodenmaterialien für Batteriezellen, die Herstellung der Gehäuse für Module und Packs (insbesondere aus Aluminium), den Energiebedarf und den Energiemix für die Zellproduktion sowie die metallurgische Technologie und der Energiemix für das Recycling.

Summary

Battery electric vehicles, in combination with renewable electricity for vehicle operation, represent an essential pillar in the political strategies of the EU and in Austria for the transition of the transport sector towards climate neutrality by 2050 in the EU and 2040 in Austria. The future demand for required critical raw materials in batteries and electric motors will increase worldwide by a multiple of today's demand, which contrasts with already planned additional raw material supply volumes, the average long lead time for new raw material mining and processing projects and the geographical concentration of today's known raw material deposits and their processing mostly outside Europe.

IEA HEV TCP Task 40 “Critical Raw Materials for Electric Vehicles” took up the multifaceted demand for updated information for decision support in this field. Objective and added value of Task 40 was the integrated analysis of all relevant aspects of future supply of critical raw materials for electric vehicles, which future development (scenarios) of electric vehicle fleets worldwide, technology developments of battery systems, primary and secondary raw material sources, the development of recycling technologies for electric vehicles, and environmental and social impacts of raw material and battery production.

Eleven countries and many institutions from public agencies, research, associations and industry participated in this international collaboration between 2018 and 2022, with JOANNEUM RESEARCH, Institute LIFE as Austrian representative. In a series of eight international expert workshops and in desktop research up-to-date information and data on critical raw material for batteries have been elaborated.

The main results are:

High dynamics of steep increase of global EV fleets in order to reach the climate targets in the transport sector in 2030 pose high challenges to the supply-demand-balance of batteries and critical raw materials assessed in this Task 40, which are: Nickel, Cobalt, Lithium, Graphite, Phosphate as well as Rare Earth Elements for electric motors.

Nickel-Cobalt- as well as Lithium-iron-Phosphate battery technologies are expected to remain dominant until 2030, new technologies like sodium-ion or solid-state-batteries will gain increased market shares post 2030. Lithium-iron-Phosphate batteries offer a way out of potential deficits in Nickel and Cobalt supply.

Scenarios of global EV fleet development result in 3,000 to 4,300 GWh battery capacity demand in 2030, which is 5 to 8 times more than the battery sales in 2022. Global battery production capacities in 2022 have been 1,500 GWh, which would need to increase 2- to 3-fold until 2030. In Europe, however, production capacities would need to increase 30-fold from 35 to 1,300 GWh, which is a real upscaling challenge. Within the EU, the first LFP battery production starts operation in 2023.

Critical raw material demand for EVs will follow a steep increase until 2030, depending on the market shares of the high-Nickel-Cobalt- and zero-Nickel-Cobalt-chemistries. A high share of high-Nickel-Cobalt batteries would result in a supply deficit of Nickel, Cobalt. Both scenarios likely result in Lithium and Graphite supply deficits. Graphite has the potential to be substituted by synthetic Graphite, however at the cost of increasing energy demand and associated GHG emissions. Phosphate in Lithium-iron-Phosphate batteries will not result in a supply deficit from a global perspective. Rare earth elements as magnetic metals have the potential to be substituted by use of non-permanent-magnet inductive EV motors not relying on REE.

Battery recycling is a central element of critical raw material supply, especially in Europe. Hydrometallurgy is the most likely technology enable a circular economy in this field. Large-scale NMC-recycling plants can be expected to be in place in late 2020s, large-scale LFP-recycling can be expected to be in place later than 2030, due to economic reasons with less valuable materials to be recovered.

Battery LCA identifies the most relevant life cycle phases and processes influencing the greenhouse gas emissions of the battery life cycle. These are the production of battery cell cathode and anode materials, the production of module and pack material (especially if made of aluminum), the energy demand and mix for cell production and the metallurgical technology and energy demand and energy mix for recycling.

1 Introduction

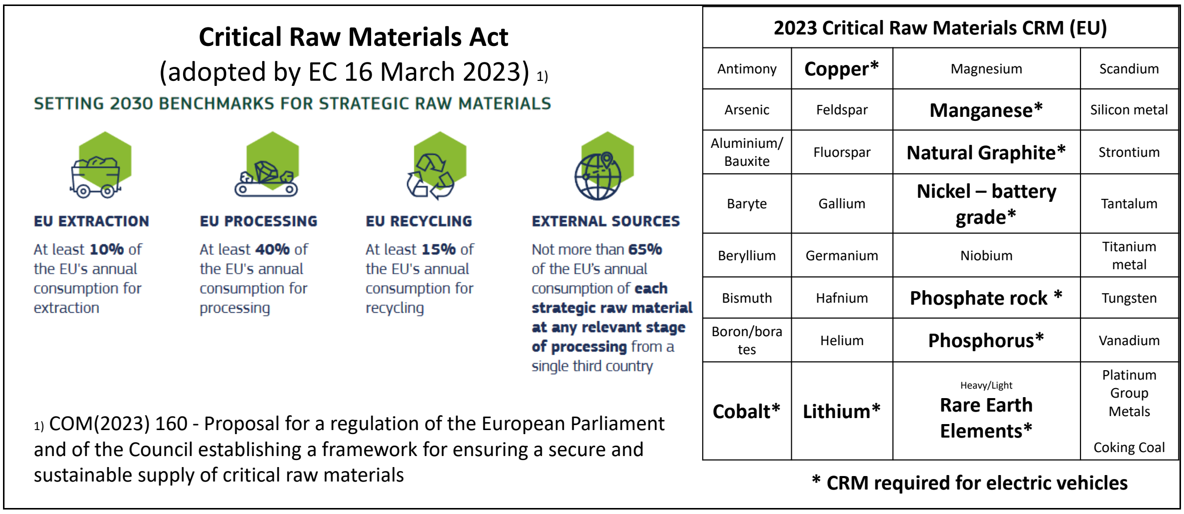
This chapter covers the motivation, the goal and scope, the approach and the cooperation and partners.

1.1 Motivation

Battery electric vehicles, in combination with renewable electricity for vehicle operation, represent an essential pillar in the political strategies of the EU and in Austria for the transition of the transport sector towards climate neutrality by 2050 in the EU and 2040 in Austria. With the replacement of gasoline- and diesel-powered by battery-electric vehicle fleets, the materials used and the associated upstream and downstream processes of vehicle and battery manufacturing and recycling are getting into the focus, which have previously not been relevant for vehicles, or to a much lesser extent. A battery electric vehicle requires approximately six times more materials of mineral origin than a gasoline or diesel-powered vehicle aside from steel and aluminum for vehicle body and chassis (IEA 2021). These materials are used for the production of the three main components of the battery-electric propulsion system - battery, electric motor and electronics.

The future demand for these raw materials will increase worldwide by a multiple of today's demand of the transition scenarios for achieving the Paris climate targets within the next three decades. The demand trend however contrasts with today's and already planned additional raw material production volumes, the average long lead time for new raw material mining and processing projects, and the geographical concentration of today's known raw material deposits and their processing in a few areas, mostly outside Europe.

In March 2023 the European Commission has adopted the Critical Raw Material Act, including a set of targets and benchmarks for an updated list of so-called critical raw materials. The definition of criticality is based on two main parameters: economic importance and supply risk of a raw material (Blengini 2020).



Critical Raw Materials Act

(adopted by EC 16 March 2023) 1)

SETTING 2030 BENCHMARKS FOR STRATEGIC RAW MATERIALS

EU EXTRACTION

At least **10%** of the EU's annual consumption for extraction

EU PROCESSING

At least **40%** of the EU's annual consumption for processing

EU RECYCLING

At least **15%** of the EU's annual consumption for recycling

EXTERNAL SOURCES

Not more than **65%** of the EU's annual consumption of **each strategic raw material at any relevant stage of processing** from a single third country

1) COM(2023) 160 - Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials

2023 Critical Raw Materials CRM (EU)

Antimony	**Copper***	Magnesium	Scandium
Arsenic	Feldspar	**Manganese***	Silicon metal
Aluminium/ Bauxite	Fluorspar	**Natural Graphite***	Strontium
Baryte	Gallium	**Nickel – battery grade***	Tantalum
Beryllium	Germanium	Niobium	Titanium metal
Bismuth	Hafnium	**Phosphate rock ***	Tungsten
Boron/borates	Helium	**Phosphorus***	Vanadium
Cobalt*	**Lithium***	Heavy/Light **Rare Earth Elements***	Platinum Group Metals Coking Coal

*** CRM required for electric vehicles**

Figure 1: European Critical Raw Material Act and updated list of critical raw materials CRM (EC 2023)

According to the Act, at least 10% of the EU's annual consumption of mined strategic minerals must be sourced domestically; 40% of processed strategic materials and 15% of its recycled strategic materials must also be domestically produced. In addition, the EU aims to diversify its global supply of minerals so that no more than 65% of its annual consumption of each strategic raw material – at any stage of processing – should come from a single third country.

Under the legislation, EU member states are expected to develop national programs for exploring their geological resources. Projects deemed as "strategic" will benefit from access to financing opportunities as well as a shorter wait for permits, like two years for mining projects and one year for processing and recycling. The EU also aims to increase its bargaining power by forming partnerships or "Critical Raw Materials Clubs" with countries with which it is on good terms, such as Canada or Australia.

Manifold aspects and research topics related to electric vehicles and batteries result in a multifaceted demand for updated information for decision support. Task 40 Critical Raw Materials for Electric Vehicles (CRM4EV) took up this task, in order to contribute to a resource-efficient, environment-compatible and socially accepted supply of critical raw materials.

1.2 Goal and scope

Objective and added value of Task 40 is the integrated analysis of all relevant aspects of future supply of critical raw materials (CRM) for electric vehicles, enabling a sustainable battery production and vehicle integration as competitive advantage in line with the European and Austrian battery initiatives. This task assesses critical raw materials in the light of future developments related to electric vehicles, including the following aspects:

- development (scenarios) of electric vehicle fleets in countries and worldwide,
- technology developments of battery systems,

- primary and secondary raw material sources,
- development of recycling technologies for electric vehicles, and
- environmental and social impacts of raw material and battery production and possible normative standards for compliance with minimum environmental and social requirements in countries supplying critical raw materials.

1.3 Contribution to the program

Task 40 addresses the thematic priority 4 Transport and mobility system, thematic field TF 4.4 "Participation in R&D cooperations of the International Energy Agency (IEA)" in the TCP HEV. With the research and technology program, the Climate and Energy Fund supports the targeted (further) development of technologies and components as well as their system integration, and the preservation and expansion of Austria as an industrial and business location by reducing the energy and CO_2 intensity of production. The objectives in Task 40 in the area of critical raw materials for electric vehicles shall contribute to the goals of the energy research program as follows:

- support international networking of Austrian industry and research,
- strengthening of Austria's competence in materials research and basic materials production,
- recommendations for sustainability in battery production and recycling as a key differentiator and competitive advantage,
- projections of global resource demand; assessment of global availability and access to resources; global production capacities and their distribution and future needs; alternatives for critical raw materials.
- available recycling methods and their profitability conditions as well as recycling research needs; best practice examples or recommendations for setting up recycling systems in terms of timing, structure as well as legal requirements.

1.4 Methods

In the international collaboration and a series of Task and expert workshops, scenarios of the battery-electric vehicle fleet development, battery technology development, critical raw material production and recycling were developed and assessed by different partner institutions. The focus was on the raw materials for batteries for electric vehicles in the light duty (passenger and van) vehicle class.

JOANNEUM RESEARCH contributed mainly with the assessment of environmental and social impacts of raw material and battery production and recycling and coordinated the work based on Life Cycle Assessment (LCA) with other international partners, like Argonne National Laboratory or Nickel Institute.

Applied methods in Task 40 included:

- 8 international expert workshops between 2018 and 2022 (final workshop in Austria in 2022)
- Development of a battery LCA model at JOANNEUM RESEARCH
- Literature search and analysis
- Dissemination of results at international workshops and conferences

1.5 Cooperation and partners

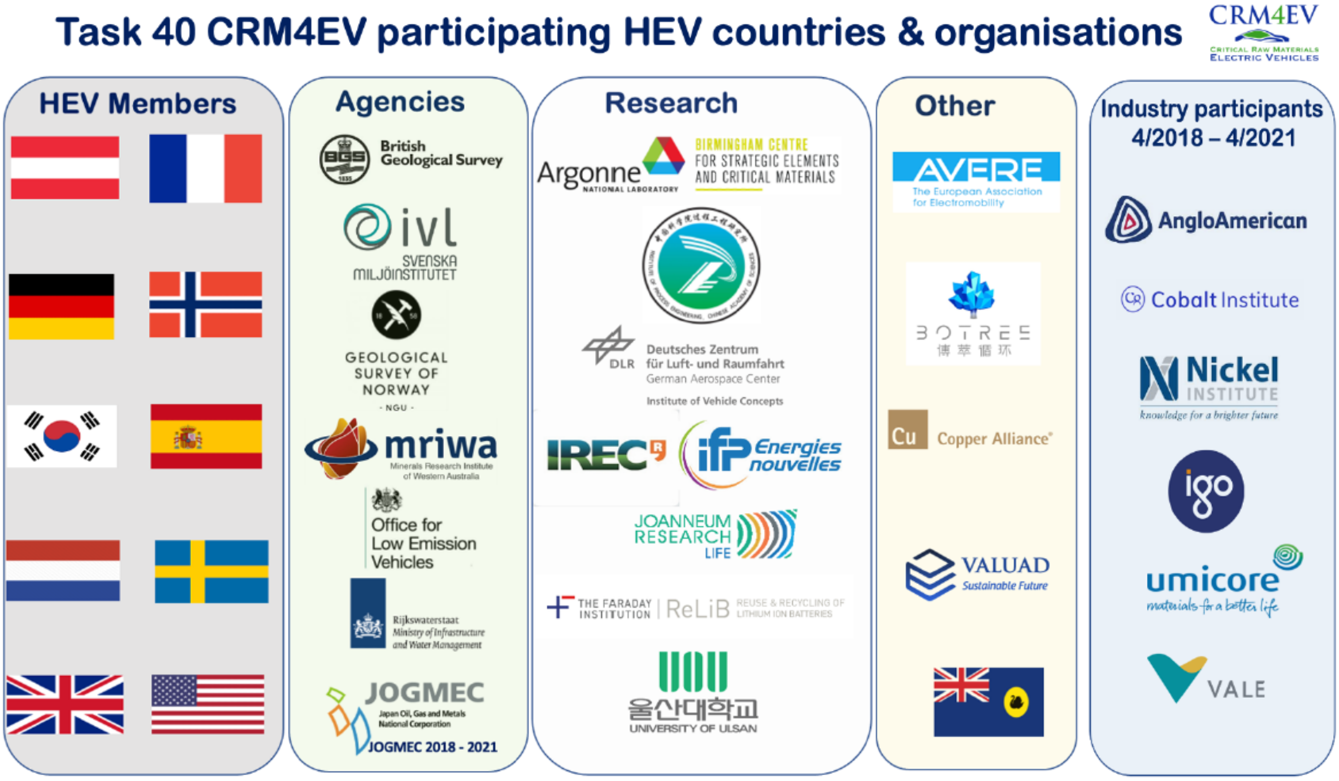
The Hybrid and Electric Vehicle Technology Collaboration Programme (HEV TCP) enables member parties to discuss their respective needs, share key information, and learn from an ever-growing pool of experience from the development and deployment of hybrid and electric vehicles. (see www.ieahev.org)

The HEV TCP was formed in 1993 to produce and disseminate balanced, objective information about advanced electric, hybrid and fuel cell vehicles. It is an international membership group collaborating under the International Energy Agency (IEA) framework. TCPs are at the core of the IEA International Technology Co-operation Programme coordinated by the IEA Committee on Energy Research and Technology (CERT). HEV TCP is now in its sixth five-year term of operation that runs from March 2020 until March 2025. An annual report is published each year, which details work completed under the HEV TCP and news from member countries. Austria is one of currently (status May 2023) 18 active Contracting Parties (member countries) in HEV TCP (further details: https://ieahev.org).

Member countries of Task 40 CRM4EV – Critical Raw Materials for Electric Vehicles were:

- Austria
- France
- Germany
- The Netherlands
- Norway
- Republic of Korea
- Spain
- Sweden
- United Kingdom
- United States of America

Task manager was Mr. Bert Witkamp (Valuad, The Netherlands), Austria was represented by JOANNEUM RESEARCH, Institute LIFE for Climate, Energy Systems and Society in Graz.



Task 40 CRM4EV participating HEV countries & organisations

Figure 2: TCP HEV member countries, public agencies, associations, research and industry participating in Task 40

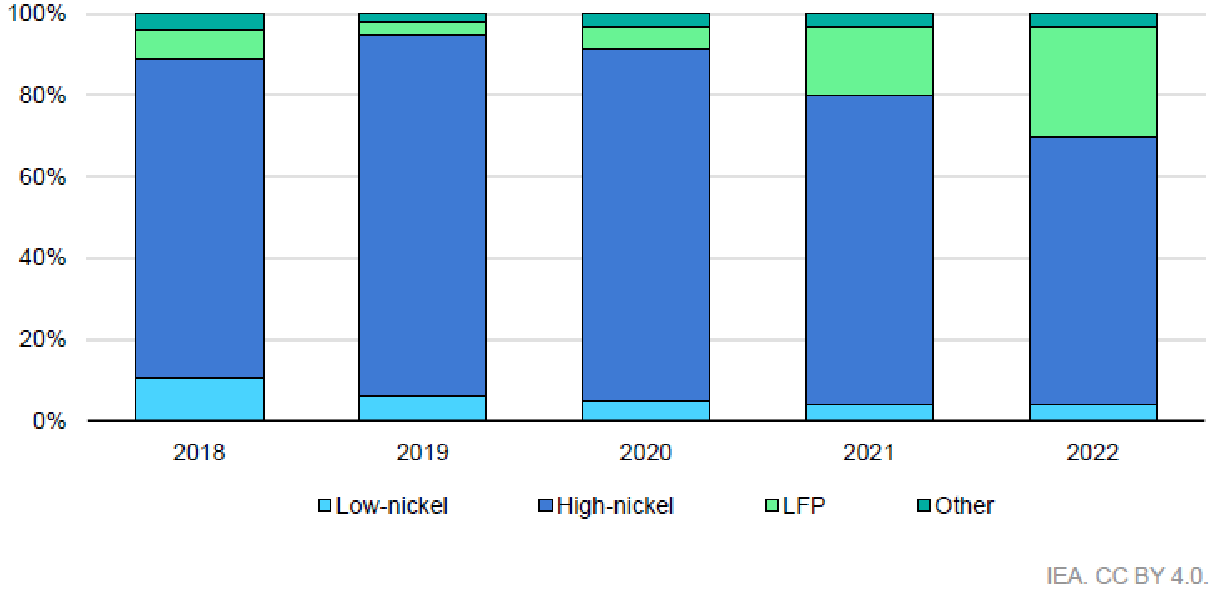
2 Results

The following sections present the results of Task 40 work and additional desktop research in relation to relevant aspects of future supply of critical raw materials for electric vehicles, which combine future development (scenarios) of electric vehicle fleets worldwide, technology developments of battery systems, sourcing of primary and secondary raw materials, the development of recycling technologies for batteries, environmental and social impacts of raw material and battery production and good practice examples in the EV battery life cycle.

2.1 EV batteries

2.1.1 Dominant battery chemistries in 2022

Today Lithium Nickel Manganese Cobalt oxide (NMC), Lithium Iron Phosphate (LFP) and Nickel Cobalt Aluminum oxide (NCA) are the dominant battery chemistries for EVs in the light duty vehicle (LDV) vehicle class. NMC batteries include low-Nickel chemistries with an even share of Nickel, Manganese and Cobalt (called NMC333 or NMC111) and high-Nickel chemistries with a high share of Nickel in the cathode and lower shares of Manganese and Cobalt (NMC532, NMC622, NMC721, NMC811). Figure 3 presents the global market shares in 2022 of cathode chemistries with 60% NMC, followed by LFP of about 30%, and NCA with a share of about 8% (IEA 2023).



IEA. CC BY 4.0.

Figure 3: Global market shares of EV LDV battery chemistries, 2018-2022 (IEA 2023)

2.1.2 EV battery developments 2022-2030 & beyond

Nickel-Cobalt based chemistries like NCA (used mainly by Panasonic and Tesla) and NMC (used by most other OEMs) as high performance batteries for EVs are still further developed and optimized with a trend to increase the Nickel content and to reduce Cobalt and to increase the energy storage capacity. The challenge is the balancing of battery properties when increasing the amount of Nickel in the cathode. While operating voltage and energy density increase, thermal stability, which is maintained by Manganese and Cobalt in the cathode, and long-term cycling performance decrease. The shares of Nickel, Manganese and Cobalt (e.g. NMC532, NMC622, NMC721, NMC811) leave a wide space of design options to find the optimum between battery performance, lifetime and costs. Also, Cobalt-free so-called NMX-batteries are currently developed.

LFP chemistry today plays a much more important role than generally expected a few years ago, it is already the dominant technology in China where the 2022 market share was 61% (Witkamp 2023). LFP batteries are safer, have lower costs, a longer lifetime and a lower environmental footprint, but also a lower energy density compared to NMC-batteries. With an increasing energy density and also the rapidly increasing fast charging networks that will reduce the need for large battery capacities, the share of LFP-batteries is likely to increase. While Iron is an abundant material, Phosphate belongs to the list of critical raw materials of the EU. Finland is currently the only Phosphate producer in the EU. Currently there is also no European producer of LFP-cells.

The potential of Sodium (Na)-ion batteries, the only post-Lithium-ion battery technology already being commercialized today, will become clear in this decade and first commercial application will start in 2023/2024. Sodium as abundant material can replace Lithium as critical raw material in both the cathode and the electrolyte. Sodium is the element in the alkali metals group next to Lithium (which is the lightest metal in the periodic table) with its mass approximately three times higher than that of Lithium. Energy density of sodium ion batteries will therefore be considerably lower than that of high-Nickel chemistries and slightly lower than that of LFP-chemistries. It will therefore be mainly suitable for stationary and mobile storage applications where energy density is not critical. A challenge to be resolved is to develop a stable, cheap and high capacity anode material (Hanzu 2022). Currently hard carbon is the preferred anode material, which comes along with the disadvantage of high energy consumption for its production in high-temperature processes. Another challenge as with all new materials is related to the time required for upscaling production processes and establishing supply chains for battery-grade sodium material. For the perspective of 2030 the Sodium-ion battery technology for EVs is estimated to only contribute with a global market share of below 5% (IEA 2022).

The development of all-solid-state batteries is another next improvement step in battery performance. Major advantages of solid-state batteries are increased safety and thermal stability, no corrosion and no leakage. Disadvantages are limited diffusion kinetics and ionic conductivity, resulting in lower power and energy density. However, this development is an enabler also of Lithium metal anodes (which cannot be used with liquid electrolytes) which can result in significant increases in battery energy density compared to current Li-ion batteries with Graphite anodes. Upscaling of production processes, but also the additional demand of critical raw materials (Lithium in the Lithium-metal anode, La, Zr, Ge, Ga, (P) in certain solid electrolytes) are further challenges to be solved, therefore all-solid-state batteries are not expected to have a significant impact on battery markets before 2030 (IEA 2022).

2.1.3 EV battery properties and material composition

NMC, NCA and LFP batteries have different properties, besides the different materials used (Figure 4). One of the key EV battery properties is the mass energy density in Wh per kg. Energy density is defined on cell level to express the electrochemical potential depending on the battery chemistry, and on pack level to also include the structural material mass required for mechanical stability and casing of cells together with peripheral components like thermal management and electronic battery management systems.

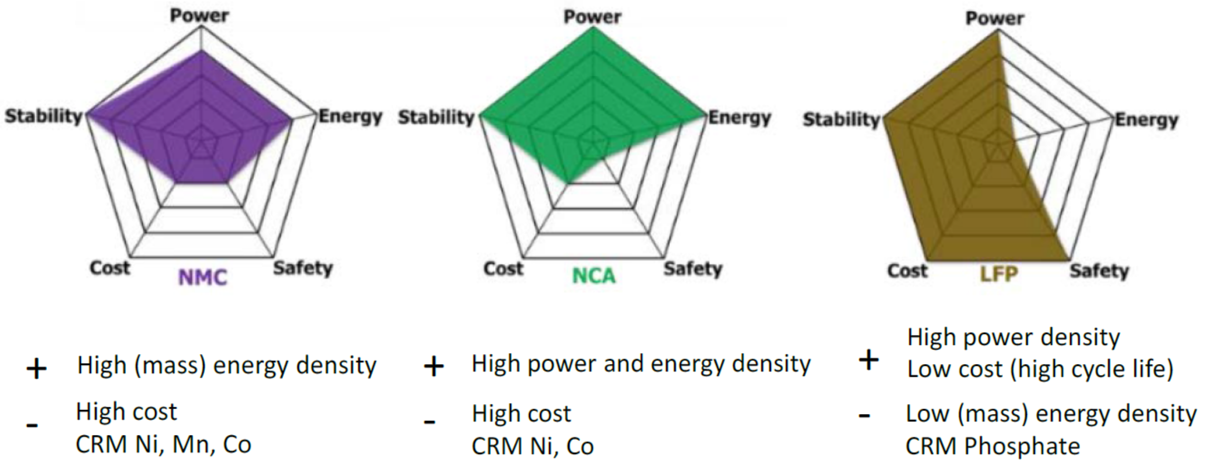


Figure 4: Radar summary of key properties of battery chemistries NMC, NCA, LFP (Houache 2022)

Energy density on pack level is the decisive parameter for EV application, which is influenced not only by cell chemistry and cell energy density, but also by the shares of aluminum and / or steel used for structural elements and module and pack casing. The impact of the choice of module and pack materials on pack energy density is shown in the following Table 1 data from Task partner Argonne (US) and its so-called GREET-model[1] include the three dominant chemistries NMC (low-Nickel NMC111 and high-Nickel NMC811), NCA and LFP. The GREET model is the most comprehensive open source inventory database for different battery types since 2012, which has been regularly updated. The values presented in Table 1 are based on the GREET2 model in two versions of 2021 (with aluminum as the main material for module and pack) and 2022 (with a significant share of steel for module and pack).

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[1] https://greet.es.anl.gov/

Table 1: Cell and pack energy densities for various battery chemistries used in this project

		NMC111	NMC811	NCA	LFP
Cell specific energy [1)]	Wh/kg	270	310	300	215
Pack specific energy (Aluminium for structure and casing) [2)]	Wh/kg	215	248	251	174
Pack specific energy (Steel for structure and casing) [3)]	Wh/kg	158	174	170	133

1) BatPAC model V4.0, V5.0, Argonne NL

2) GREET2 (V2021), Argonne NL 2021

2) GREET2 (V2022), Argonne NL 2022

The following figures present the material composition of the two above mentioned battery designs, each with 60 kWh battery capacity, with similar cells, but with aluminum in Figure 5 respectively steel Figure 6 as main materials for battery structure and casing. Figure 5 and Figure 6 show the range of results of total battery mass and of the shares of module and pack mass with 20% in the case of Aluminum and 40% in the case of Steel. This comparison shall point to the importance of transparently documenting data and assumptions as basis for discussing comparative LCA results.

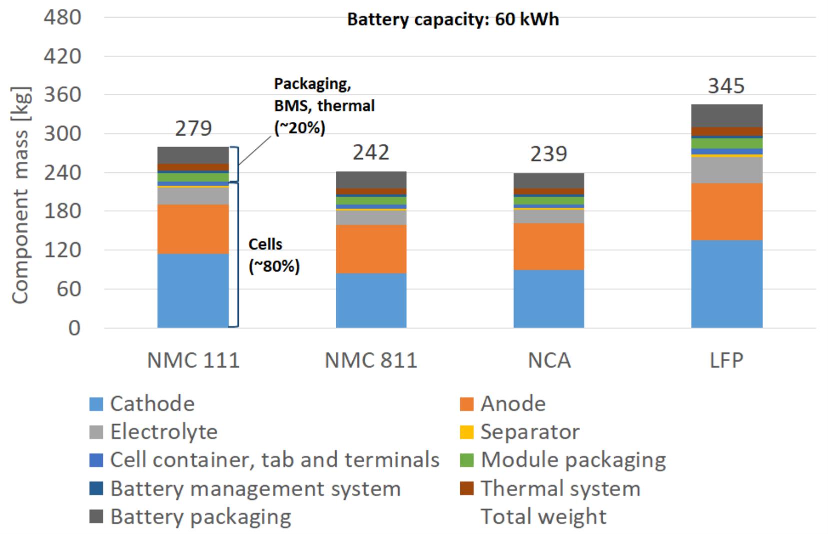


Figure 5: Material mass of battery components in a 60 kWh battery with various battery chemistries with high share of aluminum in battery casing (JR Battery LCA model, based on data from GREET 2021)

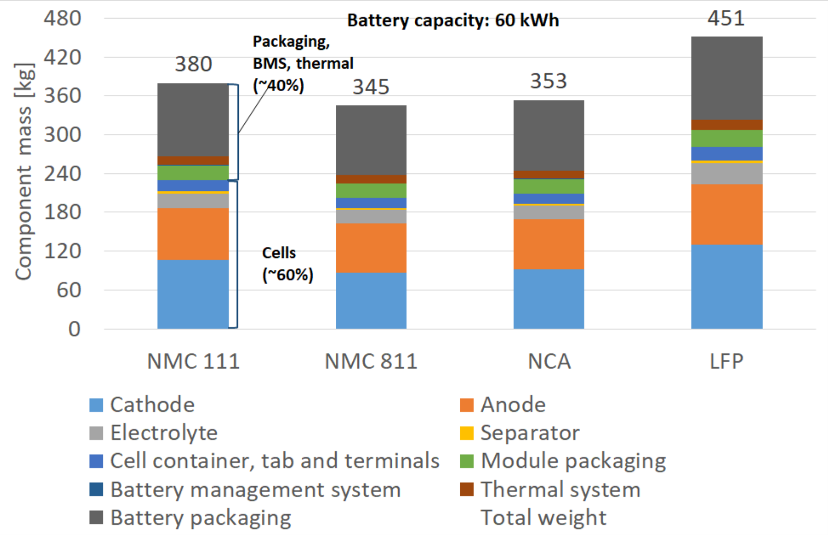


Figure 6: Material mass of battery components in a 60 kWh battery with various battery chemistries with high share of steel in battery casing (JR Battery LCA model, based on data from GREET 2022)

2.1.4 Critical raw material demand in an electric vehicle

Critical raw materials in electric vehicles are used in the batteries and the electric motors. The following Figure 7 shows the critical raw materials required in kg per kWh battery capacity in today`s dominant battery chemistries NMC (NMC111, NMC811), NCA and LFP, which sum up to about 2.1 kg/kWh battery capacity in the NMC811 and NCA batteries, 2.4 kg/kWh in the NMC111 and 2.8 kg/kWh in the LFP battery. The critical raw materials according to the list of CRM of the European Commission (EC 2023) relevant in EV-batteries are **Nickel, Cobalt, Manganese, Lithium, Copper, Graphite and Phosphate**.

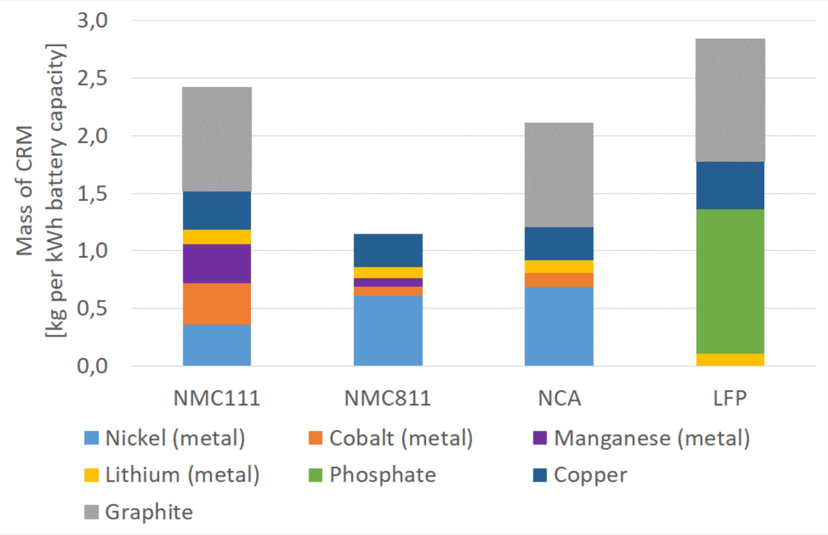


Figure 7: Critical raw materials in kg per kWh battery capacity of various battery chemistries (JR LCA model, based on data from GREET 2022)

Table 2: Critical raw materials in kg per kWh battery capacity of various battery chemistries

	NMC111	NMC811	NCA	LFP
CRM	kg/kWh battery capacity			
Nickel	0,36	0,61	0,68	0
Cobalt	0,36	0,08	0,13	0
Manganese	0,34	0,07	0	0
Lithium	0,12	0,10	0,11	0,11
Phosphate	0	0	0	1,25
Copper	0,34	0,29	0,29	0,42
Graphite	0,90	0,91	0,90	1,06

Propulsion systems for electric vehicles are currently almost exclusively based on so-called NdFeB permanent magnet (PM) motors containing rare earth elements (REE). The main components are neodymium (Nd), iron (Fe), and boron (B), in smaller quantities dysprosium (Dy) and praseodymium (Pr). The rare earths **Neodymium** (Nd) and **Praseodymium** (Pr) are used for the magnetic performance and **Dysprosium** in small quantities for the temperature stability. Per PEV about 1.5 to 2.5 kg PM are required on average for the e-drive motor (quantity depending on motor power), currently containing about 29-32% Nd,/Pr and 1-8% Dy, resulting in a total of about 0.45 to 1kg REE per EV.

2.2 Critical raw material demand for EV

2.2.1 Global EV-Fleet 2022

This section presents the current quantities of the EV fleet globally, in China and in Europe (quantities from IEA 2023):

- 26 million EV global stock in 2022 (70% BEV, 30% PHEV)
  - 13 million (50%) EV stock in China
  - 8 million (30%) EV stock in Europe (EU-27, Norway, UK)
- 10 million global EV sales in 2022
  - 4.4 million BEV + 1,5 million PHEV sales in China
  - 1,8 million BEV, 0,9 million PHEV sales in EU
- 14 million global sales expected for 2023
- 65% average year-by-year growth rate of China EV car sales 2017 to 2022
- 40% average year-by-year growth rate of EU EV car sales 2017 to 2022
- 14% share of EV sales of total car sales globally in 2022
  - 29% in China
  - 21% in EU
  - 88% in Norway (Figure 9)
  - 54% in Sweden (Figure 9)
  - 35% in Netherlands (Figure 9)
  - 31% in Germany (Figure 9)

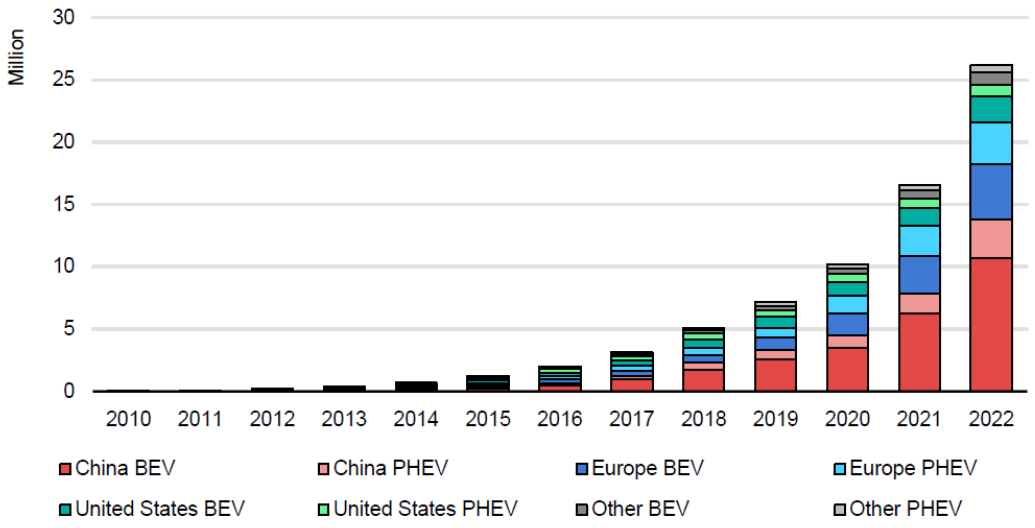


Figure 8: Global electric car stock in selected regions, 2010-2022 (IEA 2023)

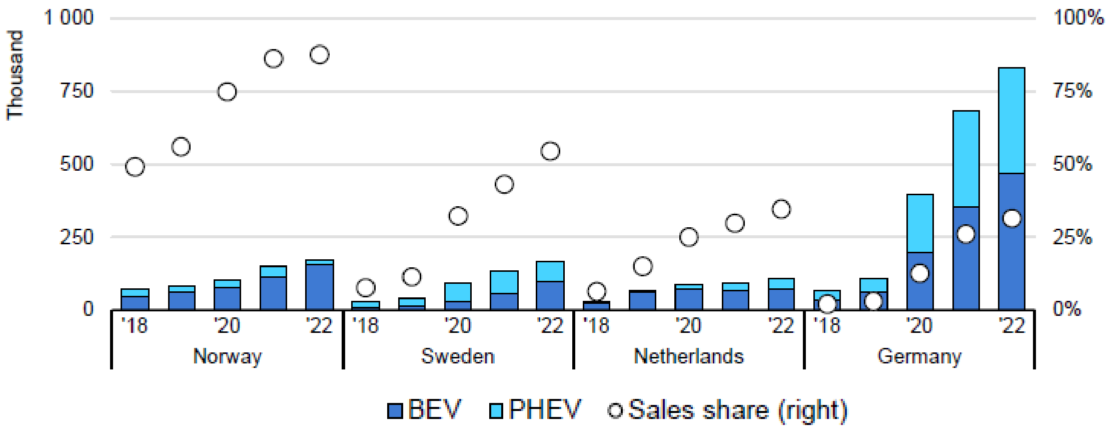
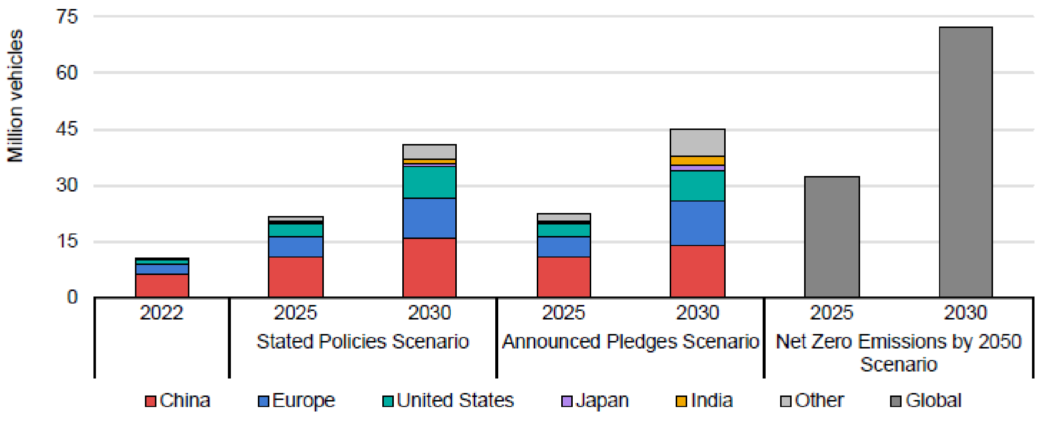


Figure 9: Electric car registrations and sales share in selected European countries, 2018-2022 (IEA 2023)

2.2.2 EV fleet development scenarios 2030

The period until 2030 is of particular interest in relation to EV development scenarios and the resulting demand of battery materials, due to potential short-term deficits of battery material supply in 2030 as a consequence of the required development time of new raw material mining sites and material processing plants.

In Task 40 forecasts of global EV development until 2030 have been reviewed from organizations like IEA, Global Battery Alliance (GBA), and major consultancies. The IEA communicates three scenarios (STEPS – Stated Policies Scenario, APS – Announced Pledges Scenario, NZE – Net Zero Emissions by 2050 Scenario). In the latest report (IEA 2023) growth scenarios of EV sales have been significantly revised upward between 30% year-by-year growth rate in STEPS (resulting in about 40 million EV sales in 2030), 35% year-by-year growth rate in APS (resulting in 45 million EV sales in 2030) and 40% year-by-year growth rate in NZE (resulting in over 70 million EV sales in 2030) (see Figure 10).



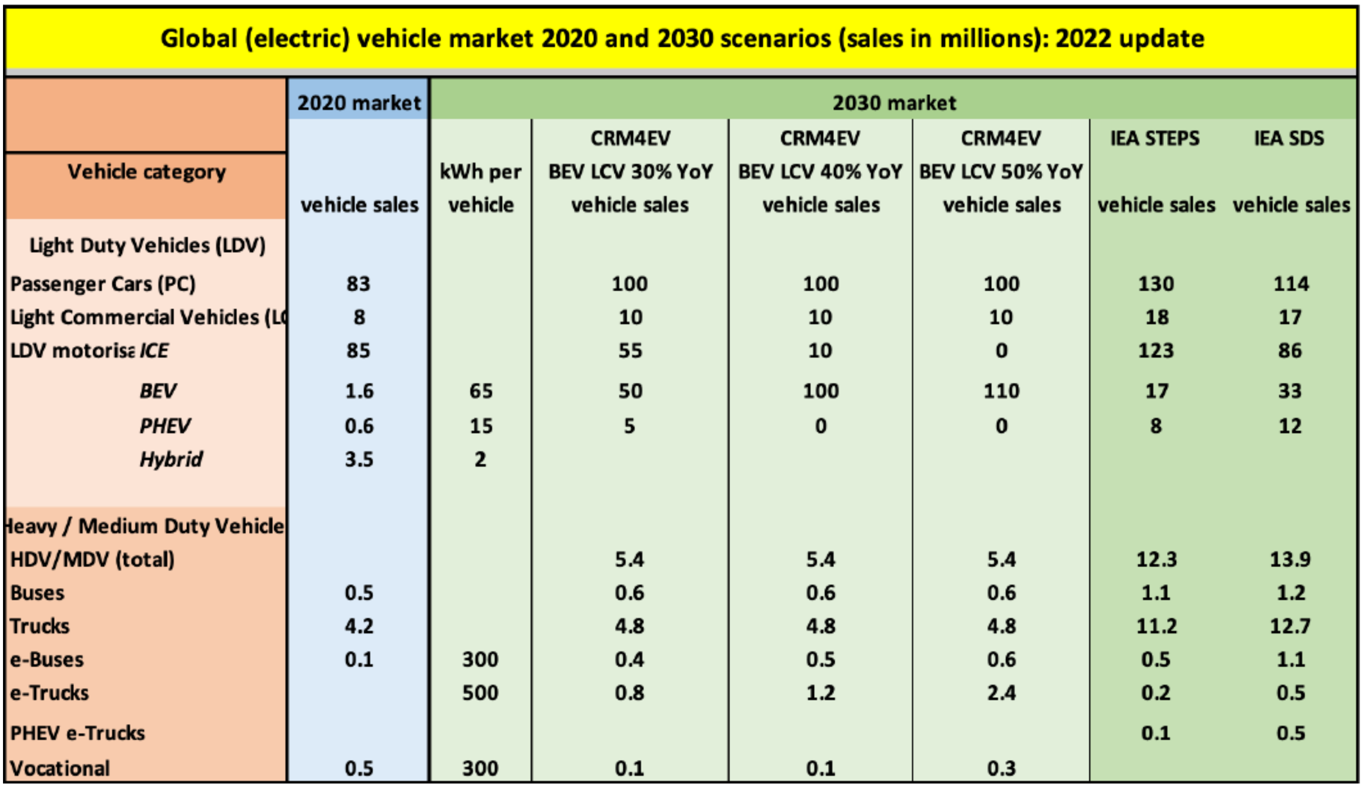
IEA. CC BY 4.0.

Figure 10: Electric vehicle sales by regions and IEA scenario 2022-2025-2030 (IEA 2023)

In Europe the share of EV sales across passenger cars, LDVs, buses and trucks is between 55% and more than 60% in 2030 in the STEPS and APS scenarios, resulting in about 10 million EV sales in Europe in 2030 (IEA 2023 [2]).

In Task 40, global scenarios of EV development (in the LDV class with passenger cars, light commercial vehicles) have been defined (Witkamp 2023) based on

- 30% year-by-year growth rate (2020-2030), resulting in 50 million global EV sales in 2030
- 40% year-by-year growth rate (2020-2030), resulting in 100 million global EV sales in 2030
- 50% year-by-year growth rate (2020-2030), resulting in 110 million global EV sales in 2030



Global (electric) vehicle market 2020 and 2030 scenarios (sales in millions): 2022 update

Vehicle category	2020 market	2030 market					
	vehicle sales	kWh per vehicle	CRM4EV BEV LCV 30% YoY vehicle sales	CRM4EV BEV LCV 40% YoY vehicle sales	CRM4EV BEV LCV 50% YoY vehicle sales	IEA STEPS vehicle sales	IEA SDS vehicle sales
Light Duty Vehicles (LDV)							
Passenger Cars (PC)	83		100	100	100	130	114
Light Commercial Vehicles (L	8		10	10	10	18	17
LDV motorisa *ICE*	85		55	10	0	123	86
BEV	1.6	65	50	100	110	17	33
PHEV	0.6	15	5	0	0	8	12
Hybrid	3.5	2					
eavy / Medium Duty Vehicle							
HDV/MDV (total)			5.4	5.4	5.4	12.3	13.9
Buses	0.5		0.6	0.6	0.6	1.1	1.2
Trucks	4.2		4.8	4.8	4.8	11.2	12.7
e-Buses	0.1	300	0.4	0.5	0.6	0.5	1.1
e-Trucks		500	0.8	1.2	2.4	0.2	0.5
PHEV e-Trucks						0.1	0.5
Vocational	0.5	300	0.1	0.1	0.3		

Figure 11: 2030 vehicle sales in scenarios developed in Task 40 for different vehicle classes

2.2.3 EV battery demand 2022 to 2030

EV battery demand in 2022 increased by about 65% to 550 GWh, from about 330 GWh in 2021 (see Figure 12). In Europe battery demand was about 130 GWh in 2022.

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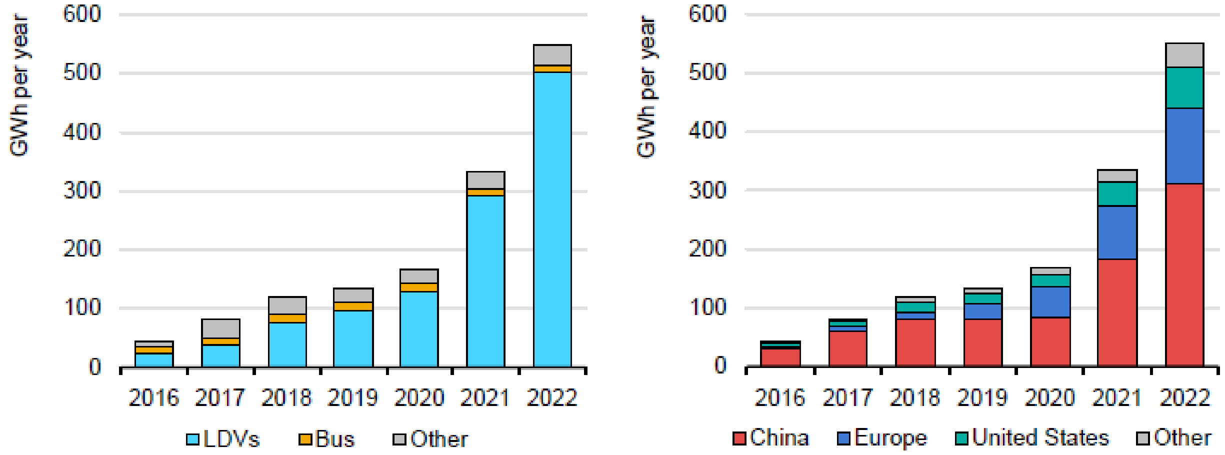
[2] https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer

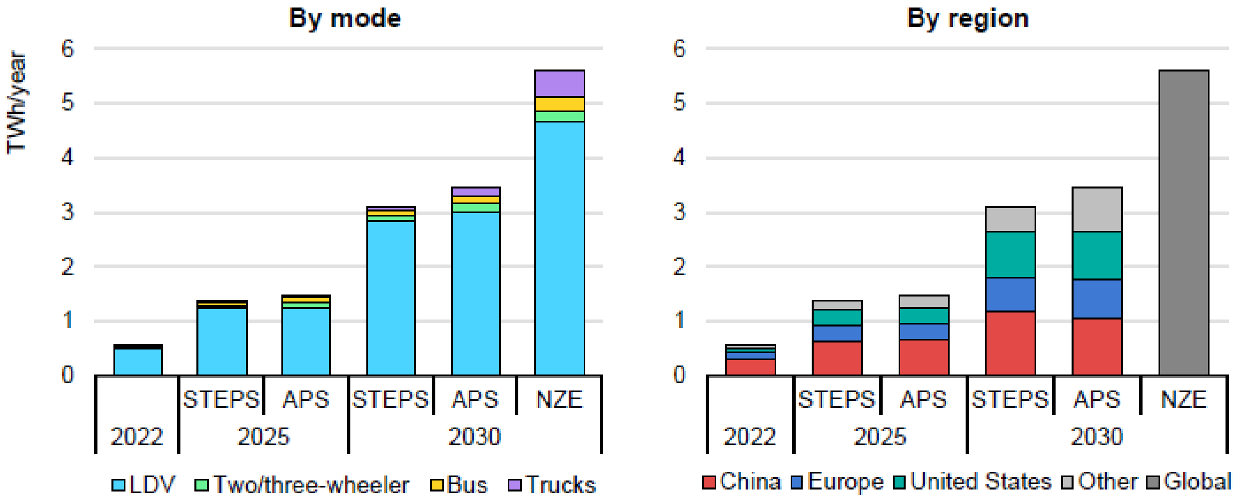
The projected battery demand in the STEPS and APS scenarios of the IEA reach 3 to 3.5 TWh in 2030, in the NZE scenario 5.5 TWh. About 90% of this demand is allocated to LDVs, 10% to buses and trucks (IEA 2023).

In the light of the EU targets for Zero Emission Vehicles in 2035 and the reduction of average emissions of new cars by 55% in 2030, the European demand for EV batteries is estimated to increase to 900 to 1,200 GWh/a by 2030 (Vorholt 2023).



IEA. CC BY 4.0.

Figure 12: Battery demand by mode and region, 2016-2022 (IEA 2023)



IEA. CC BY 4.0.

Figure 13: Projected battery demand by mode and region, 2022-2030 (IEA 2023)

In Task 40 global scenarios of EV battery demand result in

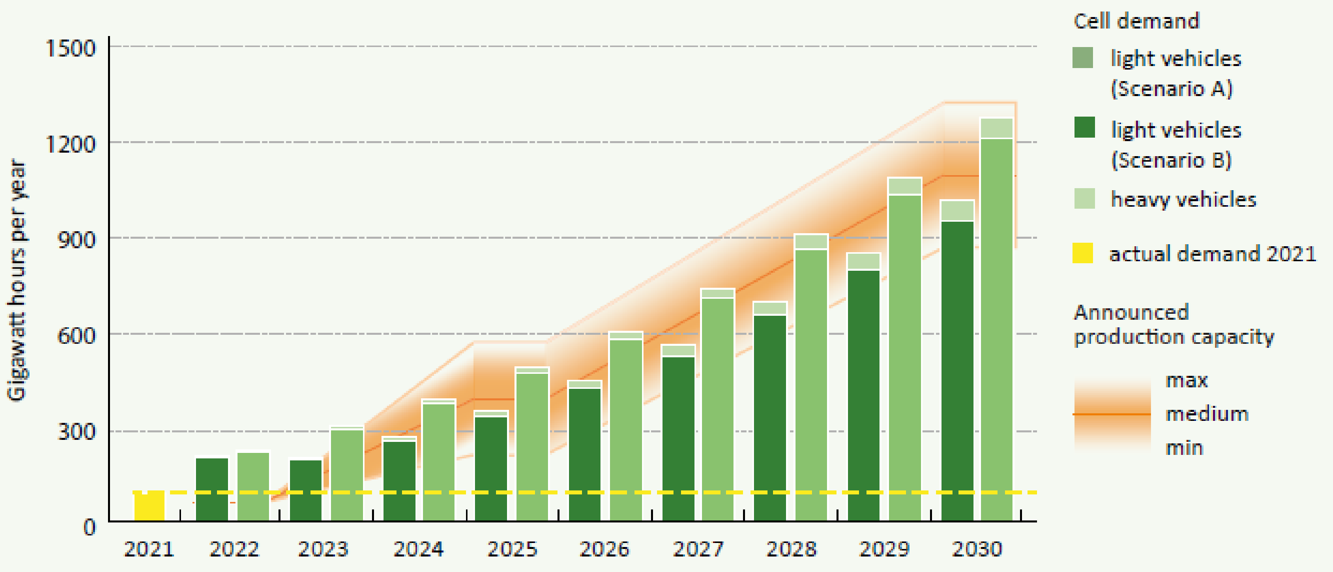
- 30% year-by-year growth rate (2020-2030) of EV sales: 4.3 TWh in 2030
- 40% year-by-year growth rate (2020-2030) of EV sales: 7.8 TWh in 2030
- 50% year-by-year growth rate (2020-2030) of EV sales: 8.9 TWh in 2030

According to IPCEI European Battery Innovation the projected annual growth rate until 2030 is 26% in the most likely scenario, resulting in about 3.2 TWh battery demand in 2030. In the long run market saturation and a slowdown of the battery cell market growth are expected. After the current phase of rapid growth until 2030, the annual growth rate between 2030 und 2040 might fall to 9%, resulting in 7.1 TWh in 2040 in the most likely scenario (Vorholt 2023).

2.2.4 EV battery production capacities in the EU 2022 to 2030

Global automotive battery production capacity in 2022 was about 1.5 TWh, exceeding the demand of 550 GWh in 2022 by about 65% (IEA 2023). This currently low utilisation rate can be expected to increase to about 90% during the upscaling phase.

The production capacities for battery cells in Europe (EU-27, UK, Norway) will increase from around 35 GWh/a in 2020 to 900 to 1,300 GWh/a in 2030. This corresponds to an increase by a factor of up to 30 (Bechberger 2022). The production capacities announced in Europe could meet future demand, however a 30-fold increase poses a real upscaling challenge. Already smaller delays in announced schedules of building production sites, challenges in raw material supply and strategic priorities of major battery manufacturers concerning production sites in EU, USA and China would prevent full coverage of demand by 2030 by European cell manufacturers (Vorholt 2023).

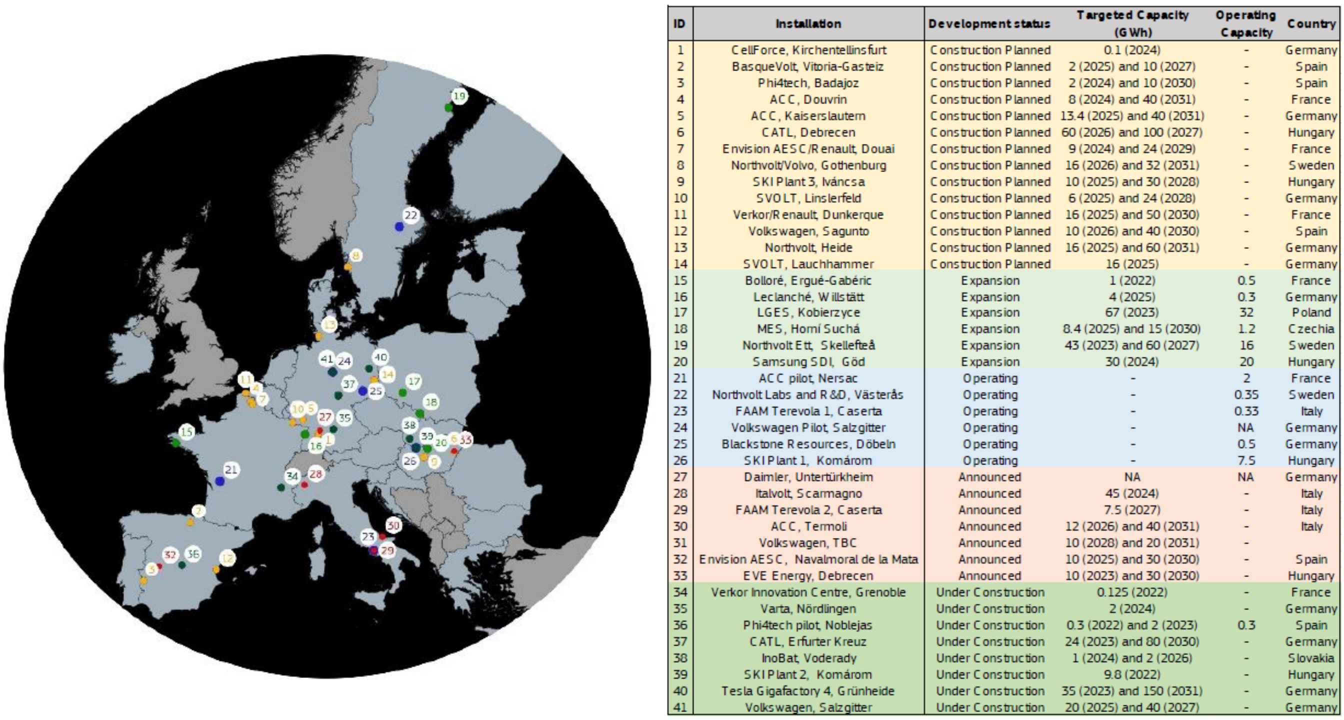


Projection of the **demand** for battery cells in automotive production in Europe for an incremental increase in the share of registrations of light and heavy electric vehicles to 81% and 40% respectively by 2030. For light vehicles, the demand was extrapolated for one scenario without and one with a significant influence of the energy supply on vehicle production (Scenario A and B, respectively).

With numerous, mostly very ambitious announcements, there are uncertainties regarding their implementation, especially after 2025. For this reason, the **production capacities** are presented in a minimum and a maximum view. Furthermore, it was assumed that all announcements by the manufacturers are maximum figures and that in practice the cell factories will achieve a yield of 90% at a capacity utilisation of 85%.

Figure 14: Announced battery production capacities and battery capacity demand in Europe by 2030 (Vorholt 2023)

In the EU, most of the operating capacity for battery cells is currently located in Germany, Sweden, Poland, and Hungary, but new installations or the expansion of existing installations have been already announced or are under construction. Figure 15 presents an overview of planned EU battery cell manufacturing capacity and locations in the EU.



ID	Installation	Development status	Targeted Capacity (GWh)	Operating Capacity	Country
1	CellForce, Kirchentellinsfurt	Construction Planned	0.1 (2024)	-	Germany
2	BasqueVolt, Vitoria-Gasteiz	Construction Planned	2 (2025) and 10 (2027)	-	Spain
3	Phi4tech, Badajoz	Construction Planned	2 (2024) and 10 (2030)	-	Spain
4	ACC, Douvrin	Construction Planned	8 (2024) and 40 (2031)	-	France
5	ACC, Kaiserslautern	Construction Planned	13.4 (2025) and 40 (2031)	-	Germany
6	CATL, Debrecen	Construction Planned	60 (2026) and 100 (2027)	-	Hungary
7	Envision AESC/Renault, Douai	Construction Planned	9 (2024) and 24 (2029)	-	France
8	Northvolt/Volvo, Gothenburg	Construction Planned	16 (2026) and 32 (2031)	-	Sweden
9	SKI Plant 3, Iváncsa	Construction Planned	10 (2025) and 30 (2028)	-	Hungary
10	SVOLT, Linslerfeld	Construction Planned	6 (2025) and 24 (2028)	-	Germany
11	Verkor/Renault, Dunkerque	Construction Planned	16 (2025) and 50 (2030)	-	France
12	Volkswagen, Sagunto	Construction Planned	10 (2026) and 40 (2030)	-	Spain
13	Northvolt, Heide	Construction Planned	16 (2025) and 60 (2031)	-	Germany
14	SVOLT, Lauchhammer	Construction Planned	16 (2025)	-	Germany
15	Bolloré, Ergué-Gabéric	Expansion	1 (2022)	0.5	France
16	Leclanché, Willstätt	Expansion	4 (2025)	0.3	Germany
17	LGES, Kobierzyce	Expansion	67 (2023)	32	Poland
18	MES, Horní Suchá	Expansion	8.4 (2025) and 15 (2030)	1.2	Czechia
19	Northvolt Ett, Skellefteå	Expansion	43 (2023) and 60 (2027)	16	Sweden
20	Samsung SDI, Göd	Expansion	30 (2024)	20	Hungary
21	ACC pilot, Nersac	Operating	-	2	France
22	Northvolt Labs and R&D, Västerås	Operating	-	0.35	Sweden
23	FAAM Terevola 1, Caserta	Operating	-	0.33	Italy
24	Volkswagen Pilot, Salzgitter	Operating	-	NA	Germany
25	Blackstone Resources, Döbeln	Operating	-	0.5	Germany
26	SKI Plant 1, Komárom	Operating	-	7.5	Hungary
27	Daimler, Untertürkheim	Announced	NA	NA	Germany
28	Italvolt, Scarmagno	Announced	45 (2024)	-	Italy
29	FAAM Terevola 2, Caserta	Announced	7.5 (2027)	-	Italy
30	ACC, Termoli	Announced	12 (2026) and 40 (2031)	-	Italy
31	Volkswagen, TBC	Announced	10 (2028) and 20 (2031)	-	
32	Envision AESC, Navalmoral de la Mata	Announced	10 (2025) and 30 (2030)	-	Spain
33	EVE Energy, Debrecen	Announced	10 (2023) and 30 (2030)	-	Hungary
34	Verkor Innovation Centre, Grenoble	Under Construction	0.125 (2022)	-	France
35	Varta, Nördlingen	Under Construction	2 (2024)	-	Germany
36	Phi4tech pilot, Noblejas	Under Construction	0.3 (2022) and 2 (2023)	0.3	Spain
37	CATL, Erfurter Kreuz	Under Construction	24 (2023) and 80 (2030)	-	Germany
38	InoBat, Voderady	Under Construction	1 (2024) and 2 (2026)	-	Slovakia
39	SKI Plant 2, Komárom	Under Construction	9.8 (2022)	-	Hungary
40	Tesla Gigafactory 4, Grünheide	Under Construction	35 (2023) and 150 (2031)	-	Germany
41	Volkswagen, Salzgitter	Under Construction	20 (2025) and 40 (2027)	-	Germany

Figure 15: Name and localization of planned EU battery cell manufacturing capacity in the EU (Carrara 2023)

2.2.5 Critical raw material demand for EVs until 2030

The demand for critical raw materials in 2030 for EV batteries has been estimated based on data presented in previous sections, specifically on

- scenarios of EV development until 2030 (section 2.2.2): the range of external scenarios and Task 40 results in 30 to about 50 million new EV sales in 2030.
- resulting demand of EV battery capacity per year until 2030 (section 2.2.3): depending on the average assumed battery capacity of different EV classes in 2030 (65 to 75 kWh for LDV, 300 to 500 kWh for HDV), the range of external scenarios (Global battery alliance, IEA, IPCEI) and the 30%-scenario in Task 40 is about 3,000 to 4,300 GWh battery capacity demand in 2030.
- scenarios for the shares of battery technologies in 2030 (section 2.1) and the critical raw material demand per kWh battery capacity (section 2.1.4).

In Task 40 CRM4EV, two major scenarios have been defined for assessing the consequences of different market shares of battery technologies on critical raw material demand and supply in 2030:

- High-Nickel-scenario: this scenario is based on a high share (90%) of Nickel-Cobalt (NMC) battery technologies in 2030 (NMC 622, NMC811, NCA) and 10% LFP batteries.
- 50% LFP scenario: this scenario considers the recent rapidly increasing shares of LFP batteries in EV battery markets with a 50% market share of zero-Nickel and zero-Cobalt LFP batteries and 50% NMC (NMC 622, NMC811, NCA) technologies in 2030.

Figure 16 and Figure 17 present the ranges of resulting critical raw material demand of Nickel, Cobalt, Manganese, Lithium, Phosphate, Copper and Graphite in the two Task40 scenarios of 2030.

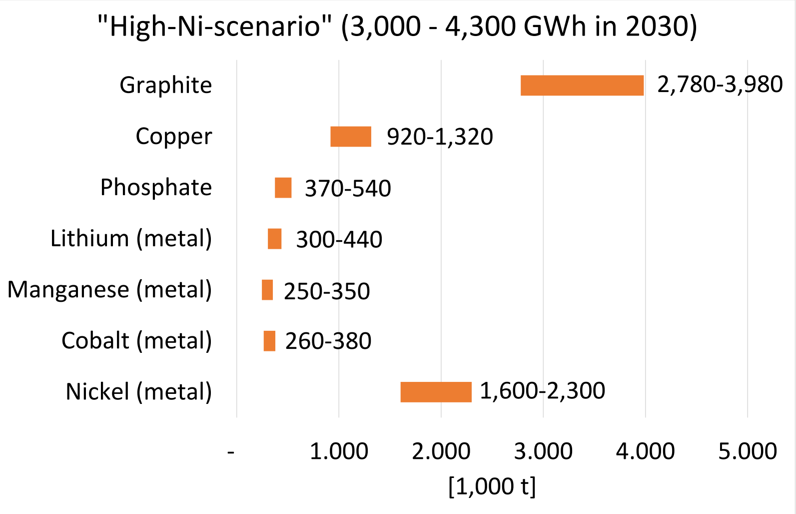


Figure 16: Global CRM demands 2030 in Task 40 CRM4EV scenario “High Nickel”

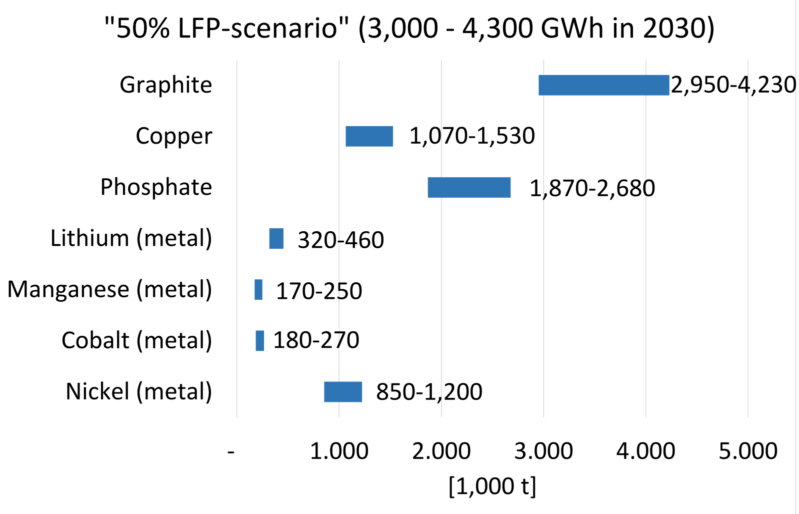


Figure 17: Global CRM demands 2030 in Task 40 CRM4EV scenario “50% LFP”

The demand of REE (neodymium, dysprosium, praseodymium) for permanent magnet electric motors is independent of battery scenarios and can be estimated based on range of EV sales of 30 to 50 million vehicles in 2030 with a demand of 0.45 to 1 kg REE per EV. The resulting range of global REE demand in 2030 has therefore been estimated with 13,500 t to 50.000 t, presuming that all EV have permanent magnet electric motors**.**

2.3 Critical raw material supply

This section provides information for the supply of the CRM Nickel, Cobalt, Manganese, Lithium, Graphite, Phosphate and REE from the global and the EU perspective. Information includes their overall demand in relevant sectors, geographical distribution of material mining und reserves, material processing technologies and battery material recycling.

In Task 40, information on CRM supply has been collected and discussed in workshops with experts from research and industry at varying levels of detail. Most information has been provided on Nickel as well as on battery recycling.

2.3.1 Nickel

2.3.1.1 Material demand

Today (2020) Nickel is used mainly to produce different stainless and alloy steels. Furthermore, it is used for super-alloys and plating for the protection of metal goods. The battery sector in 2020 still has a relatively small impact on Nickel demand.

Total Nickel demand in 2020 was about 2.3 million tons. The distribution of Nickel used for first uses globally and in the EU is shown in Figure 18, with steel production with a share of 67% globally and 79% in the EU and battery production with 2% globally and 7% in the EU. China consumed more than 55% of global Nickel, Europe about 14%. Nickel demand for battery production was about 160,000 tons.

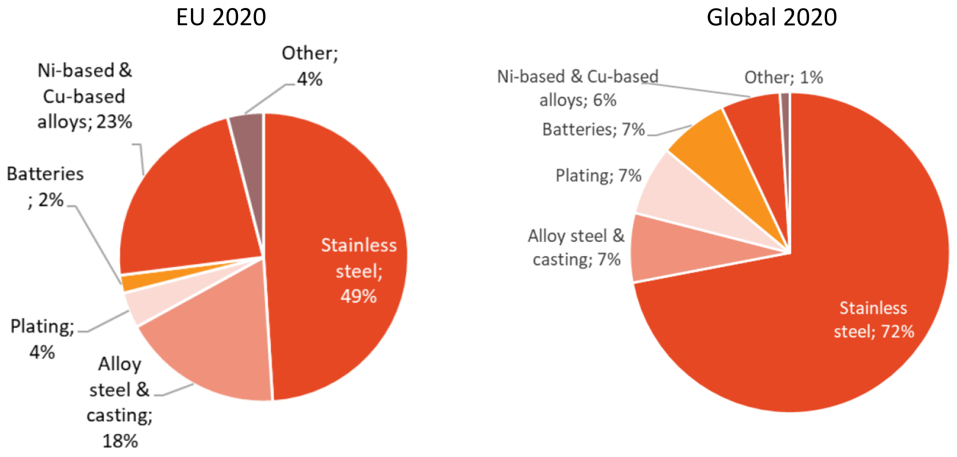


Figure 18: First uses of Nickel in 2020 globally and in the EU (SCRREEN 2023)

The future development of Nickel demand will be driven by steel industry and increasingly by battery production. Future primary Nickel demand in the steel and metal industry sector has been estimated by Fraser (2021) to increase from about 1.6 million tons in 2020 to about 3 million tons in 2030 and 3.2 million tons in 2040 (Figure 19). Future Nickel demand for battery production has been estimated in the Task 40 scenarios to be in the range of 0.85 to 2.3 million tons in 2030. This would result in a 5- to 14- fold increase compared to 2020. Fraser (2021) estimated this demand to be 1 million tons in 2030 (due to different EV sales scenarios), which adds up to a total primary Nickel demand of 4 million tons in 2030 and 5 million tons in 2040.

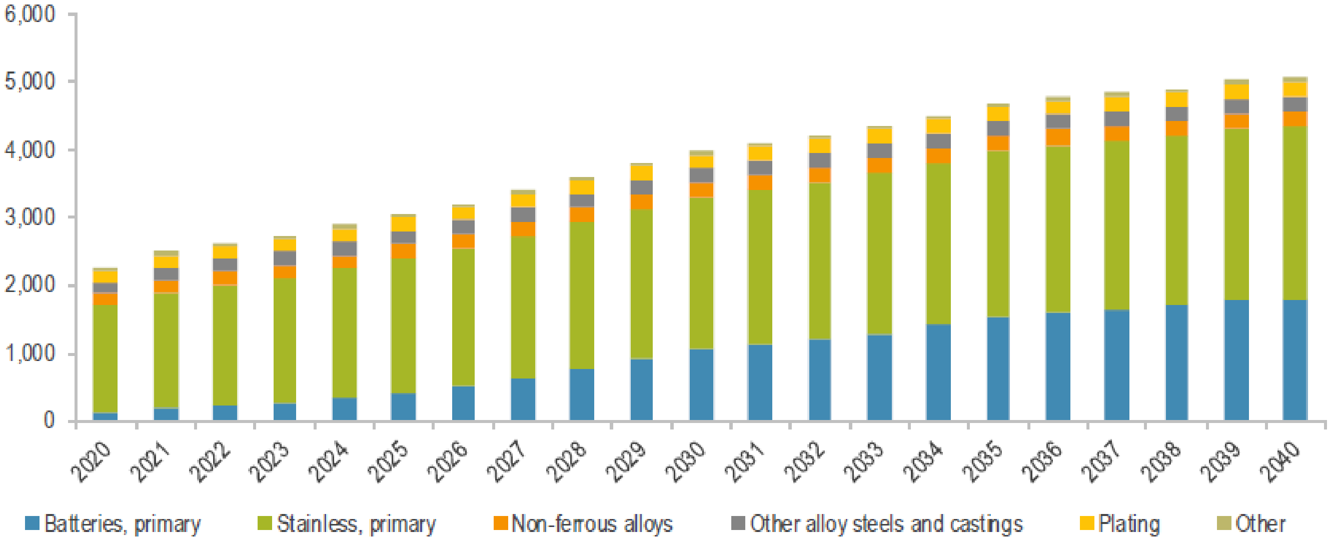


Figure 19: Total primary Nickel market demand scenario by first-use sector, 2020-2040 (kt Ni) (Fraser 2021)

2.3.1.2 Material sourcing

Total mine production of primary Nickel in 2020 was 2.5 million tons, with a steep rise during the past two years, with latest statistics reporting already 3.3 million tons for 2022 (USGS 2023). 1.6 million tons or 48% were produced in Indonesia, 0.33 million tons or 10% in Philippines and 0.22 million tons or 7% in Russia. Estimated global Nickel mine production increased by about 20% between 2021 and 2022, with almost all of the increased production attributed to Indonesia. The largest share of the increase was facilitated by integrated Nickel pig iron and stainless-steel projects. In addition, several companies continued to develop projects to produce the intermediate matte or mixed Nickel-Cobalt hydroxide that were intended to be used as feedstock to produce battery-grade Nickel sulphate (USGS 2023).

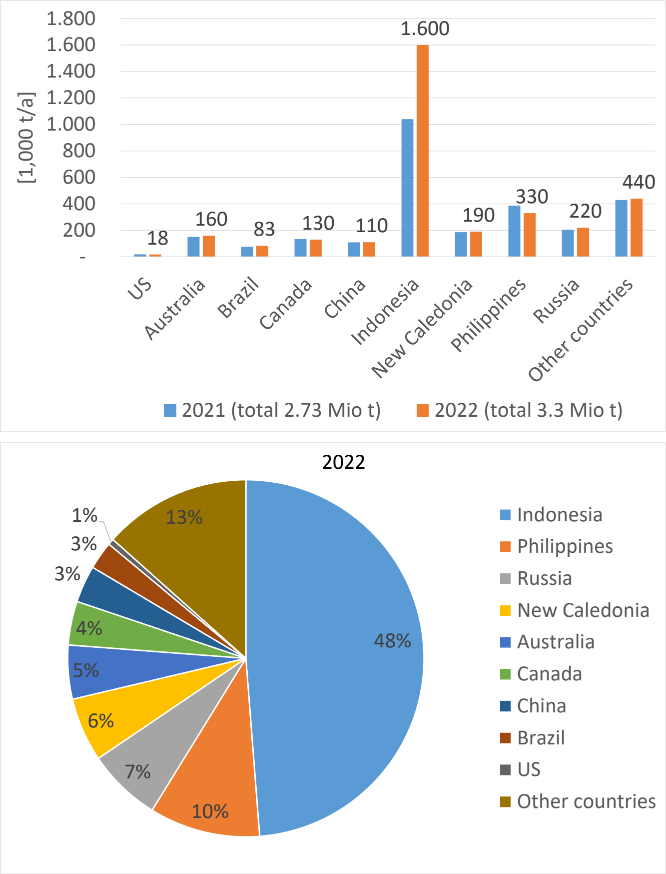


Figure 20: Global Nickel mine production 2021, 2022 (USGS 2023)

The only Nickel mining countries within the EU in 2022 are Finland and Greece. Finland produced about 45,000 t and Greece about 10.000 t in 2021, which is 1.5% of global production.

Fraser (2021) expects mine supply to rise at a year-by-year rate of 4.7% between 2020 and 2030, with the majority of this growth to come from Indonesia to feed both Nickel-pig-iron (NPI) for the stainless steel industry and also battery-grade Nickel intermediates suitable for processing to produce Nickel sulphate. Indonesia is likely to see a growth rate of 6.7% per year up to 2030.

Total expected mine production is estimated to increase to 4 million tons Nickel by 2030. Figure 21 shows the expected growth of mine production. By 2030 Indonesia could account for around 45% of global mine supply, feeding its domestic NPI and Ferro-Nickel smelters as well as battery-grade intermediate Nickel plants. Primary production in the EU will also in future focus on Finland and Greece with an expected minor rise to 60.000 tons per year in the mid 20´s (Figure 22).

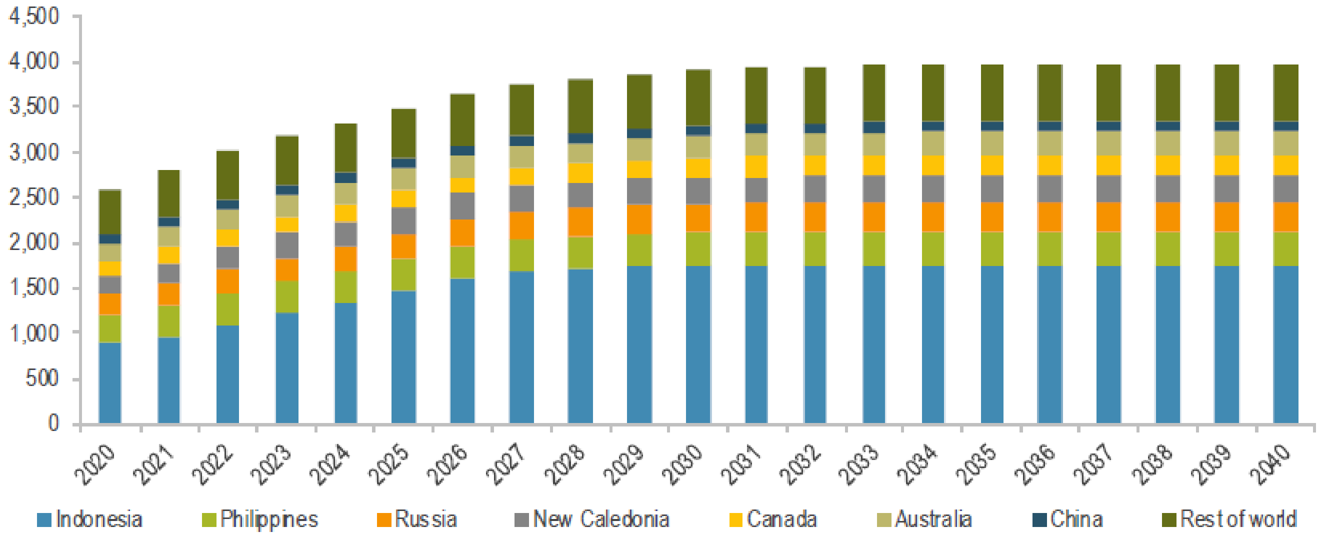


Figure 21: Outlook for expected mine supply by country, 2020-2040 (kt Ni) (Fraser 2021)

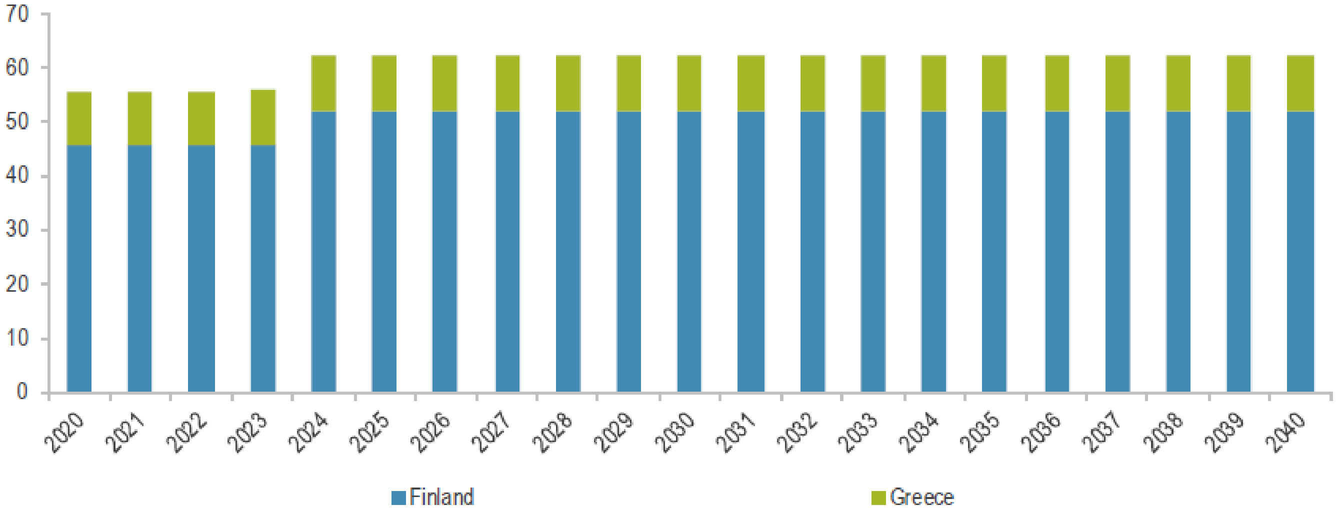


Figure 22: Outlook for expected mine supply in the EU, 2020-2040 (kt Ni) (Fraser 2021)

Global Nickel reserves (discovered resources that can be extracted commercially) of more than 100 million tons are shown in Figure 23, with 21% in Australia, 21% in Indonesia and 20% in Brazil. Nickel Institute states about 300 million tons of Nickel resources (discovered and undiscovered deposits) onshore and additional 300 million tons Nickel resources expected offshore.

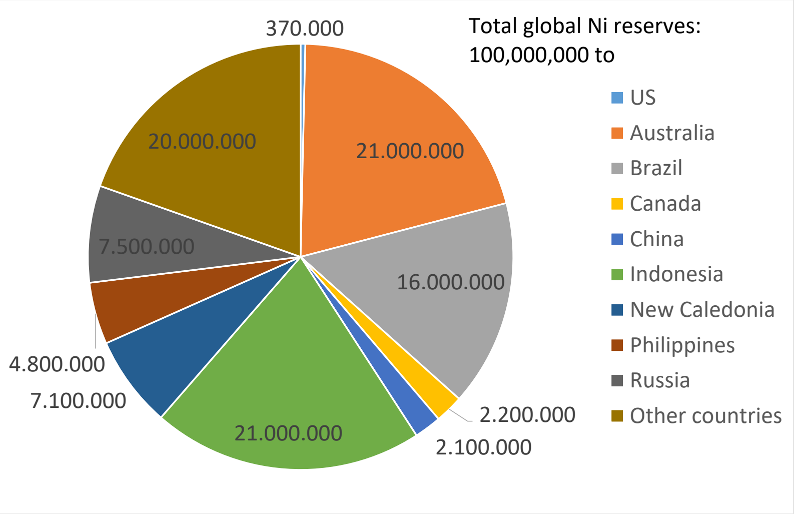


Figure 23: Global Nickel reserves (USGS 2023)

For an outlook of future Nickel quantities available for the production of battery-grade Nickel material and for comparing future Nickel demand to supply quantities, an overview of the different Nickel ores, intermediate and final Nickel products and their uses is required, which is provided in the following section.

2.3.1.3 Material processing

Nickel is extracted from two types of deposits: a) lateritic ores containing silicate (saprolite) and oxidic (limonite) minerals often together with iron, and b) sulfidic ores. Lateritic ores are mostly located in tropical and subtropical climate zones in Brazil and SE-Asia (in Europe in Greece and Albania), sulfidic ore resources are mostly located in Canada, Russia, China, South Africa and Australia (in the EU in Finland). Global reserves (reserve is the economically mineable part of an identified mineral resource) sum up to more than 100 million tons Nickel content, global resources to more than 300 to 600 million tons.

Sulfidic ores contain in average 1.5% Nickel metal and often also contain Copper, Platin group metals (PGM) and Cobalt. Sulfidic deposits can be exploited both in open-pit (globally about 20% mainly in Brazil and deep mining (80%), Laterite ores are mined open-pit (99%). About 70% of todays mined Nickel comes from laterite ores.

These two ore types contain different minerals and therefore require different processing. Laterite open-pit mining does not require explosives and usually no direct ore processing in the mine location. Laterite ores leaving the mine have an average Nickel content of 2%. Sulfidic ores are processed (flotation, magnetic separation) and concentrated to a Nickel content of 8 to 25% before they are further concentrated in metallurgical plants.

The refining of sulfidic ores in metallurgical plants is not tied to the mining location, due to the concentration of metal making long-distance transports feasible. Pyrometallurgy separates the sulphur in electric furnaces to produce the intermediate Matte with about 45% Nickel, and in an oxygen converter metal content is increased to 75%. Various hydrometallurgical processes like pressure leaching or electrolysis are then used to produce a Nickel concentrate of more than 99% Nickel which is also called “Class-I” Nickel. Class-I Nickel is used in stainless steel production and for battery production which requires Nickel Sulphate as precursor for the cathode paste.

Due to the low Nickel content of laterite ores, a long-distance transport to metallurgical plants is economically not feasible, therefore the required pyro- and hydrometallurgical processes for Nickel concentration are located close to the mine. Lateritic Saprolites are processed in blast furnaces and electric arc furnaces to so-called “Nickel Pig Iron (NPI)” with Nickel contents of 8 to 15%. NPI is then used for stainless steel production. The steep increase of Nickel mining in SE-Asia is mainly due to NPI production used in Chinese steel industry. Saprolites can also be processed in electric arc furnaces and following converters to so-called ”Ferro-Nickel” with a Nickel content of 15 to 45% which is also used in stainless steel industry. NPI and Ferro-Nickel are also called “Class-II” Nickel products.

Lateritic Limonites are commonly processed in the hydrometallurgical HPAL (high-pressure-acid-leach) process with 40 bar and 200°C. Products are the intermediate mixed hydroxide product (MHP), cathode-Nickel and Nickel briquettes. In some cases, a pyrometallurgical reduction process increases the Nickel content up to 85% before the acid leaching process to also produce “Class-I” Nickel.

It is technically also feasible to produce from Class-II NPI / Ferro-Nickel the intermediate Matte and Class-I Nickel by adding sulphur to the converter process after the smelting process.

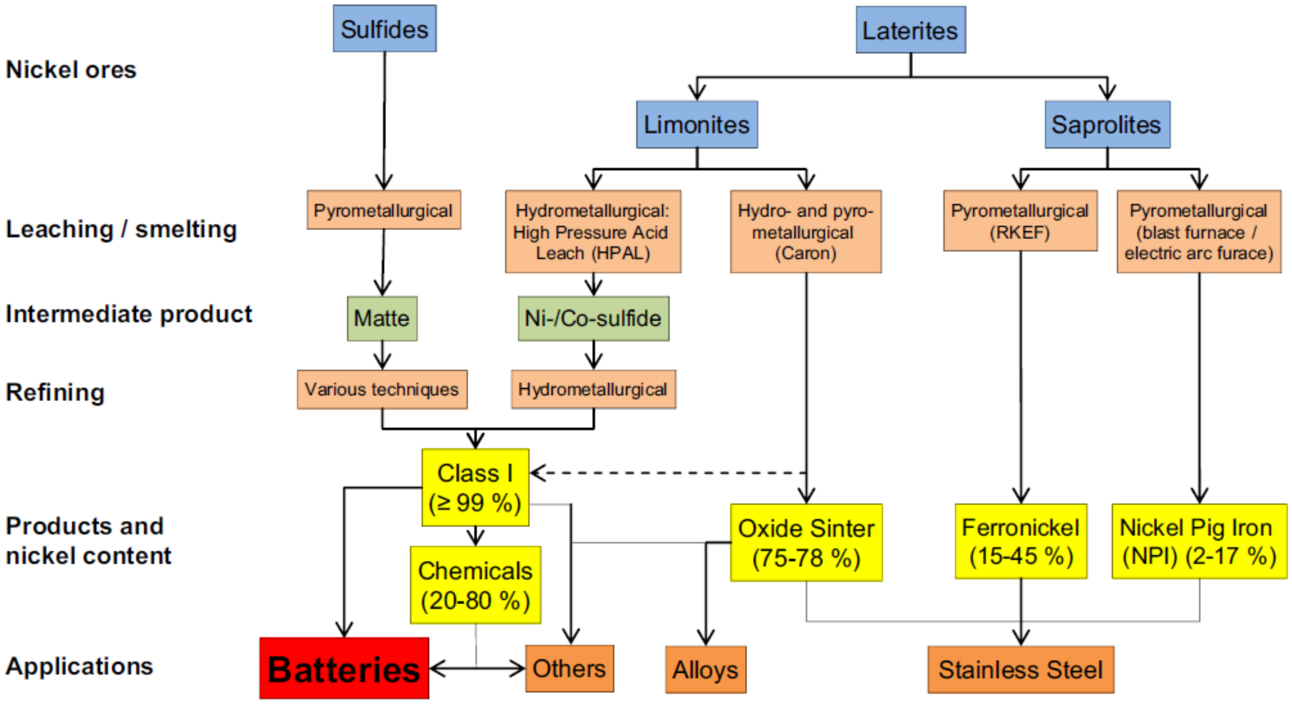


Figure 24: Most important current Nickel primary production routes, (intermediate) products, Nickel content and applications (Schmidt 2016)

For the production of Nickel containing batteries the precursor material Nickel sulphate is required. Nickel sulphate is a refined chemical product produced from a variety of intermediates (Matte, MHP, MSP, Crude Nickel sulfate), finished nickel products (powder, briquettes), as well as from secondary material (battery scrap, non-battery scrap) (Figure 25).

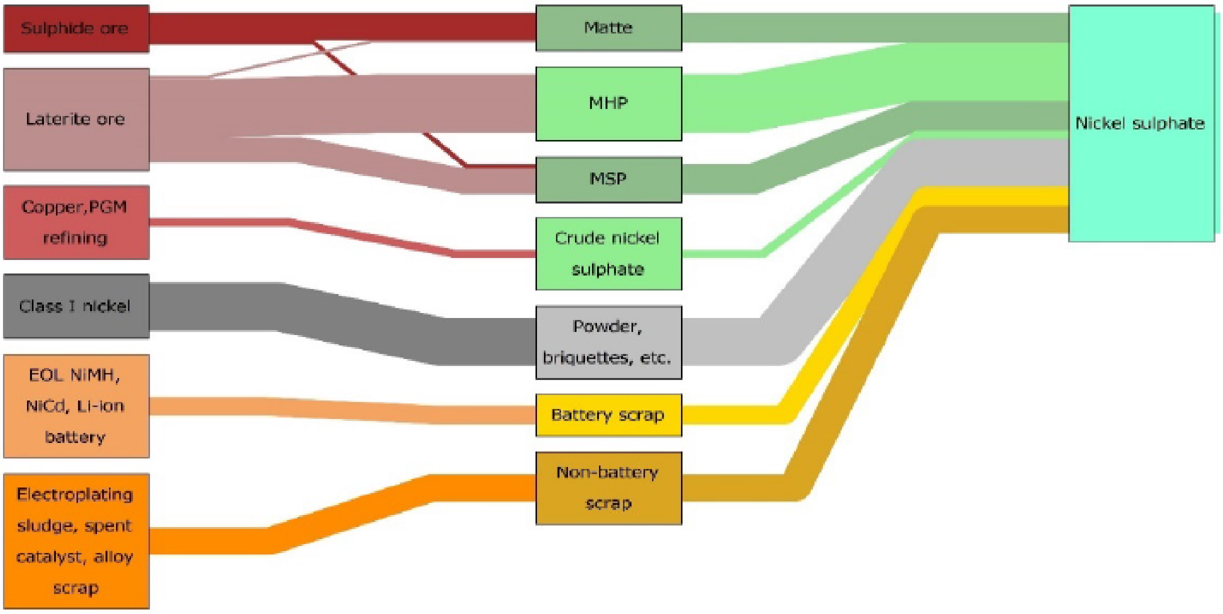


Figure 25: Nickel sulphate flowchart 2019 (Fraser 2021)

<u>Forecast scenarios of Nickel intermediate and Nickel sulphate production</u>

Figure 26 summarizes the outlook for the availability of different feedstocks suitable for processing into Nickel sulphate and subsequent use in EV batteries. These are feedstocks not already locked-in for the supply of growing demand by steel production and other markets. Intermediates are likely to be the largest feedstock source. It is expected that the mixed hydroxide product (MHP) from laterite ores will be the main form available to the market for Nickel sulphate production due to several new HPAL projects under construction in Indonesia. Class I metal is forecasted to be the second largest feedstock source to 2030. Class I available for Nickel sulphate production for batteries may be highly dependent on various factors such as critical demand from non-ferrous alloys and plating sectors, as well as usage from stainless steel and general stock levels, but also currently limited investments into new supply of Class I. Recycled material from EOL batteries is expected to become a vital source of Nickel by 2040. Between 2030 and 2040 more batteries reach their useful life limits and collection rates will be maximized. Recycled material available (battery and non-battery combined) is likely to overtake Class I Nickel by the end of the 2020s (Fraser 2021).

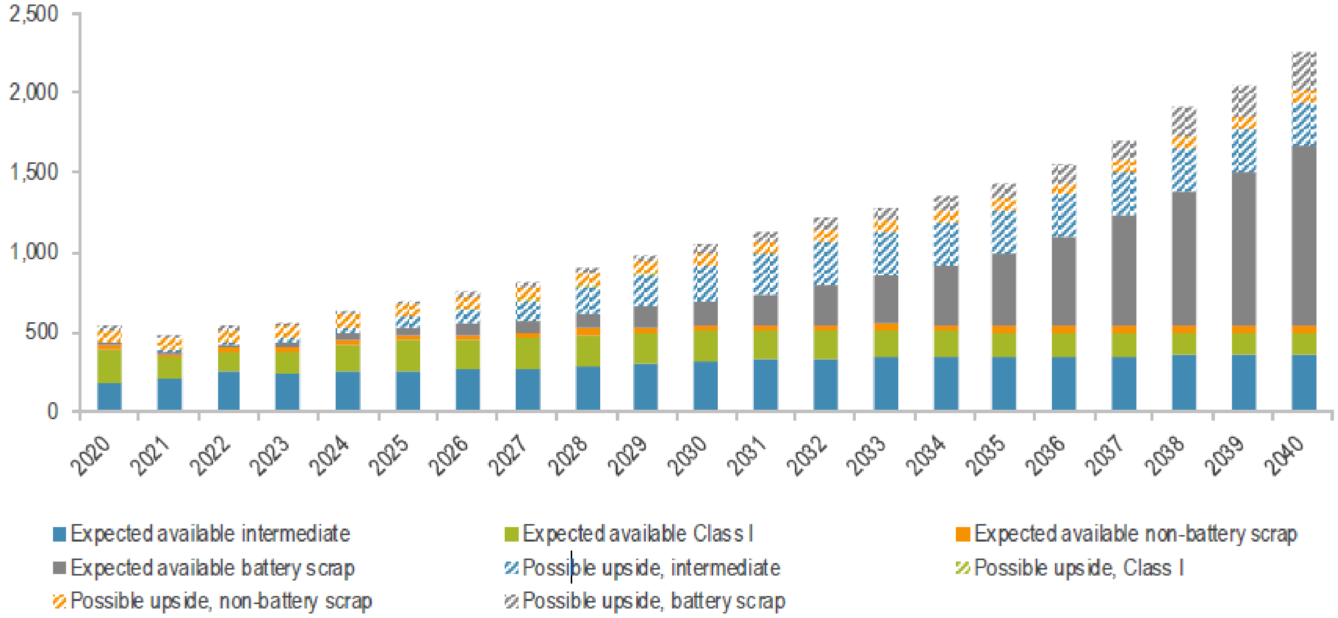


Figure 26: Outlook for feedstock availability for Nickel Sulphate by feedstock type, 2020-2040 (kt Ni) (Fraser 2021)

Geographically China is expected to remain the largest producer of Nickel sulphate. Indonesia, Finland and Australia are likely to overtake Japan and Taiwan in the near-term to become the next largest producers.

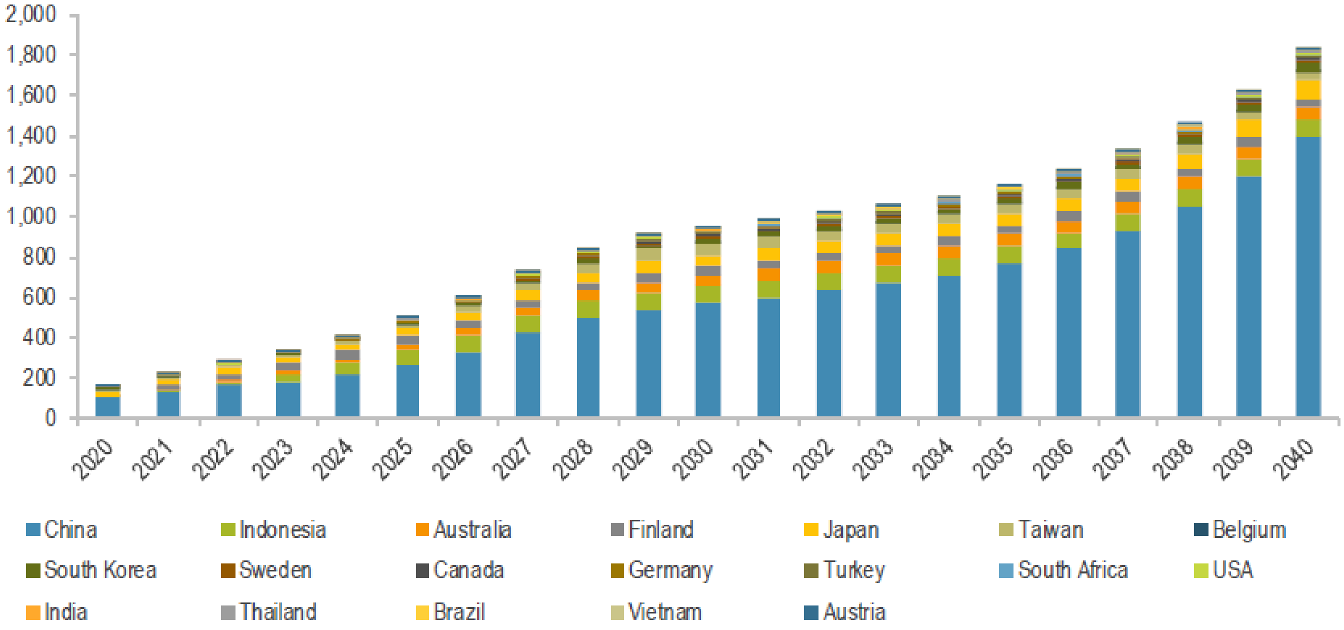


Figure 27: Outlook for Nickel sulphate production, by country 2020-2040 (kt Ni) (Fraser 2021)

2.3.1.4 Material demand and supply balance 2030

Based on the Nickel demand scenarios developed by Task 40 (“High-Nickel”, “50% LFP”) and the supply scenarios discussed above, potential deficits on the supply side can be identified. Figure 28 shows that Nickel demand in the High-Nickel scenario exceeds by far potentially available Nickel supply estimations. In the demand scenario with zero-Nickel battery chemistries (50% LFP), Nickel supply outlook will rather meet global demand. Any additional Nickel supply would require conversion of Class-II Nickel (NPI, Ferro-Nickel) to Matte and Nickel Sulphate.

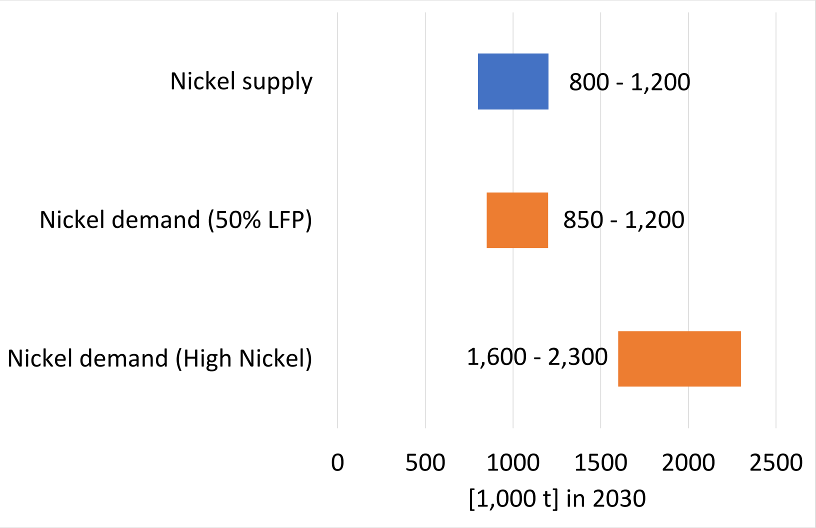


Figure 28: Outlook for global battery-grade Nickel demand and supply balance in 2030

2.3.2 Cobalt

2.3.2.1 Material demand

Today (2020) Cobalt is primarily used in manufacturing of rechargeable Lithium-ion batteries used in portable electronic devices, energy storage systems and electric vehicles. The share of batteries on the overall global demand was 57 % or 90,000 tons in 2020 (Figure 18), with 26% or 41,000 tons used for EV batteries. Other significant uses include superalloys mainly used in turbine engine components (13 % of world consumption), hard materials used in carbides for cutting tools (8 %) or pigments used in colouring glass and ceramics and in paints (6 %) (SCRREEN 2023).

Global Cobalt demand in 2020 was 158,000 tons and 175,000 tons in 2021, of which China had a share of about 32% and Europe about 24%. About 66,000 tons are used for non-battery materials, the demand for batteries about 90,000 tons.

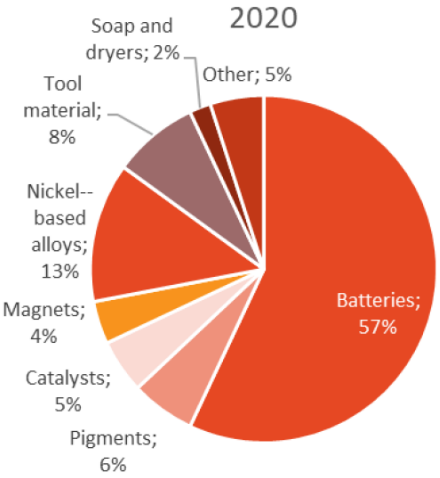


Figure 29: First uses of Cobalt in 2020 globally (SCRREEN 2023)

The future development of Cobalt demand will be mainly driven by Nickel-Cobalt battery production. Assuming a steady Cobalt demand of non-battery uses of about 70,000 tons, 180,000 to 380,000 additional tons Cobalt for batteries in 2030 (demand scenarios in section 2.2.5) would result in a total range of 250,000 and 450,000 tons in 2030. This corresponds also to demand scenarios of Alves Dias (2018) (Figure 30). Cobalt demand for EV batteries would result in a 6- to 10- fold increase compared to the demand of 2020.

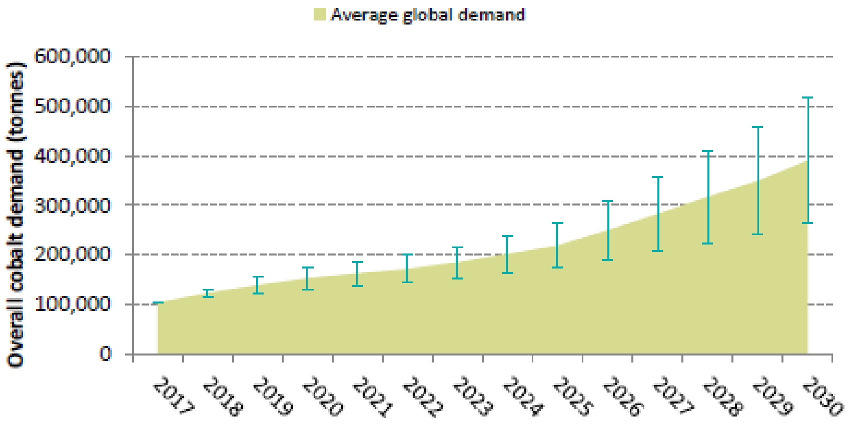


Figure 30: Annual average global demand of Cobalt until 2030 – overall uses in the global context (Alves Dias 2018)

2.3.2.2 Material sourcing

Total mine production of Cobalt in 2021 was 165,000 tons, and 190,000 tons in 2022 (USGS 2023). The largest share of production has Congo with 68%, followed by Indonesia and Russia with each 5%. With the exception of some production in the United States, in Morocco and artisanally mined Cobalt in Congo, most Cobalt is mined as a by-product of Copper or Nickel. China was the world’s leading producer of refined Cobalt, most of which was produced from Cobalt imported from Congo (USGS 2023).

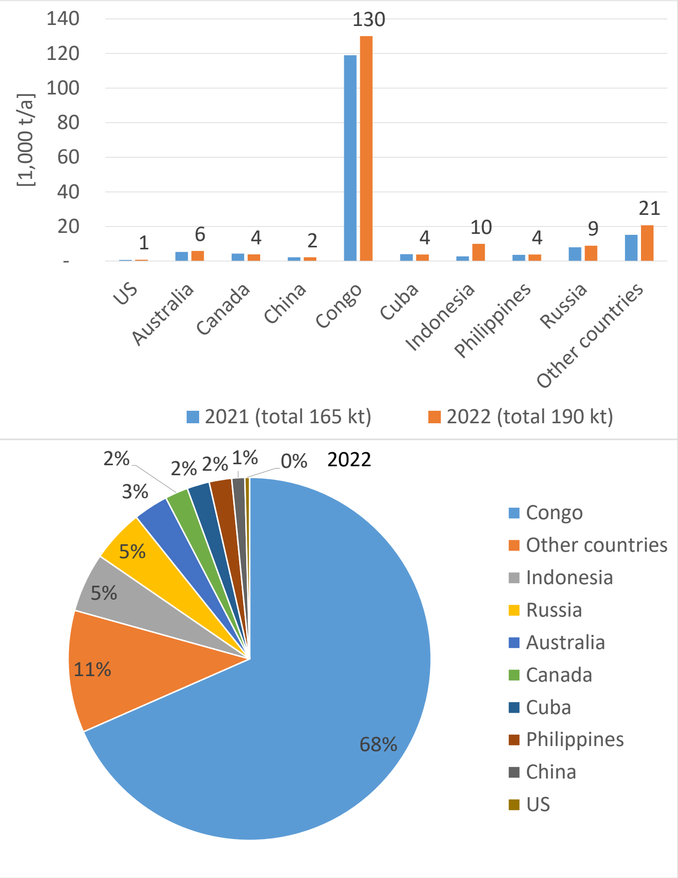


Figure 31: Word Cobalt mine production 2021, 2022 (USGS 2023)

The EU share of the global mined Cobalt was 1.1 % or 1,700 tons from Finland.

Alves Dias (2018) assessed different scenarios resulting in mine supply to rise to between 193,000 and 237,000 tons until 2030, with the majority of this growth to come from Congo and Australia (Figure 32).

Global Cobalt reserves of more than 8.3 million tons are shown in Figure 33, with 48% in Congo and 18% in Australia (Figure 33).

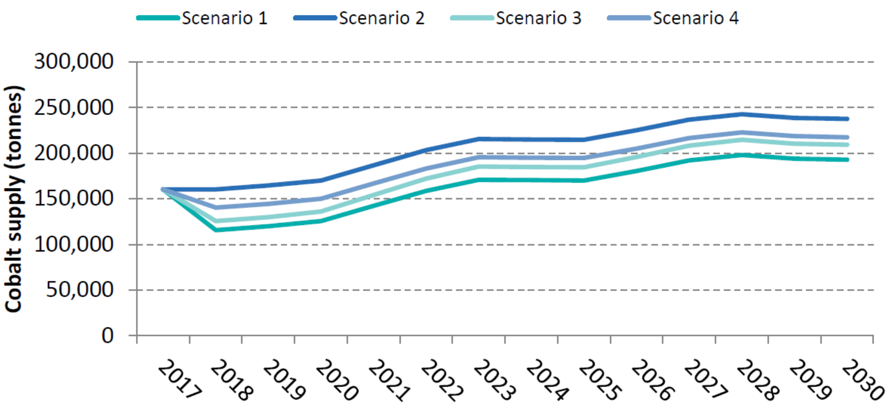


Figure 32: Outlook for expected mine supply of Cobalt until 2030 (Alves Dias 2018)

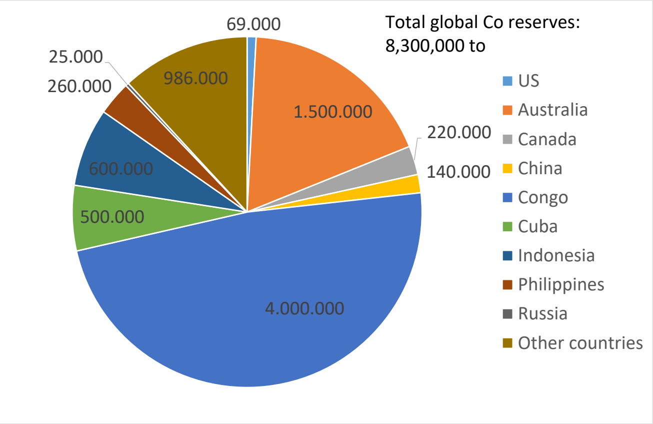


Figure 33: Global Cobalt reserves (USGS 2023)

2.3.2.3 Material demand and supply balance 2030

Based on the Cobalt demand scenarios developed by Task 40 (“High-Nickel”, “50% LFP”) and supply scenarios, potential deficits on the supply side can be identified. Figure 34 shows that Cobalt demand in the High-Nickel scenario potentially exceeds by far available Cobalt supply estimations. In the demand scenario with zero-Nickel battery chemistries (50% LFP), Cobalt supply outlook will rather result in a match of demand and supply or in a smaller deficit.

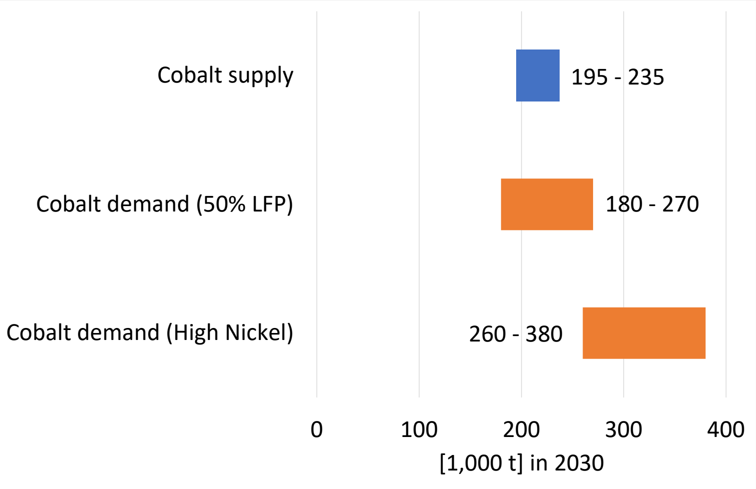


Figure 34: Outlook for global battery-grade Cobalt demand and supply balance in 2030

2.3.2.4 Material processing

Cobalt is extracted from three types of deposits: a) Copper ores, b) sulfidic Nickel-Copper ores and c) lateritic Nickel ores. Copper ores are mostly located in Congo and Sambia, sulfidic Nickel-Copper ores in Canada, Russia and Australia and lateritic Nickel ores in the Philippines, Indonesia and Cuba. In the EU the main Cobalt provinces are the Fennoscandian shield (Norway, Sweden, and Finland), Greenland, the Balkans and Greece and SW and central

Europe. Global reserves sum up to 8.3 million tons, 48% in Congo, 18% in Australia and 5 to 6% in each Indonesia and Cuba.

Copper ores contain in average 1.5 to 5% Cobalt in artisanal mines in Congo metal and are mined open-pit. Sulfidic deposits are usually exploited in deep mining and contain in average 0.04% Cobalt, laterite ores are mined open-pit and contain in average 0.08% Cobalt.

Because of its by-product status, Cobalt beneficiation processes are usually coupled to the processes required to recover the main commodity (i.e. Nickel or Copper). Figure 35 provides an overview of the processes involved with above mentioned ore types (Dehaine 2021).

Copper ores (Congo) are processed in hydrometallurgical leaching processes, resulting in the intermediate Cobalt-hydroxide. Cobalt-hydroxide is then transported to China for further refining to Cobalt metal and Cobalt chemicals like Cobalt sulphate as precursor material for battery production.

Lateritic ores are, as already described for Nickel, commonly processed in the hydrometallurgical HPAL (high-pressure-acid-leach) process with 40 bar and 200°C. Products are the intermediate mixed Nickel-Cobalt hydroxide product (MHP). In further hydrometallurgical processes Cobalt metal with up to 99% Cobalt is produced.

For Cobalt production from sulfidic Nickel-Cobalt ores many refining techniques are available. In hydrometallurgical refining route, the process typically consists of a leaching stage using acids, followed by selective precipitation to separate Cobalt and Nickel. The final step for Cobalt recovery can be hydrogen reduction where Cobalt is recovered from the solution as a powder or electrowinning, which produces Cobalt cathodes.

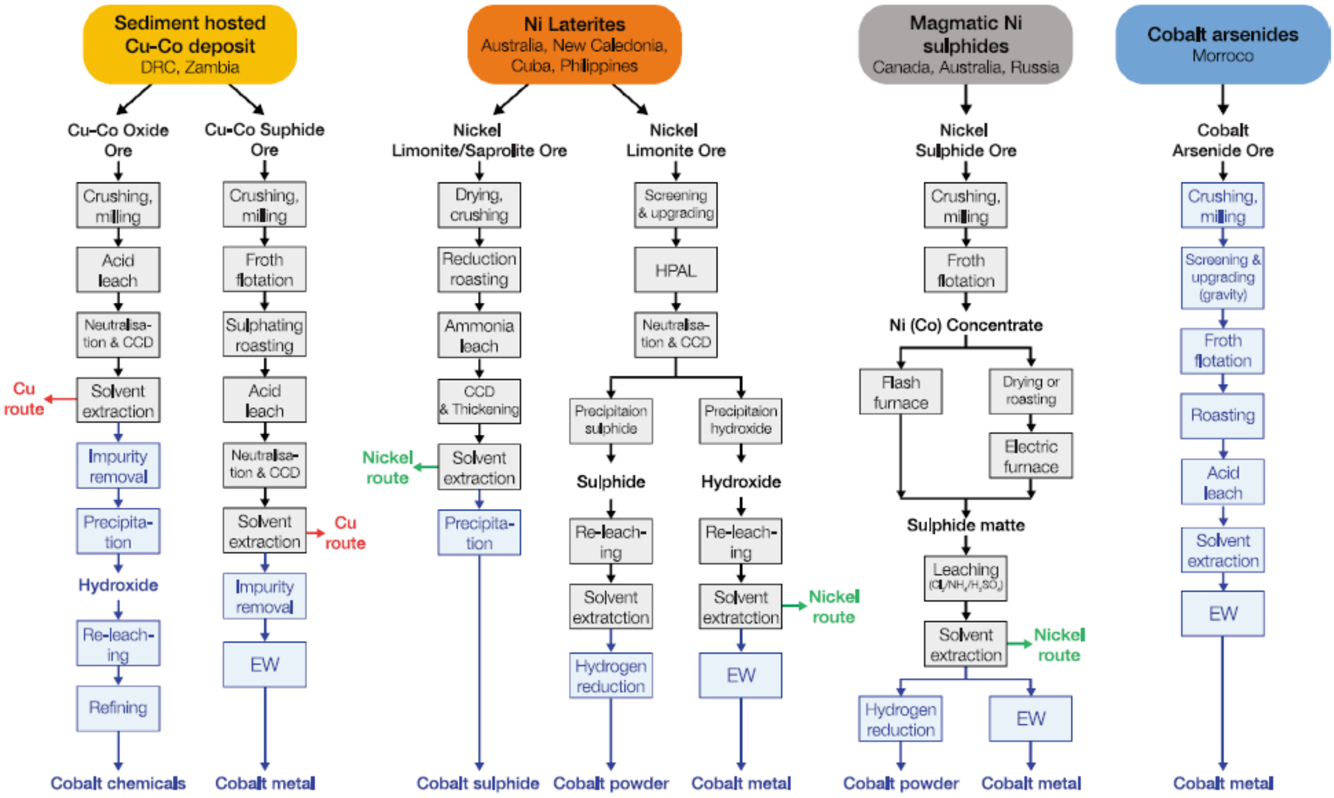


Figure 35: Overview of the main processing routes for Cobalt extraction as a function of the deposit and ore type (Dehaine 2021)

2.3.3 Manganese

2.3.3.1 Material demand

Today (2020) Manganese is mainly used in metallurgical processes, as it possesses a high oxygen and sulfur affinity and is therefore used for deoxidation and desulfurization of iron and steel as well as an alloying constituent. Globally only about 0.2 % of the Manganese mined worldwide is used for EV batteries, for all batteries about 3% (in the EU 2%, see Figure 35).

Global Manganese demand in 2019 was about 23 million ton (BGR 2022), in the EU about 1 million tons (SCRREEN 2023). About 46,000 tons are used for EV battery materials.

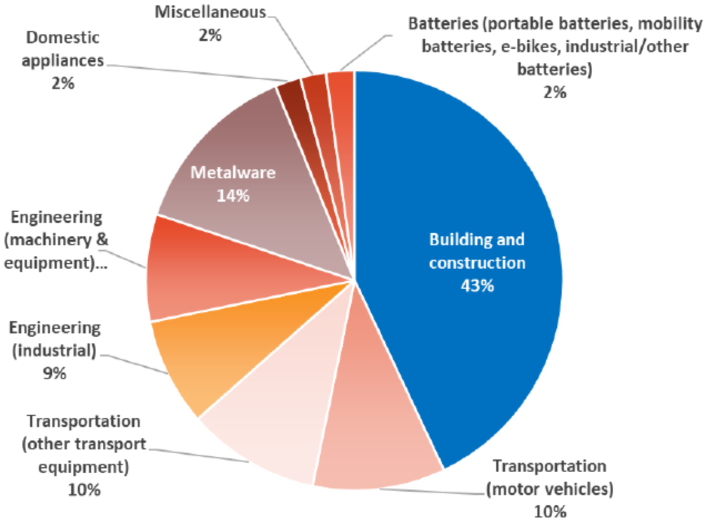


Figure 36: End uses of Manganese in 2016 EU (SCRREEN 2023)

The future development of Manganese demand is expected to grow due to increasing utilization in the battery industry. The material's strategic importance as a key alloying material for high-strength steel for use in vehicles, heavy-duty equipment, military and shipbuilding is expected to remain in the coming years.

170,000 to 350,000 additional tons Manganese for EV batteries in 2030 (demand scenarios in section 2.2.5) would result in a 4- to 8- fold increase compared to the demand of 2019. Assuming a steady demand of 23 million tons for non-battery uses, the share of Manganese demand for EV batteries ot total demand would be about 1.5%.

2.3.3.2 Material sourcing

Average annual production of Manganese was about 20 million tons according to USGS. Production was concentrated on South Africa (36%), Gabon (23%), and Australia (17%). Notable mine production also occurs in China (5%), Ghana (5%), and Brazil (2%). Primary Manganese supply in Europe comes from Bulgaria, Hungary and Romania, although jointly this accounts for less than 1% of total global supply.

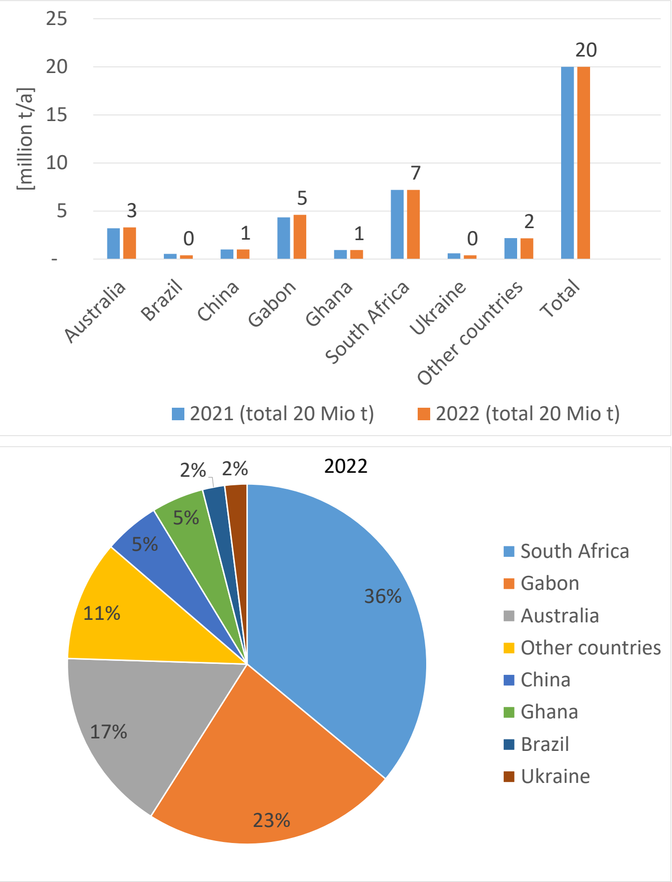


Figure 37: Word Manganese mine production 2021, 2022 (USGS 2023)

Global Manganese reserves of more than 1,700 million tons are shown in Figure 33, with 38% in South Africa and each 16% in Australia, China and Gabon (Figure 33).

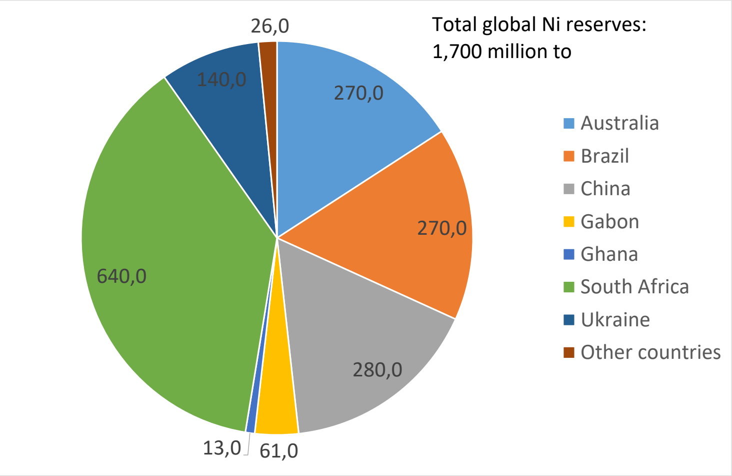


Figure 38: Global Manganese reserves (USGS 2023)

2.3.3.3 Material demand and supply balance 2030

Based on the Manganese demand scenarios developed by Task 40 (“High-Nickel”, “50% LFP”) and supply scenarios, deficits on the global supply side are unlikely. Based on additional Manganese production driven by steel production, the share of future demand for batteries might be in the range of 1 to 1.5%.

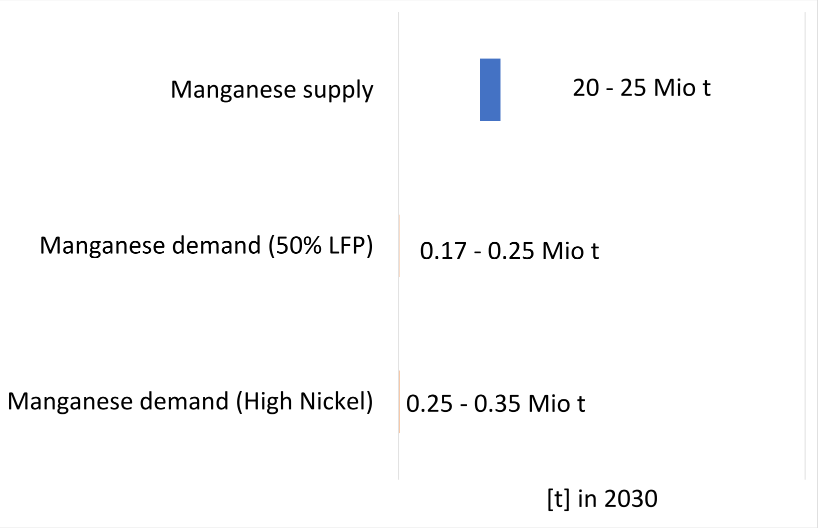


Figure 39: Outlook for global battery-grade Manganese demand and supply balance in 2030

2.3.3.4 Material processing

Manganese is extracted from ores with metal contents of 35% to 50% which is a fundamental difference to Nickel or Cobalt ores. These ores are categorized based on their Manganese content as: high-grade (>44% Mn), mid-grade (<44% and ≥30% Mn), and low-grade (<30% Mn).

Manganese is extracted by both open-pit mining (main mining form in Gabon) and underground mining. Manganese ores are then crushed and milled before ore minerals are separated from the gangue (non-ore minerals) by physical (e.g. gravity) and/or chemical (e.g. froth floatation) separation techniques. Generally, Manganese concentrates are further refined in a pyrometallurgical processes, whereby the concentrate is converted to Ferro-Manganese (with a typical Manganese content of ca. 76%). There is a global trend that an increasing production share is produced by electric arc furnaces. Ferrosilico-Manganese is produced by smelting processes in submerged electric arc furnaces (Bollwein 2022).

The process behind refining Manganese is complex and is subject of continuous innovation which makes it difficult to draw detailed conclusion regarding the refining process. As battery material Manganese sulphate is required, which can be produced form both ferroManganese, and from electrolytic Manganese. Literature on the Manganese sulphate production chain is rare, also the Manganese Institute does not supply publicly available data.

2.3.4 Lithium

2.3.4.1 Material demand

Today (2020) Lithium is primarily used in manufacturing of rechargeable Lithium-ion batteries used in portable electronic devices, energy storage systems and electric vehicles. The share of batteries on the overall global demand was 71% in 2020 (Figure 40), which is about 47,000 tons, of which about 19,000 tons were used for EV batteries (Statista 2023[3]). Other global markets for Lithium products are glass and ceramics, 18%; lubricants, 9%; metallurgical powders, 3%; air treatment, 3% (SCRREEN 2023). Global Lithium demand in 2020 was 66,000 tons, of which 5,000 tons were consumed in the EU.

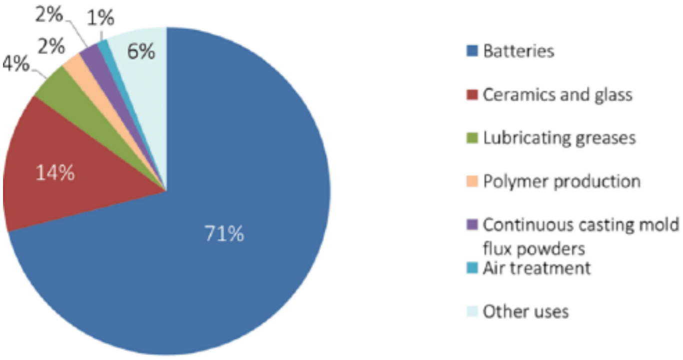


Figure 40: End uses of Lithium in 2020 globally (SCRREEN 2023)

The future development of Lithium demand will be driven by battery production including all Lithium-ion battery chemistries dominant today. Demand scenarios (see section 2.2.5) result in 170,000 to 440,000 tons of Lithium for batteries in 2030, which would be equivalent to a 9- to 23-fold increase compared to 2020.

2.3.4.2 Material sourcing

Total mine production of Lithium in 2021 was 107,000 tons, and 130,000 tons in 2022 (USGS 2023). The largest share of production has Australia with 47%, followed by Chile with 30% and China with 15%.

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[3] https://www.statista.com/statistics/1330765/ev-industry-mineral-demand-worldwide-by-type/

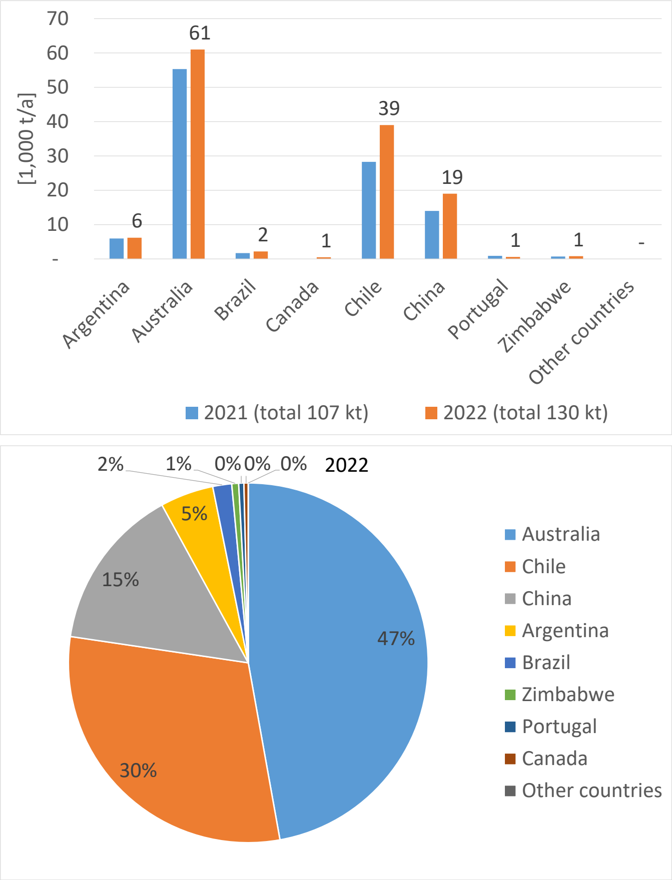

Figure 41: Word Lithium production 2021, 2022 (USGS 2023)

The EU share of the global Lithium production was 0.4 % or 600 tons (2022), all of that is from Portugal.

The IEA (IEA 2021) assessed global Lithium supply, based on increasing current production capacities and new projects under construction, to double from 2022 level to about 220,000 to 260,000 tons in 2030.

Global Lithium reserves of more than 26 million tons are shown in Figure 40, with 36% in Chile and 24% in Australia.

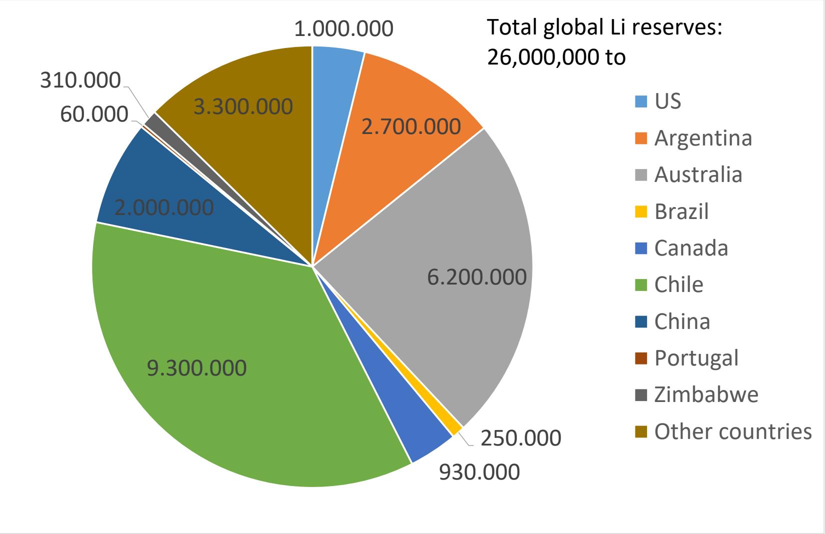

Figure 42: Global Lithium reserves (USGS 2023)

2.3.4.3 Material demand and supply balance 2030

Based on the Lithium demand and supply scenarios, potential deficits on the supply side can be identified. Figure 43 shows that Lithium demand in both the High-Nickel and the zero-Nickel battery chemistries (50% LFP) scenarios potentially exceeds by far available Lithium supply estimations.

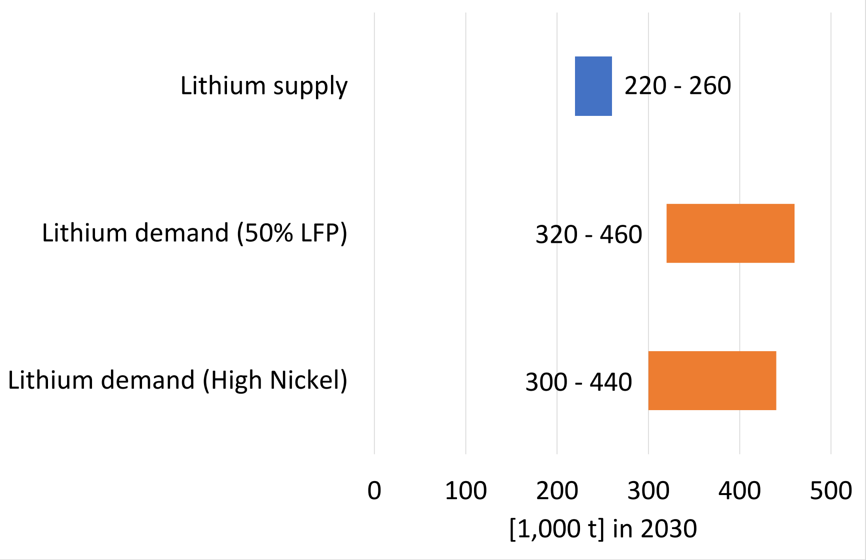

Figure 43: Outlook for global battery-grade Nickel demand and supply balance in 2030

2.3.4.4 Material processing

Lithium is not a rare resource, it is abundant in the lithosphere. Because of its high reactivity, Lithium does not occur in elemental form in nature, but in the form of compounds as silicates in igneous rocks, in some clay minerals and generally as chloride in brines. Two main deposit types are identified from which Lithium can be extracted; brine deposits in which the average

Lithium grade is about 0.1% Li_2O, and hard-rock deposits where Lithium generally grades from 0.6 to 1.0% Li_2O hosted by various Li-bearing minerals (SCRREEN 2023).

Economic Lithium deposits of brines mainly occur in areas where arid climate and high evaporation has resulted in further Lithium enrichment (0.04-0.15% Li average grade) originating from weathered Li-bearing source rocks; these deposits are usually associated with salt lakes or salt pans. Brine resources are mostly found in South American countries Chile, Argentina and Bolivia. The main processes for recovering Lithium from brines are called the lime soda evaporation process and generally consists of stages starting with concentration by evaporation, impurity removal, and precipitation by carbonation (SCRREEN 2023).

In hard-rock deposits, Lithium-bearing minerals are generally associated with granitic pegmatite deposits. Spodumene ($LiAlSi_2O_6$) is the most important and abundant of Lithium-bearing minerals hosted by granitic pegmatites. The world’s largest Lithium-rich pegmatite deposit and operating mine is Australia’s Greenbushes in Western Australia, in which spodumene reserves grade up to 3.9% Li_2O. Approximately 35% of the world’s supply of Lithium products is sourced from ores and clays, most of which (85%) is extracted from the Greenbushes deposit in Western Australia. Spodumene accounts for approximately 90% of global non-brine Lithium carbonate equivalent production. The process of LiOH and Li_2CO_3 production by spondumene and clays, respectively is complex and comprises various steps of beneficiation, pre-leaching preparation (i.e. roasting), leaching and purification. The Lithium-bearing clay deposits (hectorite) identified in the United States, Mexico and Morocco, and the Lithium zeolite deposit in Serbia containing the recently discovered mineral of jadarite, are under evaluation for future Lithium extraction (SCRREEN 2023).

2.3.5 Phosphate

2.3.5.1 Material demand

Today (2020) Phosphate (P2O5) rock is the main anthropogenic source of phosphorus and is used in agriculture and industry (fertilizer chemicals, phosphoric acid). Phosphate rock refers to rocks containing different Phosphate minerals, in particular calcium Phosphate as apatite which can be commercially exploited. Elemental phosphorus (P4) is produced in electrothermal reducing furnaces and is used for the production of chemicals.

The share of mineral fertilizers of the overall EU Phosphate demand of 2 million ton was 86% in 2016-2020 (Figure 44), 10% for animal feed. Global Phosphate demand in 2016 to 2020 was about 75 million tons. Elemental phosphorus demand in the EU was about 70,000 tons, globally about 1.2 million tons.

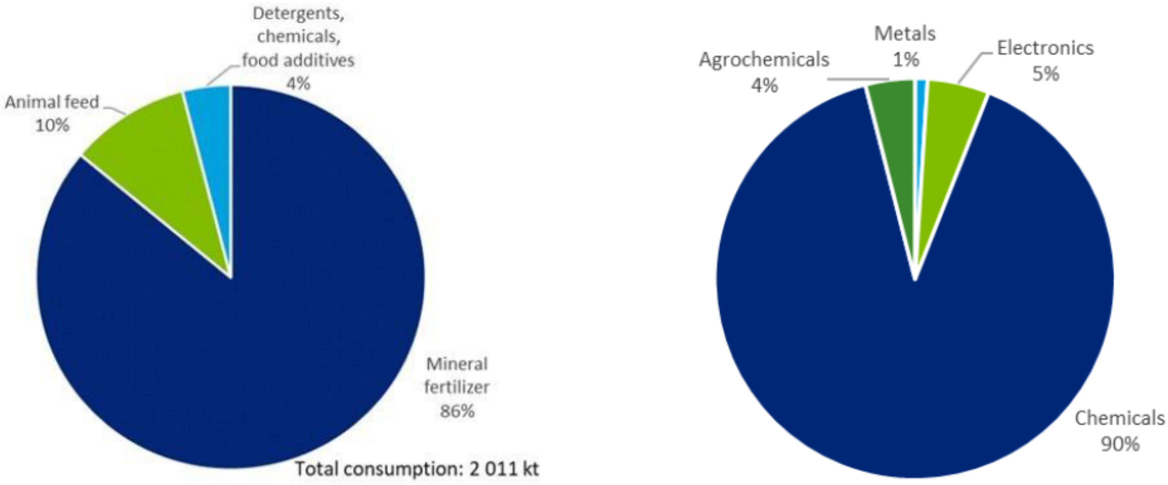

Figure 44: EU end uses of Phosphate rock and elemental phosphorus in 2012-2016 (SCRREEN 2023)

The future development of Phosphate demand will also in future be craven by the production of food, which at current yields is dependent on mined Phosphate rock for the production of fertilisers. Therefore, the future market of Phosphate rock is in a great extend controlled by changes in supply and demand of fertilisers used in agriculture and strongly connected with the global population growth. Global demand of fertilisers is expected to increase on average by 1.1% per annum, with the main rise expected in African countries. In Europe several secondary sources of phosphorus are already being considered (e.g. animal manure, wastewater and food waste) to reduce the dependence on Phosphate rock for fertiliser production.

The contributions of Phosphate demand for Lithium-Iron-Phosphate battery production will be comparatively small. Demand scenarios (see section 2.2.5) result in 1.9 million to 2.7 million tons in 2030. This would double the current demand in the EU.

2.3.5.2 Material sourcing

Total production of Phosphate in 2021 was 226 million tons, and 220 million tons in 2022 (USGS 2023). The largest share of production has China with 39%, followed by Morocco with 18% and US with 10%.

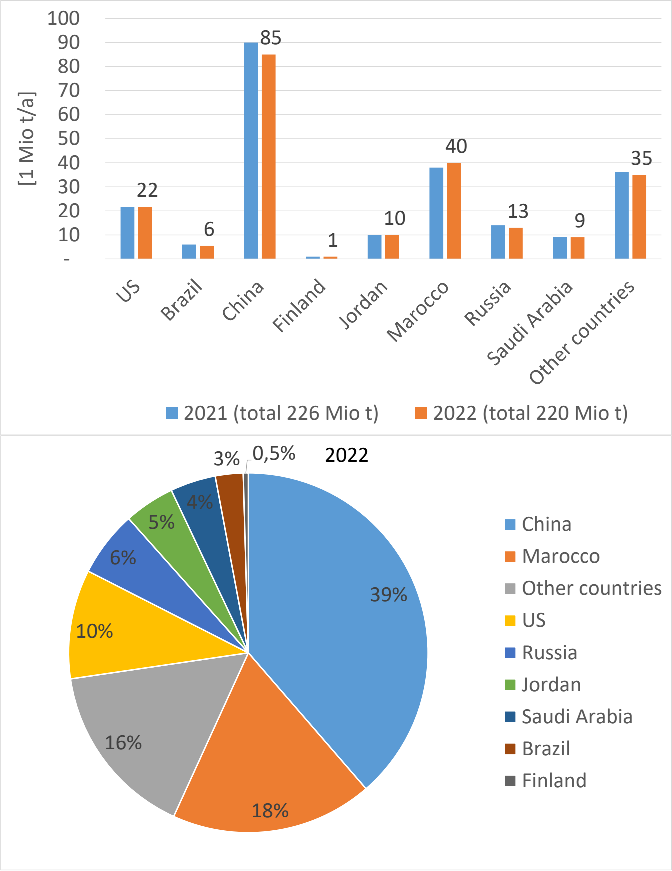

Figure 45: Word Phosphate production 2021, 2022 (USGS 2023)

The EU share of the global production was 0.5 % or 1 million tons (2022), all of that is from Finland.

According to the estimations of industry analysts, the capacity of global phosphoric rock mines was projected to increase to 261 million tons in 2024 from 238 million tons in 2020. The most significant mining production increase is going to take place in African countries. Furthermore, new mining projects are planned in US (USGS, 2021). Phosphoric rock deposits worldwide are considered as enormous. Only the deposits in Morocco are able to cover the world demand for hundreds of years (SCRREEN 2023).

Global Phosphate reserves of more than 72,000 million tons are shown in Figure 46, with 69% or 50,000 million tons in Morocco.

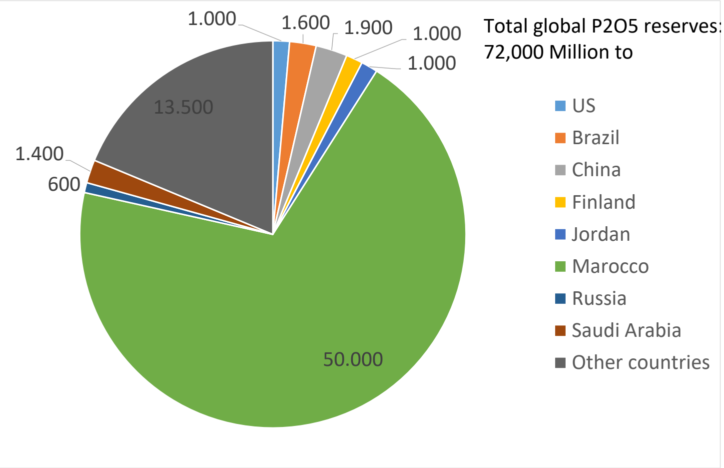

Figure 46: Global Phosphate reserves (USGS 2023)

2.3.5.3 Material demand and supply balance 2030

Based on the Phosphate demand and supply scenarios, deficits on the global supply side are unlikely. Based on additional Phosphate production driven by fertilizer production, the share of future demand for batteries might be in the range of 10%.

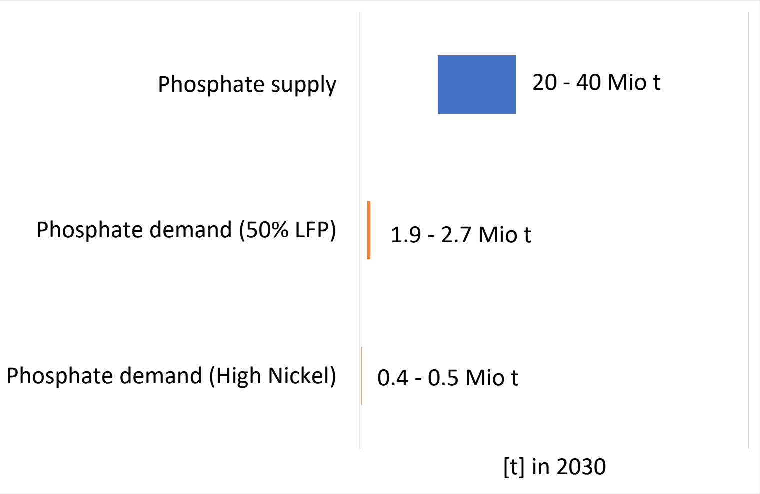

Figure 47: Outlook for global battery-grade Nickel demand and supply balance in 2030

2.3.5.4 Material processing

The most Phosphate rock production worldwide is extracted using opencast dragline or open-pit shovel/excavator mining methods, e.g. in the United States, Morocco, Russia and China. Further processing of Phosphate rock is needed to produce elemental phosphorus. Elemental phosphorus may be made by several methods. In one process tri-calcium Phosphate, the essential ingredient of Phosphate rock, is heated in the presence of carbon and silica in an electric furnace or fuel fired furnace, elementary phosphorus is liberated as vapor and may be collected under phosphoric acid, an important compound in making super-Phosphate fertilizers. Worldwide, a gradual shift to manufacturing high-purity phosphoric acid from wet process acid has taken place because it has lower production costs and none of the hazardous waste disposal issues that are associated with elemental phosphorus (JRC 2021).

2.3.6 Natural Graphite

2.3.6.1 Material demand

Today (2020) natural Graphite is mainly used for the production of refractories for steelmaking and for foundries. It is a good thermal and electrical conductor and has a high melting point (3,650 °C). Graphite has a high thermal resistance and lubricity, is resistant to corrosion, chemically inert and non-toxic. These properties make it a raw material with a wide range of uses. China is the dominant consumer of natural Graphite used in batteries, and the only commercial-scale producer for battery-grade spherical Graphite (JRC 2020).

Global demand in 2020 was about 1 million tons, of which 52% are used for refractories and 8% for batteries. The EU consumption of natural Graphite is about 86 kt, of which only 1% is sourced through domestic production. The global share for battery anode production was about 370,000 tons, produced by almost 100% in China (SCRREEN 2023).

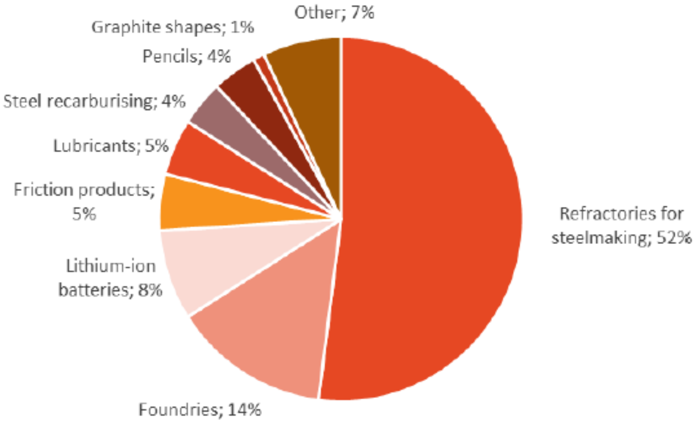

Figure 48: Global end uses of natural Graphite in 2014 (SCRREEN 2023)

The deployment of electric vehicles and the development of energy storage systems is projected to drive most of the growth of future natural Graphite demand, besides an also expected increase for refractories for growing steel industry.

Demand scenarios (see section 2.2.5) result in 2.8 million to 4.2 million tons in 2030. This would result in a 3- to 4- fold increase compared to overall Graphite demand in 2020.

2.3.6.2 Material sourcing

Total production of natural Graphite in 2021 was 1.13 million tons, and 1.3 million tons in 2022 (USGS 2023). The largest share of production has China with 65%, followed by Mozambique with 13% and Madagascar with 8%.

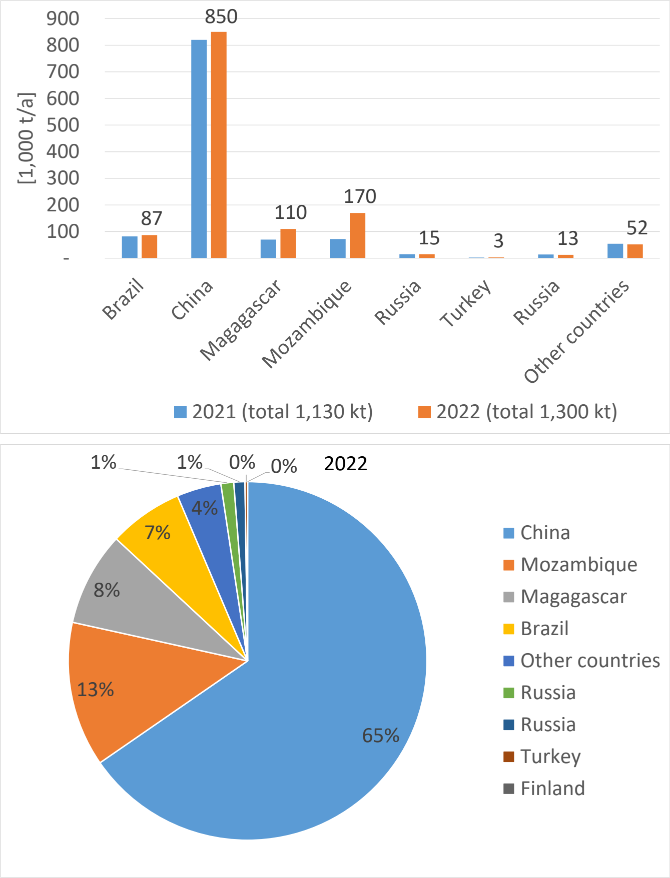

Figure 49: World natural Graphite production 2021, 2022 (USGS 2023)

The EU share of the global production was 0.1 % or 750 tons (2022), from Austria and Germany.

An increasing number of exploration companies is developing new Graphite projects worldwide. Most largescale future projects at advanced development stage moving closer to first production are situated in Africa, i.e. Mozambique, Madagascar, and Tanzania (SCRREEN 2023). In the EU the activity is concentrated in Sweden and Finland

Global natural Graphite reserves of more than 330 million tons are shown in Figure 46, with 29% in Turkey, 22% in Brazil and 16% in China.

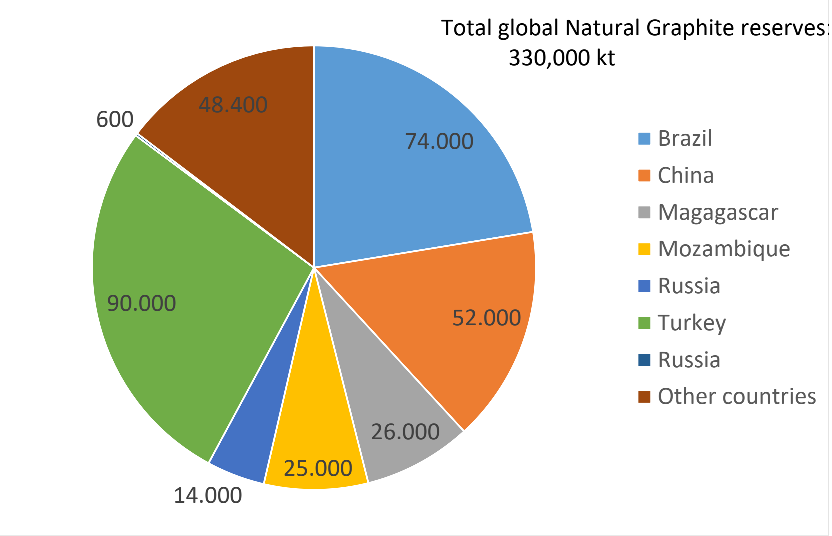

Figure 50: Global Phosphate reserves (USGS 2023)

2.3.6.3 Material demand and supply balance 2030

Based on the natural Graphite demand and supply scenarios, potential deficits on the supply side can be identified. In literature no accumulated forecasts for natural Graphite supply could be identified. As already stated, demand scenarios (see section 2.2.5) result in 2.8 million to 4.2 million tons Graphite demand for battery anodes in 2030, which would result in a 3- to 4- fold increase compared to overall Graphite demand in 2020.

Besides natural Graphite, also synthetic Graphite can be used for the production of battery grade material. The downside of synthetic Graphite is the high energy demand (and costs) for its production. The basic feedstock material is petroleum coke which comes from the heavy fractions left over from crude oil production. The graphitization of coke products into synthetic Graphite requires the largest energy input.

2.3.6.4 Material processing

After mining from the ore, the natural Graphite (NG) has to be separated from the surrounding matrix, first, by mechanical separation, and second, by flotation. Important to note is that only special fractions of NG (i.e. selected flake types without heavy metal contaminants, e.g. vanadium) can be used to produce anode materials in required quality. After drying and screening, the Graphite particles have to be reduced in size and then spheroidised in a “potato-shaped structure” as required for anode materials.

The product, known as "potato-shaped Graphite", is subsequently cleaned by chemical or thermal Treatment. For the chemical treatment, inorganic acids like hydrofluoric, hydrochloric or sulphuric acid are used. As alternative or additional treatment, the Graphite powder can be heated to over 3000 °C under inert atmosphere to vaporise the contaminants (SCRREEN 2023).

2.3.7 Rare Earth Elements

2.3.7.1 Material demand

Rare Earth Elements (REE) in the context of EVs are used for permanent magnet motors. Besides EV motors, REEs are essential in the production of wind turbines, batteries and energy-efficient light bulbs.

The main elements in EV motors are neodymium (Nd), iron (Fe), and boron (B), in smaller quantities dysprosium (Dy) and praseodymium (Pr). The rare earths Neodymium (Nd) and Praseodymium (Pr) are used for the magnetic performance and Dysprosium in small quantities for the temperature stability. Neodymium (Nd) and Praseodymium are used by 80% for magnets, dysprosium by 100% (Figure 51).

Global consumption of Nd was 26,800 tons between 2016 and 2020, of Pr 6,860 tons and of Dy 708 tons. EU consumption was 119 tons Nd, 107 tons Pr and 1 tons Dy (SCRREEN 2023).

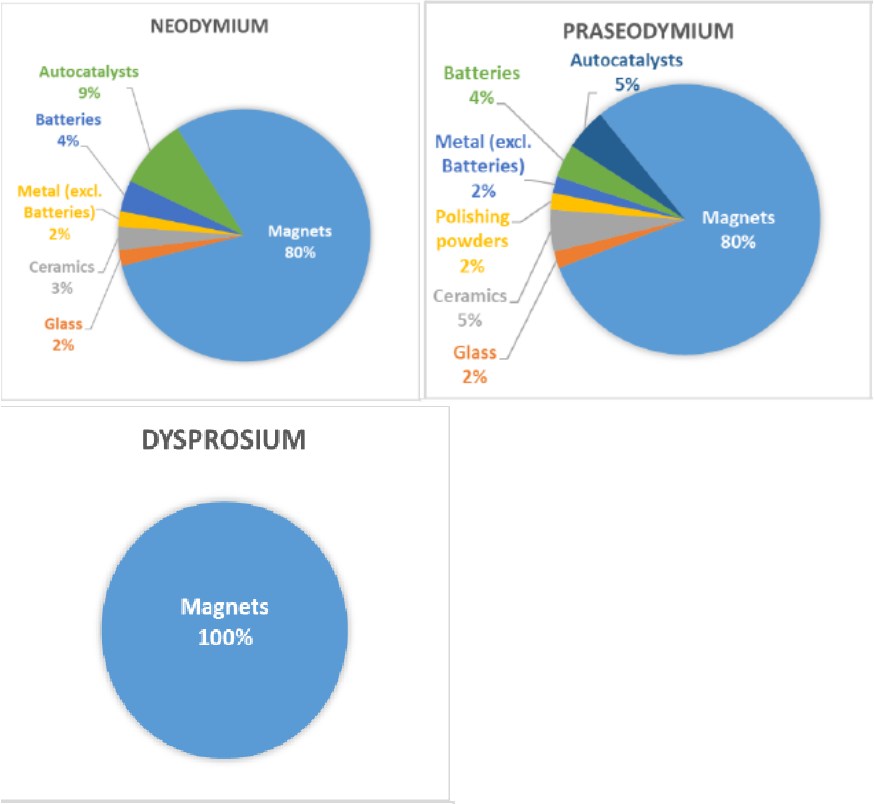

Figure 51: EU end uses of REE in 2020 (SCRREEN 2023)

The REE market is a specialty market, characterized by business-to-business trade rather than exchanges on metal markets. It is therefore a volatile market with high uncertainty and opacity (SCRREEN 2023). Demand scenarios (see section 2.2.5) result in 13,500 t to 50.000 t in 2030. This would result in about a 0,5 to 2-fold increase compared to global demand of Nd, Pr and Dy in 2020.

2.3.7.2 Material sourcing

Production quantities are only available for the entire group of REE and not for individual elements (SCRREEN 2023). Global production of REE in 2021 was 290,000 tons, and 300,000 tons in 2022 (USGS 2023). The largest share of production has China with 70%, followed by US with 14% and Burma with 8%.

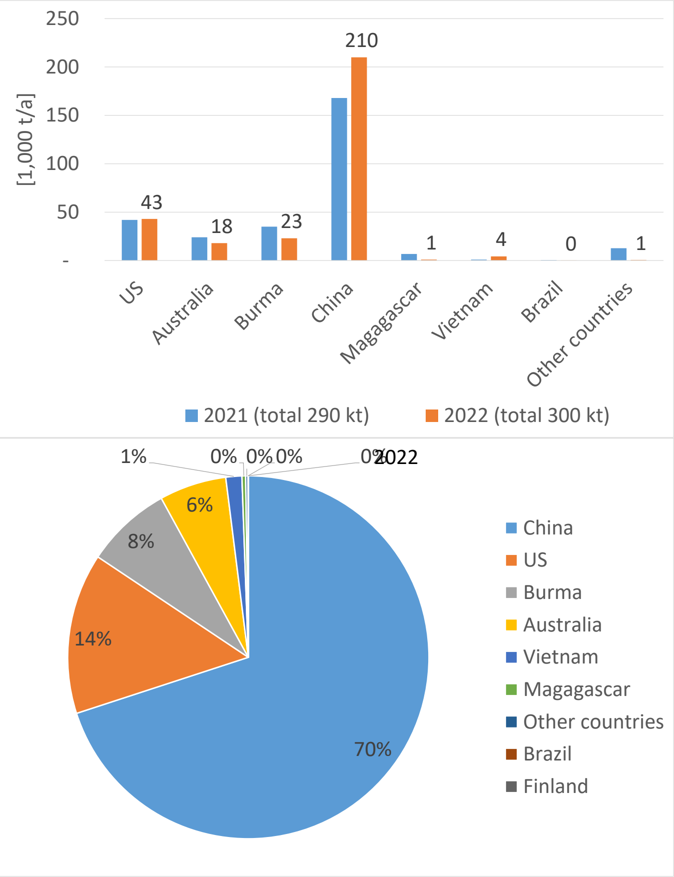

Figure 52: World REE production 2021, 2022 (USGS 2023)

The EU has no REE mining operations, but imports ores and concentrates for refining. Greenland has some deposits, mining is however uncertain due to environmental concerns.

The development of REE projects outside China and, therefore the potential supply by alternative sources/producer countries, comprises a complex issue dependent on various constrains, as technical complexity, high costs, variability of ore geologies and lack of interest from investors. For every ton of Nd/Pr produced, 3 tons of other rare earths for which there is no real demand is produced as well as rare earths as mined and refined as a mix of different elements.

Global REE reserves of more than 130 million tons are shown in Figure 53, with 34% in China, 17% in Vietnam and 16% in Brazil.

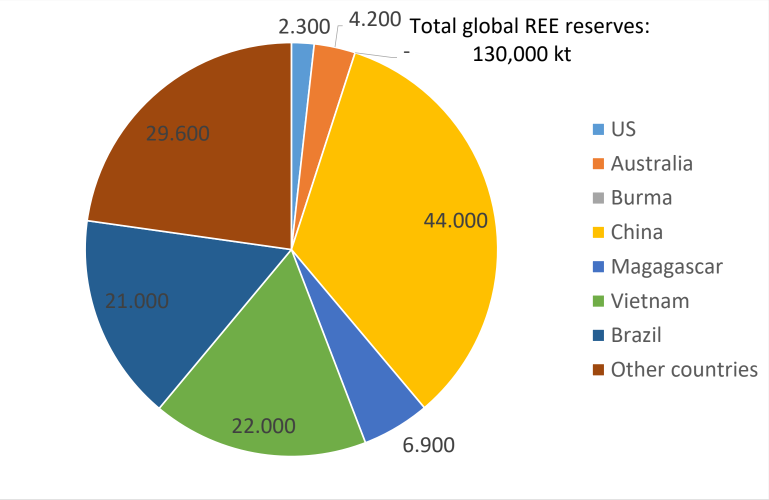

Figure 53: Global REE reserves (USGS 2023)

2.3.7.3 Material demand and supply balance 2030

Since supply scenarios are not available on the level of individual REE as required for permanent magnet motors, demand-supply-balances cannot be derived. As already stated, demand scenarios (see section 2.2.5) result in 13,500 t to 50.000 t in 2030, which would result in a 0,5 to 2-fold increase compared to global demand of Nd, Pr and Dy in 2020.

Task 40 concludes that it is likely that for EVs alternative motor solutions will be implemented, due to the challenges related to establishing additional REE supply production as described in the previous section. The most notable non-permanent magnet motor being used is the induction motor, announced to be used in some Tesla models in 2024.

2.3.8 Recycling of EV batteries and CRM

Battery recycling is essential for securing future critical raw material supply for battery production, since primary material supply potentially will show a deficit opposed to the expected global demand of most raw materials, as shown in the previous sections. Especially in Europe with the forecasted second largest demand in battery materials after China in the next decade, recycling is of central importance to address the EU's dependency on imported critical raw materials by diversifying and securing a domestic and sustainable supply of critical raw materials. Besides the already mentioned Critical Raw Material Act, also the currently updated EU Battery Directive 2006/66/EC, which is expected to be published in May 2023, sets new requirements in relation to battery material recycling.

- Minimum recycling rate:
    - 2026: 35 % Lithium, 90 % Nickel, Lead, Copper, Cobalt
    - 2030: 70 % Lithium, 95 % Nickel, Lead, Copper, Cobalt
- Minimum share of recyclate:
    - 2030: 12% Cobalt; 85% Lead; 4% Lithium; 4% Nickel
    - 2035: 20 % Cobalt; 85 % Lead; 10 % Lithium; 12 % Nickel

This section presents an overview of the state of technology of recycling processes and related benefits and trade-offs, based on Dorri (2022), Windisch-Kern (2022) and Harper (2019). Figure 54 presents possible recycling routes described in more in the following, including the collection of spent batteries, pre-treatment processes, metal recovery in pyrometallurgy or hydrometallurgy (and biometallurgy as emerging technology), and hydrometallurgical refining as final process step to produce metal concentrates for battery production.

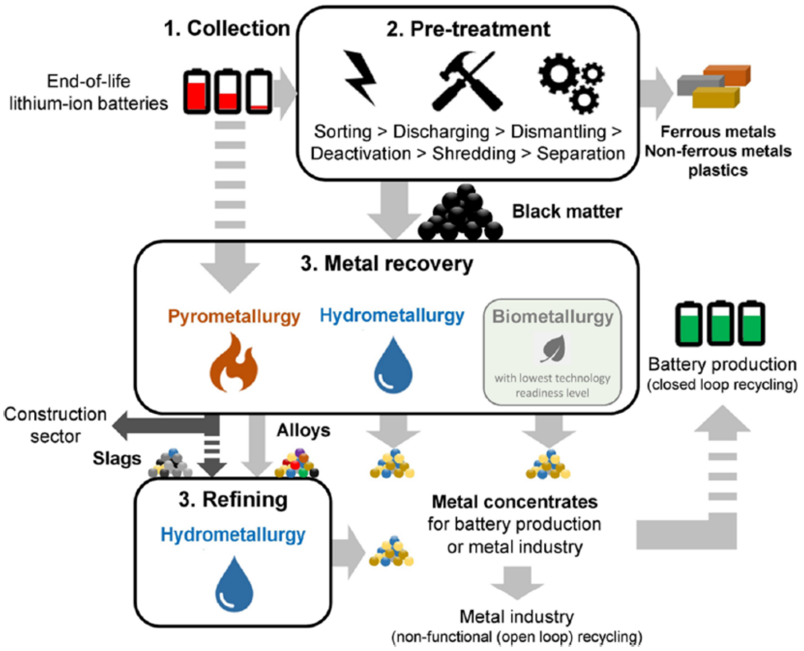

Figure 54: Schematic overview of possible recycling routes for Lithium-ion batteries (Windisch-Kern 2022)

Among all LIBs' recycling methods, pyrometallurgy (Figure 55) is considered as the most mature and technically-proved method that is commercially used by many companies worldwide, especially in North American and Europe. Spent batteries, coke and slag formers (e.g. limestone) are the main inputs into the first preheating zone of the furnace. The main goal of the preheating zone is to evaporate the electrolyte slowly, which is accomplished in temperatures around 300 °C. After eliminating the electrolyte, the heated inputs are transmitted to the plastic pyrolysis zone, where plastic parts are removed. The temperature rises to 700°C in this part of the system by burning the plastic components. Finally, the materials go to the last section, entitled the metal smelting and reducing zone, in which the temperature is about 1100 to 1500 °C to melt the metallic contents of input batteries. To reach high temperatures in this phase, oxygen and/or rich-oxygen air is injected into this part of the furnace. In the end, the final output comprises some gases, slag, and an alloy, which is accounted as the most important part, containing Cobalt, Nickel, Copper, and iron. These metals can later get recycled separately by further treatments in a hydrometallurgical process. All the other materials existing in the slag, including Manganese, Lithium, aluminium, and Silicium, are either downcycled in other industries, such as construction, glass, road, and cement, or get squandered as waste in landfills and incinerations (Dorri 2022).

The main advantage of this recycling process is its capability to recycle a wide range of batteries, without the need for any particular pretreatment process. This advantage is especially important in countries with no efficient infrastructure to separate the collected batteries. In terms of safety risks, pyrometallurgy is one of the safest ways to manage batteries because there is the least of human contact with hazardous material within batteries, such as electrolyte, and adhesives. Another advantage of the pyrometallurgical recycling process is its maturity and reliability (Dorri 2022).

Drawbacks of pyrometallurgy are that it is an energy-intensive process that is usually supplied by fossil fuels sources, such as coke and natural gas. The elements Li, Mn, Al end up in the slag, economic recovery of those materials is challenging, therefore they usually end up as filler in conrete. Recycling batteries that lack valuable materials might not be economically viable through pyrometallurgy, including LFP batteries. All carbon content is converted to CO2 (Dorri 2022).

Hydrometallurgy is the most common process for recycling LIBs in some countries, such as China. It matches more to a circular economy paradigm than pyrometallurgy. Hydrometallurgy is a collection of chemical and physical processes that can be divided into three main stages (Figure 56): pretreatment to remove the impurities, leaching, and purification and recovering the material. Unlike pyrometallurgy, pretreatment is crucial in hydrometallurgy because the chemical process for recovering the materials is usually designed for extracting specific types of materials. After removing the cover of the battery pack, the batteries are discharged, and their modules are disaggregated to obtain their cells separately. The cells are usually shredded into small pieces to segregate different parts of LIBs, including electrolytes, and positive and negative electrodes. In this phase, the metallic scraps, such as aluminium, iron, and Copper are transmitted for reuse in other industries and the cathode active materials are sent to the leaching process in the form of powder. Leaching is the first part of the chemical recovery in a hydrometallurgical process, where the inputs are mixed with water and acids to dissolve the inputs in a solution. Graphite is not dissolved in the solution and removed from the rest of the materials by precipitation (Dorri 2022).

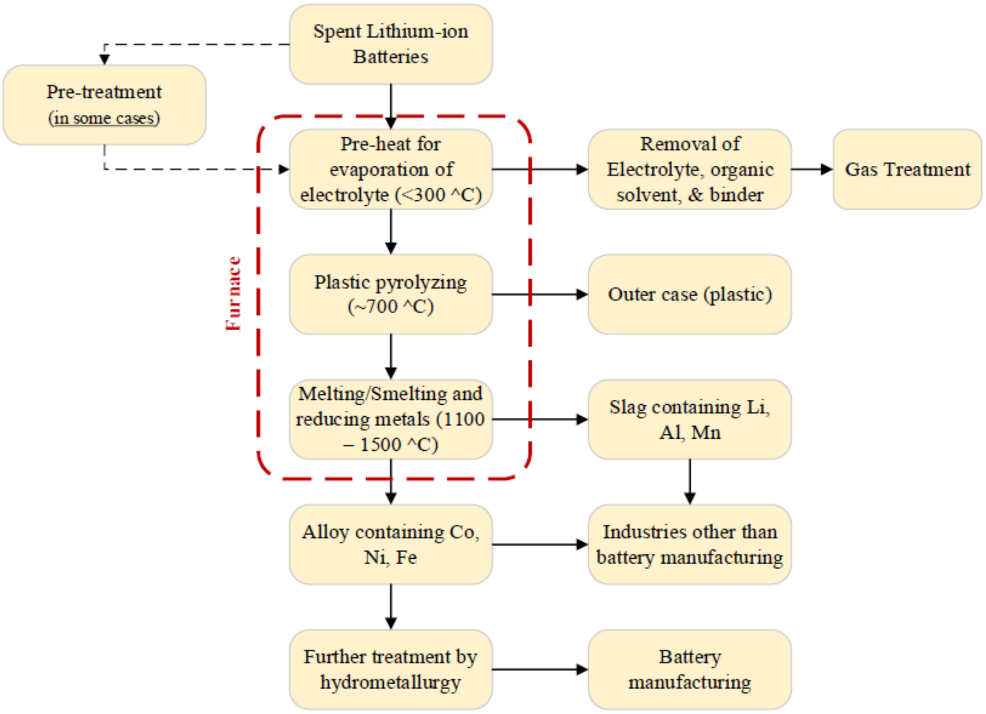

Figure 55: Outline of the pyrometallurgy recycling method (Dorri 2022)

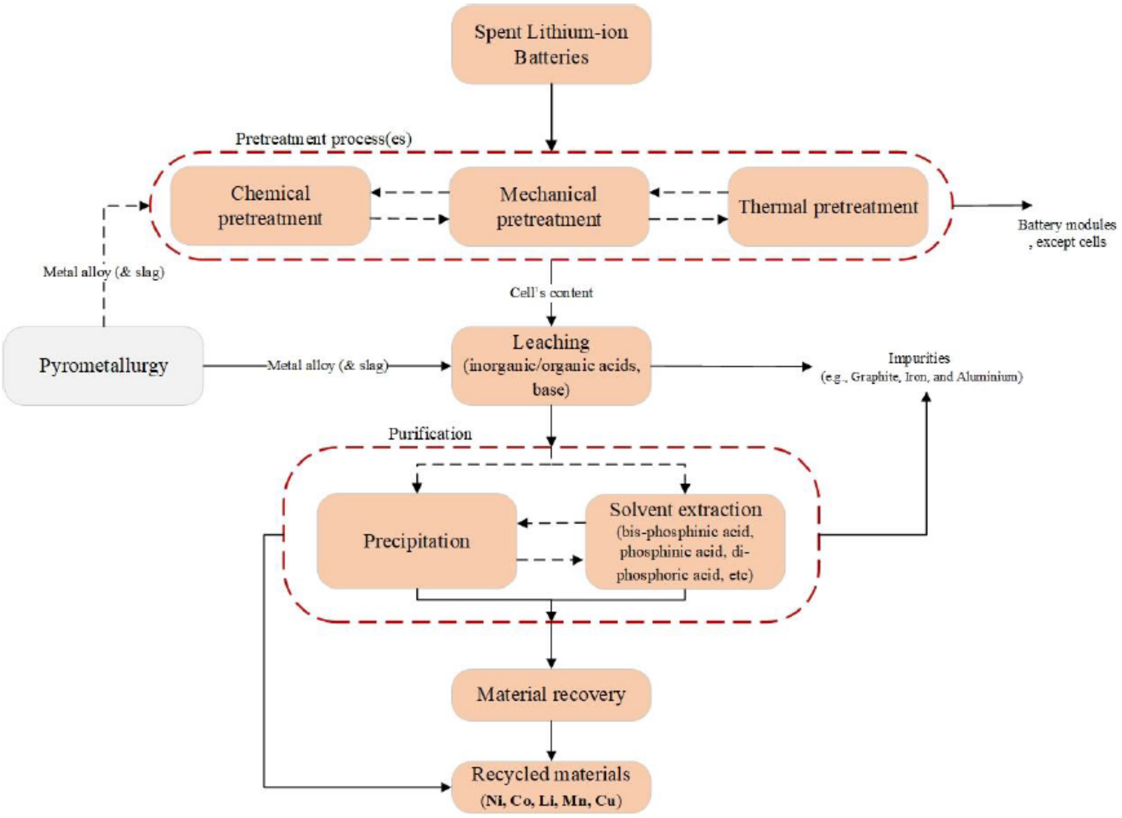

Figure 56: Outline of the hydrometallurgy recycling method (Dorri 2022)

The main advantage of hydrometallurgical recycling is that it is possible to recover most of the materials existing within LIBs, including Lithium, Cobalt, Manganese, Nickel, Copper, aluminium, and Graphite. The second reason is its lower energy consumption than pyrometallurgy. Also, hydrometallurgical recycling processes are capable of recycling LIBs with a low or even no amount of valuable materials, such as LFP (Dorri 2022).

The downside is that the hydrometallurgical recycling processes are designed for specific types of batteries, and the efficiency of the recycling process is usually higher for the cases with just one type of spent LIBs in the input. The water consumption is relatively high in this method, converted to polluted wastewater with a high amount of chemicals. Producing and using chemicals is associated with high environmental burdens (Dorri 2022).

Direct recycling is the most current method of recycling EV batteries. The main aim of this recycling method is to recover the active cathode materials without any change in their morphological state and breaking their crystal structure. Thereby, the extracted active materials can be used directly in manufacturing new LIBs (Gaines 2021). Generally, a direct recycling process can be divided to four main stages: preparation and processing of spent batteries, separation process, product upcycling, and recycled material quality investigation (Dorri 2022).

Delamination is the process of separating active materials attached to current collectors. After the delamination process, aluminium and Copper are segregated from the rest materials and can be used for making new current collectors. After delamination, a mix of electrodes is obtained, which should get separated from each other. Froth floatation is the method usually used to this end, which works based on the hydrophilicity of cathode and anode active materials. After that, the relithiation process is carried out. In Lithium-ion batteries Lithium moves between anode and cathode in the charging and discharging process. Gradually some Lithium remains in the Graphite structure and the amount of Lithium in cathode active materials decreases, which need to be replaced by new Lithium (Dorri 2022).

Direct recycling has been one of the promising solutions to reach a circular economy paradigm in LIB industry. It has the potential to make it possible to recycle all of a LIB's components, regardless of its constituents. Moreover, the recycling process is more environmentally friendly, with fewer environmental impacts (Gaines, 2018). However, there are some serious challenges concerning direct recycling. First of all, the recycling process depends on the quality of LIBs in the input. Damaged active materials are not recovered through direct recycling because they cannot be used directly in new LIBs anymore. Furthermore, direct recycling is complicated and requires a high level of knowledge and technology.). Last but not least, the development and change in the LIB industry is occurring so fast, and the chemistry and structure of manufactured LIBs are going through different changes. Hence, there is a risk that recovered LIBs may not be usable in LIBs that are produced in the future.

As a summary, the sequence and interplay of recycling processes depending of input quality and chemistry, required quality of output material remain as biggest technical and research challenge to reach EU recycling targets.

- Hydrometallurgy is the most likely technology in medium term, since all metals can be recovered separately which supports the main purpose of recycling of enabling circular economy
- Large-scale NMC-recycling can be expected to be in place in late 2020s (likely cost-efficient due to critical metals recovered)
- Large-scale LFP-recycling can be expected to be in place later than 2030 (less cost-efficient since Lithium and Copper are the only electrode-metals to be recovered); BUT: new EU-battery directive (2023) will require recovery rates for Lithium (35% in 2026, 70% in 2030)

Figure 57 presents an overview of existing and planned recycling plants in Europe. The biggest currently installed plant is in Hungary (25,000 t/a capacity), the biggest planned facility is located in Sweden at Northvolt with 125,000 t/a planned capacity, starting in 2023.

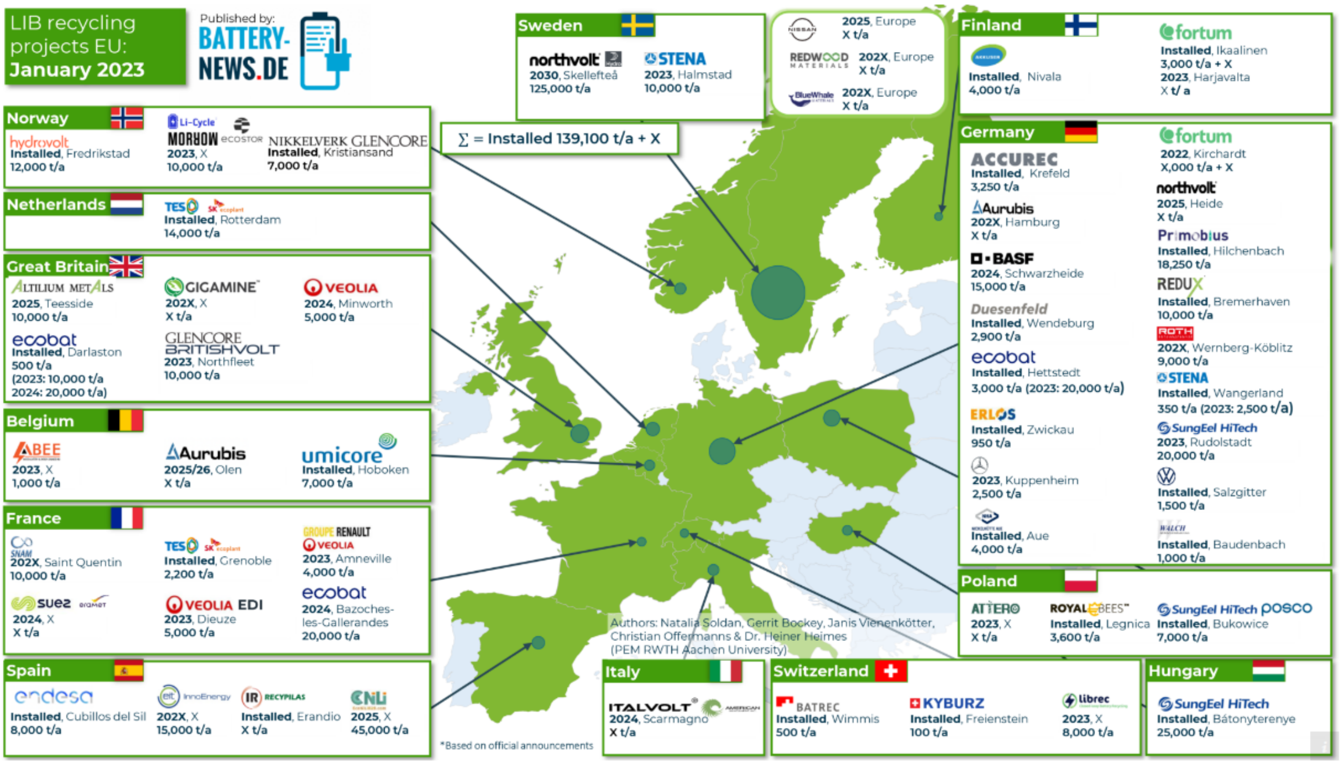

Figure 57: EV battery recycling projects in Europe (Battery-new.de[4])

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[4] https://battery-news.de/index.php/2023/01/27/batterie-recycling-in-europa-stand-01-2023/

2.4 Environmental and social impacts

2.4.1 Environmental impacts

Generally, processes for CRM extraction and processing are somewhat similar for all CRM, with mining being classified into open-pit and underground mining, beneficiation processes as first material separation and concentration processes at the mining location including crushing or flotation, and material refining processes involving pyrometallurgical smelting and/or hydrometallurgical leaching processes.

Environmental impacts in material supply are related to all of these processes and depend on the type of ore, the types of processes and on the location. Environmental impacts are classified into local (e.g. biodiversity, water use, land use), regional (e.g. acidification) and global impacts (e.g. global warming potential). Local and regional impacts are generally more associated with raw material extraction and first material concentration processes, whereas material refining involves process energy intensive as well as chemical processes, associated with regional and global impacts.

In relation to CRM extraction, Luckeneder (2021) from the mining institute at the Montanuniversität Leoben in Austria found that the rapidly expanding mining sector exerts increasing pressures on ecosystems recognized as vulnerable. Their global analysis contextualizes a detailed assessment of how metal mining volumes are distributed across almost 3,000 mining projects worldwide, covering nine metal ores (bauxite, copper, gold, iron, lead, Manganese, nickel, silver and zinc) in the period 2000–2019, and using three spatial layers as proxy indicators for ecosystem vulnerability: terrestrial biome categorizations, protected areas, and water scarcity.

The result of the study was that almost 80% of global metal extraction in 2019 occurred in the world’s most species-rich biomes, 90% of mining sites were in areas of relative water scarcity, and almost 50% of extraction occurred at less than 20 km distance or even within protected areas. The study identifies a great need for more quantitative studies on the magnitude of impacts induced by the entire mining industry. Any expansion of mining constitutes a trade-off for other human and non–human uses or values attached to land and resources. More accurate assessments of mining projects’ propensities to exert additional pressures such as biodiversity loss, deforestation, water and air pollution as well as social conflicts could help constructing spatially varying impact measures (Luckeneder 2021)

The following figure illustrates the results of the project ÖkoRess of the German Umweltbundesamt (Becker 2020) which evaluated average Environmental Hazard Potentials (EHPs) of mined critical raw materials.

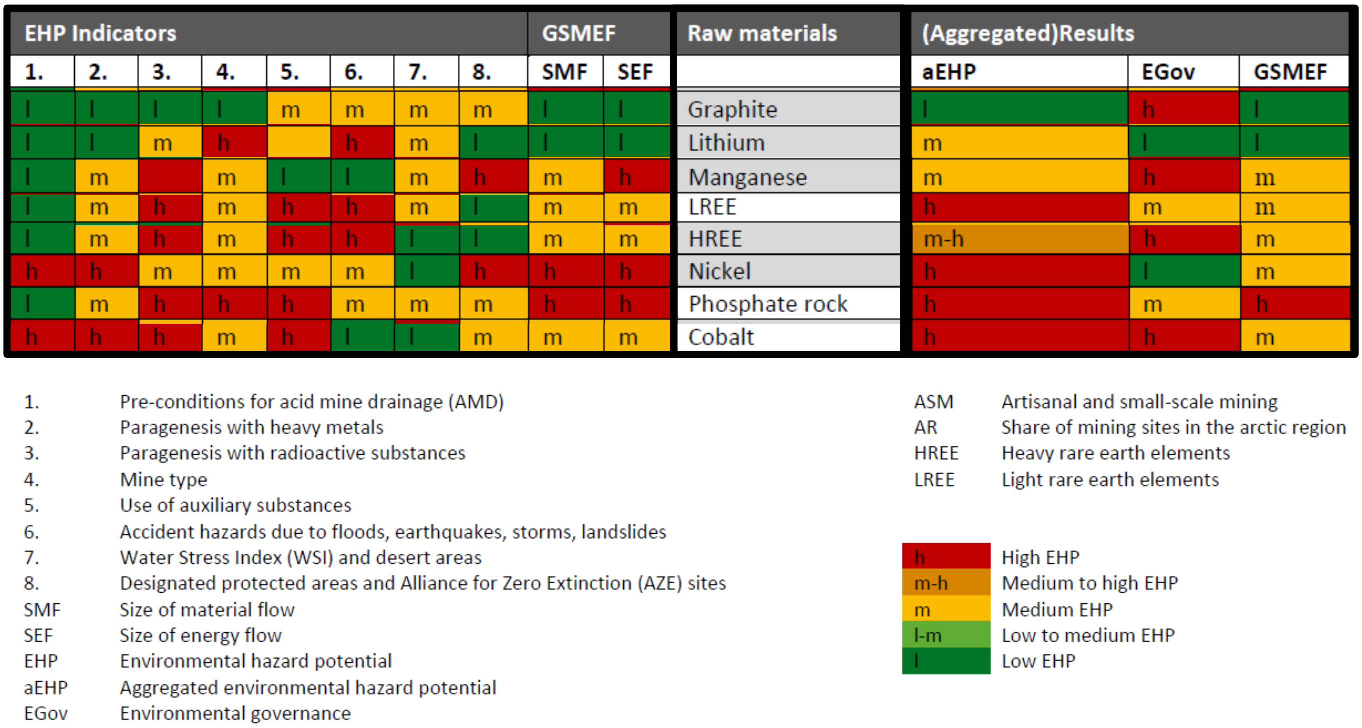
Firstly, within the area of geology, the likelihood of radioactive contamination, paragenesis with heavy metals and potential for Acid Mine Drainage (AMD) were investigated (indicators1-3). Raw materials that tend to occur in sulphidic ores pose a higher Environmental Hazard Potential than raw materials occurring in oxidic sedimentary ores.

Secondly, in the technology level the mining method and the use of auxiliary substances were assessed (indicators 4-5). Raw materials that are more likely to be mined in open-pit operations disturb larger surface areas than raw materials mainly mined underground.

Thirdly, EHPs that emanate from the natural environment were assessed (indicators 6-8). This relates to the geographic location of the mine sites and investigates hazard potentials due to floods, landslides, earthquakes and storms. If a majority of mines for a certain raw material are located in areas with frequently occurring floods, the Environmental Hazard Potential for the raw material is more likely to be high, since floods can be a cause of tailing dam failures. Moreover, it is determined whether mines are located in areas with a high water stress or low water-availablility (deserts), and if mining sites are located in protected areas.

In addition, the environmental governance (EGov) is assessed based on the weighted environmental performance index (EPI[5]) according to the production share of the producing countries. If raw materials are mined to a large extent in countries with weak environmental governance, it is more likely that the Environmental Hazard Potentials are not properly managed and the likelihood for the occurrence of environmental impacts is higher.

From this analysis, all CRM Nickel, Cobalt, Manganese, Lithium, Phosphate and REE analyzed in this report are classified as environmentally critical materials.



EHP Indicators								GSMEF		Raw materials	(Aggregated)Results		
1.	2.	3.	4.	5.	6.	7.	8.	SMF	SEF		aEHP	EGov	GSMEF
l	l	l	l	m	m	m	m	l	l	Graphite	l	h	l
l	l	m	h		h	m	l	l	l	Lithium	m	l	l
l	m		m	l	l	m	h	m	h	Manganese	m	h	m
l	m	h	m	h	h	m	l	m	m	LREE	h	m	m
l	m	h	m	h	h	l	l	m	m	HREE	m-h	h	m
h	h	m	m	m	m	l	h	h	h	Nickel	h	l	m
l	m	h	h	h	m	m	m	h	h	Phosphate rock	h	m	h
h	h	h	m	h	l	l	m	m	m	Cobalt	h	h	m

1.	Pre-conditions for acid mine drainage (AMD)
2.	Paragenesis with heavy metals
3.	Paragenesis with radioactive substances
4.	Mine type
5.	Use of auxiliary substances
6.	Accident hazards due to floods, earthquakes, storms, landslides
7.	Water Stress Index (WSI) and desert areas
8.	Designated protected areas and Alliance for Zero Extinction (AZE) sites
SMF	Size of material flow
SEF	Size of energy flow
EHP	Environmental hazard potential
aEHP	Aggregated environmental hazard potential
EGov	Environmental governance

ASM	Artisanal and small-scale mining
AR	Share of mining sites in the arctic region
HREE	Heavy rare earth elements
LREE	Light rare earth elements

h	High EHP
m-h	Medium to high EHP
m	Medium EHP
l-m	Low to medium EHP
l	Low EHP

Figure 58: Results of Environmental Hazards Assessment of CRM in the project ÖKORESS (Dehoust 2020)

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[5] https://epi.yale.edu/

In the following subsections, specific aspects for Nickel, Cobalt, Lithium and Phosphate are summarized.

2.4.1.1 Nickel

Sulfidic Nickel ores are mainly mined underground, with minor impacts on direct land use since hard rock tailings are directly used for filling mining cavities. Processing of sulfidic ores for increasing metal concentration on the mining site (e.g. flotation) however results in significant water consumption and in large acid tailing ponds. In pyrometallurgical processing of sulfidic ores, SO2-emissions and dust containing heavy metals are significant impacts to the surrounding environment, especially in Russia. Sulfidic ore mines in the northern hemisphere as in Russia, Canada or Finland are often far away from highly populated regions. Conflicts with indigenous population however are being reported.

Lateritic ores are mined on the surface with higher land use and potential impacts on natural systems e.g. deforestation, loss of biodiversity, since about 60% of lateritic deposits are located in tropical regions hosting also virgin rain forests (BGR 2022). The clearest direct impacts are those caused by forest clearance to make room for the mine footprint itself and associated infrastructure, such as roads and railway lines. This can result in considerable loss of forest cover, constituent biodiversity, and associated ecosystem services. The impacts of associated infrastructure can be far greater than just the direct clearance of forest. The expansion of roads and railways, often along predefined “growth corridors,” represents one of the biggest threats to natural habitats.

The global warming potential has been analyzed by the Nickel Institute, reporting a global average of 13 kg CO2-e per kg Class-I Nickel, with 32 % from mining and processing and 68% from metallurgical processing. Nickel from 100% lateritic ores has 45 kg CO2-e per kg Nickel content, since production is more energy intensive and energy is supplied by high share of fossil sources (coal, oil, gas).

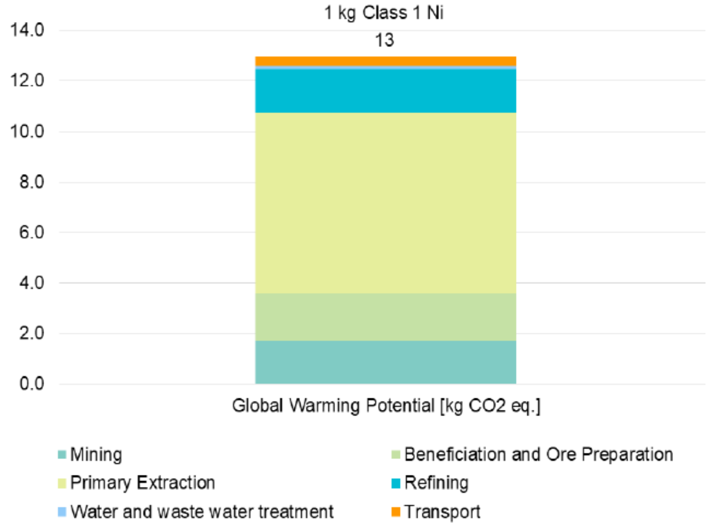


Figure 59: Global Warming Potential of class-I-Nickel (Nickel Institute 2020)

2.4.1.2 Cobalt

Environmental impacts in material supply are related to raw material mining, processing and refining activities and depend on the type of Nickel ore, the types of processes and of the location. Because of its by-product status, local environmental impacts of Cobalt ore mining and processing are generally related to those of Nickel production from sulfidic Nickel ores and lateritic ores (see section 2.4.1.1).

On average, refined Cobalt has a carbon footprint of 28 kg CO2 per kg of refined Cobalt (Cobalt institute 2019). Overall, the embodied energy involved in Cobalt producing projects varies significantly and depends on the deposit/ore type and processing route. On average, Ni-Co laterite processing is 2 to 5-times more energy-intensive than magmatic Ni sulphide or Cu-Co ore processing.

2.4.1.3 Lithium

The production of Lithium from hard rock sources especially in arid areas like Western Australia is relatively unproblematic, since these regions are also relatively unpopulated and conflicts arising from water use or emissions are unlikely. The production of Lithium form brines requires the evaporation of saline water (97%) for concentration of the brine. This results in in a fall of the salt lake´s water level, leading also to a fall of regional surrounding groundwater bodies. The risk of mixing freshwater with saltwater also increases, leading to conflicts with all other water users in the region, which is scarce in fresh water anyway.

Greenhouse gas emissions from the production of Lithium battery precursor materials Lithium-carbonate and Lithium-hydroxide are lower when produced from brine. The production of 1 ton of Lithium-carbonate from brine results in 2.7 to 3.1 tons CO2-e whereas from spodumene rock in about 20 tons CO2-e. The production of 1 ton of Lithium-hydroxide from brine results in 6.9 to 7.3 tons CO2-e whereas from spodumene rock in about 16 tons CO2-e (Kelly 2021).

2.4.1.4 Phosphate

Open-pit mining comes along with general local environmental impacts related to land use conversion, but also tailing ponds. Phosphate ore is separated from the sand and clay by a process known as beneficiation. Beneficiation creates clay-settling “ponds,” take decades to remove water and which can scar the landscape and contaminate surrounding habitat.

The wastes of most concern are the byproducts created during the wet and thermal processing steps of fertilizer production. Due to its chemical properties, Phosphate rock may contain significant quantities of naturally occurring radioactive materials. Phosphogypsum is the primary waste byproduct of the wet-acid process for producing phosphoric acid.

2.4.1.5 Graphite

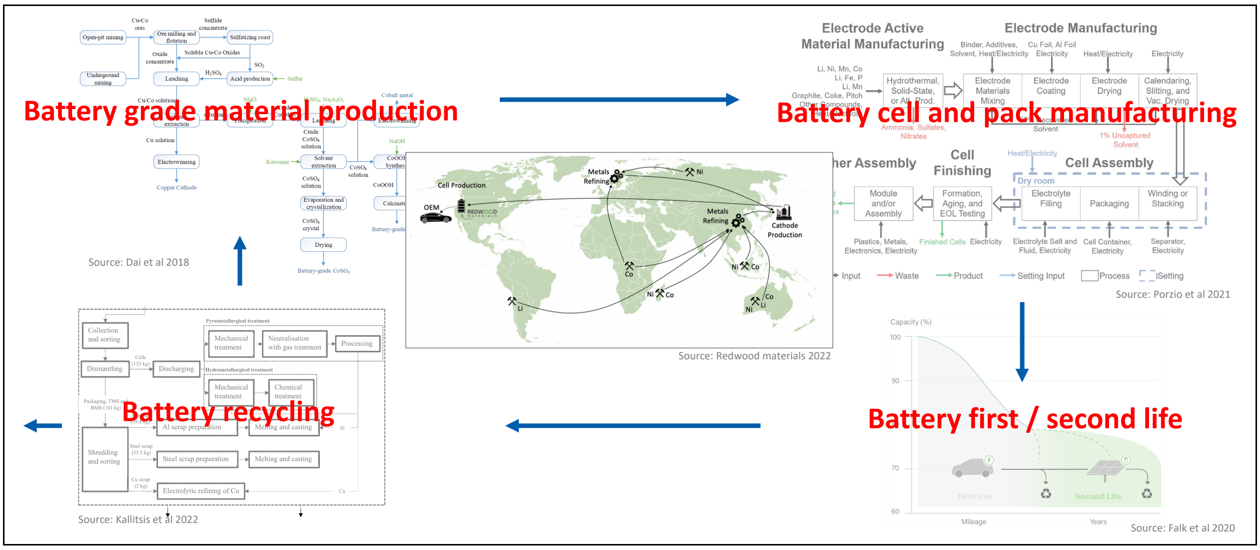
The full NG production process from mine to NG anode material results usually in less than 5% overall yield (based on the content of NG in the deposit and the following processing steps), i.e. is highly waste creating (>95%).

The biggest concern at this point results from the purification of Graphite with inorganic acids, when they are not sufficiently contained. All acids, which are part of the chemical purification process, can cause environmental damages, when exposed. Especially hydrofluoric acid is extremely toxic and dangerous. Thermal purification could be an alternative, at least concerning the direct emissions to water. However, due to the large amount of energy needed, the amount of GHG produced during this process could be even higher (Dolega 2020).

2.4.2 Life Cycle Assessment of EV battery raw materials

The main benefits from replacing vehicles with ICE by EVs arise from the higher efficiency of EVs and from using renewable electricity for driving. However, as already discussed in previous sections, the production of EV batteries causes environmental impacts, therefore the overall benefits of EVs depend on whether the impacts avoided during the use phase of EVs as opposed to ICEVs outweigh the additional impacts resulting from EV battery production. This question can be investigated using the method of Life Cycle Assessment (LCA), which includes the production, the operation, and the end of life (EoL) management of the vehicles and the fuel cycle.

In Task 40 CRM4EV, LCA focused on enhancing the understanding of environmental effects of the battery lifecycle, including battery material production, battery manufacturing and battery end-of-life treatment (Figure 60).



Source: Dai et al 2018

Source: Redwood materials 2022

Source: Porzio et al 2021

Source: Kallitsis et al 2022

Source: Falk et al 2020

Figure 60: Life cycle phases included in battery LCA in Task 40

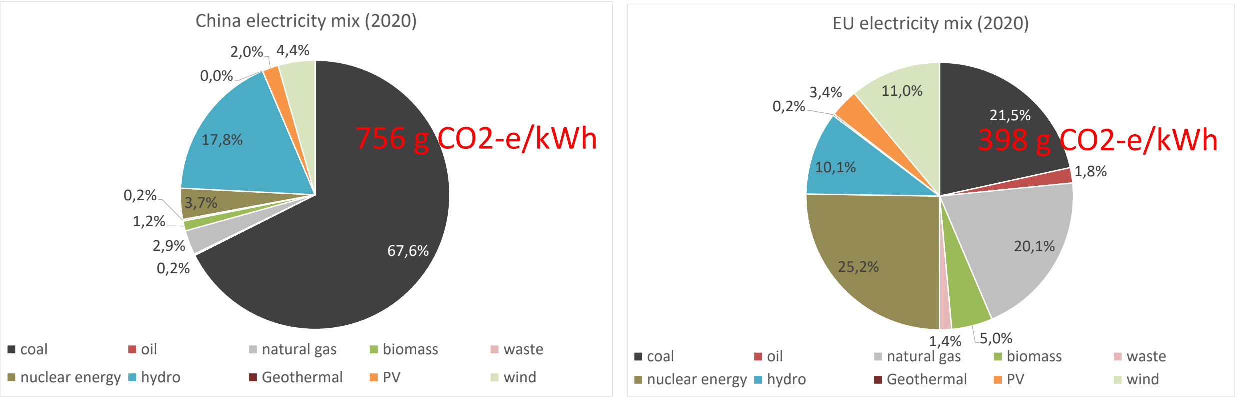
EV battery production is based on many different raw materials, processes and energy carriers in different regions around the globe, as shown in the previous sections, and is a very dynamic field of development of raw material supply, material processing, battery chemistries, battery manufacturing and battery recycling technologies. The challenge for LCA is to collect up-to-date process data covering complex process chains and new technologies in a competitive industrial field, where data access is limited due to non-disclosed industrial data. LCA work therefore benefits a lot from networks like this IEA Task with different stakeholders from research, industry and different regions involved.

The battery LCA model further enhanced in this Task 40 was used to assess the global warming potential of the battery life cycle, to analyse the contributions of battery material production, battery manufacturing and recycling, to show the influence of regions and related electricity supply to processes and to compare different battery chemistries.

The LCA results presented below are based on:

- battery capacity 60 kWh
- battery chemistries: NMC111, NMC811, NCA, LFP; material parameters see section 2.1.3
- regions for production of battery, non-critical battery materials and recycling: China, EU, Norway (each with electricity mix 2020, Norway as a country with almost 100% renewable electricity)
- production of critical raw materials based on global average industrial data (2020)
- energy demand of battery factory: 45 kWh/kWh battery capacity (50% electricity, 50% heat, based on update of GREET model 2022)
- recycling path (hydrometallurgy) for highest material recovery rates. Recycling credits (negative GHG emissions) result from the net sum of GHG emissions due to recycling processes and avoided future production of primary materials.

The specific GHG emissions per kWh electricity in the three regions is shown in Figure 61.



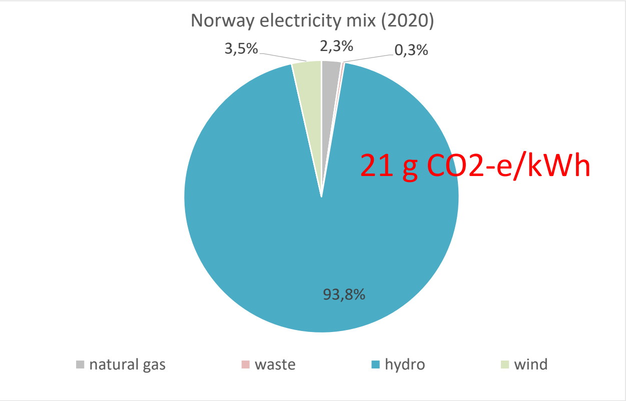


Figure 61: Electricity mix and specific GHG emissions of China, EU and Norway (primary data from IEA statistics)

The following Figure 62 shows the global warming potential (GWP) of the battery life cycle (material production, battery manufacturing and recycling) of the four compared battery chemistries in three different regional settings China, EU and Norway.

Results in Figure 62 show that the overall global warming potential of NMC111 batteries is higher than GWP of high-Nickel as well as LFP batteries. The high-Nickel battery has a GWP about 15% higher than LFP chemistry. Since many of the background data and processes are globally averaged, this difference can readily be reversed when assessing very specific battery life cycles. Results also show that the regional setting considerably influences overall GWP. GWP in China is about 76 to 82% higher than in Norway for all chemistries, with additional reduction potential with increasing the electricity share in overall energy consumption.

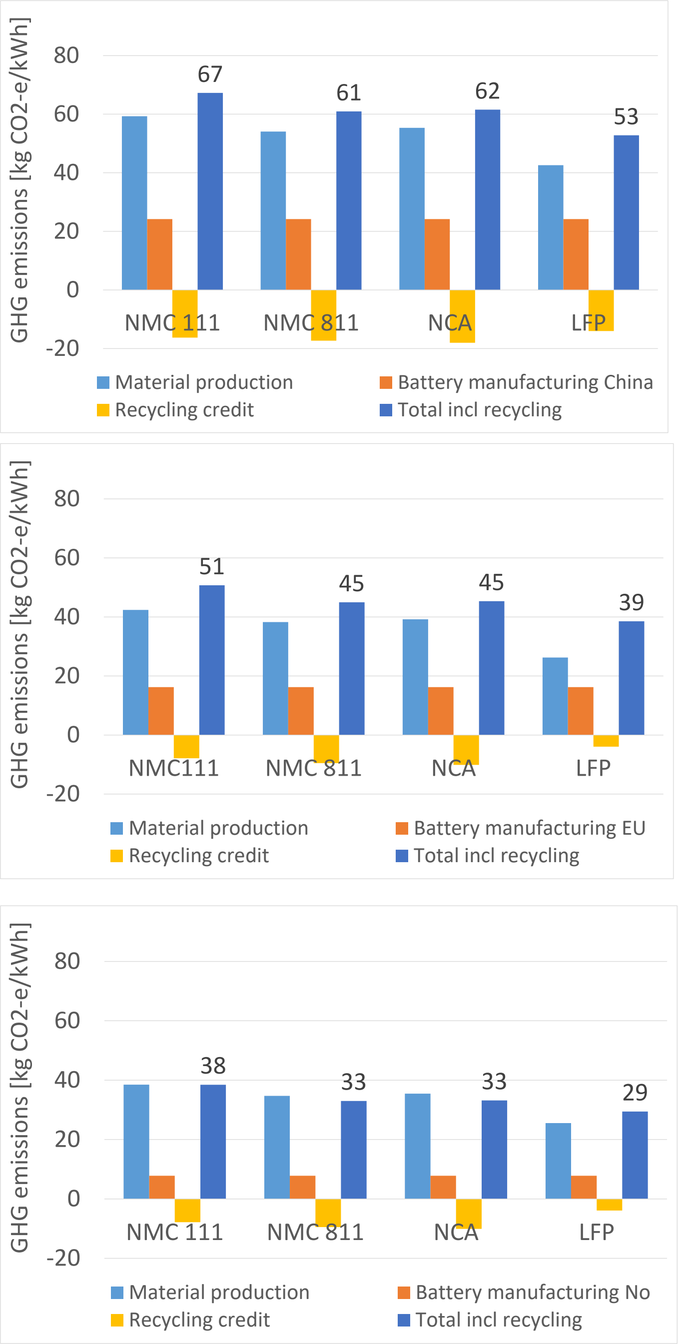


Figure 62: GWP per kWh battery capacity of NMC111, NMC811, NCA and LFP batteries produced in China, EU and Norway

Figure 63 shows the influence of different Nickel sources and regions for Nickel sulfate production, based on the high-Nickel NMC811 battery. According to the Nickel Institute, the specific GHG emissions to produce 1kg of Class-I Nickel are 13 kg CO2-e as a global average and increase to 45 kg CO2-e per kg Nickel if 100% laterite Nickel ores (from SE-Asia) are used. As a third case, Nickel is produced in Finland as the only EU Nickel producing country with about 5 kg CO2-e per kg Nickel. Results show that the GWP of material production with Nickel from laterite ores is about 70% higher than with Nickel from Finland, which is however outbalanced with the recycling credits corresponding to avoided future GHG emissions. Naturally, future avoided emissions due to recycling in more than 10 years from now are subject to higher uncertainty.

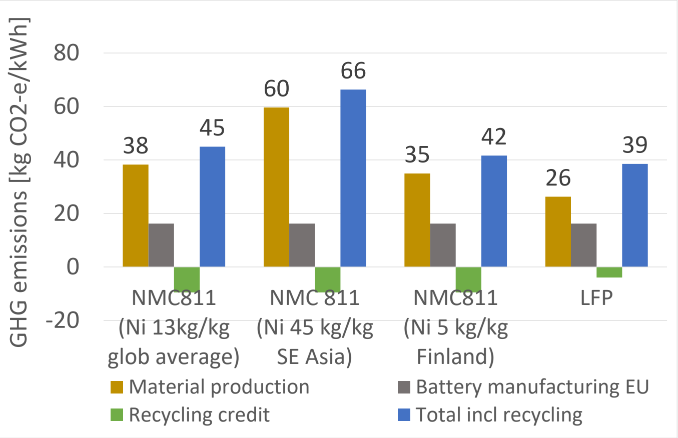


Figure 63: GWP per kWh battery capacity for a NMC811 battery produced in the EU, using Nickel from different sources and regions

2.4.3 Social impacts

The above mentioned impact categories may often proxy the risk of social disruption just as much as they indicate environmental vulnerability. Conflicting use and pollution of water is a frequent cause for resistance of local communities against mining projects, even though mining operators insist that technologies would guarantee sustainable use of water resources and concrete water monitoring plans would already be in place at major mining projects (Luckeneder 2021). Protected areas secure livelihoods and cultural values for many indigenous populations. Public resistance against mining operations may rise due to increased production within and close to protected areas (see section 2.4.1) which points to the need for investigating and monitoring social dynamics around such areas (Luckeneder 2021).

For Nickel social impacts are reported to be higher for lateritic ore mining often located in forest areas such as in SE-Asia. Loss of forest cover, constituent biodiversity, and associated ecosystem services ultimately impacts the livelihoods of local communities dependent on these resources. A second direct impact might include the displacement of forest-dwelling people. Mining roads can encourage major movements of populations into hitherto sparsely populated regions with concurrent increased pressures from land clearing for local consumption. The World Bank has initiated the Smart Forest Mining Project in order to develop guidelines especially for minimizing the impacts of mining in forest areas (World Bank 2019).

Cobalt is mainly extracted in Congo as a country that has to fight with many social issues, which can also be expected in Cobalt mining. Potential risks identified using the social hotspot database (Benoit-Norris & Norris, Gregory, A., 2015) include child labour, forced labour, below minimum wage, poverty, unemployment, low life expectancy, undemourishment, poor sanitation, bad health care, low education, bad governance, corruption, gender inequality and high potential of conflicts occurring in Cobalt mining in Congo. Similar (Murdock et al., 2021) identified Cobalt mining as the most critical raw material extraction process for Lithium-ion batteries. Furthermore, the unprotected exposure to Cobalt in the mines leads to elevated Cobalt levels in the blood and to potential heart, lung and blood complications. This also is relevant for local populations if the waste is not treated properly and reach local water systems and the food supply.

The impacts on water consumption for Lithium production also has negative impacts for local populations. Furthermore, parts of the regional populations have been forced to change location and have been confronted by an increasingly erratic water supply caused by the mining activities. Mining activities in Atacama Desert lead to decline in vegetation, elevating daytime temperature, decreasing soil moisture and increasing drought conditions. But not only negative influences have to be taken into account. Liu and Agusdinata (2020) identified mining activities in this region as an important labour source (although many workers came from other regions decreasing the share of local workers at the mining sites).

Evaluating, challenging and improving this ongoing transition also includes critically reviewing and reforming national environmental regulations. Areas with highest extraction growth rates are, with the exception of Australia, located in low- and middle-income countries of the Global South including Brazil, the DR Congo, India and China. These countries score lower in the OECD Environmental Policy Stringency Index as compared to industrialized countries (OECD, 2021). However, according to this composite measure, nations such as China and India have put significant efforts in improving environmental standards, while the index stagnates at very low levels for Brazil. The Central African Copperbelt also marks a challenging region with substantial room for improvements at the policy and company level.

Social Life Cycle Assessment (s-LCA) is a method under development with the objective to establish a quantified social impact assessment. It applies life cycle assessment methodological steps while having social impacts as focus. The s-LCA in principle follows the ISO 14040 framework and complements the environmental LCA. It has been developed to identify improvement potentials within the system in order to minimize negative social impacts or maximize positive social impacts.

An important achievement in the on-going development of s-LCA was the issuing of the UNEP-SETAC S-LCA Guidelines in 2020 (UNEP, 2020). The Guidelines are the outcome of a broad, global, transparent and open process involving many relevant stakeholders from the public, academic and business sectors and aim at providing a general guidance on the use of s-LCA, facilitating a more uniform performance of this technique.

As for stakeholders, various impact categories can be distinguished. Main categories are: I) Human rights, II) Working conditions, III) Health and Safety, IV) Cultural Heritage, V) Governance, and VI) Socio-economic repercussion. For quantification, the Product Social Impact Life Cycle Assessment database (www.psilca.net) or the Social Hotspot Database (www.socialhotspot.org) use different data sources to estimate the social risk for different subcategories in different labour market sectors in different countries. A literature review on s-LCA performed on batteries in 2022 came to the result that research evidence in this field is still limited (Kramarz et al., 2021), mainly due to missing data distinguishing individual raw materials, regions and impact categories.

2.4.4 Sustainable material sourcing

This section lists selected "good practice" aspects as identified during Task 40 expert workshops with the objective to improve the sustainability performance of critical raw material supply chains.

2.4.4.1 Raw material mining

- Use of underground mining EVs, power optimization, water optimization, zero waste, renewable energy, ventilation on demand (ventilation about 20% of power demand)
- Development of raw material mining processes with focus on resources within the EU, e.g. "raise caving [6]" as novel method for deep mining, development of digital twins and AI for mining planning
- Mining tailings: paste tailings can reduce a mine's environmental footprint by utilising less water compared with liquid tailings. Paste tailings can be used as mine backfill to maintain the structural stability of the mine;

2.4.4.2 Raw material processing and recycling

- Pyrometallurgy: greener reactants such as bio-fuels, bio-char, hydrogen and ammonia in different pyrometallurgical units. Alternatives to carbon-based reduction by use of hydrogen, metallo-reduction as well as inert anode electrometallurgy. Use of renewable energies and valorize residual heat in pyrometallurgical units. Carbon capture and storage/utilization.
- Hydrometallurgy: development of bioleaching processes based on multidisciplinary process involving chemistry, microorganisms, and metallurgy.
- Direct battery recycling: promising solutions to reach a circular economy paradigm in LIB industry

2.4.4.3 Sustainability governance

- Forest smart mining: initiative by the World Bank, focusing on large scale mining projects occurring in forests and on the development of "Forest-smart" approaches to be integrated into regulation governing mining, forests, water, climate, land use planning, and conservation, and integrated land use planning

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[6] https://bergbaukunde.unileoben.ac.at/en/

3 Conclusions

This section summaries the conclusions from the activities in Task 40 CRMEV.

High dynamics of steep increase of global EV fleets in order to reach the climate targets in the transport sector in 2030 pose high challenges to the supply-demand-balance of batteries and critical raw materials assessed in this Task 40, which are Nickel, Cobalt, Lithium, Graphite, Phosphate as well as Rare Earth Elements for electric motors.

Nickel-Cobalt- as well as Lithium-iron-Phosphate battery technologies are expected to remain dominant until 2030, new technologies like sodium-ion or solid-state-batteries will gain increased market shares post 2030. Lithium-iron-Phosphate batteries offer a way out of potential deficits in Nickel and Cobalt supply.

Scenarios of global EV fleet development result in 3,000 to 4,300 GWh battery capacity demand in 2030, which is 5 to 8 times more than the battery sales in 2022. Global battery production capacities in 2022 have been 1,500 GWh, which would need to increase 2- to 3-fold until 2030. In Europe, however, production capacities would need to increase 30-fold from 35 to 1,300 GWh, which is a real upscaling challenge. Within the EU, the first LFP battery production starts operation in 2023.

Critical raw material demand for EVs will follow a steep increase until 2030, depending on the market shares of the high-Nickel-Cobalt- and zero-Nickel-Cobalt-chemistries. A high share of high-Nickel-Cobalt batteries would result in a supply deficit of Nickel, Cobalt. Both scenarios likely result in Lithium and Graphite supply deficits. Graphite has the potential to be substituted by synthetic Graphite, however at the cost of increasing energy demand and associated GHG emissions. Phosphate in Lithium-iron-Phosphate batteries will not result in a supply deficit from a global perspective. Rare earth elements as magnetic metals have the potential to be substituted by use of non-permanent-magnet inductive EV motors not relying on REE.

Battery recycling is a central element of critical raw material supply, especially in Europe. Hydrometallurgy is the most likely technology enable a circular economy in this field. Large-scale NMC-recycling plants can be expected to be in place in late 2020s, large-scale LFP-recycling can be expected to be in place later than 2030, due to economic reasons with less valuable materials to be recovered.

Battery LCA identifies the most relevant life cycle phases and processes influencing the greenhouse gas emissions of the battery life cycle. These are the production of battery cell cathode and anode materials, the production of module and pack material (especially if made of aluminum), the energy demand and mix for cell production and the metallurgical technology and energy demand and energy mix for recycling.

4 Outlook and recommendations

This section concludes with recommendations for future demand in supporting / funding Austrian and EU research and development in the areas of battery recycling, battery cell development and life cycle assessment.

Battery recycling will most likely rely on hydrometallurgical technologies combined with battery pretreatment. Besides direct recycling, this is the only technology able to support the development of a closed loop use of battery critical raw materials and thus to reduce the geopolitical import dependence of the EU. However efficient hydrometallurgy is complex, especially when confronted with a diverse mix of battery types and chemistries as input materials. Austria has research institutions as well as industries with a profound expertise in metallurgical processes, which should be used also for further developing battery recycling technologies. Austria has a strong position in engineering services, but also in plant engineering both in the metal industry and the waste recycling branch.

Battery research needs to focus on technologies with reduced or zero demand in critical raw materials. Due to chemical and physical material properties, this comes along with reduced energy capacities compared to “close-to-ideal” materials. In terms of raw material supply a diverse portfolio of battery chemistries with different properties for different vehicle classes and applications will reduce the risk of supply deficits and geopolitical dependencies. One of the chemistries requiring significant research efforts is the sodium-ion technology. Although some first battery factories are starting production, there are still research questions to be solved.

Life Cycle Assessment is the method to assess complex technology systems in relation to their potential contribution to the “climate neutrality” challenge in the public and political agenda. One of the research areas in the LCA community is to better consider and model the dynamics of the transition of global economics within the short timeframe of 20 to 30 years. A second research area is to further develop the LCA method to integrate a circularity index to better assess the circularity potential of products and services.

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