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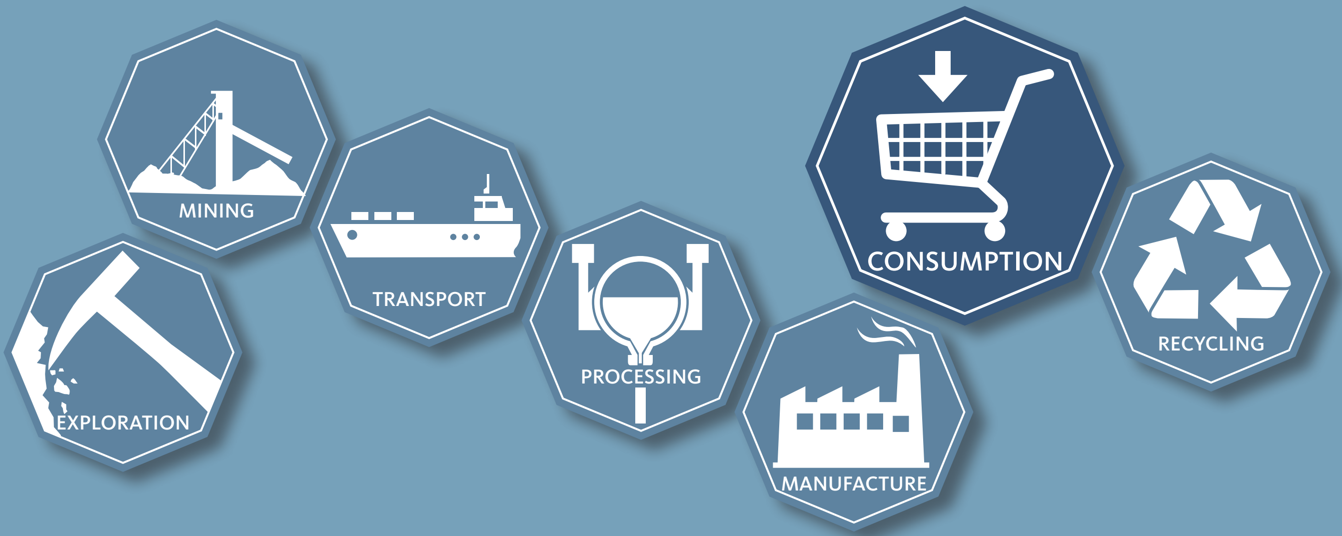
MiMa rapport 2023/3



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G E U S

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Content

Executive summary

Battery technology has emerged as a crucial element in realizing the clean energy transition and reducing the energy sector's dependence on fossil fuels. Governments worldwide are recognizing the importance of energy storage and are investing significant sums in relevant industries to enable the widespread adoption of renewable energy sources and reduce greenhouse gas emissions. However, implementation of complete decarbonization in all sectors presents a challenge that will likely boost the demand for batteries dramatically in the short term. This could result in shortages of some battery materials in the coming years, particularly cobalt and lithium, which are two critical components used in lithium-ion batteries (LIB), the most widely used type of batteries in electric vehicles and energy storage systems.

This report analyses the risk assessment of cobalt and lithium, using the Materials Flow Analysis (MFA) method in 2019 as this is the latest year with available data not affected by the COVID-19 pandemic. The entire value chains of both cobalt and lithium, from mineral exploration to waste management at the global level, are taken into consideration. Further, multiple scenarios for the supply and demand of cobalt and lithium in year 2030 are also collected from various sources to predict the risk for supply distortions with time. Finally, this report evaluates the progress of emerging battery technologies and their potential to compete with LIB technology.

The results of this report show that many new advanced battery technologies are under development worldwide, such as solid-state batteries, sodium-ion batteries, lithium-sulphur batteries, lithium-air batteries. However, none of these technologies are expected to be adopted by the market at an important scale before 2030. Lithium-ion batteries will still be the dominant technology in use during the next decade. Lithium as a crucial constituent cannot be substituted by 2030, whereas cathode materials with less or no cobalt are expected to be the new tendency.

Cobalt and lithium occur in many different minerals and geological environments found in many parts of the world. Large geological resources exist for both lithium and cobalt with estimated resources of 63 million tons and 25 million tons, respectively. The geological reserves, the part of geological resources that can be economically extracted, was estimated by USGS to be 17 million tons for lithium and 6.5 million tons for cobalt. In comparison the global production of lithium and cobalt from mining in 2019 was approximately 88,000 tons and 144,000 tons, respectively. Even with considerable growth in demand, abundant resources exit globally but the current reserves are highly concentrated in a few countries, with cobalt primarily found in the Democratic Republic of Congo (DRC) and lithium in South American countries as well as Australia.

As of 2019, the global demand for both lithium and cobalt were matched by supply, but the supply chains for both materials are highly concentrated. The DRC accounts for 69% of cobalt mining supply, while Australia and Chile provide around 80% of the world's lithium supply from mining. China plays a significant role in refining production, accounting for more than half of both cobalt and lithium refining. Eastern Asian countries dominate the cathode materials and cell production. Although there are some predictions of change, the situation is not expected to change significantly by 2030. Australia is expected to contribute more to the cobalt mine supply by 2030, while South American countries are expected to increase their share of lithium supply from mining significantly. However, China is still expected to dominate both cobalt and lithium processing. China, Japan, and South Korea are currently the dominant players in the production of batteries and cathode materials, and it is expected that they will keep this position by 2030. Although the European Union (EU) and the United States (USA) have set ambitious goals to increase their production capacities for batteries and cathode materials and have launched related regulations to invest in the battery industry, it may take some time for these efforts to yield significant results. Both EU and USA will likely still need to rely on imports from Eastern Asian countries to meet their battery needs by 2030.

This concentration of reserves raises concerns about supply security, leading main cobalt and lithium consuming countries to mitigate supply risk through foreign direct investments in overseas ownership. Foreign direct investments can occur at any stage of the supply chain, but they are currently more common at the mining stage. This allows investing countries to control a portion of the mining operations and secure their access to the minerals they need. However, this strategy is not without controversy, as it also raises concerns about resource exploitation and social and environmental impacts.

The markets for cobalt and lithium are dominated by a relatively small number of companies. In both cases, the top 10 companies control around 80% of the market share for mining and refining production. This concentration of production highlights the importance of these companies in global supply chains, as well as the potential risks associated with supply disruptions or changes in market conditions. Vertical integration is a common feature of both the cobalt and lithium supply chains. Upstream companies, such as mining and refining companies, expand into downstream activities, such as cathode or cell production, to add more value to their businesses. Downstream companies, such as battery manufacturers or automotive companies, invest in mining or refining operations to secure a reliable supply of raw materials through backward integration. However, both forward and backward integration require significant capital investment and management expertise in multiple areas of the value chain. Companies must carefully weight the benefits and costs of vertical integration when deciding whether to pursue this strategy.

Due to the increase in the need for lithium-ion batteries used in electric vehicles and stationary energy storage, the demand for both cobalt and lithium is expected to soar in the next decades. The exact increase in demand for these metals is uncertain, but multiple commercial reports suggest that there may be a deficit in the supplies of both cobalt and lithium by 2030. This potential shortage could pose a significant challenge to the global effort to transition to a more sustainable, green energy system.

To abate potential supply bottlenecks, urgent investment action is needed though the whole supply chain for both cobalt and lithium. This is particularly important at the mining stage as developing new mines and increasing production takes several years, typically 7-10 years and in some case up to 15 years. It is crucial that investments are made as soon as possible to prevent shortages in the future. Expanding refining capacities is also important, but it is not as urgent as investing in mining. Refineries can be built, and reach production faster than mines, meaning that this aspect of the supply chain can be addressed gradually since changes can be implemented more quickly.

Recycling is another important way to increase the supply of cobalt and lithium and to lower these metals' future supply risk of these metals. Recycling of lithium-ion batteries can be done locally and may thus reduce dependence on primary sources which may be particularly important for countries or regions where these metals have little or relatively low endowment and resource potential. The amount of cobalt and lithium that can be recovered through recycling is increasing as the number of retracted batteries grows. Recycled batteries could provide up to 10% of the global demand for cobalt in 2030 under the most positive scenario, presenting an opportunity to reduce dependence on primary sources. In contrast, the amount of lithium recovered from secondary source is currently negligible, but it is likely to increase significantly as a result of improved recycling technologies and more stringent environment regulations. For both metals, efforts are needed to increase the scale and efficiency of battery recycling operations, which requires companies and governments to invest in new technologies and infrastructure.

An open and transparent international trading system is essential for securing global supply chains for cobalt and lithium. The need for such a system is even more critical during times of crisis, such as the COVID-19 pandemic and the ongoing Russia-Ukraine war. These crises have disrupted supply chains and made it more challenging to access cobalt and lithium, highlighting the importance of having a secure and stable supply chain that can withstand unexpected challenges. Coordinated efforts throughout the supply chain are necessary to ensure the continued availability of cobalt and lithium. This requires collaboration between countries and companies involved in mining, refining, manufacturing, and end-use production. Governments can play a crucial role in facilitating such efforts by promoting international cooperation and creating a regulatory framework that supports open and transparent trade.

In addition to international coordination, efforts are required to ensure the responsible sourcing of cobalt and lithium. This includes implementing ethical and sustainable mining practices, protecting the rights of workers and communities, and minimizing environmental impact. Such efforts can help to build trust in the supply chain and ensure the continued availability of critical metals in the long term.

Overall, securing the supply chains for cobalt and lithium requires a multifaceted approach that involves investing in primary sources, developing secondary sources, evolving battery technologies, practicing responsible sourcing, and promoting transparency and openness in the international trade system. With such efforts, the clean energy transition can continue to grow and thrive, paving the way for a more sustainable and low-carbon future.

Abbreviations

APAC	Asia-Pacific
ASM	Artisanal and Small-scale Mining
BAIC	Beijing Automotive Group Co. Ltd
BCG	Boston Consulting Group
BGR	German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)
BGS	British Geological Survey
BMI	Benchmark Mineral Intelligence
BMLRT	Federal Ministry of Agriculture, Regions, and Tourism, Austria
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
CACB	Central African Copper Belt
CAGR	Compound Annual Growth Rate
CATL	Contemporary Amperex Technology Co., Limited
CCD	Counter-Current Decantation
CE	Consumer Electronic
CES	Circular Energy System
CGS	China Geological Survey
COP	Conference of Parties
COVID-19	Coronavirus disease 2019
CTT	Compagnie de Tifnout Tighanimine
DEC	Diethyl Carbonate
DERA	German Mineral Resources Agency (Deutsche Rohstoffagentur) at the BGR
DMC	Dimethyl Carbonate
DoD	Depth of Discharge
DRC	Democratic Republic of the Congo
EC	European Commission
ECA	Ethylene Carbonate
EDLC	Electric Double-Layer Capacitor
EMC	Ethyl Methyl Carbonate
EOL	End-of-Life
EOL-RR	End-of-Life Recycling Rate
ESG	Environmental, Social and Governance
EU	European Union
EUROBAT	Association of European Automotive and Industrial Battery Manufacturers
EV	Electric Vehicle
EW	Electro-Winning
GHG	Greenhouse Gas
GSI	Goldman Sachs International
HEV	Hybrid Electric Vehicle
HPAL	High Pressure Acid Leaching
HS code	Harmonized System Code
IEA	International Energy Agency
IOCG	Iron-Oxide Cu-Au Deposits
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCE	Lithium Carbonate Equivalent
LCO	Lithium Cobalt Oxide
LCT	Lithium-Caesium-Tantalum

LFP	Lithium Iron Phosphate
LTO	Lithium Titanium Oxide
LIB	Lithium-ion Battery
LMO	Lithium Manganese Oxide
LNMO	Lithium Nickel Manganese Spinel
METI	Ministry of Economy, Trade and Industry, Japan
MFA	Material Flow Analysis
MHP	Mixed Hydroxide Precipitate
MRDC	Mineral Resources Development Company
MVT	Mississippi-Valley Type Deposits
NCA	Nickel Cobalt Aluminium
NCM	Nickel Cobalt Manganese
NGO	Non-Governmental Organisation
PGMs	Platinum Group Metals
NIO	Nio Inc.
NMC	Nickel Manganese Cobalt
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturers
PC	Propylene Carbonate
PEO	Polyethylene Oxide
PET	Polyethylene Terephthalate
PGE	Platinum Group Element
PHEV	Plug-in Hybrid Electric Vehicles
PNG	Papua New Guinea
QR-code	Quick Response Code
RMI	Responsible Minerals Initiative
RoW	Rest of the World
SD	Sustainable Development
SSE	Solid-state Electrolyte
SEI	Solid Electrolyte Interface
SoC	State-of-Charge
SoH	State-of-Health
SQM	Salar de Atacama
SSB	Solid-State Battery
STEP	Stated Policies
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USGS	United States Geological Survey
V	Volt
VMS	Volcanogenic Massive Sulphides
WGI	World Governance Indicators

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1. Introduction

In 2015, around 196 parties signed the Paris Agreement at the COP 21 (Conference of Parties 21). This agreement is a legally binding international treaty on climate change with the goal of limiting global warming to well below 2°C, preferably to 1.5°C, compared to preindustrial levels (van Vuuren *et al.* 2018; United Nations Climate Change 2022). To reach this long-term temperature goal, countries aim for a global peak in greenhouse gas (GHG) emissions as soon as possible to achieve a climate neutral world by 2050. Decarbonization in every sector of the world's economy is needed but some sectors should be prioritized because of their larger emissions of GHG, contributing to climate change. One of the sectors with high GHG emissions is transportation, which in 2019 had the largest contribution to the total GHG emissions in both the European Union (EU) and the United States of America (USA), with a share of 27% and 28%, respectively (Epa *et al.* 2021; European Environment Agency 2021). Within the transportation sector, road transport has by far the largest share of GHG emissions. Therefore, electric mobility (especially electric vehicles) is being promoted around the world to reduce the environmental impact of transportation (Melton *et al.* 2016; Hao *et al.* 2019).

The energy sector is another significant contributor to global GHG emissions (US Environmental Protection Agency 2022a). Currently, the global energy supply depends mainly on fossil fuel combustion (International Energy Agency 2022), which is the largest source of GHG emission in this sector; even though only 24% of the electricity generated in 2019 in USA was from coal combustion, it accounted for about 61% of the GHG emissions (US Environmental Protection Agency 2022b). The ambition of many countries is to build climate-neutral energy systems, which use renewable energy instead of carbon intensive fossil fuels. An efficient, battery-based, energy storage system is crucial for the success of these ambitions (Kittner *et al*. 2017).

Battery technology is widely accepted as the best way to realize the clean energy transition and liberate the energy sector from its dependence on fossil fuel (Lebedeva *et al.* 2016; Petavratzi 2017). Governments around the world are recognizing the importance of developing battery technologies and are investing large sums in relevant industries. For example, the European Commission (EC) identified the battery value chain as a strategic element to achieve the EU's goals for climate neutrality and competitiveness of the EU industry (European Commission 2018), and the implementation of complete decarbonization in all the sectors presents a challenge that most likely will boost the demand for batteries dramatically in the short term. This might result in shortages in some battery materials in the coming years, particularly cobalt and lithium. Both of these elements, which are the topics of this report, are identified as critical and strategic raw materials by many countries and regions, due to their potential supply risks and high importance for the clean energy transition (National Development and Reform Commission of P.R.C. 2016; Mudd *et al.* 2018; Blengini *et al.* 2020; Executive Office of the president 2020; Ministry of Economy, Trade and Industry 2020; European Commission 2023). Obviously, it is important to identify and monitor possible weak links in the supply chains, but also to gain insight into environmental and social issues related to the production of cobalt and lithium. However, it is important to note that the latter point regarding the environmental and social issues is not the main focus of this report due to insufficient data.

1.1 Objectives

Objectives of this study are:

i) to provide detailed geographically explicit data on the cobalt and lithium supply chains and to evaluate possible supply risks;

ii) to predict future cobalt and lithium demand under different scenarios in 2030, especially as driven by advanced battery technology development;

iii) to identify existing and potential capacities for cobalt and lithium supply from primary sources globally and discuss the key drivers and framework conditions necessary to realize those capacities;

iv) to analyse the potential role of recycling in mitigating the supply-demand gap and identify solutions for moving towards greater circularity in the coming years, and

v) to provide recommendations for actions and material strategies based on company and country levels to secure their supplies of cobalt and lithium.

1.2 Methodology and database

1.2.1 Methods

Material flow analysis (MFA) is a tool for quantifying flows and stocks of materials or substances in a system during a defined period of time (Liu 2014; Brunner & Rechberger 2017). The principle of MFA is based on the 'Law of Conservation of Mass', therefore input, output, and trade that flows together with stocks of materials are quantified using the mass balance rules (Brunner & Rechberger 2017; Petavratzi & Josso 2021). Material flow analysis is a common method used to understand and monitor value chains and its results can be utilized in decision making and for strategy development associated with sustainable resource use, and it is therefore adopted for the present analysis.

In this report, the materials are cobalt and lithium, the period is 2019, and the boundary is the world in general, but in some cases, a selected region, such as the EU is also analysed. 2019 is selected because it is the most recent year with sufficient data and excludes the effect of the COVID-19 pandemic. Substance flows are calculated based on the mass flows of goods (ore, minerals, chemicals, etc.) and substance concentrations (cobalt or lithium concentration) in these goods, mainly expressed in tons per year (tons/y) unless otherwise specified. Source data were obtained from literature, estimations, measurements, or calculations, as detailed in Section 1.2.2. The entire value chains of both cobalt and lithium, from extraction to waste management, are analysed.

1.2.2 Data source

Several types of data are used in this report. Historical data from 2019 are used mainly in Chapter 3 and 4, whereas prediction data for 2030 are used mainly in Chapter 5. By scale, there are data at mine, plant, company, and country level. By content, there are production (supply), consumption (demand), and trade data.

Production and consumption data at country level for 2019 for both cobalt and lithium are mainly based on data from United States Geological Survey (USGS), but compared with data from other official sources, such as the British Geological Survey (BGS), German Federal Institute for

Geosciences and Natural Resources (BGR), Federal Ministry of Agriculture, Regions, and Tourism, Austria (BMLRT), China Geological Survey (CGS), etc. Production and consumption data at mine, plant, and company level for 2019 together with future prediction data for 2030 on supply and demand are mainly based on commercial consultant reports from Benchmark Mineral Intelligence (BMI), in addition to annual reports from major companies and consulting reports from other commercial companies such as Roskill, Bloomberg NEF (BNEF), Fastmarket, Boston Consulting Group (BCG), McKinsey, Roland Berger, etc. Data may also be collected from associations (e.g., Cobalt Institute and International Energy Agency (IEA)), published literature, media articles, conference presentations and interviews. Historical as well as prediction data on recycling are extremely limited and are mainly based on estimates from Circular Energy System (CES), EU Joint Research Centre (JRC) and the International Energy Agency (IEA), with the implementation from published literature, companies' roadmaps, and commercial reports.

The trade flows of cobalt and lithium are mapped with trade data mainly from United Nations (UN) Comtrade ("Welcome to the new and enhanced UN Comtrade," 2022), with Statista as a complement. The data as reported by import countries are often different from those reported by export countries. In this report we mainly use the import data, which is believed to be more reliable since imports usually generate tariff revenues while exports do not (World Bank 2010). Trade codes for both cobalt and lithium are taken from published literature, and assumptions are made regarding the cobalt or lithium content in these codes if the information is not available. To avoid complexity, only flows above a given number are analysed, such as flows of more than 100 tons when considering international trade on cobalt ores. For some flows it was not possible to differentiate Europe from the EU. In such cases, "Europe" is assumed to be equal to EU.

In some instances, it was not possible to gather statistics for 2019 or predictions for 2030, here growth rates from earlier reported years were used. Due to complexity in the value chain, lack of trade and production data and confidentiality aspects, several assumptions along the value chain are made; this might result in some uncertainties.

1.3 Structure of the report

This report is structured into seven chapters. Chapter 2 reviews relevant literature on basic battery knowledge and highlights the cutting-edge lithium-ion battery (LIB) technologies. In Chapter 3 and 4 the results of material flow analysis through the complete value chain from extraction to waste management for cobalt and lithium, respectively, are presented. Chapter 5 outlines the predictions of global future demand and supply for both cobalt and lithium by different companies and organisations and analyses the possible potential risks for the two commodities. Chapter 6 discusses the opportunities and challenges with respect to future cobalt and lithium supply and assesses potential actions and strategies to secure battery raw materials supply. Chapter 7 concludes the analysis, listing the findings and their implications for the clean energy transition and for meeting the goal of the Paris Agreement.

2. Battery overview

A battery is a device consisting of one or more electrochemical cells with external connections for converting its chemical energy into electrical energy used to power electrical devices such as flashlights, cell phones, and electric vehicles (Battery University 2021). A typical battery cell is made up of three basic components: an anode, a cathode, and an electrolyte. A separator is often used to prevent the anode and cathode from touching if the electrolyte is not sufficient. When a battery is supplying electric power, the positive terminal is the cathode, and the negative terminal is the anode. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load, a redox reaction converts high-energy reactants to lower-energy products, and the free-energy difference is delivered to the external circuit as electrical energy (Bates 2019).

2.1 Battery history

A series of inventions lead to the battery as we know it today. Figure 2-1 shows the historical timeline of the battery and the most important developments on commercialisation of the batteries (Ups Battery Center 2021).

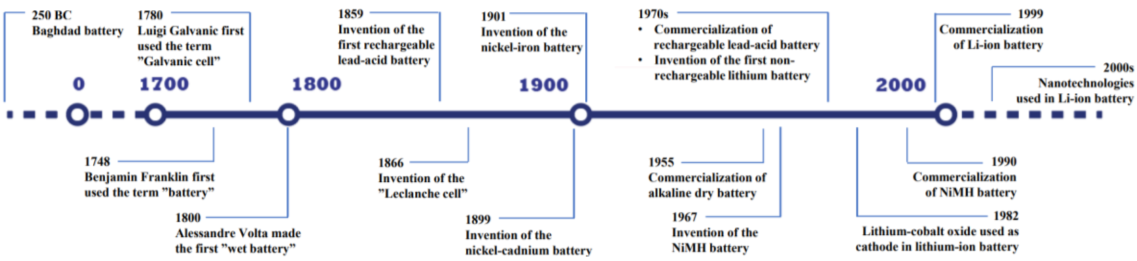


Figure 2-1 *History of the batteries based on Ups Battery Center (2021).*

The earliest use of batteries by humans may possibly be traced back to the "Baghdad battery" more than 2,000 years ago. Analysis has dated it around 250 BC and of Mesopotamian origin (Eggert 1995). It should, however, be noted that it is disputed if the "Baghdad battery" is really a battery or not.

American scientist and inventor Benjamin Franklin first used the term "battery" in 1748 when he was doing experiments with electricity using a set of linked capacitors. In 1780, Luigi Galvani firstly used "Galvanic cell" to describe "animal electricity" when he created an electrical current through a frog (Heth 2019).

The first true battery was invented by the Italian physicist Alessandro Volta in 1800. Volta stacked discs of copper (Cu) and zinc (Zn) separated by cloth soaked in salty water, this battery is also called a "wet battery" or "Voltaic cell". John Frederic Daniell invented the "Daniell cell" in 1836 to solve the electrolyte leaking problem existing in Voltaic cell, and William Robert Grove developed in 1844 the "Grove cell" based on the Daniell cell (Heth 2019; Tang 2022).

In 1859, Gaston Plant invented the first rechargeable lead-acid battery. In 1881, Camille Fauer improved the technology and increased the capacity of the lead-acid battery. The development of modern lead-acid batteries in the mid-1970s and their wide application in production and life are of great significance (Heth 2019; Tang 2022).

In 1866, Georges Leclanche invented a new battery cell with zinc as the anode, manganese dioxide as the cathode, and ammonium chloride as the electrolyte. This battery cell could provide a voltage of 1.4 volt and was named “Leclanche cell”. The chemistry of this cell was later successfully adapted by Carl Gassner in 1886 who manufactured a dry cell, which could provide 1.5 volt. On this basis, zinc-carbon batteries were successively developed later.

In 1899, the Swedish scientist Waldemar Jungner invented a rechargeable nickel-cadmium battery (Ni-Cd battery), a rechargeable battery that has nickel and cadmium electrodes in a potassium hydroxide solution; the first battery to use an alkaline electrolyte, which in turn gives it the capability to produce better energy density than the lead-acid battery. Based on this technology, a sealed Ni-Cd battery was developed in 1947, which has been widely used as a portable energy source until today (Whittingham 2012; Heth 2019).

Jungner patented a nickel-iron battery in 1899 as well. Thomas Edison modified his design in 1901 and produced a more reliable and powerful model 7 years later, which achieved great success in applications such as electric and diesel-electric rail vehicles, providing backup power for railroad crossing signals, or to provide power for the lamps used in e.g. mines (Whittingham 2012; Heth 2019).

In 1955, the modern alkaline dry battery was invented by the Canadian engineer Lewis Urry, using zinc as the negative electrode (or anode), manganese dioxide as the positive electrode (or cathode), and potassium hydroxide as electrolyte, and the alkaline battery became the most commonly used type of primary (i.e., non-rechargeable) batteries. Because these battery anode materials all use zinc metal, this type of battery is called “zinc-based battery” (Heth 2019; Tang 2022).

Work on rechargeable nickel-metal-hydride batteries (NiMH battery) began at the Battelle-Geneva Research Centre following the technology’s invention in 1967. The chemical reaction at the positive electrode is similar to that of the Ni-Cd cell as both use nickel-oxide-hydroxide (NiOOH). However, the negative electrodes use a hydrogen-absorbing alloy instead of cadmium. NiMH batteries can have two to three times the capacity of Ni-Cd batteries of the same size. In 1987, Willens and Buschow incorporated rare earth element metals for the negative electrode, and this design became the basis for modern NiMH cells. The first consumer-grade NiMH cells were commercially available in 1990 and dominated the portable rechargeable battery market until recently where they have mostly been replaced by lithium-ion batteries (LIBs), which has developed rapidly over the last decades (Whittingham 2012; Heth 2019).

The nickel-hydrogen battery (NiH_2 battery) was patented by Alexandr Ilich Kloss and Boris Ioselevich Tsenter in 1971. NiH_2 cells using 26% potassium hydroxide as an electrolyte have shown a service life of 15 years or more, which makes them attractive for the energy storage of electrical energy in satellites and space probes (Whittingham 2012).

Pioneering work of the lithium battery began in 1912 under G.N. Lewis, but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available.

Attempts to develop rechargeable lithium batteries followed in the 1980s but failed because of instabilities in the metallic lithium used as anode material. The inherent instability of lithium metal, especially during charging, shifted research to a non-metallic solution using lithium ions. In 1972, Stan Whittingham found lithium ions could be stored in spaces in the titanium disulphide in the cathode (Bartholome *et al.* 2010). John Goodenough improved the cathode materials by using lithium-cobalt oxide and it resulted in powerful, high-capacity lithium batteries in 1982. In 1999, Akira Yoshino developed a functional rechargeable battery by using Goodenough's lithium-cobalt oxide as the cathode and various carbon-based materials as the anode, which was the first commercially viable lithium-ion (Li-ion) battery, leading to a revolution in rechargeable batterie. In 2019, the outstanding contributions of three individuals to the development of lithium-ion batteries earned them the prestigious Nobel Prize. Nanotechnologies brought this best commercial battery to the next level in the new century, where it now sees the most attention and dominates the battery world (Nitta *et al.* 2015).

To summarise, the most common battery systems are based on lithium, lead, zinc, and nickel. Figure 2-2 illustrates the 2019 market distribution in terms of revenues of the different battery systems (Zhao *et al.* 2021). Around 73% of the revenue share comes from rechargeable battery systems, including 51% of Li-ion battery, 15% lead-acid battery, 5% nickel-based batteries and others. The primary battery category accounts for the rest 27% of the revenue share, with the alkaline battery being the predominant type within this group (Market Research Future 2020).

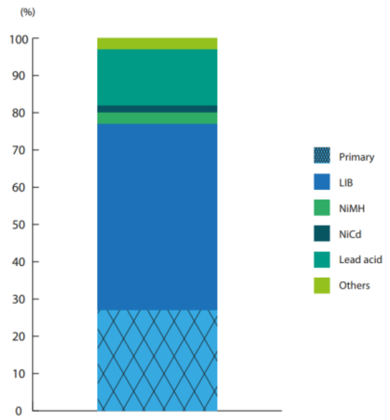


Figure 2-2 *Revenue contributions by different battery chemistries (Source: Market Research Future 2020; Zhao et al. 2021)*

2.2 Battery characteristics

Various characteristics can be used to classify battery technologies. Some of them are described below.

1. The gravimetric power density (also called the specific power density) and the volumetric power density are among the most important parameters for batteries. The gravimetric power density is the nominal battery power per unit mass (W/kg), and the volumetric power density is the nominal battery energy per unit volume (W/l). Those parameters determine the battery's weight or size required to achieve a given performance. High values usually imply a low electrical resistance, resulting in low energy losses and high-power capability.

2. The gravimetric energy density (also called the specific energy density) and the volumetric energy density are important as well. The gravimetric energy density is a measure of how much energy a battery contains in comparison to its weight and is typically expressed in Watt-hours per unit mass (Wh/kg). The volumetric energy density is a measure of how much energy a battery contains in comparison to its volume and is typically expressed in Watt-hours per unit volume (Wh/l). Along with the energy consumption, those parameters determine the battery's weight or size required to achieve a given electric range. Products requiring long runtimes at moderate load are optimized for high specific energy; the ability to deliver high current loads can be ignored. Each technology and each battery is designed following a trade-off between energy and power density (Lain *et al.* 2019). The theoretical gravimetric energy density can be calculated from the main electrochemical reaction. The realistic value is usually 25-50% of the theoretical value (Woodbank Communications Ltd. 2021) .
3. Battery capacity is a measure (typically in Ah) of the charge stored by the battery and is determined by the mass of active material contained in the battery. The battery capacity represents the maximum amount of energy that can be extracted from the battery under certain specified conditions. However, the actual energy storage capabilities of the battery can vary significantly from the "nominal" rated capacity, as the battery capacity depends strongly on the age, past history of the battery, the charging or discharging regimes of the battery and the temperature.
4. Battery energy efficiency is the ratio of the discharged energy to the charged energy. Energy losses are transformed into heat and must be removed to avoid overheating of the batteries.
5. The calendar lifetime describes the battery lifetime until failure if the battery is not used. Higher temperatures accelerate the ageing process. Many high-performance batteries in standard vehicles will probably die because of calendrical ageing rather than because of the capacity turnover (Budde-Meiwes *et al.* 2013).
6. The cycle lifetime describes how many cycles the battery can perform until it fails. For a rechargeable battery, it is defined as the number of charges or recharge cycles a secondary battery can perform before its capacity falls to 80% of the initial capacity. This is typically between 500 and 1,200 cycles (Simpson, n.d.). The cycle lifetime depends on the cycle depth, current rate, and average state-of-charge (SoC). The capacity turn-over is measured in full equivalent cycles.
7. The battery voltage is determined by the chemical reactions in the battery, the concentrations of the battery components, and the polarization of the battery. The voltage calculated from equilibrium conditions is typically known as the nominal battery voltage. In practice, the nominal battery voltage cannot be readily measured, but for practical battery systems (in which the over voltages and non-ideal effects are low) the open circuit voltage is a good approximation of the nominal battery voltage.
8. Self-discharge refers to the fact that even in the absence of a connected load, the discharge reaction will proceed to a limited extent and the battery will therefore discharge itself over time. The rate of self-discharge depends primarily on the materials involved in the chemical reaction (i.e., the type of battery system) and on the temperature of the battery.
9. Battery state-of-charge (SoC) gives the ratio of the amount of energy presently stored in the battery to the nominal rated capacity. A common way to measure the SoC is to measure the voltage of the battery and compare this to the voltage of a fully charged battery. However, as the battery voltage depends on temperature as well, this only provides a rough idea of the battery state-of-charge.

10. Cost is also relevant for choosing a battery system. However, the cost strongly depends on the specific requirements and the quality of the battery.

There are many other parameters, such as safety, toxicity, depth of discharge (DoD), that are also important. The global battery market consists of multiple applications of battery technologies with slightly different needs and requirements, which leads to each being best served by specific technologies with various key parameters.

2.3 Battery types used in automotive industry

The global battery market is currently segmented into automotive, consumer electronics, energy storage systems, industry, and others. Depending on which application the battery is intended for, some parameters are more important than others. For example, to assess if a battery is viable as an electric storage device in electric vehicles (EVs), six basic requirements are considered, and the battery is fittingly called the hexagon battery (Liu *et al.* 2019):

- High specific power density
- High specific energy density
- Long cycle lifetime
- Cost and commercial maturity
- Battery safety
- Durability (e.g., high-temperature durability)

There are mainly four types of batteries which can meet the requirements for EVs: lead-acid (Pb), nickel-cadmium (Ni-Cd), nickel-metal-hydride (NiMH) and Li-ion batteries (LIBs). Table 2-1 gives a brief overview of these four types of batteries (Liu *et al.* 2019); their characteristics are given below.

2.3.1 Lead-acid battery

Lead-acid (Pb) battery is the oldest rechargeable battery system. While the technology is outdated, they have stood the test of time and are still one of the most widely used types today. Globally, over 400 million 12 V lead-based batteries are produced every year to supply original equipment manufacturers (OEMs) and aftermarket (i.e., replacement batteries for vehicles in use) light-duty vehicle applications. In Europe, around 60 million batteries are required each year (Allen & Telford 2020). Their popularity is due to their low capital cost and ability to operate efficiently even at low temperatures, which often trumps their low energy densities and low cycle lifetimes.

There are two main types of lead-acid batteries used in electric vehicles. The flooded type is the traditional one, where the electrodes are immersed in electrode. It has optimal capital cost, approximately US$60/kWh for large systems, which is one third of the current capital cost of the Li-ion batteries used in most EVs (Baes *et al.* 2018). However, its downsides are its low cycle lifetime, low charging rate and maintenance requirements, in which the battery must be topped up with water to remain “flooded”. The second type are the sealed batteries that has a slightly more advanced design and does not require topping up with water. This eliminates maintenance costs and increases cycle lifetime, but doubles capital costs. Good quality lead batteries perform reliably when exposed to extreme environments and have a wide operating temperature, ranging from -20°C to 50°C. However, this battery type requires inspection of electrolyte

Table 2-1 *Popular types of batteries in EVs (Liu et al. 2019).*

Battery type	Service lifetime (cycle)	Nominal voltage (V)	Energy density (Wh/kg)	Power density (W/kg)	Charging efficiency (%)	Self-discharge rate (%/month)	Charging temperature (°C)	Cost	Safety
Li-ion	600–3,000	3.2–3.7	100–270	250–680	80–90	3–10	0–45	Medium	Medium
Pb-acid	200–300	2.0	30–50	180	50–95	5	-20–50	Low	High
NiCd	1,000	1.2	50–80	150	70–90	20	0–45	High	High
NiMH	300–600	1.2	60–120	250–1,000	65	30	0–45	High	High

level and has a short lifespan of approximately three years and have poor specific energy rate (30-50 Wh/kg). Because they are heavy, these batteries could represent 25-50% of the vehicle's total mass to provide sufficient energy for an EV application (Whittingham 2012). Moreover, lead-acid batteries generate harmful gases, are toxic, and contain concentrated sulfuric acid, and therefore cannot be disposed in landfills. Lead-acid batteries were used in the early EVs (e.g., General Motors EV1), but are not used in any recent EV designs.

2.3.2 Nickel-cadmium battery

Nickel-cadmium (Ni-Cd) is also a type of battery with a mature and well understood technology. Ni-Cd batteries are used where long service life, high discharge current and extreme temperatures are required (Whittingham 2012). The Ni-Cd battery is one of the most rugged and enduring batteries and is the only type that allows ultra-fast charging with minimal stress. Both specific energy density and specific power density are acceptable for EV applications, around 50–80 Wh/kg and 150 W/kg, respectively (Liu *et al.* 2019). However, Ni-Cd batteries are highly toxic, and are therefore being replaced by more efficient and environmentally friendly batteries such as NiMH and Li-ion in the automotive industry.

2.3.3 Nickel-metal-hydride battery

Nickel-metal-hydride (NiMH) batteries serve as replacement for Ni-Cd batteries since they are much less toxic and provide higher specific energy (with range of 60 to 120 Wh/kg). This feature offers lower battery weight and reduces the space required for storing the batteries. However, their performance is significantly lower than Li-ion batteries, which have a 40% higher value of specific energy (Whittingham 2012). The main advantage of NiMH batteries is their durability. NiMH batteries are well-proven for use in EVs. Many cars with these batteries have been on the road for more than 161,000 kilometers and have been operating successfully for over 7 years (Kesler *et al.* 2012).

Disadvantages of NiMH batteries include lower charging efficiency than other battery types, and a major issue with self-discharge (up to 12.5% per day at room temperature). Moreover, the rate of self-discharge increases with the prevailing temperature. Another disadvantage is a high rate of heat generation during fast charging and discharging, which requires a cooling system that in turn will increase the weight of the battery, its costs, and restricts the number of batteries that can be combined. In addition, patent encumbrance has limited the use of NiMH batteries in EVs, shifting the focus to Li-ion technology.

2.3.4 Li-ion batteries

Lithium-ion batteries (LIBs) are currently the dominant technology for EVs. According to the Boston Consulting Group, Li-ion batteries will take up to a 90% share of the EV battery market by 2025 (Kuepper *et al.* 2018). Li-ion batteries have overcome some of the shortcomings of other battery types. Compared to others the Li-ion batteries are lightweight, have a good charge cycle rate, higher power density, higher cell voltage, and a better self-discharge rate (only 3–10% per month), and a remarkably high specific energy of 140+ Wh/kg. The high specific energy density is definitely the Li-ion battery's main advantage (Cano *et al.* 2018), since it allows a lower battery weight, which in turn tends to increase the range and performance of EVs. Compared to the lead-acid batteries, the Li-ion is one third of the weight, is three times more powerful, and has three times the cycle lifetime. Li-ion batteries are expensive with production costs up to 40% higher than nickel batteries (Whittingham 2012), but intensive research on Li-ion technology has recently led to decreased production costs. According to McKinsey, from 2010 to 2017, the cost of Li-ion batteries decreased by 80% (Mongird *et al.* 2019). However, safety issues remain a big concern with these batteries, as "thermal runaway" can cause EVs to catch fire or explode if the battery is overcharging and the heat is not dissipated. Also, fluctuating battery charging can be dangerous. Because of this, an advanced battery management system (BMS) is required, which monitors each cell's voltage and temperature, the state-of-charge (SoC) and the state-of-health (SoH), helping to ensure safe and reliable operation, balance cells for long battery life and an optimized EV performance (Manthiram 2017).

Typical automotive LIBs contain lithium (Li), cobalt (Co), and nickel (Ni) in the cathode, graphite (C) in the anode, as well as aluminium (Al) and copper (Cu) in other cell and pack components. Commonly used LIB cathode chemistries are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel cobalt manganese oxide (NCM), lithium nickel cobalt aluminium oxide (NCA), or lithium iron phosphate (LFP), although battery technology is currently evolving fast and new and improved chemistries can be expected in the future (Stan *et al.* 2014). Table 2-2 summarises the most important characteristics and properties of the present Li-ion battery cathode chemistries (Harper *et al.* 2019); further details are outlined in the following sections.

Table 2-2 *Li-ion battery cathode chemistries (Harper et al. 2019).*

Cathode type	**LCO**	**LFP**	**LMO**	**NCA**	**NMC**
Chemical formula	$LiCoO_2$	$LiFePO_4$	$LiMn_2O_4$	$Li(Ni,Co,Al)O_2$	$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC111) $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532) $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622) $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811) $LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$ (NMC9.5.5)
Structure	Layered	Olivine	Spinel	Layered	Layered
Year introduced	1991	1996	1996	1999	2008
Safety					
Energy density					
Power density					
Calendar lifespan					
Cycle lifespan					
Performance					
Cost					
Market share	Obsolete	Growing (EVs and energy storage systems)	Small	Steady	Growing (from NMC111 → NMC532 → NMC622 → NMC811 → NMC9.5.5 to cobalt free chemistries)

Legend Ideal … Poor

2.3.4.1 Lithium cobalt oxide-based batteries

The lithium cobalt oxide ($LiCoO_2$)-based battery, further referred as LCO, is a mature battery technology characterized by long cycle lifetime and high energy density. It was introduced by Goodenough, and originally commercialized by SONY. LCO consists of a cobalt oxide positive electrode as a cathode and a graphite carbon negative electrode as an anode. A typical LCO battery cell is rated at 3.8 V. LCO is still the most popular battery technology used in portable electronic devices due to its excellent charging/discharging rate, good cycling performance, and high energy density (Manthiram 2020). Its theoretical specific capacity could reach 274 mAh/g, and the theoretical volumetric capacity reaches 1,363 mAh/cm^3.

The major limitations are high cost, low thermal stability, and fast capacity fade at high current rates or during close-loop recycling. LCO cathode is expensive because of the high price of cobalt and LCO batteries are therefore quite limited for automotive applications (such as Tesla), and mostly applied to consumer electronics. Low thermal stability refers to exothermic release of oxygen when a lithium metal oxide cathode is heated above a certain point, resulting in a runaway reaction in which the cell can burst into flames. Thermal runaway is a major concern in the application of Li-ion batteries. Currently, adding coatings of various metal oxides is the most effective way in enhancing LCO stability and performance characteristics, even during close-loop cycling, because mechanically and chemically stable oxide materials reduce structural change of LCO and side reactions with electrolyte (Nitta *et al.* 2015).

2.3.4.2 Lithium manganese oxide-based batteries

The lithium manganese oxide ($LiMn_2O_4$)-based battery, further referred as LMO, is a relatively mature technology with a higher nominal voltage than LCO-based battery cells, rated between 3.8 and 4.1 V. LMO consists of a manganese oxide positive electrode as a cathode and a graphite carbon negative electrode as an anode. LMO benefits from the abundance, cost and environmental friendliness of manganese compared to cobalt or nickel. Another great advantage of LMO is its high thermal stability and therefore improved safety. On the other hand, the energy density of LMO batteries is approximately 20% less than that of LCO batteries. Hence, LMO batteries do not have optimal power and energy density (Manthiram 2020). Due to its relatively short cycle lifetime and high-capacity losses, LMO battery cell is rarely used for automotive applications, and are currently only applied by Japanese OEM's. Recent developments in LMO battery technology use nano-technology to produce a novel ordered mesoporous lithium-rich $Li_{1.12}Mn_{1.88}O_4$ spinel, which is expected to show improved electrochemical performances compared to normal bulk spinel (Nitta *et al.* 2015).

2.3.4.3 Lithium nickel cobalt aluminium oxide-based batteries

The lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$)-based battery, further referred as NCA, has found relatively widespread commercial use in both consumer electronics and electric vehicles. NCA consists of a lithium nickel cobalt aluminium oxide positive electrode as a cathode and a graphite carbon negative electrode as an anode. It has a lower voltage of 3.7 V and a better safety characteristic, compared with LCO-based batteries. Furthermore, NCA batteries has the highest specific energy range (200–250 Wh/kg) in the current class of technologies as well as high specific power, combined with a lifetime of 1,000 to 1,500 full cycles. NCA is the technology preferred by manufacturers such as Tesla, and has immense potential for use in power systems in backup and peak-load shifting applications (International Energy Agency 2021).

The main drawbacks of NCA are suboptimal safety and high cost. Moreover, capacity fading is reported to be severe at elevated temperature (40–70°C) due to solid electrolyte interface (SEI) growth and micro-crack growth at grain boundaries (Nitta *et al.* 2015).

2.3.4.4 Lithium nickel manganese cobalt oxide-based batteries

The cathodes of lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$)-batteries, further referred as NMC, represent the state-of-the-art traction battery, and have become automotive OEM's preferred technology. Beside the $LiNiMnCoO_2$ cathode the NMC batteries has a graphite anode. Compared to NCA, the NMC battery has lower energy density, typically in the range of 140–200 Wh/kg, and cycle lifetime of 1,000–2,000. NMC-based batteries can operate at relatively high voltages of 3.6 V (Simon *et al.* 2015) and have various forms of chemistries. The proportions of nickel, manganese and cobalt can vary to influence the battery characteristics and provide tailored solutions for specific applications. Increasing the share of nickel favours the specific energy aspect, while increasing the share of manganese increases specific power. The most commonly used NMC composition contains equal amount of all three transition metals and is called NMC111 (i.e., ⅓Ni-⅓Mn-⅓Co). Although NMC111 was first commercialized as late as 2004, it now dominates in EV and plug-in hybrid electric vehicles (PHEV), while also being used in portable electronics, power tools and medical devices (Australian Trade and Investment Commission 2018). Owing to price spikes in the 2010s, EV producers have been working to reduce the amount of cobalt in batteries over the past several years – this implies, in many cases, an increase in the quantity of nickel. NMC111 batteries have moved increasingly towards NMC532, NMC622 and NMC811, and are expected to move towards even more nickel-rich chemistries (e.g., NMC9.5.5). This trend of trying to minimize the use of cobalt can therefore have major implications for the need for nickel. NMC111 and NMC532 are currently used predominantly for home energy storage. The transition of NMC-variants towards lower proportions of cobalt such as NMC622 and NMC811 is also valid for home energy storage systems, but with some delay due to technology development and availability (International Energy Agency 2021). However, the higher nickel content increase energy density, and batteries then become less stable and hence less safe, and complete removal of cobalt from NMC type LIBs is thus probably not feasible. Recent developments in NMC batteries aim at improving the battery safety at higher nickel contents.

2.3.4.5 Lithium iron phosphate-based batteries

The lithium iron phosphate ($LiFePO_4$)-based battery, further referred as LFP, was first commercialized in 1999 and was soon considered a promising technology. The LFP batteries have $LiFePO_4$ cathodes with graphite as the anode material or sometimes with lithium titanite oxide as a less common anode material, leading to the two designations: LFP-C and LFP-LTO. LFP batteries have become more attractive in recent years since they do not require critical raw materials (Mohr *et al.* 2020). Advantages of LFPs are lower production costs due to the abundance of raw materials, high safety due to better thermal stability, and longer cycle lifetime. Current LFP batteries endure up to 2,000 full cycles, while industry projections for an even longer lifetime are realistic. The battery tolerates operation with a wide SoC window (15–100%), and the cell display constant voltage within this range, which implies constant performance (Xu *et al.* 2020). These advantages initially made the LFP battery an interesting candidate for EV, especially in China. Despite its relatively low specific energy (90–140 Wh/kg), which is less than other Li-ion chemistries, LFP batteries could be particularly useful for heavy-duty vehicles like trucks where the size and weight of a battery are of primary concern. Moreover, LFP batteries are considered suitable for being used in stationary, e-bikes and back-up power applications because their characteristics match the demands of these applications (Liu *et al.* 2021).

From Table 2-2, it is clear that none of the discussed Li-ion battery chemistries is superior to the alternative chemistries in all aspects. In general, considering energy density, NMC > NCA > LCO > LMO > LFP; considering safety, LFP > LMO > NMC > LCO > NCA; considering lifetime, LFP > NCA > NMC > LMO > LCO (Manthiram 2020). Therefore, selection of any Li-ion battery chemistry for a specific purpose must be targeted at the individual application.

2.3.4.6 Electric double-layer capacitors

A different energy storage system for electric vehicles is the electric double-layer capacitor (EDLC). This device stores the energy in a different way compared to classical electrochemical energy storages. EDLCs have two layers of charge with opposing polarity form, one at the surface of the electrode, and one in the electrolyte. These two layers are typically separated by a single layer of solvent molecules that adhere to the surface of the electrode and act like a dielectric in a conventional capacitor. In the capacitors the energy is directly stored in the electric field.

The big advantage of the EDLCs is the high capacitance due to the adoption of active carbon electrodes characterized by a large active surface and its surface phenomenon without faradic reactions. This implies a very high-power density that enables rapid charge and discharge (Kaneko *et al.* 2016). In addition, they can charge and discharge several hundreds of thousands to several million cycles with less deterioration. Similarly with lead-based batteries, EDLCs can operate over a wide temperature range, especially when a special solvent is adopted. For this reason, EDLCs are commonly used under cold environment in combination with other energy storage systems (Kebede *et al.* 2022).

Despite of being price competitive, compared with other energy storage systems, EDLCs have not been used as the main energy storage system until now. However, they have been implemented as an assistant power supplier for heavy electric loads in hybrid electric vehicles (HEVs) for e.g., the electric air condition, the electric braking pump, or the electric steering system.

In the past twenty years, there has been a dramatic increase in the number of rechargeable battery types. This rapid increase has especially been in China and EU and has been coupled to the fast development of EVs. As Li-ion batteries dominate EV batteries, an exponential increase in the demand for Li-ion batteries has been seen (Benchmark Mineral Intelligence 2021a; Research and Markets 2022). Meanwhile, the demand for other types of rechargeable batteries has remained stable (Figure 2-3).

2.4 Future battery technologies in automotive industry

Over the past decade, the lithium-ion battery industry has achieved a remarkable 80% drop in the volume-weighted average battery pack price (Mongird *et al.* 2019). The battery pack energy density has on average doubled since 2010 and is approaching 200 Wh/kg. It is expected that the continued optimization of current technology can sustain this trajectory for the next five years. Rechargeable batteries are currently the most popular type of batteries, but they have shortcomings due to their large size and heavy weight. They also suffer from several inherent limitations such as liquid electrolyte leakage, flammability, as well as other safety and flexibility problems. In the future, a new generation of cells will be needed. In this section, three promising types of batteries for the future will be discussed. Bloomberg NEF (BNEF) expects the adoption of those next-generation technologies to open up for more opportunities to push the cell-level energy density up to 500 Wh/kg (roughly 350 Wh/kg of pack energy density) and drive battery prices down to US$61/kWh by 2030 (Bloomberg NEF 2020a).

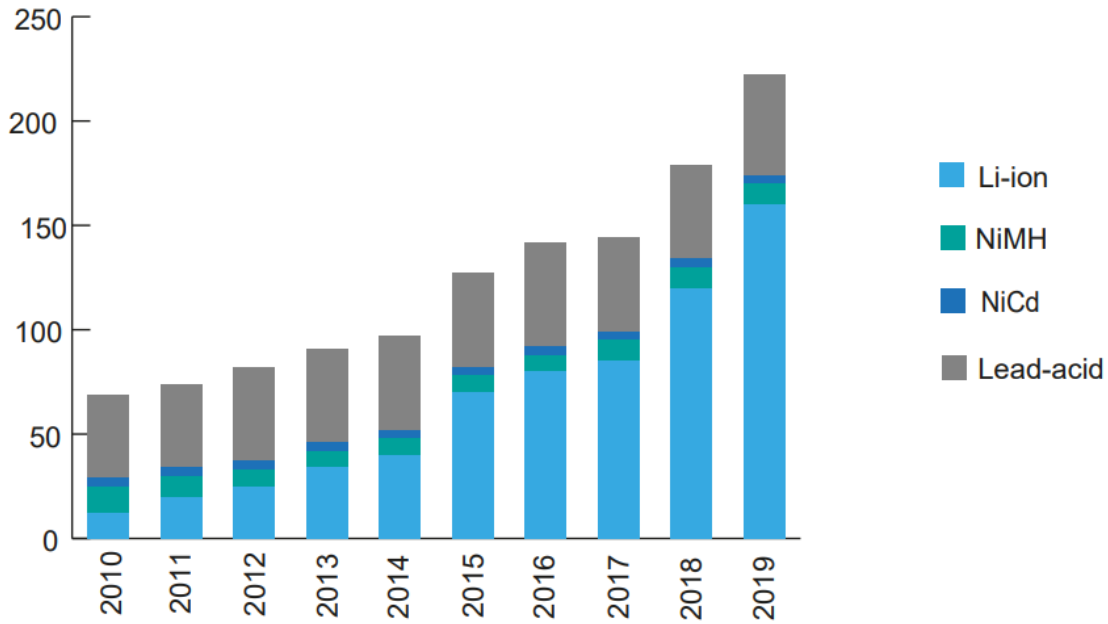


Figure 2-3 *Global market for four types of rechargeable batteries from 2010 to 2019 (Unit: GWh). Source: Roskill 2020a; Benchmark Mineral Intelligence 2021a; Avicenne Energy 2022.*

2.4.1 Solid-state batteries

Of the various next-generation technologies being researched, solid-state batteries are one of the most promising. The industry's interest in this technology originates from the pursuit of increased safety and higher energy densities. When fully developed, this technology will be a combination of an all-solid-state electrolyte (SSE), lithium metal anode and high energy-density cathode (Ding *et al.* 2019).

Solid-state electrolytes are generally classified into three main groups: polymer, oxide, and sulphide. Performance across the three types of solid-state electrolytes vary greatly, as shown in Table 2-3.

Table 2-3 *Typical solid-state electrolytes and material properties (Ding et al. 2019).*

Electrolyte types	Polymer	Sulphide	Oxide
Typical materials	PEO-$LiPF_6$	$Li_{10}GeP_2S_{12}$	$Li_7La_3Zr_2O_{12}$
Representative companies	Blue Solutions	Samsung SDI	Quantum Scope
Ionic conductivity (RT)			
Voltage window			
Energy density			
Mechanical strength			
Chemical stability & Safety			
Cost-competitiveness			

Legend Ideal Poor

As can be seen Table 2-3, there isn't a single material that outperforms others across all the key parameters. Most solid-state electrolytes currently lag behind their liquid counterparts on key properties such as room-temperature, ionic conductivity, chemical and electrochemical stability against anode and cathode. Moreover, irrespective of the type of solid-state electrolyte, the demand for lithium in solid-state batteries will increase relative to current Li-ion battery technologies (International Energy Agency 2021).

For anode materials in solid-state batteries, the companies are expected to use conventional anode materials at the beginning such as graphite, carbon-coated silicon and then perhaps move to lithium foil. To improve the performance of lithium metal anodes, ongoing efforts focus on enhancing the interface contacts with additives or through modification process, suppressing the side reactions and dangerous dendrite formation, and developing a cost-competitively process to produce thin lithium foil.

Beyond the existing cathode materials, the use of solid-state electrolytes allows for the introduction of new cathode materials with either high voltages or high active capacities, enabling high energy densities. Materials being explored can be roughly grouped into five categories: nickel-rich layered oxides, spinel oxides, lithium-rich layered oxides, polyanionic compounds and lithium-free compounds, as shown in Figure 2-4 (Li & Frith 2020).

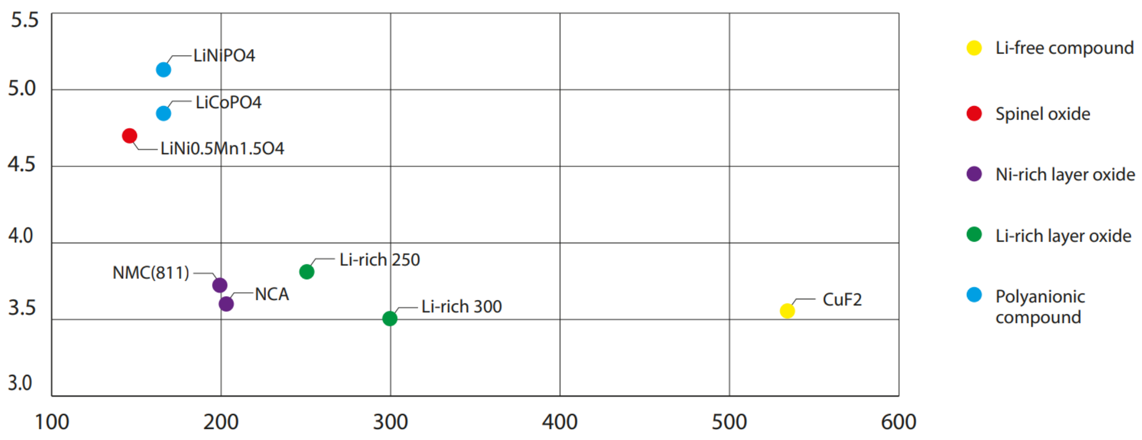


Figure 2-4 *Typical cathode candidates for the solid-state batteries (Li & Frith 2020).*

It follows that less-cobalt and cobalt-free cathode materials are the tendency for solid-state batteries. Even a lithium-free cathode is possible, but most of the candidate materials above are still far from being commercial, so in the near future, the current generation of high-nickel layered oxides, such as NMC811, will be used (Li & Frith 2020).

In the near future, the all-solid-state batteries will not necessarily be able to out-perform liquid-electrolyte based cells across all key parameters (Figure 2-5). NMC and LFP in market have better performance in one or two parameters, especially on cycle lifetime. This indicates that the solid-state batteries will not entirely replace neither the conventional Li-ion batteries nor the earlier generations of the technology (Manthiram 2020). Solid-state batteries are expected to co-exist with the conventional Li-ion batteries throughout most of the next decade (Zubi *et al.* 2018).

Currently, small sized solid-state batteries have already been used in portable devices, but large sized suitable for vehicles are still under development. Bloomberg NEF generated an outlook for the development and commercialization of solid-state batteries (Figure 2-6). The timeline indicates when the mass production of solid-state batteries for EVs is expected to start. GWh-scale facilities for manufacturing the solid-state batteries of lithium metal anodes are not expected to be available before 2026 at the earliest. Cost-competitive cells and mass-market adoption until supply chains and manufacturing technologies mature will not occur until 2030 (Li & Frith 2020).

However, the introduction of solid-state electrolytes in the foreseeable future are unlikely to impact cathode chemistry, and consequently, these technologies will not influence the demand for cobalt and nickel in the medium term (Azevedo *et al.* 2018), whereas the demand for lithium will increase if solid-state batteries are widely adopted (International Energy Agency 2021).

2.4.2 Lithium-sulphur battery

To achieve higher energy densities than today's Li-ion batteries, metallic lithium is being investigated as the active material at the anode in two types of battery systems. One is lithium-sulphur (Li-S) battery system. The anode is metallic lithium, and the cathode is a mix of elemental sulphur and carbon. Both lithium and sulphur are dissolved in the electrolyte and the lithium ions react with the polysulphides, which change their composition during discharge, whereas these processes are reversed during charge. The carbon is needed to compensate for the low electrical conductivity of sulphur. Adding carbon as carbon nanotubes creates good electric conductivity and a structure for the sulphur to make the cathodes robust. With this concept the theoretical energy density is more than 2,500 Wh/kg, but in reality, energy densities of 500–600 Wh/kg can be achieved. In addition, Li-S cells are only half the weight of Li-ion cells and free of critical raw material cobalt and may therefore be produced at lower costs (Santos & Viallon 2018). Some cells are designed for low-temperature applications. Such cells still work even at temperatures below -30°C and may thus be used for automotive applications even in Arctic environments. Another advantage of these cells is their enhanced safety due to their specific operating mechanism (Budde-Meiwes *et al.* 2013). However, currently Li-S batteries still have many drawbacks. For example, their charge-discharge efficiency is acceptable, but their cycle number and stability are poor. Another major drawback of Li-S batteries is their very low voltage, rated at 2.2 V, which has limited their use in aerospace applications, but also their higher content of lithium is a drawback (Benveniste *et al.* 2018).

The use of sulphur in lithium-based cathodes is a promising technology because of its very high theoretical energy density, but it is still in its early stages of development. The technology also faces substantial challenges (e.g., short lifetime) that must be resolved before potential commercialization (Zhang *et al.* 2022), and a large market share of Li-S in EV batteries is not to be expected in the near future (Bloomberg NEF 2020a).

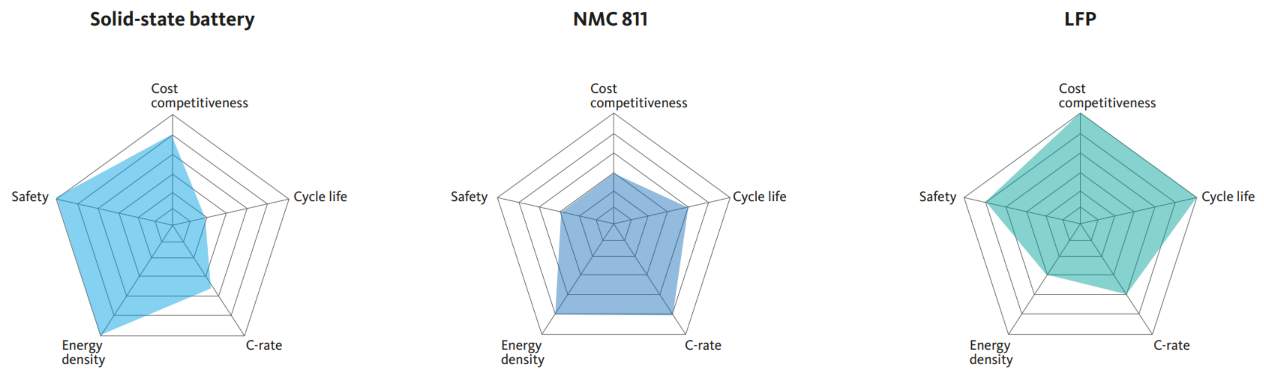


Figure 2-5 *Illustrative characteristics of solid-state batteries, analysis based on (Zubi et al. 2018; Manthiram 2020). NMC – Nickel Manganese Cobalt, LFP – Lithium Iron Phosphate*

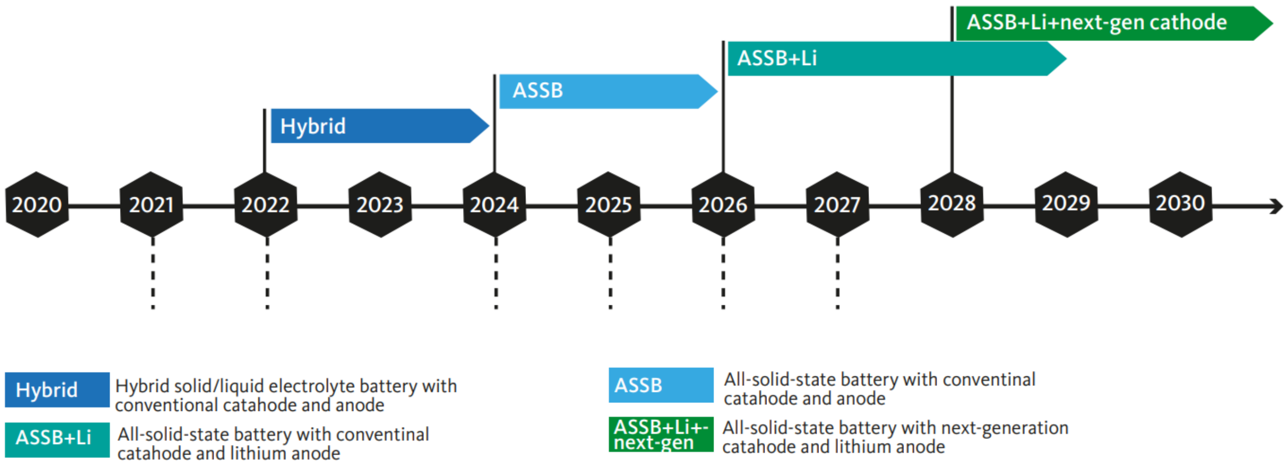


Figure 2-6 *Roadmap for the mass production of solid-state batteries (Bloomberg NEF 2020a).*

2.4.3 Lithium-air battery

Another approach to reach a high energy density is to use the oxygen of the atmosphere as the active material on the cathode. This means that the anode is a pure metal which is oxidized with oxygen. Because oxygen is available everywhere, only the metal must be stored in the battery. Therefore, the energy density increases dramatically owing to the low weight of the stored material in the battery. However, the battery weight increases with discharging (and thus the energy density decreases) because oxygen is incorporated in the form of metal oxides. Between the metal anode, e.g., lithium, and the porous membrane, which is the contact with the atmosphere, there is an electrolyte which transports the dissolved lithium cations from the anode to the membrane where it reacts with the oxygen. Because of this membrane, this battery technology is not that of a classical battery but a combination of the technologies of a battery and a fuel cell. A lithium-air battery, for example, has a theoretical energy density of 13 kWh/kg without the oxygen (Budde-Meiwes *et al.* 2013), which is comparable with that of fuel (typically also characterized without the oxygen needed for burning it). However, besides the possible high energy density, there are still great challenges in lithium-air systems such as the number of cycles (lifetime) and the safety. These parameters are massively influenced by the ambient air which also contains water, carbon dioxide and nitrogen. All these components cause side reactions with the active materials, which lead to poor reversibility of the reactions and binding of the active components. Currently, the lithium-air battery is only at an experimental stage, but could potentially improve EV ranges dramatically once successfully developed (Xu *et al.* 2020).

2.5 Summary of battery technologies

Figure 2-7 compares the theoretical energy densities of various present and future lithium-based battery technologies. Li-S batteries can reach two times and Li-air batteries up to three times the specific energy of current LIBs. With expected cost reductions these batteries have the potential to become the successors of current LIBs, but both technologies are still in their early phases of development and are unlikely to be of practical use for the foreseeable future. The third and strongest candidate to replace current LIBs is an all-solid-state battery. This innovation is based on the current LIB technologies, and most of cathode chemistries keep the same composition, so there is no dramatical improvement on energy density compared to Li-S and Li-air batteries. However, it could solve the key safety problem with existing LIBs, and this technology will probably be adopted and dominate the EV battery market beyond 2030.

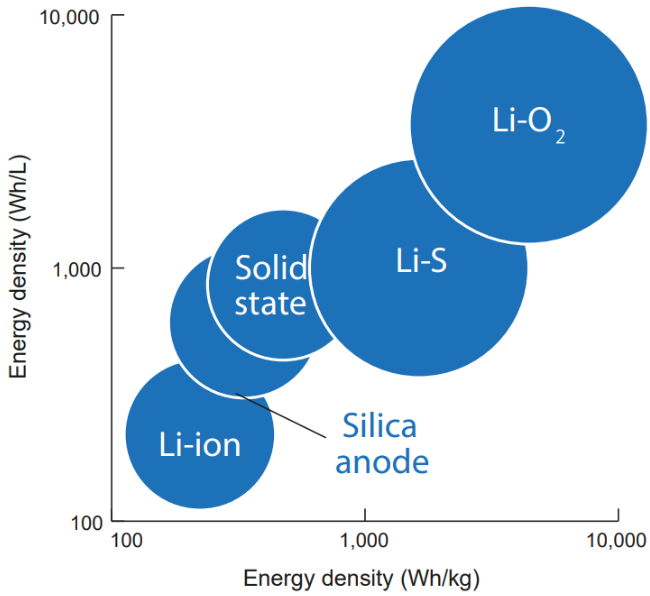


Figure 2-7 *Theoretical energy densities of various current and future lithium-based battery technologies (Baes et al. 2018).*

From 2023 to 2030, it is expected that LIBs will still be the dominant technology among rechargeable batteries, and the main cathode chemistries will remain as shown in Table 2-4, although the share of different cathode chemistries in LIBs might change with time (Figure 2-8).

Table 2-4 *Key element content in major LIB cathode chemistries (Unit: kg/kWh). Source: Benchmark Minerals Intelligence (2021a).*

	Total weight	Li	Ni	Mn	Co	Al	Fe	P	O
LMO	2.33	0.09		1.51					0.72
LFP	1.89	0.08					0.67	0.37	0.77
NMC111	1.75	0.12	0.35	0.33	0.37				0.58
NMC532	1.64	0.12	0.49	0.26	0.23				0.54
NMC622	1.54	0.11	0.56	0.18	0.18				0.50
LCO	1.5	0.11			0.89				0.50
NCA	1.4	0.10	0.67		0.14	0.02			0.47
NMC811	1.36	0.10	0.65	0.08	0.08				0.44
NCA90	1.36	0.10	0.74		0.05	0.02			0.46

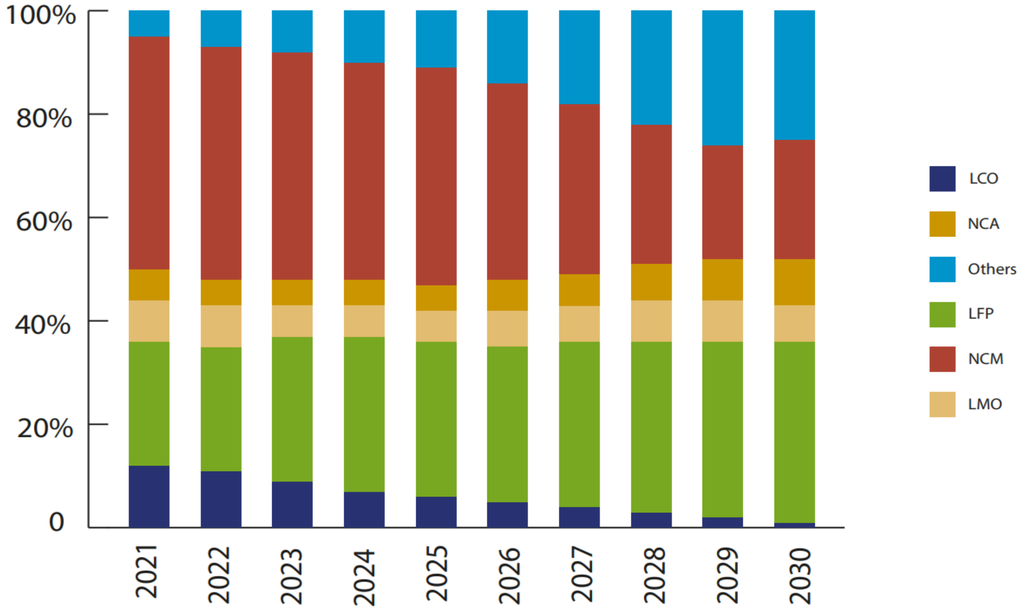


Figure 2-8 *Share of cathode chemistries in Li-ion batteries by weight (Benchmark Minerals Intelligence 2021b).*

The share of low or no cobalt cathodes tend to increase with time, and LFP cathodes will most likely become dominant in 2030. Other next generation cathodes, such as lithium nickel manganese spinel cathode (LNMO), are currently in lab stage, but expected to increase market shares dramatically after 2025. Due to the rapid growth of the EV market, the total demand of cobalt and lithium of the battery sector will still increase, leading to concerns for the sustainable supply of these two materials. Rapid upscaling of supply chains for cobalt and lithium is needed to meet the increased demand, but it is uncertain if the expansion of materials supply will be able to keep up with the demand. To try to answer this question, Chapter 3 is dedicated to the understanding of the complete supply chain of cobalt and Chapter 4 of lithium.

3. Global cobalt flow analysis

Cobalt chemical element with the symbol Co and atomic number 27. It is a hard, brittle and greyish-silver lustrous metal. Cobalt was isolated by the Swedish chemist Georg Brandt in 1735 (Roberts & Gunn 2014) but cobalt-containing minerals have been used for centuries to impart a blue colour to glass, glazes and ceramics.

Like other transition metals, cobalt is tough and can take a high polish. It has excellent mechanical properties and is even stronger than steel. Cobalt is, together with iron and nickel, the only naturally occurring magnetic metals, and cobalt can retain its magnetism up to 1,121°C (Donaldson & Beyersmann 2012). In addition to these mechanical and ferromagnetic properties, the properties of the cobalt chemicals also play an important role in its current areas of application. For example, lithium can intercalate very well in the layered structure of lithium cobalt dioxide, which forms the high energy density lithium cobalt oxide (LCO) cathodes in lithium-ion batteries (Donaldson & Beyersmann 2012). Other important useful properties are its ability to form alloys with many other metals, low thermal and electrical conductivity, and high resistance to wear and oxidation.

Because of those properties, cobalt is widely used in a broad range of products such as batteries, superalloys, cutting tools, magnetic materials, petrochemical catalysts, dyes, and pigments, though the major use of cobalt has changed over time. In 1900s, cobalt was used mainly as cobalt oxide in manufacture of pigments and decolourizers. In the 1960s, the largest use of cobalt was in superalloys, which were used widely in the aerospace and military industries. Since the advent of lithium-ion batteries (LIBs) in the 1990s, the use of cobalt in the battery sector has increased dramatically (especially for mobile applications), because the lithium cobalt oxide (LCO) batteries have a particularly high energy density. From 2000, the growing green economy has caused batteries to become the major driving force for the increasing cobalt demand, with the consumption of cobalt in batteries growing at an annual rate of 10% (Cobalt Institute 2021).

As a crucial metal used in different fields, cobalt's global supply chain involves a complex trading system with the sourcing of crude materials, processing, refining, manufacturing, use and recycling, tending to occur in different geographic locations. Figure 3-1 shows the cobalt supply chain and the individual steps which will be analysed and discussed below. Data at all steps in this chapter have been converted to cobalt content.

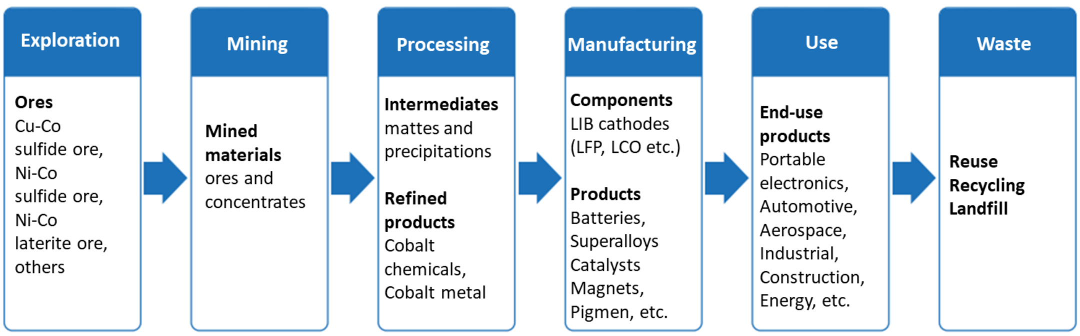


Figure 3-1 *Simplified cobalt supply chain.*

3.1 Cobalt deposit types, resources and reserves

Cobalt, though widely dispersed, has an average concentration of only 17.3 ppm in the Earth's crust (Rudnick & Gao 2003). Most cobalt is found in basic and ultrabasic rocks such as dunite and peridotite where the average levels typically are 125-150 ppm. Pure cobalt is not found in nature and due to its chalcophile and siderophile properties, cobalt is preferentially bound to iron, nickel, copper and sulphur rather than to oxygen, forming various sulphide and sulpharsenide phases (Roberts & Gunn 2014, Horn *et al.* 2021). However, the mineralogy of typical ore cobalt minerals is diverse and includes oxides, hydroxides and carbonates and both primary (hypogene) and secondary (supergene) mineral variants exist. Table 3-1 lists the common cobalt-bearing minerals, in total more than 60 cobalt-bearing minerals are known, many of which are widespread and found in different geological settings (Dehaine *et al.* 2021).

Table 3-1 *Common cobalt-bearing minerals and concentrations (Based on Petavratzi et al. 2019 and Dehaine et al. 2021).*

Mineral	Chemical formula	Mineral group	Mineral type	Co content (wt. %)	Example deposits and occurrences
Carrolite	$Cu(Co,Ni)_2S_4$	Sulphide	Primary	28.56	Chambishi (DRC), Carroll County (USA)
Cattierite	$CoS_2(Co,Ni)S_2$	Sulphide	Primary	47.89	Shinkolobwe (DRC)
Cobaltite	$CoAsS_3$	Sulpharsenide	Primary	35.52	Sudbury (Canada), Broken Hill (USA)
Erythrite	$3CoO.As_2O_5.8H_2O$	Arsenate	Secondary	29.53	Bou Azzer (Morocco), Daniel Mine (Germany)
Co-pentlandite	$(Co,Ni,Fe)_9S_8$	Sulphide	Primary	54.18	Langis mine (Canada), Sotkamo (Finland)
Co-pyrite	$(Fe,Co,Ni)S_2$	Sulphide	Primary	13.90	Outokumpu district (Finland)
Glaucodot	(Co,Fe)AsS	Sulpharsenide	Primary	26.76	Hakansboda (Sweden)
Heterogenite	$CuO.2Co_2O_3.6H_2O$	Oxide	Secondary	64.10	Katanga Copperbelt (DRC)
Kolwezite	$(Cu,Co)_2(CO_3)(OH)_2$	Carbonate	Secondary	17.84	Musonoi, Kamoto, Mupine and Mashamba West mines (DRC)
Linnaeite	Co_3S_4	Sulphide	Primary	57.95	Bastnäs mine (Sweden), Bou Azzer (Morocco), Noril'sk (Russia)
Safflorite	$(Co,Fe)As_2$	Arsenide	Primary	21.25	Elizabeth mine (Romania)
Siegenite	$(Co,Ni)_3S_4$	Sulphide	Primary	14.51	Jungfer Mine (Germany)
Skutterudite	$(Co,Ni)As_3$	Arsenide	Primary	17.95	Skutterud Mines (Norway), Bou Azzer (Morocco)
Smaltite	$(Co,Ni)As_2$	Arsenide	Primary	28.20	Langis Mine (Canada), Bou Azzer (Morocco)
Willyamite	(Co,Ni)SbS	Sulphide	Primary	20.78	Broken Hill (Australia)

There are many geological environments with endowment of cobalt, but a general feature of most cobalt deposits is that the metal is recovered as a by-product of copper or nickel mining. Cobalt-bearing minerals are found in economic concentrations in three principal deposit types: 1) stratiform sediment-hosted copper-cobalt deposits; 2) nickel-cobalt laterite deposits; and 3) magmatic nickel-copper (-cobalt-platinum group element (PGE)) sulphide deposits. These deposits type, are described below and grade-tonnage examples are shown in Figure 3-2. Finally, some other cobalt mineralization types are briefly mentioned at the end of this section.

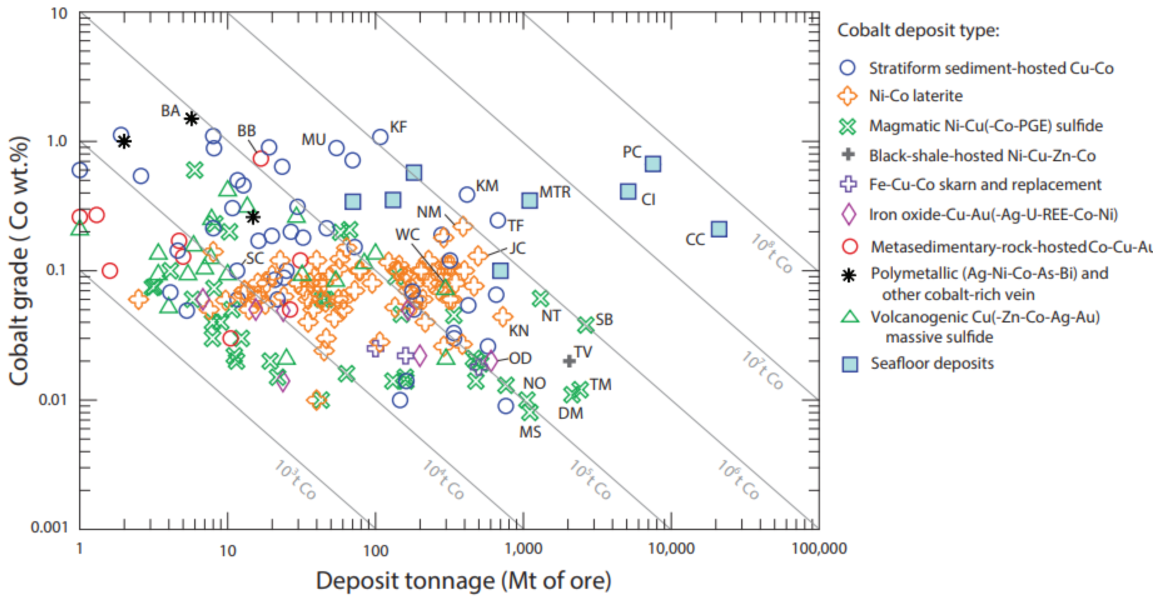


Figure 3-2 *Grade-tonnage plot for 214 cobalt deposits worldwide. Grades and tonnages include production plus reserves plus other resources where known. Abbreviations: BA, Bou Azzer (Morocco); BB, Blackbird (Idaho); CC, Clarion-Clipperton zone (Pacific Ocean); CI, Cook Islands Exclusive Economic Zone (Pacific Ocean);DM, Dumont (Canada); JC, Jacaré (Brazil); KF, Kisanfu (DRC); KM, Kamoto– KOV–Musonoi–Mupine deposits (DRC); KN, Kalgoorlie Nickel (Australia); MS, Mesaba (USA); MTR, Maderia-Tore Rise (Atlantic Ocean); MU, Mutanda (DRC); NM, Nkamouna (Cameroon); NO, Northmet (Minnesota); NT, Norilsk-Talnakh (Russia); OD, Olympic Dam (Australia); PC, Pacific prime crust zone (Pacific Ocean); SB, Sudbury (Canada); SC, Sheep Creek (USA); TF, Tenke Fungurume (DRC); TM, Twin Metals (USA); TV, Talvivaara (Finland); WC, Windy Craggy (Canada). Figure modified from Slack et al. (2017).*

3.1.1 Stratiform sediment-hosted copper-cobalt deposits

The stratiform sediment-hosted Cu-Co deposit type is the world's most important source for Co, accounting for about 47% of the global cobalt reserves and resources (Savinova *et al.* 2023). Although these deposits are predominantly mined for copper, cobalt is present with variable grades (Figure 3-2) but typically contain from 0.2 to 1 wt.% Co (Slack *et al.* 2017).

The deposits usually consist of thin, often less than three meters thick, sulphide-bearing zones that are concordant to sub-concordant with the lithological layering in the host siliciclastic or dolomitic sedimentary rocks. Lateral metal zonation in the ore bodies means that high cobalt and copper values do not necessarily coincide (Savinova *et al.* 2023). The stratiform sediment-hosted Cu-Co deposits are commonly associated with three lithological groupings: 1) a syn-rift oxidized red-bed sequence characterized by coarse-grained siliciclastic rocks; 2) a subsequent reduced layer, frequently containing organic matter, which consists of shallow marine or extensive lacustrine sediments; and 3) evaporites containing sulphates and halite (Horn *et al.* 2021).

The ore minerals in stratiform sediment-hosted deposits vary, but the copper is predominantly hosted in chalcopyrite, bornite, chalcocite and malachite, while the cobalt occurs within cobaltite, carrollite, cattierite, cobalt pentlandite and siegenite (Roberts & Gunn 2014). The specific mineralogy depends on the composition of the sedimentary rocks, the temperature and pressure conditions during mineralization, and the chemistry of the fluids involved.

The metallogenies of these deposits are debated, but the consensus is that the cobalt ore deposits derived from hydrothermal fluids, which leached and transported metals upwards from the basement. The cobalt mineralization is often associated with organic-rich sediments, such as black shales, which serve as a source of cobalt and other metals. The metal-rich fluids migrate through the sedimentary rocks, depositing cobalt minerals in favorable stratigraphic horizons or structural traps (Roberts & Gunn 2014; Slack *et al.* 2017; Petavratzi *et al.* 2019; Horn *et al.* 2021).

Significant occurrences can be found in various locations (see Figure 3-3), such as the Central African Copper Belt (CACB), the Mesozoic Kupferschiefer Basin in central Europe, and the Paleoproterozoic Udokan Basin in Russia. The CACB, situated in the Katanga province of southern DRC and north-west Zambia, holds the majority of global cobalt resources, boasting approximately 6.5 Mt of cobalt metal, including historical production (Taylor *et al.* 2013). Only this stratiform Cu-Co sedimentary district contains economic cobalt resources and many of the other sedimentary rock-hosted copper districts contain very minor cobalt (Hitzman *et al.* 2017).

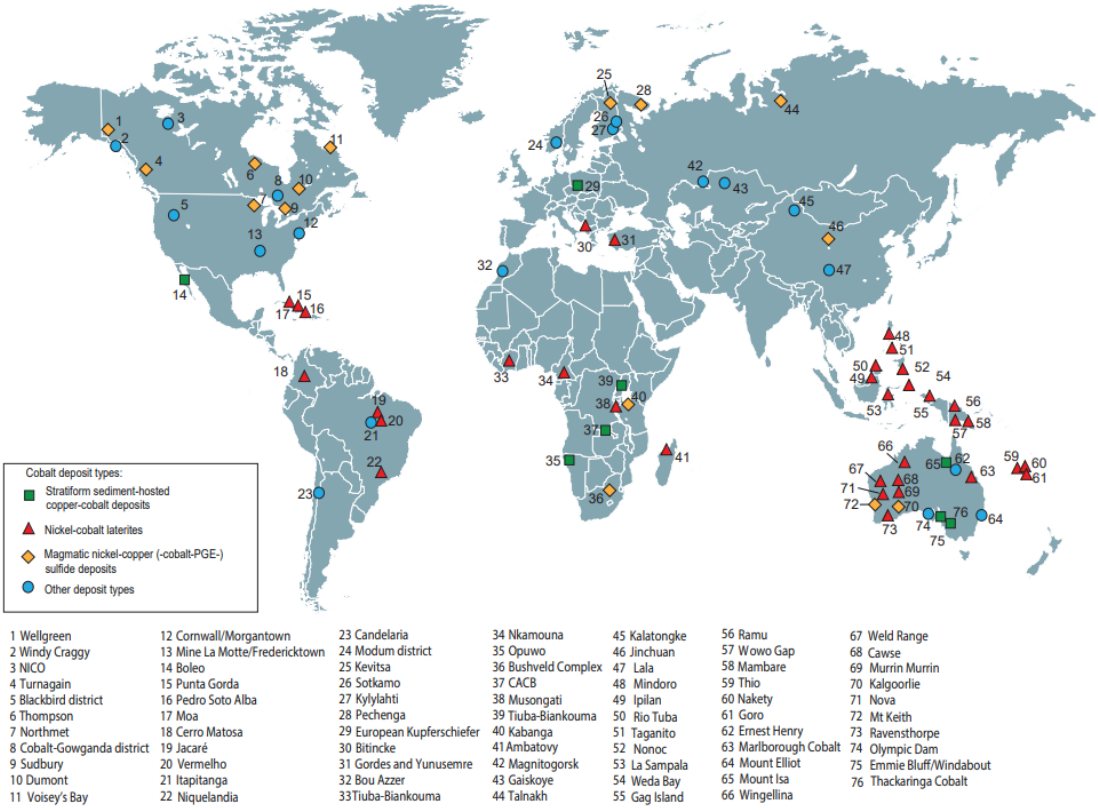


Figure 3-3 *The global distribution of significant terrestrial cobalt deposits and major occurrences. Modified from Petavratzi et al. (2019).*

3.1.2 Nickel-cobalt laterite deposits

Supergene Ni-Co lateritic deposits, which occur predominantly in equatorial regions and are the product of pervasive weathering of ultramafic rocks, account for 28% of the global terrestrial Co resources and reserves (Savinova *et al.* 2023). These deposits typically contain about 1 wt.% Ni and have a cobalt grade of 0.025 to 0.22 wt.% (Figure 3-2) with an average of about 0.05 % (Berger *et al.* 2011; Hitzman *et al.* 2017). In addition, locally they contain abundant scandium and occasionally have elevated PGE concentrations (Slack *et al.* 2017).

Nickel-cobalt laterite deposits are shallow deposits with thicknesses from 10-40 meters and can be classified into three primary types (Dehaine *et al.* 2021). The first type consists of hydrous silicate deposits, characterized by oxide laterites at the top layer, beneath which hydrous magnesium-nickel silicates are found in the lower saprolite. The second type is clay silicate deposits, where smectite clays have formed in the mid or upper layer of saprolite. Lastly, the third type comprises limonite deposits, in which altered bedrock is covered by iron oxyhydroxides.

Metal accumulation of cobalt (and other metals) in laterite deposits is a result of chemical and physical changes associated with atmospheric leaching. Humid tropical or subtropical climates with high rainfall and prolonged weathering conditions are favorable for the formation of Ni-Co laterite deposits. The combination of moisture and temperature contributes to the leaching and concentration of nickel and cobalt in the weathered profiles. Also, the topography of an area influences the formation of Ni-Co laterite deposits. Flat or gently sloping landscapes favor the accumulation of weathered material and the development of laterite profiles. Finally, the degree of permeability of the regolith material is important for the deposit formation, and thus faults, fractures, joints and cleavage plans play a key role in the mineralization processes (Petavratzi *et al.* 2019). Although some fossil Ni-Co laterites are known, these deposits are generally geologically young, with typical ages ranging from mid-Tertiary to Holocene (Slack *et al.* 2017). Major ore constituents include garnierite, nickel or cobalt-bearing clays, erythrite, heterogenite, asbolane, heazlewoodite, millerite, goethite and lithiophorite (Slack *et al.* 2017).

As this type of deposits typically forms in a humid tropical climate through weathering of ultramafic rocks, most deposits and mineral occurrences are found in equatorial regions with large resources in New Caledonia, Australia, Cuba, Indonesia, and Brazil (Figure 3-3). Important examples of this deposit type are Kalgoorlie and the Murrin Murrin deposits in Western Australia, the Goro deposit in New Caledonia and the manganiferous Nkamouna cobalt-nickel deposit in Cameroon. The latter deposit, which has not been mined yet, is one of the few in which cobalt would be the primary metal to exploited (Dzemua & Gleeson 2012).

3.1.3 Magmatic nickel-copper (cobalt-PGE) sulphide deposits

Magmatic nickel-copper (cobalt-PGE) deposits are a type of ore deposit formed by magmatic processes in mafic or ultramafic igneous rocks. They comprise three subtypes that can carry cobalt in economic concentrations: 1) magmatic sulphide nickel-copper (cobalt-PGE) deposits, 2) magmatic PGE deposits in layered intrusions and 3) komatiitic nickel-copper-cobalt PGE deposits which are typically of Archean or Proterozoic age.

Although these different subtypes vary considerably in size and shape, they tend to occur as conformable layers and lenses that occupy depressions in the base of the magmatic host bodies and economic deposits range from about 5 to more than 500 Mt of ore with cobalt grades typically between 0.05 and 0.1% Co (Mudd *et al.* 2013; Horn *et al.* 2021). Thus Ni-Cu-Co-PGE deposits tend to have relatively lower cobalt grades compared to the sedimentary-hosted Cu-Co deposits, but due to their larger size, many of these deposits still hold substantial quantities of cobalt (Figure 3-3).

The primary hosts for cobalt are cobaltiferous pentlandite and, to a lesser extent, linnaeite (Slack *et al.* 2017) and the exact mineralogy and abundance of cobalt and PGE vary depending on the specific deposit. The accompanying minerals typically comprise primary magmatic minerals like olivine, pyroxene, and plagioclase.

The mineralization processes primarily involve the segregation of sulphides during magmatic activities, usually as result of interaction with continental crustal rocks. Externally derived sulphur caused an immiscible sulphide melt to form, which scavenges metals including nickel, copper and cobalt, due to its high partitioning coefficient of such chalcophile elements. The sulphide melt is denser than the co-existing silicate melt and therefore accumulates at the bottom of the magma chamber or magma conduit where it forms a mineral deposit (Lesher & Keays 2002).

Nickel is the main economic commodity in most magmatic deposits (Dehaine *et al.* 2021). Copper can be present as co-product or by-product, with cobalt as a minor by-product and with platinum group elements occurring in some deposits as by-products or even as the main commodity, which is the case particularly for PGE deposits in layered intrusions.

Magmatic nickel-copper deposits are commonly associated with large-scale igneous provinces and can be found in various tectonic settings, including rift zones, convergent plate boundaries, or intraplate settings. Examples of magmatic nickel-copper deposits include the Sudbury and Voisey's Bay deposits in Canada, the Norilsk-Talnakh deposit in Russia, the Jinchuan deposit in China and the platinum group ores of the Bushveld Complex in South Africa.

3.1.4 Other cobalt deposit types

Cobalt can be found in significant concentrations in various geological settings. In many of these environments, cobalt is typically produced in relatively small quantities, often as a by-product of mining operations targeting copper, nickel, silver, lead, and zinc (Horn *et al.* 2021). These other cobalt deposits include black-shale hosted deposits, iron-oxide Cu-Au deposits (IOCG), metasediment-hosted Co-Cu-Au deposits, Mississippi-Valley type deposits (MVT), polymetallic and other cobalt-rich vein deposits, skarn and replacement deposits, and volcanogenic massive sulphides (VMS). For further information regarding the key features of these deposits, interested readers are encouraged to refer to the descriptions provided by Slack *et al.* (2017), Petavratzi *et al.* (2019), and Horn *et al.* (2021).

It is worth noting that in addition to terrestrial cobalt resources, significant mineral resources are also found in the seabed of the world's oceans (Hein *et al.* 2013). In fact, the deep-sea harbors some of the largest known cobalt resources (Figure 3-3). While currently not commercially exploited, ferro manganese nodules and crusts are found on the seabed and represent a major mineral potential for Co with more than 120 Mt of cobalt resources identified on the floor of the Atlantic, Indian and Pacific Oceans (USGS 2023).

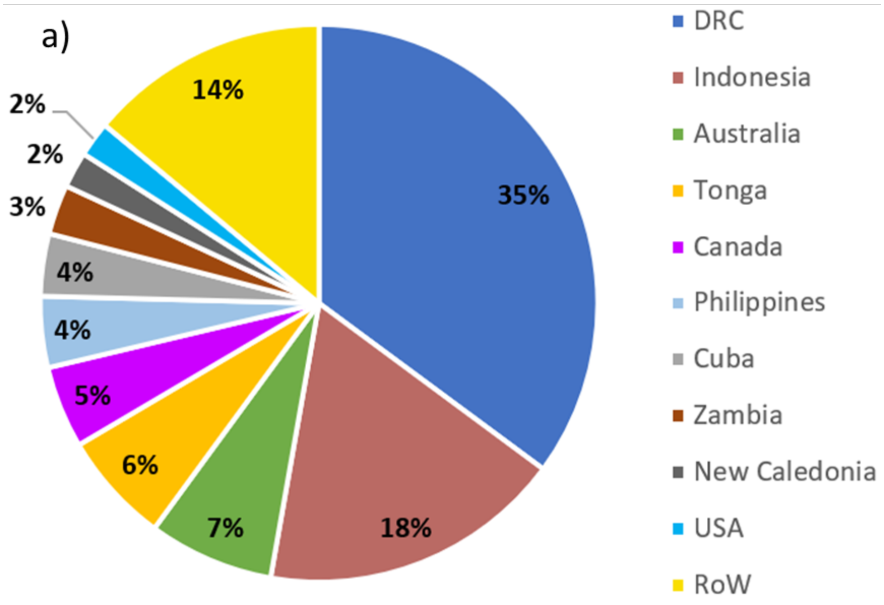
Deep sea mineral resources, including those with cobalt potential, are being closely assessed for their potential contribution to the global supply of metals. However, extracting these resources presents significant technological and environmental challenges due to the extreme depths and delicate ecosystems of the deep ocean and is not considered further here.

3.1.5 Global cobalt resources and reserves

Mineral resources represent a feasible possibility for future economic extraction, albeit with some uncertainty due to incomplete evaluation of all influencing factors. These resources are categorized in increasing levels of confidence as inferred, indicated, and measured. Ore reserves, on the other hand, are evaluations that indicate justifiability for profitable extraction at the time of reporting. These reserves are further classified with ascending confidence as probable ore reserves and proven ore reserves.

According to USGS, identified world terrestrial cobalt resources in 2019 were about 25 million tons. Most of these resources are in sediment-hosted stratiform copper deposits in the Democratic Republic of the Congo (DRC) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulphide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and USA, as shown in Figure 3-4a. More than 120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian and Pacific Oceans.

The world's total cobalt reserves in 2019 amounted to 6.5 million tons (USGS 2020a) with the largest reserves in the DRC with approximately 51%, followed by Australia (20%), Cuba (7%) and the Philippines (4%) (Figure 3-4b).



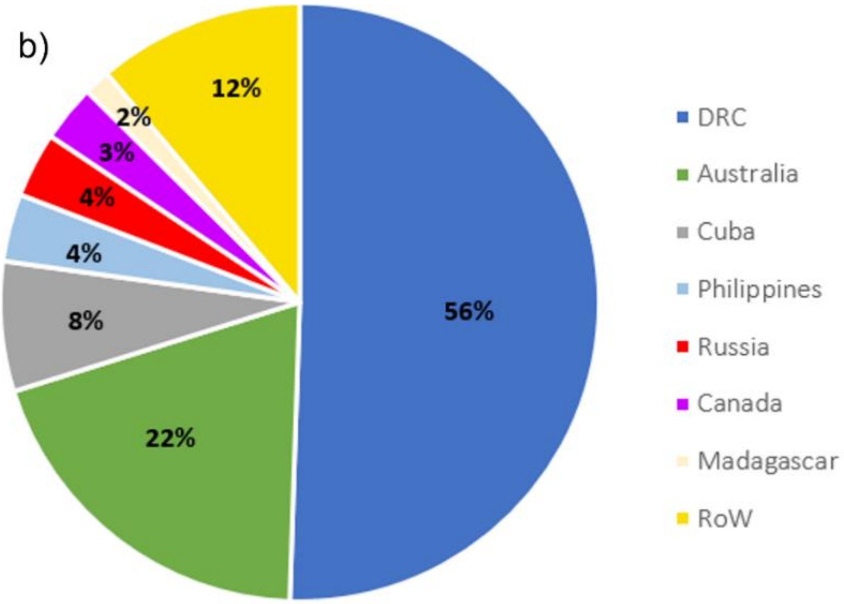


Figure 3-4 *Global cobalt resources (a) and reserves (b) in percent by country. Total resources and reserves amounted in 2019 to 25 and 6.5 million tons respectively. RoW – Rest of the World (USGS 2020a).*

3.2 Cobalt mining

Cobalt mining uses conventional open cut or underground techniques, depending on the deposit type and its location in the ground and some fields are using both methods concurrently.

In 2019, around 144,000 tons cobalt ores were mined in the world (USGS 2021). Among them, around 69% were produced in the DRC, followed by Russia (4%), Australia (4%), and the Philippines (4%); see Figure 3-5. This ranking roughly parallels the global distribution of cobalt reserves, but the DRC makes up an even higher percentage at the mining stage. If divided by deposit types, around 60% of cobalt are mined from stratiform sediment-hosted copper-cobalt deposits, 26% from nickel-cobalt laterite deposits, 12% from magmatic nickel-copper (cobalt-platinum group element (PGE)) sulphide deposits, and only 2% from other types of deposits (Cobalt Institute 2020; CGS 2021). In addition, around 20% of the DRC's cobalt comes from artisanal mining in the southern part of the DRC (Calvão *et al.* 2021).

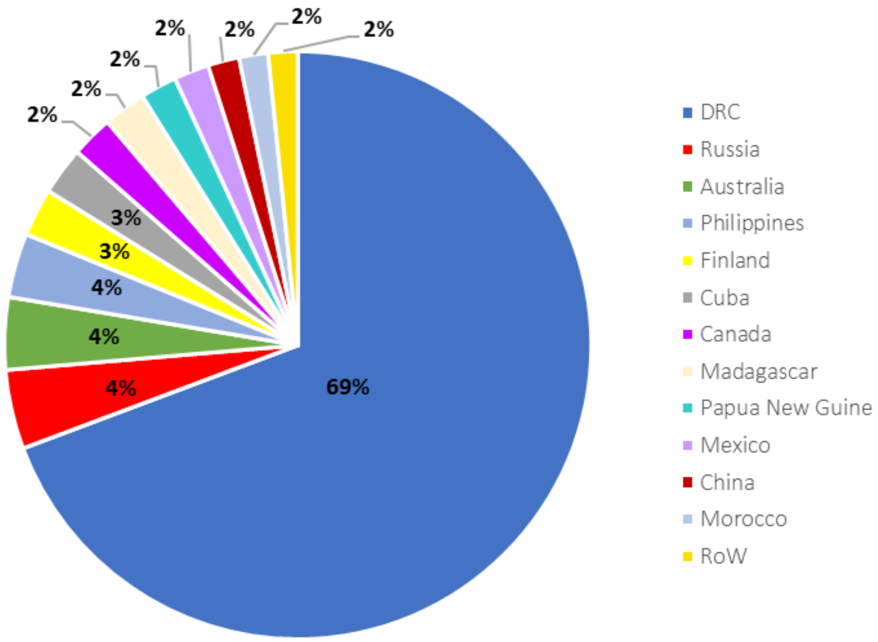


Figure 3-5 *Mined cobalt by country. Total mine production amounted to 144,000 tons in 2019. RoW – Rest of the World (USGS 2021).*

In Figure 3-6 and Table 3-2 in total 33 cobalt mines in 15 countries are shown. Figure 3-6 distinguishes itself from Figure 3-3 in that it exclusively enumerates active mines in the year 2019. Due to lack of transparency on detailed cobalt mining production, this list may not be complete.

Of the 33 mines, around 10 are in the DRC and produced around 10,000 tons in 2019 (Figure 3-6 and Table 3-2). Almost all the mines in the DRC are in stratiform sediment-hosted copper-cobalt deposits that is the most important source of cobalt globally, which located in CACB listed in Figure 3-3 and accounted for 60% of the global production in 2019 (Petavratzi *et al.* 2019). Nickel-cobalt laterites are widespread in countries such as Australia, New Caledonia, and Cuba. Magmatic nickel-copper-cobalt-PGE deposits are found in Australia, Canada, Russia, Finland and USA (Brown *et al.* 2021). EU has relatively limited cobalt reserves, and in 2019 there was only two active mines, both located in Finland (Horn *et al.* 2021).

Table 3-2 *Global active cobalt mines in 209 (China Molybdenum 2020; Eurasia Mining PLC 2020; Glencore 2020; Huayou Cobalt 2020; Jinchuan Group International Resources Co. Ltd. 2020; Nornickel 2020; Roskill 2020a; Sumitomo Metal Mining Co. Ltd. 2020; Vale 2020; CGS 2021). Deposit types: 1 refers to stratiform sediment-hosted Cu-Co deposits, 2 refers to Ni-Co lateritic deposits, 3 refers to magmatic nickel-copper (cobalt-PGE) deposits, 4 refers to other deposit types.*

No.	Country	Production in 2019 (t)	Project/mine name	Deposit type	Ownerships & Nationality
1	Australia	3,040	Murrin Murrin	2	Glencore (100%) Switzerland
2	Australia	1,000	Nova	3	IGO (100%) Australia
3	Australia	1,700	Mt. Keith, Leinster	2	BHBP (100%) Australia
4	Canada	1,608	Voisey's Bay	3	Vale (100%) Brazil
5	Canada	495	Sudbury	3	Vale (100%) Brazil
6	Canada	700	Turnagain	3	Glencore (100%) Switzerland
7	Canada	80	Thompson	3	Vale (100%) Brazil
8	China	2,030	Jinchuan Mine	2	Jinchuan (100%) China
9	China	31	Kalatongke	4	Xinjiang XinXin (100%) China
10	Cuba	3,376	Pedro Soto Alba	2	Sherritt (50%) Canada, General Nickel Company SA (50%) Cuba
11	Cuba	424	Punta Gorda	2	Sherritt (50%) Canada, General Nickel Company SA (50%) Cuba
12	DRC	25,100	Mutanda	1	Glencore (100%) Switzerland
13	DRC	16,098	Tenke Fungurume	1	China Molybdenum (80%) China, Gécamines (20%) DRC
14	DRC	8,000	Etoile and Usoke	1	Chemaf (Shalina Resources Group) (95%) UAE DRC, Government (5%) DRC
15	DRC	5,070	Ruashi (Kalukuluku)	1	Jinchuan（75%) China, Gécamines (25%) DRC
16	DRC	17,100	Kamoto	1	Glencore（75%) Switzerland, Gécamines (20%) DRC, SIMCO (5%) DRC
17	DRC	10,000	RTR	1	Eurasia Group (74%) Kazakhstan, Gécamines (26%) DRC
18	DRC	2,800	Kamoya	1	Wanbao Mining (100%) China
19	DRC	4,600	Kambove, Kasulo	1	Huayou Cobalt (100%) China
20	DRC	2,700	MKM, Luishia, SICOMINES I	1	China Railway (100%) China
21	DRC	1,200	Kisanfu	1	Somika (100%) DRC
22	Finland	445	Kevitsa	3	Boliden (100%) Sweden
23	Finland	1,500	Sotkamo	4	Terrafame 100% Finland

No.	Country	Production in 2019 (t)	Project/mine name	Deposit type	Ownerships & Nationality
24	Madagascar	3,400	Ambatovy	2	Sumitomo Corp. (57.17%) Japan, Resources Corporation (22.5%) South Korea, Sherritt (12.33%) Canada
25	Mexico	2,780	Boleo	1	Resources Corporation (93%) South Korea, Camrova Resources (7%) Canada
26	Morocco	1,900	Bou Azzer	4	Compagnie de Tifnout Tighanimine CTT, (100%) Morocco
27	New Caledonia	1,703	Goro	2	Vale (100%) Brazil
28	Philippines	2,000	Taganito	2	Sumitomo Metal Mining (100%) Japan
29	Philippines	3,100	Rio Tuba	2	
30	Papua New Guinea	3,100	Ramu	2	China Metallurgical Group Corporation MCC (85%) China, Mineral Resources Development Company MRDC (6.44%) Papua New Guinea, Nickel 28 Capital Corp (8.56%) Canada
31	Russia	6,100	Talnakh	2	Nornickel (100%) Russia
32	South Africa	1,100	Bushveld Complex	3	Anglo America (100%) UK
33	Turkey	100	Gördes and Yunusemre	2	Meta Nickel Kobalt (100%) Turkey

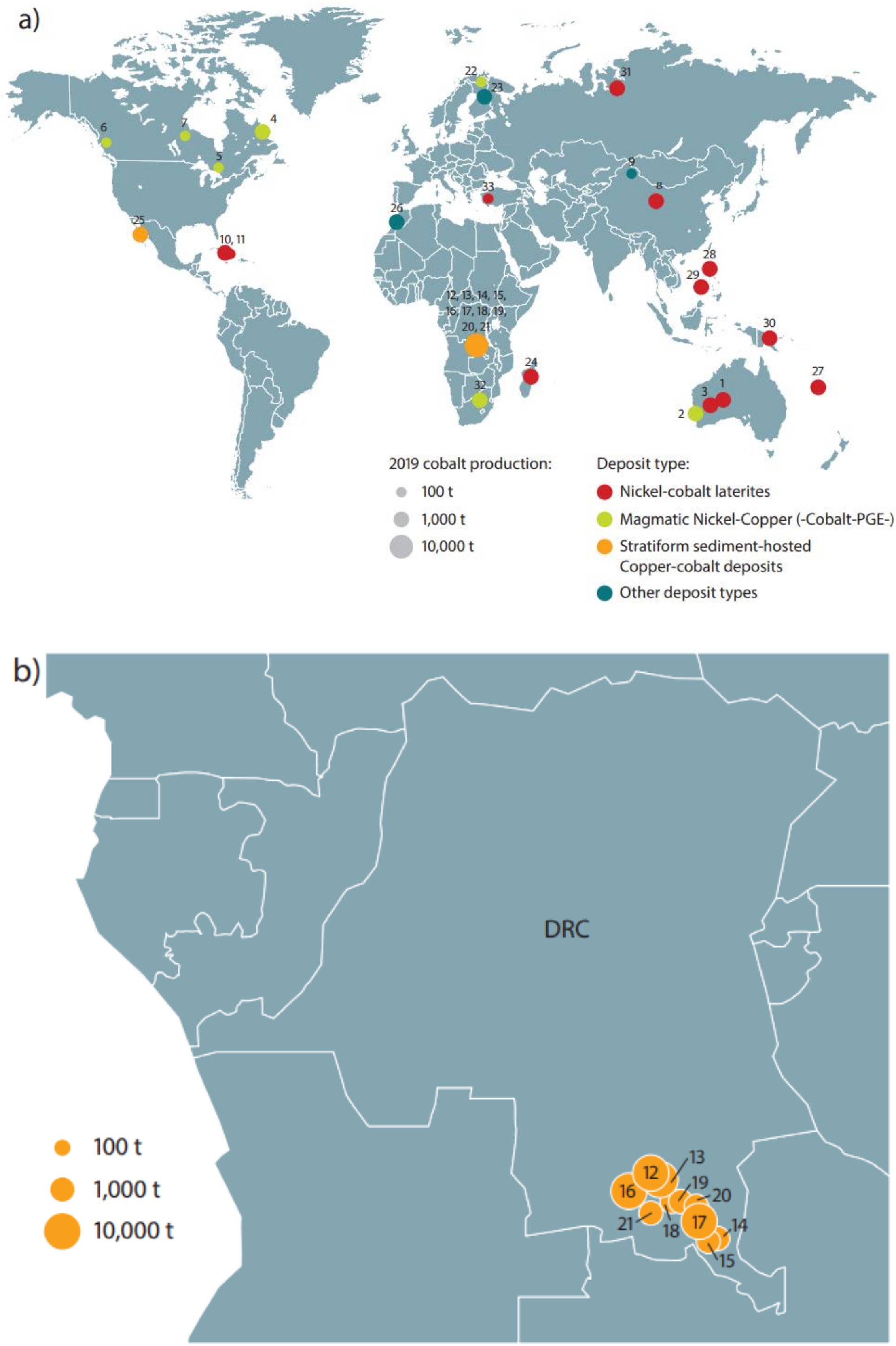


Figure 3-6 *Active cobalt production mines (a) worldwide and (b) in the DRC. (Source: data based on Table 3-2).*

Many cobalt mines are controlled by the same company. Table 3-3 lists the top 10 companies with the largest cobalt production in 2019, which together contributed with 78% of the global production (Roskill 2020a; CGS 2021). Glencore, with a first place ranking among companies, controls 100% of the production from three mines: Mutanda, Murrin Murrin and Raglan, and holds 75% of the shares of Kamoto. According to Roskill, Glencore directly controlled approximately 32% of the cobalt production in 2019 (Roskill 2020a). In addition, they control cobalt mining production indirectly; e.g., the Big Hill mine is operated by Group de Terril Lubumbashi, with which Glencore signed a business agreement to ensure Glencore to be the only market for cobalt produced from Big Hill (Glencore 2018). Meanwhile, there are more upcoming mining projects carried out by Glencore worldwide, indicating that Glencore will play an even bigger role in global cobalt mining in the future.

Table 3-3 *The top 10 cobalt mining companies with the largest production in 2019 (China Molybdenum 2020; Eurasia Mining PLC 2020; Glencore 2020; Huayou Cobalt 2020; Jinchuan Group International Resources Co. Ltd. 2020; Nornikel 2020; Roskill 2020a; Sumitomo Metal Mining Co. Ltd. 2020; Vale 2020).*

Company	Operation/Operator	Country	Production in 2019 (t)	%
Glencore	Mutanda, Kamoto, Murrin Murrin, etc.	DRC, Australia, Canada	46,265	32
Gecamines	Tenke Fungurume, Kamoto, Ruashi, RTR, etc.	DRC	13,280	9
CMOC	Tenke Fungurume	DRC	12,898	9
Shalina Resources	Etoile and Usoke	DRC	7,600	5
ERG	RTR	DRC	7,400	5
JNMC	Ruashi, Jinchang, etc.	DRC, China	5,800	4
Nornickel	Talnakh	Russia, South Africa	6,100	4
Sumitomo Metal Mining	Taganito, Rio Tuba	Philippines	5,100	4
Huayou	Kambove, Kasulo	DRC	4,600	3
Vale	Voisey's Bay, Goro, Thompson, etc.	Canada, New Caledonia, Indonesia	3,791	3

Figure 3-7 shows the cobalt mining production in selected countries with a large cobalt production as well as the countries that the main companies are associated with. The affiliation of countries with companies is primarily influenced by the location of the companies' headquarters. Switzerland, who does not have cobalt resources or reserves of its own, ranks top in mining production based on the companies' nation affiliation, since the largest mining company, Glencore, is based in Switzerland. Through overseas investments, Glencore owns the three largest cobalt production projects in DRC. Coupled with their investments in Australia and Canada, Glencore had in total around 46,000 tons cobalt output in 2019. China ranks second thanks to contributions from overseas investments with ownership of cobalt mining operators in the DRC and Papua New Guinea (PNG), as well as its domestic cobalt mines. Kazakhstan is similar to Switzerland in not having cobalt resources nor reserves of its own, but through overseas investments they own over half of the shares in the giant mining producer ERG which makes Kazakhstan the fourth largest cobalt producing country in 2019. The DRC's rank shifts from first to third if considering the operator's nation affiliation. Generally speaking, mining production distribution is less concentrated based on the main operators' nation affiliation compared with the geographic locations of the mines. However, the cobalt market is dynamic, and there are frequent changes in foreign direct investments and the operators' ownership. For example, the share of BHR New Wood DRC Holdings owned Tenke Fungurume Mine was taken over by China Molybdenum, whereby its ownership increased from 56% to 80% in 2019 (China Molybdenum 2020). Therefore, a given rank is only valid for a limited period of time.

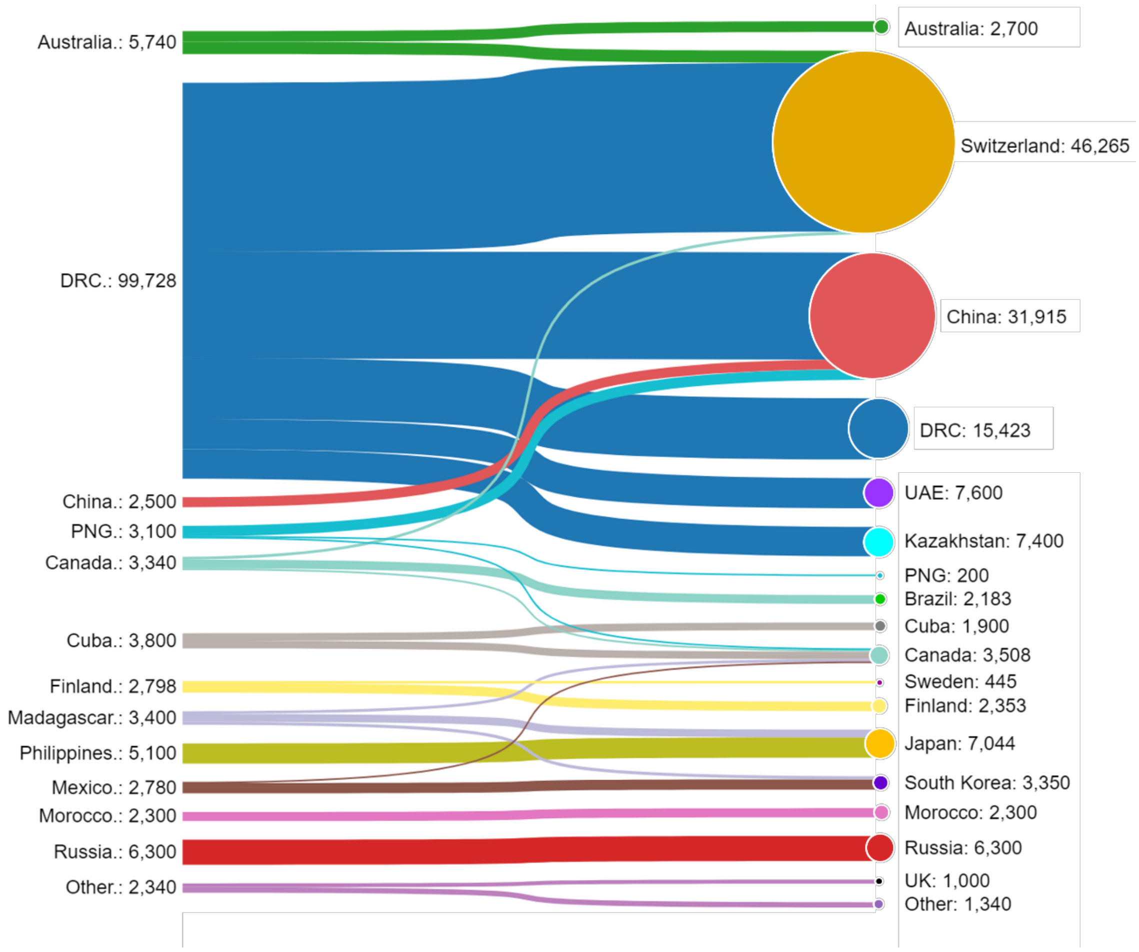


Figure 3-7 *Comparison of cobalt mine production by countries based on geological location and operator's nation affiliation (Source: data based on Table 3-2 and USGS 2020a)*

Figure 3-8 shows the global major trade flow of cobalt mined in 2019. The cobalt mining trade is based on HS code 260500 "Cobalt ores and concentrates", assuming a 7% cobalt content based on Gulley *et al.* (2019). In total around 105,000 tons gross weight of cobalt ore (equal to 7,250 tons cobalt) was traded at mine stage, comparing with the total mining production of 144,000 tons cobalt, it is clearly seen that only around 5% of the cobalt mine were traded across countries. The majority of mining producers undertake processing to intermediate products domestically to lower the high costs of shipping bulky, low value ores and concentrates (Baars *et al.* 2021), but the following exceptions were identified in 2019: Ni-Cu-Co-PGMs concentrates from Zimbabwe were shipped to China and South Korea; and Co and Cu-Co concentrates from the DRC were shipped to China and Morocco. Among them, the DRC is the world's largest net exporter of cobalt ores and concentrates; nearly 10 times greater than net exports from all other countries, and the major destination was to China in 2019.

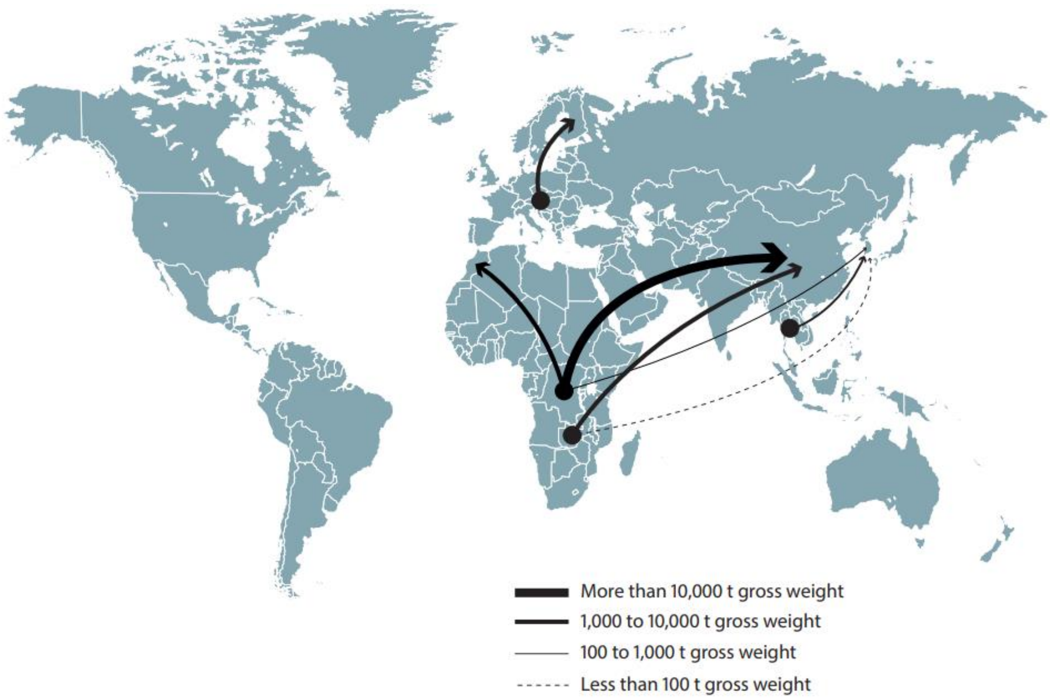


Figure 3-8 *Global major net import flow of cobalt ores and concentrates (HS code 260500) in 2019. Some trade flows cannot be shown because of the limited availability of data (Data source: UN Comtrade).*

3.3 Cobalt processing

3.3.1 Cobalt intermediate processing

Cobalt intermediate processing is a step between mining and final product refining and is often taking place near the mine. Cobalt is generally a by-product of copper and nickel extraction; hence their production is commonly linked.

A typical flow sheet for cobalt intermediate processing (marked in blue) and refining (marked in green) is illustrated in Figure 3-9, with various intermediates and refining products shown in diamond (Mulaudzi & Kotze 2013). It can be seen that concentrates, mattes and precipitants are all intermediate products which can be traded internationally. Mixed hydroxide precipitate (MHP) is the common intermediate cobalt product for the Copperbelt of Africa. MHP normally contains 17 wt.% Co when lime or limestone is used as precipitant and 35-40% wt.% when MgO is used as precipitant. Other intermediates can be in the form of carbonates, sulphides, or sulphates, depending on ore types.

Since the majority of mining producers undertake processing to intermediate products domestically, it is not surprising to see the DRC again is the largest producer, contributing with around 69% of the total production of intermediates in 2019 (Cobalt Institute 2020); see Figure 3-10. China is the second largest producer with approximately 9% of the total production, thanks to importing cobalt ore from the DRC and other countries. The other cobalt-rich countries, such as the Philippines, Australia, Madagascar, PNG, Cuba, Canada, and Russia, contribute with around 2-3% of the intermediate production, mainly based on domestic cobalt mining production.

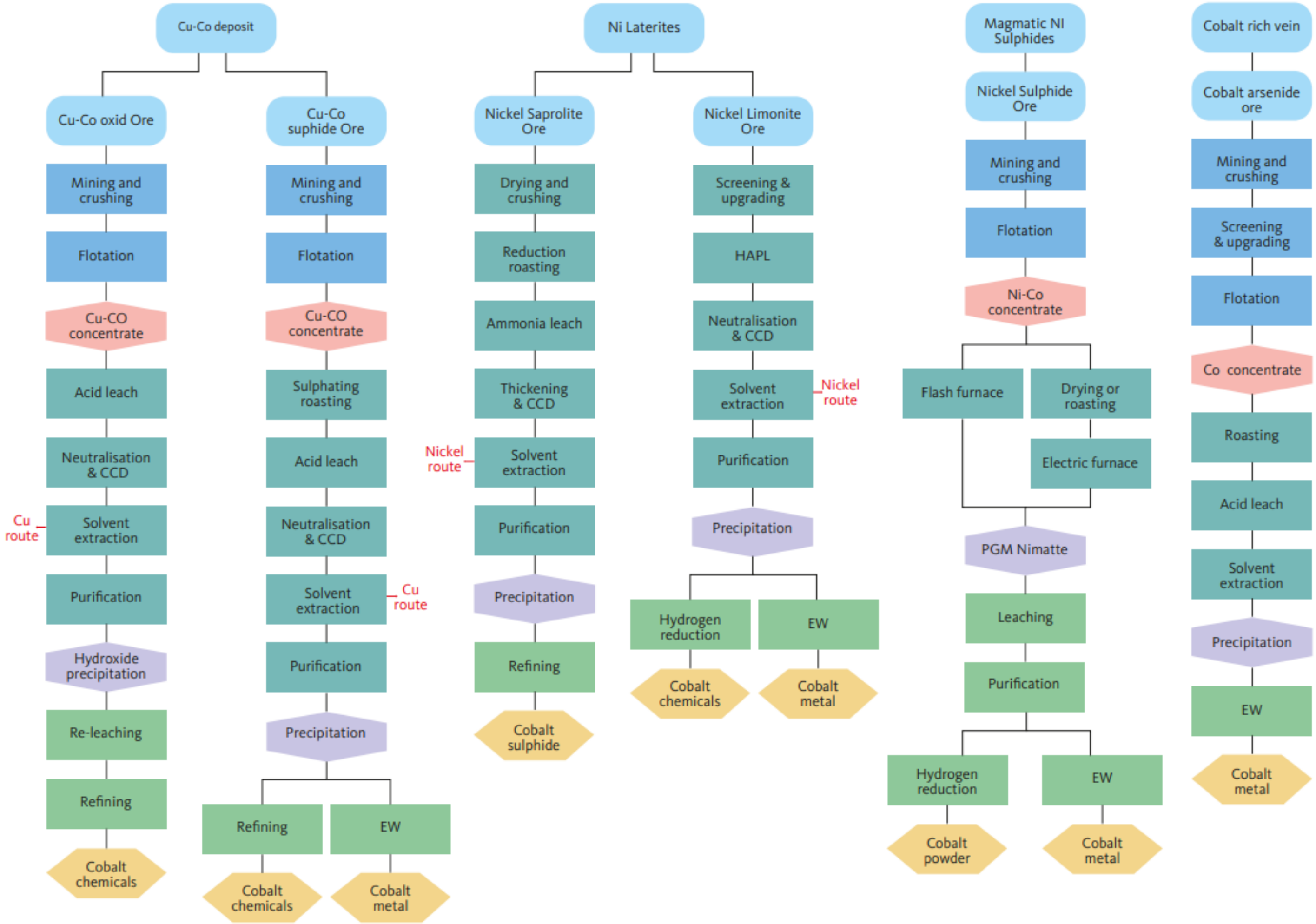


Figure 3-9 *Overview of the main processing routes for cobalt extraction as a function of the deposit and ore type (Dehaine et al. 2021). CCD: Counter-Current Decantation, EW: Electro-Winning, HPAL: High Pressure Acid Leaching.*

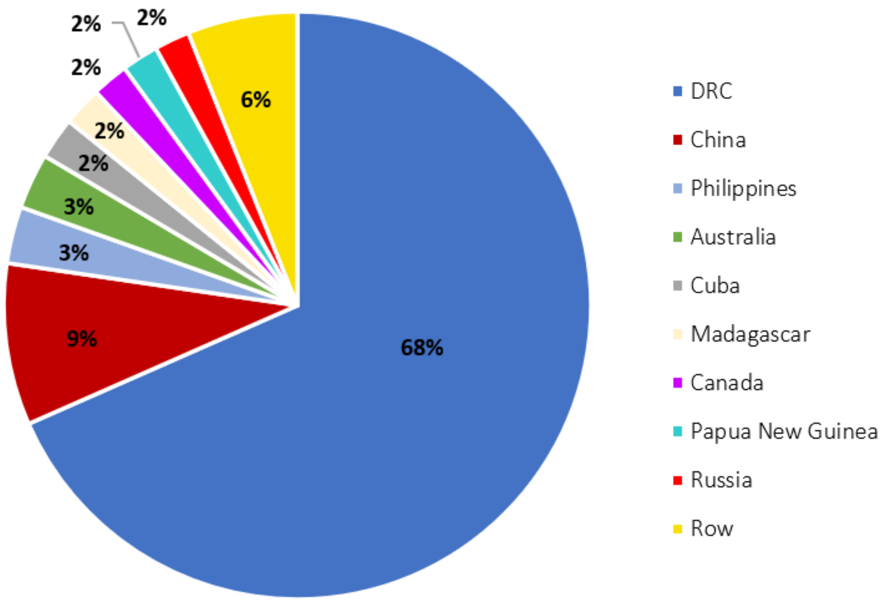


Figure 3-10 *Cobalt intermediate production by country. Total intermediates production amounted to 139,000 tons in 2019 (Cobalt Institute 2020).*

Since the intermediate production takes place near or at the same location as the mines listed in Table 3-2, the exact intermediate process locations are not replicated here. Due to the strategy of vertical integration, many mining companies are also intermediate producers. Table 3-4 lists the 2019 top 10 cobalt intermediate producing companies, 8 of them are among the top 10 mining producers as well, though the exact ranks are slightly different. It is estimated that in 2019, around 139,000 tons cobalt intermediates were produced globally, and the top 10 producers in total produced 81% of the total amount. Glencore is again the largest intermediate producer, contributing with around 33% alone. The four Chinese companies COMC, JNMC, Huayou, and Hanrui have a higher proportion of intermediate production relative to their mining production.

Table 3-4 *Top 10 cobalt intermediate companies with the largest production in 2019 (China Molybdenum 2020; Eurasia Mining PLC 2020; Glencore 2020; Huayou Cobalt 2020; Jinchuan Group International Resources Co. Ltd. 2020; Nornikel 2020; Roskill, 2020a; Sumitomo Metal Mining Co. Ltd., 2020; Vale, 2020).*

Company	Operation/Operator	Country	Production in 2019 (t)	%
Glencore	MUMI, KCC, Murrin Murrin, etc.	DRC, Australia, Canada	46,500	33
CMOC	Tenke Fungurume	DRC	16,100	12
JNMC	Ruashi, Jinchang, etc.	DRC, China	10,500	8
ERG	RTR, Boss Mining	DRC	8,100	6
Shalina Resources	Etoile, Usoke, Mutoshi	DRC	7,900	6
Huayou	MIKAS, CDM	DRC	6,800	5
Vale	Goro, Copper Cliff, Long Harbour, Sorowako	Canada, New Caledonia, Indonesia	5,300	4
SMM	Taganito, Rio Tuba	Philippines	4,500	3
Hanrui	Metal Mines	DRC	3,900	3
Sumitomo Corp.	Ambatovy	Madagascar	3,100	2

Figure 3-11 shows the 2019 global major net import flows of cobalt mattes and intermediate products of cobalt based on HS code 8105 “Mattes and other intermediate products of cobalt metallurgy; cobalt and articles thereof, including waste and scrap” and HS code 2822 “Cobalt oxides and hydroxides”. Data are derived from the UN Comtrade database assuming a cobalt content for intermediates of 27% (Gulley *et al. 2019*). The DRC is the world’s largest net exporter of both HS 8105 and HS 2822 trade items. This is not surprising considering that the DRC is the largest producer of intermediates globally. However, there is considerable uncertainty since the HS 8105 does not differentiate between different cobalt compounds. As a result, it is not possible to undertake an analysis of specific traded cobalt compounds from individual countries such as the DRC. It is possible that the net exports under the same code for the different countries represent different compounds, and consequently different stages in the cobalt supply chain (Baars *et al.* 2021). Other important net exporters are PNG (5%), the Philippines (3%), Cuba (2%), and Russia (1%), which are mainly cobalt-rich countries, but presently without or with only insufficient downstream refining capacities.

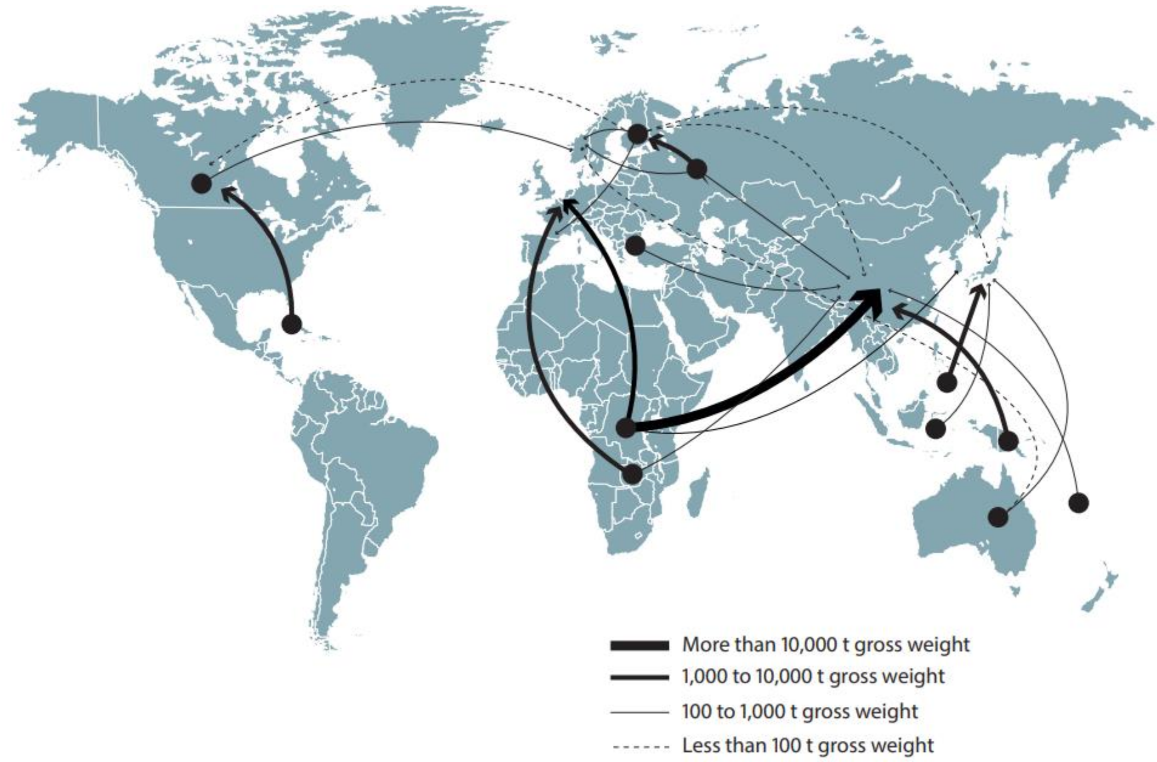


Figure 3-11 *Global major net import flows of cobalt mattes and intermediate products in 2019 (Data source: UN Comtrade). Some trade flows cannot be shown because of the limited availability of data.*

In 2019, China was the largest importer of cobalt intermediates (Figure 3-11). Compared to a decade ago, Chinese refineries now largely prefer to purchase cobalt intermediates directly instead of cobalt ores and concentrates. There are two reasons for this: 1) The government of the DRC has announced intentions to impose an export ban on cobalt raw materials (Hjelmstedt 2021). Although the DRC over the past few years has repeatedly postponed the ban, Chinese buyers have already pre-empted a potential export ban by turning to intermediates. 2) Cobalt ores and concentrates are no longer suitable for Chinese refinery systems (Gulley *et al.* 2019). Chinese refineries use cobalt intermediates as raw materials, which do not include the processing step. This change is positive for both sides: more value could be added to the DRC by extending the cobalt supply chain domestically and for China, the transportation cost is reduced dramatically while importing the same amount of cobalt, since the cobalt content in intermediates is typically around 27%, compared to the concentrates which typically hold less than 10% cobalt (Baars *et al.* 2021). Other important importers of intermediates include Finland, Belgium, Japan, France, and Canada (as shown in Fig. 3.11), and most of them have huge demands for cobalt or plan to expand refining capacity domestically.

3.3.2 Cobalt refining

Refiners rely on either intermediate cobalt products or ores to produce refined cobalt. Refining adds more value, so many cobalt-rich countries prefer to have the ores refined domestically. However, the refining process requires both energy and chemicals, which are not available everywhere. For example, the government of the DRC has several times tried to ban the export of unrefined ores and intermediates, but the shortage of electricity in the DRC makes it impossible to have all the ores and intermediates refined locally (World Bank 2020). Therefore, the current compromise is to process ores and concentrates to a certain level in the DRC, and then export intermediates to countries with the necessary refining capacities (Amber 2018). As shown in Figure 3-9, there are two types of refined cobalt products: cobalt metal and cobalt chemicals.

Cobalt metal is available in powders, granules, briquettes, cathodes, rounds, pellets, and ingots. Pure cobalt metal is produced by two principal processing routes: hydrometallurgy and pyrometallurgy (Petavratzi *et al.* 2019). Hydrometallurgy relies on differences in the solubility and electrochemical properties of different materials. Pyrometallurgy uses differences in the melting points and densities of materials to separate them.

Cobalt chemicals take various forms, including cobalt salts, oxides, and carboxylates. Cobalt salts include a long range of products, such as chlorides, sulphates, nitrates, carbonates, acetates, etc. Cobalt oxides and hydroxides are produced alongside cobalt salts in chemical refineries. The cobalt salts are derived through a variety of refining steps. For example, cobalt sulphate is produced via steps of evaporation and crystallization; cobalt sulphide can be precipitated using sodium hydrosulphide (NaHS) or hydrogen sulphide (H_2S); and cobalt hydroxide is produced through precipitation with magnesia and lime. Detailed refining processes from different types of cobalt ores are shown in Figure 3-9. Most of the African copper-cobalt sulphide concentrate is processed “in-house” to produce an impure crude cobalt hydroxide. This is then shipped to China’s chemical refineries, where a range of cobalt salts, including cobalt oxide and hydroxide, are further refined (Petavratzi *et al.* 2019; Dehaine *et al.* 2021).

In 2019, around 136,000 tons cobalt refinery products were produced worldwide (Cobalt Institute 2020). Among them, around 64% are in the form of chemicals, and the rest 36% are in the form of metal. Efforts are made to avoid double-counting, but it is not always possible to be certain. Of the produced cobalt, around 63% were produced in China, followed by Finland (9%), Belgium (5%), Canada (4%), and Japan (4%); see Figure 3-12a. From Figure 3-12b and Figure 3-12c it is clear that cobalt chemicals production is more concentrated in few countries compared with cobalt metal production. The top 3 countries China, Belgium, and Finland produced 95% of cobalt chemicals in 2019. In contrast, the top 3 producers of refined cobalt metal only produced 56% of the total cobalt metal in 2019. Thanks to international trade of cobalt ores and intermediates, countries that lack cobalt resources, e.g., Belgium, Japan, and South Korea, have started to produce refined cobalt, and their production increases with time.

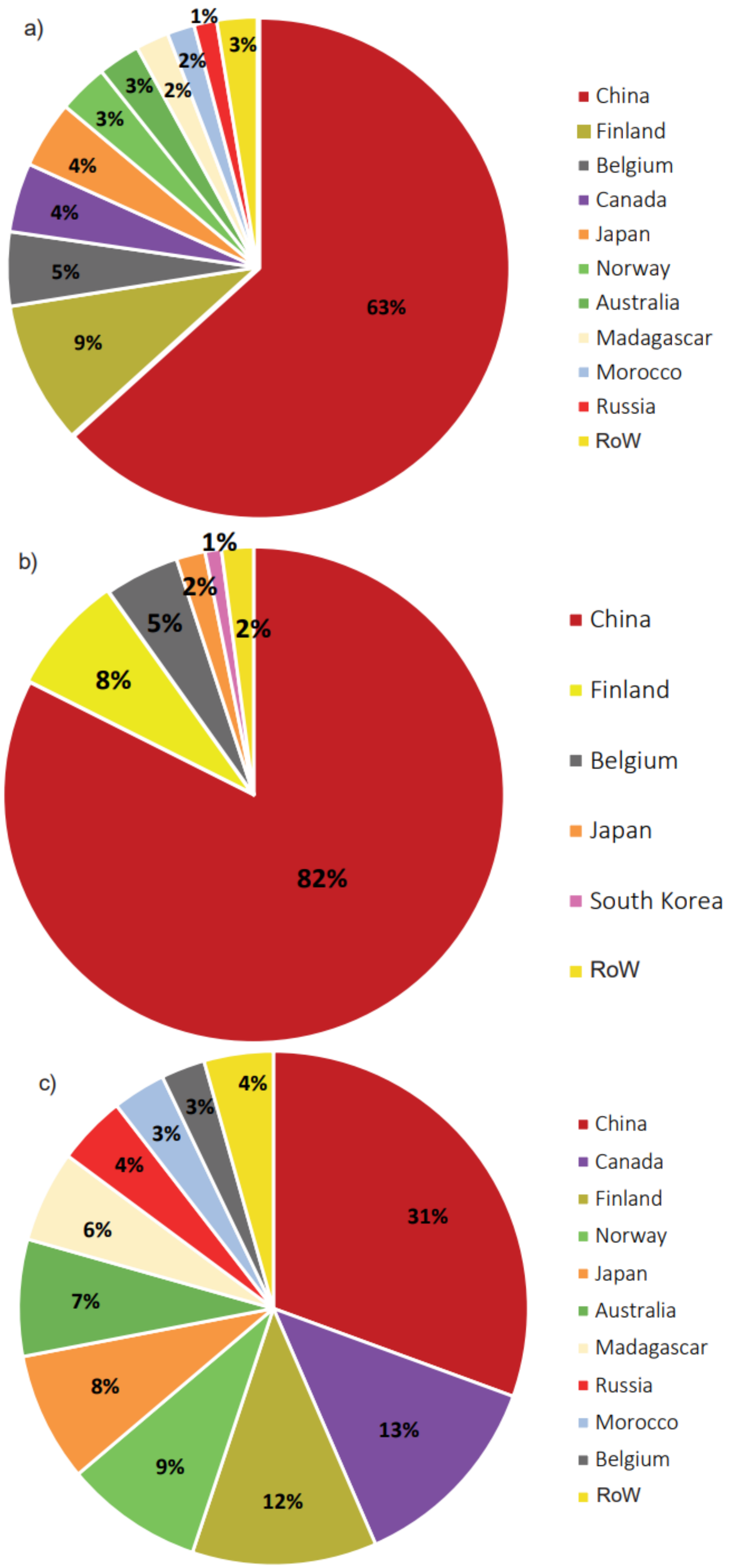


Figure 3-12 *Break-down of producing countries of a) total refined cobalt; b) refined cobalt chemicals; and c) refined cobalt metal in 2019. Source: Cobalt Institute 2020.*

Table 3-5 *Active cobalt smelters worldwide in 2019 (Glencore 2020; Huayou Cobalt 2020; Jinchuan Group International Resources Co. Ltd. 2020; Roskill 2020a; Sumitomo Metal Mining Co. Ltd. 2020; Vale 2020; Umicore 2020).*

No.	Project/mine name	Production in 2019 (t)	Country	Ownership(s) & Nationality	Product(s)
1	Quzhou	23,300	China	Huayou Cobalt (100%) China	Chemical
2	Kokkola	13,300	Finland	Umicore (100%) Belgium	Metal & Chemical
3	Lanzhou	11,300	China	JNMC (100%) China	Metal & Chemical
4	Jingmen	8,000	China	Shenzhen GEM (100%) China	Metal & Chemical
5	Ningxiang	7,800	China	CNGR (100%) China	Metal & Chemical
6	Taixing	6,000	China	Shenzhen GEM (100%) China	Metal & Chemical
7	Olen	6,000	Belgium	Umicore (100%) Belgium	Metal & Chemical
8	KwaZulu-Natal	5,900	South Africa	Shenzhen GEM (100%) China	Metal & Chemical
9	Tianjin	5,400	China	Hezong (100%) China	Chemical
10	Niihama	5,300	Japan	SMM (100%) Japan	Metal & Chemical
11	Yingde	4,900	China	GD Dowstone (100%) China	Chemical
12	Ganzhou	4,800	China	Ganzhou Tengyuan (100%) China	Chemical
13	Nikkelverk	4,700	Norway	Glencore (100%) Switzerland	Metal
14	Jinchuan Nickel Complex	4,500	China	JNMC (100%) China	Metal & Chemical
15	Zhuhai Kelixin Metal Materials	3,810	China	Zhuhai Kelixin Metal Materials (100%) China	Chemical
16	Murrin Murrin	3,400	Australia	Glencore (100%) Switzerland	Metal
17	Fort Saskatchewan	3,400	Canada	Sherritt (100%) Canada	Metal
18	Ambatovy	2,900	Madagascar	Japan Sumitomo Corp. (65.17%), South Korea Resources Corporation (22.5%), and Canadian Sherritt International Corp. (12.33%)	Metal
19	Nanjing, Chuzhou,	2,700	China	Hanrui (100%) China	Chemical
20	Monchegorsk (Kola MMC)	2,400	Russia	Norilsk Nickel (100%) Russia	Metal
21	Shangyu	2,200	China	Greatpower (100%) China	Chemical
22	Ganzhou	2,000	China	Umicore (100%) Belgium	Chemical
23	Long Harbour	1,700	Canada	Vale (100%) Brazil	Metal

No.	Project/mine name	Production in 2019 (t)	Country	Ownership(s) & Nationality	Product(s)
24	Nanjing Plant	1,500	China	Hanrui (100%) China	Chemical
25	Port Colbome	1,400	Canada	Vale (100%) Brazil	Metal
26	Kolwezi	1,200	DRC	Hanrui (100%) China	Metal
27	Springs	900	South Africa	Implats (100%) South Afraica	Metal
28	Shituru Copper Refinery	200	DRC	Gecamines (100%) DRC	Metal
29	Fukang Refinery	110	China	Xinjiang XinXin Mining Industry (100%) China	Chemical

Figure 3-13 shows the geographical distribution of the dominant cobalt refining sites according to size and product type and the individual projects are listed in Table 3-5. In 2019 there were 29 active cobalt smelters located in 11 countries. There are cobalt smelters in other countries, but their contributions to the total cobalt production are negligible (Brown *et al.* 2021) and are therefore not considered here. Of the 29 smelters, 15 are located in China and the rest in Norway, Finland, Belgium, Morocco, Russia, DRC, South Africa, Canada, etc. Some smelters produce both cobalt metal and chemicals, while others only produce one type of refining products.

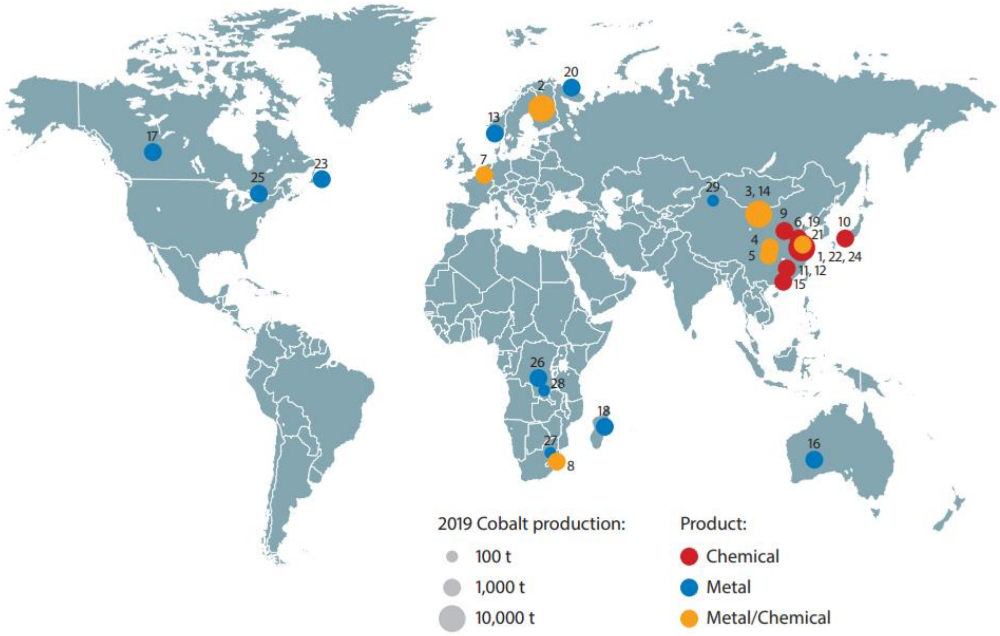


Figure 3-13 *Selected cobalt refining sites in 2019 worldwide. Data based on Table 3-5.*

As was seen with cobalt mines and intermediates plants, several cobalt smelters can be owned by the same company. Table 3-6 lists the top 10 refining companies with the largest production of both cobalt metal and chemicals; the 10 companies' share of the total production was in 2019 around 83%. As described earlier vertical integration is common in the cobalt supply chains. Many mining companies have extended their business to include refining as well, e.g., Glencore, Sumitomo Metal Mining, and Huayou.

Table 3-6 *Top 10 refining companies worldwide in 2019 (China Statistic Press 2020; Glencore 2020; Huayou Cobalt, 2020; Jinchuan Group International Resources Co. Ltd, 2020; Roskill 2020a; Sumitomo Metal Mining Co. Ltd. 2020; Washington 2020; Umicore 2020).*

Company	Operation/Operator	Country	Production in 2019 (t)	%
Huayou	Quzhou, Tongxiang	China	23,300	17
Umicore	Olen, Kokkola, Ganzhou	Belgium, Finland, China	21,300	16
GEM	Jingmen, Taixing, KwaZulu-Natal	China, South Africa	19,900	15
JNMC	Lanzhou, Jinchang	China	15,800	12
Glencore	Nikkelverk, Murrin Murrin	Norway, Australia	8,100	6
CNGR	Ningxiang, Tongren	China	7,800	6
Hezong	Ningxiang, Tianjin	China	5,400	4
Hanrui	Nanjing, Chuzhou, Kolwezi	China, DRC	5,400	4
Sumitomo Metal Mining	Niihama	Japan	5,300	4
GD Dowstone	Yingde	China	4,900	4

In Figure 3-14 the cobalt refining production of selected countries with high cobalt production and the main companies' nation affiliation is seen.

The production of refined cobalt (metal and chemicals) by country differs from the locations of the refining plants and the companies' nation affiliation; see Figure 3-14. China plays an even bigger role in the production of refined cobalt when including its overseas investments in South Africa and other countries. Belgium ranks second when taking its investments in Finland and China into account. Switzerland, ranked third, doesn't have any cobalt resources and is therefore absent in the left side of Figure 3-14 as they only have ownership through overseas investments.

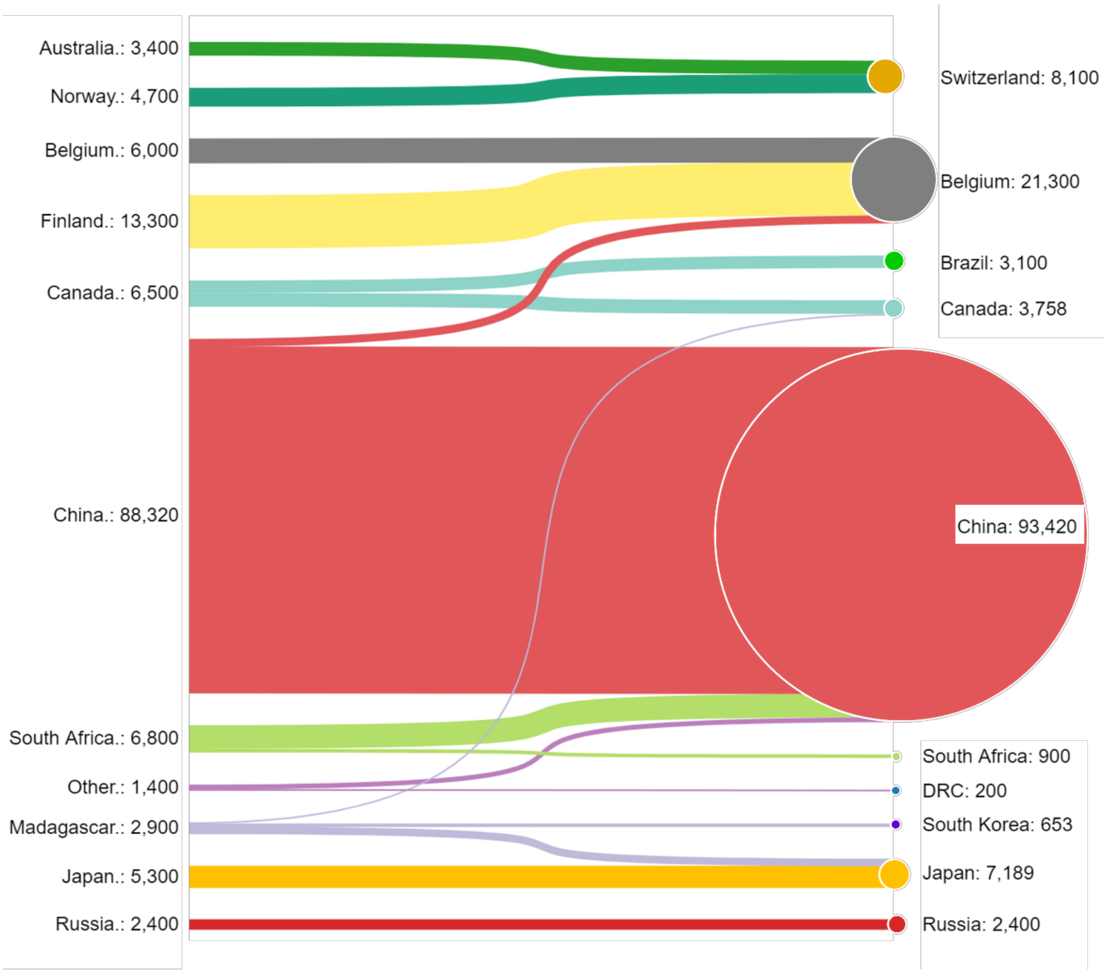


Figure 3-14 *Production of refined cobalt shift among countries by smelters' ownership (Data based on Table 3-5 and USGS 2020a)*

Figure 3-15 and Figure 3-16 shows the trade flow for cobalt metal and chemicals in 2019. In total around 14,000 tons cobalt chemicals and 38,000 tons cobalt metal were in international trade. Less cobalt chemicals were traded across country borders compared to cobalt metals, although the production of cobalt chemicals was larger than the production of cobalt metal, which mainly is because China produced a large proportion of the cobalt chemicals for domestic consumption. Japan is the most important cobalt metal importer, and South Korea is the largest importer of cobalt chemicals. The difference are probably a result of the two countries' different industry structure as cobalt metal and chemicals are used in separate industries. China is the dominant supplier of primary refined cobalt but focus mainly on production of cobalt chemicals.

China was the largest exporter of cobalt chemicals in 2019 and meanwhile the fourth largest importer of cobalt metal. In contrast, Canada, Finland, and Norway are the three most important exporters of cobalt metal. The Netherlands is the second largest cobalt metal importer, though most likely as a trade hub, considering its limited manufacturing capacities downstream. USA ranked third on importing cobalt metal, as they have a strong demand for cobalt for their aerospace and military industries.

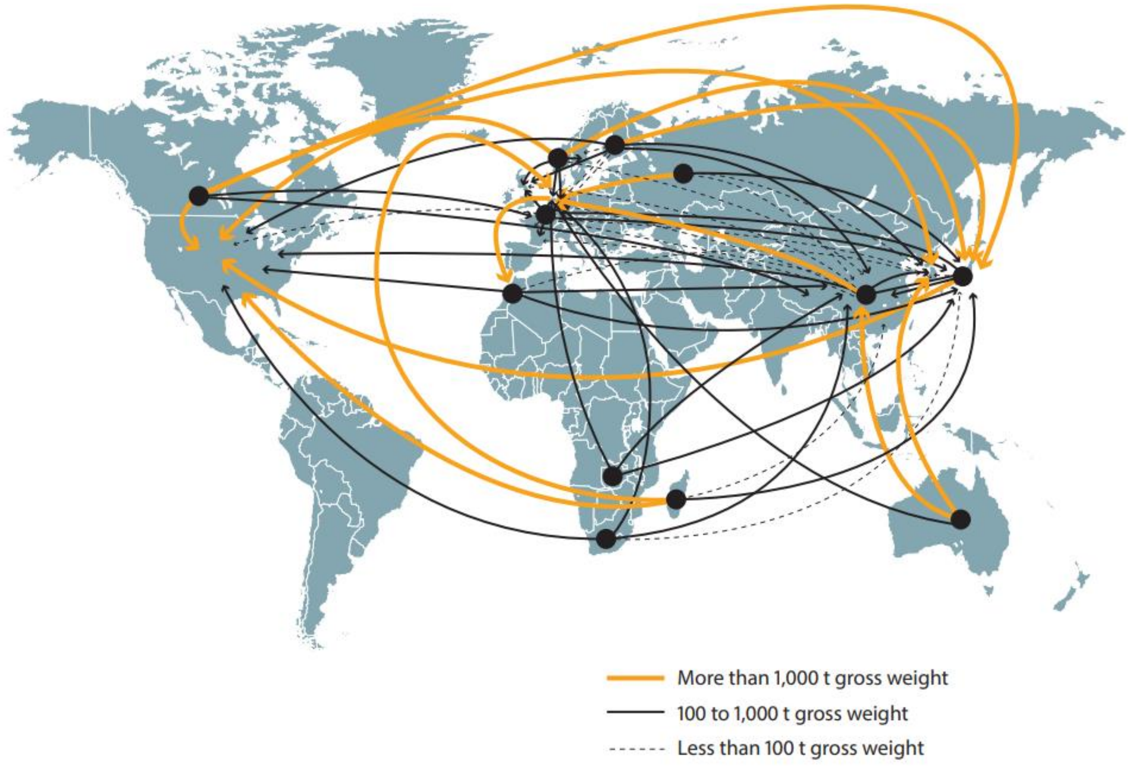


Figure 3-15 *International trade of cobalt metal in 2019 (Source: UN Comtrade).*

International trade on cobalt chemicals is relatively simple compared to cobalt metals, since there are mainly three countries producing and exporting cobalt chemicals: China, Finland, and Belgium. Important importers include South Korea, Germany, USA, and Japan, due to their emerging battery industries (Figure 3-16).

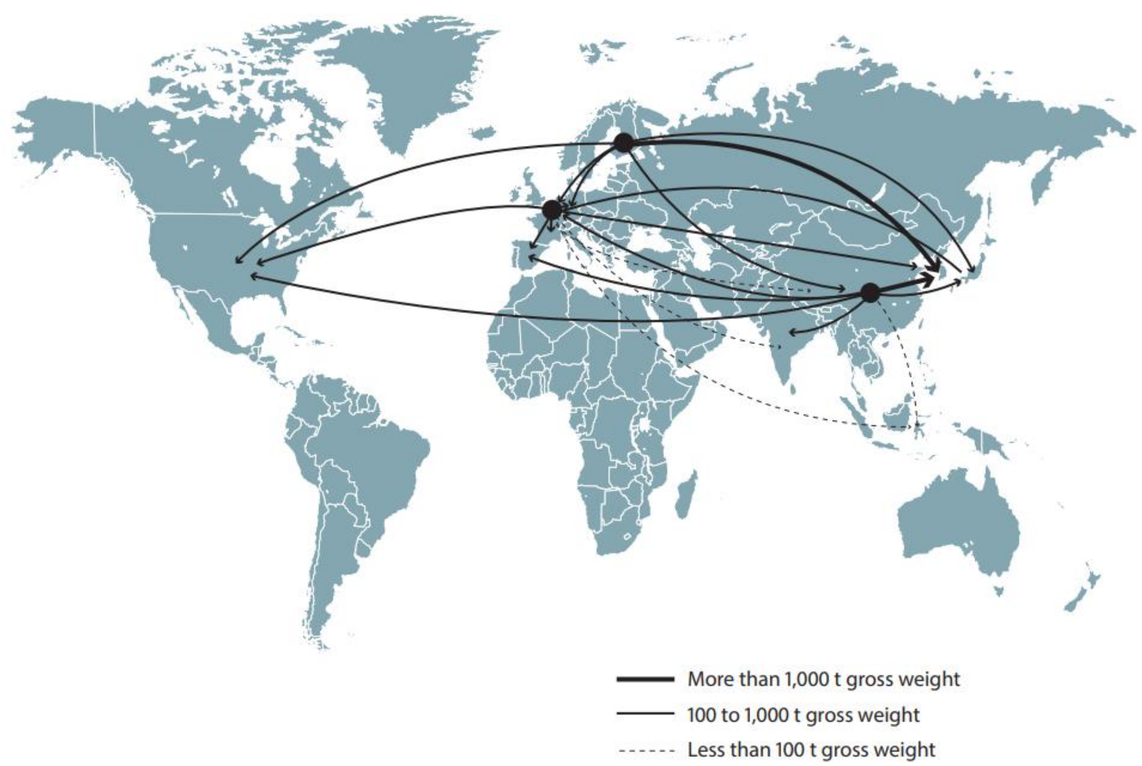


Figure 3-16 *International trade of cobalt chemicals in 2019 (Source: UN Comtrade).*

3.4 Cobalt manufacturing

The total cobalt consumption for manufacturing in 2019 was around 128,000 tons, with 34% as cobalt metal, while the rest 66% were cobalt chemicals (Zeng *et al.* 2022). If considered by applications, the cobalt demand was split into new and old economy drivers. New economy drivers include Li-ion batteries and superalloys while old economy drivers typically are industrial uses that include tool materials, industrial chemicals, and magnetic materials (Petavratzi *et al.* 2019). The break-down of different applications for cobalt in 2019 are presented in Figure 3-17.

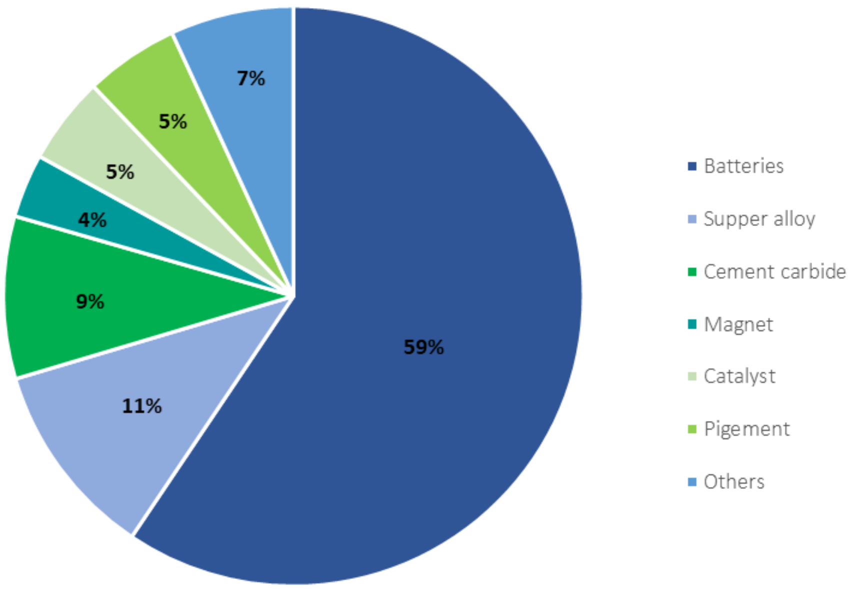


Figure 3-17 *Break-down of global cobalt consumption by application in 2019 (Zeng et al. 2022).*

Battery production is the largest consumer sector of cobalt, accounting for 59% in 2019. Cobalt is used in several battery technologies, including Ni-Cd batteries (0.4%), NiMH (6.4%) batteries, and Li-ion batteries, which are the most important market for cobalt (93.2%). Cobalt metal, oxide and hydroxide are all used in production of cathodes for rechargeable batteries, although cobalt metal only makes up a small proportion (Igogo *et al.* 2019). For LIB, if divided by cathode type, in 2019 most cobalt was used in LCO (76%), followed by NMC (16%), NCA (7%), and LMO (1%). Top 3 countries to produce LCOs are China (80%), South Korea (14%), and Japan (6%). However, the main compound to manufacture LCO cathodes is cobalt tetroxide, which is only produced by three countries, China (89%), Finland (8%), and Belgium (3%) (Roskill 2020a). International trade is therefore heavily dependent on a steady production of LCOs in South Korea and Japan; and the same is valid for NCA and NMC production as well. A general analysis of cathode production and lead producers worldwide is presented in Chapter 4 alongside with lithium, which is a critical raw material for all types of LIB cathodes.

Cobalt metal is used in a range of superalloys, including nickel-base alloys, with around 11% of the total consumption. Superalloys are used in the aerospace sector, nuclear reactors, power plants and chemical equipment where resistance to elevated temperature and high surface stability are required (Donaldson & Beyersmann 2012).

Another important application of cobalt metal (approximately 9%) is the use as a binder in cemented carbides to produce hard-wearing cutting and grinding tools, which is used by the automotive, aerospace, energy, mining, and general engineering sectors.

Cobalt metal is also used in magnets, accounting for 4% of the total consumption. Magnets are used in products such as wind turbines, hard disk drives, motor sensors, actuators, and magnetic resonance imaging (Donaldson & Beyersmann 2012).

A wide variety of cobalt compounds (approximately 5%), including oxide, sulphate, hydroxide, and diacetate, is used in catalysts in the desulphurization processes during the manufacture of natural gas and refined petroleum products. Another important use of cobalt catalysts is in the synthesis of precursors used in the creation of PET (polyethylene terephthalate) plastics.

Various cobalt salts have for a long time been used as pigments to impart a vivid blue colour to pottery, enamels, inks, and glass, and is accounting for around 5% of the total consumption.

Cobalt metal and various compounds, such as cobalt antimony, cobalt boron, cobalt germanium, and others, are used in numerous electronic products that contain integrated circuits, processors, digital storage, and semi-conductors. Cobalt also has a range of applications in healthcare, including measurement of vitamin B12 absorption and sterilization of medical equipment.

If divided by country, China is the largest consumer at the manufacturing stage (54%), as shown in Figure 3-18. Most of the consumption is for battery components manufacturing, which are further exported as semi-finished or final products. Like China, Japan has a high share of consumption on cobalt for battery manufacturing, due to its large electronic industry. In contrast, most of the cobalt consumption in USA and EU are manufactured into superalloys for use in their advanced military and aerospace industries (Zeng *et al.* 2022).

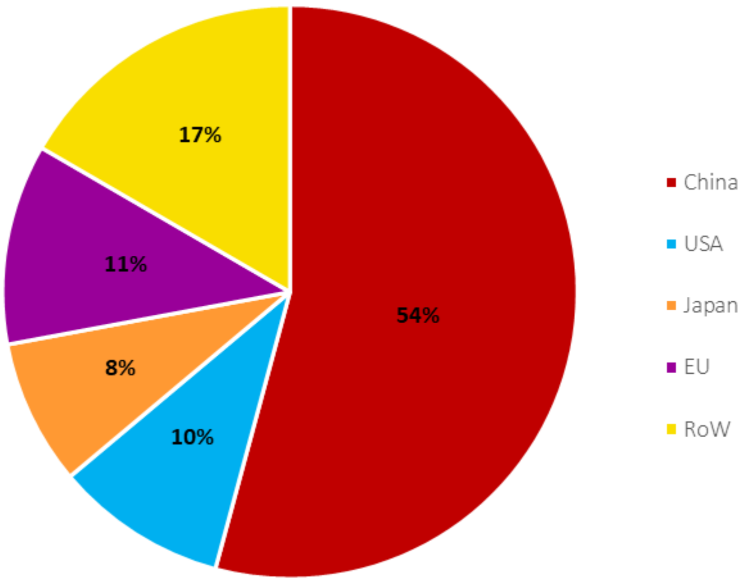


Figure 3-18 *Global consumptions of cobalt by country in 2019. RoW – Rest of the World (Zeng et al. 2022).*

Compared to the mining and refining stages, activities at the manufacturing stage are geographically more spread. Plants are generally smaller, and products are more diversified, and it is largely impossible to follow all the productions and their international trade flow. However, we do have information on most of the major types, for instance, major manufacturers of cathodes, which will be discussed in Chapter 4.

3.5 Cobalt usage

After manufacturing, cobalt-bearing components are assembled into end-use products and used widely in different sectors. Figure 3-19 summarises the end-use of cobalt worldwide in 2019.

The largest use of cobalt is in portable electronics like cell phones, laptop computers, and tablets (Cobalt Institute 2020; Roskill 2020a). Automotive follows as the second largest. This was the order for more than 10 years, but in 2021, automotive became the largest end-use sector. According to the Cobalt Institute (2021) this was due to COVID-19 recovery policies that supported EV sales growth. The demand for cobalt from the energy, industrial, and aerospace sectors is also strong, each accounting for more than 5% (Cobalt Institute 2020; Roskill 2020a).

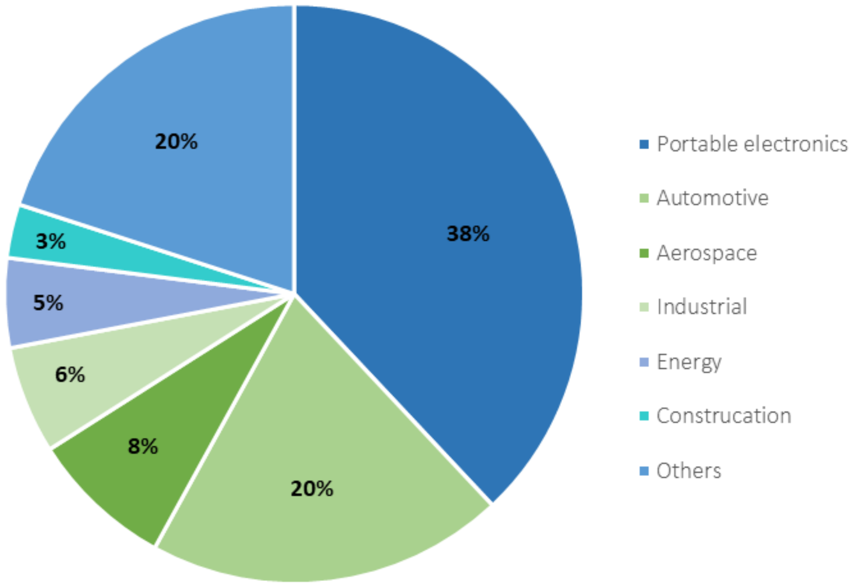


Figure 3-19 *End-use of cobalt worldwide in 2019 (Cobalt Institute 2020; Roskill 2020a).*

If divided by country, China is again the largest consumer of cobalt end-use products, accounting for 27%, followed by the EU, USA and South Korea; see Figure 3-20 (Zeng *et al.* 2022).

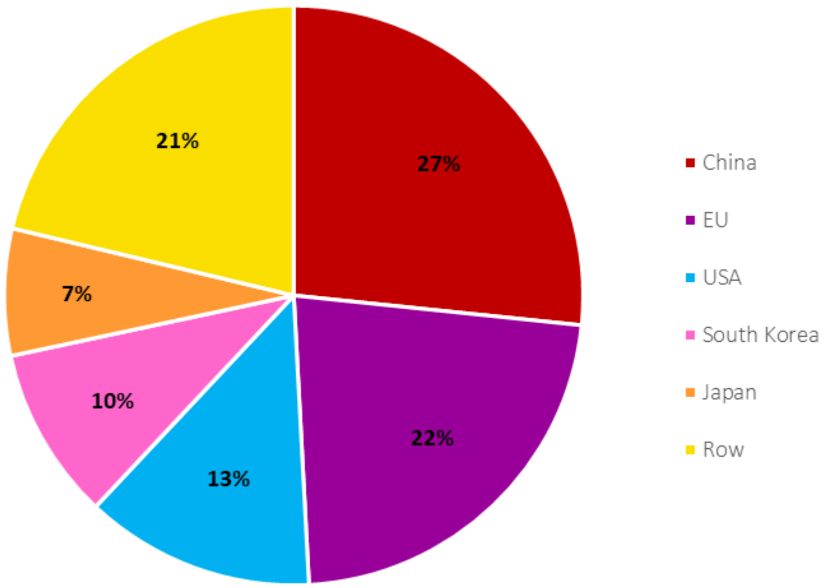


Figure 3-20 *Cobalt end-use products by country in 2019 (Zeng et al. 2022).*

As seen with the manufacturing stage, the end-user stage is also geographically widely spread, and it is impossible to follow all the productions and international trade flows. However, information on some typical products such as EV batteries, is available, which will be presented further in Chapter 4.

3.6 Cobalt recycling

Recycling of metals from new and "post-consumer" scrap is a rapidly developing topic for the political agenda within circular economy. Recycling of metals can be advantageous from both a resource conservation and an environmental perspective. For example, cobalt recycling saves 46% energy and 40% water relative to primary production. In addition, recycling contributes to the mitigation of the GHG emissions of the cobalt flow by 59% and SO_x emissions by 98% (Golroudbary *et al.* 2022). But some cobalt usages, such as pigments, ceramics, paints, etc., are dissipative, making the metal unavailable for recycling. Conversely, cobalt used in, e.g., superalloys, hard metals, batteries, or catalysts can be collected and either reused or recycled (Cobalt Institute 2020). Batteries constitute the largest waste stream for cobalt recycling, which is partly because recycling of batteries is easier if a dedicated system for return exists. LIB recycling is also driven by legislation (European Commission 2018). For instance, the European Commission (2020a) proposed a Battery Regulation, with the objective to ensure that industrial and EV batteries will contain a minimum of 12% recovered cobalt, 4% lithium, and 4% nickel in 2030.

However, the recycling of rechargeable batteries is complex due to the wide range of battery types (Li-ion, Ni-Cd, and NiMH) and their different chemistries and forms. Currently, there are three main methods to recover cobalt from Li-ion batteries: hydrometallurgical, pyrometallurgical, and a hybrid of hydro- and pyrometallurgical processes (Gaines 2018; Sethurajan *et al.* 2019; Fujita *et al.* 2021).

When using hydrometallurgy to recover cobalt from Li-ion batteries, the batteries are crushed in a sealed vessel with a defined and controlled atmosphere and pressure (Hanisch *et al.* 2015). The crushed materials are then put on a vibrating screen and divided into four fractions depending on size: ≤ 0.5mm, 0.5-1mm, 1-2mm, and ≥ 2mm. Only the finest fraction, which is rich in metal oxides and carbon, is further processed. This fraction is sieved to reduce the copper content. The remaining fine powder is further treated in hydrometallurgical process steps to derive solutions of cobalt and lithium salts. The cobalt solution is electrolyzed to obtain cobalt.

When using pyrometallurgy to recover cobalt from Li-ion batteries pathway, cells are separated from other battery components and after a vacuum thermal pre-treatment process, the electrolyte and hydrocarbons evaporate, and the cells are deactivated. The deactivated cells then go through various mechanical treatment processes, resulting in four fractions: 1) an iron-nickel fraction, 2) an aluminium fraction, 3) an electrode foil fraction, and 4) a fine material fraction, which contains the electrode material (Georgi-Maschler *et al.* 2012). The fine fraction is transferred to a smelting furnace under a reducing atmosphere to produce a cobalt alloy (Hanisch *et al.* 2015).

When using the combined hydro- and pyrometallurgical process, batteries are first pyrometallurgically treated to produce a slag, a liquid metal alloy, flue dust, and gas emissions. The liquid metal alloy is further refined in hydrometallurgical processes to recover copper, nickel, and cobalt by solvent extraction.

Successful recycling of cobalt is influenced by many parameters including the specific recycling process used, the cobalt content of the end-of-life product (EOL product), the collection rates of EOL products and the cobalt price. Currently, cobalt post-consumer recycling is relatively high due to the lower costs of the recovered cobalt compared to cobalt extraction from ores. The end-of-life recycling rate (EOL-RR) of cobalt in EU is estimated to be around 32%, which is higher than globally. According to Zeng *et al.* (2022), around 25,900 tons cobalt was recycled from post-consumer scrap (containing approximately 132,100 tons cobalt) in 2019, and the global EOL-RR of cobalt is therefore estimated to be 20%.

The largest part of cobalt is recycled from the battery sector. Many batteries reached their EOL in 2019, but due to low collection rate, only around 330,000 tons EOL rechargeable batteries were collected and processed for recycling (Melin 2021). Assuming an average cobalt concentration of approximately 4% in Li-ion batteries, and a potential recovery rate of 80%, approximately 10,560 tons cobalt could be recycled from used batteries alone in 2019. No detailed data on recycling by country is available. However, 90% of cobalt is recycled in Asia, 7% in North America, and 3% in Europa (Roskill 2020a).

The scrap and recycling business is not very transparent, and it is difficult to accurately assess the actual volumes that are recycled by the major players. Table 3-7 lists the top 10 companies with battery recycling capacities worldwide (Melin 2021). All are located in Asia; 8 of them are in China. Worldwide, the recycling infrastructure capacity is believed to range between 590,000 and 696,000 tons disused batteries per year, and more than 60% of this is in China.

Table 3-7 *Top 10 companies with battery recycling capacity worldwide (China Statistic Press 2020; Melin 2020).*

Company	**Location**	**Process**	**Capacity (tons of batteries per year)**
Hunan BRUNP	China	Pre-processing, Material recovery, Material production	120,000
Hubei Xiongtao	China	Pre-processing, Material recovery, Material production	80,000
Huayou Cobalt	China	Pre-processing, Material recovery, Material production	60,000
GEM	China	Pre-processing, Material recovery, Material production	50,000
Ganfeng Lithium	China	Pre-processing, Material recovery, Material production	34,000
Jinchi Energy Materials	China	Pre-processing, Material recovery, Material production	25,000
Sungeel Hitech	South Korea	Pre-processing, Material recovery	24,000
Puqing Recycling Technology	Malaysia	Pre-processing, Material recovery	20,000
Miracle Automation	China	Pre-processing, Material recovery, Material production	20,000
Shandong Weineng Environmental	China	Pre-processing, Material recovery, Material production	20,000

A large share of the recycling capacity is located in Europe. Europe is dependent on the import of cobalt raw materials, and recycling is potentially an important element to reduce European reliance on external cobalt sources. The recycling industry is currently waiting for the battery waste-stream, but with the dramatic increase of EV sales globally, the EOL battery stream is expected to reach a high level in EU in the near future and at the same time significant volumes from abroad is also ending in European recycling facilities.

Superalloys are another important waste stream of cobalt. In 2019, around 8,400 tons cobalt were recycled from super alloy-waste, assuming a recovery rate of 80% (European Commission 2018). The sectors of cement carbide and catalysts contributed with 4,600 and 2,140 tons of recycled cobalt in 2019, respectively (Zeng *et al.* 2022).

Currently, the volume of recycled cobalt is relatively small, but with increasing flows of EOL battery cells and developments in the recycling technologies, the most optimistic predictions expect that approximately 25% of the required cobalt in Europe will be supplied from secondary sources by 2050 (Golroudbary *et al.* 2022).

3.7 Summary of cobalt global supply chain analysis

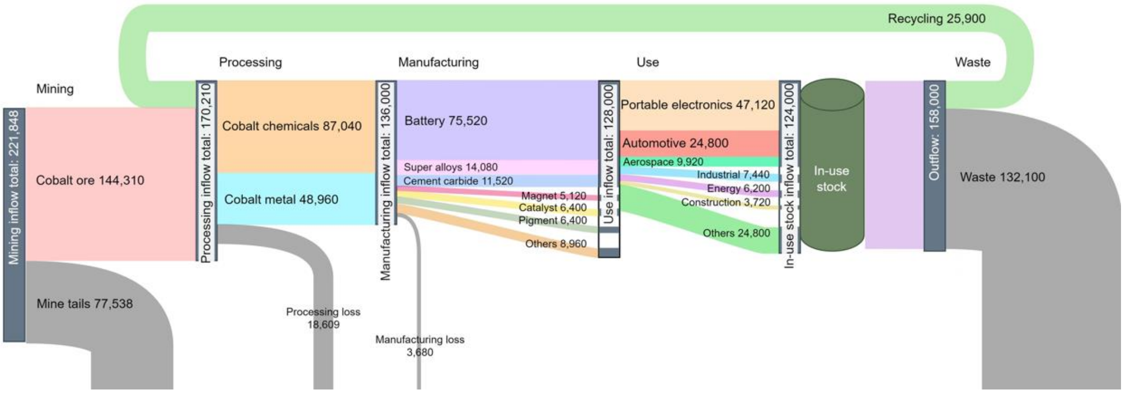


Figure 3-21 *Global cobalt flows in 2019 (Unit: tons).*

The global cobalt mine production in 2019 was approximately 144,000 tons. According to USGS (2022a), the world cobalt resources was around 25 million tons and cobalt reserves was around 7.6 million tons in 2021. If the primary production remains at the same level as in 2019 and no additional reserves are discovered, the current global cobalt reserves will last for 45 years. Cobalt intermediates and refining productions in 2019 were around 139,000 tons and 136,000 tons respectively; the production of both is higher than the demand from manufacturing (ca. 128,000 tons) and end-use (ca. 124,000 tons). Although there was a surplus production of cobalt in 2019, cobalt is for several reasons regarded as a commodity with a high supply risk.

Firstly, both the mined cobalt, and the refined production are highly concentrated in a few countries. Approximately 69% of the cobalt mining production and 63% of the refined production was produced in the DRC and China, respectively. Hence, the cobalt supply is in general dependent on international trade. Taking EU as an example, the cobalt demand for end-use in EU is around 28,000 tons, but there is only 3,900 tons cobalt mined in EU and most of the supply depends on import from other countries, either as refined products or manufactured semi-products.

Secondly, cobalt is mainly a by-product of copper and nickel production. In 2019, 70% of the cobalt was mined as a by-product of copper, and 20% as a by-product of nickel. Being a by-product, cobalt production depends on the production of the “host” commodity, which implies a high supply risk (Ding *et al.* 2019). Hence, the cobalt supply is to a large extent affected by the prices of copper and nickel (Van den Brink *et al.* 2020).

Thirdly, many operator companies have identical shareholders. For instance, Glencore owns shares in five mining operators, while Vale and Shalina Resources own shares in three mining operators. At the same time, many companies are highly integrated and expand their business to many stages of the cobalt supply chain: in 2019, Glencore alone directly controlled more than 30% of the global cobalt mining and intermediates production, together with around 6% of the cobalt refined metal production. To some extent, vertical integration tends to reduce a company's supply risk and cost, but if a company with many linkages fails, it is more likely to disrupt the global cobalt supply, than a company with only a few linkages (Nuss *et al.* 2016). Therefore, strict supervision of critical players is necessary to keep the market alert to possible problems and reduce the supply risk.

Fourthly, in 2019 a large proportion of the cobalt mining production originated from artisanal mining. BGR mapped around 80 artisanal copper-cobalt mines in the DRC, and more than 10,000 tons of cobalt is estimated to be produced this way, accounting to approximately 20% of the DRC's annual production (Mathieu & Mattea 2021). Artisanal and small-scale mining often take place in unstable underground mines in dangerous environments without access to safety equipment, sometimes using child or forced labour. Such unsustainable conditions in the artisanal mining business are likely to spill over to the supply chain, resulting in unstable cobalt supply.

Fifthly, cobalt supply risk is exacerbated by this geographic concentration among few countries, some of which are politically unstable. The DRC, the largest cobalt mining producer, has the lowest World Governance Indicators (WGI) score on political stability and the absence of violence/terrorism of all mining countries (Yigzaw 2019). Historically, civil war and regional conflicts have disrupted or eliminated cobalt mining production several times in the DRC and resulted in dramatic price fluctuations.

Lastly, environmental damage poses a significant supply risk in the extraction and processing of cobalt. Western societies, in particular, deem certain levels of environmental damage associated with cobalt extraction unacceptable (Graedel *et al.* 2012). Environmental risks vary among different types of deposits, including factors such as stripping ratio, metal-ridge sludge generation, the production of reactive waste leading to higher concentrations of dissolved metals, and acidic mining drainage waters. Countries with robust environmental regulations may restrict the development of cobalt deposits with high environmental impacts or prevent the expansion of existing sites. Consequently, strict environmental regulations can significantly limit the accessible reserves (Achzet & Helbig 2013). The sourcing of minerals and metals has garnered broad interest due to environmental and social concerns. To mitigate risks in the upstream supply chain, companies opt for sourcing materials through "sustainability schemes." These schemes and responsible sourcing initiatives have emerged in recent years, each with their own requirements and approaches to responsible sourcing (van den Brink et al. 2020).

To summarise: although it is currently possible to keep the supply-demand balance, potential future cobalt supply risks exist, mostly caused by the factors discussed above.

The most significant driving factor in global cobalt demand is the rapid development of the LIB industry and plans and mitigation strategies should be developed to contain the supply risks. Further actions regarding cobalt are discussed in Chapter 6 together with lithium, which is another important commodity.

4. Global lithium flow analysis

Lithium is a soft, silvery-white lustrous metal with the chemical symbol Li and atomic number 3. Lithium was discovered by Swedish chemist Johan August Arfwedson in 1817, but due to its high reactivity, it was not isolated until 1821, when the British scientist William Thomas Brande obtained it by electrolysis of lithium oxide (Makuza *et al.* 2021).

At room temperature, lithium is the lightest metal and has the lowest density of all solid elements. In addition, it has the lowest redox potential. When cut, it exhibits a metallic lustre, but moist air corrodes it quickly to a dull silvery grey, later black tarnish. Lithium reacts vigorously with water, and since it is less dense and thus floats on oil, it is usually stored coated with a petroleum jelly (Stanford Advanced Materials 2022).

Lithium has excellent electrical conductivity (i.e., low resistivity) and it is also the most electronegative metal, which is one of the properties that make it ideal for use in batteries. The addition of lithium to alloys imparts high mechanical strength and in ceramics and glass it improves thermal shock resistance (BGS 2016). Different forms of lithium-compounds, e.g., lithium hydroxide (LiOH), lithium oxide (Li_2O), and lithium carbonate (Li_2CO_3), are used for various purposes. Special attention should be paid when dealing with lithium-related data, because different units are used to describe the lithium quantities involved. In this report, both Li metal content (tons Li) and Li_2CO_3 content (tons LCE (Lithium Carbonate Equivalent)) are used. Conversion factors between these various forms, and other common compounds, are shown in Table 4-1.

Table 4-1 *Conversion factors for lithium and selected compounds.*

To convert from	Chemical formula	To convert to		
		Lithium content	Lithium oxide content	Lithium carbonate equivalent
		Multiply by:		
Lithium	Li		2.153	5.323
Lithium oxide	Li_2O	0.464		2.473
Lithium carbonate	Li_2CO_3	0.188	0.404	
Lithium chloride	LiCl	0.163	0.362	0.871
Lithium hydroxide monohydrate	$LiOH.H_2O$	0.165	0.356	0.88

Lithium is a crucial element used in the production of Li-ion batteries, and its global supply chain is complex, including the sourcing of crude materials, refining of lithium in different forms, manufacturing necessary components, producing end-use products, and initial attempts to recycle lithium back to the system. In this chapter, lithium's supply chain will be analysed through all the steps shown in Figure 4-1.

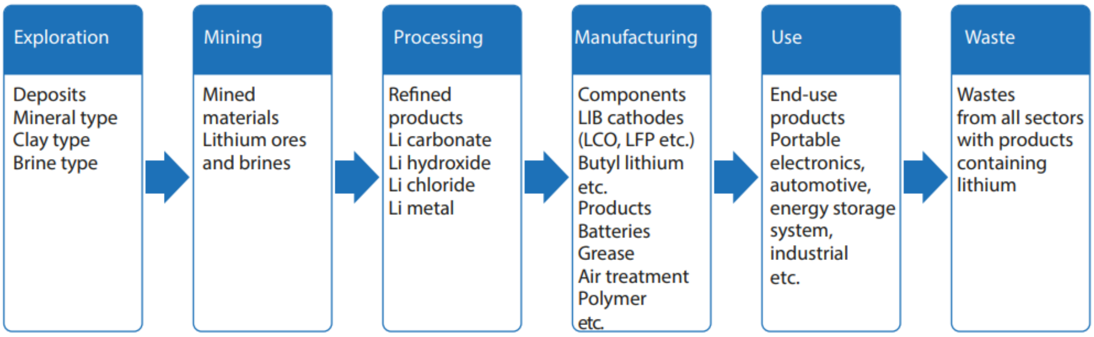


Figure 4-1 *Simplified lithium supply chain.*

4.1 Lithium deposit types, resources and reserves

Lithium in economically viable concentrations is found in different geological sources that broadly can be divided into three main groups: 1) Li-rich pegmatites and granites, 2) various types of brines, and 3) sedimentary deposits. Currently, most lithium is obtained from the two first deposit types (see Section 4.2), particularly in pegmatites and continental brines. Furthermore, certain manganese deposits contain notable amounts of lithium, however, none of these deposits are currently considered economic for lithium exploitation (Bowell *et al.* 2020; Grew 2020).

There are more than 100 named lithium-bearing minerals, of which 9 are considered economically viable (Table 4-2) with spodumene, petalite, lepidolite, and amblygonite being the four most important Li ore minerals (Mohr *et al.* 2012) containing 2–8% Li_2O. Figure 4-2 illustrates the typical grades and tonnages of some important lithium deposits. It is worth noting that a typical commercial run of mine ore, when extracted using current mining technologies, generally contains 0.5–2 wt.% Li_2O.

Table 4-2 *Important lithium minerals. Source: Garrett (2004), BGS (2016) and Schmidt (2023).*

Name	Chemical formula	Theoretical maximum Li2O content (wt.%)	Average Li2O% of ores
Spodumene	$LiAlSi_2O_6$	8.0	2.9–7.7
Petalite	$LiAl(Si_4O_{10})$	4.7	3.0–4.7
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(OH,F)_2$	7.7	3.0–4.1
Amblygonite	$(Li,Na)Al(PO_4)(F,OH)$	7.4	N.A.
Eucryptite	$LiAlSiO_4$	9.7	2.1–4.4
Zinnwaldite	$KFe_2Al(Al_2Si_2O)_{10}(F,OH)_2$ to $KLi_2Al(Si_4O_{10})(F,OH)_2$	4.0	N.A.
Polylithionite	$KLi_2Al(Si_4O_{10})(F,OH)_2$	6.5	N.A.
Hectorite	$Na_{0.3}(Mg,Li)_3(Si_4O_{10})(F,OH)_2\cdot nH_2O$	3.0	N.A.
Jadarite	$LiNaSiB_3O_7(OH)$	7.3	N.A.

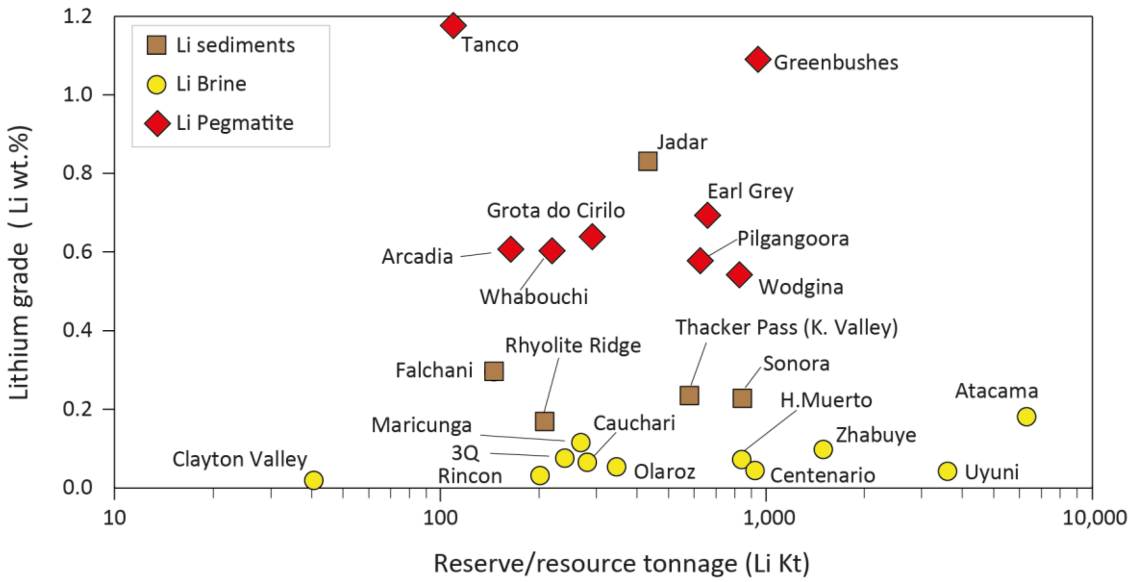


Figure 4-2 *Grade-tonnage plot of select important lithium deposits. The diagram was made using reserves (probable reserve) or resources (using only measured and indicated categories). Modified from Bowell et al. (2020).*

4.1.1 Lithium pegmatites and granites

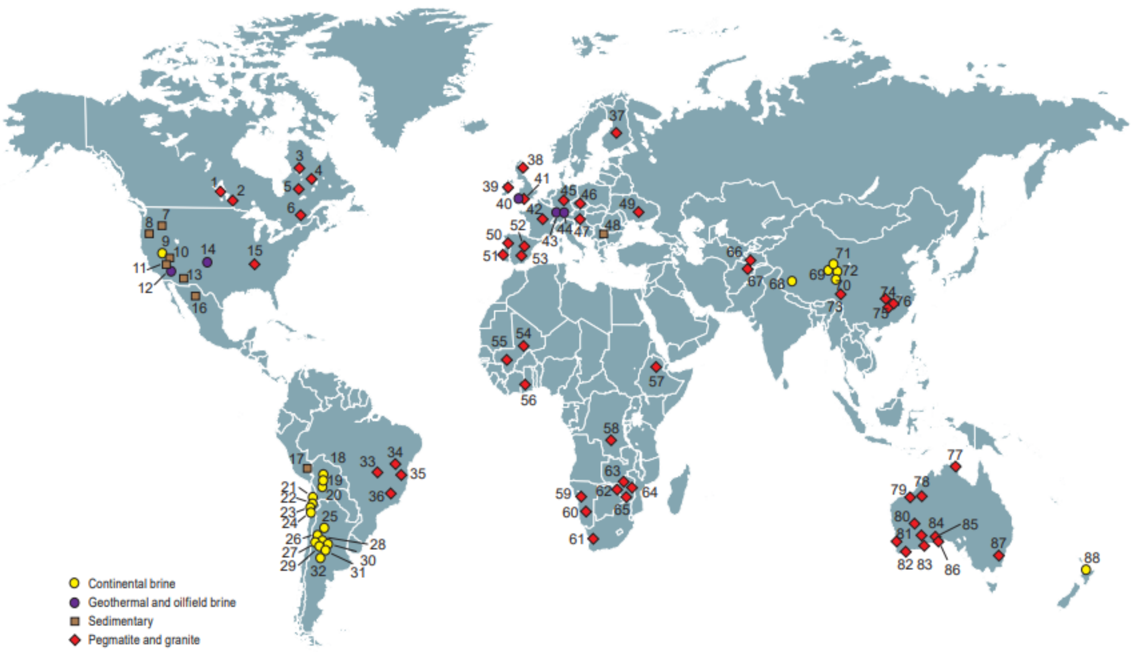
Pegmatites are very coarse-grained rocks that can occurs as dikes, sills, veins or irregular bodies within their host, and they are an important source for lithium and other rare metals (London 2008). Pegmatites are characterized by their exceptionally coarse-grained texture with mineral grains often exceeding several centimeters which have crystallized slowly from a volatile-rich melt.

Most pegmatites are granitic in composition and while these rocks are widely distributed and relatively abundant, rare metal pegmatites constitute only a minor portion, approximately 0.1% of the total, and lithium-rich pegmatites represent an even smaller fraction (Laznicka 2006). Pegmatites with potential for Li extraction predominantly belong to the lithium-caesium-tantalum (LCT) pegmatite type that comprises a compositionally defined subset of granitic pegmatites characterized by being enriched in Li, Cs, Rb, Be and Ta (London 2008; Goodenough *et al.* 2019). These rocks account for about 45% of the world's lithium production, see Sections 4.2, but are also major sources of other special metals like Sn, Ta, Be, Rb, and Cs and industrial minerals such as high purity quartz, potassium feldspar, kaolinite and white mica (Bradley *et al.* 2017a; Bowell *et al.* 2020).

Certain muscovite granites contain zones characterized by high concentrations of lithium, tantalum, tin, and fluorine. Such lithium-enriched granites are closely associated with LCT pegmatites, and these two types have not been differentiated in the most recent worldwide evaluations of lithium occurrences and resources (Bradley *et al.* 2017b) and are for simplicity treated and grouped together here.

Some pegmatites are homogenous but generally exhibit distinct zoning patterns, with different mineral assemblages occurring in specific zones. These variations can be attributed to changes in the composition of the parent magma, the cooling rate, and the fluid activity during pegmatite formation. Although LCT pegmatites can have a very complex mineralogy, the majority of economic mineralization has the Li-Al silicate spodumene as the main ore mineral and is considered to be primary magmatic in origin (Goodenough *et al.* 2019). Lithium is a large-ion lithophile element that is incompatible in most rock forming minerals and the Li is concentrated in the pegmatites as a result of extreme magmatic differentiation.

The majority of LCT pegmatites whose parent granites are peraluminous, i.e., sedimentary (S) igneous (I) or mixed S+I types granites, are commonly associated with granitic intrusion and found within metamorphic terrains. Although the optimal tectonic setting of pegmatites still remains under debate, the LCT pegmatites appear predominantly in convergent orogenic belts and correlate with orogenic, especially post orogenic, magmatism (Bradley *et al.* 2017a).



1 Tanco, Canada
2 Separation Rapids, Canada
3 James Bay, Canada
4 Rose, Canada
5 Whabouchi, Canada
6 Val-d'Or, Canada
7 McDermitt, USA
8 Kings Valley, USA
9 Silver Peak, USA
10 Bonnie Claire, USA
11 Boron, USA
12 Salton Sea, USA
13 Clayton North, USA
14 Magnolia, USA
15 Kings Mountain, USA
16 Sonora, Mexico
17 Falchani, Peru
18 Salar de Coipasa, Bolivia
19 Salar de Uyuni, Bolivia
20 Salar de Pastos Grandes, Bolivia
21 Salar de Atacama (2 operators), Chile
22 Salar de Aguilera, Chile
23 Salar de Pedernales, Chile
24 Salar de Maricunga, Chile
25 Salar de Olaroz, Argentina
26 Salar de Cauchari (2 projects), Argentina
27 Salar del Rincón (3 projects), Argentina
28 Salar de Pozuelos, Argentina
29 Salar de Pastos Grandes, Argentina
30 Salar de Ratones, Argentina
31 Salar de Diablillos, Argentina
32 Salar del Hombre Muerto (3 projects), Argentina
33 Mibra, Brazil
34 Mina da Cachoeira, Brazil
35 Jequitinhonha, Brazil
36 Volta Grande, Brazil
37 Länttä (and 5 others), Finland
38 Glenbuchat, United Kingdom
39 Aclare, Ireland
40 United Downs, United Kingdom
41 St Austell, United Kingdom
42 Chédeville (and 4 others), France
43 Rittershoffen, France
44 Upper Rhine Valley, Germany
45 Zinnwald (and 4 others), Germany
46 Cinovec, Czech Republic
47 Wolfsberg, Austria
48 Jadar, Serbia
49 Polokhovskoe (and 2 others), Ukraine
50 Mina do Barroso (and 3 others), Portugal
51 Alijó, Portugal
52 Valdeflórez/San José, Spain
53 Alberta I, Spain
54 Bougouni, Mali
55 Goulamina, Mali
56 Ewoyaa, Ghana
57 Kenticha, Ethiopia
58 Manono-Kitotolo, Democratic Republic of Congo
59 Uis, Namibia
60 Karibib, Namibia
61 Orange River Area, South Africa
62 Kamativi, Zimbabwe
63 Zulu, Zimbabwe
64 Al Hayat, Zimbabwe
65 Arcadia, Zimbabwe
66 Parun area, Afghanistan
67 Nuristan area, Afghanistan
68 Zhabuye Salt Lake, China
69 Yiliping, China
70 Jiajika, China
71 Taiji Nai'er, China
72 Qarhan, China
73 Sichuan Aba, China
74 Yifeng, China
75 Yichun, China
76 Ningdu, China
77 Finniss, Australia
78 Pilgan, Australia
79 Ngungaju, Australia
80 Kathleen Valley, Australia
81 Mount Holland, Australia
82 Greenbushes, Australia
83 Mount Cattlin, Australia
84 Mount Marion, Australia
85 Bald Hill, Australia
86 Buldania, Australia
87 Narraburra, Australia
88 Ohaaki, New Zealand

Figure 4-3 *The global distribution of lithium deposits and major occurrences. Modified from Shaw (2021).*

Lithium pegmatites are found in various regions worldwide. Major lithium pegmatite occurrences include Australia, Canada, Brazil, Zimbabwe, DRC, China, and the United States (Figure 4-3). On a regional scale, LCT pegmatites tend to occur in districts alongside fertile granites with distal pegmatites exhibiting the highest concentration of lithium (Bradley *et al.* 2017b). Lithium is currently extracted from 52 pegmatite deposits with the Greenbushes deposit in Australia standing out with a high grade and tonnage of Li and the Tanco deposit, Canada for its exceptionally high concentration of lithium (Figure 4-2). For more comprehensive information on Li-rich pegmatites, readers are encouraged to refer to the works of Kesler *et al.* (2012) and Bradley *et al.* (2017a), which offer detailed reviews.

4.1.2 Brine deposits

Brine refers to any fluid containing a high level of dissolved solids. Lithium exists in many natural brines, but usually at low concentrations. For example, seawater contains on average 0.18 ppm Li (from total dissolved solids of approximately 35,000 ppm). There are mainly three types of lithium brine deposits: continental, geothermal, and oil field (Schmidt 2023). The most common and important source of lithium from brines is continental saline desert basins (also known as salt lakes, salt flats, or “salars”) that occur in geologically recent enclosed basins containing lacustrine evaporites that were produced by high rates of evaporation relative to precipitation. They occur in areas with geothermal activity and are made up of sand, minerals, and saline water with a high concentration of dissolved salts. Lithium brines tend to be characterized by concentrations of dissolved ions that are near the saturation point for many salts, particularly halite in mature salars. Besides sodium and chloride, other elements which are commonly observed together with lithium in brines include boron, calcium, potassium, and magnesium. Typically, the brines are concentrated in evaporation ponds before lithium is precipitated as lithium chloride or lithium carbonate (Roskill 2020b).

Many factors control the concentration of Li (and other salts) and the final formation of salars, but these deposits exhibit several common features, such as an arid climate, a closed basin that holds a salt lake or salt flat, subsidence caused by tectonic activity, the presence of igneous or geothermal processes, lithium-bearing source rocks, the availability of one or more suitable aquifers to contain the brine reservoir, and a considerable amount of time for brine concentration (Bradley *et al.* 2017b). The conditions for optimal evaporation are intense solar radiation, low humidity, moderately strong winds, and minimal rainfall. When considering evaporation processes, it is crucial to consider factors such as lithium concentration and the magnesium-lithium ratio. A high magnesium-lithium ratio can impede evaporation rates and diminish the overall yield. Hydrothermal and/or geothermal influences on groundwater may also alter the composition of the inflowing waters to basins.

Salars form in Earth’s two low-latitude dry belts and particularly in areas with extremely low precipitation often as a result of rain-shadows cast by mountain ranges. The largest Li-brine resources occur in South America within the Puna Plateau of Argentina, Bolivia, and Chile, collectively known as the Lithium Triangle, which holds more than 50% of the world's lithium reserves. Additionally, significant continental brine deposits can be found in China, as well as to a lesser extent in the western United States and Northern Africa (Kesler *et al.* 2012). The basins hosting lithium brines vary greatly in size, with notable examples including the Salar de Atacama in Chile and the Salar de Uyuni in Bolivia. The Salar de Atacama, discovered in 1969 and commencing production in 1984, boasts a surface area of 3000 km^2 and reserves of 6.3 Mt lithium (Mohr *et al.* 2012). This makes it the world's most abundant commercially viable lithium brine deposit (Cabello 2021). On the other hand, the Salar de Uyuni covers an area of approximately 14,000 km^2 and has a catchment area of about 47,000 km^2, likely making it the largest salar globally (Kesler *et al.* 2012). Although this deposit holds reserves of 3.6 Mt Li (Mohr *et al.* 2012), it remains unexploited at present.

Other more unconventional lithium brine resources include oil-field and geothermal brines. Oil-field brines are produced as a waste product of certain oil extraction processes, and they can occur at a depth of more than 2 km and have up to 700 ppm Li as reported from the Smackover Formation primarily located in southern Arkansas and northern Louisiana in the United States (Evans 2014). Extraction techniques are being evaluated to determine the feasibility of commercial lithium production from this and other oil fields, however, no production is currently taking place. The extraction of lithium from continental deep waters is being evaluated by companies and research institutions in several countries, and it is being investigated in pilot plants. Sanjuan *et al.* (2022) reviewed the Li resource potential in geothermal brines (and hydrocarbon wells) in Europe and found six areas with potential for lithium in Italy, Germany, France, and the United-Kingdom with concentrations of Li from 125 to 480 mg/l. These were predominately Na-Cl type high temperature brines (120 - 380 ºC) and could either be a source primarily for Li or be used for energy generation and subsequent Li exploitation.

4.1.3 Lithium sedimentary deposits

Lithium-bearing sedimentary deposits have gained attention as a potential source of lithium due to their relatively high lithium content although they are not currently in production. These deposits can be categorized into three types based on the occurrence of lithium: 1) deposits where lithium is present within the clay mineral hectorite and other mixed-layer clays (smectites); 2) deposits where lithium exists as adsorbed ions onto clay minerals (referred to as ion-clay deposits); and 3) jadarite deposits (Benson *et al.* 2017; Bowell *et al.* 2020). The source of the Li in sedimentary deposits and their formation remains disputed. Most of them are clay deposits that exhibit a genetic and/or spatial connection to rhyolite volcanics. The clay deposits have been associated with geochemically anomalous accumulations of lithium (Evans 2014) and there is consensus that the lithium-containing clays are formed through the weathering of lithium-rich volcanic intrusive rocks where further enrichment can occur through hydrothermal processes. The most significant clay mineral in this context belongs to the smectite group, particularly the endmember known as hectorite, in which the lithium tends to replace magnesium.

Important examples of lithium sedimentary type deposits include the Thacker Pass, sometimes also referred to as the Kings Valley, lithium deposit in Nevada, USA, and the Jardar deposit in Serbia. The former deposit is associated with hotspot magmatism beneath the Yellowstone Plateau formed around 16.3 Ma. Within the moat of a caldera, the deposit consists of five lenses of clay rich in hectorite, situated at shallow depths amidst sedimentary and volcanic rocks (Evans 2014). Total resources have been estimated to be 13.4 Mt LCE (Lithium Americas 2021) making this the largest Li sedimentary deposit in the USA (Bradley *et al.* 2017b). The Jardar deposit was discovered in 2004 by Rio Sava Exploration, a subsidiary of Rio Tinto, and contains the lithium zeolite jadarite, which is a boron, lithium, and sodium-rich silicate hydroxide mineral (Table 4-2), which is a mineral unique to this deposit. The jadarite mineralization, which can vary from 1-2 m to over 50 m in thickness, is formed by geothermal-hydrothermal fluid alteration of volcano-clastic sediments (Bowell *et al.* 2020). The deposit has indicated resources of approximately 700,000 t Li (Rio Tinto 2022) and is the largest lithium deposit in Europe.

4.1.4 Lithium resources

According to USGS (2020b), lithium resources have increased substantially worldwide to a total of more than 63 million tons in 2019, with lithium-bearing brine resources accounting for the largest part. The top 10 countries with identified lithium resources are listed in Table 4-3.

Due to their higher lithium concentration (grade), hard-rock deposits are the primary focus of exploitation, making up 55% of the global production (Section 4.2) but they constitute less than 40% of the total known resources. Generally, as the ore grade increases, the total tonnage of ore in the deposit tends to decrease. Nevertheless, as pointed out by Kesler *et al.* (2012), pegmatites despite being smaller in size and constituting significantly fewer resources, will continue to be of interest due to their broader geographical distribution, making pegmatites less prone to supply disruptions. Additionally, their lithium-dominant compositions offer greater flexibility in responding to market changes.

Table 4-3 *Top 10 countries with largest identified lithium resources in 2019 (USGS 2020b; CGS 2021).*

Rank	Country	Lithium resources (million tons)
1	Argentina	14.8
2	Bolivia	9
3	Chile	8.5
4	Australia	7.7
5	China	4.5
6	Canada	2
7	Mexico	1.7
8	Czechia	1.3
9	DRC	1.1
10	Russia	1

Lithium mineral resources are mainly found in Australia, Canada, Finland, China, Zimbabwe, South Africa, and DRC, whereas lithium brines are mainly found in Bolivia, Chile, Argentina, China, and the USA. The top 10 countries account for more than 90% of the world's lithium resources. Continuously exploration for lithium resources are increasing the resources and in 2020 the global lithium resources increased to 80 million tons, with the Bolivian lithium resources alone reaching 21 million tons (USGS 2021).

4.1.5 Lithium reserves

The total lithium reserves grew as well due to an increasing number of prospecting projects. In 2019, the global lithium reserves were estimated by USGS (2020b) to be 17 million tons and with more than 96% of the global reserves concentrated in 4 countries (Figure 4-4). Chile, which is rich in saline lake lithium reserves, accounts for more than 50% of the global lithium mineral reserves, followed by Australia (16%), Argentina (10%), and China (6%) (USGS 2020b).

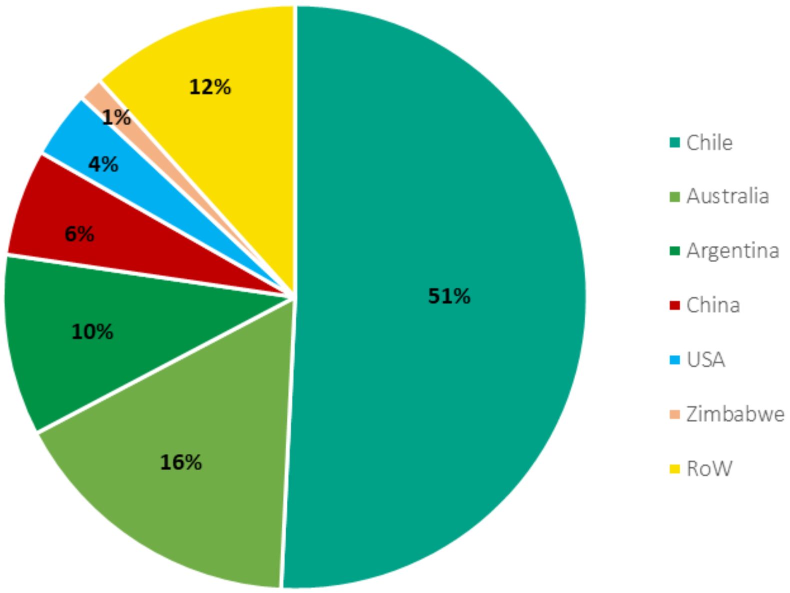


Figure 4-4 *Global lithium reserves by country. Total reserves were 17 million tons in 2019 (USGS 2020b). RoW – Rest of the World.*

4.2 Lithium mining

Lithium mining refers to both lithium rock mining and exploitation from lithium brines. Global lithium mining production in 2019 was 478,000 tons LCE (equals to 88,000 tons Li metal), including 264,000 tons LCE lithium production from minerals and 214,000 tons LCE from brines (Benchmark Minerals Intelligence 2021a) corresponding to 55 % and 45 % of the global production, respectively. By country, about 52% is mined in Australia, followed by Chile (23%), China (13%), and Argentina (7%) (Figure 4-5) (USGS 2020b).

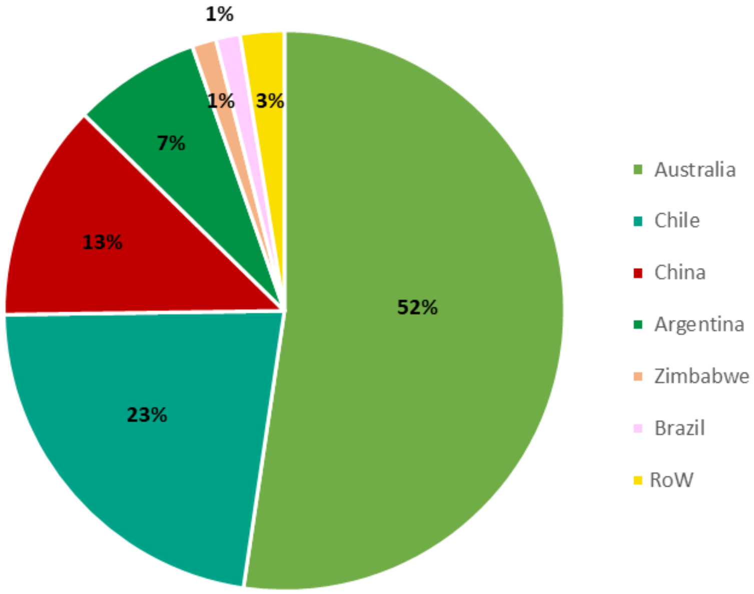


Figure 4-5 *Lithium mine production by country in 2019 (USGS 2020b). RoW – Rest of the World.*

In 2019 there were 28 active lithium mines, distributed in 9 countries (Figure 4-6), Of these, five are producing lithium minerals (Australia, Zimbabwe, Portugal, Tanzania, and Brazil), three are extracting lithium from brines (Chile, Argentina, and the USA) while China is the only country with both types of production. 14 of 28 mines are located in China, but the largest mines are located in Australia, Chile, and Argentina, as shown in Table 4-4.

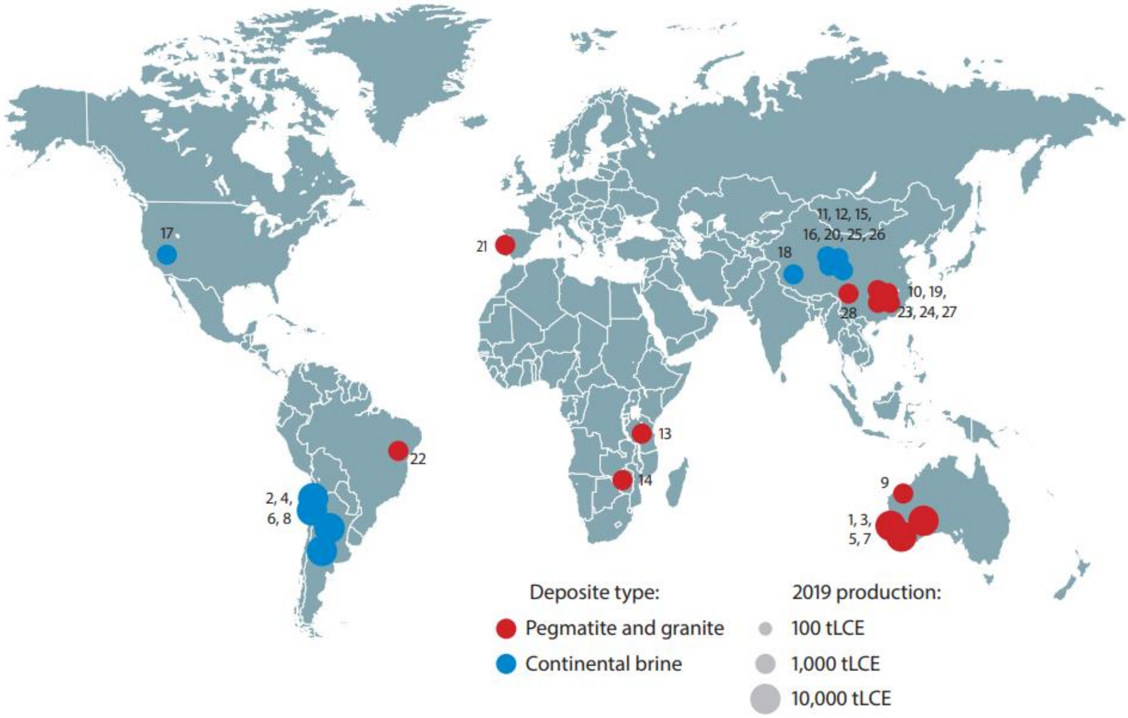


Figure 4-6 *Active lithium mines in 2019. Numbers refer to mines listed in Table 4-4.*

In Chile, lithium is recovered from two brine operations from Salar de Atacama in the Andes Mountains. Concentrated brines are transported to Antofagasta on the coast, and processed at two lithium carbonate plants, one lithium chloride plant, and one lithium hydroxide plant. In the Andes Mountains of Argentina, lithium carbonate and lithium chloride are produced from brines from Salar del Hombre Muerto, and lithium carbonate is produced from brines from Salar de Olaroz. A substantial percentage of the lithium carbonate produced in South America is exported to the USA. Australia is by far the leading producer of lithium mineral concentrates. Brazil, China, Portugal, and Zimbabwe also produce significant quantities of lithium concentrates, most of which are used directly in the production of ceramics and glass. China produces large quantities of lithium carbonate and lithium hydroxide from mineral concentrates, mostly from spodumene imported from Australia. In China, lithium carbonate is produced from brines from the Zabuye Salt Lake in western Tibet and from the Taiji Nai'er Salt Lakes in Qinghai Province (USGS 2020b).

Approximately 87% of the global lithium mining production is produced from 10 mines, some of which have the same ownerships through different operators. Three companies, Albemarle, SQM, and Tianqi, controlled more than half of global lithium mining production in 2019 (Benchmark Minerals Intelligence 2021a). Table 4-5 lists the top 10 lithium mining companies after summarizing their productions in different mines through ownership. However, the ownership of the mine operators changes quite frequently. For example, Albemarle took over 60% interest of

Mineral Resources in 2019 (Bloomberg NEF 2021b). With more new mining companies joining the mining production, the predominance of the top 3 companies is expected to change in the coming years.

Figure 4-7 shows volume from lithium mining production by country in 2019, using two different statistical methods. China, the USA, and Australia are the top 3 countries of operator owners of lithium mining production. Australia is first by mine location, but third based on operator's ownership. However, as mentioned earlier, the operator's ownership develops dynamically with the companies' economy and this rank was therefore probably only valid for a very limited period.

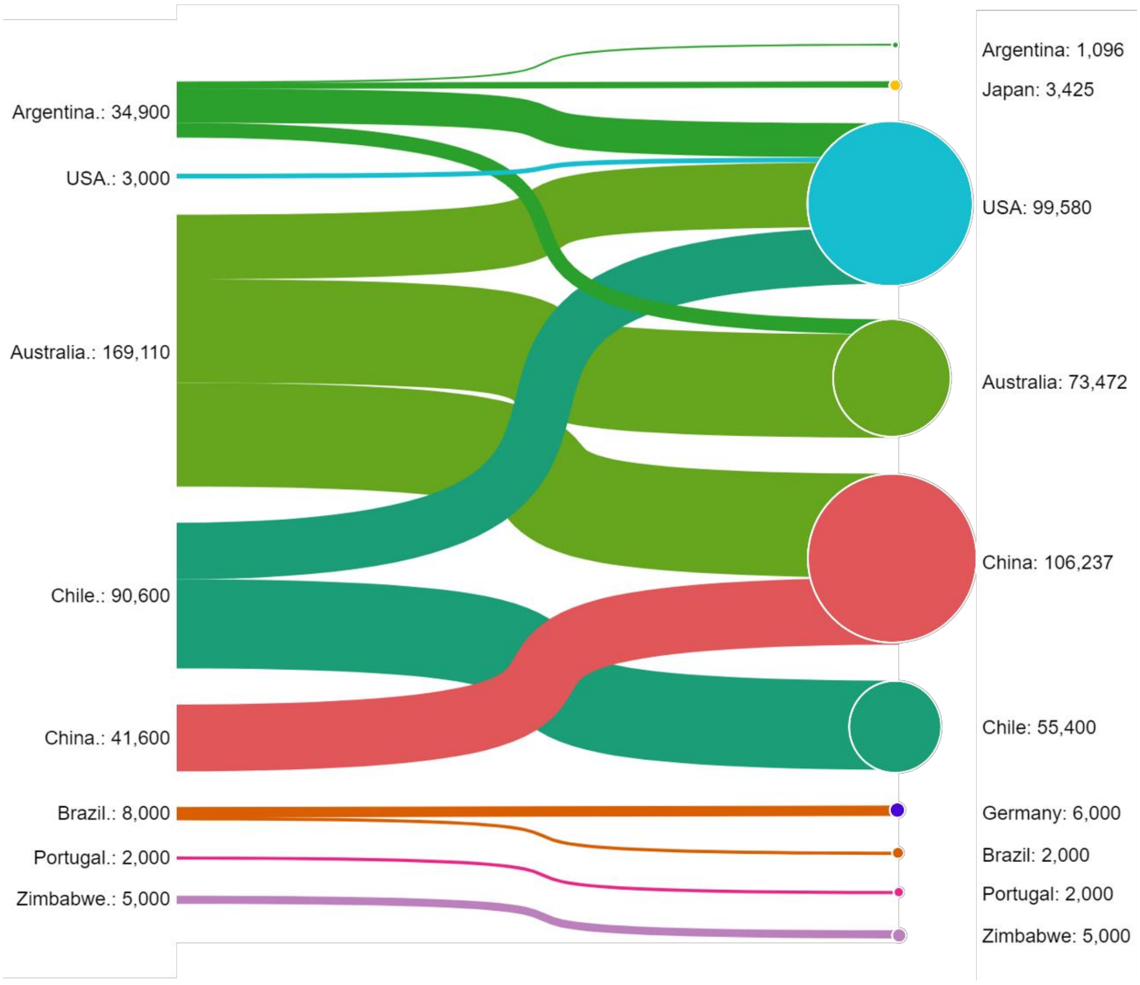


Figure 4-7 *Lithium mine production shift among countries by operator's ownership (Unit: tons LCE) (Source: USGS 2020b; Benchmark Minerals Intelligence 2021a).*

Table 4-4 *Active lithium mines production, country, ownership and ore type in 2019 (Roskill, 2020b; Benchmark Minerals Intelligence, 2021a). Deposit types: 1 refers to pegmatites and granites, 2 refers to brine.*

No.	Mine	2019 (tons LCE)	Country	Ownership	Deposit type
1	Greenbushes (Base)	82,000	Australia	Albermarle, 49%, USA; Tianqi, 51%, China.	1
2	Salar de Atacama (SQM)	55,400	Chile	SQM 100% Chile	2
3	Mt Marion	36,800	Australia	Mineral Resources, 50% Australia; Ganfeng, 50% China	1
4	Salar de Atacama (SQM)	35,200	Chile	Albermarle, 100% Chile	2
5	Pilgan (includes improvement works)	25,550	Australia	Pilbara Miner, 87% Australia; CATL, 7% China; Ganfe, 6% china	1
6	Hombre Muerto	21,200	Argentina	Livent, 100% USA	2
7	Mt Cattlin	15,960	Australia	Galaxy Resources, 100% Australia	1
8	Salar de Olaroz	13,700	Argentina	Orocobre, 67% Australia; Toyota Tsushc, 25% Japan; JEMS, 8.5% Argentina	2
9	Ngungaju	8,800	Australia	Pilbara Minerals, 100% Australia	1
10	Yichun Tantalum (414)	8,000	China	Yichun Mining Co., 100% China	1
11	West Taiji Nai'er, Qinghai, CITIC	6,000	China	Qinghai Guoan (CITIC),100% China	2
12	Qarhan, Qinghai	6,000	China	Qinghai Salt Lake Industry Group (QSLG), 100% China	2
13	Mibra	6,000	Brazil	AMG, 100% Germany	1
14	Al Hayat	5,000	Zimbabwe	Bikita Minerals, 100% Zimbabwe	1
15	East Taiji Nai'er, Qinghai	4,400	China	Qinghai Lithum (QLL), 100% China	2
16	West Taiji Nai'er, Qinghai, HXR	3,000	China	Qinghai Henxingrong (HXR), 100% China; Fulin Precision (cathode producer) Plansto acquire 25%	2
17	Silver Peak	3,000	USA	Albemarle, 100% USA	2
18	Zabuye, Tibet	2,000	China	Tibet Mining, 82% China; BYD,18% China	2
19	Yifeng Huashan Porcelain, Yifeng Baishuidong Kaolin	2,000	China	Yongxing & Yichun Mining Co.,70% China; Yichun Mining Co., 30% China	1
20	East Qarhan, Qinghai	2,000	China	Zangge, 100% China	2
21	Mina do Barroso	2,000	Portugal	Sociedade Mineira de Pegmatites, 100% Portugal	1
22	Cachoeira	2,000	Brazil	CBL, 100% Brasil	1
23	Yifeng Huaqiao Dagang Porcelain	1,500	China	Feiyu New Energy, 70% China; Yichun Mining Co. 30% China	1

No.	Mine	2019 (tons LCE)	Country	Ownership	Deposit type
24	Ningdu	1,500	China	Ganfeng Lithium 100%, 100% China	1
25	Jiajika	1,100	China	YYoungy (Rongjie), 100% China	2
26	Yiliping	1,000	China	China Minmetals, 100% China	2
27	Yichun others	1,000	China	Yichun Others, 100% China	1
28	Fengxin Jinfeng Silicon	1,000	China	Nanshi, 49% China; Yichun Mining Co. 51% China	1

Table 4-5 *Top 10 lithium mining companies with largest production in 2019 (Roskill, 2020b; Benchmark Minerals Intelligence, 2021a).*

Produce company	Project locations	Project mine production by ownership (tons LCE)	2019 total mine production (tons LCE)	Nationality
Albemarle	Greenbushes, Australia (49%)	40,180	96,580	USA
	Silver Peak, USA (100%)	21,200		
	Salar de Atacama, Chile (100%)	35,200		
SQM	Salar de Atacama, Chile (SQM) (Including Expansion I) (100%)	55,000	55,000	Chile
Tianqi	Greenbushes, Australia (Base) (51%)	42,000	42,000	China
Pilbara Minerals	Pilgan, Australia (includes improvement works) (87%)	22,000	31,000	Australia
	Ngungaju, Australia (100%)	9,000		
Ganfeng	Mt Marion, Australia (50%)	18,000	21,000	China
	Ningdu, China (100%)	2,000		
	Pilgan, Australia (includes improvement works) (6%)	2,000		
Livent	Hombre Muerto, Argentina (100%)	21,000	21,000	USA
Galaxy Resources	Mt. Cattlin, Australia (100%)	16,000	16,000	Australia
Yichun Mining Co.	Yichun Tantalum, China (414) (100%)	8,000	9,500	China
	Yifeng Huashan Porcelain, Yifeng Baishuidong Kaolin, China (30%)	1,000		
	Fengxin Jinfeng Silicon, China (51%)	51		
	Yifeng Huaqiao Dagang Porcelain, China (30%)	450		
Lanke	Qarhan, Qinghai, China (100%)	6,000	6,000	China
CITIC Guoan	West Tijnaier, Qinghai, CITIC, China (100%)	6,000	6,000	China
AMG	Mibra, Brazil (100%)	6,000	6,000	Germany

Lithium products derived from brine operations can be used directly in end-markets, whereas rock lithium concentrates must be further processed before they can be used in value-added applications such as Li-ion batteries (Kavanagh *et al.* 2018a). The company SQM, the main exporter in Chile, exported a small volume of lithium chloride brine to Ganfeng Lithium in China in 2019, but generally trade of lithium brines is not common. Nearly all brines are evaporated locally and then traded as refined products (such as lithium carbonate, lithium hydroxide, and lithium chloride). Therefore, 'trade with lithium mine' generally equals lithium ore trade.

Rock deposits are mined using standard techniques such as surface (open-pit) or sub-surface (underground) mining (Champion & Australia 2018). Spodumene is the principal lithium mineral in the trade, and the largest exporter is Australia. Most of Australia's lithium is exported overseas for further processing to China, South Korea, and USA (Figure 4-8) as a bulk concentrate with only 6% Li_2O (Australian Trade and Investment Commission 2018). In contrast, petalite concentrate produced in Zimbabwe is exported mainly to Eastern Asia and Germany, while lithium mineral ore concentrate from Canada is mainly exported to China and USA (Roskill 2020b).

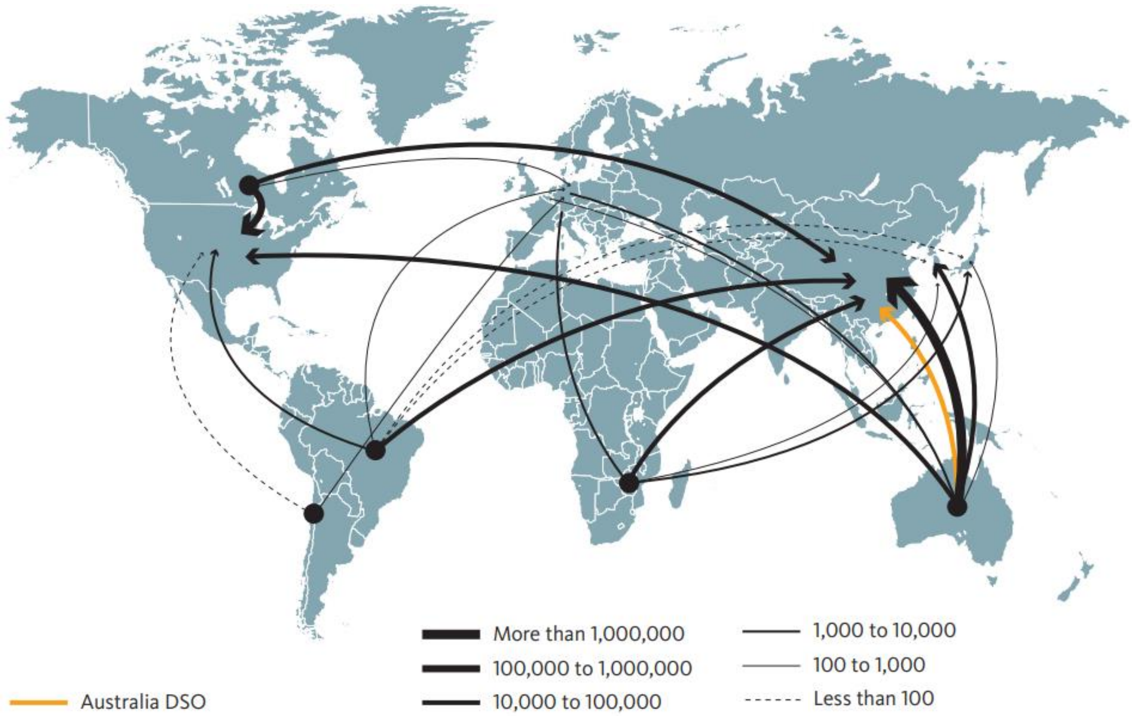


Figure 4-8 *Global trade flow of lithium from ores in 2019 (Source: UN Comtrade).*

4.3 Lithium processing

Initial processing of lithium ore involves physical beneficiation to increase the lithium content. Concentration is normally undertaken at or close to the mines and includes crushing the ore and separating lithium and gangue minerals by using a range of physical processes. The concentrate then undergoes chemical beneficiation to recover the lithium. Refining spodumene deposits follows conventional hard-rock mining and processing practices. Ore is mined via drill and blast methods, then excavated and trucked to a central processing facility. The ore then undergoes multiple stages of crushing to reduce the particle size to below 6 mm. Following and magnetic separation, the wet concentrate is filtered and prepared for transportation as a 6% lithium oxide (Li_2O) concentrate (Larocca 2020). It is then crushed and roasted again, this time with concentrated sulfuric acid. Ultimately, sodium carbonate, or soda ash, is added, and the resulting lithium carbonate is crystallized, heated, filtered, and dried (Yelatontsev & Mukhachev 2021).

Capital input for producing lithium from brines is high but subsequent operating costs are comparatively low. While less expensive to mine than rock, lithium extraction from brine can take 12 to 18 months to reach extraction levels. Project scale-up usually takes between 8 to 10 years for brine operations compared to 2 to 3 years for spodumene or other mineral based lithium mining (BGS 2018). The methods used to refine brines will vary depending on the chemistries found at each deposit. However, the first step will always involve concentrating the brines, because even the higher-grade brines contain only very low concentrations of lithium. For continental brine deposits solar evaporation in a series of surface ponds is the most common (Figure 4-9). Sodium and potassium are often first harvested from the first ponds, while later ponds have increasingly high concentrations of lithium. When the lithium chloride in the evaporation ponds reaches an optimum concentration, the solution is pumped to a recovery plant where extraction and filtering remove any unwanted boron and/or magnesium. It is then treated with sodium carbonate (soda ash), thereby precipitating lithium carbonate. The lithium carbonate is then filtered and dried (BGS 2016).

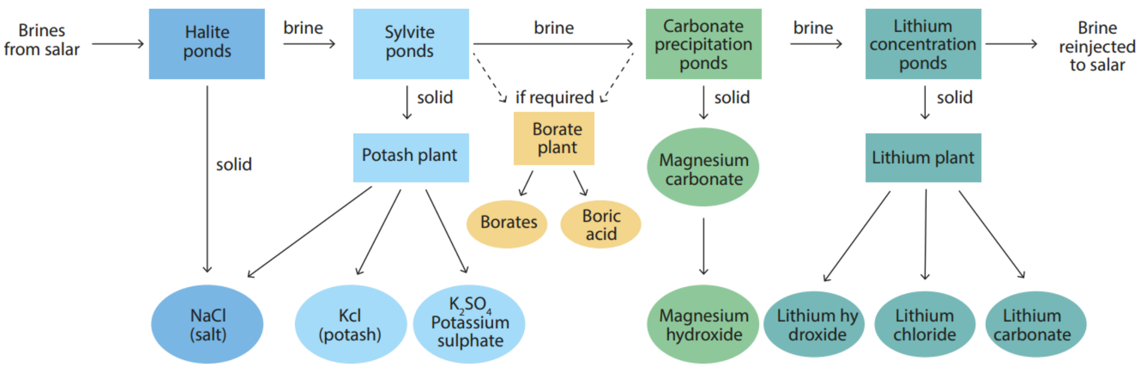


Figure 4-9 *Generalized process for lithium extraction from continental brine deposits, with associated co-products (BGS 2016).*

A wide variety of lithium compounds is commercially available, although lithium carbonate is the most widely used and accounts for more than 90% of the consumption. Other forms of lithium with important industrial uses include lithium hydroxide, lithium chloride, lithium metal and butyllithium. The majority of the available compounds are obtained by processing lithium carbonate (Mohr *et al.* 2012). These basic chemicals are then used to produce many derivatives. Lithium carbonate is mainly used to produce LIB cathode materials including lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt manganese oxide (NCM), etc. Lithium carbonate is also used for glazing and primary aluminium production. Lithium hydroxide can also be used to produce LIB cathode materials, but is limited on lithium iron phosphate (LFP), though it is the essential raw material for lithium-base lubricating greases which have good low temperature performance. Lithium chloride is the essential raw material for LIB electrolytes and is also used for brazing flux and desiccant. In addition to the applications above, lithium chemicals are also used in pharmaceuticals, alloys, polymers, etc. Obtaining accurate global data on lithium-refining production is challenging compared to mining production data. This is due to the fact that some lithium brine-based mining products are already chemicals, such as Li_2CO_3, LiCl and LiOH, and those mining products are also reported as lithium chemicals. To avoid duplicating statistics, many organizations do not provide specific refining production figures (USGS 2020b). Information on lithium refining production by different countries is typically available through commercial data consulting companies, such as Benchmark Mineral Intelligence and Roskill (Figure 4-10) (Roskill 2020b; Benchmark Mineral Intelligence 2021a). Total world production in 2019 of lithium refines was 334,000 tons LCE (equal to 62,765 tons Li content). China dominates with 65% of the total lithium refining production, followed by Chile (28%), Argentina (11%) and USA (4%) (Roskill 2020b; Benchmark Mineral Intelligence 2021a).

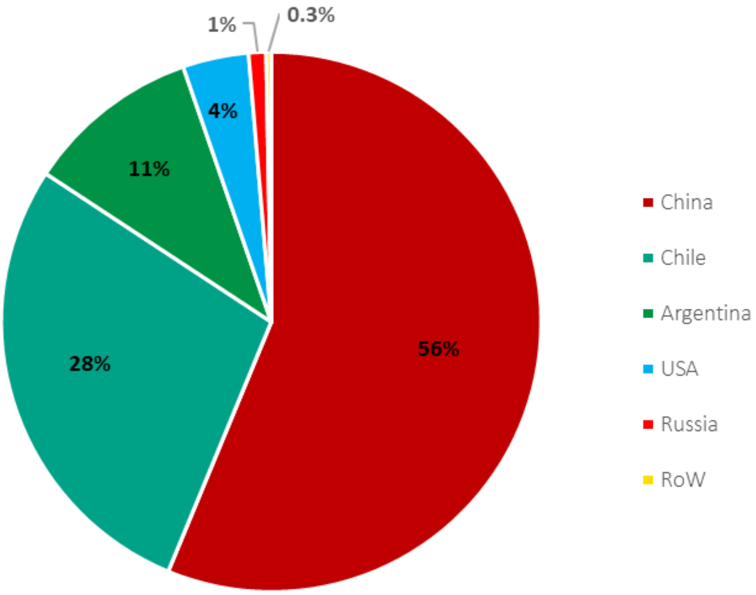


Figure 4-10 *Lithium refining production by country in 2019 (Roskill 2020b; Benchmark Mineral Intelligence 2021a). RoW – Rest of the World.*

A total of 41 refining plants across five countries are depicted in
Figure ***4-11*** and Table 4-6. Of these 31 are located in China and the remainder in USA (3), Chile (3), Argentina (2), and Russia (2). Some plants produce two or three different types of lithium chemicals, which are listed separately in Table 4-6. Therefore, in total 54 plant productions are listed. Around 70% of the total refined lithium is produced by the top 10 refining plants. China dominates the production of lithium hydroxide, accounting for an estimated 89% of the world's lithium hydroxide production in 2019, but Chinese refineries also produce both lithium carbonate and lithium chloride. Conversely, lithium carbonate is the main refining product of Chile and Argentina.

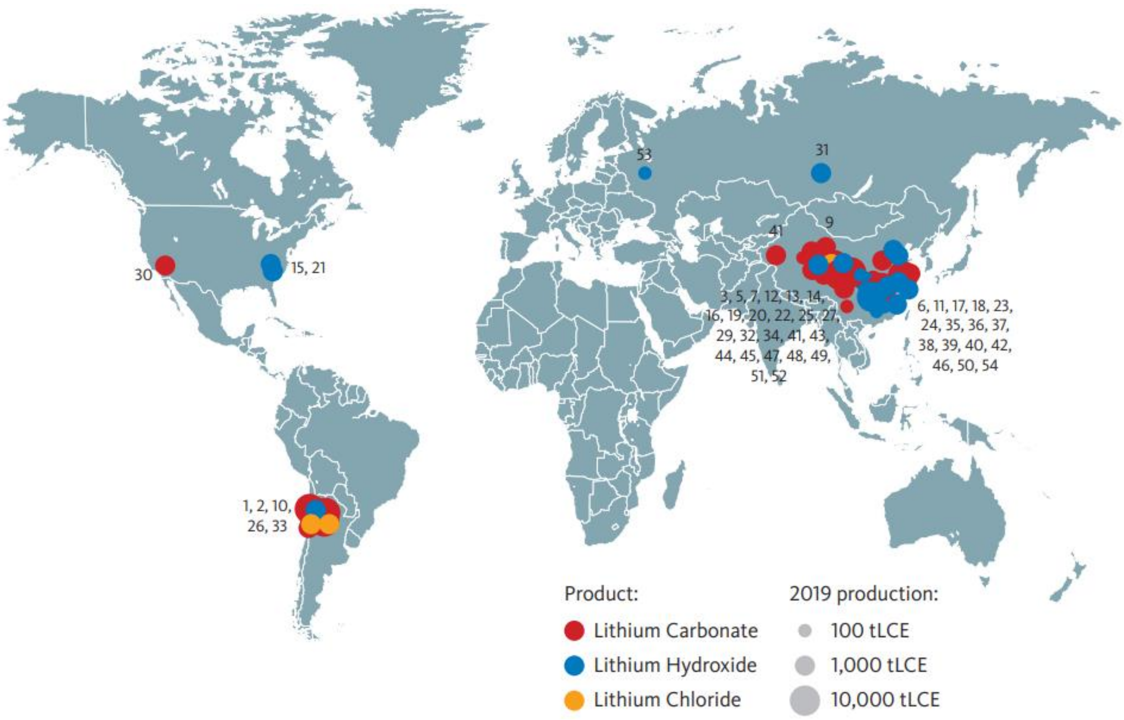


Figure 4-11 *Active lithium refining plants in 2019 (China Statistic Press 2020; Roskill 2020b; Benchmark Mineral Intelligence 2021a). Numbers refer to Table 4-6.*

Table 4-6 *Active lithium refining plants in 2019 (China Statistic Press 2020; Roskill 2020b; Benchmark Mineral Intelligence 2021a).*

No.	Plant	Production in 2019 (tons LCE)	Country	Ownership & Nationality	Product
1	Salar del Carmen (Carbonate)	46,100	Chile	SQM, 100% Chile	Lithium Carbonate
2	La Negra I/II	31,700	Chile	Albemarle, 100% USA	Lithium Carbonate
3	Mahong	22,000	China	Ganfeng Lithium,100% China	Lithium Carbonate
4	Fenix (Hombre Muerto)	18,200	Argentina	Livent, 100% USA	Lithium Carbonate
5	Zhangjiagang	15,500	China	Tianqi Lithium,100% China	Lithium Carbonate
6	Mahong	14,500	China	Ganfeng Lithium,100% China	Lithium Hydroxide
7	Shehong	14,500	China	Tianqi Lithium,100% China	Lithium Carbonate
8	Olaroz	13,700	Argentina	Orocobre, 67% Australia; Toyota Tsushc, 25% Japan; JEMS, 9% Argentina	Lithium Carbonate
9	Mahong	12,000	China	Ganfeng Lithium,100% China	Lithium Chloride
10	Salar del Carmen (Hydroxide)	9,300	Chile	SQM, 100% Chile	Lithium Hydroxide
11	Xinyu	9,000	China	Albemarle, 100% USA	Lithium Hydroxide
12	Nantong	7,500	China	General Lithium, 100% China	Lithium Carbonate
13	Feicheng	7,000	China	Ruifu Lithium; 100% China	Lithium Carbonate
14	Qarhan, Qinghai	6,000	China	Qinghai Salt Lake Industry Group (QSLG), 100% China	Lithium Carbonate
15	Bessemer City	6,000	USA	Livent, 100% USA	Lithium Hydroxide
16	West Tijnaier, Qinghai	6,000	China	Qinghai Guoan, 100% China	Lithium Carbonate
17	Xinyu II	5,000	China	Albemarle, 100% USA	Lithium Hydroxide
18	Ya'an	5,000	China	Sichuan Yahua Group, 100% China	Lithium Hydroxide
19	Meishan	5,000	China	Sichuan Yahua Group, 100% China	Lithium Carbonate
20	East Taijnaier, Qinghai	4,400	China	QLL (Qinghai Lithium), 100% China	Lithium Carbonate
21	Kings Mountain	4,200	USA	Albemarle, 100% USA	Lithium Hydroxide
22	Zhiyuan	4,000	China	Chengxin Lithium, 100% China	Lithium Carbonate
23	Meishan	4,000	China	Albemarle, 100% USA	Lithium Hydroxide
24	Shehong	4,000	China	Tianqi Lithium,100% China	Lithium Hydroxide
25	Ya'an	4,000	China	Sichuan Yahua Group, 100% China	Lithium Carbonate
26	La Negra II	3,500	Chile	Albemarle, 100% USA	Lithium Chloride
27	Yichun	3,000	China	Nanshi, 100% china	Lithium Carbonate

No.	Plant	Production in 2019 (tons LCE)	Country	Ownership & Nationality	Product
28	Fenix (Hombre Muerto)	3,000	Argentina	Livent, 100% USA	Lithium Chloride
29	Qinghai	3,000	China	Qinghai Hengxinrong, 100% China	Lithium Carbonate
30	Silver Peak	3,000	USA	Albemarle, 100% USA	Lithium Carbonate
31	JSC	3,000	Russia	CMP - JSC, 100% Russia	Lithium Hydroxide
32	Aba	3,000	China	Sichuan Yahua Group, 100% China	Lithium Carbonate
33	La Negra	3,000	Chile	Albemarle, 100% USA	Lithium Carbonate
34	Yichun	2,800	China	Yongxing, 100% China	Lithium Carbonate
35	Zhiyuan	2,500	China	Chengxin Lithium, 100% China	Lithium Hydroxide
36	Meishan	2,500	China	Sichuan Yahua Group, 100% China	Lithium Hydroxide
37	JB (Jiangsu Baozong)	2,000	China	Livent, 100% USA	Lithium Hydroxide
38	Jiujiang	2,000	China	General Lithium, 100% China	Lithium Hydroxide
39	Feicheng	2,000	China	Ruifu Lithium, 100% China	Lithium Hydroxide
40	Fuzhou	2,000	China	Minfeng, 100% china	Lithium Hydroxide
41	Zhabuye, Tibet	2,000	China	Tibet Minerals, 100% China	Lithium Carbonate
42	Yongzheng	1,500	China	QZ (Quzhou) Yongzheng,100% China	Lithium Hydroxide
43	Yichun	1,500	China	Feiyu New Energy,100% China	Lithium Carbonate
44	Yiliping	1,000	China	China Minmetals,100% China	Lithium Carbonate
45	Nantong	1,000	China	General Lithium, 100% China	Lithium Carbonate
46	Binzhou	1,000	China	Lubei Chemical,100% China	Lithium Hydroxide
47	Golmud	1,000	China	General Lithium, 100% China	Lithium Carbonate
48	Yichun	1,000	China	Jiangte Motor,100% China	Lithium Carbonate
49	Panzhihua	800	China	Sevenstars,100% China	Lithium Carbonate
50	Yichun	700	China	Nanshi, 100% china	Lithium Hydroxide
51	Ningdu	500	China	Ganfeng Lithium,100% China	Lithium Carbonate
52	Meishan	500	China	SCEI Dingsheng,100% China	Lithium Carbonate
53	Tula	500	Russia	TD Halmek,100% Russia	Lithium Hydroxide
54	Meishan	200	China	SCEI Dingsheng,100% China	Lithium Hydroxide

In contrast to lithium mining production, shared ownership is uncommon among the refining plants, probably due to the much smaller capital requirement to operate a refining plant. However, it is common for leading companies to operate several plants in different countries or locations. Table 4-7 lists the 10 companies with the largest refining production, which combined accounts for around 87% of the total global lithium refining production in 2019.

Table 4-7 *Top 10 lithium refining companies with largest production in 2019 (Benchmark Minerals Intelligence 2021a).*

Operator	Project locations	Project refine production (kt LCE)	2019 total refine production (kt LCE)	Market share	Nationality
Albemarle	La Negra I, Chile (100%)	32	63	19%	USA
	Xinyu, China (100%)	9			
	Xinyu II, China (100%)	5			
	Kings Mountain, USA (100%)	4			
	Meishan, China (100%)	4			
	La Negra II, Chile (100%)	4			
	Silver Peak, USA (100%)	3			
	La Negra, Chile (100%)	3			
SQM	Salar del Carmen, Chile (Carbonate) (100%)	46	55	17%	Chile
	Salar del Carmen, Chile (Hydroxide) (100%)	9			
Ganfeng Lithium	Mahong, China (100%)	22	49	15%	China
	Mahong, China (100%)	15			
	Mahong, China (100%)	12			
	Ningdu, China (100%)	1			
Tianqi Lithium	Zhangjiagang, China (100%)	16	34	10%	China
	Shehong, China (100%)	15			
	Shehong, China (100%)	4			
Livent	Fenix, Argentina (Hombre Muerto) (100%)	18	29	9%	USA
	Bessemer City, USA (100%)	6			
	Fenix (Hombre Muerto), Argentina (100%)	3			
	JB (Jiangsu Baozong), China (100%)	2			
General Lithium	Nantong, China (100%)	8	12	4%	China
	Jiujiang, China (100%)	2			
	Nantong, China (100%)	1			
	Golmud, China (100%)	1			
	Hubei, China (100%)				
Ruifu Lithium	Feicheng, China (100%)	7	9	3%	China
	Feicheng, China (100%)	2			
Ya'an Lithium	Ya'an, China (100%)	5	9	3%	China
	Ya'an, China (100%)	4			
Sichuan Blossom Lithium Industrial	Meishan, China (100%)	5	8	2%	China
	Meishan, China (100%)	3			
Lanke	Qarhan, Qinghai, China (100%)	6	6	2%	China

The top 3 companies, Albemarle, SQM, and Ganfeng Lithium, controlled more than half of the global lithium mining production in 2019 (Benchmark Minerals Intelligence 2021a). In addition, all the three companies are vertically integrated lithium producers. Albemarle and SQM are also top lithium mining producers, while Ganfeng Lithium recently started to invest heavily in lithium mining. Other lithium mining companies, such as Tianqi and Livent, also have strategies to extend their business to refining.

Like lithium mining production, lithium refining production by country depends on the statistical methods used. If based on the nationality of operator's ownership, China, USA, and Chile are the top 3 countries on lithium refining production. Argentina ranked third by refining plant location but has only very limited production owned by local companies. However, as mentioned earlier, the operator's ownership develops dynamically with companies' economy, and this ranking was only valid for a limited time in 2019.

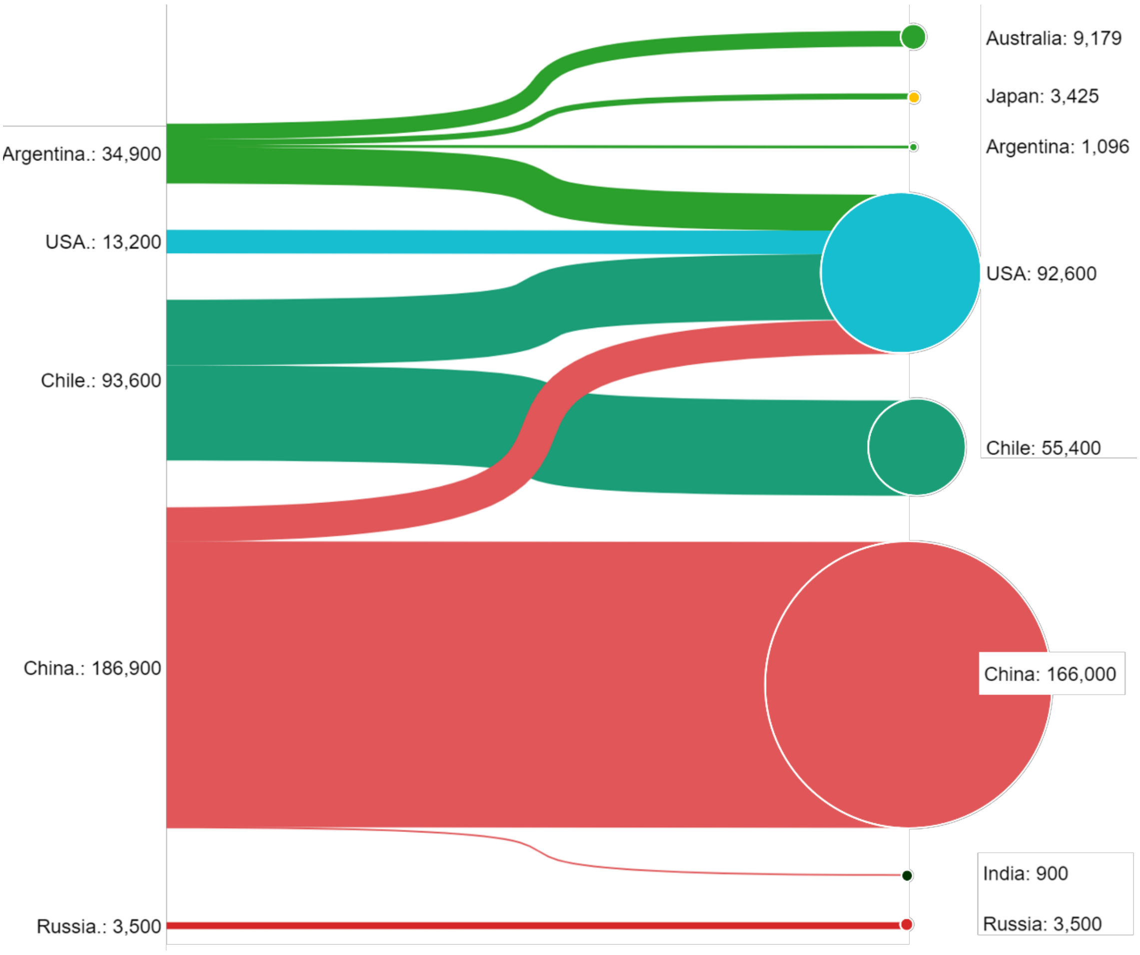


Figure 4-12 *Lithium refining production shift among countries by operator's ownership (Unit: tons LCE). Source: Benchmark Minerals Intelligence 2021a.*

The international trade of refined lithium products is dominated by lithium carbonate. In 2019, global lithium carbonate export was approximately 140,000 tons LCE. There are two different grades of lithium carbonate, namely battery-grade and technical-grade. Normally the purity of battery-grade lithium carbonate is higher than that of technical-grade, and thus more expensive (Chen *et al.* 2020). Figure 4-13 shows the total trade of the two grades of lithium carbonate. Chile and Argentina have limited demand for lithium carbonate and are thus major exporters.

Lithium carbonate export from these two countries accounted for over 80% of the global trade in 2019 (Figure 4-13). China exported 11,820 tons lithium carbonate and ranked third in 2019 but at the same time, China was also the second largest importer, importing mainly from Chile and Argentina. South Korea and Japan ranked first and third, respectively, in 2019 regarding the import of lithium carbonate. Both imported mainly from Chile, supplemented by smaller amounts from Argentina and China.

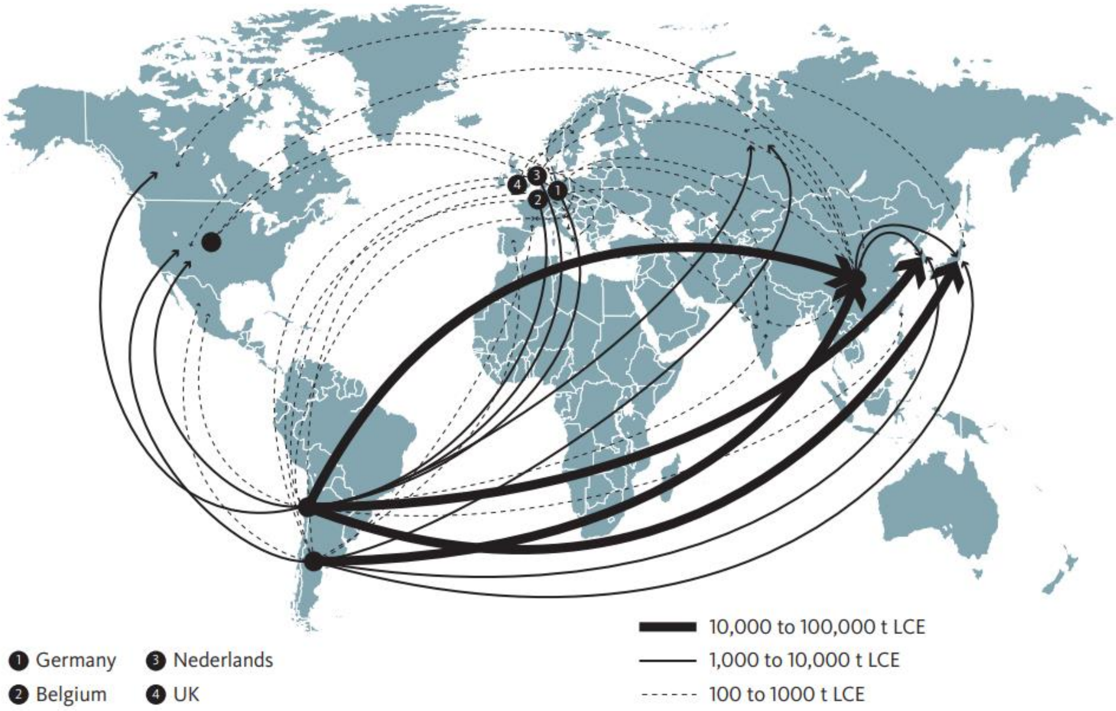


Figure 4-13 *International trade of lithium carbonate in 2019 (Source: UN Comtrade). Lithium carbonates are mainly exported from South America to Eastern Asia.*

Lithium hydroxide is another important product in the international lithium trade. In 2019, global lithium hydroxide export reached 53,417 tons. In line with lithium carbonate, lithium hydroxide is also categorized into battery-grade and technical-grade. Figure 4-14 shows the total trade of lithium hydroxide in 2019. China was the largest exporter of lithium hydroxide, accounting for over 56% of the world trade in 2019 followed by Chile and Russia. Global imports of lithium hydroxide reached 45,000 tons in 2019. South Korea and Japan are again the largest importers and accounted for more than 67% of the global import (Figure 4-14).

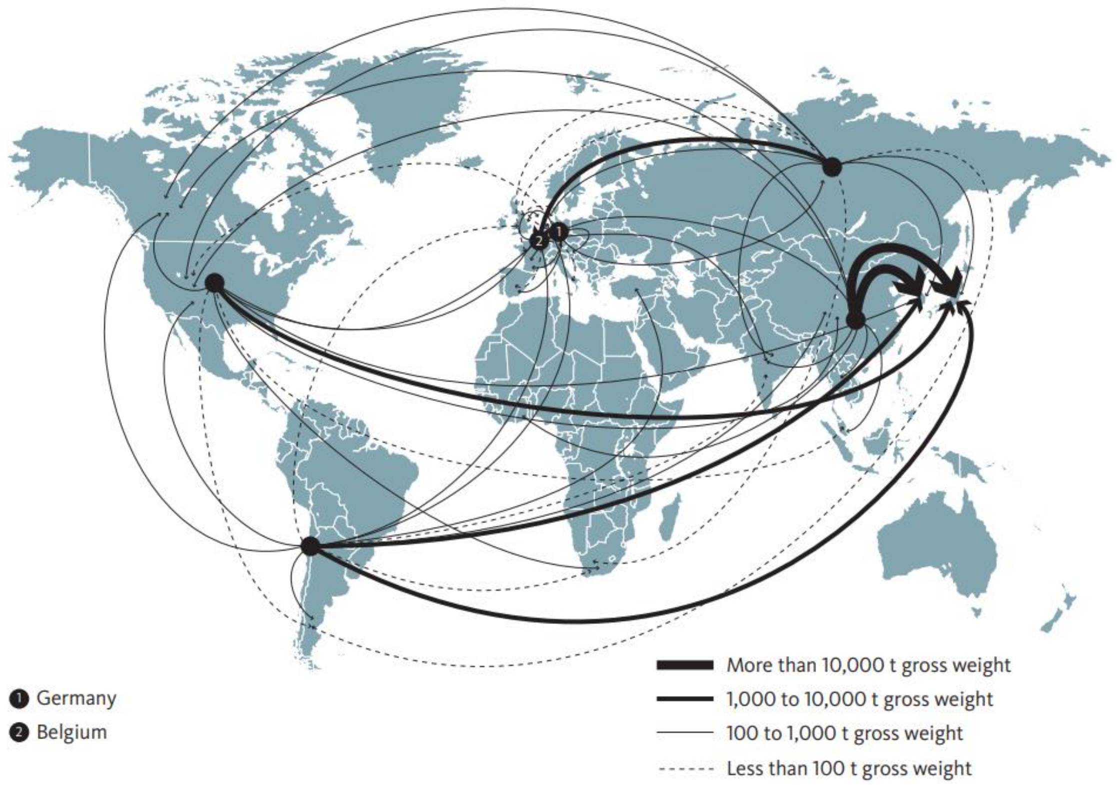


Figure 4-14 *International trade of lithium hydroxide in 2019 (Source: UN Comtrade).*

International trade also includes other types of refined products, such as lithium chloride, lithium metal and butyllithium. Due to their small volumes, they are not considered here.

In summary, Japan and South Korea are the two major importers of both lithium carbonate and lithium hydroxide; mostly because both countries are main battery producers without domestic lithium resources. China is a major importer of lithium carbonate, and at the same time a main exporter of lithium hydroxide (Chen *et al.* 2020). Argentina and Chile are the main exporters of lithium carbonate. Only three countries in the world supply more than 95% of the global lithium production: Chile, Argentina, and China.

4.4 Lithium manufacturing

4.4.1 Manufacturing of components containing lithium

One of the downstream supply chain steps includes the production of lithium chemical derivates such as the precursors of the Li-ion battery cathode materials, and the cathode powders; these steps involve not only lithium, but also elements such as nickel, manganese, and cobalt. Lithium is also used in other components of the battery cell (e.g., electrolyte and anode), and in other semi-products. In some cases, lithium refining products are used directly for final products, lithium hydroxide is e.g., used directly in lithium grease. Other refined lithium products must first be manufactured into chemical derivatives before they can be used in final products. Because of this, data on the lithium consumption by country for these steps are generally inaccurate. Figure 4-15a shows the lithium consumption in different countries and regions; the data are based on Statista (2022), who estimated input-output together with historic stock data and calculated that the global lithium consumption at the manufacturing stage in 2019 was approximately 327,000 tons LCE of lithium (ca. 61,000 tons Li content), including the fraction used directly for final products.

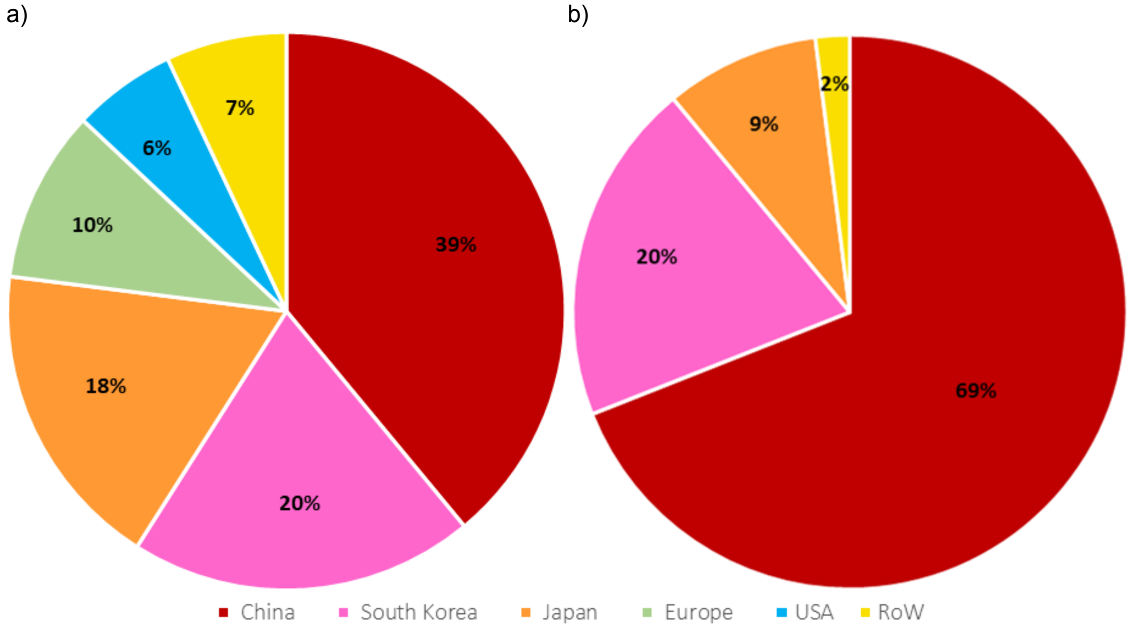


Figure 4-15 *a) Percentage of lithium consumption at lithium-contained components manufacturing stage and b) Percentage Li-ion battery cathode production by country in 2019 (Benchmark Minerals Intelligence 2021a; Statista 2022). RoW – Rest of the World.*

China, South Korea, and Japan were the three principal consumers of lithium in 2019. In all three countries, lithium is mainly used in the battery sector, and a high proportion of the lithium consumed in China, Japan and South Korea was exported worldwide as LIBs. Europe and USA are also important consumers of lithium, mainly for the ceramics and glass sectors.

Batteries require refined lithium compounds mostly in the cathode, and a small amount in anode and electrolyte. Figure 4-15b shows the Li-ion battery cathode production by country in 2019. Cathode production is concentrated in Eastern Asian countries. China alone contributed with around 69% of the global cathode production in 2019, followed by South Korea (20%) and Japan (9%). Both Europe and USA are moving fast to establish a domestic LIB industry and have recently invested large sums to build a complete production line, which will help to increase the cathode production and reduce the dependence on Asian production.

In Figure 4-16, the leading cathode producers shares of the global market in 2019 are shown. There is no single company dominating the cathode production. The productions from the top 10 producers accounted for less than half of the global cathode production in 2019. However, the tendency of vertical integration of lead companies is the same as observed in the mining and refining sectors. Umicore has expanded its business backwards to lithium refining and forwards to LIB production as well as lithium recycling. Sumitomo Metal Mining has invested in both the lithium mining and refining business worldwide.

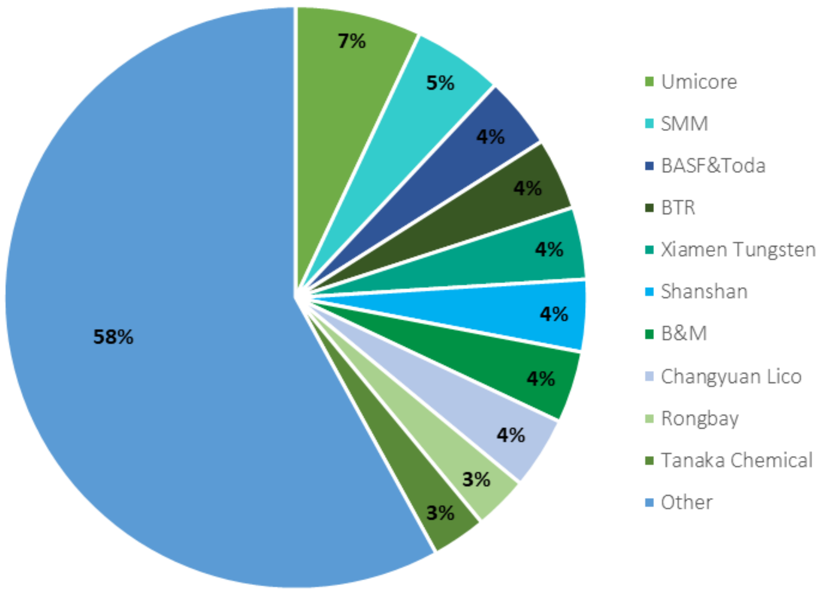


Figure 4-16 *Leading cathode producers in 2019 (Roskill 2020b).*

The electrolyte production, like the cathode production, is concentrated in a few countries. China, South Korea, and Japan are the top 3 electrolyte producing countries, but the production in USA was almost at the same level as that of Japan in 2019. Other countries, such as Poland, United Kingdom (UK), and Malaysia have built fully commissioned assets, and more are under construction or announced. Most of the electrolytes used in commercial Li-ion batteries are non-aqueous solutions, in which lithium salts, such as hexafluorophosphate ($LiPF_6$) or tetrafluoroborate ($LiBF_4$) are dissolved in organic carbonates, in particular, mixtures of ethylene carbonate (EC) with dimethyl carbonate (DMC), propylene carbonate (PC), diethyl carbonate (DEC), and/or ethyl methyl carbonate (EMC) (Li *et al.* 2016).

Anode production requires lithium too, but due to the small volumes, the consumption of lithium in anode production is not discussed further here.

4.4.2 Manufacturing of products containing lithium

Lithium-ion battery is probably the most well-known product which contains lithium in daily life, but other products, such as glass and ceramics, greases, metallurgical powders, and polymer, are also common products which consume lithium in everyday use. The proportion of lithium contained in main products are shown in Figure 4-17.

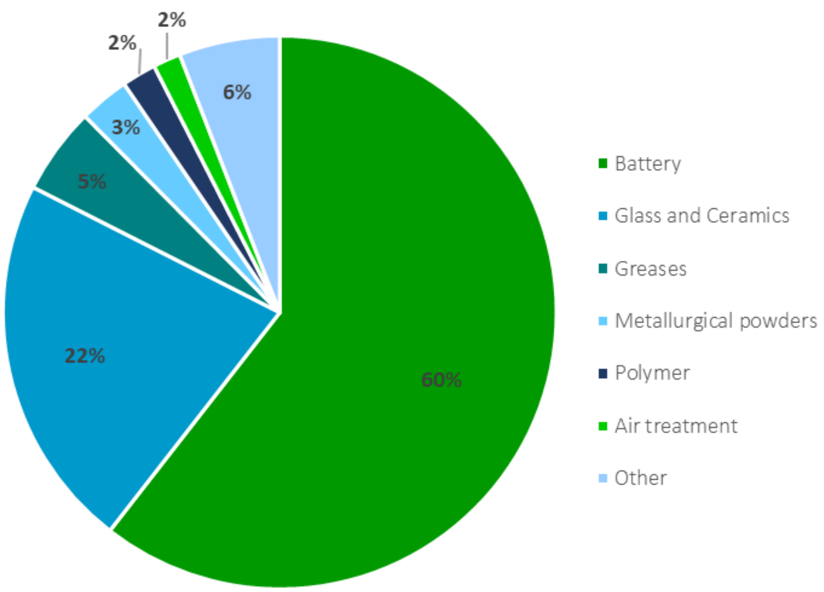


Figure 4-17 *The proportion of lithium contained in final products in 2019 (Benchmark Minerals Intelligence 2021a).*

In Figure 4-18 the production proportion of lithium-contained products and Li-ion battery respectively by country in 2019 is seen. China was the largest lithium-contained products producer, accounting for 33% of the global production, followed by EU, Japan, USA and Australia (S&P Global 2020). In contrast, China was the largest Li-ion battery (LIB) producer, accounting for 72% of the global production, followed by USA, EU, South Korea, and Japan (Benchmark Mineral Intelligence 2021b). The numbers indicate that China dominated the LIB production, while EU, USA and other western countries produced more of other lithium-containing products.

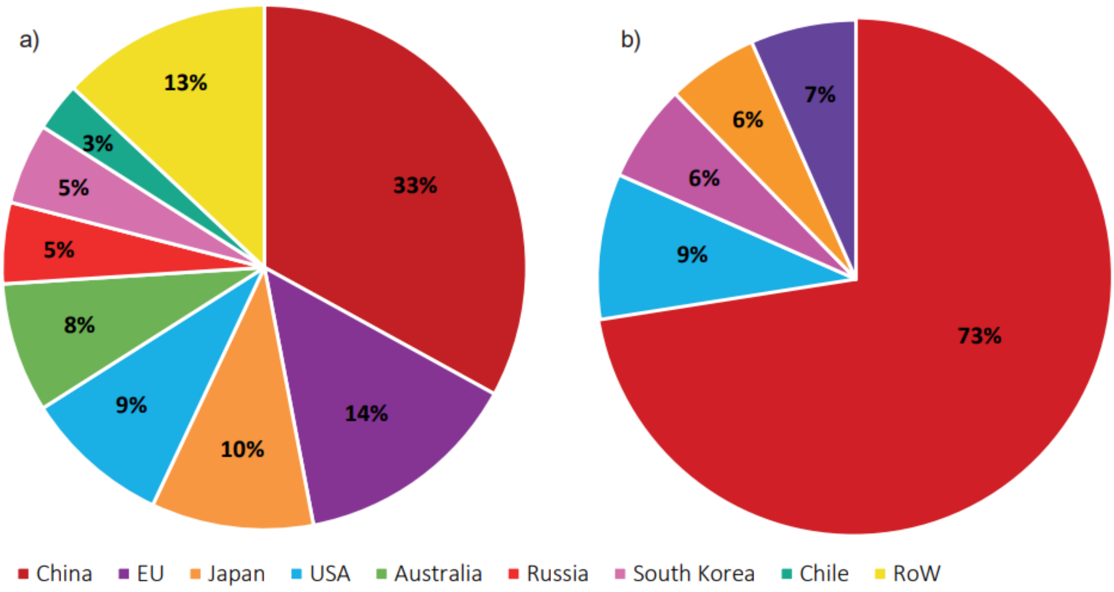


Figure 4-18 *Proportion of a) lithium consumption at lithium-contained products manufacturing stage and b) lithium-ion battery production by country in 2019 (Data source: S&P Global 2020; Benchmark Mineral Intelligence 2021b).*

In 2019, approximately 86% of the world's Li-ion battery cell production capacity was located in Asia, owing to longstanding public and private investments in Li-ion battery technology. This is mirrored in the lithium consumption by country shown in Figure 4-15a, where China, Japan and South Korea are the top 3 lithium consumers. However, considering the use of lithium for cathode production (Figure 4-15b), the use by USA and EU are negligible, indicating that large volumes of LIB cell components manufactured in Asia are exported to USA and EU for final assembly.

In Figure 4-19 the top 10 international owners of gigafactories for global LIB production, which in 2019 combined contributed to 54% of the global LIB production, are shown. Gigafactory refers to facilities that produce batteries for EVs on a large scale. Although 6 of 10 gigafactories are located in China, many companies have built (such as LG Energy solution, Samsung SDI and Tesla) or plan to build (such as CATL and BYD) battery plants in USA, which are expected to contribute to the domestic production of LIBs in USA.

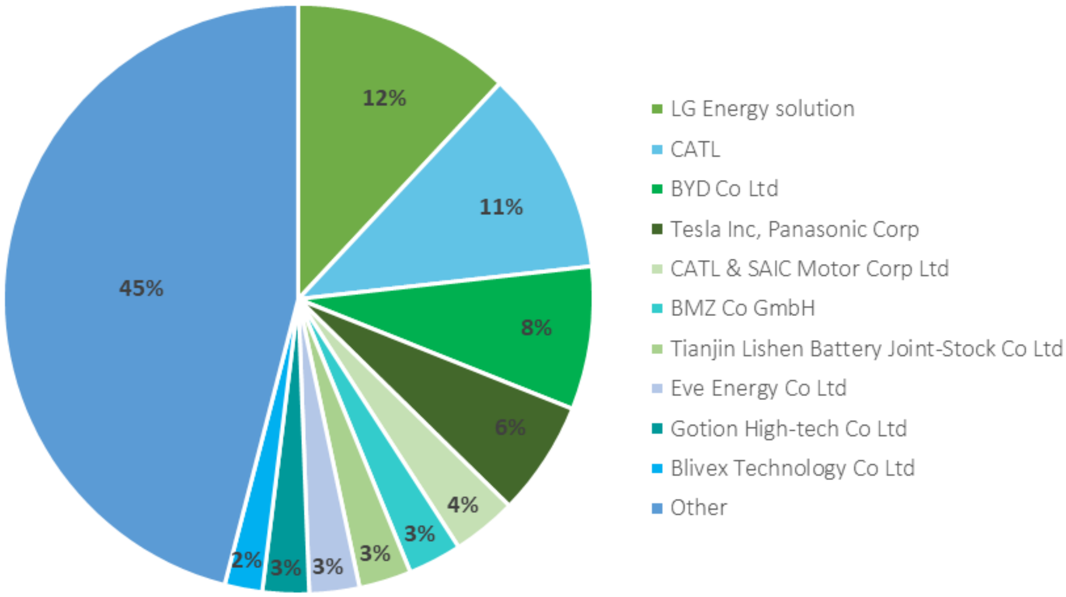


Figure 4-19 *Leading gigafactories for LIB production in 2019 (Roskill 2020b).*

The EU is making significant progress in battery production as well. Since the establishment of the European Battery Alliance in 2017, relevant industries have experienced rapid development, leading to an increase in the number of battery plants. In 2022, approximately 252 GWh of batteries were manufactured in Europe (Bockey & Heimes 2023). Several prominent companies, including LG Chem, Magna Energy Storage, Samsung SDI, and SK Innovation, have operational plants located in Eastern Europe. Moreover, Envision AESC produces cells in the UK, Blue Solutions in France, and Leclanché in Germany. There are plans for the construction of additional plants, particularly in Germany (Albatts 2021; Betz *et al.* 2021). Despite these advancements, Europe still relies on the importation of battery raw materials and chemicals, a dependence that is expected to continue in the near future.

4.5 Lithium end-uses

Approximately 298,000 tons LCE (equals to 56,000 tons) lithium was used in 2019 at the end-use stage and with Li-ion batteries as the main product. Within the end-use application, lithium is used predominantly in automotive applications (35%), followed by portable electronics (14%), and energy storage systems (4%) with various other applications within industry (19%), while the rest 28% are for other use (Figure 4-20) (Benchmark Minerals Intelligence 2021a).

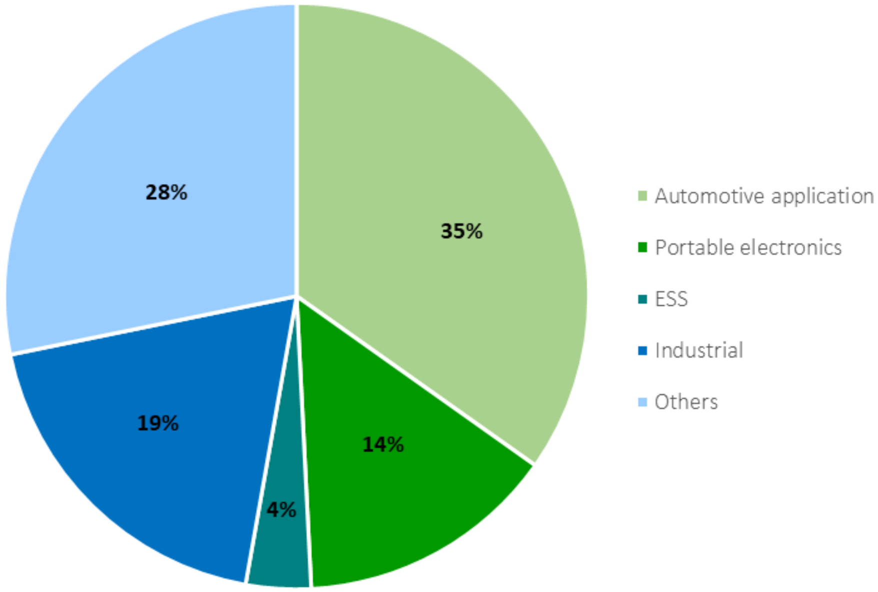


Figure 4-20 *Global lithium demand by end-use in 2019 (Benchmark Minerals Intelligence 2021a). ESS – energy storage systems.*

If divided by country, China was the largest consumer in 2019, accounting for around 60% of the global total consumption by end-use, followed by USA and EU (Roskill 2020b). The three regions, Asia-Pacific (APAC), Europe and North America, consumed more than 90% of lithium-contained end-use products, as shown in Figure 4-21.

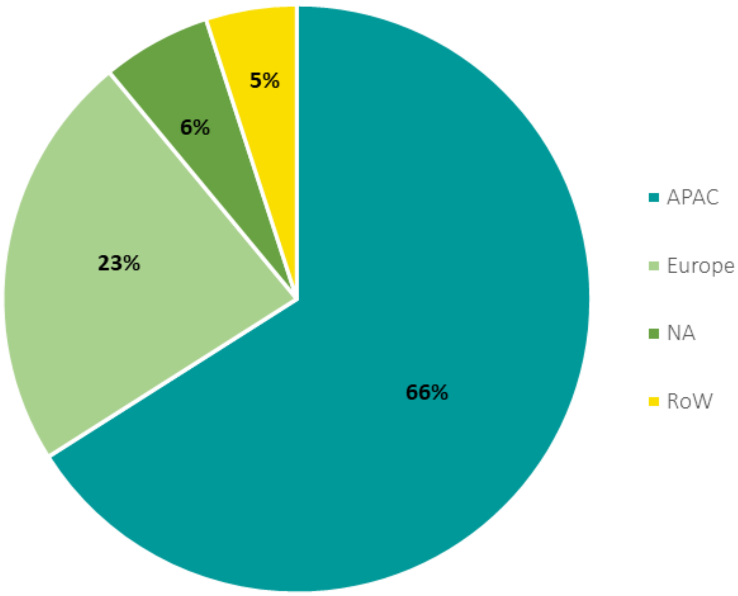


Figure 4-21 *Global lithium end-use consumption by region in 2019 (Fastmarket 2022). APAC – Asia-Pacific, NA – North America, Row – Rest of the World.*

4.6 Lithium recycling

Lithium can theoretically be recycled repeatedly without loss of performance. However, for several reasons, lithium recycling has not yet taken off as an industry. Firstly, lithium resources are relatively abundant, and the primary production price is modest, leaving little incentive to develop secondary production. Secondly, historically important end-uses of lithium such as aluminium refining, lubricants and greases, pharmaceuticals, and synthetic rubber are dissipative rather than cumulative, making it difficult to recover and recycle lithium. Lithium used in ceramic glazing is not recoverable at all, as the glazing tends to wear out over time. Other products that contain lithium but essentially non-recoverable include air conditioning desiccants and defence applications (Blagoeva *et al.* 2019; Mohr *et al.* 2020). These are the traditional uses for lithium prior to the advent of the Li-ion battery technology. The battery sector is therefore the main end-use that has potential for major lithium recovery. Until 2010, Li-ion batteries were mainly used in portable devices. The batteries were therefore most likely in small size and tended to behave dissipative. The collection rate for Li-ion batteries used in portable devices sector is low since consumers either tend to keep the batteries at home or dispose them together with other types of industry batteries. Since 2010, more and more Li-ion batteries have been produced in large sizes to be used in EVs, but there is still not enough Li-ion battery waste from the EV sector for efficient recycling, mainly because the lifetime of EV batteries is much longer than that of consumer electronic (CE) batteries. The expected lifetime is around 7-8 years, but in practice the working life of most EV batteries is longer. Moreover, most disposed EV batteries can be reused in energy storage systems, instead of going to recycling directly. As a result, a sufficient EV battery waste stream to allow efficient recycling is not expected before 2025-2030 (Harper *et al.* 2019).

Similar to cobalt and other metals in Li-ion batteries, there are three possible methods (pyrometallurgical, hydrometallurgical and direct recycling) to recycle lithium in Li-ion batteries (Figure 4-22) (Gaines 2018; Xu *et al.* 2020).

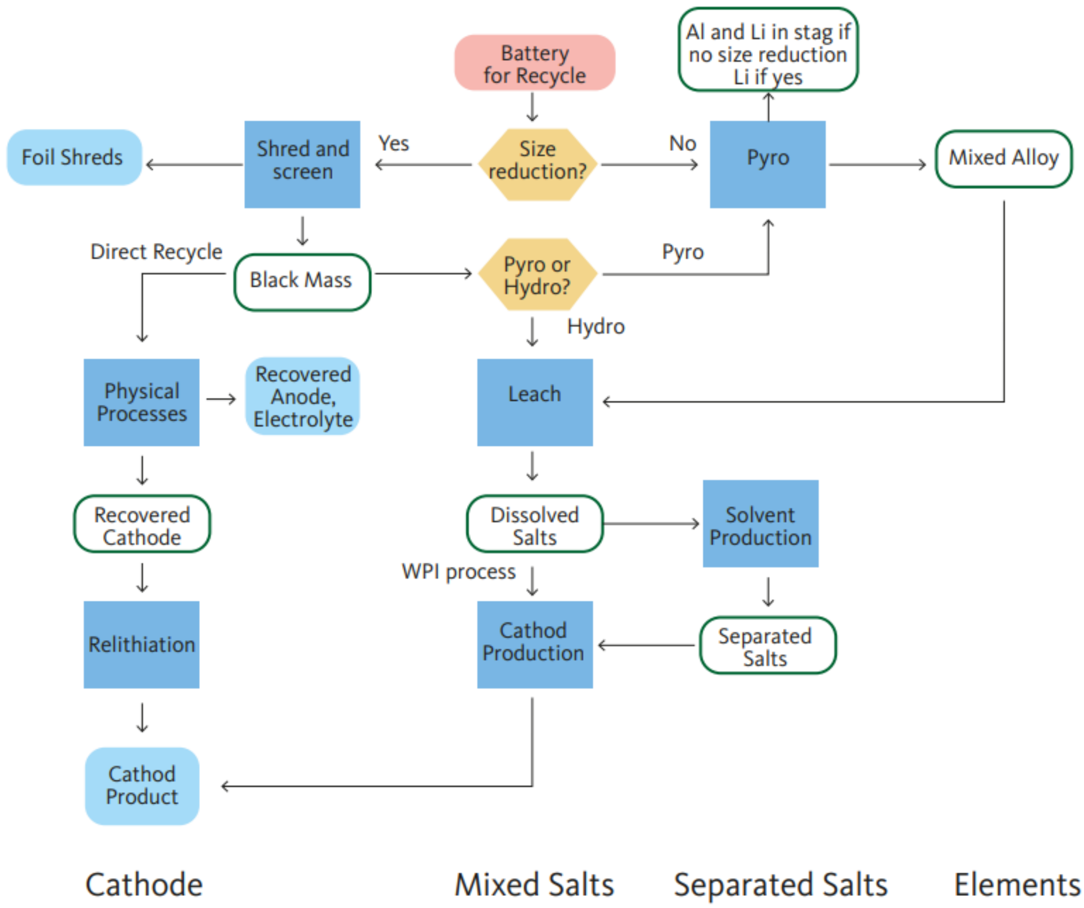


Figure 4-22 *Three possible methods to recycle lithium in Li-ion batteries- Figure based on Gaines (2018) and Xu et al. (2020).*

Commercial recycling technologies include pyrometallurgical (pyro) and hydrometallurgical (hydro) recycling. Direct recycling is under development for cathode-to-cathode recycling. Recycling technologies differ in recycled materials, chemical forms, recovery efficiencies, and economic prospects (Mohr *et al.* 2020).

The pyrometallurgical recycling is in most cases a hybrid pyro and hydro process (Xu *et al.* 2020). After feeding disassembled battery modules and/or cells to the smelter, graphite is burnt off, aluminium and lithium end up in the slag, and nickel, cobalt, and copper end up in a matte. After leaching of the matte, copper is recovered as copper metal through electrowinning, while the nickel and cobalt ions are recovered as battery-grade nickel and cobalt compounds through solvent extraction or precipitation. Lithium in the slag can be refined to produce battery-grade lithium compounds, but it is only economical when the lithium price is high, and the recycling takes place at a large scale.

The hydrometallurgical recycling starts with shredding disassembled modules and/or cells (Gaines 2018). The shred then goes through a series of physical separation steps to sort the materials into cathode powder, anode powder, and mixed aluminium and copper scraps. The copper scraps can be incorporated back into the battery supply chain with minimal processing (i.e., remelting). The cathode powder is subsequently leached with acid, where nickel, cobalt, and manganese leach out as ions, and are recovered as battery-grade compounds after solvent extraction and precipitation. Lithium ends up in the solid waste from the leaching step. It can be refined to produce battery-grade lithium carbonate, but the economic viability depends on the lithium price (Liu *et al.* 2021).

The direct recycling method is the same as hydro except for cathode powder recycling. In the direct process, the cathode powder is recovered and then regenerated by reacting with a lithium source (relithiation and upgrading). Lithium, nickel, cobalt, and manganese are therefore recovered as one battery-grade compound. Since lithium refining is not needed here as with pyro and hydro, lithium recovery in direct process is economical at least from a lab-scale perspective. Due to technological limitations, the combination of hydro and pyro is presently the most common method for major recycling companies.

Circular Energy Storage (CES) estimated the volumes generated from pre-processing. In 2019 approximately 330,000 tons EOL rechargeable batteries were collected, of which 223,000 tons were processed in China, accounting for 74%, followed by RoW 17%, EU 6%, and USA 3% (Figure 4-23). In the rest of the world, significant recycling took place in South Korea and Japan, but the capacity is growing in India, Indonesia, and the rest of Southeast Asia (Melin 2021).

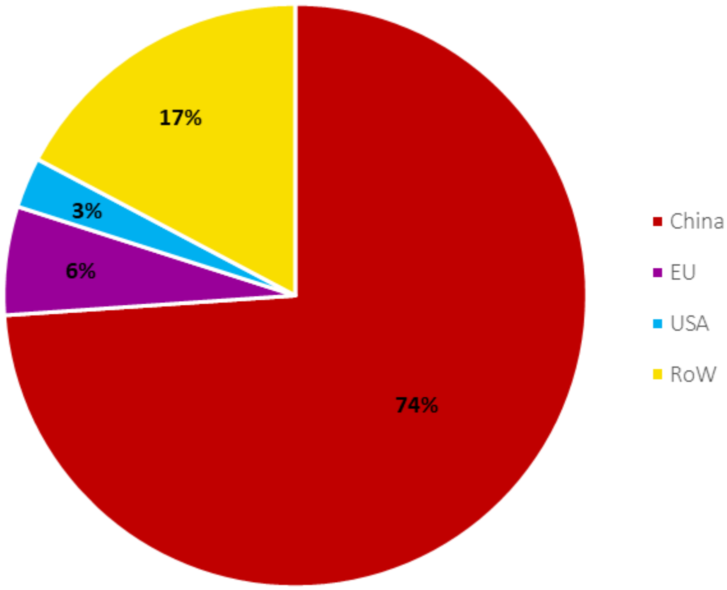


Figure 4-23 *Waste batteries processed by country and region (Melin 2021). RoW – Rest of the World.*

It is difficult to accurately assess the actual lithium volumes recycled since the scrap and recycling business is rarely transparent. Recyclers are reluctant to disclose their actual volumes as well as what materials they recover. Roskill (2020b) tentatively estimates that 1,000 tons LCE (equals to 188 tons Li) lithium was recycled globally in 2019, but without detailed information on volumes by country (Roskill 2020b). According to Circular Energy Storage's estimation, approximately 13,600 tons lithium are included in the 330,000 tons of waste batteries (Melin 2021), suggesting that the global End-of-Life (EoL) recycling rate is around 1.5%. For China, the number is slightly higher, since the main waste stream here was Li-ion batteries with failures, directly from battery producers. It is relatively easy to establish the exact battery type as well as the chemical form of cathode materials, and subsequently select the optimal method to improve the recovery efficiency and economic prospects of recycling (Securities 2021). Since there are no other countries which have the same scale of battery production as China, sorting the battery waste stream into right categories is a big challenge, because currently there is no specific regulations on disposal of Li-ion batteries, which are collected mixed with other industry batteries and thus impossible to treat separately at later stages. Therefore, the recycling rate of lithium outside China is much lower than often anticipated (Melin 2021). To change this, it is necessary to develop advanced lithium recycling technologies, to increase the Li-ion battery waste stream and to adopt more strict battery waste management regulations. This will be discussed further in Chapter 5.

4.7 Discussion and summary

In this chapter, the global lithium flow was analysed through its complete supply chain, summarised in Figure 4-24.

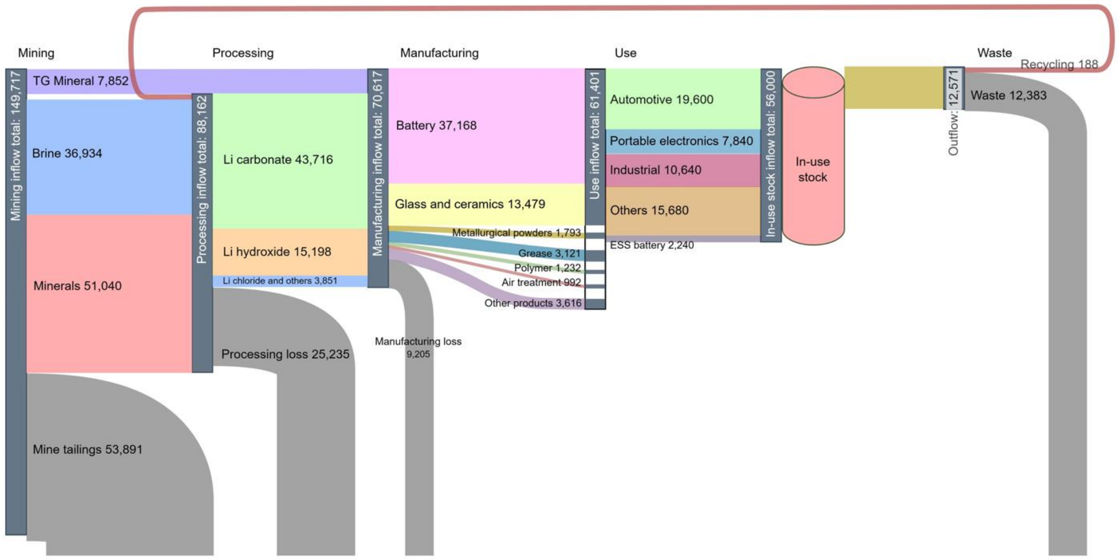


Figure 4-24 *Global lithium flow analysis in 2019 (Unit: tons).*

The global lithium mining production in 2019 was around 86,000 tons Li (equals to 478,000 tons LCE). The world lithium reserves according to USGS (2020b) in 2019 was around 17 million tons, which means that global lithium reserves could last approximately 200 years if the production remains the same level as in 2019. Thus, the lithium reserves will be able to meet the global demand for a long time, even if the production is increased significantly. The lithium refining production in 2019 was approximately 63,000 tons (equals to 334,000 tons LCE), and lithium going directly or indirectly through the manufacturing stage was around 61,000 tons (equals to 327,000 tons LCE). The demand of lithium end-use products in 2019 was around 56,000 tons (equals to 298,000 tons LCE), and 60% of the demand came from the battery sector. Hence, the current lithium supply capacity meets the global demand on a short-term basis, but there is a potential supply risk with the increasing demand due to the complete electrification of the transportation sector expected in the near future.

Lithium distribution and production are highly concentrated throughout the whole supply chain. Geographically, more than 95% of the lithium mining production is concentrated in Chile, Argentina, Australia, and China. Therefore, international trade is extremely important for resource-deficient countries or regions such as for instance EU. Portugal is the only country in EU currently mining lithium, and the production in 2019 was 900 tons Li (equals to 4,800 tons LCE), accounting for 1% of the world production (USGS 2020b). Lithium mining production in Portugal is directly used in glass and ceramics manufacturing, filling a small part of the in-use demand in this sector. All the lithium required for other applications and the remaining demand of the EU glass and ceramics sector are imported, which means that EU imported around 93% of its total demand for lithium in 2019. It is obvious that EU is short in domestic lithium resources. Thanks to active international trade, EU's demand for lithium for both traditional usages and emerging battery needs can be met. In addition, value can be added through importing raw materials or semi-products and exporting final products, which benefit EU's economy.

Although historically, the lithium consumption is relatively low compared with other metals, it is treated as a critical raw material by China, USA, Japan, and EU, because lithium is the key mineral for emerging industries to secure the IPCC 2°C maximum temperature increase target (Greim *et al.* 2020). Despite numerous advanced battery technologies under development, the tendency is to use more lithium-intensive materials in the future. It is forecasted that we will see a strong increase in the demand for lithium and that the annual growth rate may reach 10% (Benchmark Mineral Intelligence 2021b). Although the lithium production capacity might also increase, the time needed to establish a completely new mine project, approximately 7 years for lithium mines and 10 years for lithium brine, implies a potential lithium supply risk in the medium term (Ambrose & Kendall 2020; Zhou *et al.* 2020).

The lithium production is unbalanced and highly concentrated not only on a country basis but also on a company level. For example, in 2019, the three companies Albemarle, SQM, and Tianqi accounted for more than 54% of the lithium mining production (Benchmark Mineral Intelligence 2021a). In addition, many companies are integrated, controlling both mining and refining, and a few of them even expand their business to downstream components manufacturing, battery production, and lithium recycling. Therefore, it can be concluded that the supply of lithium is approaching a monopoly, which can result in unstable lithium supply and trade (Helbig *et al.* 2018).

Another concern is that Li-ion battery technologies should not be developed at the expense of our environment. There are many environmental challenges associated with lithium mining. Commonly, the mineral spodumene is extracted in open pits and underground mining operations in Australia. The associated environmental impacts are like the extraction and refining of other ores. Increasingly strict environmental protection legislation will potentially restrict projecting new mines. Lithium brines in South American are extracted traditionally by pumping brines to the surface and subsequently precipitate different salts by evaporation, resulting in, for instance, a lithium chloride concentrate. The evaporated water is removed from the local water cycle and the withdrawal of larger volumes may disturb the delicate water balance in the surrounding areas with limited surface and/or ground water resources (Schuler *et al.* 2018). The steeply increasing demand for primary lithium will exert pressure to increase production volumes and to open new brines or mines. Therefore, a more intelligent management and a more sophisticated approach to Li-ion battery recovery and lithium recycling are needed worldwide to solve the environmental problems. The extent to which lithium criticality risks can be reduced through recycling will be discussed further in Chapter 6.

5. Global cobalt and lithium market balance

The global market balance for cobalt and lithium has attracted increasing attention due to the critical roles of these elements in Li-ion batteries (LIBs) and the future demand for LIBs has been forecasted in numerous studies by both academia and industry. Current and projected LIB demand is dominated by electric vehicles (EVs), but Li-ion batteries are ubiquitous in consumer electronics (ECs), critical defence applications, and stationary storage facilities for the electric grid (Chen *et al.* 2012). The demand for LIBs is growing exponentially in all sectors, and it is critical for achieving a transition to a clean energy economy that the supply can keep pace with the soaring demand (Richa *et al.* 2014; Armand *et al.* 2020; Avicenne Energy 2021; Gordon 2022; Zeng *et al.* 2022). A screening analysis has shown that the bottleneck of the LIB supply is likely to be the supply of battery raw materials (Kushnir & Sandén 2012; Olivetti *et al.* 2017; Pehlken *et al.* 2017; de Koning *et al.* 2018; Harvey 2018; Valero *et al.* 2018; Bobba *et al.* 2019; Watari *et al.* 2019; Dunn *et al.* 2021). In consequence, this chapter will focus on the availability of the two key battery raw materials cobalt and lithium through 2030. The year 2030 has been chosen as the timeframe for analysis due to the dynamic nature of the battery market, which makes long-term predictions challenging. We have collected and analysed the available investigations on cobalt and lithium primary supply and the potential role of secondary supply, as well as the demand across a variety of applications. We have compared and explored to which extent the supply of cobalt and lithium can be shifted to meet the demand through 2030, geographically and by source.

5.1 Demand on battery raw materials cobalt and lithium

The demand for cobalt and lithium is primarily caused by the demand for LIBs, making this the major demand driver for the two metals.

The forecasts of the LIB demand in 2030 are presented in Figure 5-1 and vary, from less than 1,000 GWh to more than 3,500 GWh with an average of 2,200 GWh in the 15 modelled scenarios assessed. Although a rapid increase from today's low volumes is forecasted by most predictions, there are large variations in the different demand simulations and there is no clear picture in terms of the future market growth rates. This is due to the LIB sector still being a relatively small emerging market, and with annual growth rates of up to 20% (Grand View Research 2022), it is difficult to forecast compared to larger and more mature markets with typical growth rates of 2-4%. For example, lowest estimates for global stationary storage installed in 2030 range from 8 to 100 GWh, while more optimistic calculations assume up to 400 GWh in the EU alone (Tsiropoulos *et al.* 2018).

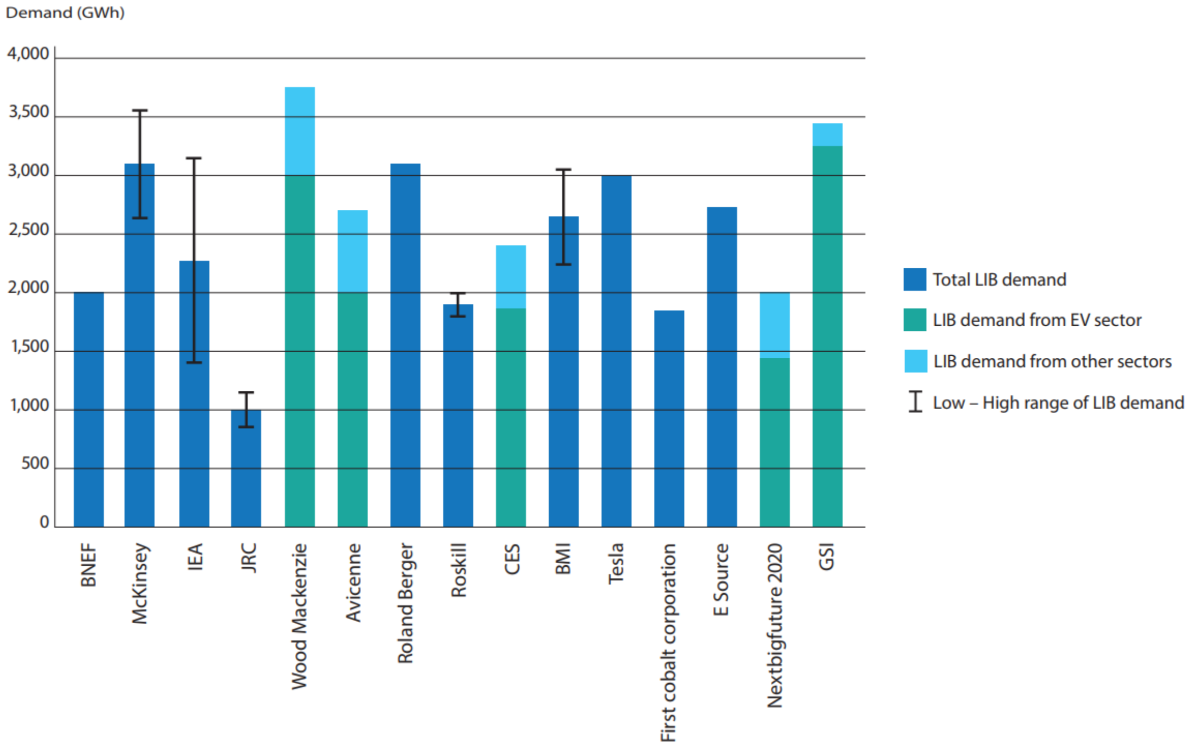


Figure 5-1 *LIB demand forecast in 2030 (Narins 2017; Azevedo et al. 2018; Bloomberg NEF 2020b; European Commission 2020b; Roskill 2020a; Xu et al. 2020; Avicenne Energy 2021;Benchmark Mineral Intelligence 2021a; Federal Consortium for Advanced Batteries 2021; Gregoir & van Acker 2022; Hjelmstedt 2021; International Energy Agency 2021; Melin 2021; Berger 2022).*

There are normally two types of methods to estimate the LIB demand.

The first method is treating electrification of transportation as the main driving force of LIB growth. Since many governments have set clear national electromobility strategy aims for 2030, it is possible to calculate the demand for EV batteries based on such scenarios, for instance the STEP scenario (Stated Policies scenario), the SD scenario (Sustainable Development scenario), the 2D scenario (IEA's 2 Degree scenario), and the B2D scenario (IEA's Beyond 2 Degree scenario) (Deetman *et al.* 2018; Watari 2020; Xu *et al.* 2020). A proportion of the total LIB-demand is assumed to come from EV batteries, allowing the total demand to be calculated. Commercial organisations, such as WoodMac, Bloomberg NEF (BNEF), Avicenne, and CES are using this method to forecast the LIB demand in 2030 (Bloomberg NEF 2020b; Avicienne Energy 2021; Melin 2021; Gordon 2022). However, since different scenarios and percentages are assumed, the estimated LIB demand shows large variations despite identical principles of forecasting.

The principle of the second method is to initially predict the global energy demand in 2030. The global energy demand is likely to rise by 15-40%, depending on the different scenarios used (International Energy Agency 2020). This energy demand will be supplied by different technologies, such as wind, solar, biomass, nuclear, battery, etc., and LIB will contribute with a proportion of this demand. Various researchers, institutions, and companies favour different estimates of the proportion, resulting in variable forecasts of the LIB demand. In addition to the total LIB demand in different scenarios, the demands in key countries and regions are in some cases estimated as well.

Based on the LIB demand, the corresponding demand for battery raw materials cobalt and lithium demand can be predicted, which will be discussed in the following.

In parallel with the estimated LIB demand, the estimated global demand for lithium varies widely, ranging from 60,000 to 700,000 tons (Figure 5-2). In particular, maximum estimates by different researchers can be several times higher than minimum estimates by the same researchers. The lithium demand estimated by commercial organisations is relatively stable close to 350,000 tons. The reasons for this are two-fold. Firstly, there is a significant difference in estimated LIB demand when analysed by different organisations (Figure 5-1), which is mirrored in the estimated lithium demand. Secondly, the EV battery chemistry is variable, each cathode chemistry has a different lithium content, which is reflected in the different forecasts. Since most lithium is used for LIBs, and EV batteries are supposed to account for more than 80% of the total LIB demand, these two reasons combined can lead to widely different projections of the total lithium demand in 2030.

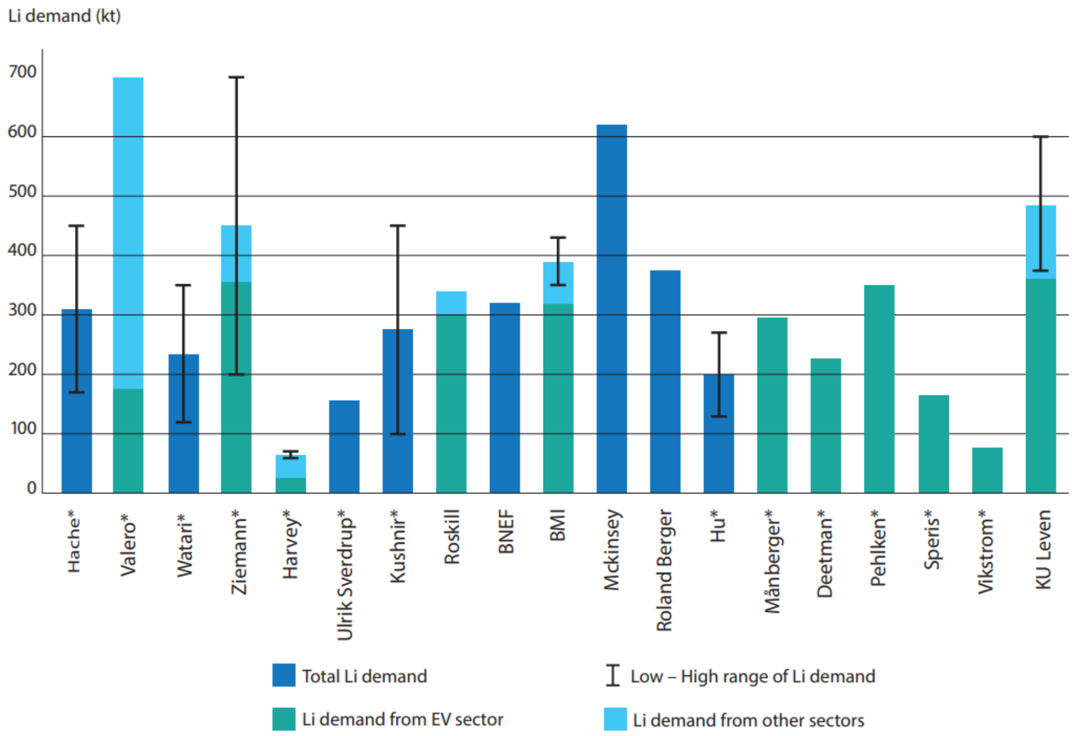


Figure 5-2 *Lithium demand forecast in 2030 (Kushnir & Sandén 2012; Sverdrup 2016; Azevedo et al. 2018; Harvey 2018; Månberger & Stenqvist 2018; Valero et al. 2018; Watari et al. 2018; Ziemann et al. 2018; Hache et al. 2019; Bloomberg NEF 2020; Miller 2020; Roskill, 2020b; Benchmark Mineral Intelligence 2021a; Bloomberg NEF 2021; Federal Consortium for Advanced Batterie 2021; Hjelmstedt 2021; Berger 2022; Bloomberg NEF 2022; Gregoir & van Acker 2022;).The asterisk indicates the demand predicted by individual researchers.*

Some commercial organisations, such as for instance BMI, have been tracking global EV sales and market shares of different types of cathode chemistries for a relatively long time (around 10 years). This allows a more robust modelling of the adoption of new cathode chemistries, which combined with the announcements of new EV models from the manufacturers tends to provide a sound basis for continuously predicting the global cathode chemistry mix and the total lithium demand (Figure 5-3). In 2020, less than ⅔ of the lithium demand was for batteries. By 2030, batteries are expected to account for more than 90% of the lithium demand, and the lithium demand from the battery segment will make up more than 90% of the total growth.

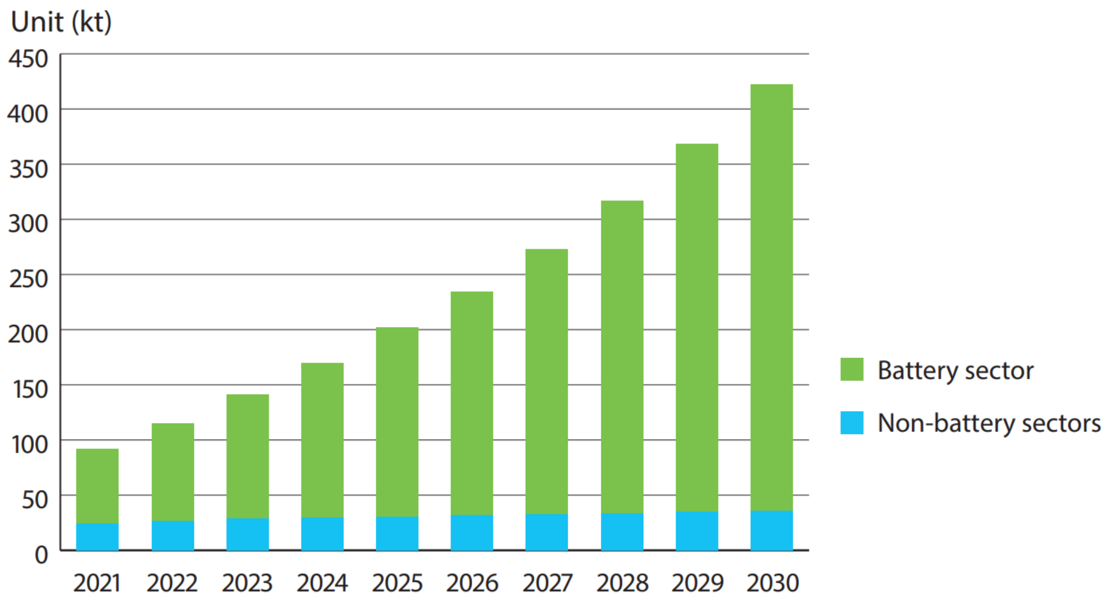


Figure 5-3 *Predicted lithium maximum demand continues to grow by 2030. Data source: Benchmark Mineral Intelligence 2021a).*

The demand for cobalt is also expected to rise rapidly as the EV transition gains pace. The cobalt demand is forecasted to approach 200,000-450,000 tons in 2030 by different researchers and organisations but in general, most predictions are in the range of 250,000-300,000 tons (Figure 5-4). The range in the estimated cobalt demand is less than that of the lithium demand, probably because the cobalt demand is being split into new and old economy drivers. New economy drivers include Li-ion batteries and superalloys while old economy drivers typically are industrial uses that include steels, tools, industrial chemicals, and magnetic materials (Koshy *et al.* 2019). The old economy drivers are mature and expected to grow at a stable rate, whereas the new demand driver from LIB is difficult to predict, since the current trend is towards less- or no-cobalt containing batteries, leading to uncertainty with respect to the cobalt content in the future batteries. However, the cobalt demand for the battery segment is expected to reach 70% in 2030 (Cobalt Institute 2022), which is somewhat less than the 90% seen for lithium.

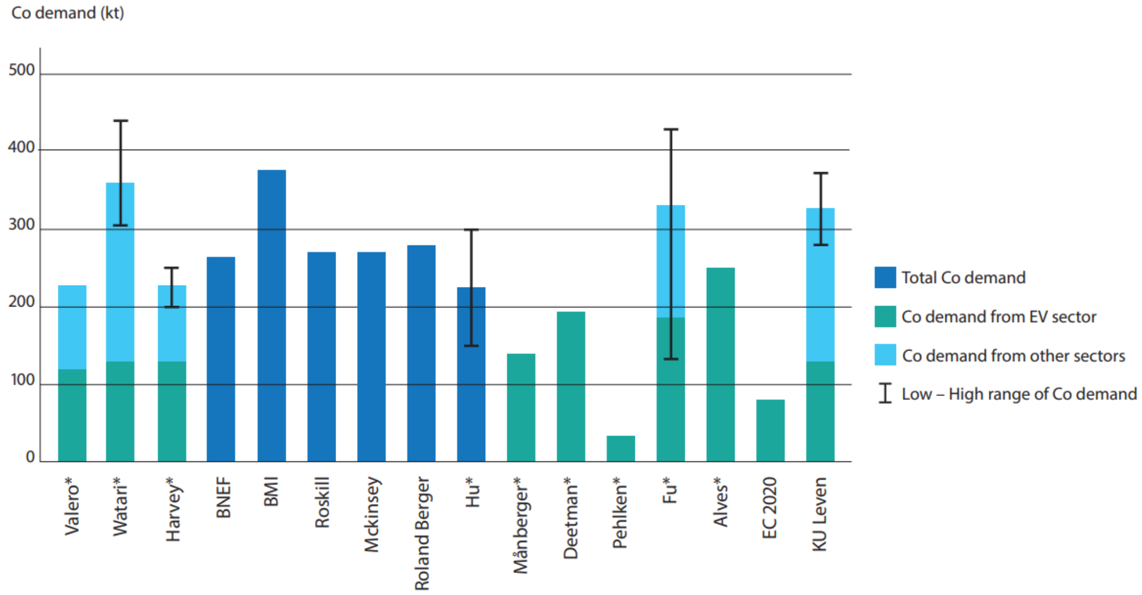


Figure 5-4 *Cobalt demand forecast in 2030 (Azevedo et al. 2018; Harvey 2018; Valero et al. 2018; Watari et al. 2018; Miller 2020; Roskill 2020b; Benchmark Mineral Intelligence 2021a; Federal Consortium for Advanced Batteries 2021; Hjelmstedt 2021; Berger 2022; Bloomberg NEF 2022; Gregoir & van Acker 2022). The asterisk indicates the demand predicted by individual researchers.*

Figure 5-5 presents the estimated total cobalt demand growth through 2030. Despite the trend towards less- or no-cobalt batteries, the cobalt demand from LIB segment is expected to make up more than 90% of the total growth, with a compound annual growth rate (CAGR) of 19% over the 2020-2030 period. The new economy demand will continue to dominate the cobalt demand for the foreseeable future. The cobalt demand from the non-battery segment is expected to grow continuously as well, but with a slower growth rate of around 5% annually.

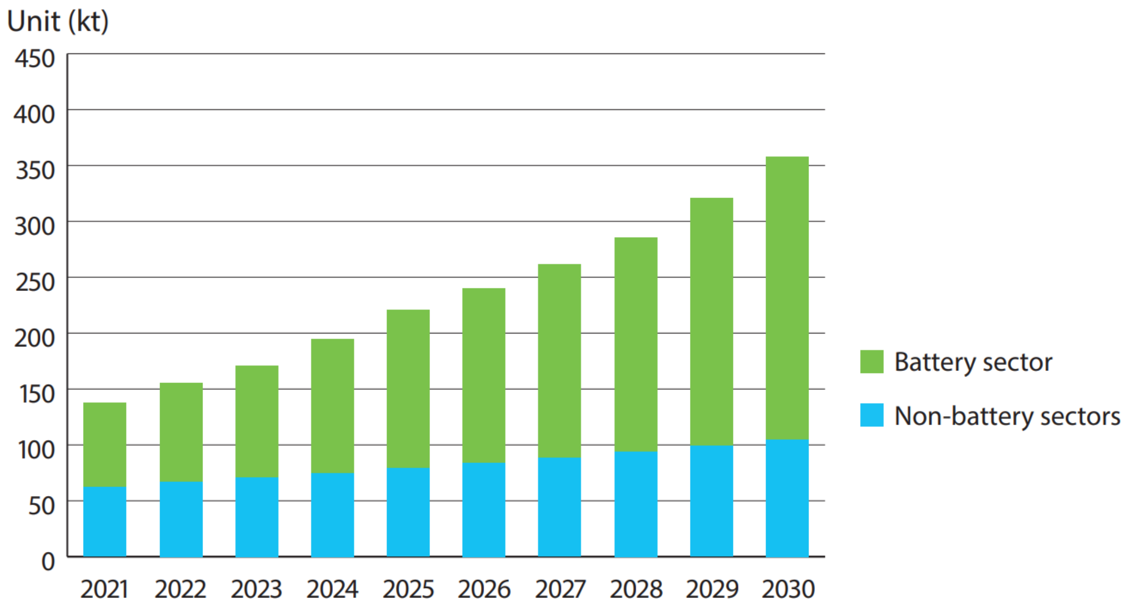


Figure 5-5 *Cobalt demand continues to grow by 2030 (unit: kt) (Dias et al. 2018; Bloomberg NEF 2020b; Miller 2020; Roskill 2020b; Berger 2022; Cobalt Institute 2022).*

5.2 Supply of battery raw materials cobalt and lithium

Ensuring a sufficient supply of battery raw materials to meet the soaring demand of the LIB industry is important for the clean energy transition. As opposed to the demand, the supply of raw materials is driven directly by the market and early-stage investments and is therefore extremely dynamic. Hence, supply forecasts by commercial organisations are viewed as more reliable than those of different researchers, since most commercial organisations have tracked the raw materials market for a long time and have built a sound basis for predictions of future market trends. Estimations of lithium and cobalt production carried out by researchers are often based on static algorithm-based models, which are considered suboptimal (Mohr *et al.* 2012; Sverdrup 2016). Accordingly, predictions of both cobalt and lithium supplies used here are mainly based on indications by commercial organisations.

The supply of cobalt and lithium includes both primary supply and secondary supply components. The primary supply is based on mining production, which is affected by many factors, including new technologies and sources. However, it is worth noting that the timeline from the discovery of a deposit to actual production typically spans 10-15 years. To account for this, companies often make predictions about primary supply within a shorter timeframe of less than 10 years. These predictions are based on mining production capacities, which represent the projected output levels determined by mining operators and disclosed in advance. The assessment of primary supply takes into account both active mining operations and ongoing exploration projects, such as expansions of existing sites and projects with varying degrees of probability (highly probable, probable, and possible). Companies rely on information provided by mining companies to estimate the evolution of mine types and capacities over time, using different estimation standards. For instance, Benchmark Mineral Intelligence (BMI) uses estimations based on 100% of production capacity for operating mines. However, estimations for ongoing exploration projects vary depending on their current status. For brownfield exploration and highly probable projects, BMI utilizes estimations equivalent to 90% of the production capacity, while 70% is estimated for probable projects when forecasting future supply. Inactive projects are excluded from BMI's assessment. It is important to acknowledge that there is a significant level of uncertainty when predicting medium-term mining production due to various factors, including market conditions and production costs. Therefore, commercial organizations often assess supply trends based on different scenarios to account for this uncertainty. When estimating primary supply forecasts, these organizations also take into consideration refining production, which plays a crucial role. In some cases, the refining production capacity may be a limiting factor in the overall primary supply, and we will delve into this topic in more detail later.

Secondary supply, i.e., recycling, represents an alternative supply stream, although the contribution from recycling is expected to be very limited by 2030. Both cobalt and lithium are widely used in many products, but most of the uses are dissipative and the products are difficult to recycle, as discussed in Sections 3.6 and 4.6 of this report. Therefore, the potential recycling of significant volumes of cobalt and lithium hinges heavily on LIB recycling, especially EV battery recycling (Church & Wuennenberg 2019; Melin 2021). Two important factors determine the global volume of EV batteries available for recycling: *viz.* battery lifetime and the future collection rate of disused batteries. Commercial organisations estimate these factors differently, which is mirrored in their forecasts.

Figure 5-6 shows the lithium supply prediction in 2030 by six commercial companies. Only Roskill and BNEF provide separate predictions of mining (shown in blue) and refining production (shown in green), whereas the remaining companies only provide general estimates (shown in grey). The supply predictions show some variation, but a prediction of around 300,000 tons seems to attract some consensus. McKinsey is the most optimistic company, estimating a production capacity of more than 500,000 tons lithium in 2030, whereas Roskill (2020b), the most conservative company predicts less than 200,000 tons lithium mining production capacity in 2030. Currently, almost all lithium mining occurs in Australia, South America, and China (accounting for a combined 98% of the production in 2019), as described in Section 4.2, but announced projects in the pipeline will hopefully introduce new players and geographies to the lithium-mining map (Benchmark Mineral Intelligence 2021a).

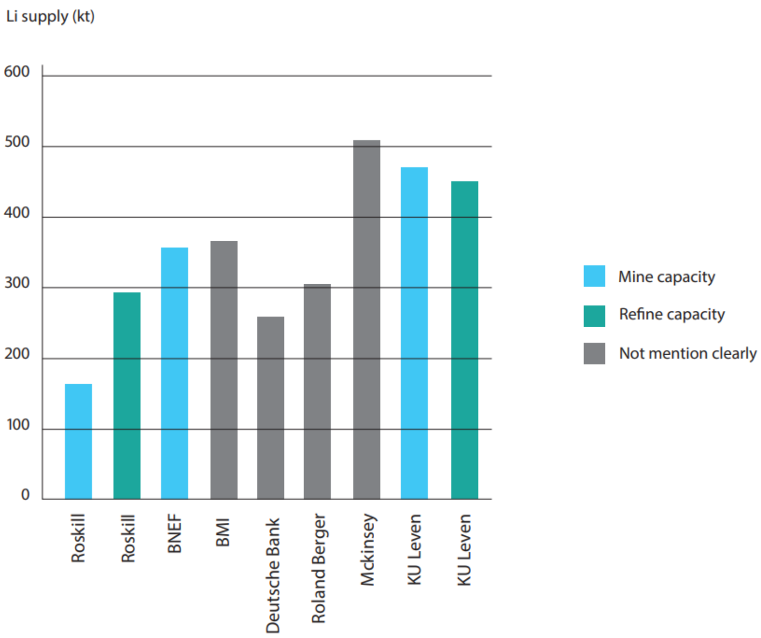


Figure 5-6 *Lithium supply forecast in 2030 (unit: kt) (Azevedo et al. 2018; Bloomberg NEF 2020b; Miller 2020; Roskill 2020b; Benchmark Mineral Intelligence 2021a; Bloomberg NEF 2021a; Federal Consortium for Advanced Batteries 2021; Berger 2022).*

Figure 5-7 shows the annual lithium production capacity predicted by Benchmark Mineral Intelligence. Both operating mines and ongoing exploration projects are included, using internal database information (Benchmark Mineral Intelligence 2021a). Secondary production of lithium is also considered. Given the nature of the mining industry and lead time for exploration/mining projects (10-15 years from discovery to production), estimates of any potential future production are only reasonable under certain preconditions of growth in demand and rising prices. According to Benchmark Mineral Intelligence, some projects are expected to bring additional material into the market by 2030, however, the greatest potential is bound to operating mines. It is expected that the lithium production will grow at an average annual rate of 20% to reach over 360,000 tons by 2030. The main source is still primary production. Lithium recycling remains small but could reach 10% of the predicted supply by 2030.

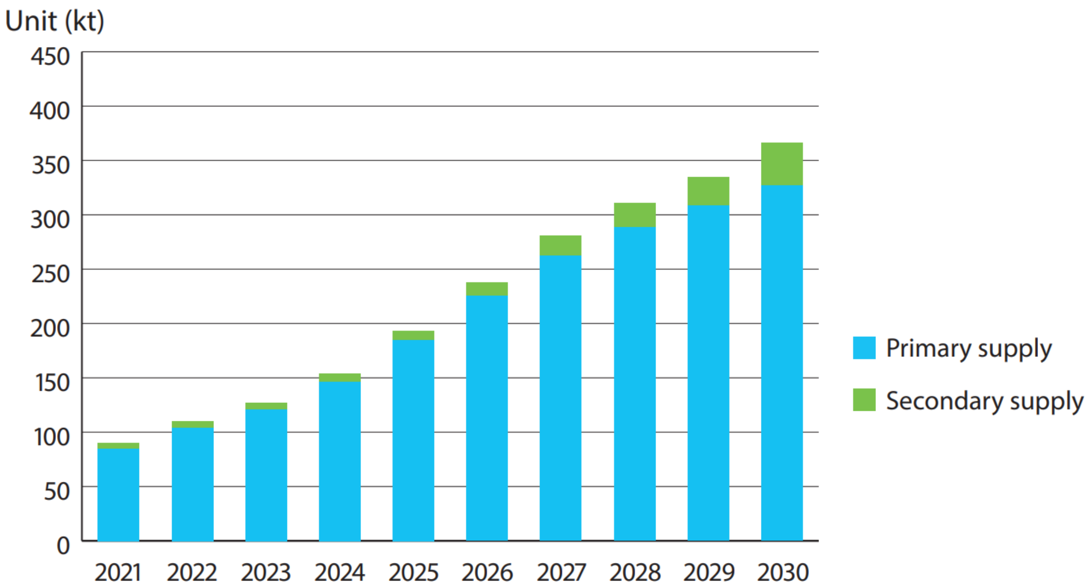


Figure 5-7 *Annual lithium supply growth predicted by Benchmark Mineral Intelligence (unit: kt) (Benchmark Mineral Intelligence 2021a).*

Figure 5-8 shows the cobalt supply prediction in 2030. Commercial companies consistently predict a supply capacity of cobalt in the range of 205,000 to 350,000 tons by 2030. More than 98% of the cobalt produced is a by-product of nickel or copper mining, both of which are mature metals with a relatively stable growth rate. Any predictions on the cobalt production are thus closely linked to the production of nickel and copper. Compared to 2019, Cu-principal Co mines will still account for the largest fraction of the total mining production, but more cobalt will be derived from Co-principal and Ni-principal mines in the future.

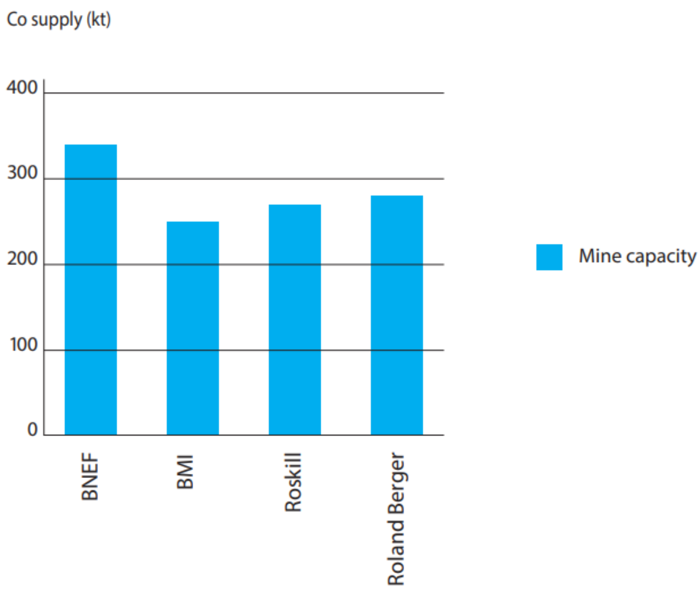


Figure 5-8 *Cobalt supply forecast in 2030 (unit: kt) (Bloomberg NEF 2020b; Miller 2020; Roskill 2020a; Berger 2022; Gregoir & van Acker 2022).*

The cobalt supply is expected to continue to grow through 2030 (
Figure ***5-9***). The growth concerns all elements of the total supply, including scheduled primary supply, secondary supply from electronics and LIB recycling, and an estimate of unscheduled primary supply. Compared to the lithium supply, the secondary supply of cobalt takes a larger share of the cobalt supply, but the primary supply is still the main source.

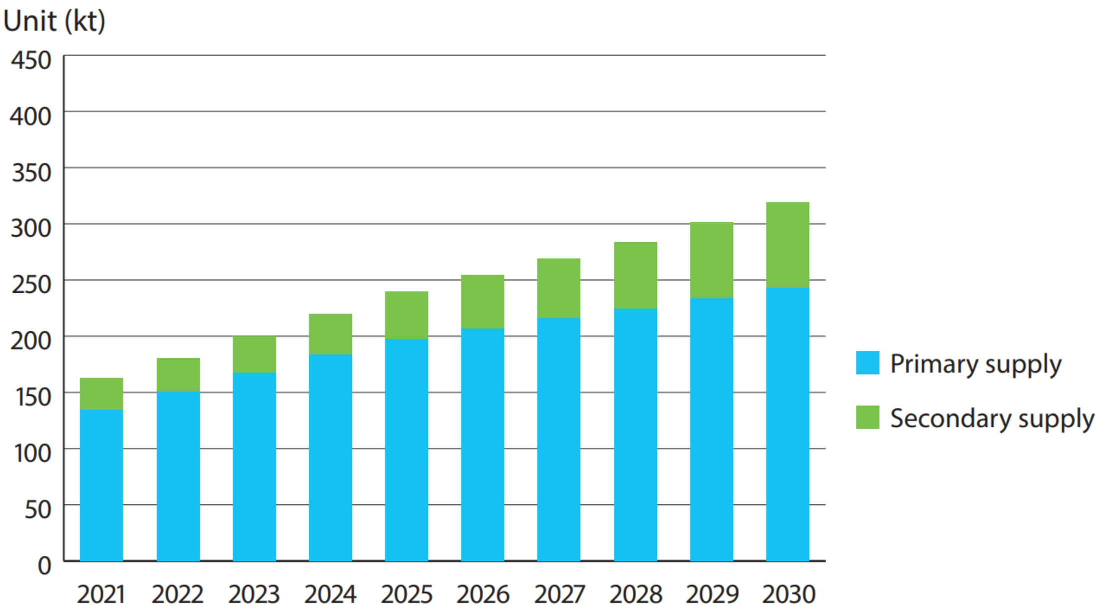


Figure 5-9 *Annual cobalt supply growth by 2030 (unit: kt) (Roskill 2020b; Leighton 2021; Berger 2022; Cobalt Institute 2022).*

5.3 Demand-supply balance

Figure 5-10 shows the demand and supply balance for lithium, and except for BNEF, top commercial companies expect a lithium deficit from 50,000 to 120,000 tons lithium by 2030. However, the companies differ slightly in their predictions of when the lithium deficit starts. For example, Roskill (2020b) expects the lithium deficit to occur in 2024, whereas Roland Berger and McKinsey expect a deficit to come about in 2026 and 2028, respectively.

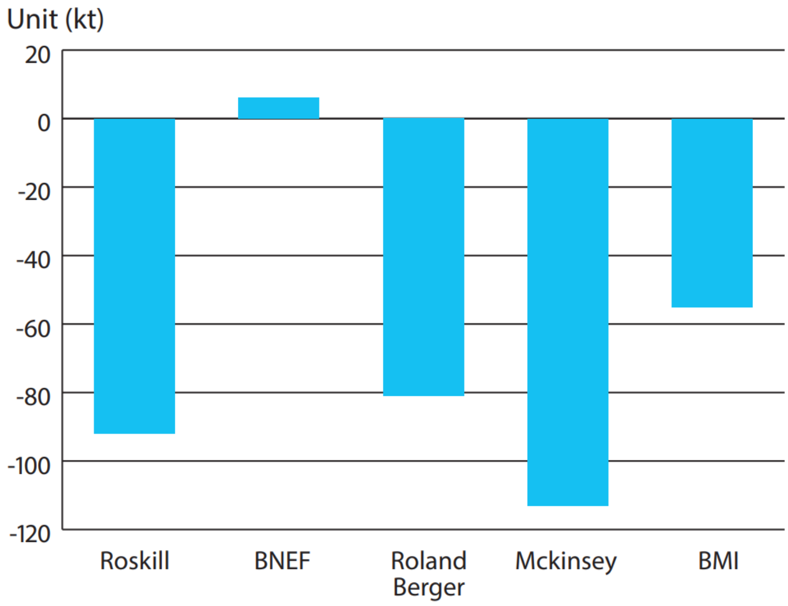


Figure 5-10 *Lithium supply-demand balance in 2030 predicted by several companies (unit: kt) (Azevedo et al. 2018; Bloomberg NEF 2020b; Miller 2020; Roskill 2020b; Benchmark Mineral Intelligence 2021a; Berger 2022; Gregoir & van Acker 2022).*

Benchmark Mineral Intelligence has assessed if the lithium supply exceeds the demand and vice-versa on a year-by-year basis through 2030. According to their model, lithium production is currently using all the production capacity of available mines and battery recycling output; the amounts that are not consumed are stockpiled and stored for use for the following years (Benchmark Mineral Intelligence 2022). According to this model, the first year of lithium deficit was expected in 2021 (Figure 5-11). Though, due to COVID-19 and rising lithium prices, the actual consumption of lithium was much lower than early prediction and lithium shortage was not seen in 2021. However, insufficient lithium supply will according to their model persists until 2026 when the production accelerates, and the lithium market will move to a surplus. However, the deficit recurs in 2028 and the supply-demand gap grows larger and larger with time through 2030. To bridge the gap, there is an urgent need to introduce new capacity before 2030. Additional lithium sources may be early-stage conventional mineral and brines projects as well as yet unknown resources, and unconventional brines such as geothermal or oilfield brines.

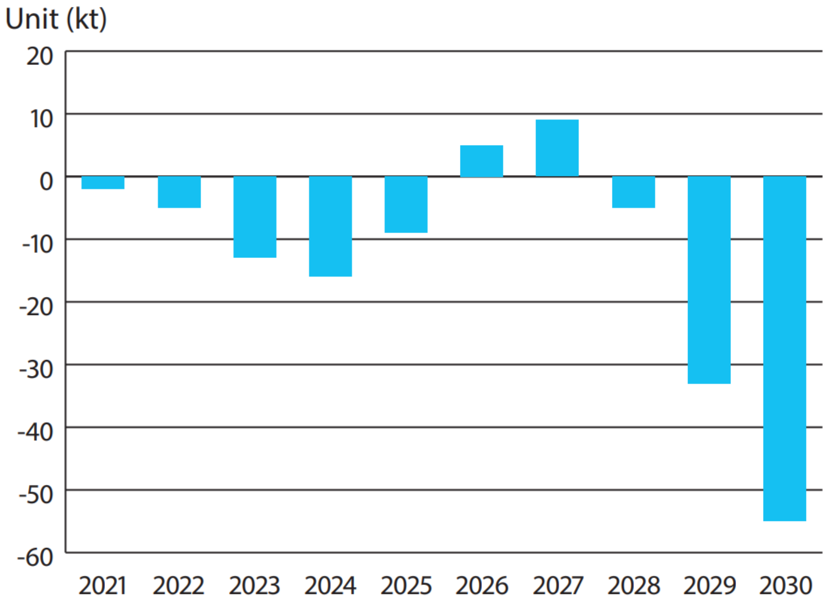


Figure 5-11 *Year-by-year lithium surplus/deficit in average mine supply and demand scenarios (unit: kt) (Benchmark Mineral Intelligence 2021a).*

Benchmark Mineral Intelligence's model calculates potential supply deficits and surpluses based on the average mining capacity projected for the next 10 years. However, when taking into account the refining production capacity, the supply-demand balance profile can undergo changes. Another company, BNEF, holds the expectation that there will be sufficient mining capacity to meet the demand for batteries by 2030 (Figure 5-12). Nevertheless, the growth of the lithium chemical supply curve is anticipated to be slow over the next decade. BNEF predicts a deficit of over 200,000 tons of LCE hydroxide in 2030, despite an excess of carbonate capacity.

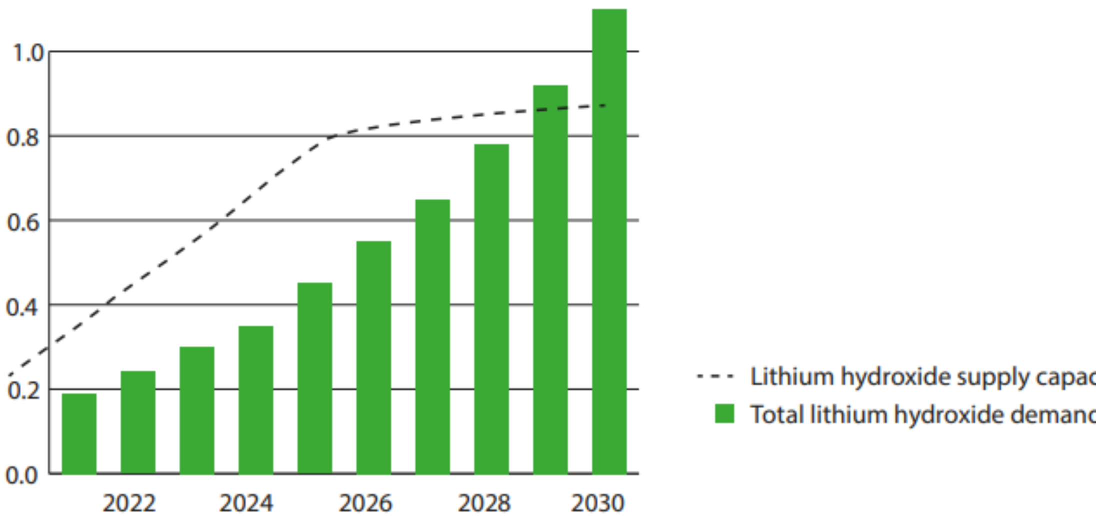


Figure 5-12 *Lithium hydroxide supply and demand balance. Unit: million tons LCE (Data source: Bloomberg NEF 2021a).*

Top companies with knowledge of the cobalt industry are divided on the topic of cobalt availability in 2030. Most companies balance or surplus in the cobalt market in 2030 with BNEF even expecting a surplus of around 70,000 tons. Conversely, Benchmark Mineral Intelligence (2021a) expects shortage already after 2025 and a deficit of 150,000 tons in 2030 (Figure 5-13).

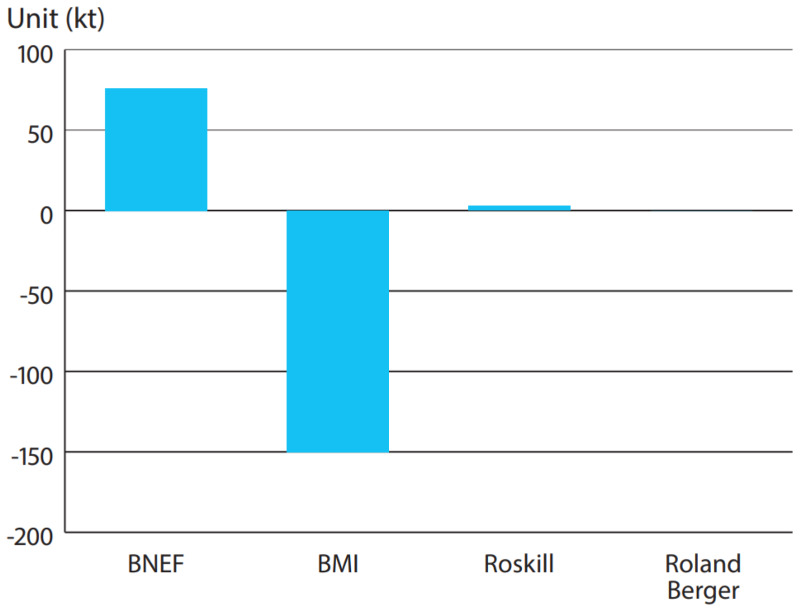


Figure 5-13 *Cobalt supply-demand balance in 2030 predicted by different companies (unit: kt) (Bloomberg NEF 2020b; Miller 2020; Roskill 2020a; Berger 2022; Cobalt Institute 2022; Gregoir & van Acker 2022).*

In a publication by Roskill (2020a), year-by-year cobalt surplus/deficit in mining supply and demand scenarios from 2021 to 2030 were presented (Figure 5-14). Based on the existing production capacity, a slight supply deficit was predicted for 2021, and this prediction aligns with the actual outcome. According to the Cobalt Institute, cobalt mine supply reached 160 kt, while the cobalt market grew to 175 kt in 2021 (Cobalt Institute 2022). The introduction of additional cobalt production capacities leads to a projected temporary surplus in 2024 and 2026. However, a shortage is anticipated, reaching up to 10,000 tons by 2027 and increasing further to 19,000 tons by 2030. Regarding the refining supply, a slight deficit was predicted for 2021, which also matched the real situation (Cobalt Institute 2022). However, the forecast suggests that the cobalt refining supply should meet the increasing demand from 2022 to 2027. From 2029, the forecast suggests shortage, but the planning time for refining capacity is merely around 2-3 years, eventually the supply may keep pace with the demand by the end of this decade.

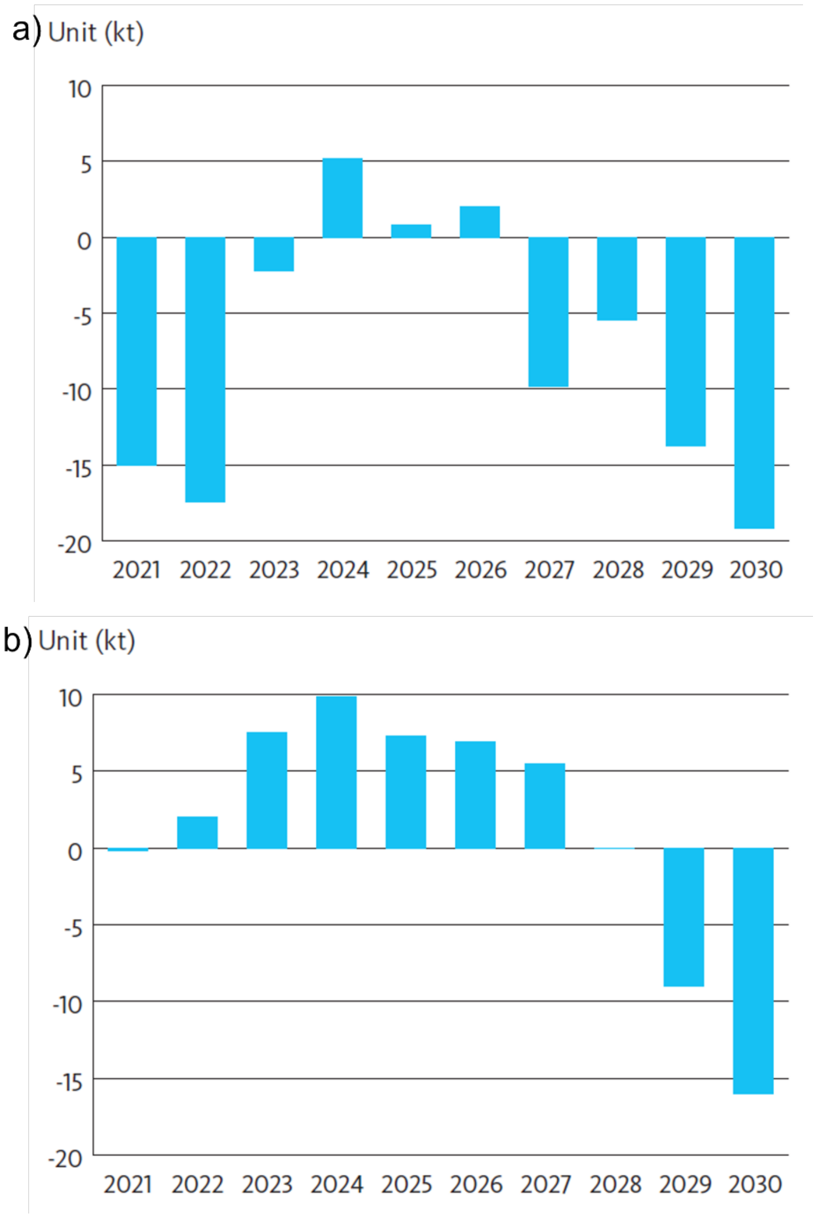


Figure 5-14 *Year-by-year cobalt surplus/deficit in average, a) mining supply and demand scenarios; b) refining supply and demand scenarios. Unit: kt (Miller 2020; Roskill 2020a; Leighton 2021; Berge 2022; Cobalt Institute 2022).*

To summarise, both cobalt and lithium are likely to see mining supply deficits in the short- and medium-term, which will affect the planned LIB production as announced by gigafactories worldwide. However, large uncertainty exists in the forecasts made by different companies, and several factors are affecting the future supply and demand growth of cobalt and lithium.

Price is affecting both demand and supply. Figure 5-15 depicts international lithium prices and production for three decades. Both price and production were low until the advent of LIBs around 1990, when the demand for lithium increased, driving increasing production. Prices rose as the supply was not able to keep up with the demand, and high prices provided incentives for new production. Generally speaking, producers will expand mining operations and introduce greenfield developments when the price makes it profitable (Miatto *et al.* 2020). However, since it takes time for commercial activities to ramp up, we see a lag in production while the price is increasing.

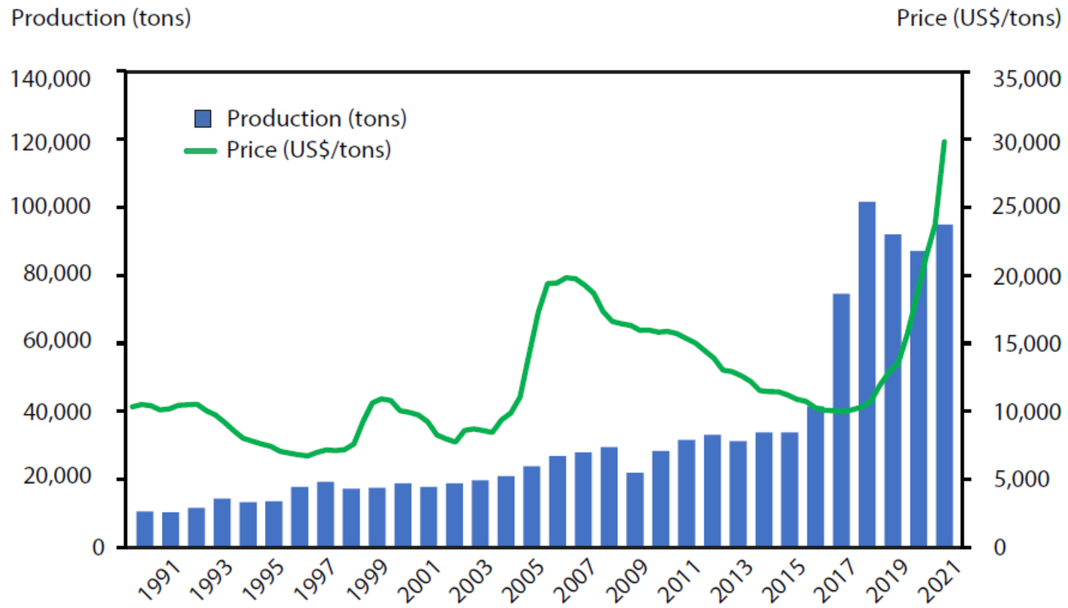


Figure 5-15 *Historical lithium mine production and inflation adjusted lithium metal prices (Sverdrup 2016; Roskill 2020b; Benchmark Mineral Intelligence 2021a; Bloomberg NEF 2022).*

Cobalt mining production remained relatively stable until 1993 when an increase set in after the commercialization of LIBs (Figure 5-16). Conversely, cobalt prices have fluctuated significantly and have been affected heavily throughout the period by various events, for example, the invasion of Zaire's copper-cobalt mining region resulting in soaring cobalt prices in 1979 (Fraser & Larmer 2010). Compared to lithium, the cobalt production has not been very sensitive to cobalt price fluctuation, since around 98% of cobalt is produced as a by-product of copper or nickel. The prices of copper and nickel have historically determined the rate of mining of multi-mineral cobalt bearing ores. However, the cobalt price may affect the cobalt production to some extent. For example, the world’s largest cobalt mine Mutanda closed in 2019 due to plummeting cobalt prices, which reduced the global production in 2020 by approximately 10% (Copper Belt Katanga Mining 2022). As cobalt prices recovered in 2021, Glencore announced a restart of the dormant Mutanda mine, and the global cobalt output rose approximately 17% in 2021 (Cobalt Institute 2022).

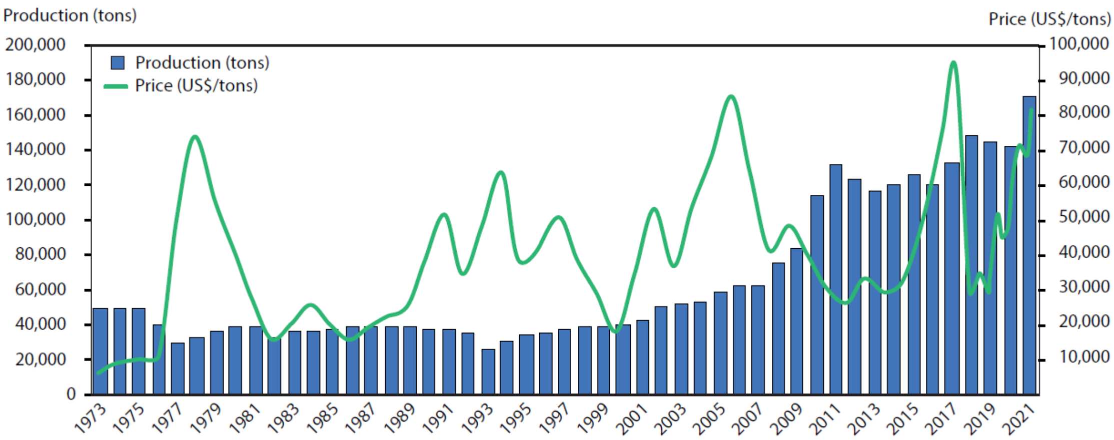


Figure 5-16 *Historical cobalt mining production and inflation adjusted cobalt prices (de Groot et al. 2012; Dias et al. 2018; Roskill 2020b; Barchart 2022; Bloomberg NEF 2022; Gordon 2022).*

Analysts in most companies predict rising prices for both cobalt and lithium in the future, which will encourage further investment in both cobalt and lithium production. Higher cobalt and lithium prices will motivate battery manufacturers to search for substitutions and thus reduce the future demand for cobalt and lithium. For instance, in the period 1977-1979, extremely high cobalt prices caused an estimated 19% reduction in the demand for cobalt otherwise expected (Roskill 2018; Hjelmstedt 2021). Over time, higher prices can effectively motivate material substitutions, and thus serve to adjust the market.

Another important factor is technology development. As mentioned in Section 2.4, there are numerous emerging battery technologies currently being developed and substitution is one of the key directions of technology affecting the demand. For lithium, there is currently no substitution to meet the demands of the transportation sector. One potential alternative is sodium-ion batteries, which represent a relatively mature technology but which can only be used in energy storage systems (Chen *et al.* 2012). The solid-state battery is another technology which might affect the lithium demand. On single cell basis, the demand for lithium is higher than for LIBs due to the use of lithium salt as electrolyte and lithium metal as anode, but since the energy density of solid-state cells is expected to be up to 45% higher than that of conventional cells, the total demand for lithium will potentially decrease (Armand *et al.* 2020). Mass production of solid-state batteries before 2030 is generally not expected, but if break-throughs take place in related technologies widespread use of solid-state batteries may be seen earlier than expected and thus reduce the lithium demand by 2030 (Li & Frith 2020). Reducing the cobalt content in batteries is the tendency by top producers due to economic, security, and societal reasons. Currently the state of art is CATL's NMC811, which is gradually replacing the dominant NMC111 and NCA batteries (Cobalt Institute 2021; Houache *et al.* 2022). The even lower cobalt content battery NMC9.5.5 is by SK Innovation expected to be released in 2023 (Battery Industry 2020). Completely cobalt-free options do already exist, and one of them is LFP. However, due to its lower energy density, early-generation LFP-batteries are mainly used in entry-level vehicles in China. However, the technology is developing, and advanced cells, such as that from Gotion High Tech, are exceeding 210 Wh/kg (Electrive 2022). Several world-leading car manufacturers, such as Tesla, Ford, and Volkswagen, already offer or will start to offer vehicles with LFP batteries. Gotion High Tech is continuing to invest in advanced LFP batteries with higher energy density, which could be comparable with ternary batteries. It is possible that before 2030, ternary lithium batteries will be replaced by LFP batteries on a larger scale in high performance applications, such as portable electronics. If so, this will change the landscape of cobalt usage and lower the demand significantly by 2030.

Technology development also affects raw materials supply, principally the secondary supply. Battery raw materials have been recycled for more than 15 years with varying efficiencies and recovery rates. Currently the recycling rate for cobalt is less than 30% (Cavallero 2021), whereas it is less than 1% for lithium (Sun *et al.* 2018; Melin 2021;). There are two main reasons for the low recycling rates. Firstly, world recyclers have struggled to consolidate sufficient volumes of battery raw materials for recycling. Secondly, LIBs were often used as secondary feedstock in non-dedicated processes, leading to low recycling efficiency and high costs. With the increasing interest in a secondary supply of battery raw materials, numerous players are involved in research in new LIB recycling technologies. Specialized recyclers have invested in automated disassembly and dedicated separation technologies and aim at achieving higher recovery of both cobalt and lithium. In addition, there are companies that use direct recycling or cathode-to-cathode recycling, without the traditional pyrometallurgical steps (Section 3.6 and 4.6), which includes an unavoidable average loss of 50% (Gaines 2018). Such technologies are presently at the research and development or early commercialization stage, but once operational at a larger scale, the secondary supply of cobalt and lithium can make a significant impact on the supply and demand balance.

Most of the discussion above adopts a global view, but in practice, the supply and demand imbalance are characterized by significant geographical variability. For instance within EU, there are some domestic cobalt and lithium reserves, but according to the qualitive analysis carried out by EUROBAT (Corbetta & Dalwigk 2022), the current mining in EU is negligible compared to its demand in 2030, as shown in Figure 5-17.

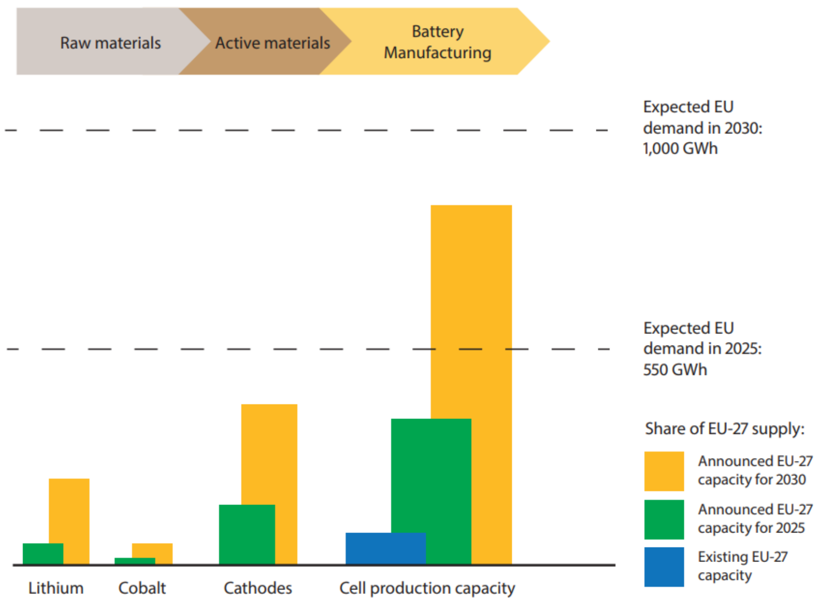


Figure 5-17 *Demand-supply gaps along the battery value chain for EU-27 in 2025 and 2030 (Corbetta & Dalwigk 2022).*

Based on EUROBAT's data on production capacities and resources in active European projects on cobalt and lithium, including both operating mines and exploration projects, and considering the evaluation methods here implemented, the future cobalt and lithium production capacity is expected to increase significantly. Nonetheless, the levels of domestic production fall far short of what will be required by 2025 or 2030 to meet the internal European demand from even the EV sector alone, not to mention the projected consumption of the European LIB mega-factories announced for 2025 and 2030.

Besides, KU Leuven has conducted a quantitative estimation and concluded that the European lithium market has the potential to grow to 100,000-350,000 tons LCE by 2030(Gregoir & van Acker 2022). Europe is currently only mining small volumes of lithium for ceramics and glass applications in Portugal. After EU in 2017 made it a strategic priority to improve its self-sufficiency of lithium, more than 10 new European lithium mining projects have been announced in Austria, the Czech Republic, Germany, Finland, Portugal, Spain, and Serbia with a total project pipeline of 130,000 tons LCE by 2030. Despite of some barriers, such as local community opposition, viability of untested technologies, or uncertain economy to several projects, if it is possible to generate incentives and create the right conditions for all these projects to come through, Europe will be able to supply 55% of its 2030 needs for domestic battery production (European demand could reach 235,000 tons LCE in a medium case demand scenario) (Gregoir & van Acker 2022). Also new refining capacity has been announced, independently of domestic mining plans. The total potential refining capacity may reach 155,000 tons LCE by 2030, which is 25,000 tons more than the mining capacity. Hence 25,000 tons LCE battery-grade lithium must be produced from imported spodumene, so securing a supply of spodumene is expected to be a challenge for Europa in the next few years.

Today Europe consumes relatively low volumes of cobalt for mainly metallurgical alloys, carbide diamond tools and pigments. However, the ambition of developing a local European battery value chain, including cathode production capacity, will increase Europe's cobalt demand strongly, and the European cobalt market has the potential to grow to 30,000-50,000 tons by 2030. From the supply side, Europe is mining relatively little cobalt, supplying only 10% of the present demand domestically. A decline in the cobalt mine output is expected in the next decades according to KU Leuven, which means that the European domestic mining supply will be negligible in relation to the six-fold increase in the demand expected for 2030 (Gregoir & van Acker 2022). In contrast, Europe has significant cobalt refining operations in Finland, Norway, and Belgium, supplying around 70% of current domestic demand in Europe.

At present, Europe imports large volumes of lithium and cobalt chemicals and export related lithium and cobalt products after value-added manufacturing has taken place within Europe. EU seeks to accelerate the development of a domestic LIB market and is set to meet 69% and 89% of its increasing demand for batteries by 2025 and 2030 respectively (European Battery Alliance 2022). Should Europe be successful in developing a full battery value chain, the bottleneck will be raw cobalt and lithium ore. In this case Europe will face fierce competition for resources with China, who also lacks raw cobalt and lithium ore but have overcapacity for refining.

To summarise, towards 2030, a rapidly growing LIB demand will test the market's ability to expand the supply and reduce the lead times. While estimates vary and projections can change, and as compelling as the supply risks are, the potential for a huge demand growth underlies the differences in opinions on the cobalt and lithium supplies (Benchmark Mineral Intelligence 2021b; Snowdon 2022).

6. Discussion

Cobalt and lithium are critical elements for the clean energy transition and for reaching the environmental goal of the Paris Agreement. Unfortunately, for both materials, shortage may be a problem, and the supply risks are high, albeit for slightly different reasons. Figure 6-1 presents an overview of the geographical location of cobalt and lithium reserves and supply through all steps of the supply chain.

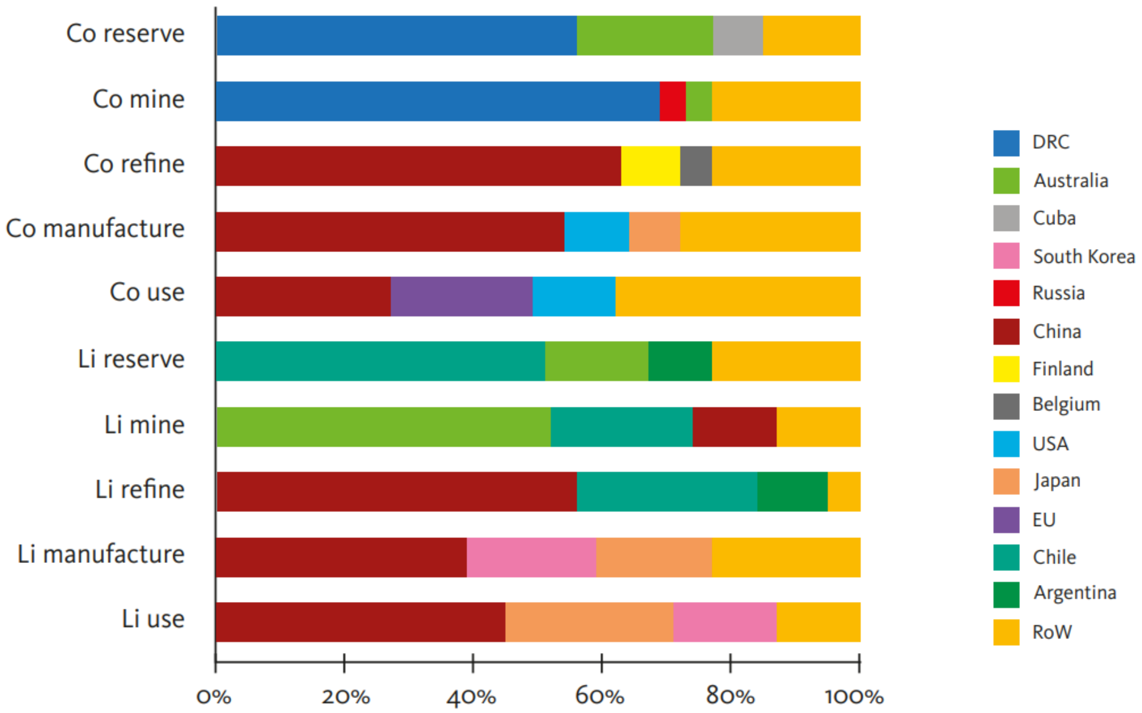


Figure 6-1 *An overview on the geographical location of cobalt and lithium reserves and supply (analysis based on data in Chapter 3 and 4).*

Both lithium and cobalt reserves are highly concentrated in specific geographical areas/countries. Considering the contributions of the top three countries, lithium is more concentrated than cobalt throughout the entire supply chain. Especially at the refining stage, the top three countries account for 95% of the global lithium refining production, whereas the top three countries of cobalt refining production account for 77%. Although lithium is more concentrated than cobalt, their primary supply risks are at the same high level, due to the following reasons: Firstly, more than half of the cobalt mining production is centred around the DRC, who in 2007 had the lowest World Governance Indicators (WGI) score on political stability and absence of violence/terrorism of all mining countries. Historically, civil war and regional conflicts have disrupted or eliminated cobalt mining production several times in the DRC and resulted in fierce price fluctuations (Cavallero 2021). Secondly, more than 98% of cobalt is produced as a by-product of nickel and copper. Hence, the economics of cobalt mining is fundamentally tied to not only the cobalt market, but also to the market of the host metals (van den Brink *et al.* 2020). Thirdly, artisanal and small-scale mining (ASM) are important contributors to cobalt mineral supply and constituted approximately 10% of the DRC's cobalt mining production in 2019 (Cobalt Institute 2021). However, this part of the production is informal and difficult to secure as a steady supply. Besides, due to the absence of traceability and responsibility in the ASM sector, many downstream and midstream buyers may restrict their consumption of ASM material to avoid being associated with potential negative impacts on workers and local communities.

Current forecasts suggest that the demand for EVs will continue to rise in the coming decades and with it, the demand for cobalt and lithium as a component of Li-ion batteries will increase too. Therefore, reducing the supply risk is important for society in general. Overseas investments; vertical integration; recycling; technology and business model innovation; open and transparent international trade; and environmental, social and governance effects may serve well to end this and will be discussed below.

6.1 Overseas investments

Overseas investments will typically decrease the resource concentration and diversify the suppliers, especially at the mining stage (Fig. 6.2).

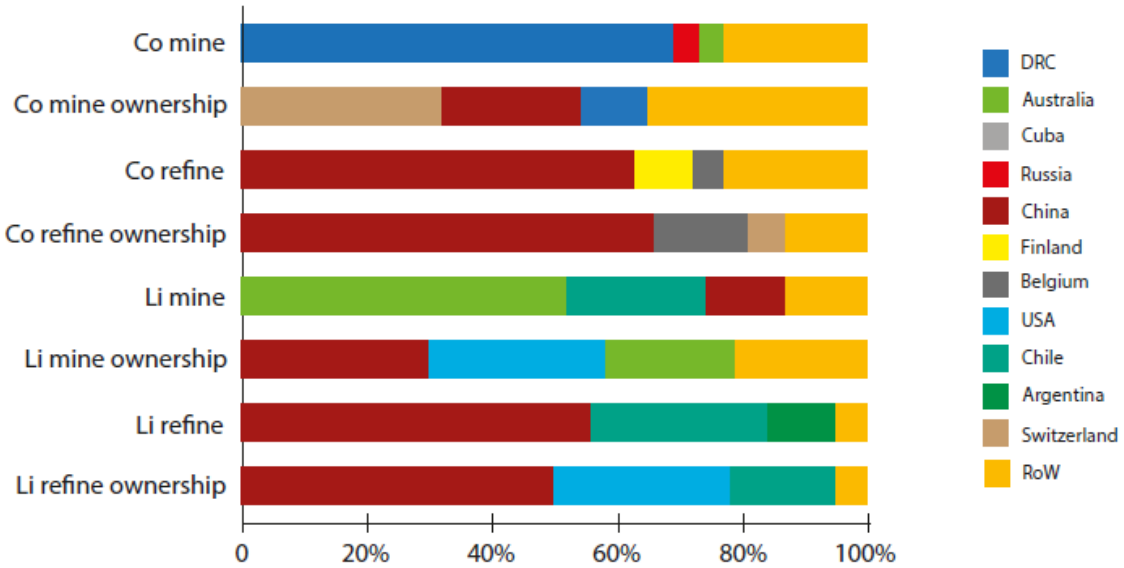


Figure 6-2 *Mining and refining ownership shift due to overseas investments (analysis based on data in Chapter 3 and 4).*

At the mining stage, the top three countries' share is seen to decrease from 78% to 65% for cobalt, and from 87% to 79% for lithium in 2019. However, this effect is not so obvious at the refining stage. Data for the manufacturing and application stages are not available.

Most cobalt and lithium reserves are found in developing countries such as the DRC, Chile, and Argentina, whereas countries with major LIB industries such as China, South Korea, Japan, and USA are lacking domestic raw materials. By investing in overseas mines, Switzerland and China hold 32% and 22% of the cobalt mining, respectively, and China's and USA's lithium mining ownership increase to 30% and 28%, respectively, taking 2019 as an example. Countries such as South Korea and Japan also own some percentage of the cobalt and lithium mines, which serves to reduce their domestic demand on battery raw materials.

For countries investing in overseas mining ownership, it is important to prioritize responsible and sustainable mining practices over the long term. Mining companies should not only be in compliance with international standards and ensure safe working conditions, but should carry out social and environmental assessments to secure optimal net benefit for the citizens of the host country over the long term with the lowest social and environmental impact (Goodland 2012). For example, mining must not reduce available land and water where such resources are scarce. In addition, mining companies should secure the sustainability of the mining, adding value and keeping doors open for future generations and provide a plurality of options without compromising future options. For example, they could provide mining engineering education for local citizens. For all pre-emptive measures, the perception of effectiveness and the acceptance of the social environment must be monitored systematically and regularly.

For resource-rich countries, mining can provide significant local employment, business opportunities, and government revenue. However, focusing on the present development is not sufficient. Resource-rich countries should take advantage of the soaring demand for EV raw materials to ensure sustainable investments and that the trade policies in place promote the growth of their mining and manufacturing sectors in a sustainable way. They should capture value from this market expansion while managing the risks of overinvestment so as to provide a reliable source of revenue and improve development and economic outcome (Kavanagh *et al.* 2018). To attract more foreign investments, resource-rich countries could provide an enabling environment including an open and predictable trade regime, effective border clearance mechanisms, good connectivity, including transport, logistics services, and information and communication technology. From an investor's perspective, lack of transparency and accountability (including complex and opaque licensing regimes), difficulties for investment due to corruption, complexity, or simply a slow-moving bureaucracy can create significant barriers to investment and trade (Hjelmstedt 2021). Local governments should try to solve any problems and aim to remove barriers. The governments should also maintain stable policies and regulations, which support and guide mining companies to sustainable practices. In some cases, governments may restrain export to encourage local processing and capture a higher share of the value flowing from extraction domestically, thus enabling the country to move up the value chain and diversify its economy. Governments in resource-rich countries have a range of trade and investment policy options available to them to maximize the development outcomes they can achieve from the EV boom. Policies should obviously be chosen to fit the particular political and economic contexts, but with a clear view of the long-term development of this fast-changing industry.

6.2 Vertical integration

As found in Chapter 3 and 4, the supply chains for both cobalt and lithium are quite concentrated, not only at country level, but also at company level. Figure 6-3 summarises the market share of the top 10 producers along the cobalt and lithium supply chains.

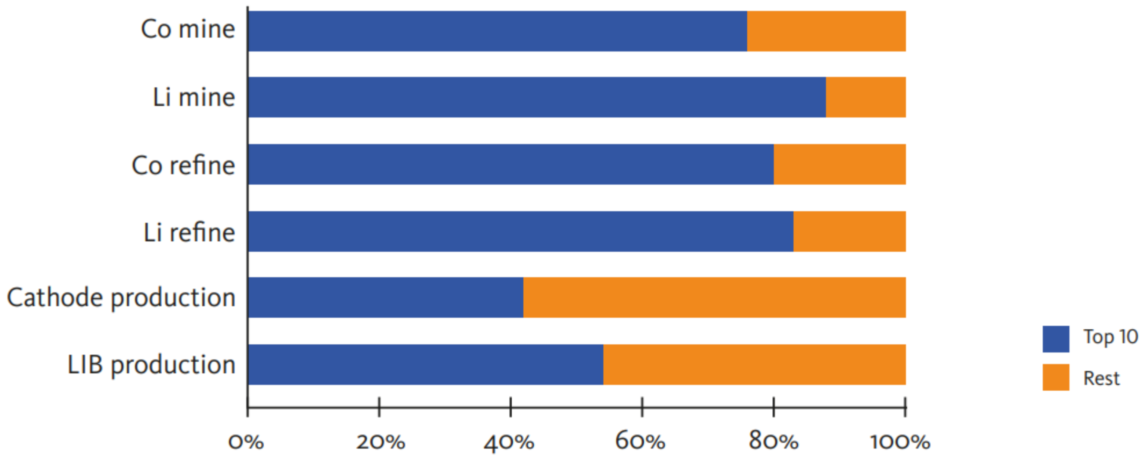


Figure 6-3 *Overview on market share of the top 10 producers along cobalt and lithium supply chain (analysis based on data in Chapter 3 and 4).*

Lithium is more concentrated than cobalt when considering the contribution from the top 10 companies. In 2019, the top 10 companies contributed with 88% and 83%, respectively, at the lithium mining and refining stages. The corresponding percentages for cobalt were 76% and 80%, respectively. For the manufacturing and application stages, we only consider LIB related companies, which are the same for both lithium and cobalt. The concentration decreases downstream, and the top 10 companies contributed with 42% and 54%, respectively. However, among the top 10 companies, there is a growing trend towards increasing vertical integration through the LIB supply chain.

Vertical integration refers to the expansion of business activities within a company's own supply chain. Vertical integration projects vary in terms of the means used to expand business activities, the degree of integration and its direction. The direction of vertical integration can either be forward or backward, as shown in Figure 6-4. Forward integration refers to integration with downstream companies in the value chain (i.e., closer to the end-use). Backward integration refers to integration with upstream companies in the value chain (i.e., closer to raw material producers) (Koster *et al.* 2022).

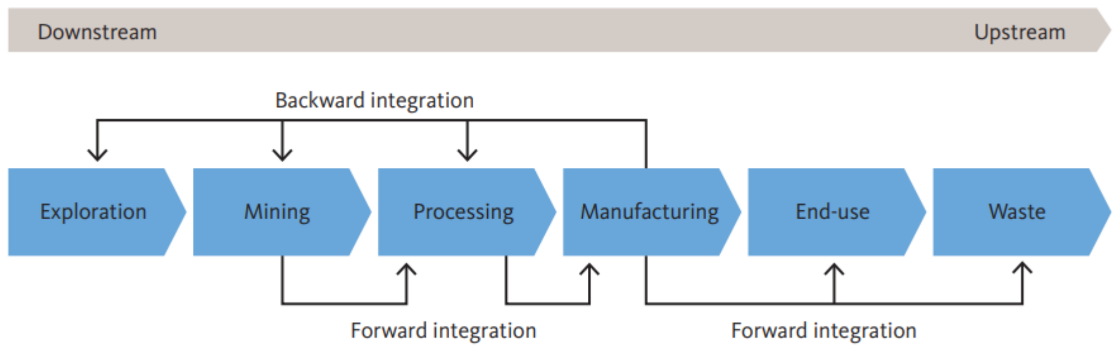


Figure 6-4 *Vertical integration in the value chain (Koster et al. 2022).*

Forward integration is the most common process for large mining producers to add values. For example, top cobalt mining producers, such as Glencore, JNMC, Sumitomo Metal Mining and Huayou, all have expanded their business to cobalt refinery. Sumitomo Metal Mining goes even further to develop its own cathode precursor operations. The same goes for lithium mining producers. Half of the top 10 lithium mining producers, i.e., Albemarle, SQM, Tianqi, Livent and Lanke, are also among the top 10 lithium refining producers. Gigafactories engage in backward integration, and several Asia-based leading companies have long-standing vertically integrated supply chains. CATL for example, pioneers a full vertical integration from mining to battery production. CATL acquired a 23.75% share of the Kisanfu cobalt project in 2021 and has built a value chain that includes the production of precursors and cathode materials together with the recycling of battery waste (Cobalt Institute 2022). Some battery producers in North America and Europe are seeking to develop similar structures (Mayyas *et al.* 2019). For instance, Umicore, the largest battery producer in Europe, acquired the cobalt refinery and cathode precursor production in Kokkola (Finland). Northvolt is planning to do the same with the production of battery materials to pack assembly. To secure a sufficient supply of batteries, original equipment manufacturers (OEMs) join this competition as well. Tesla and BYD have from opposite directions paved the way for the cell-to-vehicle integration, whereas LG Chem and BYD have done the same for stationary energy storage.

Integration can take place either directly by bringing activities in-house through acquisition, or by establishing a joint venture, or via offtake agreements and partnerships that commit downstream buyers to purchase a substantial portion of an upstream producer's output. Acquisition is primarily used by upstream companies in a strong financial position and with a substantial demand for raw materials. Joint venture is more common between automotive original equipment manufacturers (OEMs) and battery producers, although offtake agreements and partnership are also suitable for OEMs. Tesla, e.g., has agreements with Piedmont Lithium for lithium from spodumene, and Glencore for cobalt from the DRC. Similarly, BMW has direct agreements with Glencore as well as sourcing agreements for its cell suppliers CATL and Samsung SDI. This shows the strategic positioning of OEM companies to secure their long-term battery raw materials supply.

The advantages of vertical integration include a more reliable procurement planning and supply of raw materials, multiple opportunities to increase profitability, increased knowledge and capability and greater independence from external suppliers. Vertical integration is potentially very important for batteries' lifetime cycle, since multiple parts of the value chain, from material to usage, remain under the control of one or a few players, thus enabling them to optimize the value created through the battery lifetime cycle. Overall, vertical integration serves to decrease the companies' supply risk. Vertical integration is, however, a strategy for large companies requiring large quantities of raw materials, and there is therefore a latent risk of developing unfair competition, not only in the LIB industry, but in the non-battery cobalt and lithium sectors. In case of future shortage of cobalt and lithium, vertically integrated OEMs, backed by strong financial support, can be more competitive in obtaining cobalt and lithium raw materials, compared to smaller cobalt and lithium consumers. Strict supervision is necessary to prevent all cobalt and lithium resources from entering the automotive industry, thereby causing serious damage to other industries.

6.3 Recycling

Lithium-ion battery recycling is viewed as an important way to safeguard the supply of battery raw materials. If usable materials can be recovered from used batteries, fewer raw materials need to be extracted from the limited supplies in the ground. Since LIB recycling can be done locally, it may reduce the domestic dependence on primary cobalt and lithium for countries or regions where cobalt and lithium are not naturally available. Recycling domestically reduces the quantities that need to be imported, improving the balance of payments, and recycling of materials avoids processing costs for waste treatment. With the soaring lithium and cobalt prices, there are potential economic benefits in recycling raw materials as well. The environmental benefits are also clear. LIB recycling operations contribute significantly to reducing energy consumption, water use and to the mitigating of GHG and SOx emissions, compared to primary production. Studies show that around 10% of GHG emissions and 0.5% of SOx emissions in the cobalt life cycle originate from secondary production, which consumes around 13% of the total energy and 16% of the total water used in all cobalt production stages (Golroudbary *et al.* 2022). Moreover, LIB recycled locally reduces the need for long-distance transport and, consequently, mitigates transport-related emissions and energy consumption.

Recycling of LIBs has been done since they came on the market and have many advantages. However, for several reasons, the recycling efficiency has been low for a long time.

Firstly, LIBs often were used as secondary feedstock in non-dedicated waste-treatment processes. An obvious reason for this is that the volume of wasted LIBs has been very low, and the recycling market is generally waiting for the waste stream of batteries to grow. Until 2021, portable batteries were the largest sector of LIBs (Cobalt Institute 2022), and portable LIBs are expected to constitute the most important type of LIB-waste for a long time. However, despite a much shorter working life than EV batteries, the overall volume of recycled portable batteries is in practice much smaller than that of EV batteries which primarily is due to an extremely low collection rate. EV batteries came to market only after 2010 and have a very long working life, extending to more than 10 years or even 15 years (Watkins & Farmer 2021). The first EV batteries put into service hence gradually reached their end-of-life (EoL) from around 2020 and are starting to constitute the main waste stream locally. However, as battery packs age and decline in capacity, vehicles may not be scrapped but, alternatively, find new lives as vehicles used for short distance driving or their battery packs and cells could be remanufactured for stationary storage applications. Vehicles that are uneconomical to operate in one country are often exported to countries with lower labour costs. This trend has already been observed in early-generation EVs; around ⅓ of first-generation “Nissan Leaf” cars sold in the UK and Germany have now been exported (Melin 2021). Therefore, appropriate strategies for secondary resources management that take such resale into account should be implemented to ensure efficient recycling of cobalt and lithium. Not all batteries possess material with a value sufficiently high to cover the costs of recycling. This is especially the case for LFP containing cells, used in buses and stationary storage systems. Another problem is that the safe handling of LIBs to avoid a "thermal runaway", which can start from a charge level of 30% or higher for all LIBs, is extremely expensive (Graulich *et al.* 2021). A key challenge is that battery packs from electric vehicles have very different types of designs, each then requiring different types of special transport boxes, thus rendering the logistics of handling very costly.

Secondly, there might not be enough recycling capacity available to match the emerging waste stream of batteries expected in the near future. Although the present global recycling capacity is sufficient, the distribution of recycling capacity is uneven. Most capacity is located in Eastern Asia, and a few pilot plants are in Europe and in North America, but almost nothing is available in the rest of the World, resulting in deficient recycling capacity in most of the world. This tendency will become worse in the near future as the number of retracted batteries is growing with the recycling capacity lagging behind. EV sales have risen sharply in recent years, and while it will take several years for the waste stream from these to develop, it is expected to grow steadily. In the meantime, the waste stream will significantly increase from car batteries recalled due to technical problems or safety risks. Another important waste stream comes from the production waste from LIB manufacturing. As production of LIBs is soaring, so will the waste production, posing a big challenge to the recycling capacity. If 1% of the produced output is faulty and ends up as production waste somewhere along the production line, waste volumes comparable to the expected waste stream of stationary energy storage batteries will be produced (Graulich *et al.* 2021). This will be particularly a problem at the locations of new gigafactories. Moreover, the infrastructure to transport and store the growing number of disused batteries is still mostly lacking and needs to be established to handle the expected stream of end-of-life (EoL) batteries.

To meet these challenges, there are some actions for the relevant stakeholders, the public and the governments, in particular, should take.

6.3.1 Policy support on LIB recycling

The European Commission recently proposed a new Battery Regulation, which emphasizes the use of recovered raw materials: As of 2030, industrial and EV batteries must contain minimum shares of recycled cobalt, lithium, and nickel of 12%, 4%, and 4%, respectively, increasing to 20% cobalt, 10% lithium and 12% nickel by 2035 (Watkins & Farmer 2021). This will encourage cobalt and lithium domestic recycling in EU and prevent EoL batteries to be exported to non-OECD countries. However, economically efficient Li-ion battery recycling is yet difficult to achieve, mainly due to the high safety risks during transport and recycling, and the material values (e.g., cobalt or nickel) not being high enough to cover the costs of recycling. Governmental subsidy policies for EV battery recycling may be helpful, in parallel with the efforts to promote EV sales a decade ago (Mock & Tietge 2016). It is important for both recycling companies and EV consumers to have sufficient recycling capacities, including waste logistics and recycling infrastructure.

6.3.2 Design for LIB recycling

Battery design is important for the recycling potential. Batteries should use electronics suitable for both automotive and stationary applications, and battery packs should be easy to disassemble. Harmonization of battery chemistry and design should be promoted to minimize the recycling costs. However, because battery technologies and chemistries are still under development and changing, global harmonization is particularly difficult.

6.3.3 Better collection and sorting

The public awareness of the importance of recycling must be improved to enhance the collection rate of used batteries. Despite the Batteries Directive 2006/66/EC and the Regulation No 493/201246, the collection rate of portable batteries is much lower than the minimum required regulation by EU of 45%. The collection rate for EV batteries is only 50% with respect to the vehicles that left the EU fleet in 2013-2014 (Schuler *et al.* 2018). Information on the importance of the recycling of battery cells to reduce the need for primary production of raw materials should be disseminated to the public. Batteries should be labelled with information on chemistry, the need for separate collection, the presence of hazardous substances, etc. to increase the consumers' awareness of a product's recyclability, reduce non-selective collection, and promote a higher collection-to-recycling rate. The concept of a battery passport (e.g., with a QR-code) could support the tracking of battery streams and provide relevant information for collection, logistics, reuse, and recycling. In general, different material scraps must be kept separate as far as possible, as recycling them separately makes everything easier. Advanced technologies are also needed to improve the separation efficiency, since research shows that every 1% of improvement on the efficiency of waste separation technologies represents roughly a 4% increase of material recovery (Golroudbary *et al.* 2022).

6.3.4 Close-loop recycling

Closed-loop recycling is the manufacturing process whereby materials recovered from recycling and the reuse of post-consumer products are utilized to create new versions of the same products. Currently, battery recycling is mainly open recycling. Batteries are disassembled through shredding in low oxygen environments and materials are then separated via a combination of physical, thermal, or chemical processes. 50 to 60% of the constituents can be recovered by this type of recycling. Recyclers recommend a modular design of large batteries. Close-loop recycling enables material recovery rates of up to 90% or even higher, since some processes could be omitted if products identical to the originals are made (Xu *et al.* 2020). Large Chinese battery producers have today either in-house recycling (BYD, BAK, CALB) or vertically integrated recycling capacity in subsidiaries (CATL, Gotion High Tech), while manufacturers in South Korea are working closely with both recyclers and material producers. In addition, Tesla announced that they too will start their own recycling operations and Northvolt in Sweden will have recycling integrated into their operations (Cobalt Institute 2022). Those are important preconditions and positive signs to implement close-loop battery recycling.

6.4 Technology and business model innovation

6.4.1 Extend battery's lifetime and enhance energy density

Lithium-ion batteries are constantly being developed and improved, forced by the battery raw materials market. Enhancing the batteries' energy density and extending their lifetime are the most important methods to reduce the demand for raw materials and to meet the requirements of different sectors.

Solid-state batteries (SSB) are considered as the most promising next-generation high-energy-density devices due to the extra-high capacity and the low electrochemical potential of lithium metal anode. SSB can utilize the existing, mature, cathode materials, such as NMC, but the graphite anode can be replaced by the lithium metal anode and the flammable liquid electrolyte is avoided. Therefore, SSBs are safer than current LIBs using liquid electrolytes. However, SSBs are still challenged by lithium dendrite growth, low coulombic efficiency, and a thick film system (Li & Frith 2020). Researchers around the world are working to overcome these barriers, but it is costly and time-consuming, and requires national or international support. EU, China and USA all maintain special funds for this kind of research (European Commission 2020a). However, efforts are also made to improve current LIB systems. For example, studies show that to increase the energy density a nonuniform catalyst that enhances the reaction rate only at the separator-cathode interface is more efficient than a uniformly distributed catalyst (Andrei *et al.* 2012). Other enhancements to the energy density, including the use of solvents with high oxygen solubility and partly wetted electrodes are expected to be employed soon.

Today's average battery lifetime lies between 5 and (more realistically) 20 years, depending on the usage. For a given cell chemistry, a better design with a smoother interface between electrolyte and electrodes may retard battery degradation and increase the lifetime by nearly 45% (Sowe *et al.* 2022). In this case, the demand for cobalt and lithium is almost halved, but the technique is currently only at an early laboratory stage. Currently, a more practical method to extend battery lifetime is to improve the battery management system. Temperature is the most significant stress factor for battery degradation, where deviations from the ideal 25°C can lead to accelerated failure. Advanced battery management systems can keep the temperature within an optimal range to increase battery lifetime. In addition, collection of data on the batteries' state of health allows accurate predictions of EoL batteries and minimizes the risk of thermal runaway.

6.4.2 Battery chemistry substitute

Substitution is an important way to counter battery materials shortage. Less or even cobalt free cathodes are increasingly used. Currently, cobalt makes up to 20% of the weight of the cathode in Li-ion EV batteries, and many battery producers have already prioritized to reduce the cobalt content in LIBs by producing NMC811 instead of NMC111. Cobalt free cathode LFP's are becoming increasingly widespread. However, due to the rapid expansion of the EV market and the increasing battery capacity needed, the total cobalt demand of the battery sector is expected to still increase and reach a peak after 2030 (Zeng *et al.* 2022).

With respect to lithium, many alternatives are currently being explored, including sodium-ion batteries, magnesium-ion batteries, zinc-ion batteries, aluminium-ion batteries, and metal-sulphur batteries. Among them, sodium-ion batteries (SIBs) attract the most attention because of the obvious advantages of the low cost and natural abundance of natrium sources (Yang *et al.* 2023). Moreover, commercialization of SIB is moving much faster than was originally expected, and CATL is pioneering the development of SIBs. SIBs have already been used for grid-scale energy storage systems in China (Contemporary Amperex Technology 2021), and CATL will begin mass production of SIBs for vehicles in Q4 2023 (Pacific Securities, 2023). If the entire ESS demand could be met by Na-ion batteries, the lithium demand is expected to be reduced by approximately 10% by 2030 (Li & Frith 2020).

6.4.3 New battery ownership models

To support a circular economy, several initiatives have been launched on battery ownership. One business model includes battery producers owning batteries and leasing them to the OEMs. In the UK, Zenobe Energy offers bus operators to lease batteries for buses from Alexander Dennis/BYD, and in USA, Proterra is doing the same for their own buses (Melin 2021). Similar arrangements are expected to be increasingly common within the heavy transport sector, whereas the model seems less obvious for smaller passenger vehicles. Another business model includes OEM battery ownership and provision of service to the customers through battery swapping programs. Each brand has its own type of battery and will take EoL batteries into close-loop recycling. This business model is suitable for passenger vehicles, and in China leasing options to customers are on the rise through both Beijing Automotive Group Co. Ltd (BAIC) and Nio Inc. (NIO), which have established networks of battery swap stations that essentially are used as an alternative to charging (Melin 2021). The batteries are charged at the stations and thereafter made available for new customers. Additional OEMs are now starting up, including Volkswagen, BYD, and many of the makers of commercial vehicles, which already have their own systems. The biggest advantage of these new business models is that battery ownerships remain with professional companies, instead of with individuals without specific battery knowledge. In this way, batteries can be managed more efficiently (Bridge & Faigen 2022). Many batteries have only 70% capacity left after 8 years of usage, since as lithium batteries cycle, they accumulate little islands of inactive lithium that are cut off from the electrodes, thereby decreasing the battery's capacity to store charge. Recent studies show that this "dead" lithium creeps towards one of the electrodes until it reconnects after an extremely fast discharging step, thereby partly reversing the process, but only professional companies can manage this potential recovery (Liu *et al.* 2021). Collective battery ownership by either OEMs or battery producers can alleviate this recovery and make full use of the LIB capacity. In addition, collective battery ownership enables close loop recycling. If the scale is large enough, long-distance battery transportation can be avoided and significantly reduce recycling costs.

6.5 Open and transparent international trade

Since distribution, production and processing of both lithium and cobalt are all geographically concentrated, a stable and open international trade is extremely critical to secure the material flow and stable global supply chains.

An open and stable international trade requires transparency and predictability in export restrictions for current resource-rich and producing countries. In practice, export restrictions can take the form of export bans, quotas, duties and taxes, or mandatory minimum export prices. DRC is a good example of the use of export restrictions, since the government of the DRC uses such measures as a tool to regulate the production and processing of cobalt products. The government of the DRC wants to change some unethical practices in artisanal mining and plans to assign the national company Gécamines as the monopoly buyer of artisanal mined cobalt (Cobalt Institute 2022). This can improve the management of artisanal mining, but at the same time it can also increase the supply chain risks because there will be less diversification among the suppliers. Moreover, the government of the DRC aims to capture domestically a higher share of the value flowing from extraction and encourages local refining of cobalt. In 2013 the government of the DRC imposed an export ban on unrefined cobalt, in the hope to divert these materials to the domestic market and allow local industries access to cheap raw materials, thus creating opportunities for employment and industrial development. However, the plan failed due to the absence of reliable energy supply and refining capacity in the country. In consequence, fewer cobalt refining products were available, which affected cobalt prices. Even though the ban was finally waived in 2020, such unstable export policies by resource-rich countries make the supply chains vulnerable. This could be avoided through notification requirements on export restrictions and duties, and by providing incentives to resource-rich countries to bind their level of export duties to a maximum (Espa 2015).

Trade tensions with China have pushed countries to consider new cobalt supply chains, potentially breaking the de facto DRC-China monopoly of cobalt-based battery production. A similar situation exists for the lithium supply since China also plays a key role in lithium refining. Recent global events, such as the COVID-19 pandemic and the Russia-Ukraine war, have highlighted the geopolitical vulnerability of the lithium and cobalt supply chains, and the need to diversify sources and reduce import dependence on a few specific countries (OECD 2020; Cobalt Institute 2022). One increasingly common way to diversify lithium and cobalt supply chains is through trading partners and like-minded nations, using bilateral agreements and multilateral forums. Countries like Canada and Australia, despite only contributing little to the current global cobalt mining production, will become increasingly important for the Western world's green and digital economy in the future. Both countries are viewed as trusted suppliers of responsibly sourced mineral and metal products by western countries, which are the main consumers of cobalt products. For example, since January 2020, Canada has formalized bilateral cooperation with USA, EU, and Japan, and is actively engaging with additional allies like Australia, UK, and Korea. Australia has already commenced its journey into downstream processing of lithium and cobalt with investment from EU and USA (Gasson *et al.* 2021). Additionally, European's battery and auto manufacturer have higher planned capacity in Australia until 2025 than the expected demand of EU. Chile, another major lithium-producing country, also has its own strategic ambitions to build a domestic manufacturing system around the extraction of lithium and to take the added value. Currently, Chile is already the main lithium supplier for EU, South Korea, and USA, and Chile's interest in developing battery-related technologies attracts many investments from these countries. The American-lead company Albemarle promised to build the whole lithium supply chain inside Chile. Four European giants have signed an agreement for the sustainable refining of Chilean lithium locally. In addition, corporate investors, including South Korean electronics giant Samsung, plan to build three factories in Chile to produce battery parts for EVs (Hjelmstedt 2021). A such multifaceted development suggests that there may be a new complete supply chain without dependence on China in the future.

An open and stable international trade on lithium and cobalt enables economic growth for all, and diversification of supply chains could improve the security of stable international trade.

6.6 Environmental, social and governance effects

Environmental, social and governance (ESG) considerations are becoming increasingly prominent in business and investment decisions. It matters that the carbon emissions of the end-product are minimized, but markets are also increasingly demanding sustainability along the entire value chain, including extraction, processing, production, and hiring practices etc.

Criteria for assessing a company's environmental impact cover its approach to measuring and managing air, water, soil pollution and biodiversity. The criteria extend not just through the life of a mine, but also to post-production activities and reclamation. Other factors for a mining company to consider when building a sustainable business strategy include energy consumption and gross CO_2 emissions, and vulnerability to catastrophes, in both physical and logistical terms. Criteria for examining a company's social impact include: the company's labour management policies; its health, safety, and wellbeing commitments; the impact it has on the local and indigenous community; and the labour standards of any suppliers. Governance criteria assess a company's corporate governance practices by focusing on board structure, in particular board diversity, transparency, and the company's relationship with governmental and regulatory bodies, as well as NGOs.

For countries with higher transparency of mineral and product provenance, such as Canada and Australia, governments could supervise ESG management through effective rule of domestic or international laws and well-developed regulatory frameworks. Generally, companies' ESG record will be improved by alignment to a series of international standard frameworks, such as the UN Guiding Principles on Business and Human Rights, the UN Guiding Principles Reporting Framework, the Global Industry Standard on Tailings Management, etc.

In countries where ESG-practices are not thought as important or the most important factor in a company's operation, external forcing might be needed. Lead international partners could implement high ESG standards in countries with less concern for ESG management and strengthen best practices in ESG. For example, the German holdings Daimler AG, Volkswagen AG and BASF joined the Dutch smartphone manufacturers Fairphone to create "The Responsible Lithium Partnership" to ensure that the extraction of the mineral, which is essential in the production of batteries, does not affect the ecosystem or people who live in the surrounding areas. In addition, end-user producers or other raw materials consumers could also trace and supervise the ESG record in the whole supply chain. Companies such as Tesla, BMW, Volkswagen, and Ford are also committed to the Responsible Minerals Initiative (RMI), which seeks to ensure that cobalt that are used in EV batteries was mined responsibly. In addition, various downstream companies such as Volkswagen, BASF, BMW, and Samsung support the Cobalt for Development Initiative, which seeks to train artisanal miners on the environmental, social, and governance aspects of responsible mining (BASF 2020). Another example of directly engaging with supply chains is the teaming up of Ford, Huayou Cobalt, IBM, LG Chem, and RCS Global to use blockchain technology to trace cobalt provenance (Lewis 2019). Additional examples include the "Fair Cobalt Initiative" and the "Responsible Cobalt Initiative" that include Chinese refiners and top cobalt producers such as Glencore and others. A lot of these initiatives are new, and their ability to influence unethical practices should be seen in the near future.

To some extent, ESG-requirements are viewed as barriers to lithium and cobalt mining expansion, for example, ESG compliance can potentially lead to significantly higher prices for these minerals. However, strong ESG prepositions will generate value in a longer perspective. Public awareness of environmental issues serves to increase the consumer's willingness to pay extra for a green and sustainable product. A high ESG-standard impacts the companies' reputations and their ability to make a profit. Protection of human rights could boost employee motivation and attract talents through greater social credibility. For mining companies, ESG-awareness can alleviate access to resources through stronger community and government relations, help to secure a stable and sustainable mining, and consequently avoid loss of investments due to longer-term environmental issues.

6.7 Summary

In this chapter, we have discussed measures to reduce supply risks for the two critical battery raw materials lithium and cobalt under six broadly defined headings: overseas ownership, vertical integration, recycling, technology and business model innovation, open and stable international trade, and ESG effects. For each of the six headings, both opportunities and challenges exist. Due to lack of data, there are other important factors which might affect future lithium and cobalt supply/demand balance, that are not discussed here. These include among others loss rate of materials through the whole supply chain, the policy lag effects, and uncertainties for supply, demand, and recycling prediction models.

In a short summary, a consequence of the booming consumer electronic and emerging EVs industries is a soaring demand for the battery raw materials cobalt and lithium. This presents a potential barrier to reach the global climate goals. To meet the challenges, we need all the stakeholders, from governments to companies and individuals to cooperate and work hard in their respective fields.

7. Conclusion

- Many new advanced battery technologies are under development worldwide, such as solid-state batteries, Li-air batteries, Li-S batteries, Na-ion batteries etc. However, none of these technologies are expected to be adopted by the market before 2030. Lithium-ion batteries will still be the most widespread technology in use during the next decade. Lithium as a crucial constituent cannot be substituted by 2030, whereas cathode materials with less or no cobalt are expected to increase in importance.
- The supply of both lithium and cobalt matched the global demand in 2019. However, the distributions of both supply chains are highly concentrated. 69% of the cobalt mining supply comes from the Democratic Republic of Congo (DRC), and around 80% of the lithium mine supply comes from Australia and Chile. China contributes with more than half of both the cobalt and lithium refining production. Cathode materials and cell production are dominated by Eastern Asian countries, particularly China.
- Cobalt and lithium reserves are highly concentrated in a few countries; cobalt in the DRC and lithium in South American countries as well as in Australia. However, through overseas mining ownership investment, the main cobalt and lithium consuming countries, such as China, USA, South Korea, Japan, and some European countries could mitigate their own supply risk of related invested minerals and increase the diversity of ownerships on cobalt and lithium reserves. Foreign direct investments occur at any stage of the whole supply chain, but currently it is more common at the mining stage.
- For both cobalt and lithium, the top 10 companies accounted in 2019 for approximately 80% of the market for mining and refining production. Vertical integration is common along the cobalt and lithium supply chains. Upstream companies add more value to their business through forward integration, whereas downstream companies secure a sufficient supply of battery raw materials through backward integration.
- Driven by the increased demand for lithium-ion batteries used in electric vehicles and stationary energy storage, the demand for both cobalt and lithium will be soaring in the next decades. Exact increases in demand for both metals are difficult to predict, but several scenarios foresee deficits in both lithium and cobalt supplies in 2030, which might become a barrier to the global green transition.
- To abate potential supply bottlenecks for both cobalt and lithium, urgent investor action is needed in the mining sector, since some mines require up to 15 years to reach production, lack of investment in mining now will translate to shortages further down the value chain. It is also necessary to expand refining capacities, but because it takes shorter time to build and reach production, this need is not urgent.
- ESG principles are crucial in addressing the unique environmental and social impacts of cobalt and lithium mining. Governments must establish frameworks that incentivize responsible practices aligned with ESG requirements. Collaboration among stakeholders is essential in developing comprehensive solutions that prioritize sustainability, social responsibility, and good governance throughout the cobalt and lithium supply chains.
- Recycling is viewed as an important way to increase the security of battery raw materials supply. Recycling of lithium-ion batteries can be done locally and may thus reduce the domestic dependence on primary cobalt and lithium for countries or regions where cobalt and lithium are not naturally available. The number of retracted batteries is growing faster in the coming years and can provide up to 10% of the cobalt demand in 2030. In addition, recycling presents a more sustainable supply solution for cobalt and lithium,

mitigating the reliance on traditional mining activities and helping address potential challenges associated with ESG requirements. As the demand for these minerals continues to grow, recycling offers numerous environmental and economic advantages.

- A transparent and open international trading system is extremely critical to secure global supply chains for both cobalt and lithium. Therefore, coordinated efforts throughout the supply chain from mining to processing, manufacturing, and end-use across different countries are indeed needed.

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