JRC SCIENTIFIC INFORMATION SYSTEMS AND DATABASES

# RMIS – Raw Materials in the Battery Value Chain

## Final content for the Raw Materials Information System – strategic value chains – batteries section

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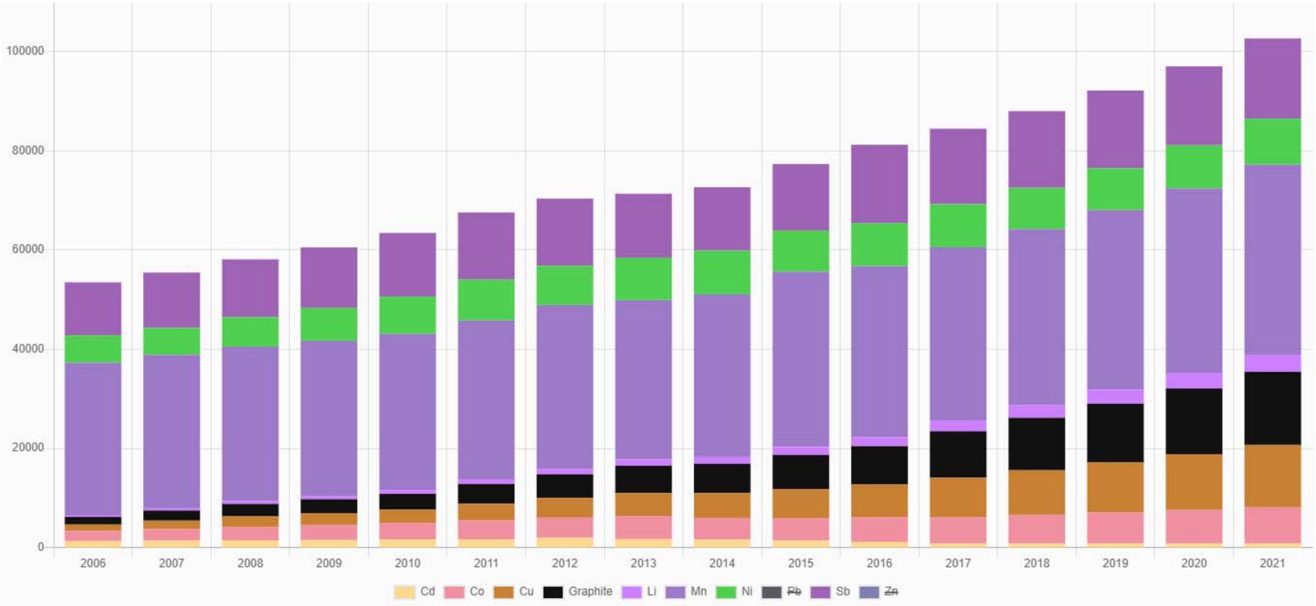

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# Contents

## Foreword

The Raw Materials Information System (RMIS) is the European Commission's reference web-based knowledge platform on non-fuel, non-agriculture raw materials. Since its conception and first release in 2015, the RMIS has been developed in close cooperation with the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW). DG GROW helps the JRC to recognise policy and knowledge needs related to raw materials, and supports the JRC in identifying how the RMIS can best meet these needs. RMIS development is part of the EU Raw Materials Knowledge Base: a well-established and extensive network of knowledge providers in the area of raw materials, which includes European Commission-funded projects, European agencies (Executive Agency for Small and Medium-sized Enterprises, European Environment Agency, etc.), academia, Geological Surveys of Europe, and industry and business associations.

In the circular economy action plan of 2015, the RMIS was tasked with improving the availability of data on secondary raw materials and with supporting EU-wide research on raw material flows. More recently there is increased focus to the analysis of strategic value chains for products, for example batteries. Such an approach is likely to develop in the near future, as the political guidelines and mission letters of the new Commission highlight the strategic value chain and sectoral dimension.

The proposed new industrial value chains and material flows tile (described in the present report) and the related RMIS data browser have a double objective: to capture in a compact manner relevant raw material stocks and flows information for specific value chains; and to increase the availability of data on secondary raw materials for a specific sector. This is developed, in the first instance, for the battery value chain.

## Acknowledgements

The authors would like to thank Perrine Chancerel and Johanna Emmerich from TU Berlin and Claude Chanson from Recharge – the Advanced Rechargeable and Lithium Batteries Association – for their data gathering and analysis work on secondary raw materials from batteries. Their efforts enabled the population of the data viewer and a 2019 update building on the previous version developed as part of the ProSUM project on prospecting secondary raw materials in urban mine and mining wastes. We also thank colleagues at DG GROW-C2 for their continuous support in developing the RMIS in relation to the policy and knowledge needs related to raw materials. Finally, we thank colleagues from unit B3 of the Directorate-General for Environment for their review of the battery information that the RMIS aims to provide.

## Authors

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## Summary

This report provides the web content for the battery value chain and the related battery raw materials data browser for the European Commission's Raw Materials Information System (RMIS), accessible online: https://rmis.jrc.ec.europa.eu/apps/bvc/#/. This content includes information and data on both primary and secondary raw materials.

The main sections developed are presented in the table below. The content is structured around general questions that both the general public and policy-makers may have. Datasets that particularly contribute to improving the availability of data on secondary raw materials, in accordance with the circular economy action plan (2015), are found in the sections Stocks and flows and Reuse. These can also be found in each interactive chart by clicking on the representations of 'stock' and 'waste'.

| Menu | Main content/leading questions |
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| Demand | A. How many new batteries are placed on the market?<br>B. Which chemistries were used in the past and what are the main trends?<br>C. What is the current raw material content in batteries?<br>D. What will change in the future with new chemistries?<br>E. How will e-mobility affect the demand for raw materials? |
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| Reuse | A. What is the difference between reuse, remanufacturing and repurposing?<br>B. What will happen to traction batteries after their first use?<br>C. Is repurposing of batteries good for the environment? |
| (NEW) Data viewer | Interactive graphs:<br>- Weight per application<br>- Relevant materials<br>- Materials per chemistry<br>- Materials per Batteries Directive<br>- Materials per sector<br>- Materials in e-mobility |
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# 1 Introduction

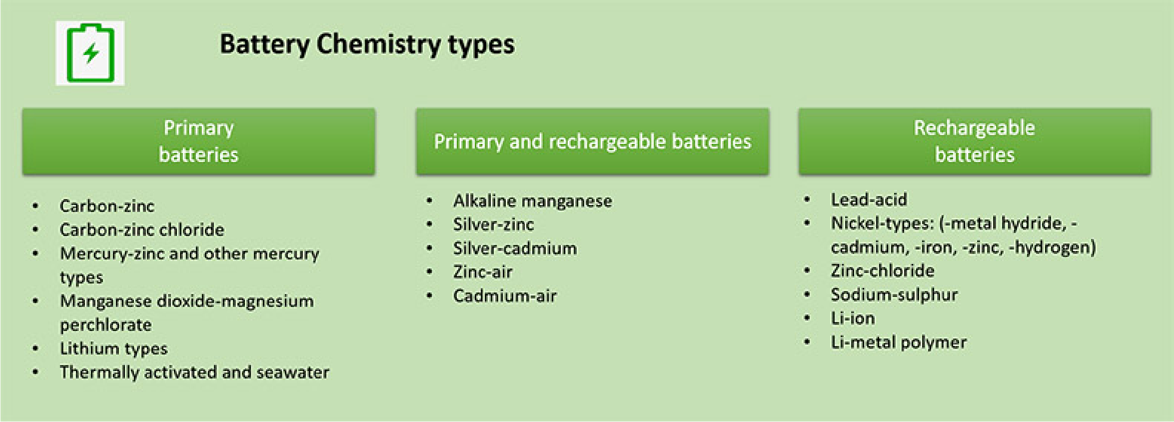
This Raw Materials Information System (RMIS) tile focuses on raw materials for batteries and their relevance for the sustainable development of battery supply chains for Europe. The first five sections cover the main trends and some key parameters in supply, demand, stocks and flows and reuse. The last section, in the form of an interactive data viewer, contains the latest data from research on batteries (all chemistries) and the associated materials that are entering, exiting or in use in the EU territory. These pages focus on the current and future trends related to the introduction of lithium-ion batteries for e-mobility. The content of the tile will be updated in the future when more information on trends in sourcing and manufacturing of battery primary raw materials and on actual collection and recycling flows becomes available.

## 1.1 What are batteries?

A battery is an electrochemical cell that stores energy in a chemical form. The battery can convert this chemical energy to usable electrical energy. Batteries are used in a wide range of applications in our daily lives. By using different chemical compounds for cathodes and anodes, a discharging process provides electrical current. Ideally, for rechargeable – or secondary batteries – this process is reversible by recharging and reconverting the materials in the cell to their original state.

A wide range of batteries with different chemistries exists (Figure 1). These contain a wide range of raw materials. For example, single-use – or primary – batteries are based on various chemistries such as zinc, mercury, manganese and lithium. For rechargeable – or secondary – batteries, the main chemistries are traditional lead–acid based batteries or nickel based batteries, of which nickel–cadmium and nickel–metal hydride batteries are the best known. The largest volume by weight are lead–acid batteries used in vehicles for starting, lighting and ignition. Generally speaking mercury batteries and most of the cadmium batteries have been banned from being placed on the market. Lithium based chemistries are growing rapidly; these types of batteries were originally used in portable electronic products, and are now increasingly used in electric vehicles (xEVs).

**Figure 1.** Main chemistries for different battery types



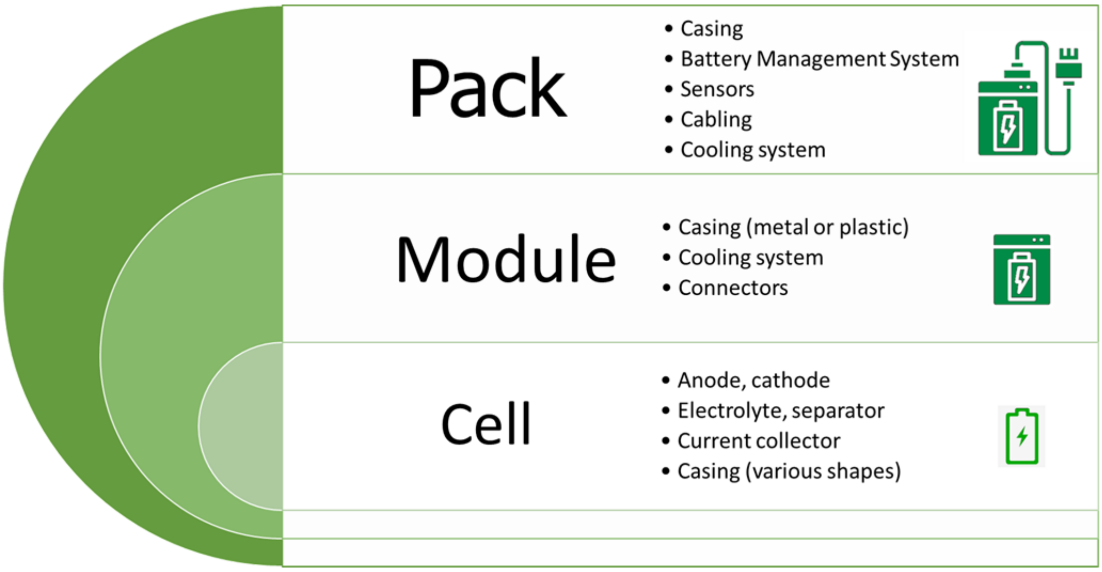
**Battery Chemistry types**

| Primary batteries | Primary and rechargeable batteries | Rechargeable batteries |
|---|---|---|
| Carbon-zinc | Alkaline manganese | Lead-acid |
| Carbon-zinc chloride | Silver-zinc | Nickel-types: (-metal hydride, -cadmium, -iron, -zinc, -hydrogen) |
| Mercury-zinc and other mercury types | Silver-cadmium | Zinc-chloride |
| Manganese dioxide-magnesium perchlorate | Zinc-air | Sodium-sulphur |
| Lithium types | Cadmium-air | Li-ion |
| Thermally activated and seawater | | Li-metal polymer |

*Sources*: Blagoeva et al., 2019b; Crompton, 2000

Battery cells are clustered in modules containing a casing for the cells, cooling systems and connectors. For xEVs, these modules are subsequently grouped in a 'battery pack' that includes an outside casing, a battery management system, various sensors, a cooling system and cables (Figure 2).

**Figure 2.** Battery packs, modules and cells for xEV applications



*Source*: JRC

## 1.2 What are battery raw materials and where do they originate?

There are many individual materials potentially present in the cell electrodes, electrolytes and separators. When focusing on the inorganic content of the active materials, the most relevant are antimony (Sb), cadmium (Cd), cobalt (Co), copper (Cu), graphite (C*), lithium (Li), manganese (Mn), nickel (Ni), lead (Pb), silicon (Si) and zinc (Zn). Of these materials, antimony, present in lead–acid batteries in vehicles and energy storage, and cobalt plus natural graphite, used in lithium-ion (Li-ion) batteries, are marked as critical in the 2017 list of critical raw materials. Equally, silicon metal is highlighted as critical and considered to be likely to improve the energy density of future Li-ion battery types.

## 1.3 What are the issues in the supply chain of battery raw materials?

Supply chains comprise several stages, starting with raw material sourcing, then refining materials into chemically active materials, followed by component and cell manufacturing, and finally where applicable necessary module/pack assembly (e.g. for large-capacity end-products such as xEVs and energy storage systems). The technically most complex and costly step along the battery value chain is the cell manufacturing.

At the start of the supply chain, there can be specific supply risks related to geopolitical stability in producing countries. For raw materials such as cobalt, mining in the Democratic Republic of the Congo (DRC) is associated with unstable political conditions and various business difficulties. According to BGR, last year 15–20 % of the cobalt produced in (and exported from) the DRC stemmed from artisanal and small-scale mining (BGR, 2018). This share fluctuates significantly depending on the actual price of cobalt. From a social point of view, working in such mines can expose miners to heavy metals through dust inhalation, food and water contamination and high levels of radiation and to increased risks of landslides. Poor sanitary conditions and insufficient safety measures in miners' camps are often observed. Harsh working conditions and widespread child labour are also reported (BGR, 2017; Öko-Institut, 2011).

Another supply risk issue relates to positive and negative price peaks affecting business stability and long-term investments in mining and refining capacities in particular. Despite the recent fears of shortages and price volatility, according to some analysts (McKinsey & Company, 2019), the supply of lithium, for example, is not expected to be an issue for the battery supply chain in the short or medium term. This is due to unused capacity and new mining projects coming onstream in the near future. This may be different for cobalt and nickel in particular. Not all nickel in the global supply chain is suited for Li-ion battery production. High-grade nickel products are economically efficient derived from the production of nickel sulphate, which is a principal ingredient in NMC (lithium–nickel–manganese–cobalt oxide) and NCA (lithium–nickel–cobalt–aluminium oxide) batteries. Because of past price collapses, the investments in refining capacity for nickel have been low, threatening the required supply of nickel class I (with a purity above 99.8 %) in particular.

In the case of global production of natural graphite, supply is concentrated and it comes predominantly from China. However, synthetic graphite is a viable substitute for natural graphite. Thus, the supply risk for graphite can be considered moderate.

Supply risk also relates to subsequent **refining of extracted minerals**: for instance, cobalt refineries are rarely located near the source mine sites. Instead, major refiners purchase cobalt concentrate from various mines, ship it to their own locations and refine cobalt into a usable form for cathode production. Following large investments made in this sector in China, the majority of cobalt refining takes place there, posing a second-level supply risk. Overall, China is the major supplier of around half of the volume of three key raw materials used in Li-ion batteries (i.e. cobalt, nickel and natural graphite). The same applies to lithium refining, for which there is currently no European capacity.

## 1.4 What EU policies and initiatives are relevant regarding battery raw materials?

There are a number of key EU policies and measures advocating a more sustainable supply of battery raw materials.

In 2008, the Commission adopted the raw materials initiative, which sets out a strategy for tackling the issue of access to raw materials in the EU. The strategy has three pillars that aim to ensure a fair and sustainable supply of raw materials from global markets, a sustainable supply of raw materials within the EU and resource efficiency, and a supply of ‘secondary raw materials’ through recycling.

The European innovation partnership on raw materials (EIP-RM) (EC, 2018a) is a stakeholder platform that brings together representatives from industry, public services, academia and non-governmental organisations. Its mission is to provide high-level guidance to the European Commission, Member States and private stakeholders on innovative approaches to the challenges related to raw materials. One of the tasks relates to enhancing the EU Raw Materials Knowledge Base and managing the RMIS, hence the provision of the latest battery raw materials data on the RMIS.

Another EIP-RM activity relates to the preparation of the EU Raw Materials Scoreboard. Here, specific information related to e-mobility and raw materials in batteries is provided in the introduction. Other research activities under the EIP-RM relate to conflict minerals and responsible sourcing as well as research and development on substitution and new battery chemistries for the future.

The circular economy action plan (CEAP) was adopted 4 years ago. This plan covered, among other things, improving the markets for secondary raw materials, including recovery of critical raw materials (CRMs) from batteries. This is discussed in more detail in the Critical Raw Materials and the Circular Economy – Background report (Mathieux et al., 2018). That report highlights that the EU is relatively well positioned globally with established collection and recycling practices. On 4 March 2019, the European Commission adopted a comprehensive report on the implementation of the CEAP.

More information on the EIP-RM, the CEAP and other policy documents and initiatives on raw materials can be found in the RMIS policy and legislation tile. In 2017, the renewed industry policy strategy targeted investments in a smart, innovative and sustainable industry for Europe. One of the actions under that strategy – a revised list of CRMs – helps to highlight the need for a secure, sustainable and affordable supply for EU manufacturing industry. Several of the CRMs are found in batteries.

As part of the third mobility package of the renewed industry policy strategy, the strategic action plan on batteries aims, mainly in its first pillar, to support the of the Battery Alliance’s (primary and secondary) raw material activities. The strategic action plan on batteries aims to develop a significant and fully competitive European battery cell manufacturing value chain.

In 2018, a recent overview of raw material developments was highlighted in a specific Commission Staff Working Document – Report on raw materials for battery applications. Various work streams of the strategic action plan on batteries are currently being implemented (see the Commission report on the implementation of the strategic action plan on batteries).

The Batteries Directive (2006/66/EC), is the only piece of EU legislation entirely dedicated to batteries. It establishes rules for batteries placed on the market in the EU regarding their content of hazardous substances and sets out specific rules for the collection, treatment, recycling and disposal of waste batteries and accumulators. It seeks to improve the environmental performance of batteries and accumulators and of the activities of all economic operators involved. The directive is under revision and will take into account technical developments, such as newer chemistries and applications, as well as further enhancing circularity.

For more information, in April 2019, the Commission report on the implementation of the Batteries Directive and its impact on the environment and internal market was released, as well as a Commission Staff Working Document on the evaluation of the directive. Information on the stakeholder consultations and the evaluation of the roadmap of the Batteries Directive is also available on the Commission's website.

## 1.5 Will there be sufficient raw materials for e-mobility?

The overall supply–demand balance depends on many factors. On the one hand, the demand for battery raw materials is expected to rise sharply, especially as the market for e-mobility increases. On the other hand, the supply side is also expected to increase, as there are many new mining and refining projects in the pipeline. The following chapters introduce step by step the latest data on supply and demand and provide more information on recent trends.

Reuse and recycling can have a significant mitigating effect on future material needs and offer distinct opportunities for Europe to improve circularity and access to secondary raw materials. The stocks and flows section provides information on market inputs and outputs as well as on accumulation of batteries in Europe.

Currently information on collection and recycling volumes is not yet included. This will be added as a separate new section of the RMIS at a later stage. In the coming year the JRC plans further comprehensive assessment of the main trends in supply, demand, stocks, reuse and recycling, covering all relevant battery raw materials and supply chain stages.

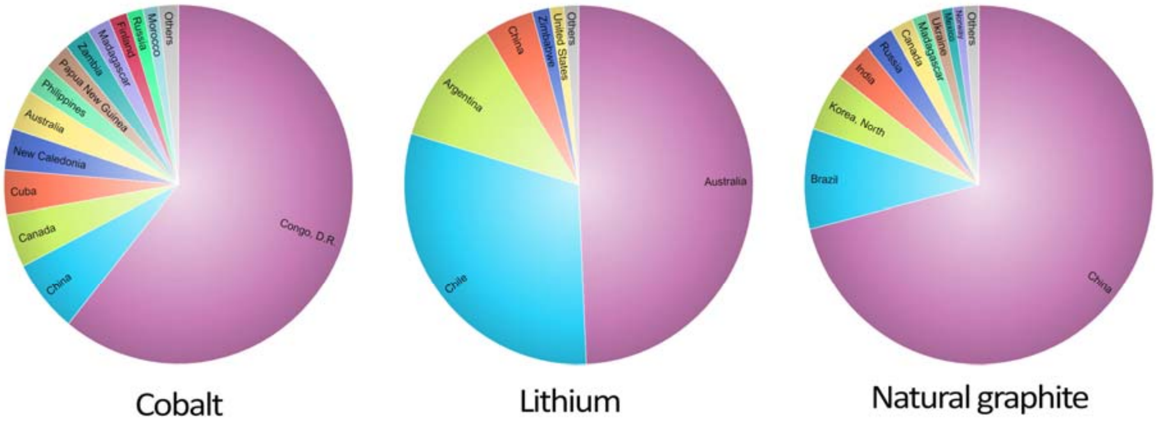
# 2 Supply

## 2.1 Where are battery raw materials sourced?

In 2016, 54 % of global cobalt from mines originated from the DRC, followed by China (8 %), Canada (6 %), New Caledonia (5 %) and Australia (4 %). Refined cobalt comes from China (46 %), Finland (13 %), Canada and Belgium (both 6 %).

Around 90 % of global lithium mine output from Chile (40 %), Australia (29 %) and Argentina (16 %) (Figure 3), mostly from brine and spodumene sources. Despite the recent fears of shortages and price spikes, the supply of lithium is not expected to be a major issue for the battery supply chain in the short or medium term because of sufficient capacity being available and coming online in the near future. Nevertheless, according to Roskill (2019) an increase in the currently low price is deemed necessary to support the development of new production capacity. China (45 %) hosts the majority of the world's lithium hard-rock minerals refining facilities. Chile (32 %) and Argentina (20 %) dominate refined lithium capacity from brine operations. In the EU, there are 14 exploration and mine developments in the pipeline in various Member States, of which six are at a late stage of development.

**Figure 3.** Global mine production output shares for cobalt, lithium and natural graphite per country



*Source*: RMIS raw material profiles

China supplies around 70 % of the global production of natural graphite, with the iron and steel industry being the main driver for its demand. About 10 % of natural graphite demand (typically higher grades) finds its way to battery anode material manufacturing. There are a significant number of exploration projects under development. At the end of December 2018 there were 157 known projects globally, 10 of which were located in Europe, with Finland, Germany and Sweden anticipating an increasing demand. Although more expensive, synthetic graphite is a viable substitute for natural graphite.

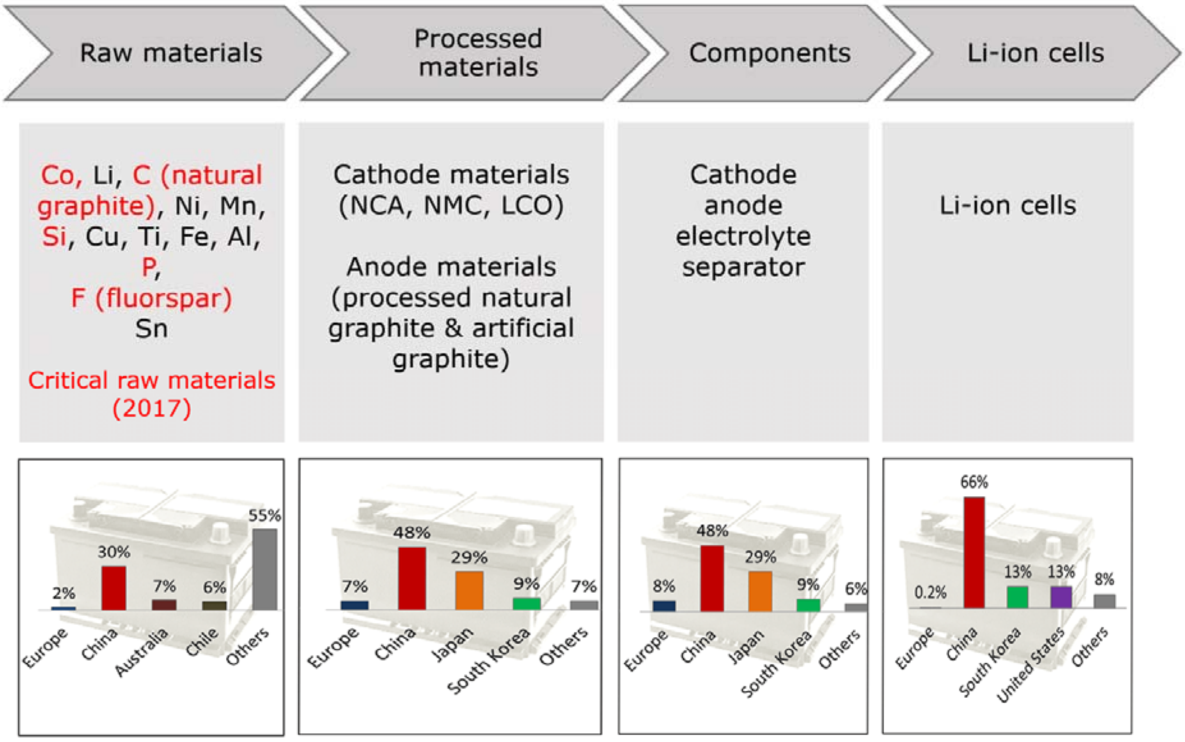
The supply of nickel ore is more diversified than that of lithium and cobalt. Still, two thirds originate from Indonesia, Philippines, Australia, Russia and Canada. For refined nickel, the main producer is China with about a 30 % share, followed by Russia, Japan, Canada and Australia. Europe's reliance on imports of nickel is about 56 %, with about 10 production locations onstream and another roughly 10 locations at a late stage of development. These are primarily located in Finland and Sweden. However, not all nickel in the global supply chain is suitable for Li-ion battery production. Specific new investments are in the pipeline to, for example, produce high-purity nickel sulphates feeding the production of nickel based cathode active materials.

More information on each battery raw material, including EU versus global production and the number of new mine development projects, can be found in the raw material profiles.

## 2.2 Where are the bottlenecks in the supply chain?

The bottlenecks are predominantly in Asia. For example, China is the major supplier along the whole Li-ion cell supply chain – from raw materials to battery cells. Other key players along the supply chain are Japan and South Korea for processed materials and components, plus South Korea and the United States for the production of Li-ion cells. Europe's current contribution to global manufacturing of cell components for Li-ion batteries is negligible (< 1 %) as indicated in Figure 4, showing the shares of the main players for each of the battery supply chain stages.

**Figure 4.** Li-ion batteries: key players along the supply chain



*Source*: Blagoeva et al., 2019

In more detail: a critical aspect is the lack of European capacity to produce important **processed materials** for Li-ion batteries, such as anode materials and NCA cathode materials. European companies are producing less than 20 % of the global volume of NMC and LCO (lithium–cobalt oxide) materials, which is deemed insufficient to satisfy the European demand for Li-ion batteries. Finally, refined materials are subsequently converted into battery-grade **semi-manufactured materials**.

Asia, represented by China, Japan and South Korea, supplies 86 % of the processed materials and **components** for Li-ion batteries globally, and China alone provides 48 %, followed by Japan and South Korea. Europe has a relatively small share of the supply at 7–8 %. Other countries deliver only 6–7 %, which gives very little margin for supply diversification. In particular, Europe is fully dependent on Asia for the supply of processed natural graphite, artificial graphite, NCA cathode material, anodes and separators. The supply concentrations in the various stages of the battery value chain is outlined above.

Europe is almost fully dependent on imports of **battery cells**, exposing the industry to supply uncertainties and potentially high costs. China is the major player in the manufacture of Li-ion cells – 66 % of global cell production. Other suppliers are South Korea and the United States with 13 % each. Europe's production is very marginal at only 0.2 % of Li-ion cells. Other suppliers provide around 8 % of the global supply; therefore, the margin for supply diversification is also limited in this case.

Europe's capacity to produce xEV **battery packs** in 2021–2023 is expected to increase to 40 GWh, increasing from the 3 GWh currently in place. In particular, new companies such as Northvolt in

Sweden, which is planning to ultimately realise 32 GWh of production capacity for battery packs, LG Chem in Poland and a few other developments will contribute to this planned production increase. Several of these production facilities are Asian investments. These European figures are in contrast to a current global capacity of 150 GWh, of which two thirds is located in China, and an expected capacity of 400–600 GWh in roughly only 5 years from now! For a more complete overview of planned production capacities, see Tsiropoulus et al. (2019).

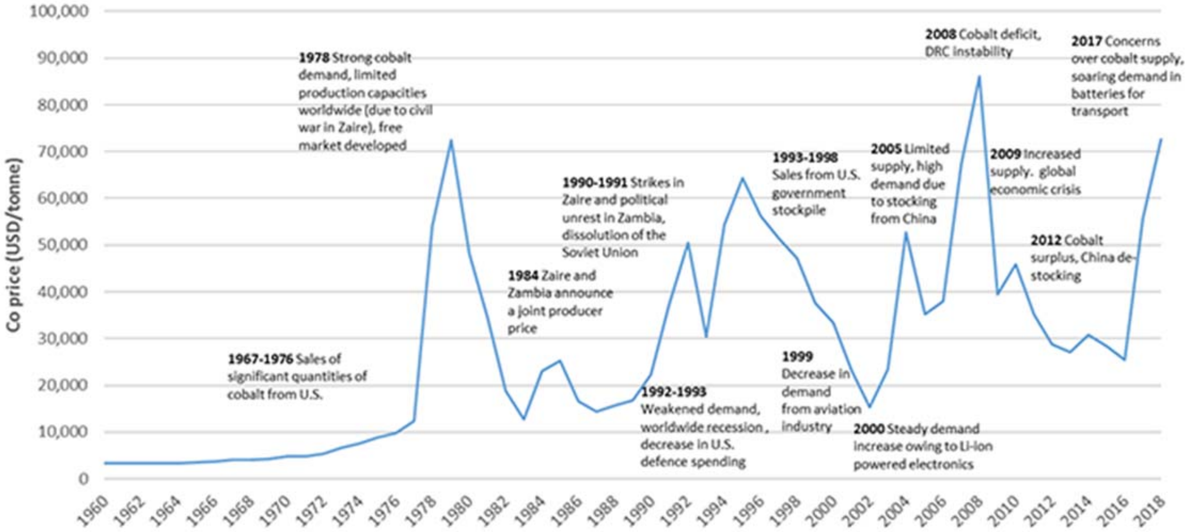
## 2.3 How do battery raw material prices affect the future global supply?

The key investment factor for future mine development projects is a stable price. This is needed for financial planning and business stability in order to commercially realise intended production projects. Mine projects are intrinsically financially risky and the risks of a downturn in prices significantly reduces incentives to develop the necessary future capacity.

As an example, for cobalt, there is significant price volatility and not only recently. Cobalt prices have been notably volatile since the late 1970s. Various events have influenced cobalt prices, ranging from de-stocking to geopolitical unrest in the DRC or recession and concerns over future supplies. Since 2000, cobalt demand has risen gradually, driven by strong demand for rechargeable batteries, used in portable electronic equipment. The significant price rises seen over the 2002–2004 and 2006–2008 periods were due to decreases in supply and uncertainty over the adequacy of future supplies, linked to a high level of global economic growth supported by strong Chinese demand. The rise in cobalt metal prices was interrupted by the global economic crisis, and prices decreased dramatically between 2008 and 2009 as supply exceeded demand.

In 2017, market expectations of an anticipated substantial increase in demand for battery raw materials in view of the increased penetration of xEVs prompted a sharp rise in cobalt prices: the price of cobalt in March 2016 was close to USD 22 000 per tonne, and it more than quadrupled within 2 years to more than USD 90 000 per tonne in March 2018, reaching a 10-year high. Since then, an oversupply of cobalt hydroxide from the DRC has brought about a period of continuing and drastic price cuts; in June 2019 (not displayed yet in Figure 5), cobalt prices dropped to around USD 30 000 per tonne.

**Figure 5.** Annual average prices of cobalt from 1960 to 2018 and significant events affecting cobalt prices



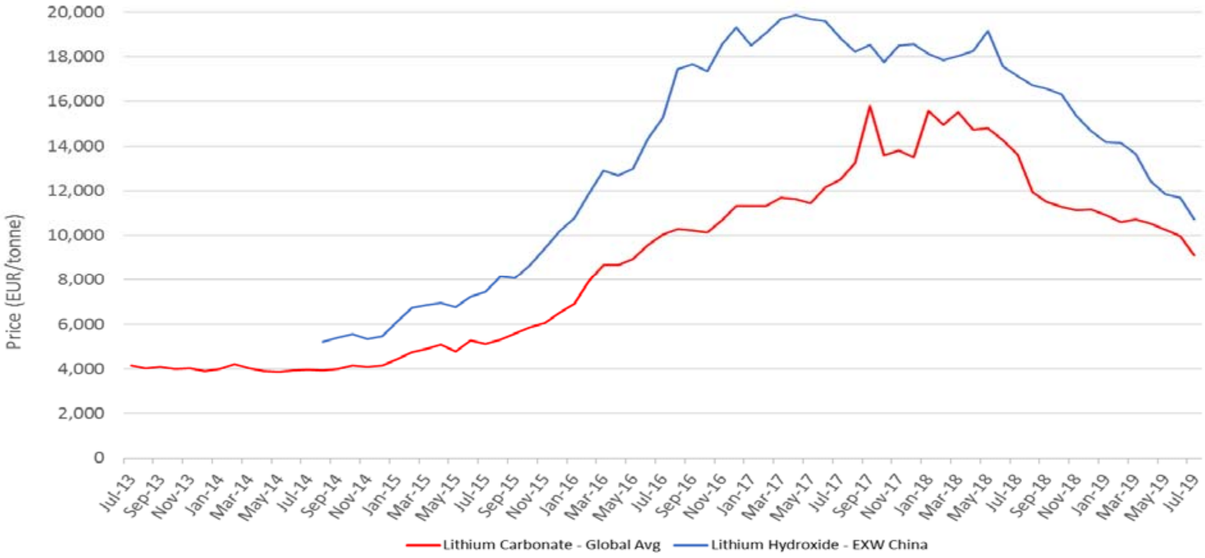
*Sources*: European Commission 2020; JRC compilation based on background data from USGS, 2013; DERA, 2017, 2018

From a short-term perspective, Lithium prices rose significantly from mid-2015 onwards, reflecting the very dynamic market developments in e-mobility and the industry's expectation of a sharp rise in demand in the future. Consequently, prices in the small lithium market nearly quadrupled within 3 years, reaching historical peaks (Figure 6). In particular, the global average price of lithium carbonate was around USD 5 200 per tonne at the end of 2014, and it rose by 260 % to USD 18 900 per tonne in March 2018. However, since then, a strong downwards trend in lithium prices has been observed.

The global average price of lithium carbonate in July 2019 had dropped by 42 % compared with the price in March 2018 to USD 10 300 per tonne.

Technically speaking, there has been a strong shift recently in battery manufacturing towards using lithium hydroxide instead of lithium carbonate.

**Figure 6.** Lithium carbonate (global average) and lithium hydroxide (China) monthly price trends (EUR/tonne)



*Source*: JRC compilation based on data from S&P Global Market Intelligence, 2019

The industry has to deliver supply growth to fuel the forthcoming wave of electric vehicle market penetration. The supply growth can only be sustained by functioning economics. However, current prices are providing limited incentive to develop much of the necessary capacity currently being evaluated or in the pipeline, and that in turn could impact future supply. The current price levels may not support the development of new capacity.

For more information on the overall cost development of Li-ion batteries for e-mobility and energy storage, see (Tsiropoulus et al., 2019).

# 3 Demand

## 3.1 How many new batteries are placed on the market?

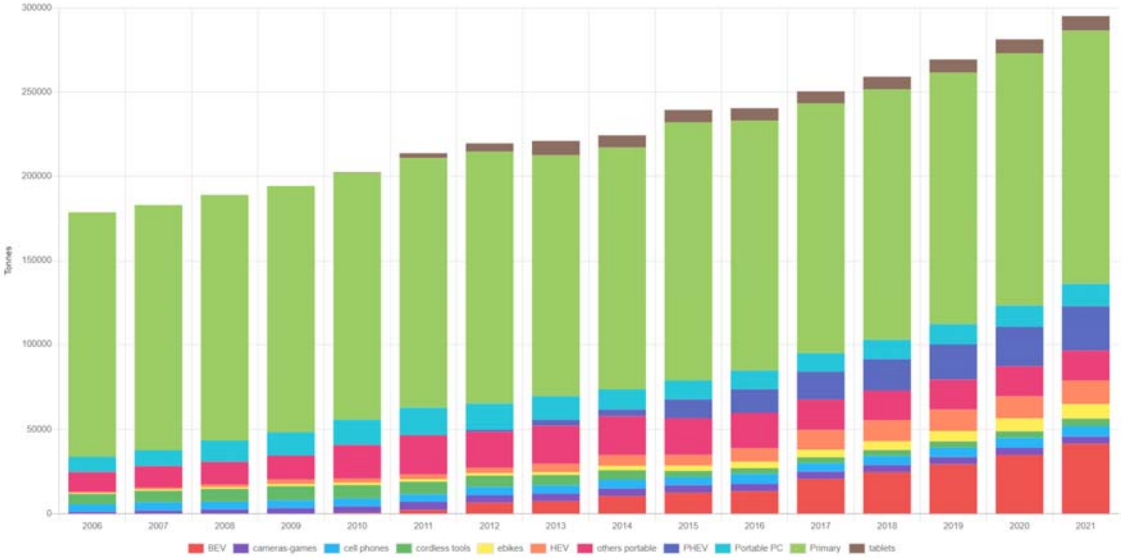
The data viewer developed for the RMIS website is based on a new update of the ProSUM battery data, realised in collaboration with researchers from TU Berlin and Recharge. These datasets complement the official Eurostat batteries dataset. For research purposes, the scope of the information in the RMIS tile is wider, covering all battery chemistries and applications, detailed composition trends, stocks and lifespans and longer times series. This includes checking the consistency of quantities placed on the market (inputs) and waste volumes generated (potential outputs) in relation to the computed and measured stocks.

A total of 2.65 million tonnes of batteries (all chemistries) were placed on the European market in 2018, and this is estimated to reach about 2.79 million tonnes in the year 2021. By weight, about 64 % of the batteries placed on the market are SLI batteries (for starting, lighting and ignition). This share consists of lead–acid rechargeable batteries mainly used in cars, followed by those for industrial applications, for example for medical equipment or power storage.

Other applications, such as e-bikes, cordless power tools, laptops and tablets (portable PC), are less relevant in terms of battery mass put on the market, but highly relevant for their material content.

Although still comparatively low in numbers, traction batteries used for e-mobility are increasingly contributing to total weights. In 2017, traction batteries already represented more than half of the total mass of all Li-ion applications placed on the market. Figure 7 shows that this trend is likely to continue in the coming years.

**Figure 7.** Total weight of batteries placed on the market in the EU-27, UK, Switzerland and Norway, 2006–2021



*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

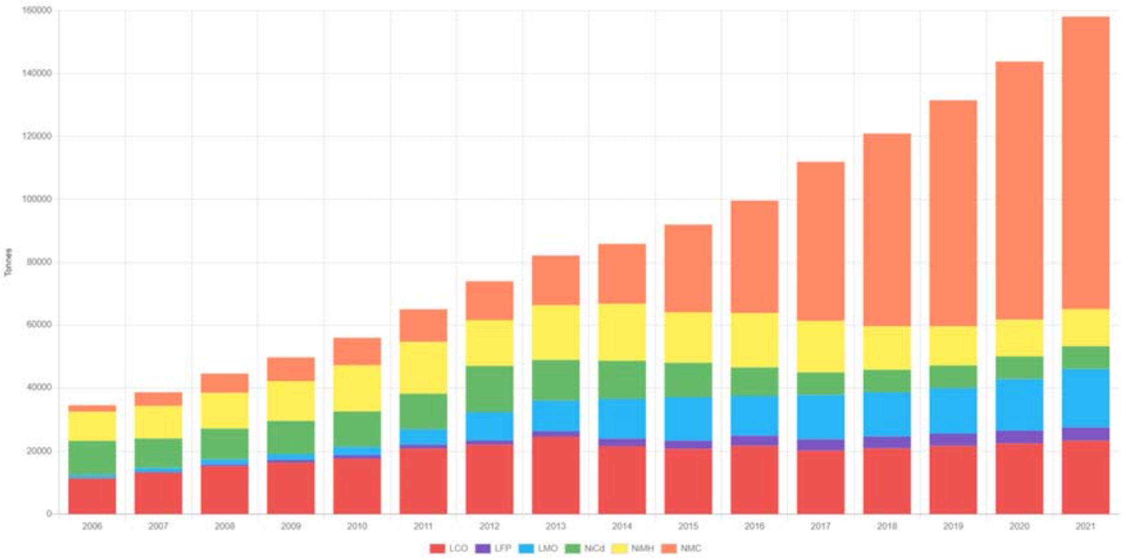
An interactive version of this chart is available in the data viewer – Total weight of batteries per application. Click on the top-left menu to select individual materials. Click on the legend keys at the bottom of the chart to customise the visualisation.

## 3.2 Which chemistries were used in the past and what are the main trends?

The new dataset available in the data viewer shows that battery types such as rechargeable batteries have been gaining an increasing market share relative to traditional single-use and SLI batteries. Until recently, nickel batteries were the main choice for hybrid vehicles, energy storage and electronic products, as shown in Figure 8. In recent years, Li-ion batteries have been quickly replacing nickel batteries across multiple applications. These trends obviously affect the amount and type of CRMs consumed over time.

The 2019 data update corrected previous ProSUM predictions on the chemistry mix expected. For instance, the previously (2016) expected shift in technology towards lower cobalt-containing NMC chemistries in the form of pouch cells, replacing LCO batteries in laptops and tablets has not materialised as quickly as expected. Instead, the new data show that LCO batteries remain the main technology for smartphones, tablets and the majority of laptops. These uncertainties related to market uptake will remain and will affect the forecasts presented. Hence, Figure 8 presents estimations for the period from 2018 until 2021, obtained by extrapolation of observed trends. Regular updates of the data shown are therefore needed, in particular on the demand from new applications such as xEVs becoming a reality. Furthermore, specific changes from one dominant chemistry to another need to be monitored closely.

**Figure 8.** Total weight of batteries placed on the market per chemistry, excluding lead–acid and single-use batteries, in the EU-27, UK, Switzerland and Norway, 2006–2021



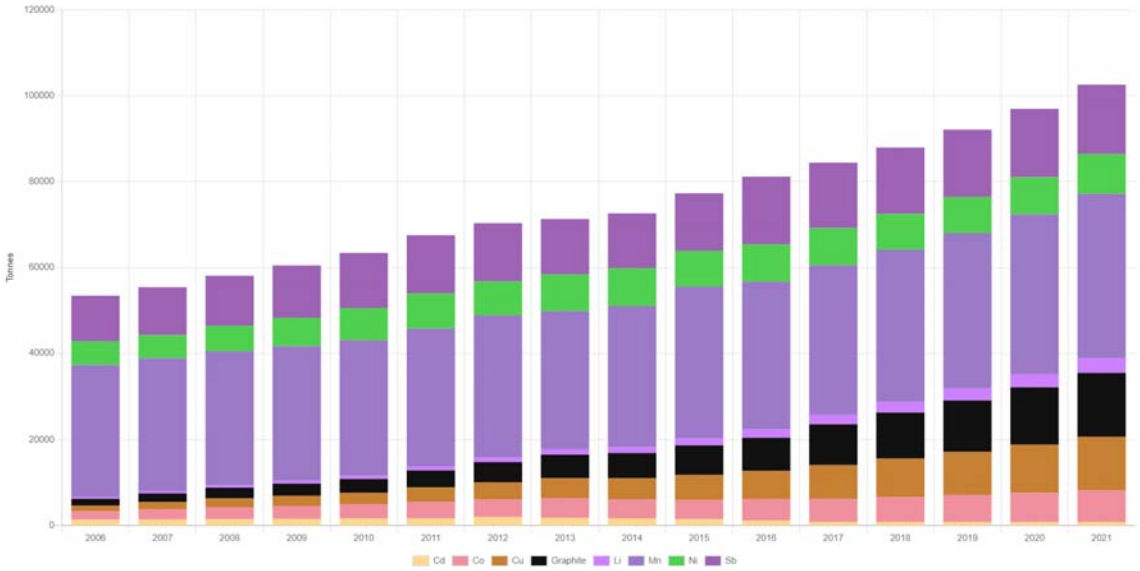
*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

An interactive version of this chart is available in the data viewer – Materials per battery chemistry. Click on the top-left menu to select individual materials. Click on the legend keys at the bottom of the chart to customise the visualisation.

## 3.3 What is the current raw material content in batteries?

Increasing pressures on the supply of cobalt are pushing the market towards reducing the cobalt content in cathode materials for Li-ion batteries. However, the new dataset shows that, despite the lower cobalt content, because of high increases in unit sales, the total mass of cobalt in batteries such as NMC, NCA  and LCO continues to increase rapidly. This is largely driven by the growth of the e-mobility sector. Figure 9 shows the amounts of raw materials in batteries placed on the market over time, for all relevant battery materials and present in all chemistries, excluding lead–acid and zinc. (In the data viewer click on the corresponding legend keys to (de)select.)

**Figure 9.** Total weight of raw materials placed on the market in tonnes, excluding lead and zinc, in the EU-27, UK, Switzerland and Norway, 2006–2021



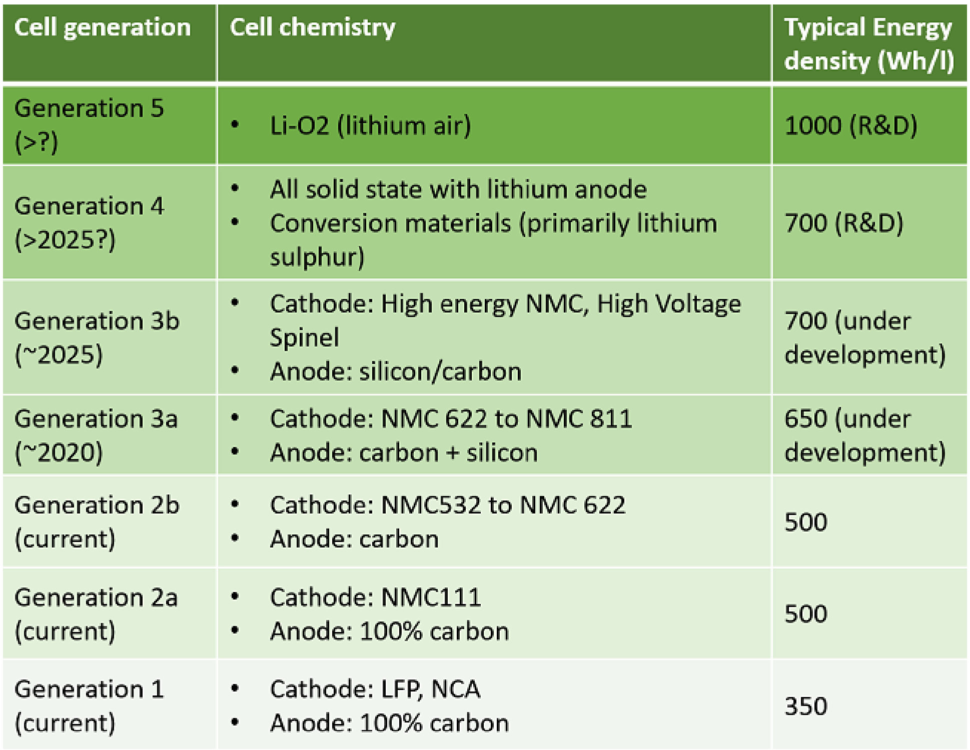
*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu/

An interactive version of this chart is available in the data viewer – Relevant raw materials in all batteries. Click on the legend keys at the bottom of the chart to customise the visualisation.

## 3.4 What will change in the future with new chemistries?

Incremental improvements in Li-ion batteries have recently been made in recent years in terms of gravimetric density (more Wh/kg) and volumetric energy density (more Wh/l) (Figure 10). Battery research now focuses on new anodes (lithium metal, silicon), new cathodes (high voltage, high capacity) and tighter packaging (less electrolyte, thinner separators, thinner current collectors). The main aim is to increase the specific energy stored (Wh/pack) while maintaining the high specific power output (W) capability. At the same time, enhancing safety is increasingly important. Here, research focuses on fire-retarding electrolyte additives, ionic liquid electrolytes, and the use of ceramic separators, ceramic coating of electrodes and solid-state batteries. Increasing safety, however, means a trade-off in specific energy and power. Such research also needs to address the potential issues linked to material supplies, in particular of lithium and cobalt, used in certain types of cathodes. For example, by changing the cathode chemistry mix, the overall proportion of cobalt in Li-ion batteries can be decreased as a result of its substitution with other materials such as nickel and/or aluminium (Blagoeva et al., 2019).

**Figure 10.** Future chemistries and energy densities for Li-ion batteries



| Cell generation | Cell chemistry | Typical Energy density (Wh/l) |
|---|---|---|
| Generation 5 (>?) | • Li-O2 (lithium air) | 1000 (R&D) |
| Generation 4 (>2025?) | • All solid state with lithium anode<br>• Conversion materials (primarily lithium sulphur) | 700 (R&D) |
| Generation 3b (~2025) | • Cathode: High energy NMC, High Voltage Spinel<br>• Anode: silicon/carbon | 700 (under development) |
| Generation 3a (~2020) | • Cathode: NMC 622 to NMC 811<br>• Anode: carbon + silicon | 650 (under development) |
| Generation 2b (current) | • Cathode: NMC532 to NMC 622<br>• Anode: carbon | 500 |
| Generation 2a (current) | • Cathode: NMC111<br>• Anode: 100% carbon | 500 |
| Generation 1 (current) | • Cathode: LFP, NCA<br>• Anode: 100% carbon | 350 |

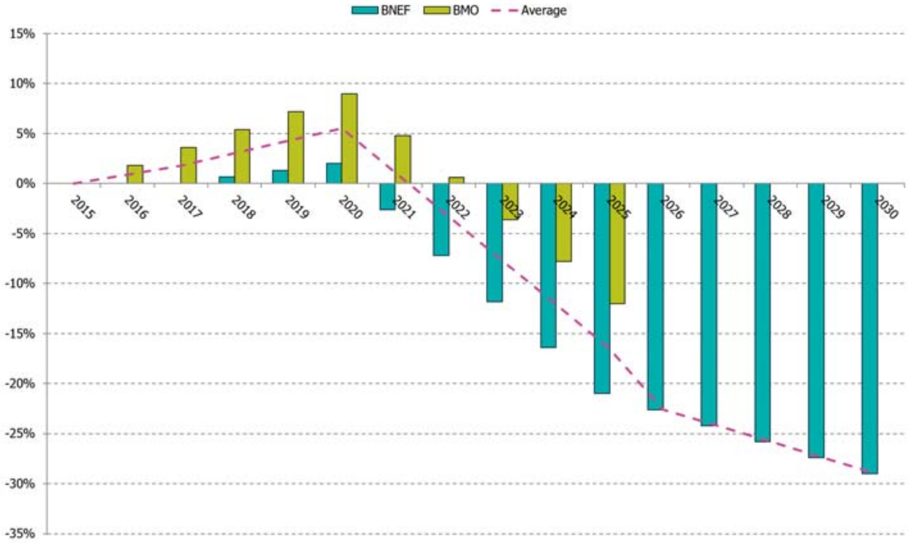
*Source*: JRC compilation based on Commission Staff Working Document – Report on raw materials for battery applications (EC, 2018b)– and IDtechX, 2018

A number of risk factors, including price volatility and industry concerns over supply shortages, have created shifts in the chemistries used for rechargeable batteries. Over time, this will lead to a decrease in the use of cobalt in the average battery. It is expected that the use of NMC substitutes that are lower in cobalt will prevail in the long term. Although not happening as quickly as anticipated, for example LCO containing 60 % cobalt, applied especially in electronics, is likely to be gradually replaced by NMC with a cobalt content of 10–30 %.

In the context of xEV batteries, several NMC configurations with different cobalt contents are currently under development. Today, NMC111 (containing nickel–cobalt–manganese in the proportion of 1:1:1) is the most commonly used. Until 2020, either NMC111 or NMC532 is thought to remain the first choice for xEVs. Such a trend, combined with the use of NCA, now containing 14 % cobalt, and NCA+, containing 5 % cobalt in the future, and the reduced use of cobalt-free cathodes (e.g. LFP – lithium–iron–phosphate), at least in Europe, is likely to push up demand for cobalt before it starts to decline after 2020, driven by substitution. Around 2025 and 2030, other chemistries, such as NMC622 and NCM811, requiring less cobalt and with higher nickel and aluminium contents are increasingly likely to be used.

Although there is broad consensus over the reduction in cobalt consumption in batteries (e.g. less cobalt per kWh), at least from 2020 onwards, there is no general agreement on which cathodes will be prevalent in the future (Alves Dias et al., 2018). The latest estimate of the combined effect of this substitution and improvement is shown in Figure 11, representing the average cobalt content over time per battery.

**Figure 11.** Reduction in cobalt content per battery



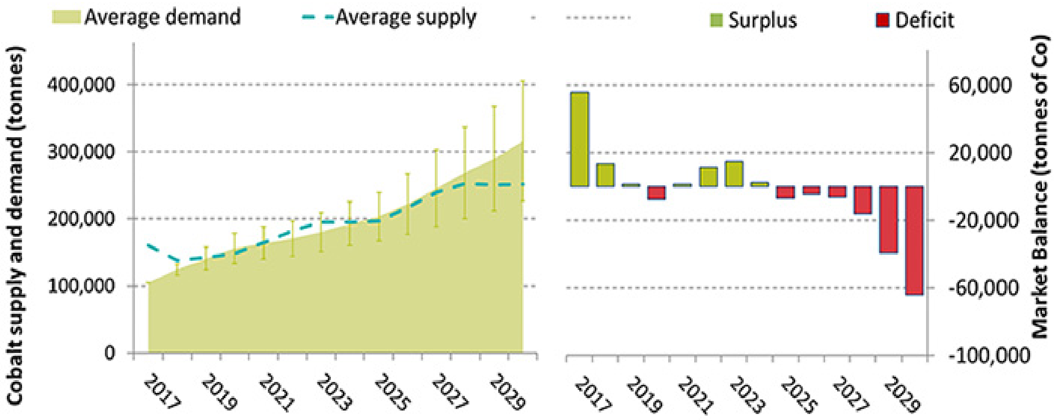
*Source*: JRC compilation from Alves Dias et al., 2018

## 3.5 How will e-mobility affect the demand for raw materials?

The answer depends on many factors: trends in the supply, the opening of new mines, the actual speed of xEV uptake in many continents and the change in mobility systems will affect the combined totals. Moreover, the level of substitution of materials, the level of reuse and recycling and other factors such as prices for raw materials, technical and environmental/social constraints in increasing production, and the technical and economic lifetime of battery products all significantly affect the balance between supply and demand. The JRC report *Cobalt: demand–supply balances in the transition to electric mobility* (Tsiropoulus et al., 2019) gives an overall assessment, as displayed in Figure 12.

The assessment as well as the current (2019) trends in cobalt prices, which have seen relatively low prices recently (see supply section), reveals a situation that is not ideal for long-term investment in cobalt mining: there is an expected over-supply in the near future and significant potential for deficits after 2025. Figure 12 shows on the left-hand side the total global demand for cobalt (solid green bars), based on the average of various e-mobility scenarios, and the projected average supply (dashed blue line), based on actual (planned) production volumes. The right-hand side of the figure zooms in on the difference between supply and demand. It should be noted that these values, in particular those in the right-hand panel, are highly uncertain. Nevertheless, the general trend indicates a future shortage of cobalt, in spite of significant cobalt substitution efforts already being taken into account.

**Figure 12.** Prognosis for the global cobalt supply–demand balance, 2017–2030
*Source*: Alves Dias et al., 2018



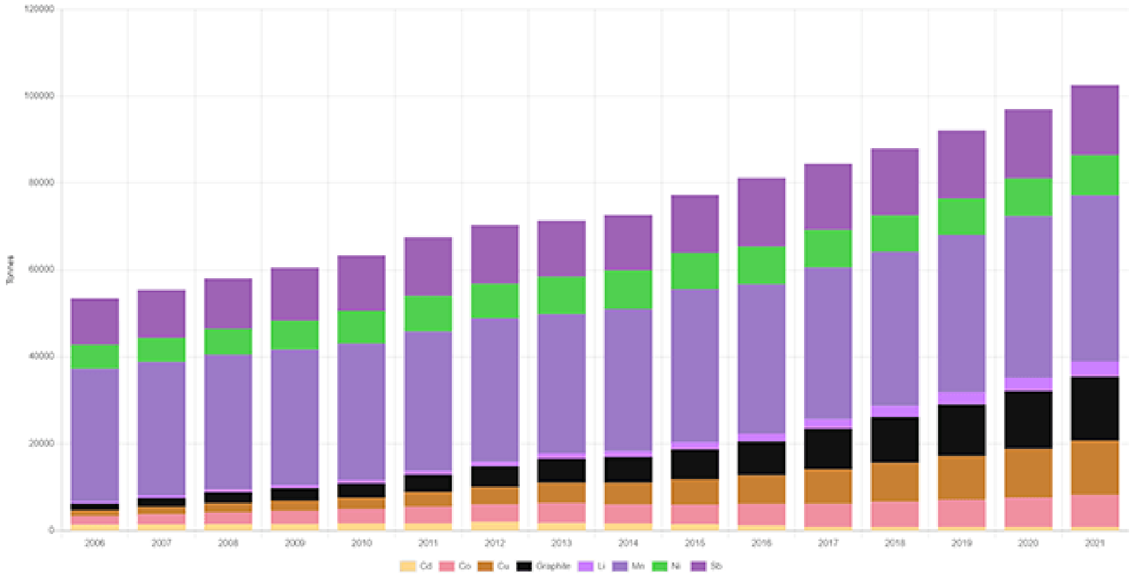
# 4 Stocks and flows (of battery raw materials)

## 4.1 How many battery raw materials are in in-use stocks or hibernated in the EU?

Based on the battery compositions research tool, created in the ProSUM project and further developed in the ORAMA project on optimising the quality of information in raw material data collection across Europe, market inputs and stocks and waste generation potential are computed. A sales–lifespan approach is taken for each chemistry–application combination by applying a specific set of Weibull parameters. These describe the lifespan distribution for each entry. This mathematical approach is identical to the common methodology for determining market inputs and waste generated as set out in the Waste Electrical and Electronic Equipment (WEEE) Directive. The units of portable batteries and the number of electronic items placed on the EU market are aligned. More information on the data sources used is available in the methodological notes.

Based on this approach, the following results are obtained for the stocks of battery raw materials present in the EU-28. Figure 13 shows that in the last 15 years the stocks of relevant battery raw materials accumulating in the EU have more than doubled, with the highest growth rates observed for cobalt, copper, graphite and lithium.

**Figure 13.** Growth of battery raw materials in tonnes in stocks in use and hibernated, excluding lead and zinc, in the EU-27, UK, Switzerland and Norway, 2006–2021



*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

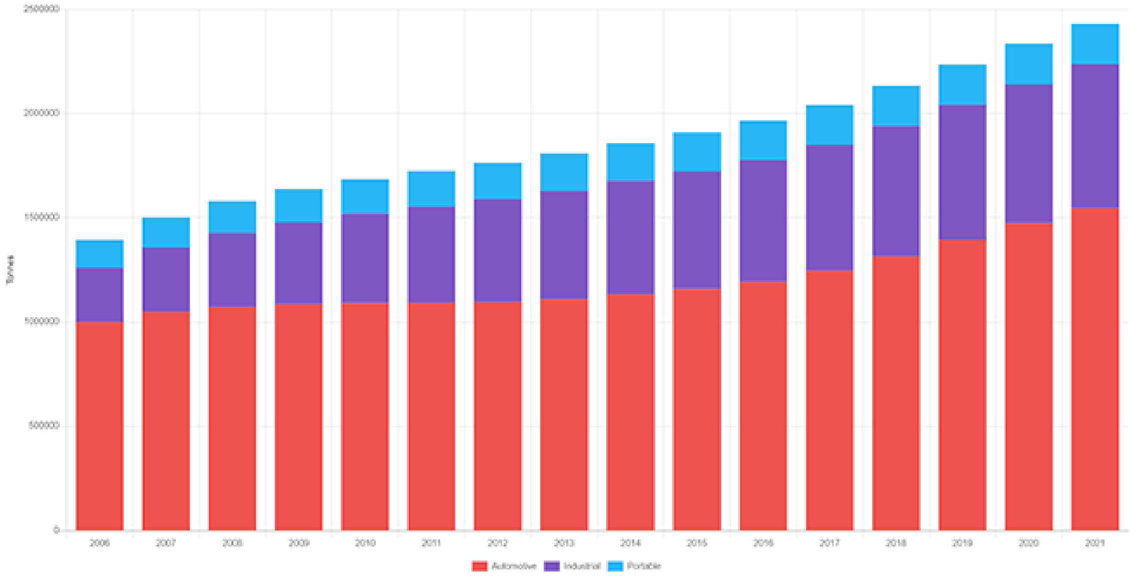
An interactive version of this chart is available in the data viewer – Relevant raw materials in all batteries. Click on the legend keys at the bottom of the chart to customise the visualisation. Select below the chart to view by 'PoM', 'Stock' and 'Waste' to see the values for different life cycle stages

## 4.2 How much battery waste is potentially being generated in the EU?

Reporting obligations concerning batteries are regulated by the Batteries Directive (2006/66/EC). Three battery types are distinguished: portable, industrial and automotive batteries. For portable batteries, three subtypes are relevant: lead–acid (PbA), nickel–cadmium (NiCd) and other batteries.

Figure 14 shows the amounts of waste batteries generated over time if they are grouped according to the Battery Directive category. There is significant growth over the years in the total amount of waste batteries potentially becoming available for collection and recycling. It should be kept in mind that these amounts are the (potential) total number or weight of products estimated to be discarded and physically leaving the stock as waste. This includes batteries for reuse leaving the EU in the form of exports of second-hand electronics and used vehicles. This reduces the theoretical volume that could be collected. More detailed numbers are available in the data viewer.

**Figure 14.** Total weight of potential battery waste generated in the EU-27, UK, Switzerland and Norway, 2006–2021, grouped by types of battery



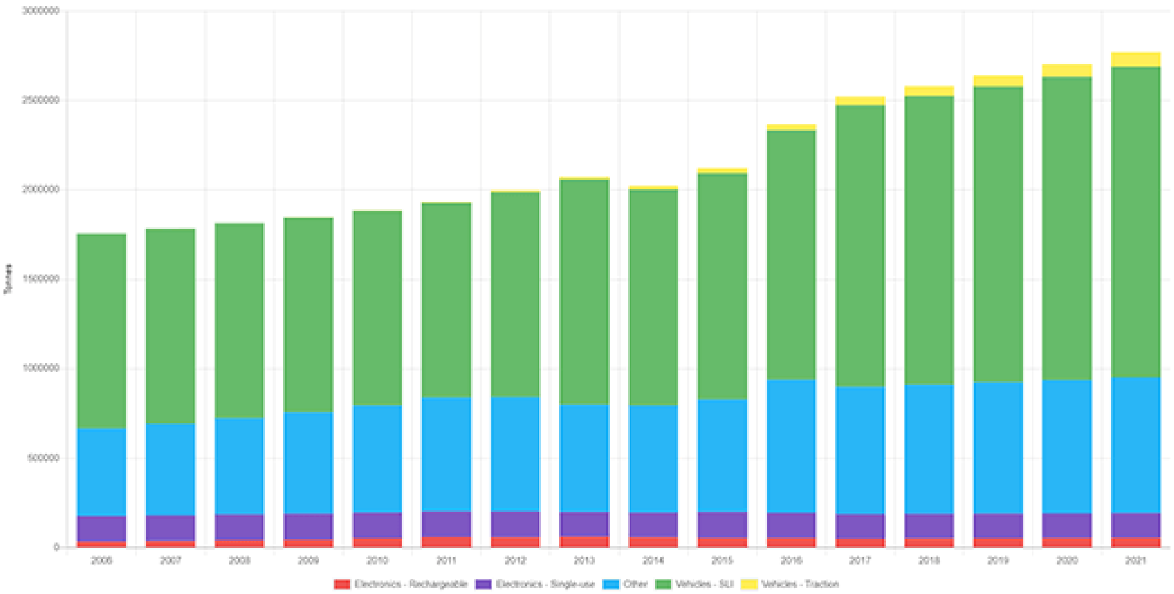
*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

An interactive version of this chart is available in the data viewer – Materials per Battery Directive. Click on the top-left menu to select individual materials. Click on the legend keys at the bottom of the chart to customise the visualisation

## 4.3 What is the share of traction batteries in the totals?

Li-ion batteries play a dominant role in the xEV battery market and therefore deserve special attention. Figure 15 shows in yellow the total weight of the new types of traction batteries for xEVs compared with the total market inputs of other types of batteries. To provide more detail than Figure 14, automotive batteries are split into vehicle traction versus SLI batteries. Portable batteries are split into electronic single-use versus rechargeable batteries. The latter portable–rechargeable category includes batteries used for e-bikes. Other batteries include all other and industrial batteries, but exclude traction batteries, now shown separately.

**Figure 15.** Total weight of batteries placed on the market (tonnes), divided per sector, EU-27, UK, Switzerland and Norway, 2006–2021



*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

An interactive version of this chart is available in the data viewer – Materials per sector. Click on the top-left menu to select individual materials. Click on the legend keys at the bottom of the chart to customise the visualisation

Figure 15 shows that traction batteries have a relatively small share of the market, but these volumes will increase sharply and form a significant share of total battery volumes in the future.

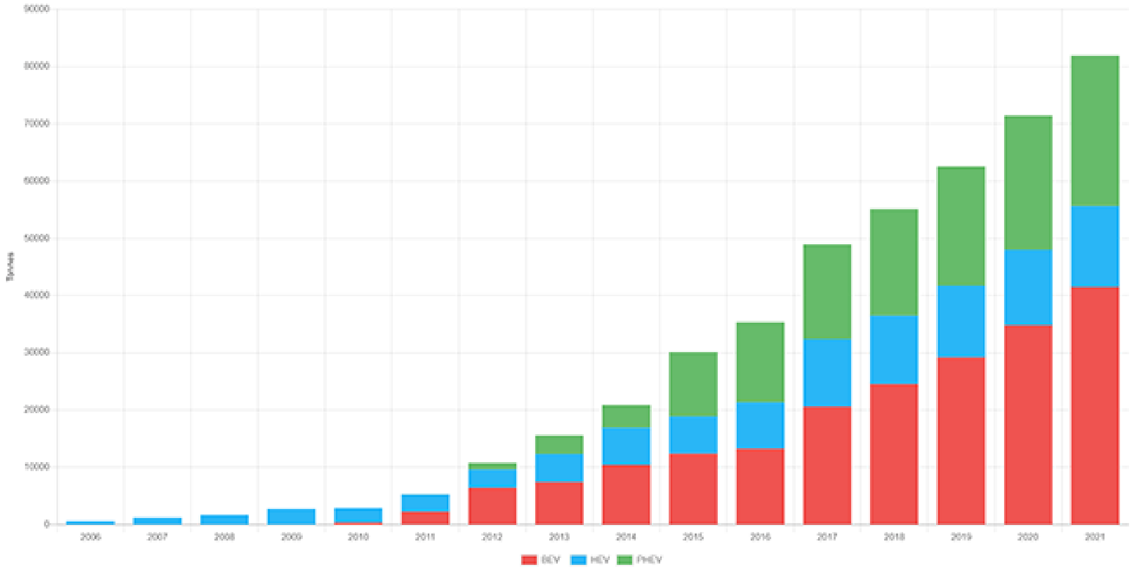
## 4.4 What is the effect of the new traction batteries on raw material demand?

The total amounts placed on the market per xEV drivetrain – hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – are shown in Figure 16. Apart from Li-ion batteries, nickel–metal hydride (NiMH) batteries still play a role in HEVs and PHEVs. Apart from nickel, NiMH batteries contain a variety of CRMs such as cobalt and rare Earth elements. More detailed data on raw materials per traction battery type are available in the data viewer. Here, the effects of the amounts of new traction batteries placed on the market, in-use stock and potential waste generated can be investigated for each individual material. More information on the number of xEVs is available on the Eurostat website.

Currently, there are four main chemistries used in the xEV sector: NMC, NCA, lithium–manganese oxide (LMO) and lithium–iron phosphate (LFP). A fifth chemistry on the horizon is lithium–titanate (LTO). Each of these chemistries have different advantages and disadvantages related to performance, lifetime, costs, energy density and power density (Hill et al., 2019).

A case study was conducted as part of the ORAMA project, looking at improved datasets of batteries in xEVs, updated classification code lists and CRM flows in end-of-life vehicles (ELV) in Norway. In Wagner et al. (2019), specific data are available on the chemistry and weight of the battery packs per vehicle type. The market for xEVs is currently growing at a rate of more than 25 %, depending on the application and region. A diversification in the application of the technology beyond cars to buses, lorries, other light and heavy commercial vehicles and even drones can be observed from market data (VITO et al., 2018).

**Figure 16.** Total weight of batteries placed on the market in per vehicle drivetrain (tonnes), EU-27, UK, Switzerland and Norway, 2006–2021



*Source*: 2019 TU Berlin/Recharge/JRC update for www.urbanmineplatform.eu

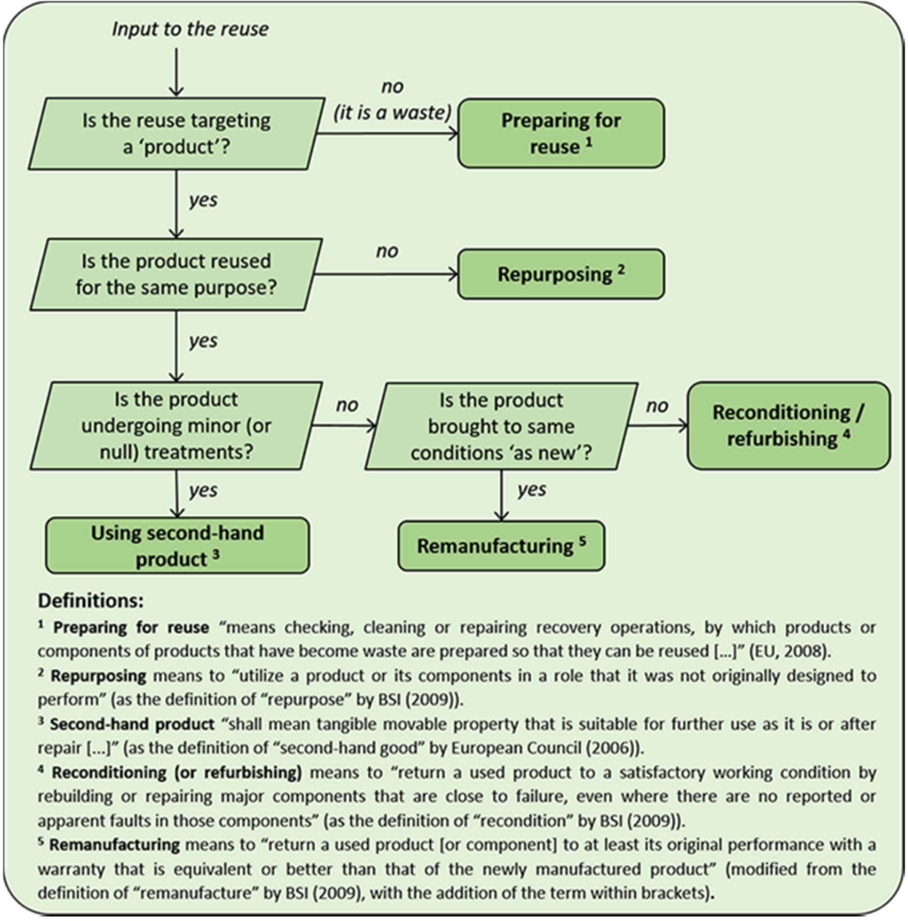
An interactive version of this chart is available in the data viewer – Materials in e-mobility batteries. Click on the top-left menu to select individual materials. Click on the legend keys at the bottom of the chart to customise the visualisation.

# 5 Reuse, repurposing and remanufacturing

## 5.1 What is the difference between reuse, remanufacturing and repurposing?

After their use in xEVs, batteries have to be properly collected and recycled, in accordance with the Batteries Directive and ELV Directive. However, their lifetime can be further extended through different strategies. Considering the 'level of treatment undertaken and the quality of the output' (Ardente et al., 2018), battery packs can be remanufactured to be reused again as traction batteries in vehicles or repurposed to be used in applications other than the xEVs. An overview of these strategies and definitions is provided Figure 17.

**Figure 17.** Strategies for and definitions of reuse, repurposing, reconditioning, refurbishing and remanufacturing



**Definitions:**

[1] **Preparing for reuse** "means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused [...]" (EU, 2008).

[2] **Repurposing** means to "utilize a product or its components in a role that it was not originally designed to perform" (as the definition of "repurpose" by BSI (2009)).

[3] **Second-hand product** "shall mean tangible movable property that is suitable for further use as it is or after repair [...]" (as the definition of "second-hand good" by European Council (2006)).

[4] **Reconditioning (or refurbishing)** means to "return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components" (as the definition of "recondition" by BSI (2009)).

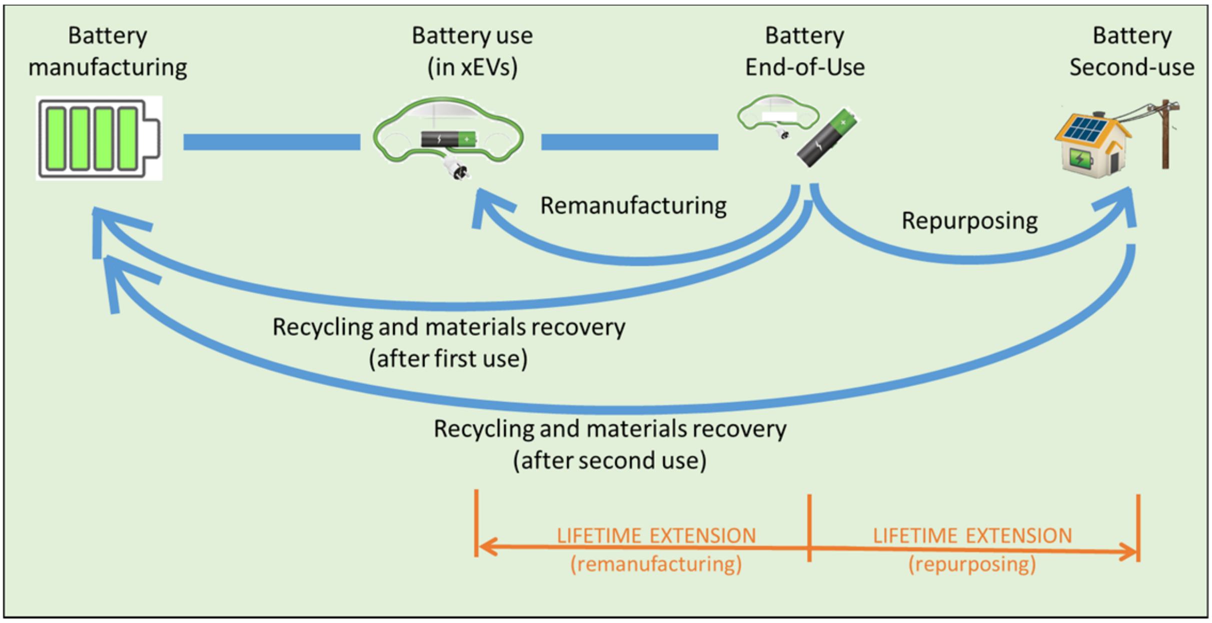
[5] **Remanufacturing** means to "return a used product [or component] to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product" (modified from the definition of "remanufacture" by BSI (2009), with the addition of the term within brackets).

*Source*: Ardente et al., 2018

## 5.2 What will happen with traction batteries after first use?

Batteries removed from xEVs typically have a residual capacity ranging between 60 % and 80 % of the nominal capacity. Therefore, they can be reused in xEVs (i.e. through remanufacturing), or their lifetime can be further extended though adopting them for less energy-demanding applications (i.e. through repurposing), such as energy storage for residential houses. Hence, the resource efficiency of batteries can in principle be improved by their second use, as illustrated in Figure 18.

**Figure 18.** Schematic representation of the end-of-life patterns for xEV Li-ion batteries



*Source*: Bobba et al., 2019

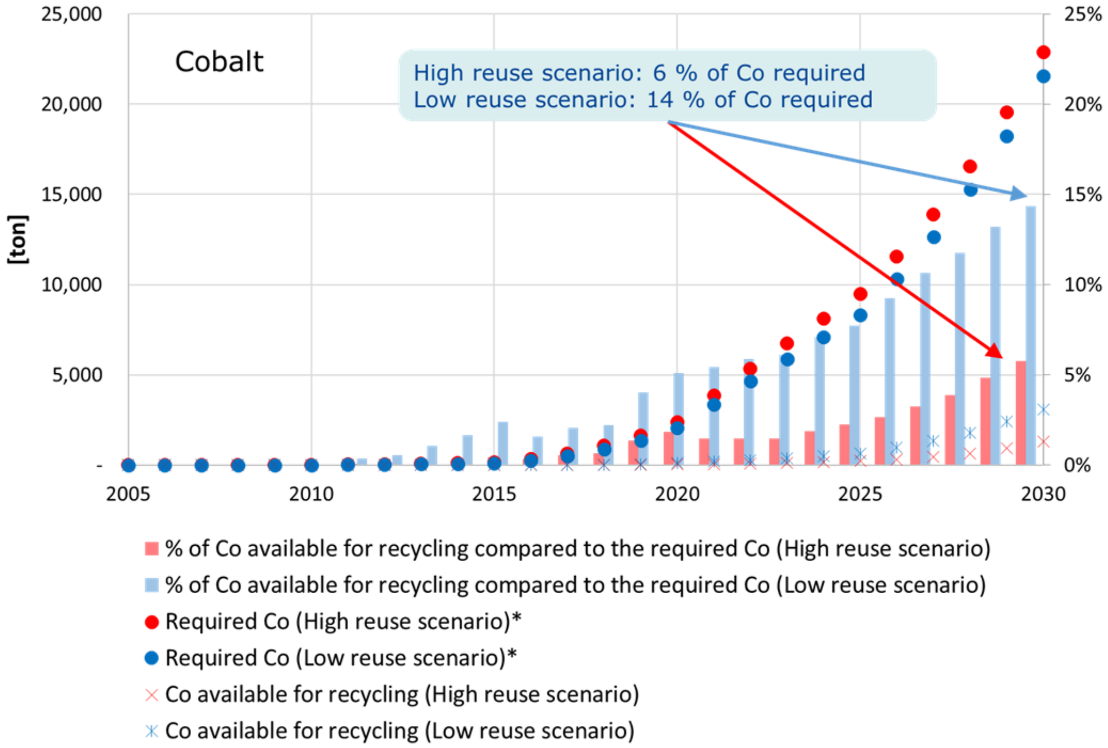
## 5.3 Is repurposing and recycling of batteries good for the environment?

Knowledge about repurposing and second use of batteries is still limited, but there are already some industrial initiatives and research projects worldwide undertaking technical assessments and focusing on the sustainability of second use of batteries. The JRC SASLAB project proved that second use of batteries is technically feasible (Podias et al., 2018) and can bring life cycle environmental benefits. This is especially the case when repurposed batteries are coupled with sources renewable energy , that is, when more of the electricity mix is originating from wind and solar power (Bobba et al., 2019; Richa et al., 2015). However, extending the lifetime of batteries through second use can decrease the amount of secondary raw materials recirculating in the EU economy (Bobba et al., 2019). In any case, according to the Commission Staff Working Document on the evaluation of the Batteries Directive, the environmental impact of repurposing and its economic viability remains under discussion. But it is widely accepted that the result depends on several scientific, technical, social and economic considerations.

In Figure 19, the red and blue dots represent the trend in the total demand for cobalt, taking into account a high (red) versus low (blue) level of second life. The high-reuse scenario is assumed to be 70 % of collected traction batteries from both full BEVs and PHEVs to be available for repurposing plus 20 % of collected traction batteries to be available for remanufacturing. The low-reuse scenario assumes repurposing of collected traction batteries from both BEVs and PHEVs to linearly increase from 2005 to 2030 from 0 % to an assumed level of 20 %, with no remanufacturing. The blue and red dots represent the total amounts of cobalt required for BEVs and PHEVs in Europe until 2030 for both scenarios.

The red (high-reuse scenario) and blue (low-reuse scenario) bars represent the percentage that recycling could fulfil relative to the demand in the same year. The lower levels represented by the bars compared with the dots is due to the time it takes before reused batteries are out of use again; for the low-reuse scenario, the cobalt available for recycling is less than 15 % of the projected demand for new batteries up until 2030. For the high-reuse scenario, which means extending the lifetime, recycling can only fulfil less than 6 % of the cobalt demand in the same year. This means that, due to the lifetime delay, recycling can only play a limited role in the medium term to fulfil the total demand for cobalt.

**Figure 19.** Cobalt required for BEVs and PHEVs, EU-28, (for NMC and NCA chemistries only) and cobalt available for recycling for two scenarios



*Source*: Adapted from Bobba et al., 2019

As a general conclusion, more reuse, refurbishment and repurposing of materials could reduce the intensity of the environmental pressures due to mining new raw materials by keeping materials in the loop for longer. At the same time, the short-term availability of secondary raw materials could be reduced as a result of the increased residence time of battery materials – about an additional 8 years compared with direct materials recycling. This is also highlighted in the flagship JRC report on the future of road transport (Alonso Raposo et al., 2019). More information on the collection and recycling of batteries will be added in the course of 2020.

# 6 (New) Data viewer

## 6.1 Data sources

The Research Centre of Microperipheric Technologies of Technische Universität Berlin (TUB) and Recharge, commissioned by the JRC, reviewed, updated and consolidated data on secondary raw materials from batteries. The datasets included in the RMIS cover the years 2000–2016 and provide extrapolated trends up to 2021 for EU-27, UK, Switzerland and Norway, 2006–2021, based on observed trends, market information and expert interviews. These data are an update on the battery information provided by the ProSUM project.

A variety of data sources is compiled, updated and combined to get a comprehensive picture of the total mass of batteries placed on the European market. Data originating from Avicenne on the volumes of rechargeable batteries are combined with information sourced from Eurostat and the European Alternative Fuels Observatory (EAFO). These are linked to statistics from several national authorities and to the ProSUM data for the number of electronic items. The extensive data structure takes into account battery lifetimes to calculate battery stocks and waste generation trends. Together with expert interviews, the chosen approach allows detailed differentiation between electrochemical systems and applications used in portable, industrial and automotive batteries.

Compared with the ProSUM data, the updated dataset includes more accurate information for the market for 2016–2017. It includes a review of the world battery market per application, cross-checking of the battery chemistries according to their applications, and a review of the quantities placed on the market in units, their residence times in different applications and the changes in chemical composition over time and for a longer time series. The EU-28 specific stocks and flows models are updated to calculate the batteries residing in stock in the EU and the expected waste generation for each of the 52 combinations of chemistry (electrochemical family) and application (see methodological notes).

From these data, the quantities on the market are assessed and compiled per country for the EU-28. The stocks and flows of CRMs and other metals are calculated using composition data for 20 elements, including aluminium, antimony, cadmium, cobalt, copper, lithium, manganese, natural graphite, nickel, niobium, lead, rare Earth elements and zinc.

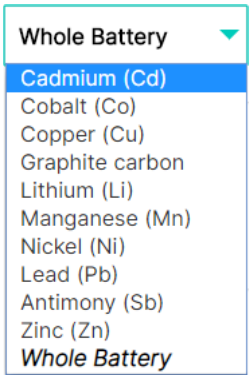
More disaggregated data per country and detailed chemistry is available at www.urbanmineplatform.eu (currently being updated).

## 6.2 How to use the data viewer

The data in the data viewer are aggregated at the EU-28 level and, where present, the 10 most relevant materials are highlighted (antimony, cadmium, cobalt, copper, graphite, lithium, manganese, nickel, lead, zinc). All data are represented as totals in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021, for the years 2006–2021. The data from 2018 to 2021 are forecast from existing observed trends. They are not based on policy scenarios or on demand scenarios provided by commercial entities.

In all charts except one, in the top left corner either the individual material or the total battery weight can be selected (Figure 20).

**Figure 20.** Selection of ‘Whole Battery’ versus individual materials



As not all battery materials, for example plastics and electrolytes, are represented in the data viewer, the sum of the weights of the individual materials **does not equal** the total battery weight. The total battery weight, however, does include these additional materials and components, including the weight of the electrolytes, packaging and battery management system.

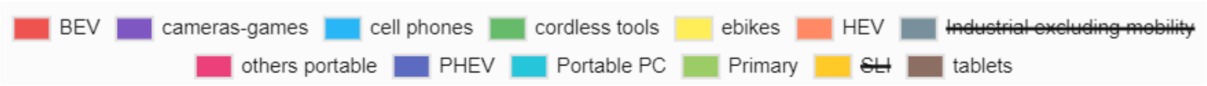
For each chart provided, the following life cycle stage can be chosen (Figure 21): placed on the market (PoM) as new batteries; residing as in-use and hibernated batteries in stock in households and businesses; and generated as waste (potential).

**Figure 21.** Selection of Placed on Market (POM, Stock or Waste stage

View by ● PoM ○ Stock ○ Waste

In addition, the legends at the bottom of the chart can be selected or deselected to customise the chart and to see the trends for individual applications with relatively low values (Figure 22).

**Figure 22.** Selection of individual applications



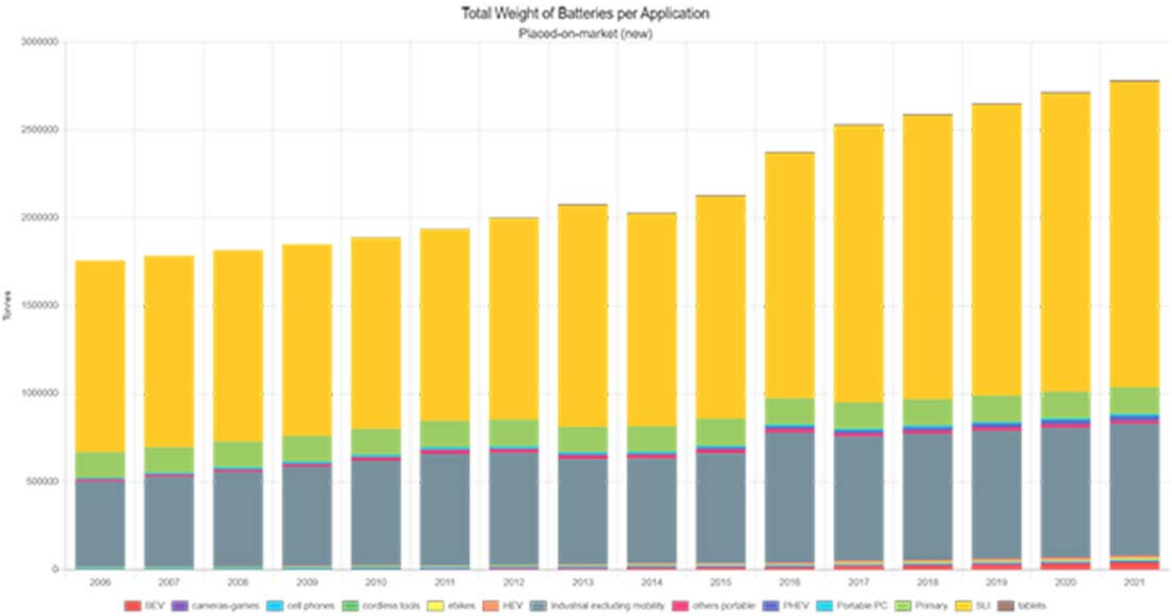
The following six starting visualisations are provided to access and visualise the battery dataset.

### 6.2.1 Total weight of batteries per application

This graph illustrates the total weight of batteries per application (Figure 23). Apart from the active materials, other materials and components, such as electrolytes, packaging and the battery management system, are included in the total weight.

Data are in tonnes for the EU-27, UK, Switzerland and Norway for the years 2006–2021. The data from 2018 to 2021 are forecast.

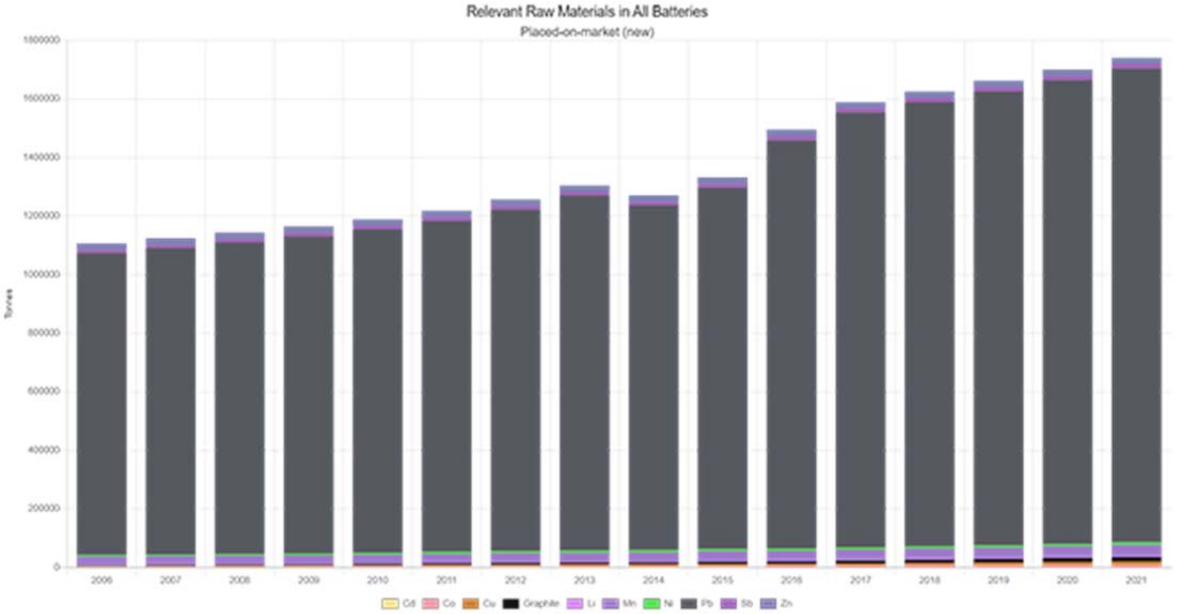
**Figure 23.** Total weight of batteries per application, 2006–2021



### 6.2.2 Selected materials in batteries

This graph illustrates the **total weight of raw materials** in all possible battery types, including PbA, single-use (primary) batteries and industrial batteries (Figure 24). The trends for one or more relevant materials can be observed by (de)selecting individual materials by clicking on the legend for the battery type. Data are in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021. The data from 2018 to 2021 are forecast.

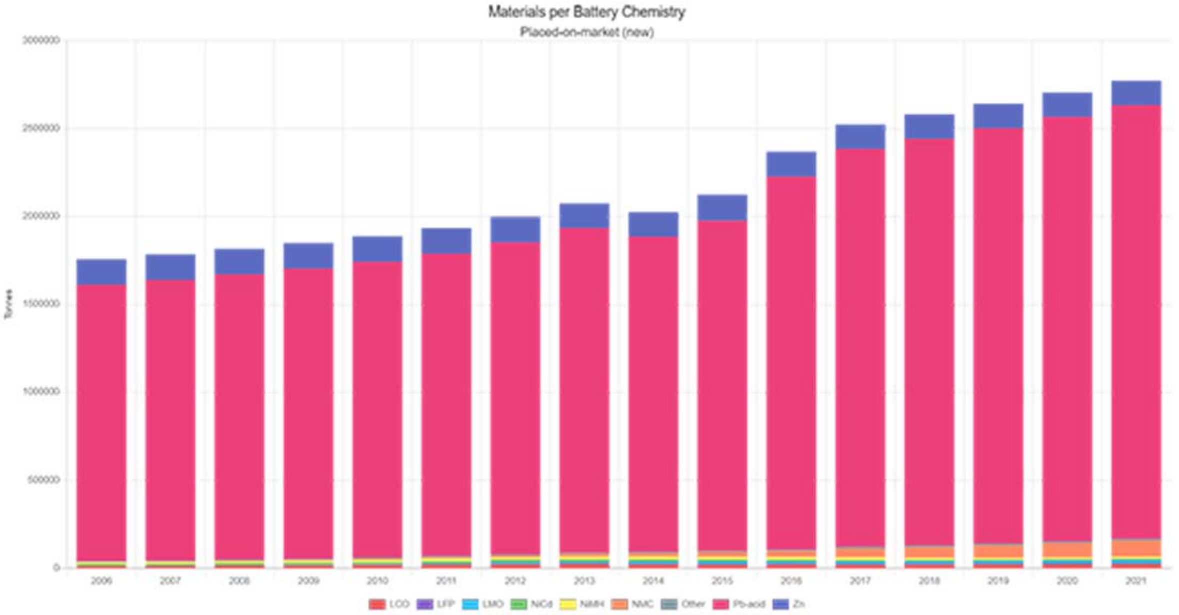
**Figure 24.** Relevant raw materials in all batteries, 2006–2021



### 6.2.3 Materials per battery chemistry

This graph illustrates the total **weight of batteries and of individual materials per chemistry** (Figure 25). This chart also includes all battery materials and components. Data are in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021. The data from 2018 to 2021 are forecast.

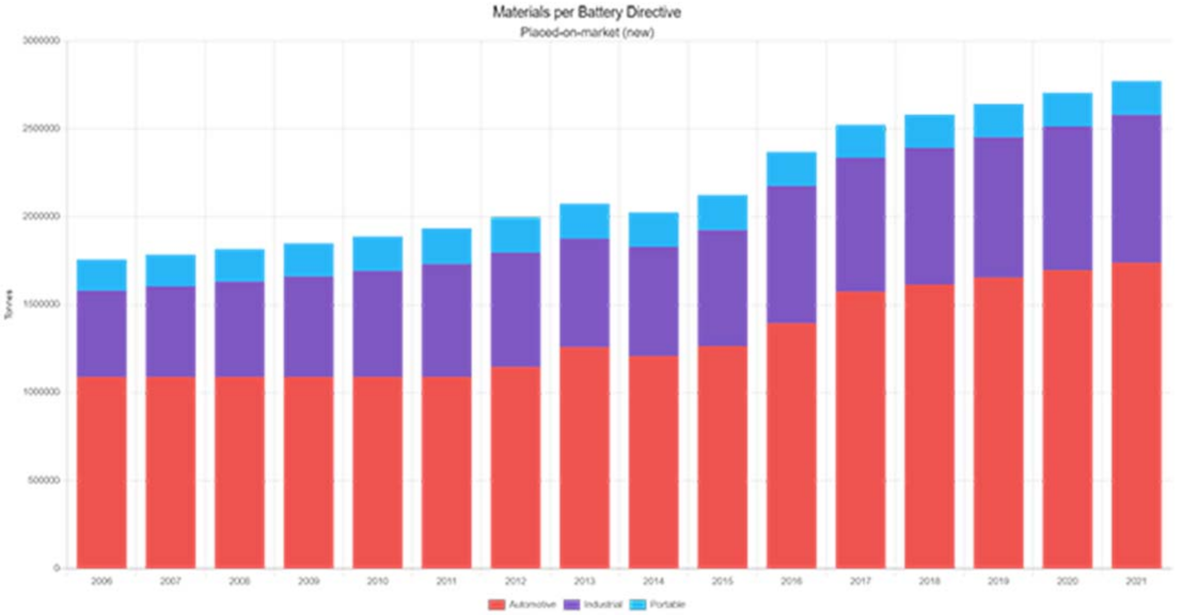
**Figure 25.** Materials present per battery chemistry, 2006–2021



### 6.2.4 Amounts according to the Batteries Directive

This graph illustrates the **total weight and of individual materials in portable, industrial and automotive batteries** displayed according to the Batteries Directive, which groups them into three categories (Figure 26). Data are in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021. The data from 2018 to 2021 are forecast.

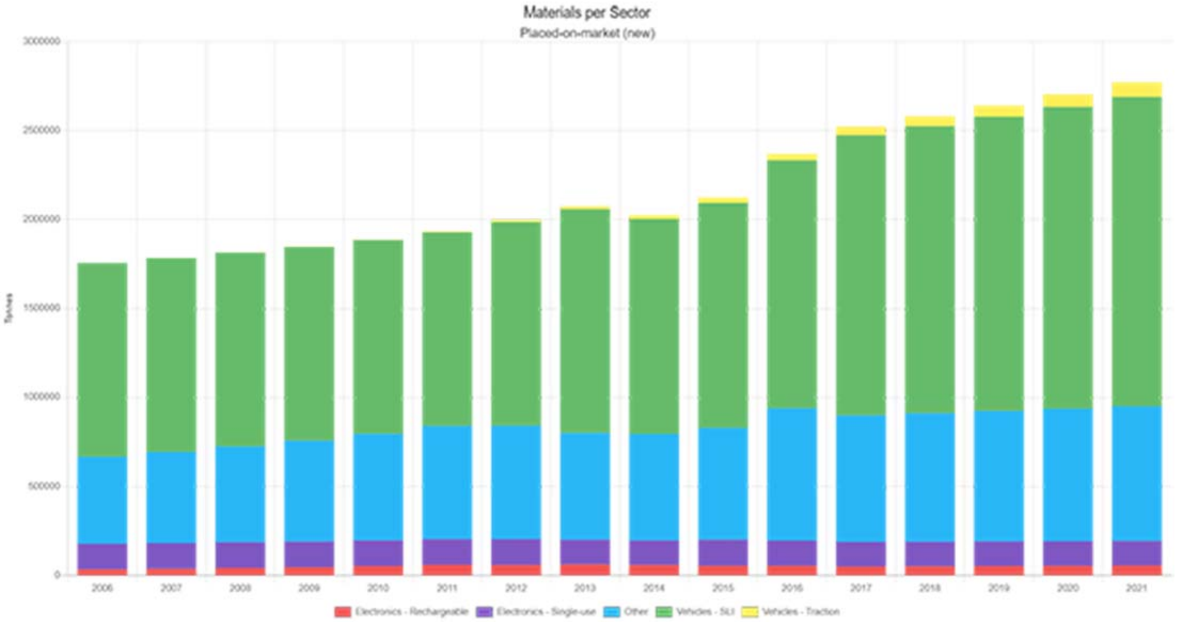
**Figure 26.** Materials per Battery Directive grouping, 2006–2021



### 6.2.5 Batteries per sector

This graph illustrates the **total weight of batteries and of individual materials grouped by sector** (Figure 27). The data are categorised into five groups. To reflect recent developments, portable batteries are split into single-use and rechargeable applications (including e-bikes). xEV traction batteries are presented as a separate group 'Vehicles – traction' (excluding e-bikes). Other types include all industrial batteries, except the aforementioned traction batteries. Data are in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021. The data from 2018 to 2021 are forecast.

**Figure 27.** Materials per sector, 2006–2021

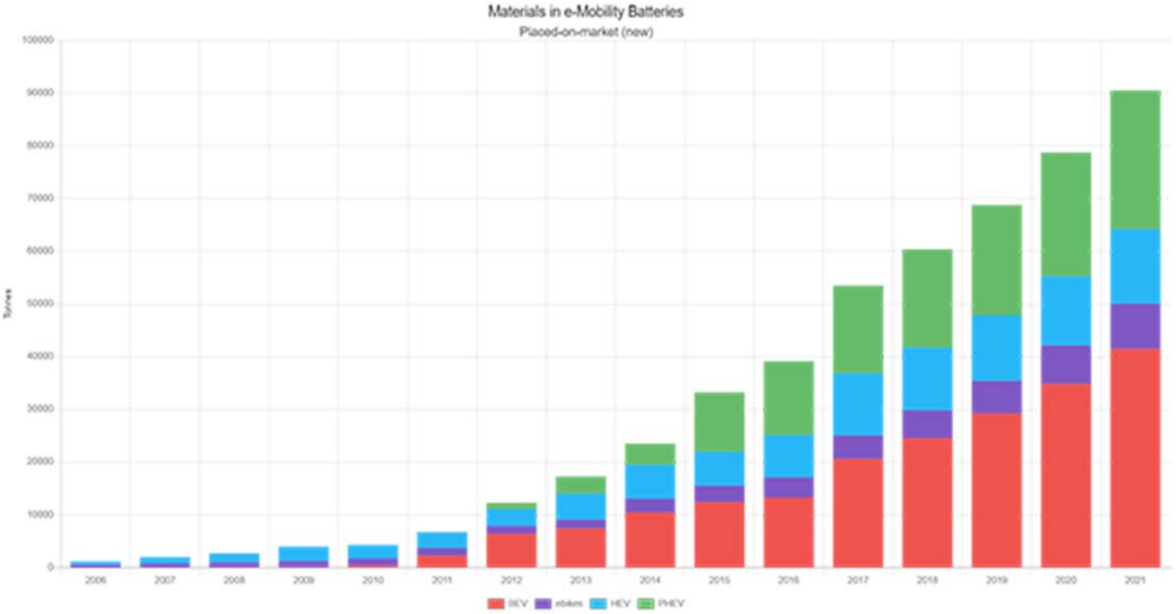


### 6.2.6 Zoom on materials for e-mobility

This graph illustrates the **total weight of batteries and of individual materials grouped by individual xEV drivetrain type** (Figure 28). E-bike batteries are included in this chart.

Data are in tonnes for the EU-27, UK, Switzerland and Norway, 2006–2021. The data from 2018 to 2021 are forecast.

**Figure 28.** Materials in e-mobility batteries, 2006–2021



# 7 Methodological notes

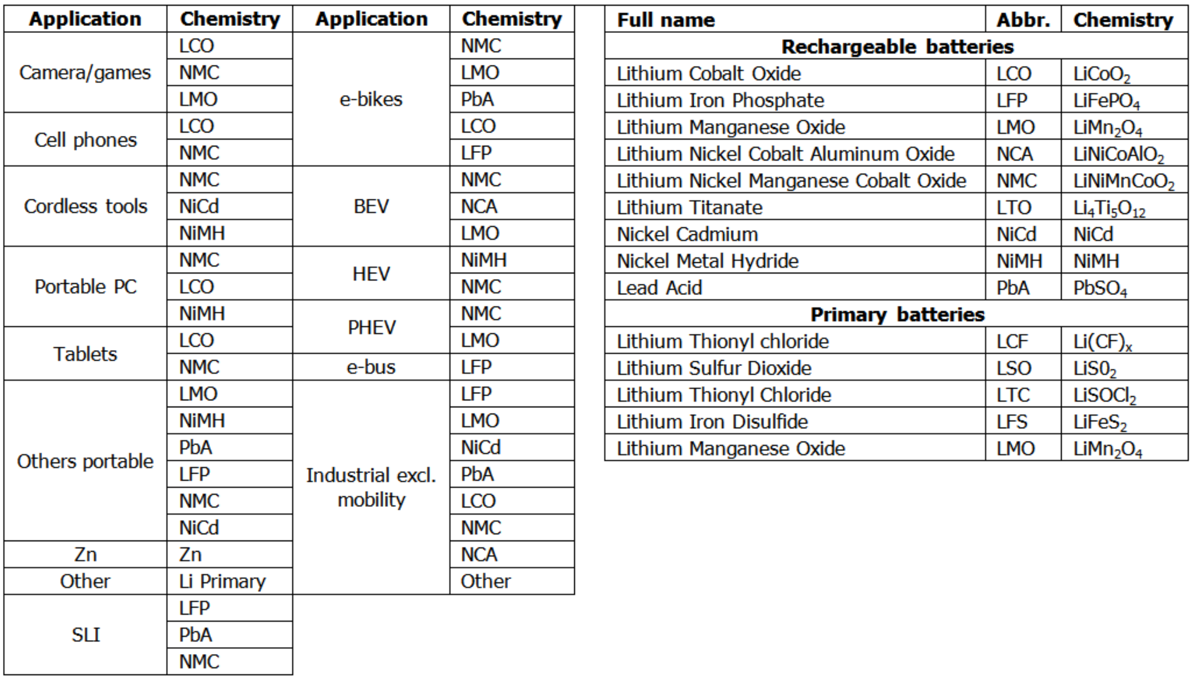
For research purposes, several approaches to classifying batteries are available, depending on cell chemistry, hazard rating, chargeability and area of application. However, there was no well-structured classification based on the raw material content of batteries. In this context, the H2020 ProSUM project proposed, for research purposes, a structured classification taking into account several aspects of battery composition (e.g. chemistries, applications). Based on expert knowledge of battery systems and their compositions, as well as an analysis of existing battery classifications, the ProSUM battery classification for electrochemical cells was developed.

The battery types cover the seven current main electrochemical systems based on lithium (single-use and rechargeable batteries), zinc, NiCd, NiMH, lead and others. These seven battery types were further divided into 14 sub-groups, named BATT (sub)keys. These keys are compatible with classification by chargeability type, the Battery Directive descriptions, battery recycling flows and other trade codes such as the EU List of wastes, ProdCom, the Combined Nomenclature and the United Nations Committee of Experts on the Transport of Dangerous Goods (Chancerel et al., 2016). The classification is being further updated to 52 BATT keys under the scope of the H2020 ORAMA project. These represent the most important battery chemistry–application combinations (Wagner et al., 2019), including new chemistries appearing on the horizon for commercial applications such as LFP in e-buses and heavy duty vehicles. The classification forms the analytical structure for describing all compositions, lifetimes, weights and other parameters for the dataset provided through the data viewer.

The distinction between single-use (primary) and rechargeable (secondary) batteries is important, as most of the CRMs are contained in rechargeable batteries. The same is true for the chemistries. There are differences in the ways that Member States collect and publish data on batteries placed on the market and on end-of-life batteries collected, and the level of detail of the reporting varies significantly (Wagner et al., 2019). For research purposes, information on the different chemical types of batteries gives a good indication of the embedded CRMs. This information is also valuable to recyclers. Improving the harmonisation of reporting and market analysis by changing the level of detail in the data reporting will support future assessment of the CRM flows in the European urban mine.

The BATT keys used can have a role to play in comparing and harmonising different datasets and providing a way towards a common language for use among manufacturers, reporting authorities, other stakeholders in the value chain and recyclers to ensure more consistent and improved knowledge on battery flows within Europe. A compact version of this classification is presented in Tables 1 and 2.

**Table 1.** Main chemistries per application

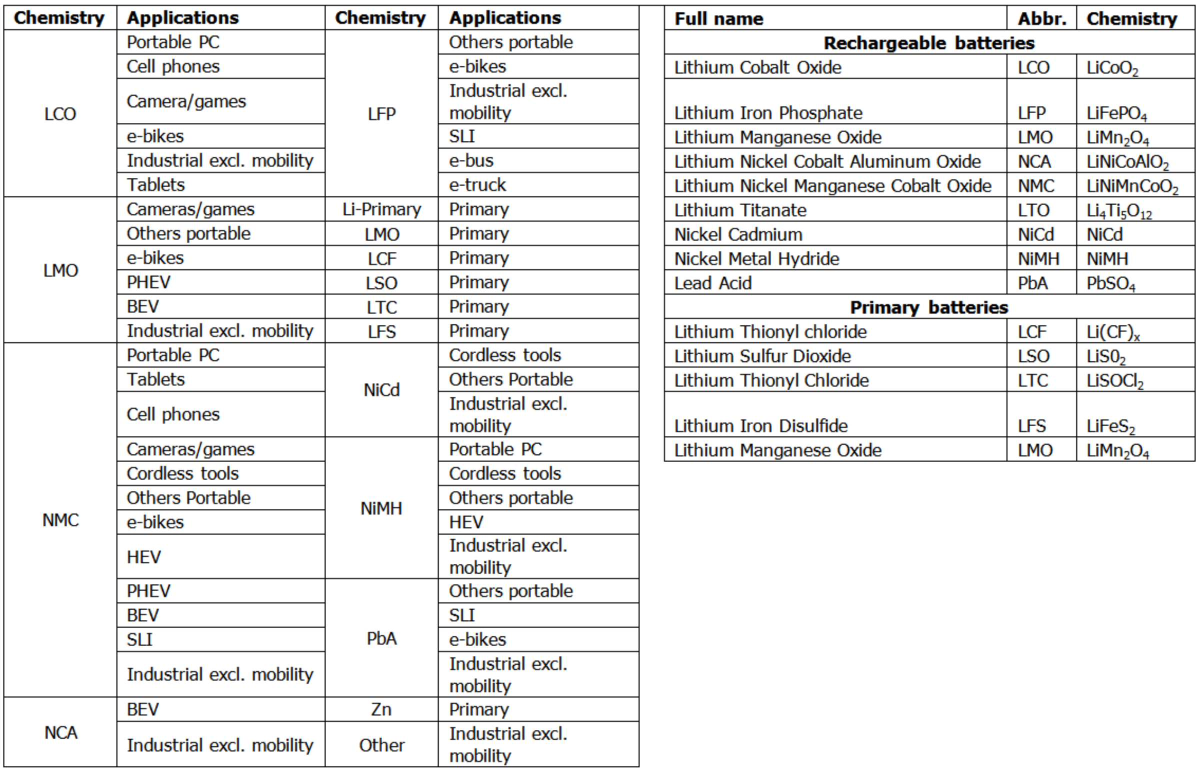


| Application | Chemistry | Application | Chemistry |
|---|---|---|---|
| Camera/games | LCO | e-bikes | NMC |
| | NMC | | LMO |
| | LMO | | PbA |
| Cell phones | LCO | | LCO |
| | NMC | | LFP |
| Cordless tools | NMC | BEV | NMC |
| | NiCd | | NCA |
| | NiMH | | LMO |
| Portable PC | NMC | HEV | NiMH |
| | LCO | | NMC |
| | NiMH | PHEV | NMC |
| Tablets | LCO | | LMO |
| | NMC | e-bus | LFP |
| Others portable | LMO | Industrial excl. mobility | LFP |
| | NiMH | | LMO |
| | PbA | | NiCd |
| | LFP | | PbA |
| | NMC | | LCO |
| | NiCd | | NMC |
| Zn | Zn | | NCA |
| Other | Li Primary | | Other |
| SLI | LFP | | |
| | PbA | | |
| | NMC | | |

| Full name | Abbr. | Chemistry |
|---|---|---|
| **Rechargeable batteries** | | |
| Lithium Cobalt Oxide | LCO | $LiCoO_2$ |
| Lithium Iron Phosphate | LFP | $LiFePO_4$ |
| Lithium Manganese Oxide | LMO | $LiMn_2O_4$ |
| Lithium Nickel Cobalt Aluminum Oxide | NCA | $LiNiCoAlO_2$ |
| Lithium Nickel Manganese Cobalt Oxide | NMC | $LiNiMnCoO_2$ |
| Lithium Titanate | LTO | $Li_4Ti_5O_{12}$ |
| Nickel Cadmium | NiCd | NiCd |
| Nickel Metal Hydride | NiMH | NiMH |
| Lead Acid | PbA | $PbSO_4$ |
| **Primary batteries** | | |
| Lithium Thionyl chloride | LCF | $Li(CF)_x$ |
| Lithium Sulfur Dioxide | LSO | $LiS0_2$ |
| Lithium Thionyl Chloride | LTC | $LiSOCl_2$ |
| Lithium Iron Disulfide | LFS | $LiFeS_2$ |
| Lithium Manganese Oxide | LMO | $LiMn_2O_4$ |

The main advantage of the classification is that it allows flexible grouping and sorting of the underlying battery data. As an example, when clicking on this table, the main applications are shown per chemistry instead of vice versa.

**Table 2.** Main applications per chemistry



| Chemistry | Applications | Chemistry | Applications |
|---|---|---|---|
| LCO | Portable PC | LFP | Others portable |
| | Cell phones | | e-bikes |
| | Camera/games | | Industrial excl. mobility |
| | e-bikes | | SLI |
| | Industrial excl. mobility | | e-bus |
| | Tablets | | e-truck |
| LMO | Cameras/games | Li-Primary | Primary |
| | Others portable | LMO | Primary |
| | e-bikes | LCF | Primary |
| | PHEV | LSO | Primary |
| | BEV | LTC | Primary |
| | Industrial excl. mobility | LFS | Primary |
| NMC | Portable PC | NiCd | Cordless tools |
| | Tablets | | Others Portable |
| | Cell phones | | Industrial excl. mobility |
| | Cameras/games | NiMH | Portable PC |
| | Cordless tools | | Cordless tools |
| | Others Portable | | Others portable |
| | e-bikes | | HEV |
| | HEV | | Industrial excl. mobility |
| | PHEV | PbA | Others portable |
| | BEV | | SLI |
| | SLI | | e-bikes |
| | Industrial excl. mobility | | Industrial excl. mobility |
| NCA | BEV | Zn | Primary |
| | Industrial excl. mobility | Other | Industrial excl. mobility |

| Full name | Abbr. | Chemistry |
|---|---|---|
| **Rechargeable batteries** | | |
| Lithium Cobalt Oxide | LCO | $LiCoO_2$ |
| Lithium Iron Phosphate | LFP | $LiFePO_4$ |
| Lithium Manganese Oxide | LMO | $LiMn_2O_4$ |
| Lithium Nickel Cobalt Aluminum Oxide | NCA | $LiNiCoAlO_2$ |
| Lithium Nickel Manganese Cobalt Oxide | NMC | $LiNiMnCoO_2$ |
| Lithium Titanate | LTO | $Li_4Ti_5O_{12}$ |
| Nickel Cadmium | NiCd | NiCd |
| Nickel Metal Hydride | NiMH | NiMH |
| Lead Acid | PbA | $PbSO_4$ |
| **Primary batteries** | | |
| Lithium Thionyl chloride | LCF | $Li(CF)_x$ |
| Lithium Sulfur Dioxide | LSO | $LiS0_2$ |
| Lithium Thionyl Chloride | LTC | $LiSOCl_2$ |
| Lithium Iron Disulfide | LFS | $LiFeS_2$ |
| Lithium Manganese Oxide | LMO | $LiMn_2O_4$ |

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## Abbreviations and definitions

| | |
|---|---|
| BEV | battery electric vehicle (or fully electric vehicle) |
| C | carbon – natural graphite |
| Cd | cadmium |
| Co | cobalt |
| CRM | critical raw material |
| Cu | copper |
| EIP-RM | European Innovation Partnership on Raw Materials |
| EUR | euro |
| HEV | hybrid electric vehicle |
| LCF | lithium–thionyl chloride – Li(CF)x primary batteries |
| LCO | lithium–cobalt oxide – $LiCoO_2$ rechargeable batteries |
| LFP | lithium–iron phosphate – $LiFePO_4$ rechargeable batteries |
| LFS | lithium–iron disulphide – $LiFeS_2$ primary batteries |
| Li | lithium |
| Li-ion | lithium ion |
| LMO | lithium–manganese oxide – $LiMn_2O_4$ (primary and rechargeable) batteries |
| LSO | lithium–sulphur dioxide – $LiSO_2$ primary batteries |
| LTC | lithium–thionyl chloride – $LiSOCl_2$ primary batteries |
| LTO | lithium titanate – $Li_4Ti_5O_{12}$ or $Li_2TiO_3$ rechargeable batteries |
| Mn | manganese |
| NCA | lithium–nickel–cobalt–aluminium oxide – $LiNiCoAlO_2$ rechargeable batteries |
| Ni | nickel |
| NiCd | nickel–cadmium – NiCd rechargeable batteries |
| NiMH | nickel–metal hydride – NiMH rechargeable batteries |
| NMC | lithium–nickel–manganese–cobalt oxide – $LiNiMnCoO_2$ rechargeable batteries |
| Pb | lead |
| PbA | lead–acid – $PbSO_4$ rechargeable batteries |
| PHEV | plug-in hybrid electric vehicle |
| PoM | placed on the market: the number or weight of products entering the EU market each year as the sum of sales to consumers, businesses and organisations |
| Stock | The total number or weight of products that are in use or stored/hibernated in households, businesses, and organisations before being discarded |
| Sb | antimony |
| SLI | starting, lighting, ignition |
| USD | US dollar |
| Waste generated | The (potential) total number or weight of products estimated to be discarded and physically leaving the stock as waste. This can include batteries for reuse leaving the EU in the form of export with, for instance, second-hand electronics and used vehicles |
| xEV | electric vehicle (any type, including BEV, HEV and PHEV) |
| Zn | zinc |

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