Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Analyzing the value chains of electric vehicle batteries

Comparing the United States and Europe and giving international collaboration perspectives for the battery supply chain

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Introduction

1.1. Context

The transportation industry is historically a significant contributor to the worldwide greenhouse gas (GHG) emissions. Road transport accounted for roughly 77% of all transport emissions in 2020 in the European Union, next to aviation, railways and maritime transport. It is also strongly dependent on external influences and economic prosperity, as can be observed in Figure 1. From 1990 onwards, emissions have been increasing up until the global financial crisis in 2008. It recovered after that but sharply dropped again as a result of the COVID-19 pandemic in 2020. National projections expect a peak in GHG emissions before a structural decrease can be observed due to sustainability efforts, such as zero-emission drivetrains.

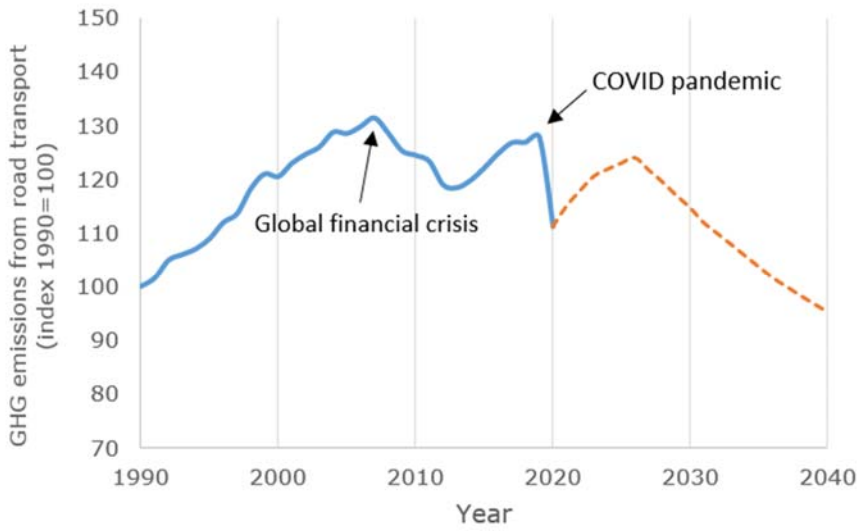


Figure 1 GHG emissions from road transport in the EU. Source: European Environment Agency (2022)

Even though the environmental importance of GHG reduction has been recognized decades ago and has reached scientific consensus, adequate political action was lacking to achieve this. At the Climate Conference in Glasgow in 2021 (COP26) however, formal commitments have been made by car manufacturers and governments to move away from internal combustion engines (ICE) and transition to zero-emissions vehicles (ZEV) fully in 2035 (leading markets) and 2040 (worldwide). More recently, a formal agreement has been signed in the European Union that all new car sales must be zero-emission by the year 2035. The state of California has signed a similar agreement as the first state in America. The currently available zero-emission vehicles are predominantly electric vehicles (EVs), although some manufacturers are also expanding with hydrogen fuel-cell electric vehicles (FCEV) as of writing. This hybrid technology combines a hydrogen fuel cell with batteries. The hydrogen fuel cells deliver high power-output at cruising speeds while the batteries assist in start-up and low speeds. When maximum power is needed during acceleration, both systems engage. Stellantis has developed a FCEV platform for light-commercial vehicles as well, which offers high range (over 400 km) and quick charging capability (3 min).

1.2. EVs and supply chains

Consumer adoption of non-ICE technology is still in development (EVs most notably), as it introduces new types of difficulties such as: flammability, range anxiety, charging times, cold-weather performance and high purchase costs. Many of these issues are being improved on significantly and should not pose a threat to the zero-emission transition. For example, average battery lifetimes are approximately 15 years[1] and can offer plenty of range (up until ±600 km[2]). From the logistical point-of-view however, the supply chain of EVs is considered vulnerable and receives growing attention in academia, industry and government. For the production of EV batteries large amounts of raw materials are required such as: iron, graphite, cobalt, nickel, manganese, lithium, copper and aluminum. Some of these are recognized as critical raw materials (CRMs) by the European Commission due to their strong economic importance and supply risk (see Figure 2).

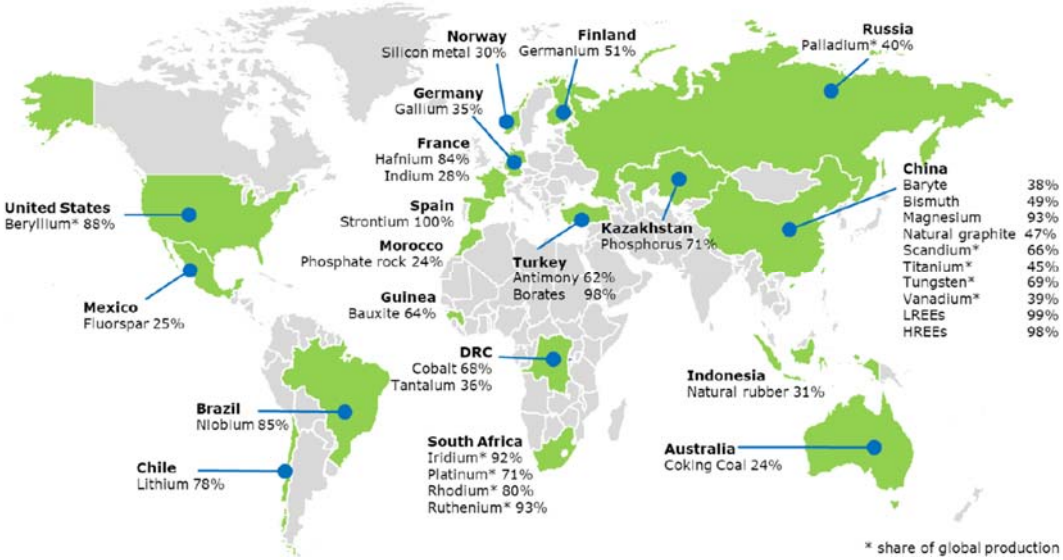


Figure 2 Countries holding the largest share of EU sourcing of CRMs. Source: European Commission (2020)

These raw materials often originate from a small number non-Western countries where labor standards and human rights are below par. For example, the majority of the EU's cobalt supply originates from Congo and lithium from Chile. In addition, the subsequent processing of the raw materials involves large amounts of GHG emissions and it is executed in countries where environmental-impact monitoring and regulation is poor. This strong dependency on a handful of countries with regard to the supply chain of EV batteries presents a geopolitical risks that has the potential to severely delay ZEV transition targets.

[1] KU Leuven (2022). *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge.*
[2] https://www.tesla.com/nl_be/models

Consequently, alliances have been formed with both EU and non-EU countries to collectively mitigate these supply chain risks. The efforts are mainly focused on raw materials extraction, refinery processes, and building battery production facilities. Geopolitical dependencies on fossil fuels have often demonstrated their effects on society and economies and serve as a reminder of the importance of diversified supply chains.

1.3. Goals and outline

This report analyzes and compares the value chains of EV batteries for two global regions: Europe and United States. These two make a valuable case study because of three main reasons:

1. They have a comparatively developed EV market share and infrastructure
2. They share similar political climates to advance this transition
3. They both have vulnerable supply chains to meet these goals

In extension of the value chains comparison, a list of recommendations is presented with international collaboration perspectives. This report contains additional field information from a field interviews to California during November 2022. Considering the fact that California and the Netherlands are leading economies for EVs, these findings are considered rather valuable.

The report first describes the essential background information on batteries in Chapter 2. After that, the current global supply chain of batteries is explained in Chapter 3. Next, the European situation and US situations are elaborated in terms of policies, supply chain challenges, and community challenges in Chapter 4 and 5 respectively. Chapter 6 presents a list of recommendation with international collaboration perspectives. The main findings and conclusions are summarized in the final chapter.

2 Battery fundamentals

2.1. Technology background

Car batteries are technologically advanced storage systems that are the result of decades of research and development. The currently dominant technology is based on lithium-ions. This dates back to early research in the 1960s which laid the foundation to commercialization in 1991 by Sony. Three notable researchers (Goodenough, Whittingham & Yoshino) were awarded the Nobel Prize in chemistry in 2019 for their important contributions to the development of lithium-ion batteries. The importance of lithium ion technology is found in the excellent physical and electrochemical properties it achieves; the combination of high energy density and volumetric energy density enables lightweight and efficient engineering applications. This means that battery packs have the potential to provide prolonged and controlled energy output and involve minimal dead weight in a car, thereby keeping overall efficiency high. In addition, an electric motor has an already significantly higher efficiency (85-90%) than gasoline ICEs (≤35%)[3]. Battery prices (expressed in USD per kilowatt-hour) have also dropped significantly since its discovery, as can be seen in Figure 3.

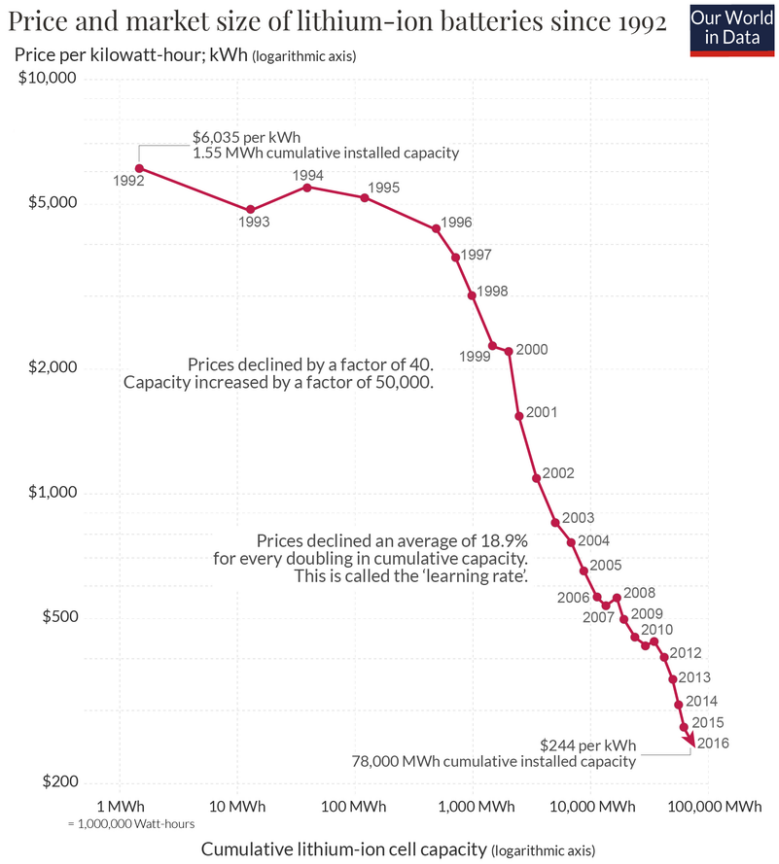


Figure 3 Price development of lithium-ion batteries from 1992 to 2016. Source: https://ourworldindata.org/battery-price-decline

[3] https://www.nrdc.org/experts/madhur-boloor/electric-vehicles-101

Initial applications involved mostly hybrid technologies with conventional (downscaled) ICEs in the drivetrain, where kinetic energy recovery systems (KERS) slightly improved the vehicles overall efficiency. This is done with regenerative breaking to store otherwise dissipated energy. Depending on the configuration, hybrid vehicles can be powered by the batteries alone at low speeds. Plug-in hybrid vehicles (PHEV) have the additional capability of being charged externally via an electrical outlet. As the battery efficiency increased and the price per kWh dropped, full-electric drivetrains were made possible to replace the ICE completely. Some manufacturers opt for in-wheel motor designs, to increase luggage capacity in the 'engine bay' and offer direct traction control at the wheel. For these situations lightweight and compact motors are required to maximize handling responsiveness.

The working principle of lithium-ion batteries relies on the movement of lithium ions between the two electrodes, which both contain lithium atoms. The design is further elaborated in the next paragraph. Although this technology has a strong foothold in the industry, alternative non-lithium technologies are also being developed to tackle mineral scarcity or improve safety for example. On the other side, lithium-ion technology is being improved as well on component-level (cathode, anode, electrolyte). Both are explained in the next sections.

2.2. Components overview

An overview of the different component within a typical lithium-ion battery is provided in Figure 4. The purpose of each component is explained in the next subparagraphs along with the variations or future developments of each component.

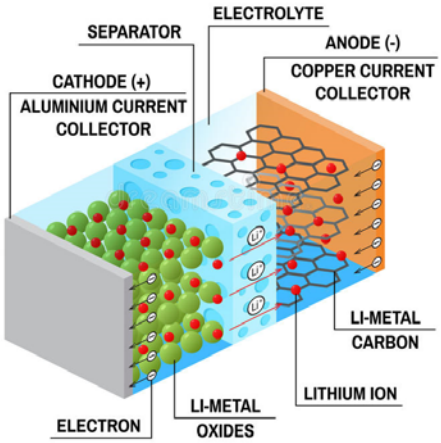


Figure 4 Battery schematic. Source: https://www.ucl.ac.uk/chemical-engineering/lithium-ion-batteries

2.2.1. *Cathode*

The cathode is the positive electrode of the battery and is typically a metal oxide. This can be a lithium cobalt oxide, lithium iron phosphate, or lithium manganese oxide for example. The most common cathode chemistries are shown in Table 2 with relevant element requirements in Table 2. The typical batteries used in Tesla long-range and standard-range models are of NCA type and LFP, respectively. This is due

to the slightly lower energy density of LFP batteries compared to LCA or NMC. Tesla intends to more broadly use LFP batteries in all their models however, due to its limited use of scarcely available materials such as cobalt and nickel[4]. Other big OEMs have followed this trend to cut production costs, such as Ford, Rivian, Volkswagen and General Motors[5]. Still a large share of car manufacturers use NMC type batteries, where the number suffix indicates the relative weight distribution of the three elements (nickel, manganese and cobalt). Modern battery cathode manufacturers tend to limit the use of cobalt due to its price and scarcity, hence the '8-1-1' element ratio. The most popular EVs in 2021 are shown below with their corresponding cathode chemistries.

Table 1 Best-selling EVs in Europe and the US with the corresponding cathode chemistries. Source: https://electrek.co/2023/01/09/the-top-10-best-selling-electric-vehicles-in-the-us-of-2022/; https://cleantechnica.com/2023/01/08/100-best-selling-bevs-in-10-european-countries/

Europe	**Cathode**	**United States**	**Cathode**
1. Tesla Model Y	NCA / NCMA	1. Tesla Model Y	NCA / NCMA
2. VW ID.3	NMC-721	2. Tesla Model 3	NCA / LFP
3. Tesla Model 3	NCA/LFP	3. Mustang Mach-E	NMC-811

Table 2 Typical element requirements per battery cathode chemistry expressed in kg per kWh. Graphite is denoted as 'C' for carbon. Source: Notter, D., Gauch, M., Widmer, R., Wagner, P., Stam, A., Zah, R., and Althaus, H. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles. Environ. Sci. Technol. 44, 6550–6556.

Cathode chemistry:	*Li*	*Fe*	*Co*	*Ni*	*Mn*	*Al*	*Cu*	*C*
Lithium nickel cobalt aluminum oxide (NCA)	0.11	0	0.14	0.76	0	2.92	0.56	0.98
Lithium nickel manganese cobalt oxide (NMC-622)	0.13	0	0.21	0.61	0.2	3.02	0.61	0.96
Lithium nickel manganese cobalt oxide (NMC-811)	0.11	0	0.094	0.75	0.088	2.92	0.55	0.96
Lithium iron phosphate (LFP)	0.1	0.68	0	0	0	3.53	0.95	1.09

[4] https://electrek.co/2022/04/22/tesla-using-cobalt-free-lfp-batteries-in-half-new-cars-produced/
[5] https://cen.acs.org/energy/energy-storage-/Lithium-iron-phosphate-comes-to-America/101/i4

During discharging of the battery a reduction reaction takes place at the cathode where the lithium is recombined with the cathode material. For any metal oxide (MO) the half reaction looks like:

$$MO + Li^{+} + e^{-} \leftrightarrows LiMO$$

During charging the electrons flow in the opposite direction. The microstructure of the cathode is chosen or tailored to allow diffusion of lithium ions. The opposite reaction (oxidation) takes place at the anode, as explained below.

2.2.2. *Anode*

The anode is the negative electrode of the battery and is typically made from graphite or other carbon materials. Its main function is to store lithium ions and thereby electrical charge whilst retaining its volume (within several percent) or its integrity (with tolerant design). The planar crystal structure of graphite allows this via a process called intercalation. For every six carbon atoms one lithium ion can be accommodated. Most battery manufacturers use graphite, either naturally occurring or synthetically produced. The quality of the graphite is highly important and determines the efficiency of the anode and thereby the battery as a whole. The level of crystallinity is an important factor. Natural flake graphite is considered the most desirable type for batteries, along with primary synthetic graphite. Synthetic graphite is produced from petroleum coke and is highly energy-intensive and emits a considerable amount of GHG.[6] A sample of natural flake graphite is shown below in Figure 5.

Figure 5 Natural flake graphite sample (left) and cross-section (top-right) along with the crystal structure (bottom-right). Source: Next Source Materials; Indiamart.

During discharging of the battery an oxidation reaction takes place at the anode where lithium ions and electrons are produced. For a carbon anode the half reaction looks like:

$$LiC_6 \leftrightarrows C_6 + Li^{+} + e^{-}$$

Future developments are mostly focused on incorporating silicon in the graphite material, with silicon nanowires for example. Silicon has the advantage of being widely available (graphite is comparatively rare) and the ability to accommodate 10 times more lithium ions. Some companies (such as the Dutch start-up LeydenJar) develop full-silicon anodes to improve energy density and charging speed[7]. Dealing

[6] The Hague Centre for Strategic Studies (2022). *Graphite – Supply chain challenges & recommendations for a critical mineral.*
[7] https://leyden-jar.com/

with the significant volume expansion that occurs when lithium ions enter silicon is the main challenge to overcome, in order to ensure adequate battery lifetime is achieved.

2.2.3. *Electrolyte*

The electrolyte acts as a conductive pathway for the movement of lithium ions, but provide an electrically insulating layer (solid-electrolyte interphase) on the anode during charging. This layer is stable and prevents short circuiting of the battery, yet allows the ions to pass through. The most common types of electrolytes are liquid electrolytes that consist of lithium salts (e.g. $LiPF_6$) in an organic solvent. The most notable innovations here are solid-state electrolytes that use a ceramic material instead (such as the US start-up QuantumScape)[8]. These are lithium metal oxides which allow lithium ions to move through the solid easily due to the highly ordered microstructure with lithium atoms. The main benefits are in fire safety, as it is leak-free and therefore much safer to use in electric vehicles.

2.2.4. *Casing, separator and collectors*

The outer casing of the battery depends on the cell shape, but is usually from steel and aluminum. For cylindrical cells (can-shaped) steel is often used in the range of 0.1-0.6 mm thickness[9]. The casing material has a safety function, providing structural rigidity and damage absorption in case of impact. It also serves a function in thermal management by dissipating heat. In between the two electrodes a thin, porous polymer layer is placed to prevent contact between the electrodes and short-circuiting. At the anode and cathode current collectors are at place to transfer electricity to and from the cells. These are made from copper and aluminum.

One level above, the cells are paired in modules and then housed in a rigid frame. These are also often made from sheet metal. On all levels of the battery assembly the components are sealed tight to prevent external contact, as lithium is highly reactive. The casing and housing structures are optimized to minimize weight and volume while retaining adequate properties. The scope of this report focuses only the functional battery components however.

2.3. Low-CRM technologies

As mentioned in the previous paragraph, there is continuous development and improvement in the field in lithium-ion batteries. On the other hand alternatives are in the pipeline which can play a role in powering EVs, with less use of critical raw materials (or perhaps even none). These can range from material substitutes, to new technologies altogether. This paragraph covers the most notable developments.

Within lithium-ion technology, the cathode can be altered to effectively lower the need for CRMs. For example, a 8-1-1 NMC chemistry (or even 9-.5-.5) can reduce the required cobalt and manganese content by compensating with higher nickel content. This trade-off is debatable given the high supply risk of nickel as well. More effective is the use of lithium iron-phosphate cathode, where essentially all critical minerals except lithium and phosphorus are omitted. Phosphorus, as well as phosphate rock from which it is obtained, are also recognized by the European Commission as a critical raw material due to high supply risk and economic importance (mainly in agriculture). Studies have estimated that the global phosphorus demand in 2050 may reach >3 million metric tons in a sustainable

[8] https://www.quantumscape.com/technology/
[9] https://insideevs.com/news/598656/tesla-4680-battery-cell-specs/

development scenario, which is merely 5% of today's global demand. Mining is strongly concentrated in Morocco, China and Russia, with the largest reserves in Morocco. Due to the relatively low prices of phosphate rock compared to other critical minerals, the phosphorus material costs do not play a significant role in overall battery production costs. Although the energy density (both volumetric and gravimetric) of LFP is slightly lower compared to NMC chemistries the cycle life is improved. Apart from the technical aspects, the NMC battery supply chain is well-established despite its vulnerability, whereas the iron phosphate supply chain can require additional scaling up for mass production. Another route is sulfur cathodes, which is an abundant material and possesses a rather high theoretical energy density of 2600 Wh/kg (3 times higher than current lithium-ion technology). This technology typically uses lithium metal anodes. Production models have already reached 500 Wh/kg. Its main disadvantage is limited cycle life (~500) which is about a third of NMC batteries. Lyten is currently the largest company in this battery sector. [10] [11] [12] [13] [14]

On the anode, the most notable development is the addition of silicon to graphite. The shear amount of graphite used per battery presents an impactful potential reduction of CRMs. Furthermore, the theoretical capacity of silicon is about ten times higher (3600 vs. 372 mAh/g) which allows for a more efficient battery. Current battery manufacturers that use silicon add only slight amounts (<10%) compensate for the strong swelling (300 - 400%) that can potentially disintegrate the anode. If higher amounts of silicon can be used safely, it can realize substantial lowering of CRMs. [11]

Non lithium-ion technologies often boil down to sodium-ion technology. The typical and most promising cathodes are made from sodium phosphate-based materials while the anodes are mostly designed with hard carbon (non-graphitic) or graphene. Advantages include the lower price of sodium compared to lithium, as well as the abundancy of raw materials. Additionally, the underlying technology and chemistry is similar to widely-studied lithium-ion batteries. The main disadvantage is the comparatively low energy density of around 150 Wh/kg. This solution may be targeted at budget applications and/or stationary energy storage (which can be supporting the vehicle charging infrastructure). [11]. See overview below:

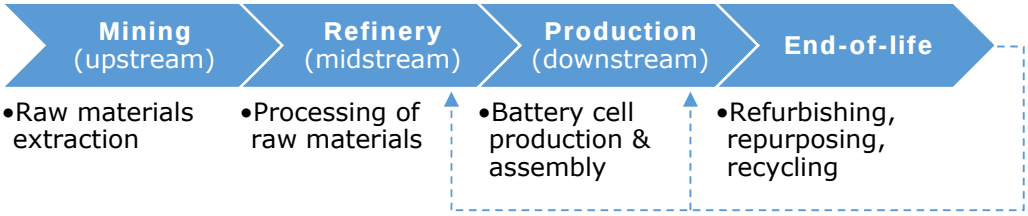
[10] Li, M. et al. (2021). *Nanomaterials for electrochemical energy storage.* Frontiers of Nanoscience, 19.
[11] Volta Foundation (2022). Battery Report.
[12] https://lyten.com/products/batteries/
[13] Spears, M.B. (2022) et al. (2022). *Concerns about global phosphorus demand for lithium-iron-phosphate batteries in the light electric vehicle sector.* Communications Materials, 3.
[14] U.S. Geological Survey (2023). Mineral Commodity Suymmaries (Phosphate Rock).

3 The supply chain

3.1. Overview of the supply chain

The supply chain can be subdivided in four main stages, namely: mining, refining, production and recycling. The mining stage sources raw materials from the earth's crust, after which materials refinery takes place. These processed materials can then be used in the production of functional components for batteries. After batteries reach their intended life, they can be refurbished, repurposed or recycled. Although there are much more actual steps involved, Diagram 1 presents a basic overview and understanding of the main stages. The next paragraphs focus on the four individual stages in more detail and provide the current state of affairs, and briefly mention current trends and innovations that can play a role.

Diagram 1 Overview of the battery supply chain, including arrows for closed-loop production



3.2. Mining of raw materials

Many different raw materials are mined for the production of batteries. This paragraph focusses on the most relevant ones. As introduced in the previous chapter, there are several critical minerals that are required for the production of different battery components. A list is provided below with the raw materials of interest for this report.

Table 3 List of raw materials in batteries. Source: Systemiq (2022). Critical Raw Materials for the Energy transition in the EU.

Material	*Used in:*	*Typical amount in a 400kg battery*:*	*Recognized as CRM by EC:*
Lithium	Cathodes, Electrolytes	8 kg	Yes
Cobalt	Cathodes	9 kg	Yes
Manganese	Cathodes	12 kg	No
Nickel	Cathodes	41 kg	No
Graphite	Anodes	71 kg	Yes
Copper	Wiring, collector foil at anode	22 kg	No
Aluminum	Packaging, collector foil at cathode	126 kg	Yes* (bauxite)
Silicon	Anodes	n/a	Yes

**Typical amounts can vary with battery chemistry, a 50kWh NMC battery is assumed here*

While the geological availability of these raw materials can be widespread, the mining operations are often localized within a region or country. Hence, these minerals should be considered *scarce* instead of *rare*. The current sourcing of materials often takes place outside Western countries. Table 4 shows the same list of materials and its main sources from mines worldwide, along with the total output in 2020 or 2021. It can be observed that a large amount of materials are mined in South America, Asia and Africa. This is graphically illustrated as well in Figure 6. The economies of these countries are often reliant on large export volumes of such materials. Some minerals are also obtained as a byproduct of mining, such as cobalt, which is a byproduct of copper and nickel mining mostly[15]. The prices of copper and nickel consequently determine the amount of cobalt-containing ore that will be mined. This is not the case with artisanal mining, however. Lithium from Chile and Argentina is obtained from brines beneath salt flats. Via a lengthy process the brine is pumped up to the surface and left to evaporate for a long period of time until the moisture content decreases significantly (and the lithium content is high). Once the brine is ready it receives several filtration- and chemical treatments to produce a solid form of lithium. On the other side, Australian and Chinese lithium comes from hard rock/spodumene which is first heated and pulverized, and then receives several chemical treatments to produce lithium carbonate. Lithium production from brines is often more cost-effective compared to hard rock mining due to the added energy consumption. Even though a few countries possess a majority of the mining operations, the remainder of the supply chain is distributed otherwise, as can be seen in the next paragraphs.

Table 4 Raw battery materials sourcing (globally). Sources: KU Leuven (2022), HCSS (2022), Statista (2021), Systemiq (2022)

Material	*Mainly sourced from (% of global mine output):*	*Total mine output in 2020:*	*World's resources (estimated)*
Lithium	Australia (45%), Chile (29%), China (13%)	430 kt	89 Mt
Cobalt	Democratic Republic Congo (72%)	170 kt* (2021)	25 Mt
Manganese	South Africa (39%), Gabon (14%), China (14%)	49.5 Mt* (2021)	n/a
Nickel	Indonesia (27%), Philippines (13%), Russia (11%)	2.2 Mt	300 Mt
Natural graphite	China (79%)	3.0 Mt* (2021)	800 Mt
Copper	Chile (29%), Peru (11%), China (10%)	20.5 Mt	5,6 Gt
Aluminum (Bauxite)	Australia (28%), Guinea (25%), China (18%)	370 Mt	n/a
Silicon	China (75%)	3 Mt	n/a

[15] International Energy Agency (2021). *The Role of Critical minerals in Clean Energy Transitions*

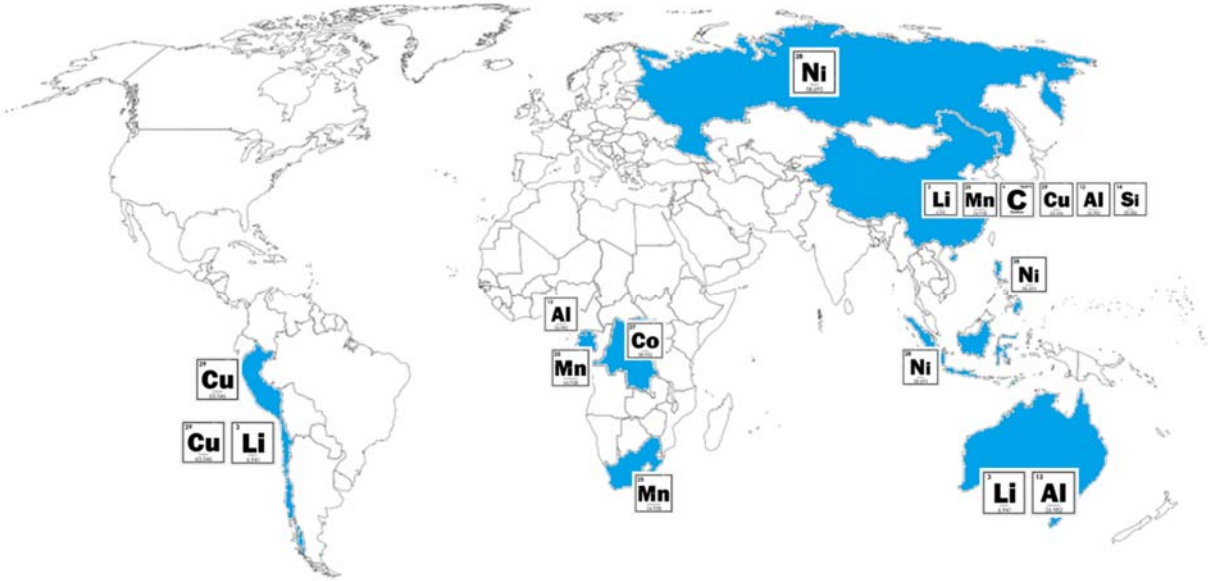


Figure 6 Map with largest miners of raw battery materials, highlighted in blue with the relevant element symbols.

3.3. Refinery of raw materials

As introduced in the previous paragraph, mined raw materials require processing to be usable in battery component manufacturing. This involves multiple steps to acquire the desired material shape, consistency and quality. For example, natural graphite comes from flake graphite ore which is processed to increase the graphite content with chemicals (hydrofluoric acid) to a purity of 99.9% (referred to as three nines '3N'). For battery anodes the flake graphite must be reduced to 10-20 micron particles, done with a cascading series of crushing mills. After the particles are spherical and finished they receive a final surface treatment (coating). The coating provides a protective layer to the particles which makes them less reactive with other parts of the battery, as well as increased electrochemical properties which benefit the energy density. This last step is crucial to create battery-grade graphite. More environmentally friendly processing methods also exist without the use of toxic hydrofluoric acid. Additionally, these newer methods yield higher output and require less energy per ton graphite. Synthetic graphite on the other hand is made from calcined petroleum needle coke. This is a residual product from petroleum refining. First, the needle coke is ground, mixed and shaped at high temperatures (pre-processing). During the subsequent graphitization stage it is heated to 3000 degrees Celsius to convert the carbon into graphite and thereby remove impurities from the needle coke. Once the graphite has attained sufficiently high purity it is coated similarly as natural graphite to obtained the finished product.[16]

In general, raw materials refinery is a very polluting industry which has led to it being offshored outside the West. Countries that impose less stringent environmental laws and safety standards welcomed this industry to develop their economies and international competitiveness. This effect is visible in Table 5 and Figure 7, where most of the refinery has shifted to China. As part of the Belt and Road Initiative (BRI) China has made considerable investments in the battery supply

[16] The Hague Centre for Strategic Studies (2022). *Graphite – Supply chain challenges & recommendations for a critical mineral.*

chain both domestically and overseas. Early investments even started in the 1990s to secure the critical minerals supply chain. These strategic choices have led to a considerable supply capacity and low prices of battery components and materials. It has also been reported that dumping schemes (due to overcapacity) were utilized which resulted in unfair competition against European or American. This is particularly the case for silicon and aluminum. Most importantly, the uneven distribution of battery materials supply and battery production poses a realistic threat to European and American zero-emission targets. This is especially the case if the Chinese domestic demand for minerals rises to a critical level – when foreign export might lose priority against domestic decarbonization targets.

Table 5 Battery raw materials refining distribution (globally). Sources: KU Leuven (2022), HCSS (2022), Statista (2021), Cobalt Institute (2021)

Material	*Mainly refined in (% of refined materials globally):*	*Total refined output in 2020:*
Lithium	China (60%), Chile (27%) Argentina (7%)	430 kt
Cobalt	China (68%), Finland (10%), Canada (5%)	144 kt
Manganese	China (90%)	18 Mt
Nickel	China (35%), Indonesia (19%), Japan (9%)	2.6 Mt
Graphite	China (100% natural graphite) China (78% synthetic graphite)	1.0 Mt* (in 2021)
Copper	China (41%), Chile (9%), Japan (8%)	25 Mt
Aluminum	China (57%), Russia (7%), India (6%)	72 Mt
Silicon	China (75)	3 Mt

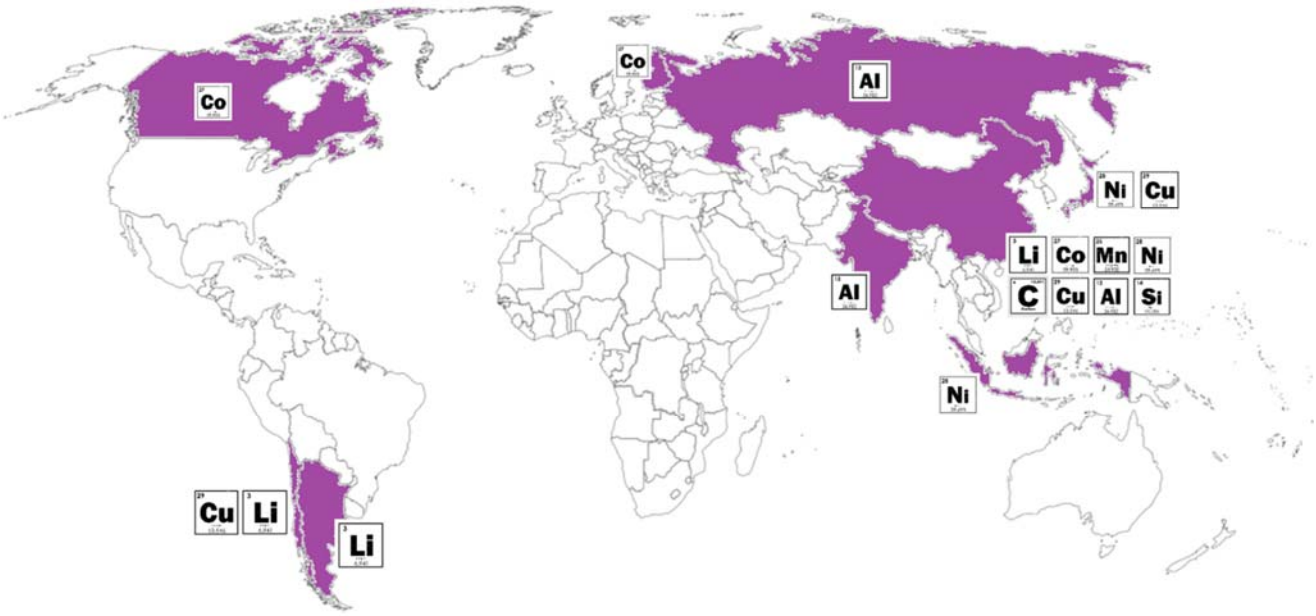


Figure 7 Map with largest refiners of raw battery materials, highlighted in purple with the relevant element symbols.

3.4. Battery manufacturing

The production of battery cells consists of sandwiching sheets of electrode material with an electrolyte in between. Depending on the desired cell shape, the material is wrapped inside a cylindrical housing or layered flat. Car manufacturers apply different types of battery cell shapes in EVs, illustrated in Figure 8. The cylindrical cells are one of the first to be mass-produced and are still widely used. The design is structurally stable and inexpensive to produce. However, the packing density inside a battery pack is not optimal due to the cylindrical shape, meaning that there can be less stored energy per unit volume. Tesla is most notable for using cylindrical cells provided by Panasonic, as these were the best available at the time and had proven reliability (with modern thermal- and electrical management systems). For the newer generation LFP batteries a pouch assembly is used, provided by manufacturer CATL. The remaining manufacturers are adopting pouch cells as well, wherein multiple layers are sandwiched together to create a lightweight and highly packed battery. Looking ahead, pouch cells have the potential to become the leading type of battery cell due to their superior properties and unique ability to accommodate solid-state battery technology. For the near future however, many car manufacturers such as Tesla, General Motors and BMW have announced continued use of cylindrical cells (with variable dimensions) for their newer generation cars [17].

[17] https://www.electrive.com/2023/01/26/gm-to-switch-from-pouch-to-round-battery-cells/

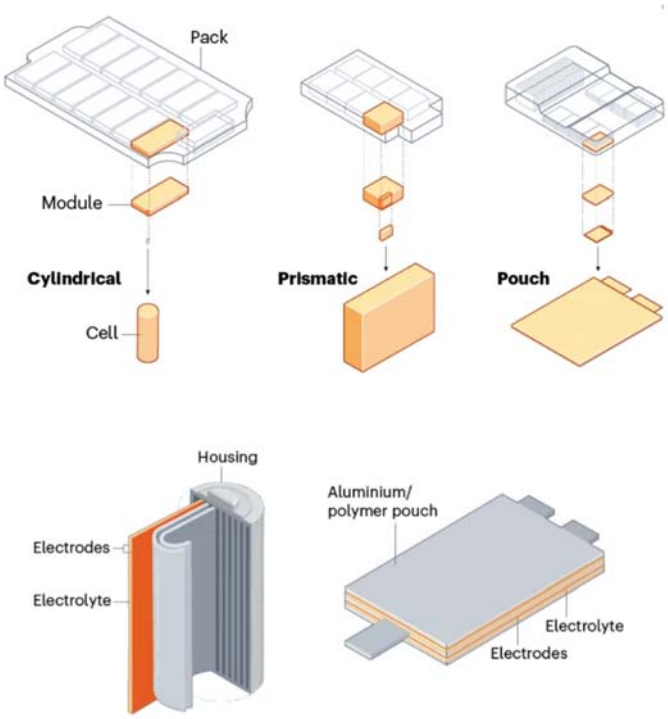


Figure 8 Different types of battery cell assembly's. Adapted from: G. Harper et al. Nature 575, 75–86 (2019), G. Offer et al. Nature 582, 485–487 (2020).

Battery production capacity is strongly concentrated in China as well. As mentioned before, considerable investments and greenfielding have allowed their industry to gain experience and know-how in the industry. Economies of scale have been key in minimizing the battery price per kWh which allowed car manufacturers to price their EVs competitively against ICE vehicles. Even for the LFP batteries, which have becoming increasingly popular, China has had an advantage on the international markets. Until recently, they held most of the core patents behind its manufacturing process and had unique access to abundant iron sulfate from domestic chemical industries, both aspects enabling inexpensive manufacturing.

The total capacity of installed batteries in the first half of 2022 amounted to more than 200 GWh, as can be seen Table 6. In 2021 China held a staggering share of 78% of the world's battery manufacturing capacity (see Figure 9). In addition to that, they also control the majority of battery component manufacturing, producing 70% of all cathodes, 85% of anodes, 66% of separators and 62% of electrolytes. In recent years investments from European and US companies have caught up as well, in order to gain more independence and provide domestic employment opportunities. This trend is further elaborated in the subsequent chapters for both

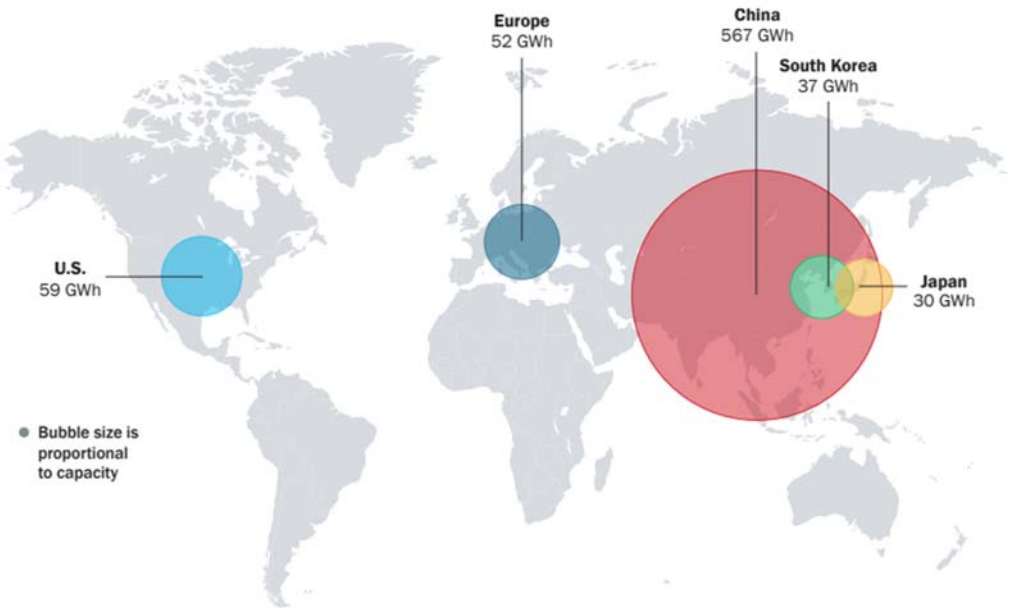


Figure 9 Cell manufacturing capacity by region/country in 2021. Source: Benchmark Mineral Intelligence (2021)

regions. In short, most of the midstream and downstream operations are concentrated in China.

Table 6 Total EV batteries installed in first half of 2022. Source: SNE Research (2022)

Manufacturer	*Location*	*Capacity in GWh (H1 2022)*	*Market share (%)*
CATL	China	70.9	34.8
LG Energy Solutions	South Korea	26.2	14.4
BYD	China	24.0	11.8
Panasonic	Japan	19.5	9.6
SK On	South Korean	13.2	6.5
Samsung SDI	South Korea	10.0	4.9
CALB	China	8.4	4.1
Other	various	31.4	13.9
Total capacity		*203.4*	

3.5. End-of-life management

After a battery has reached its intended life, there are several future scenarios possible:

1. The battery components are **refurbished**, which are then able to be used again in a second-life battery
2. The battery is **repurposed** in another application wherein its properties still meet the new application requirements
3. The battery is discarded and **recycled**, from which raw materials are recovered to a certain degree to serve as secondary feedstock

The recycling of lithium-ion batteries is still in its infancy compared to the earlier supply chain operations. The topic of end-of-life waste management has received comparatively little attention and investments from both enterprise and governments. From a time perspective, the issue of recycling (and repurposing & refurbishing) has an understandable lower priority, as the average battery lifetime is approximately 15 years and does not immediately present an issue with waste management. In general, recycling of batteries consists of three main steps:

EV batteries are difficult to recycle due to their complex chemical composition and designs. The simplest available method is via pyrometallurgy whereby the battery is smelted to recover some metals. This method is not desirable due to the high energy requirements and low recovery rates (and no lithium recovery). It also requires additional energy to reprocess the metals into battery grade components. More modern approaches are focused on hydrometallurgical processing whereby extremely high recovery rates can be achieved (approximately 99% of e.g. lithium) with lower energy needs as well. Although this approach has higher initial costs to open a plant, it can recover much more costly minerals (nickel, lithium) which could potentially make the difference. In addition, the secondary materials feedstock can play a significant role in decreasing the need for mining activities, and effectively lower geopolitical dependency. Different companies in North America (e.g. Li-Cycle[18], Redwood Materials[19]) have launched pilot plants to experiment with this technique to supply secondary materials. Umicore has pyrometallurgical recycling plants already in Europe[20].

As opposed to complete battery dismantling and recycling, components can be refurbished independently to rejuvenate electrochemical properties. This is done by refurbishing the cathode, with a process referred to as direct cathode recycling (or: cathode relithiation/healing). In short, it re-introduces lithium via a hydrothermic process which replenishes the lithium shortage in the cathode (roughly 15%) with conservation of crystallinity. The advantage is that this process is non-destructive and only needs ca. 10% of the energy requirements, which makes it highly efficient. The disadvantage is that it still requires complex sorting and dismantling whereby information about the battery (e.g. state of health, chemistry, etc.) must be known.

[18] https://li-cycle.com/blog/li-cycle-lithium-battery-recycling-efficiency-and-recovery-rates/
[19] https://www.redwoodmaterials.com/solutions/
[20] https://rbm.umicore.com/en/applications/energy-storage-systems/

Direct cathode recycling is rather flexible as well, being suitable for both NMC and LFP type batteries. Figure 10 shows the two types of recycling along with a cost-decomposition for different world regions. [21]

Another route is repurposing batteries for non-mobile applications. For automotive applications batteries are considered 'worn out' at a residual capacity of +- 80%. For less strenuous applications, they can still be useful and play an important role. Stationary energy storage systems can be designed with used car batteries to support the electricity grid via peak-shaving or grid-balancing. After the set of batteries are rigorously tested and checked, they can be placed in bulk inside a container to serve as a flexible stationary storage system. By repurposing batteries it prolongs its intended life which could improve its life cycle impact. Usually this adds another 6 years to its useful lifetime. Car manufacturer Nissan is one of the first players in this market due to their longstanding experience with EVs and the increasing availability of discarded Nissan Leaf batteries (manufacturing year 2010). However, many enterprises which aim to deliver this serve struggle to make it commercially viable. The deterioration of properties quickly outweighs the cost-savings of the second-hand product. As a result, new batteries are more attractive due to their modern performance in terms of both safety and energy carrying properties. Additionally, by extending its lifespan the valuable components are kept unavailable to recycling facilities, which then delays the potential secondary feedstock streams. Considering the potential scarcity of raw materials, it could exacerbate supply chain problems. Figure 11 illustrates the effect of lifespan-extension versus recycling availability.

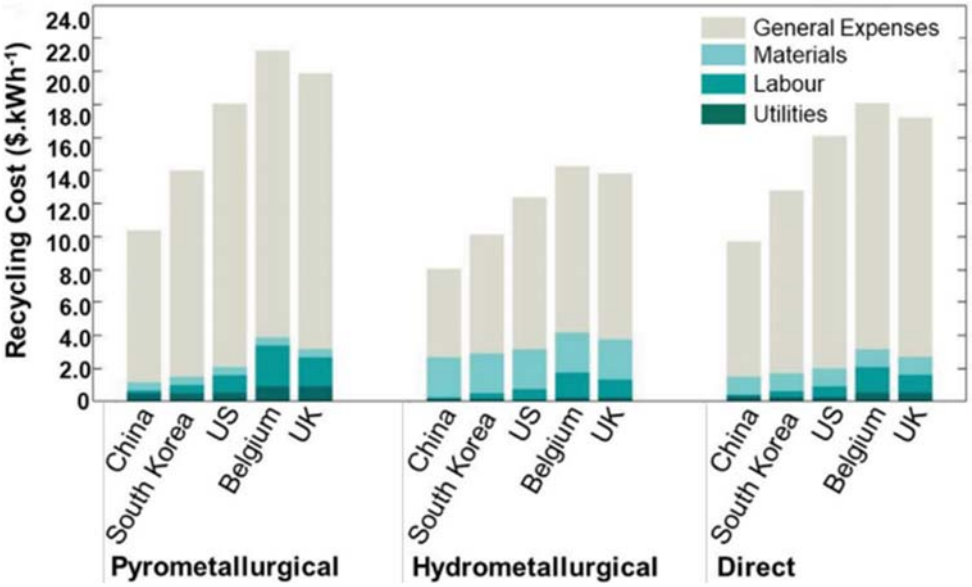


Figure 10 Schematic illustrating the closed-loop recycling approach. Source: D. J. Garole, R. Hossain, V. J. Garole, V. Sahajwalla, J. Nerkar, D. P. Dubal, ChemSusChem 2020, 13, 3079.

[21] Sloop, S.E. et al. (2019). *Cathode healing methods for recycling of lithium-ion batteries.* Sustainable Materials and Technologies, 22. https://doi.org/10.1016/j.susmat.2019.e00113

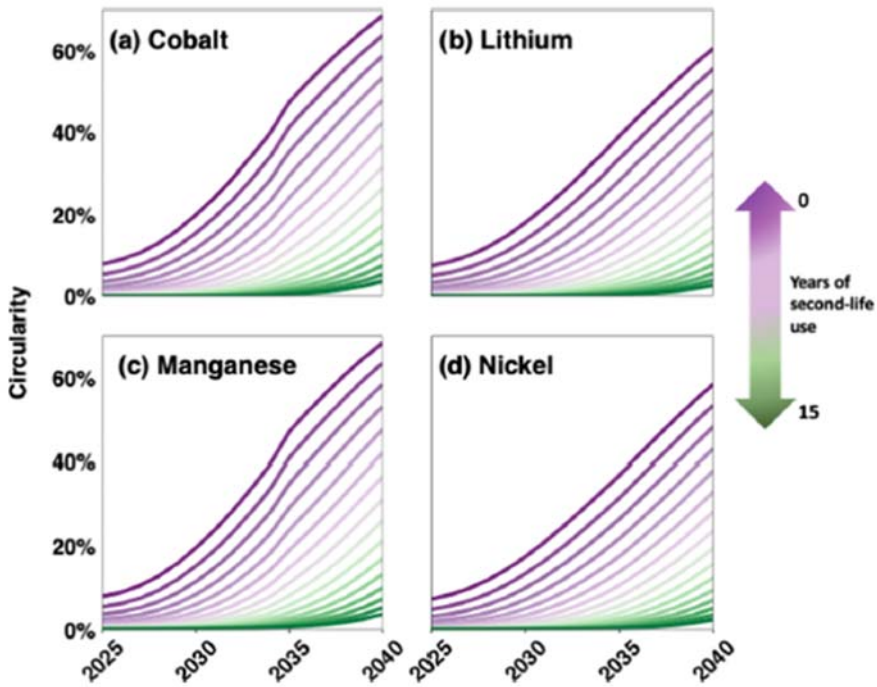


Figure 11 Potential recycling capacity (circularity) of raw materials from 2025-2040 with varying degrees of lifetime extension (0-15 years). Source: Dunn, J. et al. (2021). Circularity of Lithium-Ion Battery Materials in Electric Vehicles. Environ. Sci. Technol., 55, pp. 5189-5198.

4 European situation

4.1. European policy initiatives

The European Green Deal is a massive policy package of 1 trillion EUR to push the European Union (EU) towards net-zero emissions in 2050. An important component that falls under this arrangement is the decarbonization of car transportation and expanding the vehicle charging infrastructure. These funds can be spent across different specific investment programs via the European Investment Bank Group (InvestEU). Aside from monetary investments, legal frameworks are also implemented such as the goal of 100% EV sales (or other types zero-emission vehicles) by 2035. Although the remaining non-member states in Europa fall outside this scope, it can reasonably be expected that these policies will affect beyond EU borders. For batteries specifically, projects are devoted to value chain development in terms of competitiveness, innovation and sustainability. These Important Projects of Common European Interest (IPCEI) bring financial resources together with experts in the field to address the entire value chain, from raw materials extraction to end-of-life recycling. EU member states can join individually, depending on interest and position within the battery value chain. Overall, the EU has spent over 20 billion EUR to develop its battery value chain.

The EU has also announced a Critical Raw Materials Act in 2022 which aims to secure critical raw materials supply chains for many important future industries. These include energy storage, semiconductors, hydrogen, and so on. The initiative is a reaction to the growing demand rate of certain raw materials, such as lithium and rare-earth elements, which were previously considered less important than oil and gas for example. The current state of affairs with regard to China's quasi-monopoly is also an important reason for Europe to act, and lessen its dependency on imports. Concrete actions from this Act will follow in the coming months. In any case it will contain plans for: diversification of third-country sourcing, raw material projects in the EU and domestic production legislation (i.e. hard targets on EU-refined lithium), strategic storage capacity and recycling incentives, and streamlined procedures and ESG (environmental, social and governance) certification schemes to attract investments. This approach is considered more assertive and protectionist than traditional EU initiatives. In February 2023 the European Commission presented a Green Deal Industrial Plan to build on previous initiatives (as mentioned above) which consists of four main pillars: (1) simplified regulatory frameworks, complemented by the Critical Raw Materials Act, (2) faster access to funding, which can contribute to streamline IPCEI approvals for example, (3) developing newly skilled workforces as 35-40% of all jobs could be affected by the green transition and (4) fair global trade, to address unfair foreign competition and expand the EU's free trade agreements network. A 'Critical Raw Materials Club' is also explored to gather resource-rich countries and materials consumers, to ensure the functioning of diversified, global supply chains. There is 270 million EUR available altogether as part of this plan.

In 2017 the European Battery Alliance (EBA) was formed to build an innovative, sustainable and competitive battery value chain in Europa. This alliance brings together EU countries, industry and the scientific community and is supported by the European Investment Bank. The industrial development program operates through EIT InnoEnergy which has brought over 800 industrial/innovation partners on board, focusing on mining, refinery, production and recycling. Over 100 major industrial projects have been announced together with the EBA. Its goal is to realize

a 250 billion EUR market worth by 2025. The EBA has set out 6 top-priorities to reach its goal: (1) securing access to raw materials, (2) supporting European battery production (through IPCEI), (3) strengthening industrial leadership through R&D programs, (4) securing a skilled workforce in the value chain, (5) supporting sustainable battery production with renewed regulation and (6) ensuring consistency with broader EU frameworks.

A legal framework has been proposed to impose a sustainable battery value chain with the renewed Battery Regulation (successor of EU Battery Directive from 2006). This applies to all types batteries sold in the EU and therefore includes EV batteries as well. For consumers it will deliver more transparency on sustainability, by introducing a carbon footprint declaration and label on every battery. A mandatory "battery passport" will also be introduced which holds important information on (remaining) capacity, chemical composition, performance and durability. This way consumers have access to vital battery information and statistics which can be useful for second-hand markets and end-of-life management. Re-use, recycling or refurbishing facilities can also access this passport to safely and effectively sort and process spent batteries. On the producer's side, a comprehensive Extended Producer Responsibility (EPR) regulatory framework is included which ensures free-of-charge battery collection and recycling. Both collection targets and recycling targets are set to increase over time, to allow industry to adapt. In 2025 65% of a lithium-ion battery's weight must be recycled, which is increased to 70% in 2030. Specific requirements will also be introduced per materials, such as 35% for lithium by 2026 which increases to 70% by 2030. Other valuable materials such as copper, cobalt and nickel are of course specified as well. An overall recycling efficiency of 50% is set for EV batteries by 2025. Regarding actual re-use of materials (closed-loop production) the targets are somewhat less ambitious. Minimum levels of recovered cobalt (16%), lithium (6%) and nickel (6%) from manufacturing waste of spent batteries must be reused in new batteries. To formally lock in the regulation it must first pass European parliament and council.

The EU is also reaching out to strategic international partners such as the United States. The EBA and US Li-Bridge Alliance have entered collaboration in 2022 to strengthen supply chains and accelerate deployment of next-generation batteries and secure raw materials. They have committed to invest in R&D, sustainability aspects, workforce, and just transition. This alliance results in the collaboration of two strong knowledge institutions: EIT InnoEnergy and Argonne National Laboratory to jointly carry out specific research tasks. These partnerships are however not binding agreements, and can sometimes be conflicting of national interests and other policies, such as the Inflation Reduction Act, elaborated further in the next chapter.

4.2. Challenges in the value chain

Europe has currently a strong dependency on imports of critical minerals required for batteries. The extraction and refinement of multiple critical raw materials is highly localized, as explained in Chapter 3. For example, EU countries represent 12% of refined copper demand while producing only 4%. This geopolitical realization (and resulting monetary budgets) has sparked domestic mining and refining projects to secure access to raw materials. Lithium mining projects are among the most prevalent. Over the past months a high number of newly discovered mineral deposits have been announced in several European countries. According to reports, Europe could be producing two-thirds of all cathode active material (which contains the most valuable metals) by 2027. The sourcing of raw materials is a bigger challenge however, where mining activities take long times to yield results. This

complicates projections on domestic raw materials supply, as exact production quantities and time frames are often vague. The estimated demands of CRMs for batteries are highlighted below for 2030 which quantifies the challenges.

Table 7 Refined CRM demand and supply in 2020 and 2030, assuming medium scenarios. Source: KU Leuven (2022). Metals for Clean Energy; CPM Group (2021); JRC analysis (2021)

Material	*Demand in 2020:*	*Demand in 2030:*	*Projected European supply share in 2030:*
Lithium	20 kt	235 kt	55%
Cobalt	17 kt	40 kt	35%
Manganese	10 kt	200 kt	25%
Nickel	380 kt	500 kt	60%
Graphite	50 kt	450 kt	4%
Copper	525 kt	4 Mt	50%
Aluminum	1.5 Mt	17 Mt	25%
Silicon	450 kt	800 kt	38%

There is a clear gap in the raw materials extraction and refinement industries to catch up with the battery production goals. One answer to this problem lies in the societal challenges of mining, examples of which are treated in the next paragraph. Benchmark Material Intelligence reported that more than 300 new mines are required to meet global battery demand by 2035, and even predicts a shortage of global battery supply this decade.[22] [23] It must be noted that the supply and demand of battery minerals are still dependent on several parameters such as:

- Evolution of battery chemistry
- Discovery of domestic raw materials
- Time needed to actually commence mining operations
- Personal mobility behavior
- Governmental policies

The European Union is also rethinking their import needs with large CRM producers such as Chile for example. Association agreements with Chile have been modernized to ensure raw materials such as lithium through the Advanced Framework Agreement[24]. This promotes free trade between the two regions (99% will be tariff-free) and ensures common support of environmental and societal values. Estimates do however show that over 50% of Europe's refined lithium demand can come from European projects by 2030. There is also potential for secondary feedstock to meet 8-12% of materials demands between in 2030, through recycling of manufacturing waste or spent batteries. This is of course incentivized with the renewed Battery Regulation that legally requires recycled content in batteries.

Much more optimistic are downstream operations, where battery cell production is forecast to cover 100% of domestic EU-demand by 2027. This only includes cell production capacity however, which still requires foreign imports of refined battery

[22] https://source.benchmarkminerals.com/article/more-than-300-new-mines-required-to-meet-battery-demand-by-2035
[23] https://source.benchmarkminerals.com/article/shortage-of-top-tier-battery-supply-expected-this-decade
[24] https://ec.europa.eu/commission/presscorner/detail/en/statement_22_7603

minerals. The important side note here is the need for a strong industrial policy to streamline and actually realize such projects along the entire value chain.[25]

An overview of the announced battery production capacity (per country) is presented in Figure 12. According to Transport & Environment, Europe could provide more than 1000 GWh by 2027 and up to 1800 GWh by 2030. This is assuming all projects come to their full realization and announced deadlines are met. For a medium (base) scenario a battery cell demand of 1050 GWh by 2030 is expected and 1645 GWh by 2035. A summarized list of major projects is shown below in Table 8.

Table 8 Several large-scale factories announced in Europe with planned production capacity in 2030 (no claims on completeness). Source: Transport & Environment (2023)

Country	*Company*	*Annual production capacity in 2030 (estimated):*
Germany	Tesla	125 GWh
	CATL	100 GWh
	Northvolt	60 GWh
	Volkswagen	40 GWh
	QuantumScape	21 GWh
France	Verkor	50 GWh
	ACC	40 GWh
United Kingdom	West Midlands	60 GWh
Poland	LG Chem	115 GWh
Portugal	CALB	45 GWh
Italy	Italvolt	70 GWh
Hungary	ACC	40 GWh
	CATL	100 GWh
	SK On	50 GWh
	Samsung SDI	40 GWh
Norway	Morrow	43 GWh
Sweden	Northvolt	60 GWh
Total		*1800 GWh*

[25] https://www.transportenvironment.org/discover/a-european-response-to-us-inflation-reduction-act/

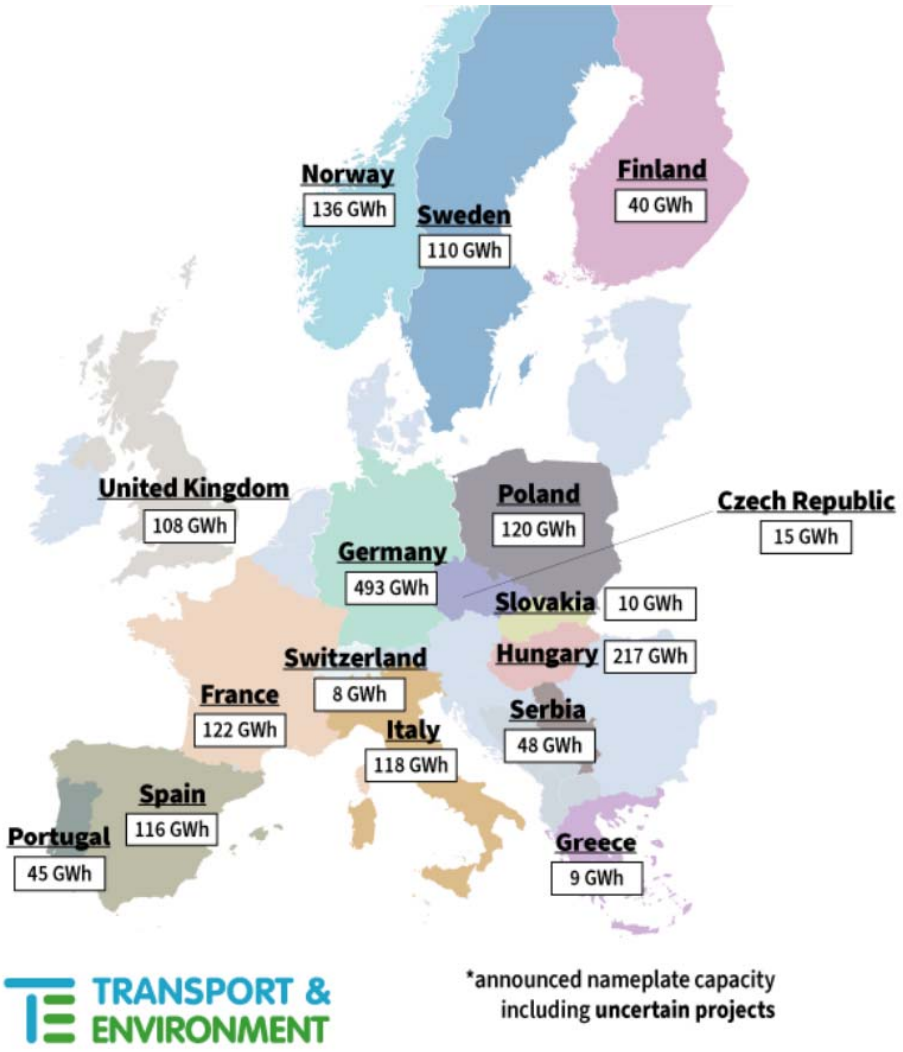


Figure 12 Overview of announced battery production capacity in Europe. Source: Transport & Environment (2023)

It is also worth noting that along with these massive industrial investments the pressure on the job market will increase as well. McKinsey estimated that one 40 GWh gigafactory requires more than 2,000 skilled employees[26]. The International Energy Agency similarly predicts that EV and battery manufacturing are set to be the largest areas of employment[27]. It is important to provide good worker training to prepare employees for the next generation of 'green' jobs. These findings are equally relevant for the United States economy. A portion of the labor force can also be attracted from diminishing industries such as coal to provide employment continuation.

[26] https://www.mckinsey.com/capabilities/operations/our-insights/unlocking-growth-in-battery-cell-manufacturing-for-electric-vehicles
[27] International Energy Agency (2022). *World Energy Employment.*

4.3. Challenges in local governments and communities

As mentioned earlier, there is a shortage of mines to secure strategic minerals for EV battery cell production. Companies inside and outside of Europe, as well as local governments are exercising efforts to promote mining activities for such minerals. To successfully integrate and embed governmental policies, their effect on local communities and surroundings must be studied and accounted for. The mining industry is historically a notorious polluter and carries a bad reputation. On a more fundamental level, there is always a societal discussion about the need for potentially harmful resource extraction intended for 'green' technologies.

For example, protestors have criticized the 'Jadar Project' of Rio Tinto in Serbia, who intended to exploit Europe's largest (current) lithium mine with 11kt capacity. Local opposition argued that environmental considerations were not adequate, and that agriculture could suffer from the waste water. Moreover, locals felt that foreign conglomerates are unrightfully exploiting their natural resources. After prolonged debates and clashes the project was legally halted by Serbian government, although reports claim that mining and processing activities have not ceased after this.[28]

Similar opposition have been observed in Spain as well with the Valdeflores project (lithium), Las Navas Project (lithium) and Extramadura (nickel) for example. Local community groups worry that air quality will be affected due to mining pollution, and are skeptical about the numbers of promised jobs. Although the EU has listed metals such as lithium as critical to the energy transition, it must consider the right frameworks of introducing such projects while following proper ESG standards.

Public reception has been different for projects announced in pre-existing mines, where the mined minerals are simply adjusted to updated interests. This was the case in central France (Beavoir), where Imerys announced plans in 2022 to produce 34 kilotons of lithium hydroxide annually for at least 25 years (equal to 700,000 EVs per year). The plan was welcomed by the French government and local authorities and is therefore not expected to present any significant risks in planning permissions, according to CEO Alessandro Dazza.[29]

Studies have also measured the environmental, social and governance (ESG) scores for various resource extractions in terms of water use, land use, communities, environment, and so on. The results are discussed in more detail in the following chapter (Figure 14) to avoid repetition.

[28] https://balkangreenenergynews.com/green-left-mp-cuta-says-entire-serbia-to-be-blocked-if-rio-tinto-continues-its-lithium-project/
[29] https://www.reuters.com/business/frances-imerys-wants-become-leading-lithium-producer-europe-2022-10-24/

5 United States of America

5.1. US policy initiatives

The issue of battery minerals scarcity is well-recognized in US politics nowadays. In 2020 the Energy Act defined critical minerals as those which are essential to economic and/or national security and have a vulnerable supply chain. The technical input is provided by the US Geological Survey (USGS) which tracks and studies scientific data on natural resources. The resulting list consists of 50 critical minerals including aluminum, cobalt, lithium, manganese, nickel and graphite. These have been identified as highly relevant to the battery supply chain in this report. As a response, several initiatives have been launched by the current Biden administration to tackle future supply chain problems. These are needed to ensure the goal of reaching 50% EV sales nation-wide by 2030, with the state of California even showing more ambition with a 100% EV (or other zero-emission cars) sales target by 2035.

The Infrastructure Investment and Jobs Act (Bipartisan Infrastructure Law) signed in 2021 has opened up financial access to support the domestic battery value chain. The Department of Energy is implementing a 6 billion dollar grant which includes 3 billion dollars for battery manufacturing and recycling. This is aimed at demonstration projects and commercial-scale recycling facilities. Another 3 billion dollars are designated for domestic materials production, including the refining of nickel, lithium and cobalt (as well as rare-earth elements). Lilac solutions is one of the first companies to be selected for this grant and has received 50 million dollars to advance low-concentration lithium brine extraction. Cirba Solutions has also received 82 million dollars funding to develop a battery recycling facility. In total, more than 135 billion government dollars are available for the whole EV battery value chain.

In addition, the more recently signed Inflation Reduction Act offers federal tax credit (up to $7,500.-) for EVs, with the requirement that the critical minerals contained must be extracted, processed, or recycled in the US or with countries with which there are free-trade agreements (e.g. Canada, Chile, Argentina). More specifically, 40% of the battery metals must come from the US and half of all battery components by the year 2024. Unfortunately this complicates collaboration from European companies as it unlevels the international playing field. Lastly, the President has the authorization to mobilize industry for national defense reasons via the Defense Production Act (1950) to incentivize companies to expand domestic mining.

The USA and US states participate in numerous international organisations aimed at knowledge sharing and policy development. For instance the Electric Vehicles initiative[30], the Hybrid and Electric Vehicle Technology Collaboration Programme[31], the International ZEV Alliance[32] and so on.

5.2. Challenges in the value chain

From the USGS critical minerals list, the US was 100% reliant for 14 minerals in total. From a logistical point of view, the concentration of the EV battery supply

[30] https://www.iea.org/programmes/electric-vehicles-initiative
[31] https://ieahev.org/
[32] https://zevalliance.org/

chain as described earlier in Chapter 3, presents a sizable challenge for the US government. Current politics and undertakings are very dynamic at the time of writing, which makes quantitative forecasting supply and demand rather difficult and with high uncertainty. There are no transparent sources with official minerals forecasts available for the US market alone, although studies have estimated mineral requirements for batteries in 2040 which are shown in Table 9. It must be noted that the supply and demand of battery minerals are still dependent on several parameters such as:

- Evolution of battery chemistry
- Discovery of domestic raw materials
- Time needed to actually commence mining operations
- Personal mobility behavior
- Governmental policies

In terms of projected battery demand, there is an expected tenfold increase from the levels in 2021 if all stated policies are carried through. This implies a 3.5 TWh annual battery capacity demand in 2030, which is equal to roughly 90 gigafactories (assuming an average production of 35GWh). Both the ICE-to-EV transition and the increase in battery size contribute to this growth number. [33]

Table 9 US battery minerals demand in 2040 based on policy targets, compared with 2020 production. Source: Dunn, J. et al. (2021). Circularity of Lithium-Ion Battery Materials in Electric Vehicles. Environ. Sci. Technol., 55, pp. 5189-5198.

Material	*US mineral demand for batteries in 2040:*	*Global refined output in 2020:*
Cobalt	113 kt	144 kt
Lithium	101 kt	430 kt
Manganese	109 kt	18 Mt
Nickel	470 kt	2.6 Mt

The current governing mining law in the US (General Mining Law) dates back from 1872 and is not up to today's standard. It does not take into account sufficient environmental protection during mining operations, and it involves plenty of paperwork to get the proper approvals. This hinders the exploitation of mines where natural resources are perhaps already discovered. It is also criticized for its lack of transparency and communication towards local stakeholders. The Biden administration has also established a workgroup to make the necessary reforms. Both mining and processing operations involve very long lead times, with mines taking up 5-20 years (from exploration to production) and refineries 3-8 years[27]. This delays domestic production ramp-up and leads to prolonged import dependency.

Looking at the more downstream production, there are numerous projects being announced for battery cell plants in North America. As a result of the Inflation Reduction Act many companies have entered the market confidently with large investments, as can be seen from the list in

Table 10 below. Some projects announced in Canada have also been included in this list due to the existing free-trade agreement that covers the IRA requirements. The expected growth is a staggering twenty-fold increase in battery production facilities compared to 2021. Only one car company so far has made upstream investments with raw materials suppliers, namely General Motors and Lithium Americas.

[33] International Energy Agency (2021). *Global Supply chains of EV Batteries.*

Comparing the projected supply with demand, it can be derived that there is a significant shortcoming of capacity in 2030.

Diagram 2 Summary of announced battery production projects

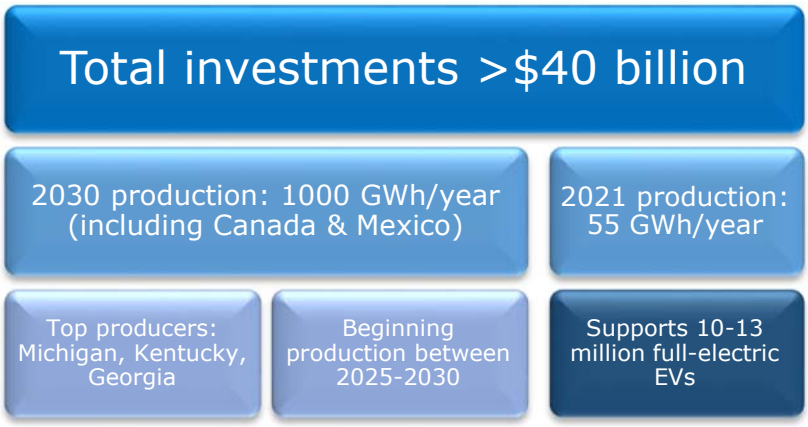


Table 10 Major announcements on battery production facilities in North America. Source: CIC energigune (2022); Argonne National Laboratory (2022); US Department of Energy (2022)

Company	*Location*	*Planned capacity per year*	*Operational in*
Ultium cells (joint venture GM & LG Chem)	Ohio	50 GWh	2023
	Tennessee	35 GWh	2023
	Michigan	50 GWh	2025
	Indiana	TBD	TBD
Ford & SK On	Tennessee	40 GWh	2025
	Kentucky	86 GWh	2026
SK On	Georgia	50 GWh	2023
Stellantis & LG Chem	Ontario	45 GWh	2024
Stellantis & Samsung SDI	Indiana	33 GWh	2025
Toyota	North Carolina	TBD	2025
SK On & Hyundai	Georgia	TBD	2025
Tesla	Texas	up to 100 GWh	2022
	Nevada	100 GWh	TBD
Britishvolt	Quebec	60 GWh	TBD
Stromvolt	Quebec	10 GWh	2030

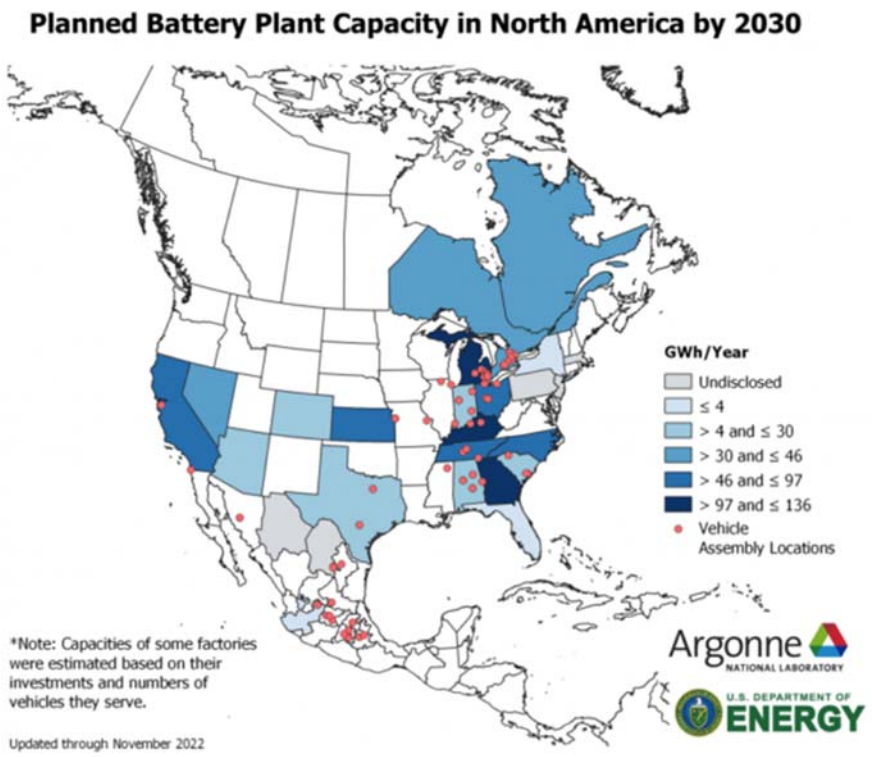


Figure 13 Source: David Gohlke, Yan Zhou, Xinyi Wu, and Calista Courtney, Argonne National Laboratory, Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021, ANL-22/71, 2022.

From a recycling perspective, there are also major projects announced in North America. Redwood Materials (based in Nevada) is a company that utilizes hydrometallurgical processing for battery minerals recovery, and has goals to deliver 100 GWh of recycled content by 2025. In 2030, they aim to supply 500 GWh of recycled content for EVs, amounting to roughly 5-10 million EVs (depending on battery capacity). They have partnered up with Tesla to deliver recycled materials for their battery production facility in Gigafactory Nevada, making it a true closed-loop production facility[34]. Furthermore, they have received a conditional 2 billion USD loan from the DoE to finance these projects. Ascend Elements has recently received 480 million USD of DoE funding to produce a recycling plant for battery materials in Kentucky, which will have the capacity to deliver recycled content for 250,000 EVs annually[35].

In Canada, big players have also emerged such as Lithion and Licycle, both utilizing a hydrometallurgical process for battery minerals recovery. Lithion has plans to commission over 20 battery recycling plants in the next 15 years, which have a minimum capacity of 20,000 electric car batteries per year. In 2025 they are scheduled to launch their first commercial plant. Lithion has multiple facilities in the pipeline for the US, Europe, and Asia[36]. Licycle already has a running plant in

[34] https://www.teslarati.com/tesla-giga-nevada-recycled-battery-materials-from-redwood-no-waste-stream/
[35] https://ascendelements.com/ascend-elements-awarded-480m-in-grants-from-u-s-department-of-energy-to-manufacture-sustainable-battery-cathode-active-materials/
[36] https://www.lithionrecycling.com/lithium-ion-battery-recycling-plant/

Arizona with similar capacity, and is also looking at expansion in Europe (Germany, Norway)[37].

As mentioned before in the European analysis, the pressure on the job market will increase as well. McKinsey estimated that one 40 GWh gigafactory requires more than 2,000 skilled employees[38]. The International Energy Agency similarly predicts that EV and battery manufacturing are set to be the largest areas of employment[39]. It is important to provide good worker training to prepare employees for the next generation of 'green' jobs. A portion of the labor force can also be attracted from diminishing industries such as coal to provide employment continuation.

5.3. Challenges in local government and communities

To successfully integrate and embed governmental policies, their effect on local communities and surroundings must be studied and accounted for. With the renewed interest in domestic mining and refinery, but also battery production sites, there are concerns for the impact on local stakeholders. These can range from local businesses, inhabitants and environment. The mining industry is historically a notorious polluter and carries a bad reputation. On a more fundamental level, there is always a societal discussion about the need for potentially harmful resource extraction intended for 'green' technologies. For example, the Thacker Pass Lithium Mine (Nevada) has met considerable resistance from local communities. This mine has one of the largest lithium deposits known in the world and can produce 25% of the world's current lithium demand annually. Indigenous tribes have opposed the project as it was located on sacred site. Other protesters questioned the environmental review, wildlife-impacts, disruption of cultural sites and even the missing and murdering of indigenous women. In short, local communities feel inadequately informed and involved which fuels distrust.

California's Lithium Valley project, which contains enough deposits to provide 90,000 tons of lithium per year, has also met resistance. The Imperial Valley region (where the plant is located) is one of the most economically disadvantaged communities in California. Unemployment is high and inhabitants have suffered disproportionately during the Covid-19 pandemic. Air quality issues are also at an already poor level. From the Californian government a commission (Blue Ribbon Commission) has been established in 2021 to review and investigate the lithium extraction methods. A community benefit fund has been established together with the California Infrastructure and Economic Development Bank (IBank) to secure a portion of the revenue to feed back to the community. A percentage of the profits are used to support local government and community restoration programs. An additional 5 million USD has been freed for the county to assess the environmental impacts and health impacts of Lithium Valley. Protestors raise the importance of a 'just transition' in which green transitions also incorporate socio-economic equity and development.

Studies have measured the environmental, social and governance (ESG) scores for various resource extractions in terms of water use, land use, communities, environment, and so on. The results are combined in Figure 14. It shows contrasting ESG risk profiles for cobalt and lithium for example; about 70% of cobalt resources

[37] https://ascendelements.com/ascend-elements-awarded-480m-in-grants-from-u-s-department-of-energy-to-manufacture-sustainable-battery-cathode-active-materials/
[38] https://www.mckinsey.com/capabilities/operations/our-insights/unlocking-growth-in-battery-cell-manufacturing-for-electric-vehicles
[39] International Energy Agency (2022). *World Energy Employment.*

(by tonnage) are located in contexts with high-very high scores (light red- dark red bars), while 65% of lithium resources are located in low-medium range (light blue-white bars) ESG risk scores. They also differ in which type of risk it involves. Lithium tends to bring higher environmental risks (water) and cobalt more social risks. These confirm the potential issues with mining operations, if adequate measures are not taken from both government and enterprises. They also nuance the type of risk and required attention across different ESG aspects.
Local governments have also been opposing to Chinese companies under

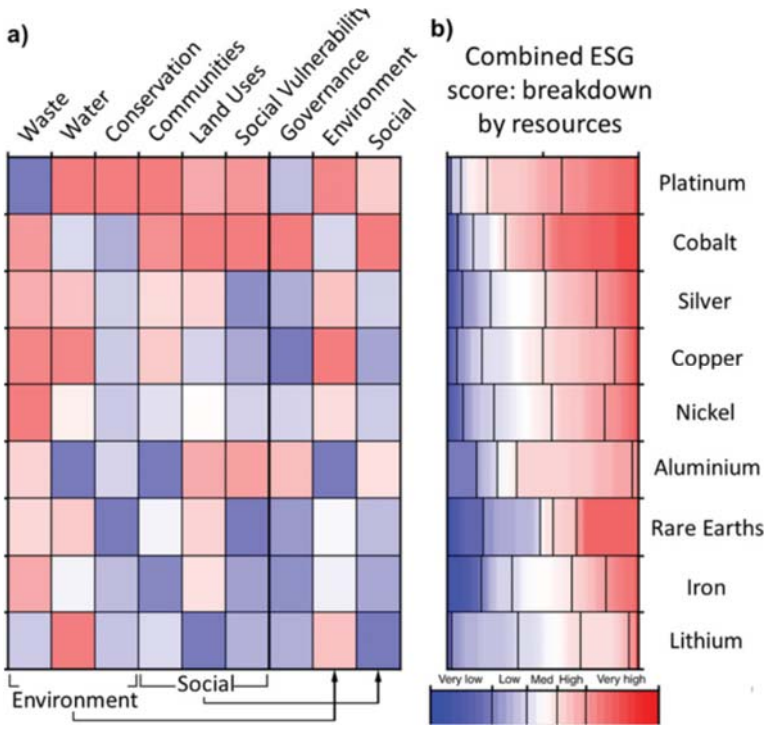


Figure 14 ESG risk matrix for nine metals ranked by total score in nine differente categories. Right figure shows the breakdown of total risk by resource tonnage. Red corresponds to higher risk and blue to lower risk. Source: É. Lèbre et al. (2020). Nat. Commun. 2020, 11.

geopolitical pressure. The fear of critical infrastructure and industry being compromised by external parties has led to several bans of Chinese companies that are often tied to the government. These type of export bans have also been observed in high-tech semiconductors industry. Recently the governor of Virgina, Glenn Youngkin, has abandoned their candidateship for the Ford-CATL battery plant. This joint operation was formed to produce Chinese CATL batteries under Ford ownership, thereby satisfying the IRA requirements for subsidies. The technical expertise of CATL was needed to quickly build the facility. The planned facility is relocated in Michigan instead.[40] It is clear that geopolitical tensions are a decisive factor in the realization of non-domestic joint ventures.

[40] https://www.reuters.com/technology/ford-invest-35-billion-build-michigan-battery-plant-2023-02-13/

6 International collaboration perspectives

Although both regions have expressed ambitious goals and presented matching policies to reach them, international collaboration can still play an important role. Forging alliances with strategic partners can accelerate transition targets and broaden opportunities for both policymakers and investors/companies. Firstly, there must be long-term collaboration instead of mere trade agreements with countries. This also means partnering with established CRM suppliers to secure the short-term supply. The US and Europa should also share best practices of exploiting domestic potential (in all stages of the supply chain) across public and private sectors. This could also entail American enterprises partnering in European mining projects and vice versa, in which state-of-the-art technologies are shared to limit pollution during extraction for example. Moreover, open-access technologies are needed in research and development to remove barriers and advance clean practices.

Consistent environmental policies are needed to level the playing field in the US and Europe, to promote an equally conducive climate for investors in green technologies. This can range from EV sales targets up to recycled content requirements in batteries, as presented recently in the renewed EU Battery Regulation for example. Equally important is the need for truly free markets, in which both the US and Europa have equal opportunities to invest across regions. The Inflation Reduction Act conflicts with European companies and thereby obstructs international collaboration. A good example is the delay of Swedish battery manufacturer Northvolt from Germany as a location for their 60 GWh plant. The rising cost of energy in Europe as a result of the conflict with Russia has threatened the viability of the facility. There are concerns that the company might choose the US over Europe due to tax incentives, as insinuated by a Northvolt spokesman: "*IRA has changed the dynamics for suppliers, the entire value chain is looking at North America instead of at Europe. European politicians on various levels need to act quickly to ensure that Europe remains attractive to invest in*."[41] The precise results and effects of the similar European Green Deal Industrial Plan must be examined over the next months.

To acquire sufficient minerals for the nearby future a collective importing strategy of CRMs is useful to ensure best prices and uniform demands on ESG standards for example. It can be concluded from the previous chapters that neither region has a significant advantage in the value chain, as both global regions struggle to prepare their industries to accommodate for EV demand. Especially in the upstream supply chain difficulties are encountered with strong dependencies on foreign imports and very little to no domestic capacity. However there is increased activity of lithium mining and recycling in both the US and Europe (at this moment mostly announcements) from which a optimistic scenario can be expected. Other than that, the two regions should also focus on the lesser available minerals that are critical to battery chemistries (e.g. nickel, manganese, cobalt). Strategic partnerships (as a method for clever importing) between the US and Europe can prevent them from battling for the same raw materials. Especially when other global regions such as Asia are determined to consolidate their existing supply chains.

[41] https://insideevs.com/news/624170/northvolt-may-delay-german-battery-plant-is-looking-at-us/

As illustrated in Chapter 2, different battery chemistries require different raw materials, which are distributed differently across the globe. Projections on the development of batteries are difficult, however some trends can be assumed for the near future. For example, the increased use of silicon in anodes (either as partial/full substitution of graphite) is very likely, as well as the shift to low-cobalt chemistries. For some applications which allow lower energy densities, LFP batteries can be a solution which eliminates cobalt, nickel and manganese altogether. The two regions should provide policies to advance the silicon anode transition to avoid complete reliance on Chinese graphite. Given the lack of domestically available graphite and the lack of mining/processing activities, it could be an effective strategy to decrease dependency on Chinese imports. The US and Europe should also cooperate in fundamental research programs which aim to develop new technologies that require less or no CRMs for EV batteries for the future. In general, substitutions to bypass CRMs as a whole are a more elegant and effective solution to the supply chain problems.

To facilitate a just transition, the US and Europe should also share best practices to both showcase successes and provide useful feedback on conflict resolving with local communities for example. They should also exchange best practices regarding environmental considerations to limit exposures and potential hazards to surrounding communities. If US companies would engage in mining, refining or production facilities in Europe (or vice versa) it would be beneficial to have unified legislation and practices that ensure the highest ESG standards. Considering the fact that a lot of mining and refining activities are faced with (strong) community protest, significant progress could be achieved here. This can lead to lessened protests and accelerated approval processes which allows both regions to duly reach their shared decarbonization targets.

7 Conclusions

Both the US and Europe have expressed ambitious goals to advance the zero-emission vehicles transition to mitigate the effects of climate change. The currently available zero-emission vehicles are predominantly electric vehicles (EVs). From the logistical point-of-view however, the supply chain of EVs is considered vulnerable and receives growing attention in academia, industry and government. For the production of EV batteries large amounts of raw materials are required such as: iron, graphite, cobalt, nickel, manganese, lithium, copper and aluminum. Most of these materials are imported from non-Western countries. This strong dependency on a handful of countries with regard to the supply chain of EV batteries presents a geopolitical risks that has the potential to severely delay ZEV transition targets.

Current EVs rely on portable lithium-ion batteries which possess good properties in terms of energy storage capacity, power, and safety among others. Nonetheless, lithium-ion batteries are being improved upon continually through research and development. Although this technology has a strong foothold in the industry, alternative non-lithium technologies are also being researched to tackle mineral scarcity or improve safety for example. The most common battery cathode chemistries are NMC, NCA, LCA and LFP coupled with graphite anodes. LFP-type batteries require far less CRMs (only lithium in the cathodes) but have a slightly lower energy density compared to the competitors which prohibits their wide scale use. It should also not be ignored that phosphorus is a recognized critical raw material with high supply risk. Many manufacturers however intend to more broadly use LFP batteries due to the reduced need for CRMs. Some companies are also developing (partly) silicon anodes to improve charging times and capacity, as silicon has the ability to accommodate 10 times more lithium ions compared to graphite. Solid-state batteries are also being developed which have superior safety features, although the timeframes are not always clear.

The supply chain can be subdivided in four main stages, namely: mining, refining, production and recycling. The mining stage sources raw materials from the earth’s crust, after which materials refinery takes place. These processed materials can then be used in the production of functional components for batteries. After batteries reach their intended life, they can be refurbished, repurposed or recycled. The current sourcing of materials often takes place outside Western countries as mentioned. It can be observed that a large amount of materials are mined in South America, Asia and Africa. Some minerals are also obtained as a byproduct of mining, such as cobalt, which is a byproduct of copper and nickel mining mostly. Even though a few countries possess a majority of the mining operations, the remainder of the supply chain is distributed otherwise. In fact, most of the refinery operations are located in China nowadays. Battery production capacity is strongly concentrated in China as well. China has made considerable investments in the battery supply chain over the past decades, both domestically and overseas. In general, raw materials refinery is a very polluting industry which has led to it being offshored outside the West. Countries that impose less stringent environmental laws and safety standards welcomed this industry to develop their economies and international competitiveness. The uneven distribution of battery materials supply and battery production poses a realistic threat to European and American zero-emission targets. This is especially the case if the Chinese domestic demand for minerals rises to a critical level – when foreign export might lose priority against domestic decarbonization targets.

The European Union has presented a variety of policy initiatives to advance the zero-emission mobility transition. It has also announced more specific policies targeted at raw materials scarcity and battery regulations, which address multiple challenges in the value chain. For example, the renewed battery regulation introduces extended producer responsibility for battery collection and sets concrete recycling targets. The announced Critical Raw Materials Act is expected to provide measures to secure the CRM supply chain for many important industries. Additionally, the European Battery Alliance brings together EU countries, industry and the scientific community to build a competitive and sustainable battery value chain in Europe. It does so by addressing the raw materials scarcity, industrial leadership, and regulatory frameworks among other priorities. This is highly needed considering the gap in the upstream materials capacity to catch up with battery production. There is not enough mining and processing activity (except for lithium, for which there are major announcements) expected in this decade. This is partly due to difficult and lengthy approval processes, and local community protests. Downstream operations are much more advanced, as domestic battery cell production in the EU is expected to fully cover the demand by 2027.

The US have also issued several policies to address the EV battery value chain challenges. Most notably the Bipartisan Infrastructure Law opened up financial access to support the domestic value chain. Via this package both downstream and upstream operations are supported with 135 billion USD in total. Additionally, the Inflation Reduction Act offers federal tax credit for EVs with the requirement that the critical minerals contained must be extracted, processed, or recycled in the US or with countries with which there are free-trade agreements (e.g. Canada, Chile, Argentina). Unfortunately this complicates collaboration from European companies as it unlevels the international playing field. The measure is considered necessary to incentivize private investments and increase strategic autonomy. As in Europe, the US is highly dependent on imports and has an insufficient domestic production capacity to accommodate for targeted EV sales. Downstream battery production is catching up quickly however, as the cell production capacity is expected to increase 20-fold in 2030 compared to 2021.

Although both regions have expressed ambitious goals and presented matching policies to reach them, international collaboration can still play an important role. Especially in the upstream supply chain difficulties are encountered with strong dependencies on foreign imports and very little to no domestic capacity. Forging alliances with strategic partners can accelerate transition targets and broaden opportunities for both policymakers and investors/companies. Governments must act flexible and anticipate for the future, thereby building on policies that satisfy both national and international interests and stakeholders. It is also important to carefully balance protectionism and free-market forces. Consistent environmental policies are needed to level the playing field in the US and Europe, to promote an equally conducive climate for investors in green technologies. Strategic partnerships (as a method for clever importing) between the US and Europe can prevent them from battling for the same raw materials. Especially when other global regions such as Asia are determined to consolidate their existing supply chains. To facilitate a just transition, the US and Europe should also share best practices to both showcase successes and provide useful feedback on conflict resolving with local communities for example. They should also exchange best practices regarding environmental considerations to limit exposures and potential hazards to surrounding communities. This can lead to lessened protests and accelerated approval processes which allows both regions to duly reach their shared decarbonization targets.