CLEAN AND CONNECTED

2030 TECHNOLOGIES AND MATERIALS ENABLING THE MOBILITY TRANSITIONS

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As the world transitions toward a more sustainable future, electric vehicles (EVs) have emerged as a one of the key solutions to reduce greenhouse gas emissions of transportation. According to the IEA, the global sales of EVs were doubled in 2021 from the previous year to 6.6 million and exceeded 10 million in 2022. In 2023 the sales of EVs are expected to exceed 14 million. EV technologies, dominated mostly by lithium-ion batteries, require large quantities different raw materials such as lithium, cobalt, nickel, manganese and graphite. The lithium demand has grown rapidly, and the overall demand already exceeded the supply in 2022, 60% of lithium was used for EV batteries. Similarly, the demand for cobalt and nickel for EV batteries has grown compared to previous years. To ensure production and widespread distribution of EVs, the sustainable mining and extraction of these critical raw materials must be expanded rapidly. Finding alternatives to reduce the reliance on these critical materials through innovative battery technologies and recyclability of the secondary raw materials are also crucial to support EV production in the future.

This report offers a holistic perspective on the challenges and opportunities within the electric vehicle industry, contributing to informed decision-making for a more sustainable future. The enabling technologies of EV production (batteries, fuel cells, traction motors, lightweight construction, and electronics) are introduced. Additionally, the criticality of the main raw materials used in electric mobility, their availability and potential shortages that could impact the EV industry by 2030 are forecast. With rapid advancements in battery technology, ensuring a skilled workforce becomes imperative to meet increasing demand. Hence, the report delves into the skills gaps that may hinder the growth and innovation of the EV battery sector. To ensure the maximum GHG reduction of EVs there is a need to understand the environmental impact throughout the whole life cycle including raw material extraction, manufacturing, use and end-of-life management. The report evaluates the potential of Life Cycle Assessment (LCA) to analyse the environmental impact and to provide valuable insights into areas where sustainability improvements can be made.

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Abbreviations

battery electric vehicle (BEV)

electric vehicles (EV)

greenhouse gas (GHG)

life cycle assesment (LCA)

lithium nickel cobalt aluminium (NCA)

lithium nickel manganese cobalt (NMC)

lithium iron phosphate (LFP)

lithium manganese oxide (LMO)

lithium titanate (LTO)

original equipment manufacturers (OEMs)

plug in hybrid electric vehicle (PHEV)

rare earth elements (REE)

solid state battery (SSB)

lithium ion battery (LIB)

vehicle-to-grid (V2G)

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1. Introduction

The European Union (EU) has established an ambitious goal to achieve climate neutrality by 2050. In order to meet these targets, the transportation sector must significantly reduce its greenhouse gas emissions. Cleaner and more sustainable mobility is a key challenge of our time, demanding concerted efforts. European institutions have an essential role in shaping the future of mobility. It is important to establish ambitious sustainability objectives and provide a clear industry roadmap. Implementing emissions standards, enhancing fuel efficiency, and promoting the adoption of electric and alternative vehicles are the main implementation needed to facilitate the incorporation of cleaner and sustainable technologies and practices into the transportation sector.

The demand of electric vehicles is estimated to increase significantly in the coming years. EVs can reduce overall greenhouse gas (GHG) emissions, if the sustainability of the whole value chain has been considered carefully. The transition towards low-carbon transportation will be material intensive. Lithium-ion batteries have a dominant role in electric vehicles and according to International energy agency (IEA) the demand of lithium is estimated to grow 40 times compared to current level cobalt and nickel 20-25 times and rare earth elements (REE) three times until 2040. The production and demand from 2020 until 2030 of nickel, cobalt, lithium, copper, graphite and REE are summarized in Appendix. To ensure the availability of the raw materials, many new mines and extraction facilities need to be started in near future. It is important to pay attention to support the mining projects with beneficial environmental, social and ethical impacts.

Manufacturing of the batteries is a major cause of the GHG emissions of electric vehicles (EV). High reduction of the emissions can be achieved in use phase of the EV. The overall GHG reduction potential is highly depended on the electricity mix used in use phase. The circularity of the raw materials and the second life applications need to be considered in the end of the life cycle. The Life Cycle Assessment (LCA) need to be integrated into all parts of the life cycle and there is urgent need for transparent collaboration and primary data access in order to be able to create comparable tools to measure the overall environmental impacts of the electric vehicles. This includes also the integration of the geologists, mining and mineral processing into the LCA processes.

2. Enabling technologies

2.1 Batteries

Li-ion batteries have found widespread success as a vital technology for decarbonizing the automotive industry. A key feature of Li-ion batteries is the cathode chemistry which determines its performance and the materials required to manufacture the battery. Cobalt and nickel-rich chemistries provide the best energy density therefore lithium nickel manganese cobalt (NMC) has emerged as the most preferred battery for automotive OEMs over the years. However, the growing prominence of lithium iron phosphate (LFP) batteries in the EV sector shows a desire to shift towards materials that have more secure supply chains. Projections on which chemistry will dominate by 2030 vary. There is great uncertainty due to the rapid innovation and research taking place in this field. Some experts even express that the assumption that Li-ion batteries will continue to lead for the next 10 years is quite conservative. A considerable improvement in energy density and a sharp decline in battery prices in next-generation battery technology would completely disrupt the current Li-ion battery market.

2.1.1 Technology trends

Battery chemistries

The key components of a battery cell are the cathode, anode, liquid electrolyte and separator. Material requirements for batteries vary significantly depending on the chemistry used. Currently, six main Li-ion battery chemistries exist classified based on the varying compositions of the cathode as shown in Figure 1.

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strong | moderate | weak

Material	Description	Safety	Cost (US$/kWh)	Energy density (kWh/kg)	Cycle life[d] (times)	Ni content (kg/kWh)
LCO ($LiCoO_2$)	Mostly used in consumer electronics. Limited application for xEVs[b] (e.g. Tesla).	Low	Low	0.58	1,500–2,000	0.0
NMC[a] ($LiNi_xCo_xMn_xO_2$)	Used mainly in consumer electronics but increasingly used in xEVs.	Mid	Mid	0.60	2,000–3,000	0.69 51 wt%
LMO ($LiMn_2O_4$)	Relatively mature technology. Used in xEVs by Japanese OEMs (e.g. Nissan Leaf, Mitsubishi i-MiEV, Chevrolet Volt).	High	High	0.41	1,500–3,000	0.0
LFP ($LiFePO_4$)	Relatively new technology used in xEVs and ESS.[c] Driven by A123 Systems and Chinese manufacturers (e.g. BYD, STL).	Very high	High	0.53	5,000–10,000	0.0
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	Used mostly in consumer electronics (often blended with other chemistries) and e-vehicles (e.g. Tesla)	Mid	Mid	0.72	n/a	0.68 (49 wt%)

Figure 1. Comparison of the main Li-ion battery chemistries (Concawe, 2019).

All of the chemistries, except lithium cobalt oxide (LCO), have found some level of application in the automotive industry today (Concawe, 2019). Lithium titanate (LTO) has traditionally been used in the defence industry, however, now the battery is also finding application in electric bikes, scooters, and vehicles such as the Honda FIT EV and TOSA bus (Welch, 2022). Although lithium manganese (LMO) cells were initially used in some electric vehicles such as the Nissan Leaf, Mitsubishi i-MiEV and Chevrolet Volt, interest in this chemistry has diminished over time (Fraunhofer ISI, 2021). The battery shows moderate safety and relatively low specific energy. Despite its drawbacks, it possesses a cost-competitive advantage over the lithium nickel cobalt aluminium (NCA). NCA has successfully been deployed in some of Tesla's products due to its superior specific capacity (Ding, Cano, Yu, Lu, & Chen, 2019). Since their commercialisation in the early 2000s, NMC batteries have dominated the battery electric vehicle (BEV) and plug in hybrid electric vehicle (PHEV) markets (International Energy Agency, 2021). Currently, NMC 622 represents the state-of-art cathode chemistry in the automotive industry. Ni-rich NMC811 will most likely be adopted in the near future owing to its higher specific energy and lower cost (Fraunhofer ISI, 2021).

LFP is mostly used for most medium- and heavy-duty vehicles because of its exceptional cycle life, (International Energy Agency, 2022). Eliminating cobalt and nickel provides a cost-benefit in entry-level BEVs because material costs for LFP are four to five times lower than that of NMCs although it also means there is a trade-off with the vehicle's driving range (Yu & Sappor, 2021). Key trends in the Li-ion battery industry show the need to reduce raw material costs and improve energy density while also minimising environmental, social and political impacts of sourcing the necessary materials. Vehicle manufacturers have increased efforts on limiting the amount of cobalt in batteries due to price fluctuations and concerns surrounding unethical mining practices. Over the years, NCA batteries have transitioned to NCA+ while NMC 111 batteries transitioned to NMC 532, NMC 622, NMC 811 and NMC 9.5.5. This represents an overall shift to more nickel-rich chemistries and a decrease in cobalt (International Energy Agency, 2021).

The choice of increasing nickel in batteries to compensate for cobalt has obvious implications for the demand for nickel (appendix). High-grade nickel sulphate is the key ingredient in NMC and NCA cells therefore not all nickel on the market is suitable for battery production (Joint Research Centre, 2020). Due to potential shortages of battery-grade nickel, there is another desire to shift to lower nickel-containing chemistries and capitalise on the potential of manganese, which is in relatively abundant supply (International Energy Agency, 2021). On the other hand, the automotive industry is showing an increased interest in LFP batteries in order to completely do away with nickel, manganese and cobalt.

In terms of anode materials, graphite remains the main anode material for most Li-ion batteries (Appendix). Silicon composites are a promising alternative however silicon anodes swell during charging which diminishes the battery's performance (International Energy Agency, 2021). Nevertheless, the use of silicon is expected to continue increasing in Li-ion batteries and the maturation of Si-rich technology and its implementation is expected by 2025 (Fraunhofer ISI, 2021). Another alternative is pure lithium metal, but it cannot be used in traditional liquid electrolyte systems as it reduces the cell's lifetime (International Energy Agency, 2021).

Future Battery chemistry forecasts

Premium vehicles are expected to use nickel-rich batteries such as NCA95, NMCA and NMC9.5.5 or potentially those with even higher energy density. In lower-end, high-volume and mainly urban vehicles, LFP batteries will be the primary battery chemistry due to cost savings which are more important than driving range. For mid-range vehicles, the manganese-rich chemistry is more appealing due to its higher energy density than LFP. For medium and heavy-duty vehicles, LFP will dominate as cost and reliability are a priority in early electric trucks (International Energy Agency, 2022).

Nickel-based chemistries such as NMC and NCA retained dominance of the market in 2021 with 85% of EV battery demand. However, the LFP battery has begun to tap into the market competitively as LFP EV demand has doubled from 7% in 2020 to 15% in 2021 mainly due to the increasing uptake of LFP in electric cars in China (International Energy Agency, 2022). UBS analysts stated in August 2022 that LFP batteries will represent 40% of the global battery market by 2030. This is 25% higher than previously projected due to improved driving range and the growing desire of battery makers to move away from high-nickel content battery chemistries (S&P Global, 2022). Automotive manufacturers are starting to compromise on lower energy density in favour of better safety, long lifecycle and lower costs that LFPs offer. Thus, LFP is expected to dominate the 3000 GWh global lithium-ion battery market by 2030 (Wood Mackenzie, 2022), (Colthorpe, 2022). Goldman Sachs have also raised their projection of LFP market share from 25% to 38% by 2030 (Goldman Sachs, 2022). The International Energy Agency states that the future of battery chemistries is still not certain, but it is expected the market will be more diversified by 2030.

Next-generation technology

To achieve further significant cost reduction and improvement in energy density, research needs to look beyond conventional lithium-ion batteries. The solid-state battery (SSB) is a promising technology which eliminates the liquid electrolyte and graphite-based anode which are two components responsible for limiting functionality and energy density in the Li-ion battery system. SSBs with lithium metal anodes could improve energy density by 70% compared to LIBs with conventional graphite anodes which means that batteries of the same size would have much more energy. Furthermore, researchers estimate a 10-15% reduction in the total cost of a battery pack compared to their liquid electrolyte counterparts. It is not clear when SSB technology will receive widespread market uptake as the biggest hindrance is scaling up the production to make it commercially feasible (The World Bank, 2021). The International Energy Agency states that if the mass production of these cells is possible within the next five years, SSBs would be competing with the current LIBs on the market by the 2030s (International Energy Agency, 2021).

2.1.2 Circular economy

The accelerated uptake of batteries for decarbonization in the automotive sector warrants the need to shift away from traditional linear business models. ARUP (2021) defines several circular business models (CBM) which work together to create a circular ecosystem in the LIB industry (Figure 2.).

The proposal for a regulation pertaining to batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020 sets targets for recycled content for lithium, cobalt, nickel and lead (European Commission, 2020). In addition, this current surge in LFP presents a challenge for battery recycling because it is no longer economically viable in the absence of valuable metals such as cobalt and nickel (International Energy Agency, 2022). Currently, there are commercial-scale recyclers in Europe and in other countries, however, LIB recycling still has a long way to go. One of the main challenges in the implementation of recycling processes at an industrial scale is related to the complexity of the input matrix and its variability. First of all, the lack of a labelling system and the consequent impossibility to identify the type of chemistry is an obstacle to the development and implementation of appropriate recovery processes (Velázquez-Martínez, Valio, Santasalo-Aarnio, Reuter, & Serna-Guerrero, 2019). A battery labelling would, for example, enable different battery chemistries to be separated before processing, thus reducing the risk of

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cross-contamination (Avicenne, 2020) Furthermore, the design of LIBs is not optimized for easy disassembling: the cells are hermetically sealed and the use of adhesives, bonding methods and fixtures do not allow easy dismantling either by hand or (semi-)automatically (Thompson, et al., 2020; Harper, et al., 2020). Moreover, the design of LIBs varies significantly with different models and manufacturers, which increases the difficulty of automated disassembly. Standardization of cells, packs and modules might also be beneficial during the dismantling step, allowing automated methods of cell opening and materials separation. Most of the current commercial recycling processes make use of shredding or milling as a pre-treatment step, followed by separation of the different materials (plastic, metallic fractions, black mass etc.), for example, by froth flotation, electrostatic, magnetic or density separation techniques (Avicenne, 2020). This makes the separation of the components more difficult than if they were pre-sorted and considerably reduces the economic value of the material streams. Regarding the actual recovery step, most of the pyrometallurgical processes, which currently constitute the dominant recycling route - allow obtaining an alloy of cobalt, copper, iron, and nickel, but cannot recover lithium and manganese, which are typically lost in the slag of pyrometallurgical processes (Larouche, et al., 2020). Moreover, fractions such as the electrolyte and the anode (today, mostly made of graphite) are not yet recycled at an industrial scale. To increase the overall material recovery yield, some recycling companies adopted combined processes based on both pyrometallurgical and hydrometallurgical methods (Lv, et al., 2018).

Extensive research is being carried out to replace the commonly employed pyrometallurgical recycling methods with less detrimental approaches, such as hydrometallurgical or direct recycling methods (Yole, 2021). Pyrometallurgical methods, as traditional recycling technologies, involve high temperature operations (smelting or incineration) to extract valuable materials from waste. These methods can be energy-intensive generating emissions having potential environmental and health concerns. In hydrometallurgical methods, metals are recovered and dissolved from waste and scrap by using aqueous solutions (base or acid) with using lower temperatures and lower emissions compared to pyrometallurgical technologies. In direct recycling methods materials are used in their original form with optimized energy and resource requirements. However further efforts are needed to develop sustainable recovery technologies which are oriented to the valorisation of the entire waste fraction, paying attention not only to the recovery of the cathodic materials, but also to the anode, the separator, and the electrolyte.

Figure 2. Seven CBMs to be applied to the LIB industry (ARUP, 2021).

2.2 Fuel cells

Fuel cells are electrochemical devices in which hydrogen reacts with oxygen to form water and release protons thereby producing electricity without the need for combustion or the generation of CO_2 (Joint Research Centre, 2020). The hydrogen can be produced from a variety of sources including fossil fuels, biomass, or through the electrolysis of water. Fuel cells are expected to offer a potential clean energy source in the medium to long term.

2.2.1 Technology trends

Currently, the largest market share of fuel cells belongs to stationary power generation at around 67% followed by the transport industry at around 32% with a remaining share going to portable power generation. However, trends show that the automotive industry's share will continue to experience growth (Joint Research Centre, 2020). In 2020, the sales of passenger fuel cell vehicles reached 8,500, which is the highest compared to any previous years indicating the growing demand for fuel cell electric vehicles (The Business Research Company, 2021). It is forecasted that by 2030, fuel cell electric vehicles (FCEVs) could account for 1 in 22 passenger vehicles and 1 in 12 light commercial vehicles (LCVs) in the EU (Fuel Cells and Hydrogen Joint Undertaking, 2019).

Fuel cells and batteries are frequently described as competing technologies; however, the relative strengths and weaknesses of these technologies indicate that they should play complementary roles. In terms of volume and weight, hydrogen fuels cells have a considerably higher energy density than batteries. Hydrogen is therefore ideally suited for vehicles with heavy payloads and long ranges such as large cars, commercial vehicles, trucks and buses, while batteries are suitable for passenger vehicles (Fuel Cells and Hydrogen Joint Undertaking, 2019). The degree of these applications is likely to depend on how battery technology evolves and the rate at which cost reductions from scaling fuel-cell production is achieved. Experts believe that the growing popularity of battery vehicles may, in fact, promote the uptake of fuel cell-powered vehicles. The growing acceptance of electric mobility benefits both technologies as the continued scale-

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up reduces component costs, particularly electric traction motors and batteries, both as well needed in fuel cell cars (Heid, Linder, Orthofer, & Wilthaner, 2017).

Various fuel cells that are currently available on the market function under varying conditions based on the choice of fuel, electrolyte and operating temperature as shown in Table 1. The three major types include the Polymer Electrolyte Membrane (PEMFC), Alkaline (AFC), and Solid Oxide (SOFC) fuel cells. PEMFC being the dominant in the market 2019 but the future share is highly dependent on the technology advancements, market dynamics and policy support.

Table 1. Different types of fuel cells (LibreTexts).

	AFC	MCFC	PAFC	PEMFC	SOFC
Electrolyte	Potassium Hydroxide	Immobolized Liquid Molten Carbonate	Immobolized Liquid Phosphoric Acid	Ion Exchange Membrane	Ceramic
Operating Temperature	60°C-90°C	650°C	200°C	80°C	1000°C
Efficiency	45-60%	45-60%	35-40%	40-60%	50-65%
Electrical Power	Up to 20 kW	>1 MW	>50 kW	Up to 250 kW	>200 kW
Possible Applications	Submarines, Spaceships	Power Stations	Power Stations	Vehicles	Power Stations

PEMFCs have received the most interest in terms of research and development worldwide when compared to other cells. PEMFCs have a high energy density and can operate at relatively low temperatures ranging from −40 to 120 °C making them ideal for automotive applications (Wang, et al., 2021). On the other hand, the technology is less mature, costly, and experiences shorter lifetimes. Currently, PEMFC manufacturing capacity is less than 500 MW per year worldwide with two more projects in Europe set to raise this to more than 1 GW per year by 2023. A reduction in capital costs is foreseen as more experience is gained and manufacturing scales up. If this technology becomes dominant, the demand for platinum and iridium is set to increase. PEM catalysts currently utilize approximately 0.3 kg of platinum and 0.7 kg of iridium per 1 MW. The main challenge is the high prices as platinum costs account for more than half of catalyst production. Therefore, current research aims to reduce or completely replace these expensive metals as well as improve activity and durability (Fan, Tua, & Chan, 2021). Efforts have already resulted in the reduction of PGMs in PEMFCs by 80% since 2005. It is forecasted that the amount of platinum in the next generation of fuel cell vehicles will be around 3-7 grams which is close to the amount present in the catalytic converters of diesel vehicles (Joint Research Centre, 2020). Another alternative under development is the use of anion exchange membranes which can eliminate the need for PGMs altogether (International Energy Agency, 2021). This has the potential to drive the large-scale commercialization of fuel cell-powered vehicles (Joint Research Centre, 2020).

Alkaline fuel cell (AFC) is one of the oldest fuel cell technologies. Compared with other electrolysis technologies, the manufacturing capacity for alkaline electrolysers is much larger, with an estimated 2 GW per year available today. Manufacturers in the EU have pledged to expand and increase capacity to 6 GW per year. Alkaline electrolysers do not require precious metals as an input which partly contributes to their lower capital costs. Current designs need more than one tonne of nickel per MW (1 000 tonnes for a 1 GW electrolyser plant). In addition to nickel, 1 MW requires 100 kg of zirconium, 500 kg of aluminium and more than 10 tonnes of steel along with minor amounts of cobalt and copper catalysts (International Energy Agency, 2021).

Solid oxide fuell cells (SOFCs) are assembled completely from solid-state materials and are presently being assessed at a smaller scale compared to the other two technologies. The biggest benefit of SOFCs is their high operating efficiency of 50–60%. The waste heat can be recycled and utilized to generate additional electricity thus increasing efficiency by up to 80% (Walkowiak-Kulikowska, Wolska, & Koroniak, 2017). Although they also provide lower material costs in addition to high efficiencies, they are not expected to dominate the market. The use of SOFCs is principally limited to medium to large stationary power applications. 1 MW requires 150-200 kg of nickel, around 40 kg of zirconium, around 20 kg of lanthanum and less than 5 kg of yttrium. It might be possible to reduce each of these quantities by 50% through optimized design in the next decade (International Energy Agency, 2021).

2.2.2 Circular economy

It is expected that a considerable quantity of PEM fuel cells will reach their end-of-life by 2030. There is a high concentration of the various recyclable materials such as platinum, ruthenium and other metals of interest in the cells (Fraunhofer, 2020). Fuel cell-powered vehicles contain more platinum than combustion engine vehicles, that is, by a factor of >10; therefore their large-scale deployment can exacerbate the existing scarcity risks in the global platinum market. The recycling rates of platinum in passenger vehicles are relatively low when compared to other applications of platinum with the recycling quota for exhaust gas catalysts reaching a mere 50% to 60%. The automotive industry is the largest consumer of platinum in the EU therefore it is imperative

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to focus on the contribution of recycling for meeting future platinum demand (Wittstock, Pehlken, & Wark, 2016). However, no satisfactory industrial process targeted to recycle these fuel cells has been implemented yet. Hydrometallurgical processes have shown great potential especially since some of these processes can recover the entire membrane which can be reused while pyrometallurgy only recovers individual materials and not components (Wittstock, Pehlken, & Wark, 2016).

2.3 Traction motors

Traction motors, electric motors used in vehicles (trains, trams, electric vehicles and in some industrial machines. Traction motors convert the electrical energy into mechanical energy. Traction motors have a crucial role in sustainable electric mobility transformation, providing high energy efficiency with reduced environmental impacts.

2.4 Lightweight construction

Reducing weight is critical for all vehicles as it directly correlates with the energy spent per driven kilometre. Lightweight construction in electric vehicles improves energy efficiency and driving range as well as, potentially, reduces the environmental impact and costs of the vehicles.

2.4.1 Technology trends

The lightweight materials market is mainly driven by applications in the automotive industry. The industry accounts for around 90% of the total lightweight materials market. Metals make up a considerable percentage of the overall weight of the vehicle and are anticipated to remain the dominant material in the market. Europe is the largest market for automotive lightweight materials (Lightweight Alliance, 2019). Lightweighting or weight reduction is achieved through two main approaches. The first involves optimal material selection where conventional materials with high specific weight are substituted with those with lower densities while still maintaining other desired properties. The second aspect involves optimizing the design of components, assemblies as well as the complete vehicle (Lightweight Alliance, 2019).

As the automotive industry shifts from ICEs to EVs, lightweight design and construction will continue to be of importance. Electrification adds to the challenge of lightweighting due to the introduction of electrical components. Fundamentally, the architectures of battery and fuel cell electric vehicles and ICEs are different In BEVs, for example, the large battery pack exists instead of an engine bay, today making EVs on average 125% heavier than ICE equivalents (Halvorson, 2020), (Toyota, 2018). Vehicle rolling resistance, which consists of rolling, climbing and acceleration, is partly proportional to the vehicle mass. Therefore, reducing the mass of a vehicle results in decreased resistance (Fraunhofer ISI, 2021). A reduction in vehicle mass has a positive impact on the driving range of battery-powered vehicles, yielding around 14% improvement in electric range for a 10% reduction in weight (Luo, 2021). Since a lighter vehicle requires less energy to drive when compared to a heavier one over the same distance, manufacturers can reduce the size of batteries which in turn would improve the affordability of EVs (Held, 2019).

In ICE vehicles, the body structure, body panels and many other parts are made from different steels, accounting for about 70% of the average car weight. The desirability of steel is due to its low cost, manufacturability, recyclability, and availability of specialized alloys. Steels used in the automotive industry are classified as conventional mild steel, high-strength low alloy (HSLA) steel, and advanced high-strength steel (AHSS) (Kuziak, Kawalla, & Waengler, 2008). Research efforts are ongoing to develop new grades of AHSS; however, there is a limit up to which weight reduction can be realized just by utilizing this new group of steels. Therefore, research is also focused on optimizing material selection by substituting steel with other materials (Pervaiz, Panthapulakkal, Sain, & Tjong, 2016). These alternatives typically include aluminium, magnesium, beryllium, titanium, titanium aluminides, structural ceramics, and composites with polymer, metal, and ceramic matrices. At present, only aluminium and magnesium alloys as well as, to a lower extend, fibre reinforced plastics are of commercial interest to carmakers (Czerwinski, 2021). The amount of aluminium used per vehicle increased from 50 kg in 1990 to 151 kg in 2015 and it is forecasted that this value would rise to 196 kg by 2025 (European Aluminium, 2015). However, the application of aluminium is still limited predominantly to the engine, transmission, wheels, heat exchangers, chassis, and suspension. Currently, the high cost associated with aluminium is perceived to be the main obstacle to its large-scale implementation. Magnesium is 75% lighter than steel, 50% lighter than titanium, and 33% lighter than aluminium. Therefore, magnesium alloys are appealing structural materials for vehicles. There are challenges in the industrial-scale implementation of magnesium such as its manufacturing and processing, in-service performance, and cost. Carbon-fibre composites have around 20% of the weight of steel but have the same or even better stiffness and strength. However, the cost of carbon-fibre

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composites can significantly more expensive than steel which hinders their extensive application in the automotive industry (Czerwinski, 2021).

Table 2. Impact of material substitution (Taub, et al., 2019)

Lightweight material	Material replaced	Mass reduction (%)
Magnesium	Steel, cast iron	60–75
Carbon fiber composites	Steel	50–60
Aluminum metal matrix composites	Steel, cast iron	40–60
Aluminum	Steel, cast iron	40–60
Titanium	Steel	40–55
Glass fiber composites	Steel	25–35
Advanced high strength steel	Mild steel	15–25

2.4.2 Circular economy

The ease of separation and dismantling plays a huge role in the material selection process in the automotive industry. Nowadays, the industry is in one accord that utilizing different materials with different properties results in improved product performance. Multi-material design does not only refer to the overall vehicle but individual components as well (Czerwinski, 2021). However, a multi-material design approach also creates challenges at the end-of-life of the vehicle when it comes to dismantling and material-specific recycling (Lightweight Alliance, 2019). Vehicle structures with fewer materials will indeed offer easier dismantling and recycling opportunities but this approach offers limitations in terms of reducing the overall weight.

As electric drivetrains will be dominant in the future, using weight reduction to reduce emissions might be less important due to the corresponding increase in renewable energy sources as well as the ability to regenerate energy from braking. The general agreement is that lighter vehicles will be necessary to increase the range per charge of the vehicle (Lightweight Alliance, 2019). Different metals have different potentials to reduce vehicle weight and these materials also have different carbon footprints during their life cycles which is an important aspect to consider during materials selection. Some materials require large energy inputs during the production and manufacturing stages which affects their potential energy savings during the use phase of the vehicle (Czerwinski, 2021).

When coupled with innovative production and manufacturing, steel is considered to be the most environmentally friendly structural material by the community. A key factor is that the recycling process is deemed to be much easier than that of aluminium. Aluminium recycling requires different grades to be separated before melting thus making it a much more complex and expensive process. Different grades of steel can simply be melted and mixed to form steel with new compositions. The recycling of steel represents enormous energy savings and a reduction in CO_2 emissions. The production of 1 tonne of steel in the electric arc furnace consumes only 9-12.5 GJ per tonne of crude steel while primary production through the blast furnace consumes 28-31 GJ per tonne of crude steel (Yellishetty, Mudd, Ranjith, & Tharumarajah, 2011). Indeed, aluminium is a lower weight alternative to steel and it is an ideal material for the circular economy as it can be recycled multiple times without the loss of properties. However, an aluminium-intensive vehicle might provide energy savings during its service but it will require 30% more energy over its entire life when compared to a vehicle made mostly from AHSS. This is due to the high energy input requirements of primary aluminium production (World Auto Steel, 2023). Emissions arising from primary magnesium production is dependent on geographic location and the kind of production process used which makes it challenging to precisely determine the scale of emissions. Using magnesium in transport applications decreases greenhouse gas emissions over the entire life cycle of the vehicle. Even though the component production stage of magnesium results in higher emissions on a per kg basis when compared to that of steel or aluminium, these higher emissions are offset during the service stage of the vehicle (Czerwinski, 2021)

2.5 Electronics and ICT

Information and communication technologies (ICT) and electronics have an essential role in developing the transition towards smart and sustainable e-mobility. ICT enable the effective management of electric vehicle systems, charging infrastructure, and the overall user experience while contributing to the sustainability and growth of electric transportation.

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EVs can be connected extensively with the surroundings, including the power grid, by using advanced ICT. These technologies enable the safe charging processes, integration into traffic systems, optimizing their range and traffic flow. The communication can provide information to help the optimizing the charging of the vehicle, navigating and improving also the safety of the driving. The connectivity allows for real-time data sharing, remote diagnostics, enhancing the functionality and efficiency of electric vehicles. Additionally, by advanced ICT and electronics battery performance van be maintained to prolong battery lifetime.

ICT systems provide entertainment, navigation, and communication features within the vehicle, enhancing the driving experience for EV users. With internet and smartphone connections the available entertainment options are versatile, since there is possibility to listen podcasts, e-books or any other preferred content. From sustainability point of view, ICT provides valuable data insights into usage patterns, energy consumption and maintenance needs enabling the analysis and optimization of the environmental impact caused by driving. Meanwhile ICT can add the weight, production emissions and the energy consumption per kilometre.

2.2.1 Technology trends

The automotive industry is at a pivotal point of innovation and redefining vehicle usage. To be able to meet consumer demand and keep up with increased safety and functionality, automakers need to produce vehicles with excellent sensing capabilities (Padilla, 2021). Automation has had several setbacks over the years, but experts believe that the introduction of so-called automation level 4 can already be anticipated within the next few years, which would correspond to high automation. Whether automation level 5 (full automation) can be achieved is still debated amongst experts (Fraunhofer ISI, 2021). Nevertheless, the vision for semi or fully autonomously driving vehicles on European roads can only be realised with sufficient access to the necessary electronics and ICT.

Semiconductors play a crucial role in modern vehicles for a range of functions including safety, electrification, communication and connectivity. Semiconductors are essential for sensing and processing data to provide consistent, accurate and timely control systems for the vehicle. The sensing capabilities are provided by various sensors with complementary skills such as cameras, LiDAR and ultrasonic sensors (Kumar, 2021). Although semiconductors have one of the most costly and complex supply chains in the world, the industry's capacity has expanded modestly over the years by around 4 % annually. In parallel, the utilization of semiconductors has been consistently high over the last ten years as it even reached close to 90% in 2020. Therefore, even if the industry's production capacity has risen by almost 180% since 2000, its total capacity is under enormous pressure at the high rate at which semiconductors are used (Burkacky, Lingemann, & Pototzky, 2021). The automotive industry was one of the worst-hit by the shortage of semiconductors in 2021-2022. This is primarily because semiconductor manufacturers started to give priority to the manufacturers of consumer electronics like smartphones (Khan, Mann, & Peterson, 2021). The semiconductor mix in cars is experiencing a significant change as new electric and autonomous vehicles have higher computational needs and demand more powerful computing tools. This transition means the share of leading-edge and advanced semiconductor technologies in vehicles is increasing rapidly (Alexander, Meissner, & Kirschstein, 2021). The most critical materials used for semiconductors are silicon, germanium, and gallium arsenide. Germanium was one of the earliest used materials in semiconductors while silicon was the most important material for most of the late twentieth and early twenty-first centuries. Research for new materials such as gallium nitride, graphene and pyrite is ongoing as the demand for smaller and faster integrated circuits is increasing (IRDS, 2022). With the planned introduction of the Chips Act in Europe, a boost in research, development and manufacturing of microprocessors is anticipated (Zubașcu, 2022). The European Union has committed to at least 20% of world production of sustainable semiconductors by 2030 (European Commission, 2022).

2.6 Tyres

The production of tyres constitutes 72% of natural rubber consumption in the EU. Although synthetic rubber which is predominantly derived from fossil fuels is cheaper, natural rubber has superior technical properties, which is why tyres are made with a mix of both (European Commission, 2020). Replacing natural rubber with synthetic rubber is limited hence substitution opportunities in the tyre industry have not varied significantly over the past two decades (Cinaralp, 2018). Global natural rubber consumption is set to increase by 33% while EU consumption is expected to experience an increase of 14.5 % by 2030 (IRSG, 2021). Natural rubber comes from the rubber tree, Hevea brasiliensis, which is predominantly grown in South Asia. The EU's dependence on a single crop that can only grow in specific climatic regions is worrying

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

and experts predict that the increased consumption of natural rubber in Chinese and Asia-Pacific markets, in addition to the crop's vulnerability to fungal leaf disease and climate change will lead to a deficit in the supply. Furthermore, the majority of tyres end up in landfills at their end of life because the rubber mixes make it challenging to recycle them therefore natural rubber supply from recycled sources is not foreseen (McGovan, 2021). There is progress in the development alternative rubber tree species that can be grown in the temperate climate of Europe so that the continued demand for natural rubber does not depend on the clearing of rainforests (as in Hevea plantations) and CO2 emissions from transportation can be abated. However, from the current outlook, it does not seem that alternative sources will have a mass scale impact by 2030 especially because the present production costs of alternative natural rubber do not match the market price (McGovan, 2021).

4. Skills gaps

Batteries are considered as the dominant technologies to ensure the decarbonization of transportation. Globally, the demand for batteries is projected to surge to 2-3 terawatt-hours (TWh) by 2030, with the European Union alone requiring 400-1000 gigawatt-hours (GWh) of batteries by the same year. In order to meet the demand there is need for large scale production facilities including skilled experts and substantial know-how in the industry.

Currently, there exist skill gaps that must be addressed to expedite the adoption and implementation of sustainable mobility solutions (Fraunhofer, 2021). There is an imminent requirement for qualified experts across various domains of the entire value chain, encompassing research and development, battery and magnetic motors manufacturing, integration of applications, and the establishment of a fully circular battery economy. According to estimates from Fraunhofer ISE and EIT RawMaterials (Fraunhofer, 2021), the number of jobs needed for materials, cells to pack production, and accounting for scale effects with larger battery production factories is expected to surge from 10-20 thousand to several hundred thousand in the next decade. The greatest demand lies in the upstream value chain, estimated to necessitate 4-6 times more experts compared to battery production itself (Figure 3). Additionally, there is the downstream value chain, not reflected in these estimates. The demand for skilled experts in e-motors is also projected to be substantial to meet future requirements.

The total number of jobs required for e-motor, component, and material production in the EU is estimated to be around 16,000 by 2040 (Figure 4), with global estimates for total and direct jobs reaching 120,000 (Figure 4) (Fraunhofer et al.). The expertise required can be categorized into three distinct areas: raw materials extraction, processing and component production, and applications. Higher-level education, particularly at the PhD level, plays a critical role in the research and development of e-mobility. On the production side, vocational expertise becomes the core, while end products and applications necessitate skills in sales and marketing. Non-academic and non-technical skills will also be essential.

According to a workshop on the future needs of experts in the battery sector by EIT RawMaterials and Fraunhofer, focus areas can be divided into four categories:

- re-/ upskilling existing workforce (especially the reskilling of staff in automotive industries),
- mobilising the future workforce (e.g., internships, exchange between industry and academia),
- education on cross-cutting skills (e.g., digitalisation, cross-sectoral/ -disciplinary/ -value chain knowledge), and
- creating knowledge in large-scale production.

Addressing the shortage of expertise involves re/upskilling the existing workforce through industry-specific training programs, online courses, or seminars. This approach is crucial for both vocational and management levels to foster the development of necessary know-how. Making battery production an attractive field for young individuals is imperative to ensure a higher number of professionals in the industry. Additionally, transferring experts from different industries and cultivating individuals with crosscutting understanding and skills are essential strategies. The workforce must be trained for large-scale production, with an increased demand for skilled process engineers and management professionals possessing both micro and macro level understanding.

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EV design and maintenance, electric drivetrains, charging infra and software development play a critical role in sustainable mobility development. The knowhow of building a robust accessible charging infrastructure requires skilled professionals in electrical engineering, urban planning, construction and management for efficient design, deployment and maintenance of charging stations.

Sustainable mobility can only be fully realized when EVs are charged using renewable energy sources. Therefore, professionals who can integrate renewable energy systems with EV charging infrastructure and optimize energy management solutions are essentials. Additionally, the know-how of recycling and second-life applications is important. Specialists in this area can develop efficient recycling methods and explore ways to repurpose used EV batteries for energy storage applications as well as find new circular methods of using the raw materials or components.

Finally, supportive policies and regulations are required in sustainable transportation policy development and implementation. Public awareness and education have an essential role in the ecosystem, which is why the collaboration between academia, industry and government has to be transparent and supportive. Even though, there are available skilled professionals from different levels of expertise, the main challenge is to train the experts to understand both scientific and economic fundamentals in order to facilitate change which is both financially feasible and environmentally sustainable.

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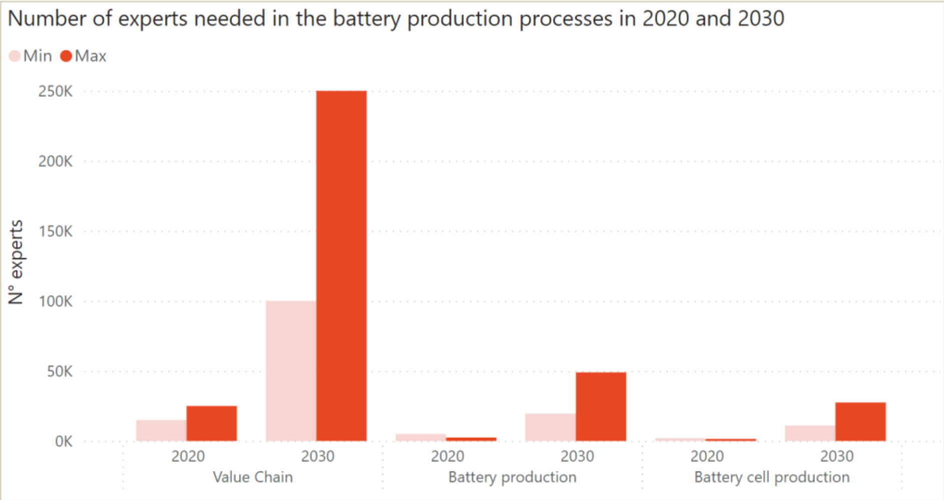
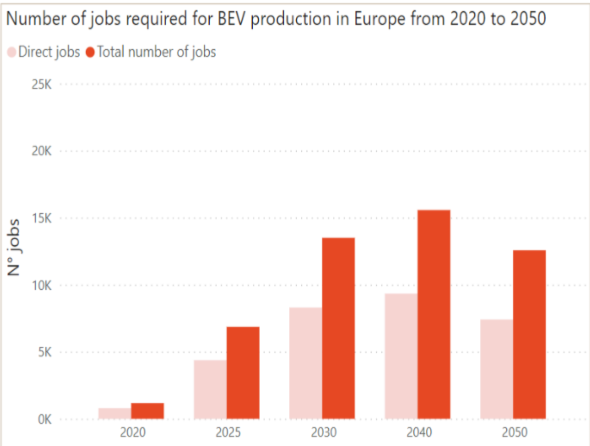


Figure 3. Number of experts needed in the battery production process between 2020-2030.



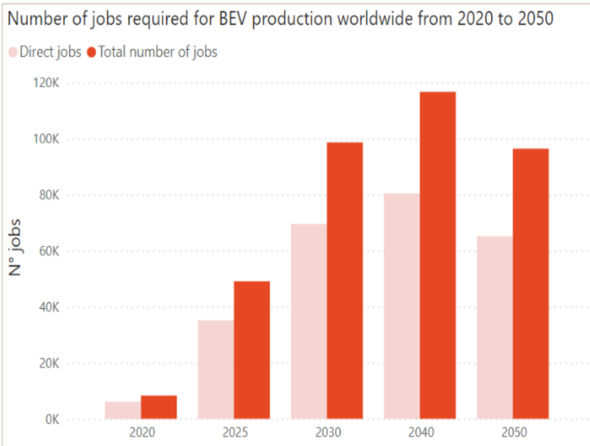


Figure 4. Number of jobs for BEV production in EU and worldwide.

5. Sustainable mobility 2030

The number of electric vehicles circulating in Europe is increasing over years (electric car registrations for 2020 were close to 1,325,000 units). To reduce greenhouse gas emissions, on February 25, 2020, the European Parliament approved new regulations on CO_2 emissions from vehicles, reduced to 95 g/km. These regulations, in force from 2021 based on 2020 sales, require many manufacturers to register several tens of thousands of electric and plug-in hybrid vehicles to avoid significant economic consequences (ICESP, 2020).

To achieve the targets, set for sustainable mobility, active collaboration between stakeholders, manufacturers, government bodies, research institutes and consumers is required. A comprehensive approach is essential to understand how technological components can be seamlessly integrated for the benefit of the entire system. The transition to sustainable mobility in Europe should be anchored in:

- The optimization the use of resources and utilizing circular economy solutions during the production phase to reduce environmental impacts, and;
- Making the end-of-life management of vehicles more efficient, i.e. reuse, recycle etc.
- Significantly increase the sources of renewable energy production (especially in self-consumption).
- Decrease the number of private vehicles.

For a process to be deemed sustainable from both economic and environmental perspectives, the technologies developed must be applicable throughout the entire value chain and designed in accordance with the principles of the circular economy. Adopting a "Life Cycle Thinking" approach is paramount, encompassing the entire lifespan of the vehicle and its components. Life Cycle Assessment (LCA), a methodology outlined in ISO 14040 (Egede, Dettmer, Herrman, & Kara, 2015), serves as a valuable tool for quantifying direct and indirect environmental impacts.

While LCA proves effective in addressing environmental impacts, analysing electric vehicles (EVs) poses challenges due to the scarcity of primary data covering the entire EV lifecycle and discrepancies in methodologies (Koroma, et al., 2022). A pressing need exists for a harmonized approach to enhance methodological transparency and ensure the full comparability of greenhouse gas emissions caused by e-mobility.

To truly achieve circularity in mobility, all phases of the vehicle's entire life cycle must be considered, encompassing the extraction of raw materials, production, the electricity mix used for charging, and the use and end-of-life/recycling of materials (see Figure 5). This holistic perspective ensures a comprehensive and sustainable approach to mobility practices.

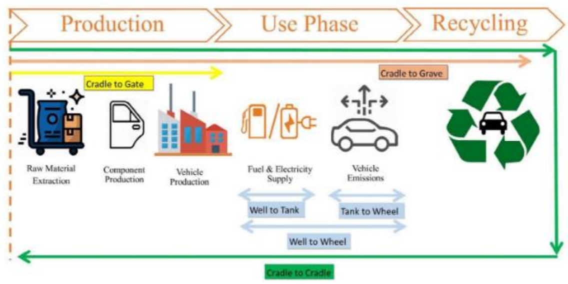


Figure 5. Different types of LCA for EV (Verma, Dwivedi, & Verma, 2022).

The role of extraction and mining plays a pivotal part in the life cycle analysis of e-mobility, and it is imperative to incorporate geologists into Life Cycle Assessment (LCA) processes for a comprehensive understanding of the entire electric mobility life cycle. Connecting geologists to the LCA framework is essential for a holistic analysis.

The materials utilized in batteries are sourced from diverse ore deposits, each with distinct environmental impacts. Taking lithium as an example, it can be extracted from hard-rock deposits or produced from brine resources, each involving unique production processes to generate lithium for batteries. Ensuring a stable supply for the high demand of elements used in batteries necessitates the establishment of new mines and extraction facilities. It is crucial to support projects that exhibit lower environmental impacts in the development of these facilities (Pell, et al., 2021). This approach aligns with the broader goal of sustainable resource utilization within the realm of electric mobility.

The production phase of electric vehicle (EV) batteries significantly contributes to the total greenhouse gas (GHG) emissions of EVs, accounting for 50% - 75% of the life cycle carbon footprint (Figure 6). Presently, GHG emissions from EV production are estimated to be approximately 50% higher than those from Internal Combustion Engine Vehicles (ICEVs), but this figure is anticipated to decrease to 30% over the next three decades. The most substantial reduction in GHG emissions from EVs is achievable during their use phase, contingent upon the source of electricity. EVs are projected to produce 30% lower emissions during the use phase compared to traditional ICEVs, with the potential for a 60% reduction through electricity decarbonization (Hill, et al., 2023).

The use of lightweight materials in battery development plays a crucial role in the overall Life Cycle Assessment (LCA) calculations of EVs. Utilizing lighter materials enhances energy efficiency, reduces battery size, and extends driving range. Recycling batteries and reusing raw materials are vital practices to minimize the need for extensive virgin resource extraction. The environmental performance of recycling technologies versus primary sources must be thoroughly understood, and second-life applications should be promoted to prevent harmful materials from ending up in landfills.

According to the European Raw Materials Alliance, 95% of electric vehicles utilize rare earth permanent magnet motors for their highest energy efficiency and driving range. The carbon footprint of magnetic motors is highly dependent on ore sourcing and recycling methods. For instance, 1 kg of Nd-Fe-B magnets can produce 20 to 90 kg of CO2 equivalent with primary raw material sourcing and even below 20 kg when secondary sources are used (European Raw Material Alliance; EIT RawMaterials, 2021). While the footprint of magnets has a minor environmental impact compared to lithium-ion batteries, the use of permanent magnet motors enables a high reduction of GHG emissions in EVs, as the battery size can be decreased while maintaining performance.

The LCA calculation of permanent magnet motors is highly dependent on the scope definition, including the determination of the functional unit (i.e., energy input, power generation, and operation hours). Various design options are available, each with pros and cons related to efficiency, motor size, cost, and long-term supply (Nordelöf, et al., 2019). Ensuring accurate calculations and facilitating correct comparisons of different units require well-defined and clarified processes.

In conclusion, key design targets to reduce the environmental impact of electric vehicle traction motors include high energy efficiency, slender housing, compact end-windings, production scrap reduction, and easy disassembly. Future research should focus on increasing access to primary data for production and material processing, as well as clarifying the environmental impacts of mining and extracting raw materials to enable more comprehensive environmental impact analyses.

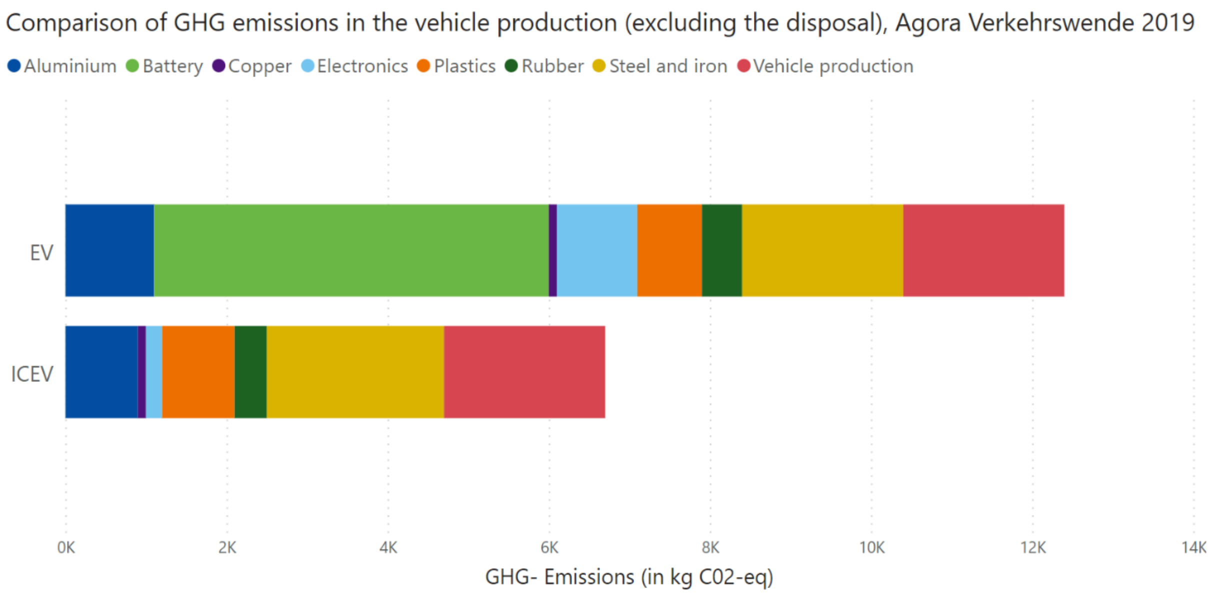


Figure 6. Comparison of GHG emissions in the vehicle production (excluding the disposal), (Agora Verkehrswende, 2019).

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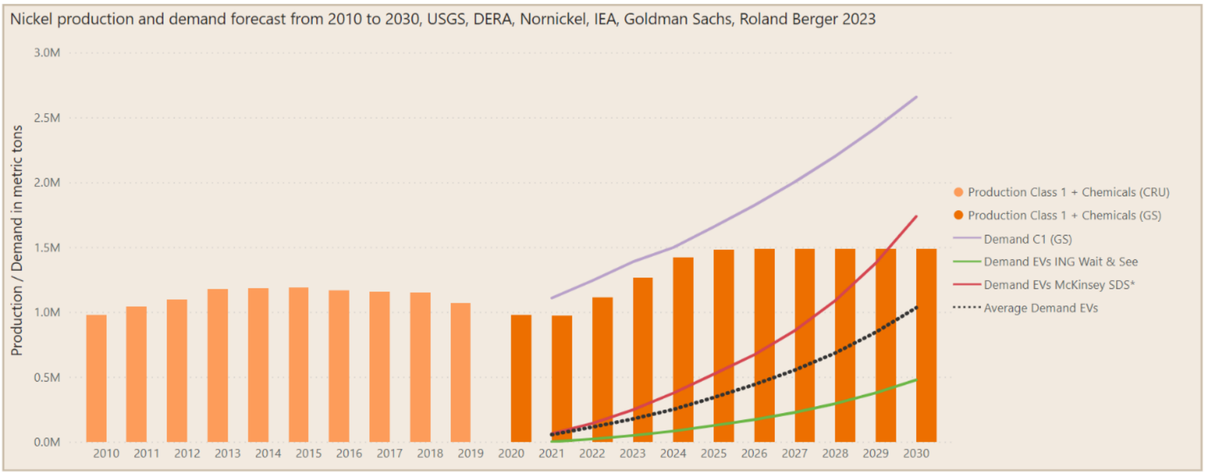
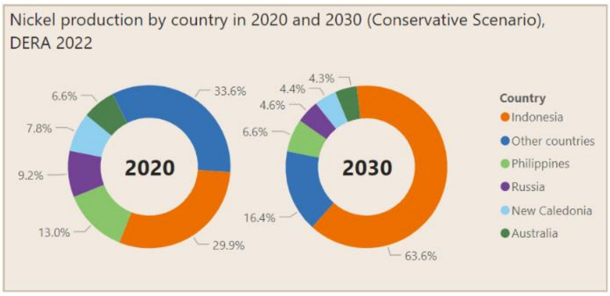
Appendix

Nickel



Supply and Demand: Whilst overall Ni production is forecast to be in balance with Ni demand, first and foremost in the steel industry, supply of Class-I-Ni used in high purity chemicals and battery cathodes may fall short to meet demand.



Price and Competition: The Ni price has shown significant fluctuations over the last decade. On 8 Mar 2023, LME closed trading after prices doubled to more than $100,000 per ton. Global Ni production is said to concentrate more in Indonesia.

Overall risk score (bubble color) and production (bubble size) for top nickel producing countries in 2022, S&P Global, USGS 2023

Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
Brazil	2.20	2.00	3.10	2.30	1.90	2.90	2.40
Canada	1.50	1.10	1.50	1.30	1.20	1.40	1.30
China	1.40	2.10	2.40	2.00	1.70	2.00	1.90
Indonesia	1.90	2.30	2.70	1.90	2.30	1.80	2.20
Philippines	1.60	2.40	2.90	2.00	2.70	2.00	2.30
Russia	5.60	4.90	4.00	2.90	2.50	4.00	4.00
USA	0.90	1.10	1.50	1.30	2.10	1.30	1.40

Production risks: The production of nickel is subject to various risks including geopolitical instability, environmental concerns, operational challenges, and market volatility, which can impact supply, pricing, and the overall viability of nickel production.

Market Demand

Nickel is set to play a key role in the implementation of new megatrends such as the clean energy and mobility transition or the decarbonization of society. The global ramp-up of electric mobility is expected to represent the largest single growth sector for nickel demand within this decade.

The global nickel market can be roughly divided into three product areas: high-purity nickel metal (>99 % nickel, Class I nickel), nickel chemicals (particularly nickel sulphate), and Class II nickel (<99 % nickel), such as ferronickel and nickel pig iron (NPI). (ELEMENTARIUM, 2023)

In 2020, Class II nickel accounted for around 65 % of the global refined supply of refined nickel, nickel metal for around 30 %, and nickel chemicals for around 5 % (Szurlies, 2021; Szurlies M. , 2022). Nickel ores and concentrates, intermediates and refined products are traded globally in different product specifications and qualities. Globally, stainless steel is estimated to constitute about 66 % of the first-use of primary refined nickel. The remainder was used for other applications, such as non-ferrous alloys, plating, steel-alloys, batteries, foundries, and other minor applications (e.g., magnets and catalysts) (ELEMENTARIUM, 2023). More nickel will be needed in the future, not only for the goals of the mobility transition but also for the overall energy transition.

Sourcing

Nickel is mined from both sulphide and laterite ores. Sulphide ores are further processed by pyro- and hydrometallurgical methdos, to produce nickel metal or nickel chemicals (mainly nickel sulphate). Laterite ores are treated mainly pyrometallurgically to produce nickel pig iron (NPI) and ferronickel (Mistry, Gediga, & Boonzaier, 2016). In the coming years, hydrometallurgical processing of laterites to produce nickel metal and chemicals is forecasted to increasingly gain importance.

Globally, more than 2,000 projects are currently being explored with nickel as either the main product or by-product. Nearly 30 of these projects are currently in operation, in commissioning or in advanced exploration. Approximately 2.4 Mt of nickel were extracted from both underground and open-pit mines in 26 countries in 2020 (BGR, 2022) (INSG, 2022). The main nickel producing regions were Southeast Asia and Oceania, together accounting for more than 66 % of global supply. The single largest producing country was Indonesia.

Future additional mine supply until 2030 is estimated to be up to 2.8 Mt (conservative scenario) and 3.1 Mt (optimistic scenario), respectively. The majority of new mine production is expected to come from Indonesia and Australia. The additional supply from Indonesia will contribute to an increasing country concentration for the global nickel mine production. Most new nickel projects have a clear focus on the battery sector. In the next few years, the nickel market is expected to be in oversupply. Due to the large number of nickel specifications, supply shortages are possible for individual nickel qualities, particularly Class I products and nickel sulphate.

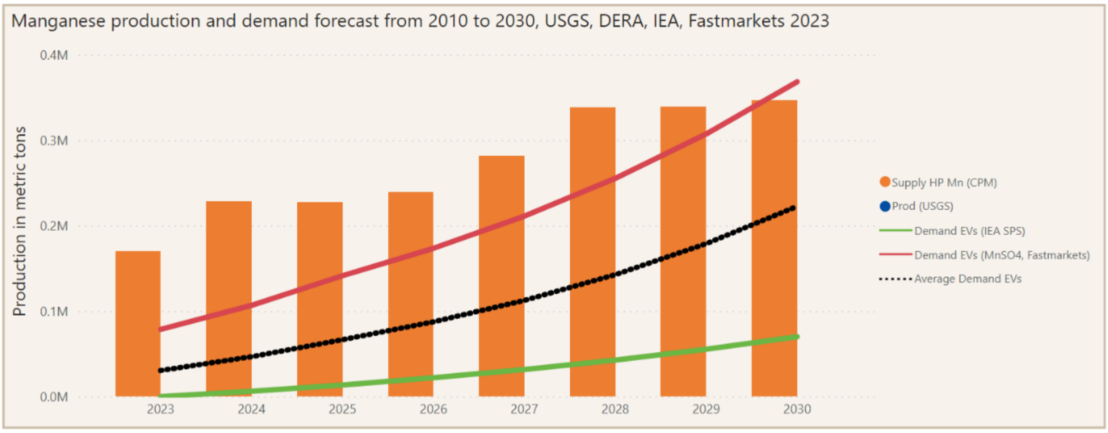
Currently, about one-third of global nickel supply is derived from secondary sources. This supply from recycling comes from a wide range of sources, most of it (mainly stainless-steel waste and scrap) is used directly in the production of new stainless steel, with only a minor share used to produce refined nickel (Szurlies, 2021).

Sustainability

Due to their genesis, laterite deposits are associated with tropical and subtropical climate zones; this is the case for the major deposits found in Indonesia. Laterite ores are extracted in shallow open-cast mines. The biggest environmental issue for mining is the large surface area required for its extraction and the related deforestation, which particularly has an impact on biodiversity.

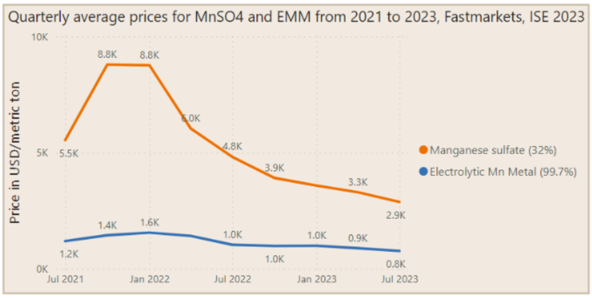
The GHG intensity of the production of nickel metal (class I) from sulphide ores is significantly higher than those of pyrometallurgically producing Class-II-nickel (ferronickel and nickel pig iron) from nickel laterite ores, currently accounting for almost two thirds of the overall refined nickel production. In order to produce nickel intermediates for class I and nickel sulphate production, the high-pressure acid leaching (HPAL) of laterite ores results in large amounts of fine sludges that have to be neutralized. These processing tailings still have high moisture contents and are frequently stored in tailing ponds. However, it is now good practice to dispose of the dewatered tailings utilizing the dry stacking method, e.g., in abandoned mining areas. The submarine disposal of leaching residues into the sea, as practiced, e.g., in an HPAL project in Papua New Guinea, is highly controversial because of the not yet fully understood environmental impacts on sea life and fishery.

Manganese

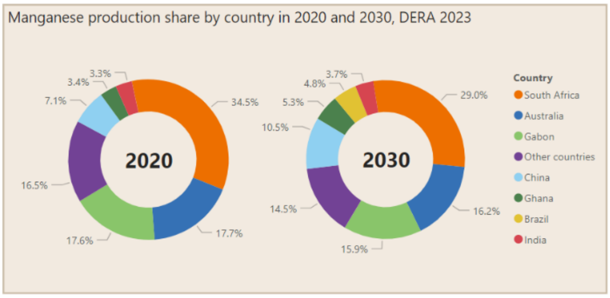


Manganese production and demand forecast from 2010 to 2030, USGS, DERA, IEA, Fastmarkets 2023

Supply and Demand: Electrolytic manganese is expected to play an important role in EV batteries, highlighting the importance of securing a stable supply of this critical metal. Can fall shortage in the future depending on the EV battery technology development.



Quarterly average prices for MnSO4 and EMM from 2021 to 2023, Fastmarkets, ISE 2023



Manganese production share by country in 2020 and 2030, DERA 2023

Price and Competition: The price of electrolytic manganese has remained constant, while the price of manganese sulfate has decreased from the level of 2022. The production will be dominated by South Africa, Gabon and Australia.

Overall risk score (bubble color) and production (bubble size) for top manganese producing countries in 2022, S&P Global, USGS 2023

Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Ukraine	5.10	3.80	3.00	3.10	3.20	2.60	3.50
Myanmar	4.90	3.00	4.40	3.50	3.90	1.90	3.60
Côte d'Ivoire	3.20	2.00	2.50	1.60	2.10	1.90	2.20
Ghana	3.20	2.50	2.70	2.30	1.90	3.30	2.70
Kazakhstan	2.70	2.40	2.90	1.90	1.50	2.20	2.30
South Africa	2.40	2.00	3.70	2.80	2.30	2.60	2.60
Gabon	2.30	2.90	3.50	2.00	1.50	3.20	2.60
Brazil	2.20	2.00	3.10	2.30	1.90	2.90	2.40
Georgia	2.00	2.00	2.40	2.00	2.10	0.90	1.90
Vietnam	1.90	1.90	2.70	1.30	1.40	2.00	1.90
India	1.70	2.10	2.80	2.10	2.60	2.10	2.20
Mexico	1.70	3.30	3.30	2.70	1.90	2.80	2.60
China	1.50	2.20	2.40	2.00	1.70	2.00	2.00
Malaysia	1.40	1.20	1.40	1.40	1.20	1.60	1.30
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
USA	0.90	1.10	1.50	1.50	2.10	1.30	1.40

Production risks: China is dominating the high purity manganese sulfate processing capacity and may cause production risk.

Market Demand

Manganese, being one of the most used metals together with iron, copper and aluminum, is used for several different industries, such as steel manufacturing, chemical industry, metallurgical applications and water treatment. The main market for manganese is the steel making industry, where manganese is added to increase the strength of the steel through sulfur-fixing, deoxidizing and alloying properties. Manganese is heavily linked into the construction industry China being the main importer together with India (Rethinkresearch, 2023).

In recent years, manganese is gaining much attraction in lithium-ion battery manufacturing and is used as a battery cell cathode. The highly refined form of manganese metal has the potential to enhance the performance of lithium-iron-phosphate (LFP) and nickel-manganese-cobalt (NMC) batteries used in electric vehicles, allowing manufacturers to reduce cobalt and nickel content for cost savings. Also, for its potential to offer energy density, power output, thermal stability and faster charging time, manganese is favored in cathode chemistries in the lithium-ion batteries. It is estimated that manganese-rich cathodes will start being produced between 2024-2025. According to Euromanganese, high purity manganese are essential raw materials to ensure the fast-growing electric vehicle and Li-ion battery industries. CPM Group expects the demand for high purity manganese to increase 13 times between 2021 to 2031 and 50 times until 2050. The lack of high purity manganese refining capacity may cause supply challenges. Additionally 91% of high purity manganese products suitable for battery industry is coming from China which is importing the manganese ore from South Africa, Australia, Gabon, and Ghana (EuroManganese, 2023).

South Africa is the largest producer and the holder of the largest reserves or manganese. They produced 7.1 million tons of manganese in 2021 having 640 million tons of manganese in reserve. Second and third largest production are located in Gabon and Australia, with 3.6 Mt and 3.3 Mt of production in 2021 respectively (Rethinkresearch, 2023). Primary manganese supply in Europe comes from Bulgaria, Hungary and Romania, but accounts less than 1% of total global supply (SCRREEN2, 2023).

The price of electrolytic manganese is vulnerable to market and policy-driven shocks in China. Manganese market is highly dominated by China. A limited consortium of developers is actively engaged in initiating high-purity manganese projects within the United States having support from incentives outlined in the Inflation Reduction Act. However, price weakness and uncertainties related to battery chemistry and electric vehicle demand could slow down investment (S&P Global). In 2016 there has been sharp increase in manganese ore prices. This was caused by China, which accumulated large volumes of ore causing supply squeeze in the market. Second price increase was seen in 2017 caused by soaring silico-manganese prices due to production cuts. 2019 and 2020 the price has decreased being below the average (SCRREEN2, 2023).

Sourcing

Manganese has similar chemical and physical properties compared to iron and is a brittle and hard metal. Manganese cannot be found as an element in nature but occurs in many minerals such as manganite, purpurite, rhodonite, rhodochrosite, pyrolusite and also found from mineraloids such as psilomelane and wad. Manganese is often found also within iron deposits such as hematite. (ELEMENTARIUM, 2023)

Manganese is extracted usually from open pits and after extraction it is transferred to a processing plant. There are also underground manganese mines in South Africa, India and Mexico. In underground mining operations, block-caving, room-and-pillar, modified cut-and-fill or longwall mining methods are used.

Ore is crushed, screened and split into particle sizes between 6 to 75 mm. After crushing and screening, ore is concentrated by various techniques and manganese carbonate ores may be calcined. The specifications of the concentrates depend on the target market and the original nature of the ore. Different grades of ores can be mixed together and after that crushed and screened into fines and lump ore. Silicon waste is removed through flotation and the contaminants washed out. China is dominating the high purity manganese processing capacity possessing a threat towards safe supply.

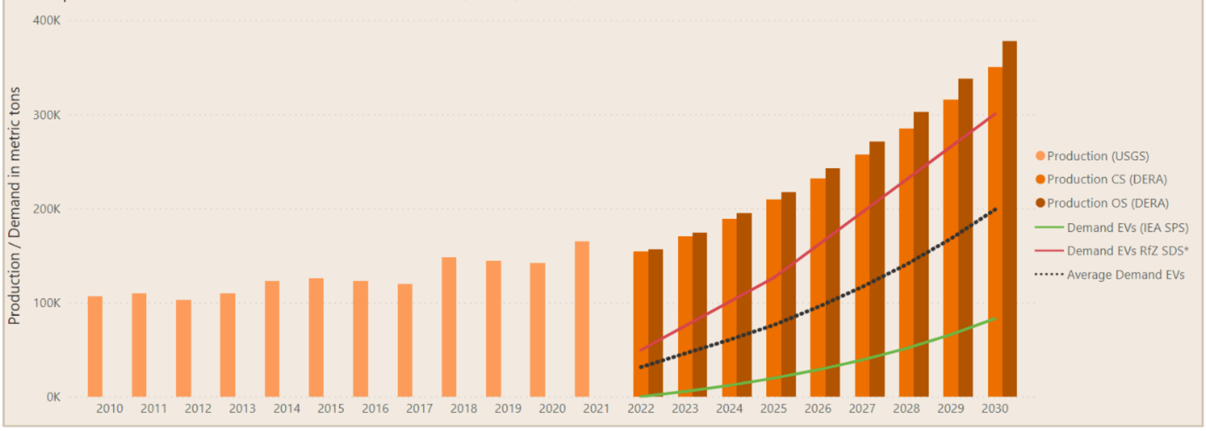
Sustainability

Production of electrolytic manganese metal consume high amount of energy causing substantial waste discharge. The waste contains heavy metals, ammonia and manganese which can cause water pollution and pose health risks towards animals and humans. There is a need to find the methods for recycling of electrolytic manganese residues by utilizing further in building industry, in functional materials or fertilizers (Wang, et al., 2021). Manganese can be produced from secondary resources. The separation and purification of electrolytic manganese can face challenges related to its production in terms of high energy consumption or complex equipment's.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

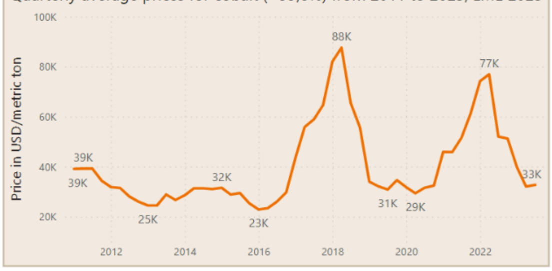
Cobalt

Cobalt production and demand forecast from 2010 to 2030, USGS, DERA, IEA 2023

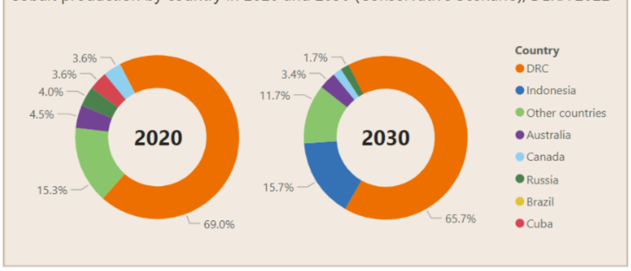


Supply and Demand: The demand for cobalt is expected to grow fast driven by the expanding electric vehicle and renewable energy sector. Cobalt market can be expected to oversupply but only if the new cobalt mines are realized until 2030.

Quarterly average prices for cobalt (>99,8%) from 2011 to 2023, LME 2023

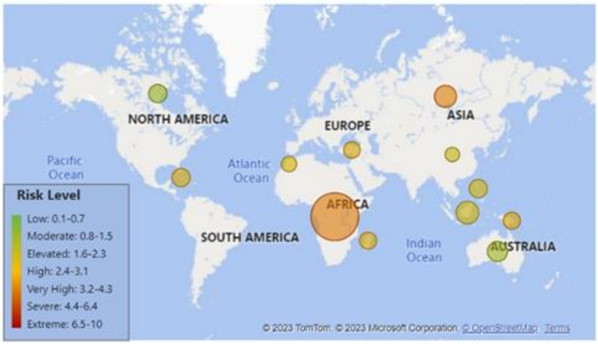


Cobalt production by country in 2020 and 2030 (Conservative Scenario), DERA 2022



Price and competition: Price of cobalt is expected to remain influenced by supply and demand dynamics. As demand from industries like electric vehicles and renewable energy increases, cobalt prices may see upward pressure, potentially leading to price volatility. The majority of new mine production is expected to come from the DRC and Indonesia.

Overall risk score (bubble color) and production (bubble size) for top cobalt producing countries in 2022, S&P Global, USGS 2023



Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
Canada	1.50	1.10	1.50	1.30	1.20	1.40	1.30
China	1.40	2.10	2.40	2.00	1.70	2.00	1.90
Congo (DRC)	3.90	4.20	5.10	3.40	3.80	4.30	4.10
Cuba	4.90	2.50	2.90	2.20	1.00	3.00	2.80
Indonesia	1.90	2.30	2.70	1.90	2.30	1.80	2.20
Madagascar	3.60	2.80	3.60	2.70	1.60	3.30	2.90
Morocco	2.40	2.30	2.80	2.10	2.10	2.60	2.40
Papua New Guinea	3.50	2.60	4.00	2.70	1.80	3.20	3.00
Philippines	1.60	2.40	2.90	2.00	2.70	2.00	2.30
Russia	5.60	4.90	4.00	2.90	2.50	4.00	4.00
Turkey	4.20	2.90	2.40	2.50	2.50	2.70	2.90

Production risks: The production of cobalt involves health and safety risks with high environmental concerns. Alternatives for cobalt are actively under research.

Market Demand

While lithium-ion batteries represent a key emerging application for cobalt today, the metal has a long history of various kinds of industrial applications, due to its specific material properties. The aerospace industry uses cobalt as a component of superalloys while the metal industry uses it as an alloying element in tool steels and advanced materials. Additional important fields of application are the pigment industry, the use of cobalt as a catalyst in the petrochemical industry and, because of its ferromagnetic properties, as a magnetic material. Almost all of these fields of application show significant growth rates and, currently, still represent around 40 % of total cobalt use. However, the market for lithium-ion batteries is growing much faster (Al Barazi, S, 2018; SCHÜTTE, 2021).

Sourcing

The majority of the cobalt ore mined today occurs in three deposit types: (1) primarily stratiform, sedimentary rock-hosted copper deposits of what is known as the Central African Copperbelt (in the Democratic Republic of the Congo, DRC, and Zambia), (2) lateritic nickel deposits (e.g., Philippines, Indonesia, Cuba), and (3) magmatic nickel-copper deposits (e.g., Canada, Russia, Australia). Lateritic ores comprise oxides and silicates while nickel-copper ores in magmatic deposits mainly comprise sulphides (SCHÜTTE, 2021).

Global cobalt production is critically influenced by market developments of the associated primary commodities, i.e., copper and nickel. Intermediate cobalt processing products are refined to either cobalt metal or high-purity cobalt chemicals. Due to the growing importance of lithium-ion batteries, the proportion of produced chemicals, relative to metal, has risen continuously over time. Refined cobalt chemicals in the form of oxides (especially tetroxide) and sulphates represent important intermediary products for producing cobalt-containing cathode precursor materials and, subsequently, lithium-ion batteries (SCHÜTTE, 2021).

Global cobalt supply was 125.000 t in 2020, with almost 70 % supplied from the DRC followed by Australia and Cuba with about 4 % each (BGR, 2022). The supply situation will change towards 2030. Future additional mine supply is estimated to be up to 224.000 t (conservative scenario) and 252.000 t (optimistic scenario), respectively. The majority of new mine production is expected to come from the DRC and Indonesia. By 2030, Congo's market share could decrease to around 63 – 65 % and Indonesia's share could increase to 15 – 17 %. The additional cobalt

supply from Indonesia will contribute to a decreasing country concentration for the global cobalt mine production. The majority of new nickel-cobalt projects in Indonesia has a clear focus on the battery sector. If all announced projects are realized until 2030, the cobalt market is expected to be in oversupply with favorable prices for cathode and battery cell producers.

Recycling still plays a relatively minor role in the cobalt market. An average recycling volume of around 13,000 t cobalt per year was estimated for the years 2017 – 2019 (SCHÜTTE, 2021). The contribution of recycling to total cobalt supply is around 10 %. This will change in the future. Lithium-ion batteries contain a large number of valuable raw materials that can be recovered using suitable recycling processes. Recycling of lithium-ion batteries could also increase resilience against supply disruptions.

Sustainability

Cobalt is predominantly obtained as a by-product of copper and nickel mining; in some mines in the DRC, it represents a co-product of copper mining. The sustainability of cobalt mining is therefore intricately linked to the extraction of these primary commodities. Key sustainability aspects of cobalt mining and processing include:

- Cobalt production associated with copper or nickel mining temporarily occupies areas for mining and processing infrastructure. In some places in Southeast Asia, for example, nickel-cobalt mining is associated with clearing ecologically valuable rainforests.
- Adequate and sustainable reclamation or renaturation efforts are a key concern for land no longer reserved for on-going mining activities.
- Processing either sulphide or laterite ore has a significant impact on the energy and emission profile of a given mine. The carbon footprint of a mine is influenced by both its direct emissions as well as the location-specific energy mix.
- ASM activities in the DRC should be regarded as especially critical. Cave-ins and other accidents in

underground drifts and adits have led to numerous fatalities. ASM activities are associated with higher risks if performed underground, rather than in open pits. Numerous accidents could be avoided if proper safety procedures were implemented.

- Due diligence risks, as defined by the OECD, include conflict financing, human rights violations, forced labor, the worst forms of child labor, corruption and fraud to conceal the origin of minerals. With the exception of conflict financing, all of the above risks are relevant in the DRC's cobalt sector

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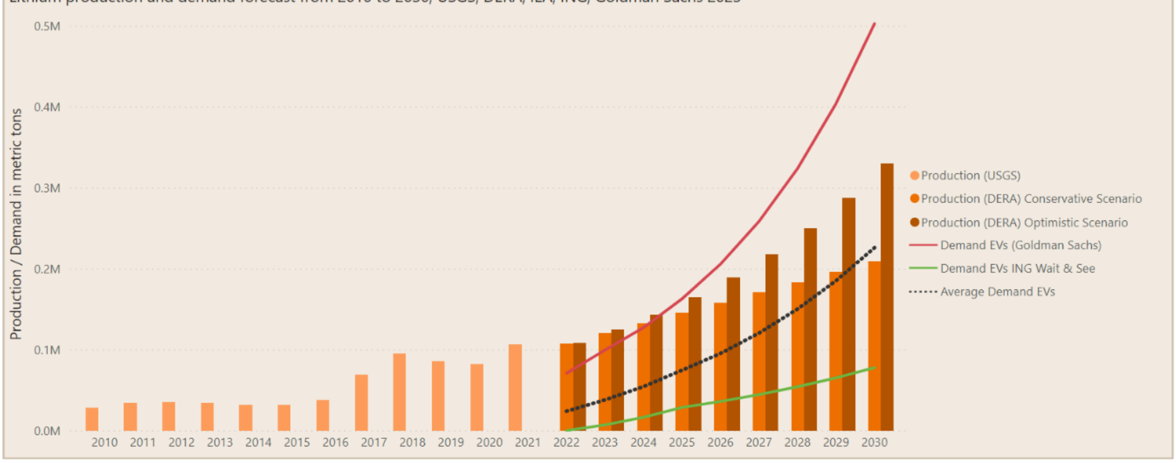
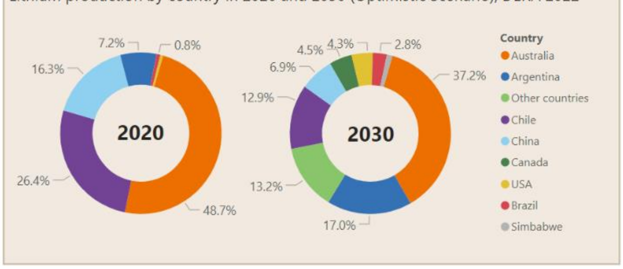
3.5 Lithium



Lithium production and demand forecast from 2010 to 2030, USGS, DERA, IEA, ING, Goldman Sachs 2023

Supply and Demand: Demand of lithium is estimated to grow fast in near future. Supply chain challenges may occur and have negative impact for lithium availability to support e-mobility, energy storage and other applications.

Quarterly average prices for Li2CO3 (>99,5%) from 2017 to 2023, IM 2023



Lithium production by country in 2020 and 2030 (Optimistic Scenario), DERA 2022

Price and competition: There have already been major price fluctuations and short-term price peaks in the past, since 2023 the price has started to fall due to different reasons. 75% of production in Australia and Chile 2020, will change towards 2030 since Latin America plans for expand it share.

Overall risk score (bubble colour) and production (bubble size) for top lithium producing countries in 2022, S&P Global, USGS 2023

Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Argentina	5.20	2.60	3.20	2.50	1.50	3.20	3.00
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
Brazil	2.20	2.00	3.10	2.30	1.90	2.90	2.40
Canada	1.50	1.10	1.50	1.30	1.20	1.40	1.30
Chile	1.70	1.60	1.90	2.20	2.00	2.30	2.00
China	1.40	2.10	2.40	2.00	1.70	2.00	1.90
Portugal	1.90	1.40	1.70	1.30	0.80	1.70	1.50
Zimbabwe	6.20	3.70	4.20	3.70	2.40	3.90	4.00

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Market Demand

Due to its specific properties, lithium is and remains an indispensable, non-substitutable key component for rechargeable batteries in the coming decades, regardless of the chosen cathode chemistry. The market has shown significant growth in terms of supply and demand over the past years due to multiple push factors, including regulatory driven demand uptake. As LIB technology cannot be substituted adequately and most, if not all, current cathode technologies contain lithium, demand will grow even stronger in the coming decade. The push from fossil to renewables will accelerate this demand growth. Demand in 2020 was about 74.000 t Lithium content (IEA, 2021). Total demand for lithium will, depending on EV and Energy storage developments, increase to 316.000 – 559.000 t lithium content by 2030.

The price development of lithium shows that there have already been major price fluctuations and short-term price peaks in the past. Above all, high price volatilities represent incalculable risks in the procurement strategies of companies. Since the beginning of 2022, unprecedented price levels have been observed. Since the beginning of 2023 prices have started to fall due to different reasons by roughly 50%.

Sourcing

In 2020, Australia and Chile accounted for almost 75% of global mine production, although through different process routes and thus environmental footprints. In total, supply in 2020 was approx. 82.000 t lithium content (USGS, 2023). Total primary supply of lithium may, depending on the demand developments, increase to 209.000 – 331.000 t lithium content by 2030. Potential surplus of mine supply does not equal supply of specialty lithium chemicals as needed by cell manufacturers.

By 2030, Australia's market share could decrease to around 37 – 43 % and Chile's share could fall from 28 % to below 13 %. Generally, Latin America will most likely expand its share of total supply to around 33 % by 2030 and thus become the second important cornerstone for the market alongside Australia. In addition to Chile, there are other countries such as Bolivia, Mexico, Serbia, US, and Canada aiming to restructure or adapt their raw material policies regarding lithium or have already done so. Therefore, future supply will also significantly depend on the developments in these countries, as they host large resources and potentials. (DERA, 2023)

The top five companies supplied approximately 70 % of global mining or chemical production in 2020 (S&P Global 2022). This situation will not change significantly by 2030. In the future, there could be further company consolidations or strategic joint ventures between individual companies. The processing industry (cell manufacturers, automotive manufacturers) may also engage upstream to secure supply. This applies primarily to Asian companies, but also increasingly to the European industry (DERA, 2023). In addition to direct participation via joint ventures, memorandums of understanding (MOUs), letters of intent (LOIs) and binding/ non-binding off-take agreements are common hedging tools.

In the EU, primary lithium mining and refining industry is currently not established, although there is great potential in many countries. Some companies have already started the construction of refining capacities and many more have announced this logical and necessary step. European companies could produce up to about 27 – 34 % of domestic demand, i.e., according to a demand scenario of 97,000 lithium content in 2030, corresponding to 750 GWh scenario of cell manufacturing. However, announced cell manufacturing capacities in Europe are already about 2TWh at the moment (Battery-News, 2023).

Secondary sources has not played a major role so far. Due to the dissipative distribution in end products and required product qualities, recovery is currently not yet economically feasible. However, the recycling of lithium-ion batteries is possible and corresponding large-scale processes are available. In Europe in particular, a corresponding industry is already developing. Recycling could provide approx. 3 – 10 % of the global lithium demand in 2030 based of DERA (Shmidt, Bastian, & Kresse, 2022). Use, disposal and recycling of LIBs are subject to the EU's Batteries Directive. Overall, the EU will remain dependent on imports.

Sustainability

Sustainability is considered as one of the most important topics in the emerging lithium market. The current market is split in lithium chemical production from brines (40%) and lithium hardrock sources (60%) with China in a very

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dominant position in the whole supply chain. Both sources yield the same product, but the environmental footprint varies quite strongly, particularly in terms of water consumption, energy consumption, CO2 emissions (effluents in general), chemical consumption, waste materials (quantity), land use and land impact (Figure 6). Depending on the country of production and/or mining, other socio-economic-aspects need to be considered as well.

Deposits	Process step	GHG emissions [t CO_2e/t]	Energy [MJ/t]	Fresh water [m³/t]
Brine	Concentration	0.08–0.18	1,300–2,800	2.95–7.3
	Li_2CO_3 production	2.7–3.1	30,000–36,000	15.5–32.8
	LiOH production	6.9–7.3	76,600–82,900	31–50
Hard rock	Concentration	~ 0.42	~ 5,500	~ 3.4
	Li_2CO_3 production	~ 20.4	~ 218,000	~ 77
	LiOH production	~ 15.7	~ 187,200	~ 69

Figure 6. LCA results for lithium carbonate and lithium hydroxide from hard rock and brine deposits (data source: Kelly et al 2021)

The most pressing concerns are connected to water consumption in brine processing and the associated question whether evaporated water in brines (approx. 70% H_2O) should be defined as water or not. Currently, in Chile, the largest brine-based lithium producer, brine is defined as a mineral resource and, thus, water related regulatory frameworks do not apply. In addition, freshwater consumption mostly occurs in chemical plants off-site from the salars in Chile, whereas its use in the salars themselves is very low. In general, the industry aims to reduce both brine as well as freshwater consumption. Another solution is the use of DLE technology (Direct Lithium Extraction) with re-injection of the lithium stripped brine. Dust suppression and waste disposal of unwanted salts in the salars are also topics of concern. Solar evaporation ponds account for most of the land use in these salars. (DERA, 2023)

In the case of hard rock extraction and processing, energy consumption in mineral processing in China is a key factor to consider from an environmental footprint point of view. These spodumene ores and concentrates, mostly imported from Australia, go through a highly energy-intensive production process. In addition, the amount of waste material that derive from that process is an issue. As a rule of thumb: per 20 kt of final product (Li concentrate), roughly 200 kt of waste material is generated that needs to be disposed or re/purposed. There are efforts to re-use these materials in different industries. Also, since the concentrates only contain about 6 % Li_2O the amount of gangue material that is transported is very large. The use of chemicals as well as overall water consumption in this process path are issues. (DERA, 2023)

Another trend in mineral conversion in China is the use of lepidolite ores and concentrates of lower quality. The processing of these feedstocks has a significantly higher CO_2 and chemical footprint than spodumenes, which in turn have a much higher CO_2 footprint than brine-sourced products. The amount of produced waste is even higher with this source.

In June 2020, the French Agency for Food, Environmental and Occupational Health & Safety (Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail, ANSES) applied to have lithium chloride, carbonate and hydroxide classified as Repr.1A (H360FD) under the REACH Regulation (ANSES 2020). Because of stricter safety regulations, the classification could lead to higher costs, which could affect the production, transportation, handling, and recycling of products containing these compounds.

A new proposed Directive has been adapted in June 2023 from the 2006 Directive (2006/66/EC) to meet current challenges. It contains labelling rules, information obligations and supply-chain due diligence standards, as well as requiring metal-specific recycling rates and the use of recycled content in batteries with a capacity above 2 kWh. This applies primarily to batteries used in electric vehicles. For the first time, information on the carbon footprint of battery production will also have to be stated. Secondary lithium content in batteries made in the EU is set to be at 6%, i.e., after year 6 of Battery Directive implementation. This will rise to 12% after 13 years of implementation.

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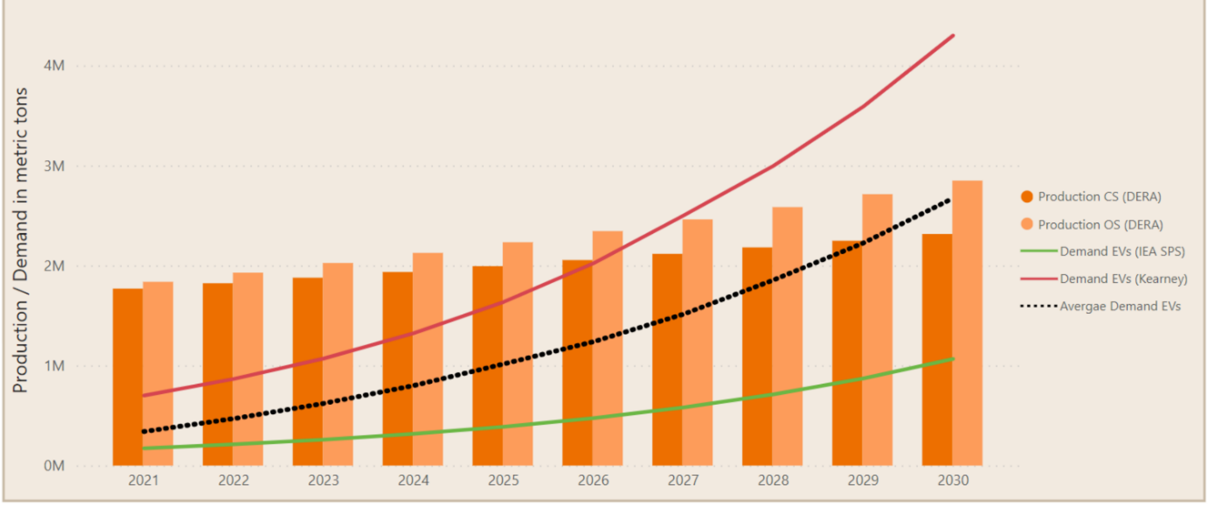
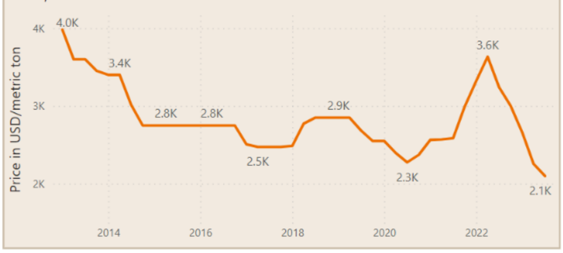
Graphite

Natural graphite production and demand forecast from 2021 to 2030, DERA, IEA, Kearney 2023

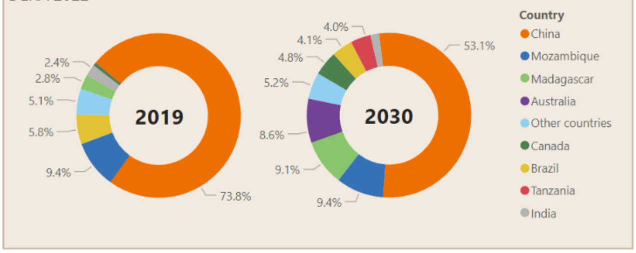


Supply and Demand: Graphite is one of the key elements in Li-ion batteries and the competition in EV battery production will be intensified in near future. Graphite shortages can be expected to rise in coming years.

Quarterly average prices for spherical graphite (>99,95%) from 2013 to 2023, Fastmarkets 2023

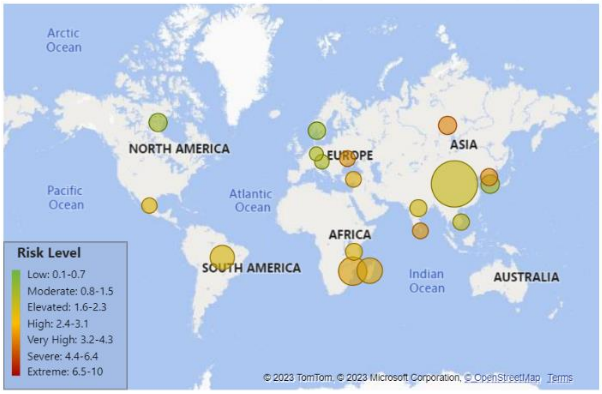


Graphite mine production by country in 2019 and 2030 (Conservative Scenario), DERA 2022



Price and competition: Graphite prices have experienced fluctuations in recent years. Production of graphite is dominated by China. Other producers of natural graphite in the future include Madagascar, Mozambique, and Australia.

Overall risk score (bubble color) and production (bubble size) for top graphite mine producing countries in 2022, S&P Global, USGS 2023



Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Austria	1.70	1.30	1.50	1.60	1.50	1.20	1.50
Brazil	2.20	2.00	3.10	2.30	1.90	2.90	2.40
Canada	1.50	1.10	1.50	1.30	1.20	1.40	1.30
China	1.50	2.20	2.40	2.00	1.70	2.00	2.00
Germany	1.80	1.30	1.60	1.40	1.70	1.20	1.50
India	1.70	2.10	2.80	2.10	2.60	2.10	2.20
Madagascar	3.60	2.80	3.60	2.70	1.60	3.30	2.90
Mexico	1.70	3.30	3.30	2.70	1.90	2.80	2.60
Mozambique	3.80	2.70	3.60	2.70	2.90	2.70	3.10
North Korea	3.90	5.40	4.20	2.40	1.30	4.60	3.60
Norway	1.00	0.90	1.00	0.90	0.90	1.40	1.00
Russia	5.20	4.90	4.00	2.90	2.50	4.00	3.90
South Korea	1.20	0.80	1.80	1.50	1.40	1.50	1.40
Sri Lanka	5.00	2.70	3.00	3.10	2.60	3.80	3.40
Tanzania	2.90	3.20	2.80	2.10	1.90	2.60	2.60
Turkey	3.90	2.90	2.40	2.50	2.50	2.70	2.80
Ukraine	5.10	3.80	3.00	3.10	3.20	2.60	3.50
Vietnam	1.90	1.90	2.70	1.30	1.40	2.00	1.90

Production risks: EU need to mitigate the dependency on supply chain risk related to China, by securing new mining actions.

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Market demand

The graphite market is composed of natural graphite and synthetic graphite, two fundamentally different raw materials each with established and highly specialized applications that are linked to several different industries. The considerable number of graphite specifications are subject to their own market dynamics. Anode material for lithium-ion batteries is the major area of competition between natural and synthetic graphite and will continue to be the main driver of future demand for both graphite types until 2030. Driven mainly by the increasing use of lithium-ion batteries in electric vehicles, this market segment is tipped to significantly gain market share by the end of the decade.

Global graphite demand of both natural and synthetic graphite was 2.5 million tons in 2018, with 62% supplied from the synthetic graphite market. The main market for synthetic graphite is electrodes for the use in electric arc furnaces (EAF); no natural graphite is used in this application. Consumption is closely linked to the global steel industry and demand driven by the global demand for EAF steel. The refractory industry is the main consumer of natural graphite, where it is used in magnesia-carbon and alumina-carbon refractories. Both types of graphite compete for market share in lithium-ion batteries where it is used as anode material.

Sourcing

Synthetic graphite is a form of graphitic carbon and is manufactured from petroleum-based and coal-based needle coke through the graphitisation process. The graphitisation process consumes substantial amounts of energy and can be tightly controlled to produce graphite grading of >99% purity and with a strict set of specifications that suit the intended application.

Natural graphite is mined via conventional mining operations and processing techniques. There are three types of natural graphite: flake graphite, amorphous graphite, and vein graphite.

Natural flake graphite requires processing into spherical graphite to be used in lithium-ion batteries. Important parameters are purity and crystalline structure. Flake size is also an important factor, with typically only small to medium flake sizes used for the production of spherical graphite. Around 30 to 70 % of flake graphite is lost as waste during processing. Synthetic graphite producers can specifically manufacture high purity synthetic graphite for use in battery applications. Due to the generally higher cost, synthetic graphite anode material is primarily used in batteries for high-performance applications, although a mix of both graphite types is common.

Global production of graphite is estimated to be at 3.2 million tons; natural graphite accounted for about 1.67 million tons (2019), and around 1.6 million tons (2018) came from synthetic graphite production. China is the largest supplier of both types of graphite, accounting for around 74 % of global natural graphite production and 49 % of synthetic graphite production. Other important producers of natural graphite include Madagascar, Mozambique, and Brazil. Japan, the United States, India, and Europe produce synthetic graphite (BGR 2022, Damm 2021). Downstream processing and anode material manufacturing is also heavily focused on China today. The introduction of stricter environmental policies has led to plant closures and production curbs and have affected the entire graphite industry.

Future additional supply is estimated to be up to 1.2 million tons by 2030. Additional capacities are expected from the commissioning of new mines, particularly in Tanzania, Mozambique, Australia, and Canada, as well as operational expansions of existing mines. This increasing supply from countries outside China may add to a lower country concentration and help lower reliance on Chinese materials. The majority of new projects have a clear focus on supplying the battery sector. However, owing to the specific requirements needed to qualify as battery-grade material, not all of the future flake graphite supply will prove suitable. Additional synthetic graphite supply is estimated to be at 1.15 million tons by 2030. As a manufactured material with a customer in mind, synthetic graphite supply is expected to align closely with future demand. However, increasing supply from additional Chinese capacities may contribute to an increasing country concentration for the production of synthetic graphite. Due to its history as an industrial mineral, graphite and its industry is inherently different in terms of market structure and dynamics than other battery minerals. The large number of graphite specifications makes forecasting future supply demand balances somewhat difficult and should therefore be treated as an approximation only. Market coverage for specific product grades for both natural and synthetic graphite are subject to their own market dynamics and may vary greatly (Damm 2021).

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Sustainability

Graphite itself is non-toxic and does not pose a direct threat to the environment. However, mining of natural graphite, the production of synthetic graphite as well as subsequent processing into battery-grade qualities is associated with a range of environmental concerns and include, but are not limited, to the following:

The manufacturing of synthetic graphite requires high temperatures of up to 3,000°C, making it a highly energy-intensive production process. There is significant potential for the production process to reduce its carbon footprint through greater use of renewable energy. Depending on the feedstock, the main potential emissions are CO2, NOX, SOX and CO. Strict requirements for exhaust gas purification and their consistent implementation and control can minimize this environmental impact.

Mining and processing of natural graphite is mainly done on an industrial scale. Potential impacts particularly include dust formation and acid mine drainage. Any potential environmental and socio-economic risks should be considered and managed prior to the start of mining, and standards to comply with should be part of the approval process of the mining license. Monitoring and, if necessary, enforcement of those standards are the responsibility of the mining authorities of the producing country. However, those standards as well as their monitoring and enforcement may vary greatly between countries.

The processing of graphite into battery-grade specifications is associated with the use of strong acids, such as HF and HCl, which can be harmful to the environment if released during the purification stage.

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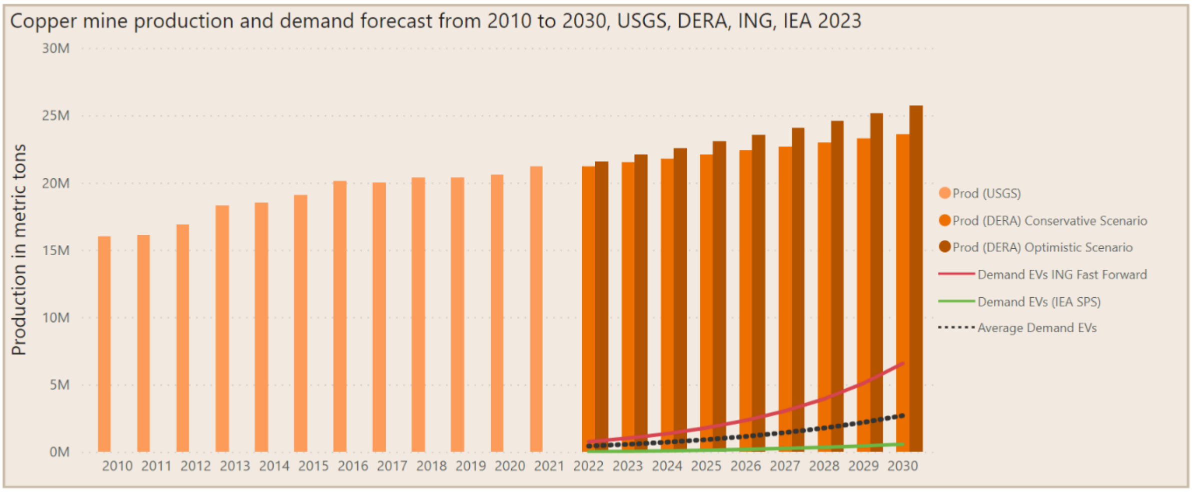
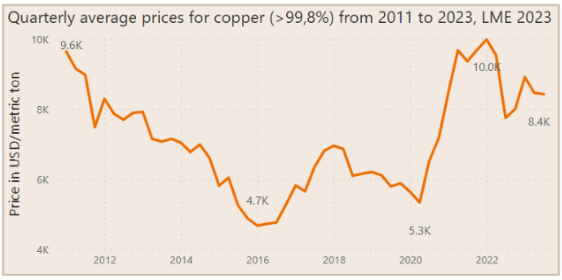
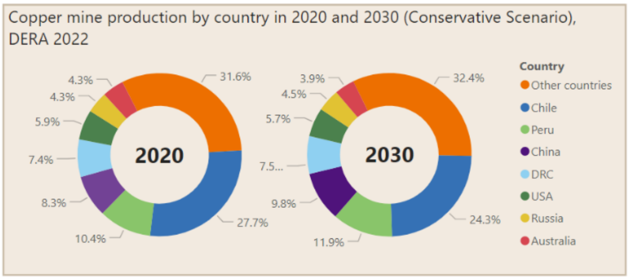
Copper



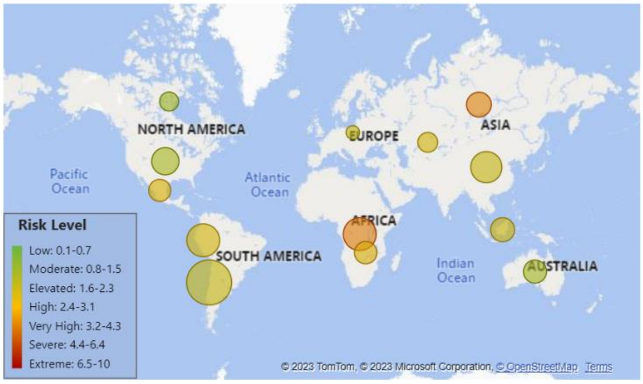
Supply and demand: Copper is a critical metal for energy transition. Increased growth in demand is expected above all in electromobility, particularly from 2025 onwards.





Price and competition: Copper price have exhibited volatility during past years. Main producers in South America, Chile, Peru and China.

Overall risk score (bubble color) and production (bubble size) for top copper producing countries in 2022, S&P Global, USGS 2023



Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
Canada	1.50	1.10	1.50	1.30	1.20	1.40	1.30
Chile	1.70	1.60	1.90	2.20	2.00	2.30	2.00
China	1.50	2.20	2.40	2.00	1.70	2.00	2.00
DR Congo	3.90	4.20	5.10	3.40	3.80	4.30	4.10
Indonesia	1.90	2.30	2.70	1.90	2.40	1.90	2.20
Kazakhstan	2.70	2.40	2.90	1.90	1.50	2.20	2.30
Mexico	1.70	3.30	3.30	2.70	1.90	2.80	2.60
Peru	1.70	2.20	2.80	2.80	2.00	2.10	2.30
Poland	2.10	1.90	1.80	1.90	1.60	2.10	1.90
Russia	5.20	4.90	4.00	2.90	2.50	4.00	3.90
USA	0.90	1.10	1.50	1.50	2.10	1.30	1.40
Zambia	3.70	2.90	2.80	2.50	1.30	3.00	2.70

Production risks: Risks in copper mining include extensive mining residues due to low copper content, the formation of acidic mine water, local conflicts arising from water quality and high water demand, environmental concerns related to emissions, and the socio-economic impact.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Market Demand

Copper is the best electrical conductor after silver. Therefore, it plays an important role as a conductive material in the green revolution and the decarbonization of society, such as in the expansion of renewable energy sources or electromobility. We can expect that future demand for copper will remain stable because of these megatrends. Increased growth in demand is expected above all in electromobility, particular from 2025 onwards (Dorner, 2020).

Since the turn of the millennium, China has been able to further grow its dominance in the copper market. It occupies a key position, particularly in global copper demand. As of 2020, China's demand for refined copper accounts for over 58 % of global demand (BGR, 2022). This dominant position comes with a high risk as global copper demand depends on China's economic development.

Sourcing

Copper supply is made up of primary and secondary (recycled) refined production. China was able to further expand its refined production: as of 2020, it grew its global market share to over 40 % (BGR, 2022). China is thus the most important producer of refined copper worldwide; Chinese smelter wages are now considered the benchmark wage for global contracted smelters. Sinking smelter wages in the last several years indicate large overcapacities in China's refining production, although this slippage in wages seems to be coming to an end. China's planned consolidation of copper smelters is not yet taking effect. We can also assume that China will keep increasing its production capacities because of expected demand led by strong growth in renewable energy and e-mobility.

South America remains the most important region for copper mining. However, Chile, the most important producing country, could not keep up with worldwide increases in mining production and therefore lost global share. As of 2020, Chile has a share of about 28 % of global copper production. In the last ten years, other countries such as Peru and the DRC have been able to ramp up their production significantly (BGR, 2022). Meanwhile, the DRC has replaced Zambia as the most important copper mining country in Africa, and is now the fourth most important copper producing country in the world. This means that global copper production is shifting to unstable and high-risk countries. In the coming years, this development is likely to continue as new copper projects are being developed in the DRC.

Copper recycling makes an important contribution to increasing copper supply. About 17 % of global refining output comes from secondary material. Most copper scrap is recovered in China. Since the end of 2018, new import restrictions on copper scrap have been in force in China. This is also affecting copper scrap imports. Meanwhile, China has been reclassifying certain scrap quality levels as raw materials; these are then no longer subject to the new import restrictions. It remains to be seen how great an impact Chinese import restrictions will have on global secondary raw material production.

Germany has the third highest copper demand behind China and the USA. This reflects just how important the German copper industry is on the global stage. Demand is met by domestic primary and secondary copper smelters as well as by imports. The share of secondary material in copper production in Germany is at 40%, i.e., well above the global average.

Sustainability

Key sustainability issues in copper mining and processing include:

- Because the ore has a relatively low copper content, extracting one ton of copper produces a very large amount of mining residues.
- In copper mining, the formation of acidic mine water is a widespread phenomenon. This is influenced by, among other things, the geochemical properties of the mining residues.
- Local conflicts like in Peru can be caused by reduced water quality as well as by high water demand, which can be up to 350 m3 per ton of copper.
- Modern separator devices in copper smelters help to minimize the discharge of metal-rich dusts. They also capture over 99% of the sulfur dioxide emissions, which are then used to produce sulfuric acid.
- A large part of the added value in the production of a ton of copper takes place at the mining site. This is particularly important for copper-producing developing countries such as the Democratic Republic of the Congo.
- As part of the Copper Mark Initiative, founded in 2019, companies in the copper industry commit to responsible production. This is defined by sustainability standards and their verification.

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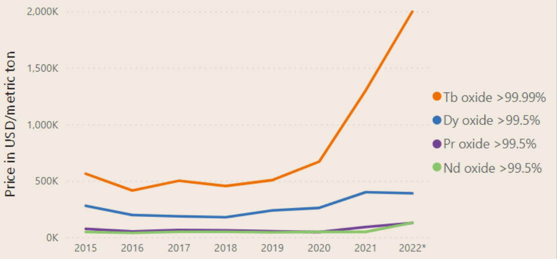
Rare Earths

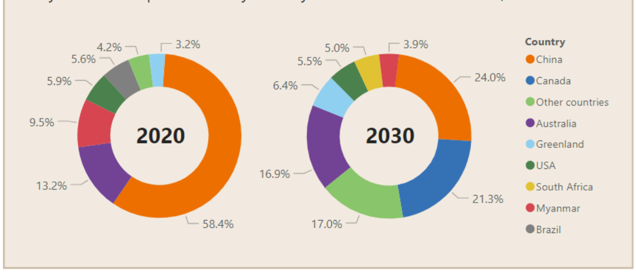
Neodymium, Dysprosium, Praseodymium, Terbium production and demand forecast from 2020 to 2030, JRC, IEA 2023

Supply and demand: Total demand for REEs is expected to be double or quadrupling depending on the development scenario. The supply chain is dominated by China which may cause shortages.

Yearly average prices for Nd, Dy, Tb and Pr oxides, Argus Media 2023



Neodymium oxide production by country in 2020 and 2030 forecast, JRC 2020



Price and competition: The price of REE used for permanent magnets remained stable between 2015-1022. Terbium had high increase between 2020 to 2022. China is dominating both production and processing .

Overall risk score (bubble color) and production (bubble size) for top rare earth oxides producing countries in 2022, S&P Global, USGS 2023

Country	Economic	Legal	Operational	Political	Security	Tax	Overall
Australia	1.30	1.10	1.30	1.50	1.10	1.60	1.30
Brazil	2.20	2.00	3.10	2.30	1.90	2.90	2.40
China	1.50	2.20	2.40	2.00	1.70	2.00	2.00
India	1.70	2.10	2.80	2.10	2.60	2.10	2.20
Madagascar	3.60	2.80	3.60	2.70	1.60	3.30	2.90
Myanmar	4.90	3.00	4.40	3.50	3.90	1.90	3.60
Russia	5.20	4.90	4.00	2.90	2.50	4.00	3.90
Thailand	1.60	1.90	2.50	2.70	2.00	2.20	2.20
USA	0.90	1.10	1.50	1.50	2.10	1.30	1.40
Vietnam	1.90	1.90	2.70	1.30	1.40	2.00	1.90

Production risks: China's dominance in REE production and processing technology has led to concerns pertaining to supply chain risks.

Market Demand

Rare Earth Elements are having important role in magnets for electronics and communication devices and also in renewable energy, robotics, aerospace, defense applications as well as electric vehicles. According to a report of European Raw Material Alliance (ERMA), 95% of EVs use rare earth permanent magnet motors because they provide the highest energy efficiency, which translates into driving range. Neodymium, praseodymium, dysprosium and terbium are the REE used for magnets, they constitute only 25% of the total REE production volume but they represent 80% to 90% of the total rare earths market value. (European Raw Material Alliance; EIT RawMaterials, 2021)

More than 90% of REE magnets are produced in China. From European perspective the dependency of Chinese cause a high supply risk for these materials because of the rising global political tensions and a growing Chinese domestic market demand particularly driven by a growth in electric mobility. The lack of supply chain transparency, standards and certification schemes regarding environmental and social impacts and governance cause also challenges for the sustainable supply chain.

The REE value chain is economically important, especially in the emerging electric vehicle (EV) market. 130 000 t of REE permanent magnets (Nd-Fe-B) were produced in 2019, 94% of these magnets were produced in China. About 5000 t of REE permanent magnets were used in EVs in 2019.
By 2030 this number may rise to between 40 000 and 70 000 t globally, depending on the anticipated growth scenario.

European Raw Material aLliance (ERMA) has identified 7.1 billions Euros of investment opportunities and the aim is to source 20% of the Europe's rare earth elements domestically by 2030. European producers can hardly compete with Chinese in terms of price and the European poliymakers must strive to establish a fair competition environment. European OEMs should consider more making commitments to purchase REE from European producers, which could offer advantages such as supply chains, accessing local suppliers, retaining material knowledge for future motor design.

Sustainability

REEs can be produced either with sustainable or less sustainable way. According to comparison between different studies made by ERMA, the CO_2 emissions of REE based magnetic motors production can vary depending on the various ore processing sources and recycling methods. There is high potential to reduce the CO_2 emissions related to REE production by considering more sustainable mining in terms of energy use and consumption. Additionally, the recyclability of the elements need to be developed in the coming years. Enforced regulations and standards for re/processing and recycling of end-of-life products should be established in EU.

The demand forecast of Nickel, Manganese, Cobalt, Graphite, Lithium and Copper for EV battery production by 2030

Source	Publication year	Reference year	Ni Demand EVs 2030 (t)
Xu et al. (SPS)	2020	2019	700,000
Xu et al. (SDS)	2020	2019	1,360,000
S&P Global	2022	2022	1,213,559
RfZ SPS*	2021	2020	540,897
RfZ SDS*	2021	2020	1,736,733
McKinsey (SPS)*	2023	2022	637,929
McKinsey (SDS)*	2023	2022	1,771,844
Lenina et al.	2018	2017	296,000
ING Wait & See	2021	2020	543,631
ING Likely Tech	2021	2020	782,347
ING Fast Forward	2021	2020	1,101,304
IEA (SPS)	2021	2020	647,275
IEA (SDS)	2021	2020	1,566,948
Goldman Sachs	2022	2020	1,511,000
Average			1,085,651

Source	Publication year	Reference year	Mn Demand EVs 2030 (t)
IEA (SPS)	2021	2020	101,889
IEA (SDS)	2021	2020	246,279
Fastmarkets	2023	2022	372,202
Average			240,123

Source	Publication year	Reference year	Co Demand EVs 2030 (t)
Xu et al. (SPS)	2020	2019	150,000
Xu et al. (SDS)	2020	2019	300,000
RfZ SPS*	2021	2020	110,892
RfZ SDS*	2021	2020	308,005
McKinsey SPS*	2018	2017	98,677
McKinsey SDS*	2018	2017	274,076
Lenina et al.	2018	2017	275,000
IEA (SPS)	2021	2020	106,184
IEA (SDS)	2021	2020	256,635
Goldman Sachs	2022	2020	257,404
Average			213,687

Source	Publication year	Reference year	Graphite Demand EVs 2030 (t)
PwC	2022	2021	3,100,000
Kearney	2023	2022	4,300,000
IEA (SPS)	2021	2020	1,065,304
IEA (SDS)	2021	2020	2,499,250
Fastmarkets	2023	2022	2,404,000
Average			2,673,711

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Source	Publication year	Reference year	Cu Demand EVs 2030 (t)
S&P Global	2021	2020	3,084,269
ING Wait & See	2021	2020	1,734,558
ING Likely Tech	2021	2020	3,223,289
ING Fast Forward	2021	2020	6,645,659
IEA (SPS)	2021	2020	717,400
IEA (SDS)	2021	2020	1,632,634
Goldman Sachs	2021	2020	2,419,000
Copper Alliance	2017	2016	2,968,146
Average			2,803,119

Source	Publication year	Reference year	Li Demand EVs 2030 (t)
Xu et al. (SPS)	2020	2019	120,000.00
Xu et al. (SDS)	2020	2019	200,000.00
S&P Global	2022	2022	434,069.83
RfZ (SPS)*	2021	2020	116,678.75
RfZ (SDS)*	2021	2020	324,075.15
McKinsey (SPS)*	2023	2022	119,843.89
McKinsey (SDS)*	2023	2022	284,370.84
ING Wait & See	2021	2020	96,228.80
ING Likely Tech	2021	2020	167,718.48
ING Fast Forward	2021	2020	219,206.39
IEA (SPS)	2021	2020	151,825.62
IEA (SDS)	2021	2020	358,390.33
Goldman Sachs	2022	2020	503,100.56
Average			238,116.05

Source	Publication year	Reference year	Cu Demand EVs 2030 (t)
S&P Global	2021	2020	3,084,269
ING Wait & See	2021	2020	1,734,558
ING Likely Tech	2021	2020	3,223,289
ING Fast Forward	2021	2020	6,645,659
IEA (SPS)	2021	2020	717,400
IEA (SDS)	2021	2020	1,632,634
Goldman Sachs	2021	2020	2,419,000
Copper Alliance	2017	2016	2,968,146
Average			2,803,119

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730227

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