14 LITHIUM

14.1 Overview

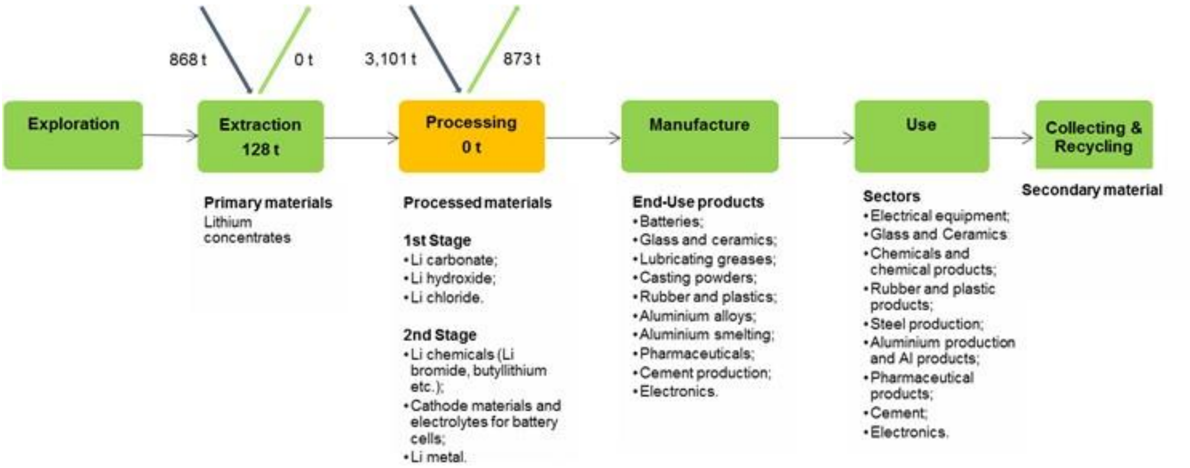


Figure 165: Simplified value chain for lithium in the EU[128] (average 2012-2016)

Lithium (chemical symbol Li) is a silver-white to grey metal belonging to the alkali metal group. With a density of only 0.53 g/cm^3, lithium is the lightest metal and the least dense solid element at room temperature. Also, lithium has excellent electrical conductivity and the highest electrochemical potential of all metals. Due to its high reactivity lithium only occurs in nature in the form of inert mineral compounds such as silicates, or, in general, as chloride in brines and seawater.

In the current criticality assessment, lithium is analysed at both extraction and processing stage. At the mine stage, lithium is assessed in the form of lithium concentrates, whereas, at the processing/refining stage, the lithium compounds considered are lithium carbonate and lithium hydroxide. The trade codes representing the trade of refined lithium are HS 283691 "Lithium carbonates" (Li content 18.8%), and HS 282520 "Lithium oxide and hydroxide" (Li content 16.5% with the assumption that all trade takes place in the form of lithium hydroxide monohydrate). No trade code specific to lithium ores and concentrates is available under the Harmonised System of trade codes, nor for other lithium compounds (e.g. lithium chloride, lithium metal).

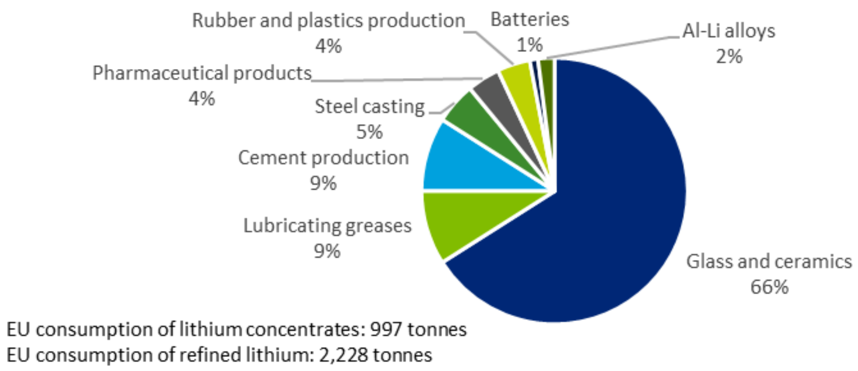
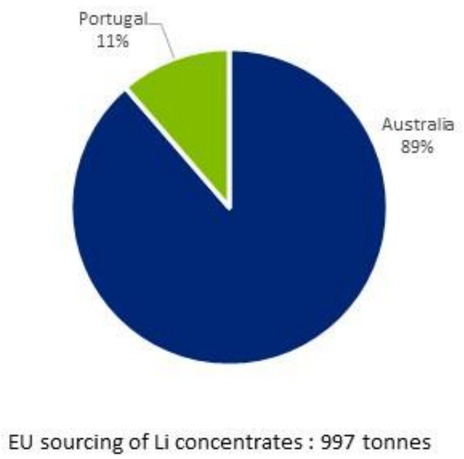


Figure 166: End uses and EU consumption of lithium, in Li content (average 2012-2016) (Eurostat 2019), (WMD, 2019)

[128] JRC elaboration on multiple sources (see next sections)



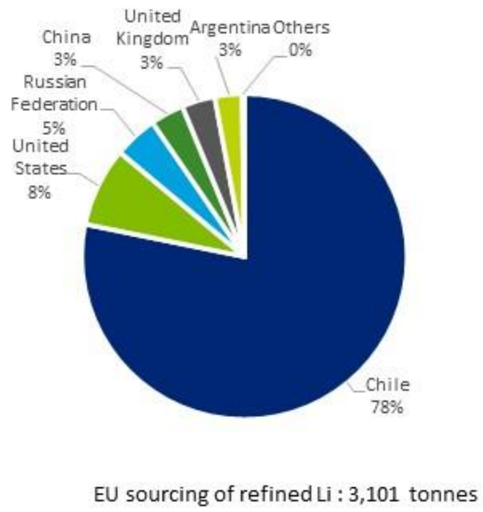


Figure 167: EU sourcing of lithium, in Li content (average 2012-2016) (Eurostat 2019)

All quantities are expressed in tonnes of contained lithium. Data provided in this factsheet is an average over 2012-2016 unless otherwise stated.

Australia dominates production and exports from hard-rock lithium minerals. Chile holds the largest share of the market for lithium carbonate from brines, with 61% of the total exports of lithium carbonate in 2016. China is the main importer of lithium concentrates, as well as the top importer of lithium carbonates (24% of the world total for lithium carbonates). In 2016, China was also the leading exporter of lithium hydroxide with 37% of total exports, whereas South Korea and Japan were the main destinations for exports of lithium hydroxide (24% each of the world total). China dominates lithium's midstream and downstream segments of the value chain for Li-ion batteries, as it hosts the majority of the global lithium refined production and the three-quarters of the global installed manufacturing capacity for Li-ion batteries. The global value of lithium production is estimated at EUR 1.84 billion in 2016.

The electrification of vehicles and the ramp-up of the related battery production will lead to significantly higher demand for lithium. Lithium supply has to increase to balance the expected demand growth for electric vehicles (EV).

There has been considerable volatility in lithium prices in the period 2015-2019. Lithium prices rose over 250% from 2015 to mid-2018 as a result of the expectations for increased demand for electric vehicle batteries in the future. However, after the period of strong growth, lithium prices have declined remarkably by nearly 40% up to July 2019 driven by oversupply in primary supply from new lithium projects as well as slower demand pickup.

The total EU consumption of lithium is about 3,208 tonnes in lithium content per year on average between 2012 and 2016 (31% lithium concentrates and 69% refined lithium). Imports from Australia cover the majority of the EU demand for lithium concentrates. The import reliance for lithium concentrates is 87%. Moreover, the EU is entirely dependent on imports for its consumption of refined lithium compounds (import reliance of 100%) as there is no domestic refining. Chile is by far the EU's largest supplier (78%) of refined lithium compounds.

Lithium and its compounds have several applications, including batteries, production of glassware and ceramics, manufacture of grease lubricants, polymer production, fluxes for steel and aluminium production, pharmaceutical products. In the EU, the glass and ceramics industry make up 59% of the total consumption. Globally, batteries represent the application with the highest consumption (39% of the total). Substitutes are available for batteries (zinc for primary, nickel and lead for rechargeable), lubricating greases, glass and ceramics. There are no substitutes foreseen in the short to mid-term that can replace the role of lithium in rechargeable batteries for electric vehicles and energy storage systems.

Lithium is currently extracted from two distinct sources, hard-rock deposits and continental brines. Brine resources are mostly found in South American countries – Chile, Argentina and Bolivia – in an area known as the "Lithium Triangle", which contains half of the world's lithium resources and 70% of global reserves. Australia hosts the world's most abundant hard-rock minerals resources. Global reserves of lithium are on the order of 14 million tonnes of contained lithium. In the EU, important hard-rock mineral deposits are located in Portugal, Czechia, Finland, Germany, Spain, and Austria. Significan brine resources exist in Germany.

The world annual production of lithium minerals is about 32,386 tonnes of in Li content (averaged over 2012-2016). 37% of this is produced in Chile and 32% in Australia. In 2015, Chile was the leading producer of processed Li compounds (44%), followed by China (39%) and Argentina (13%). EU domestic production of lithium concentrates is insignificant compared to global production, at about 110 tonnes of lithium content. The production of processed lithium compounds in the EU is also negligible, and it is assumed as zero in this factsheet.

Even though lithium-ion batteries are recycled in the EU, industrial-scale recycling of lithium is not considered economically viable. Lithium, a critical raw material for lithium-ion batteries, is an essential raw material for the implementation of the EU long-term strategy for a climate-neutral economy by 2050 as it is used in manufacturing of rechargeable batteries for electric vehicles and energy storage systems.

14.2 Market analysis, trade and prices

14.2.1 Global market

Global lithium production was relatively flat from the late 1950s through to the early 1980s at levels of about 5,000 tonnes annually of lithium content (BGS 2016). Since then it has increased by more than six times. In the last years in particular, world lithium mineral production rose from about 120 kt lithium carbonate equivalent (LCE) (or 22.5 kt of Li) in 2007, to 194 kt LCE (or 36.5 kt of Li) in 2016 at a compound annual growth rate (CAGR) of 5% per year. This is one of the highest CAGR observed for any mineral and metal (background data in (WMD 2019). The rapidly growing demand for lithium is driven by a strong growth rate in the demand for Li-ion batteries (Christmann et al. 2015). The value of world annual production was estimated at EUR 1.84 billion[129] in 2016.

Lithium is marketed in the form of various products depending on the end-use. According to Hocking (Hocking et al. 2016), lithium compounds accounted for 86% of the global lithium market in 2015.The remaining 14% are mineral concentrates marketed directly without further processing. Lithium carbonate represents the most common lithium commodity in the market, accounting for approximately 50% (see Figure 168).

[129] Estimated with an average price of lithium carbonate of EUR 9,448 per tonne (2016)

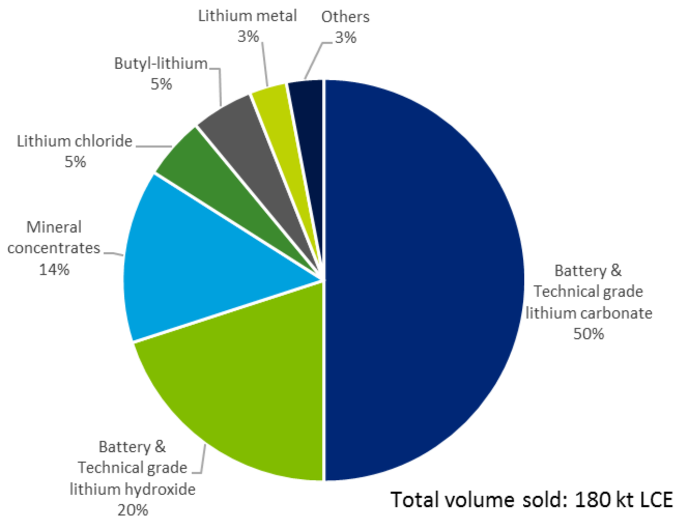


Figure 168: World lithium market by volume of products sold in 2015 (Hocking et al. 2016)

Lithium is currently produced from either hard-rock mineral deposits or brines. While in the past lithium was produced exclusively from hard-rock lithium silicate minerals, the lower production costs from lithium-rich brines made the latter increasing its share for lithium production since the early 1980s (BGS 2016) (Hocking et al. 2016). In 2017 and 2018, there has been a sharp increase in supply from hard-rock mining, due to a massive ramp-up of lithium production in Australia. In 2018, hard-rock lithium supply surpassed that from brines, with a share of approximately 55% of the world lithium supply (background data from (S&P Global Market Intelligence 2019a)).

Australia is, by far, the leading producer of lithium mineral concentrate (spodumene), and most of the spodumene produced is exported for processing, mainly to China (USGS 2018) (BGS 2016). However, the quantities involved are not reported by the usual sources of trade statistics as a specific trade code is missing.

China has the majority of the world's refining capacity, and as a result, it is also the world's largest importer, exporter and consumer of lithium. China produces large quantities of lithium carbonate and lithium hydroxide, mainly from mineral concentrates (spodumene), which are mostly imported from Australia (USGS 2018) (Hocking et al. 2016) (CRU 2019). Chile is the world's leading producer of lithium compounds from brines, followed by Argentina.

Chile exported about 65 kt tonnes of lithium carbonate in 2016 capturing the highest share of the export market of lithium carbonate in that year with a share of 61% by value of lithium carbonate exports, and this compares to just 19% from the second-largest exporter (Argentina). Countries in Asia are the leading importers, i.e. China (24%), South Korea (20%) and Japan (16%). The total exports of lithium carbonates in 2016 amounted to 109 kt with a total value of USD 821 million.

China was the largest exporter of lithium oxides and hydroxides in 2016, which amounted to almost 10 kt, or 37% of the total value of exports of lithium oxides and hydroxides. Significant exporters of oxides and hydroxides were also the US (19%) and Chile (18%). South Korea and Japan are among the top importers again with 24% each of the total value of imports. The total exports of lithium oxides and hydroxides in 2016 totalled to about 35 kt with a total value of USD 375 million.

A high amount of global trade of refined lithium compounds and lithium batteries is taking place through Belgium.

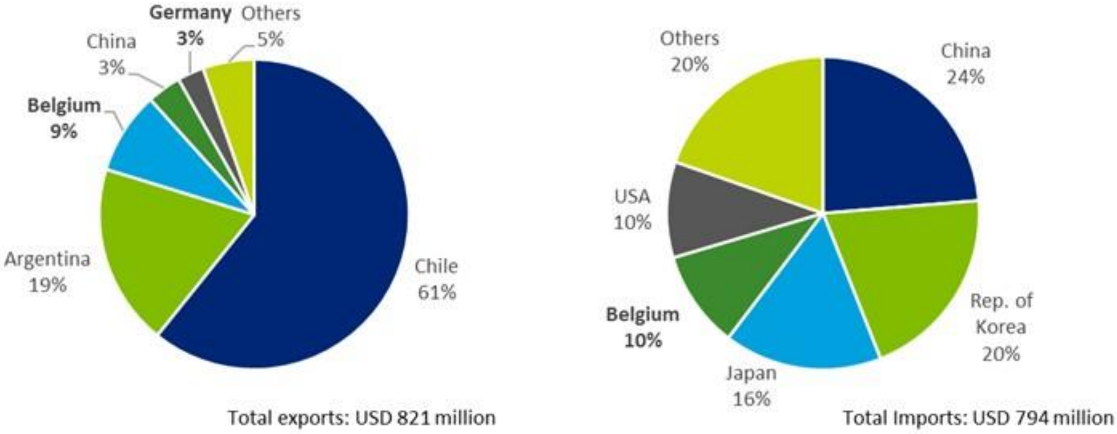


Figure 169: Top-5 exporters (left) and importers (right) of lithium carbonate (HS 283691) in 2016 by value. Data from (UN Comtrade 2019)

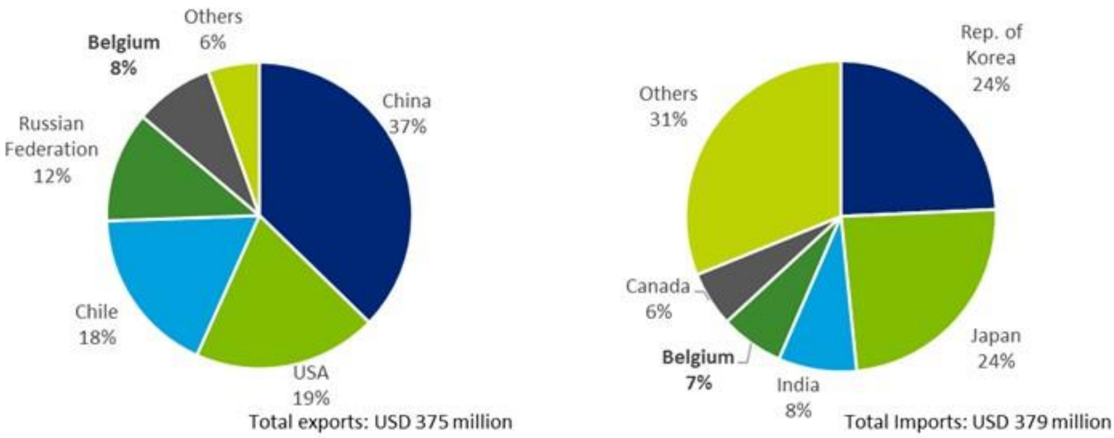


Figure 170: Top-5 exporters (left) and importers (right) of lithium hydroxide (HS 282520) in 2016 by value. Data from (UN Comtrade 2019)

It is important to note that Asian countries dominate the world trade in primary and rechargeable lithium batteries (seeFigure 171).

In 2015, about 85% of the world's Li-ion battery cell manufacturing capacity was installed in Asia due to longstanding investments made by consumer electronics companies and governments. China accounted for 50% of the commissioned capacity, whereas the Republic of Korea and Japan for 20% and 15% respectively (USGS 2018). In 2018, the installed global Li-ion battery manufacturing capacity rose to 334 GWh from 65 GWh in 2015, with China having a share of 74% of the total, followed by the US (9%), Japan (8%) and South Korea (4%). The EU-28 holds a limited share of 3.2% (Roskill 2019).

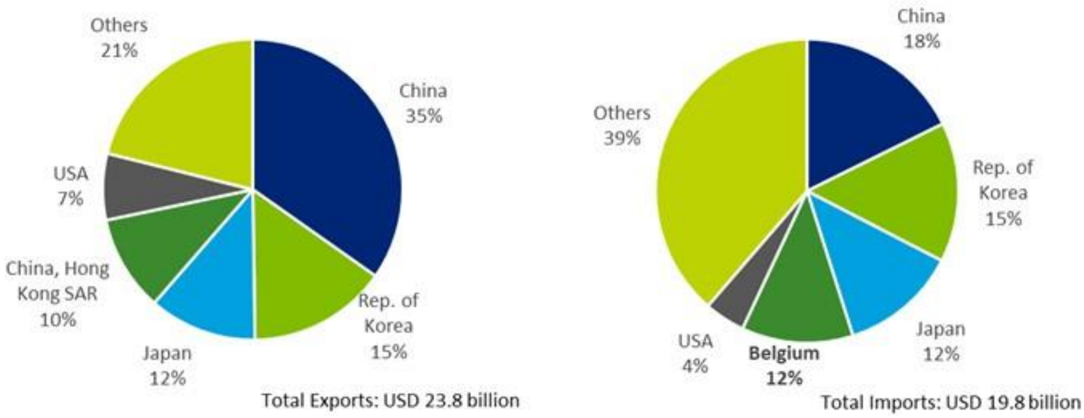


Figure 171: Top-5 importers (left) and exporters (right) of primary and rechargeable lithium batteries in 2016 by value (HS 850650 + HS 850760). Data from (UN Comtrade 2019)

Argentina removed an export tax of 5% imposed on lithium oxides and hydroxides and lithium carbonates at the end of 2015, a lift which was reconfirmed at the end of 2017 (OECD 2019). However, the Government of Argentina announced the re-establishment of export duties in September 2018 on all tariff lines which will be in force until the end of 2020. The new export duties consist of a 12% increase with respect to the previously established export duty, but the maximum amount of tax to be paid is limited of USD 0.076 per USD of the FOB value entitled to the tax. The new export tax is applicable to lithium carbonates (HS 283691) (Global Trade Alert 2018).

14.2.2Outlook for supply and demand

Lithium is one of the vital raw materials for the production of the batteries used in electric vehicles (EV). Therefore, the envisioned substantial growth of the market for electric vehicles should lead to a high increase in lithium demand. According to (Hocking et al. 2016), modest growth is expected in other lithium applications.

Various estimates are published on the outlook of lithium demand. They are based on different scenarios on the global deployment of electric vehicles, the vehicle types (e.g. plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs)), the evolution of the market growth for EVs , and the mix of battery chemistries. For example, according to Hocking (Hocking et al. 2016) global lithium demand will increase to 535 kt LCE by 2025 (or 100 kt of Li), with batteries accounting for 70% of global demand (375 kt LCE or 70 kt of Li), of which EV batteries alone will utilise 200 kt of LCE (38 kt of Li). According to (Roskill 2019), the lithium demand for batteries in 2028 is forecasted to be 1,130 kt of LCE (or around 200 kt of Li).

The outlook report published by the International Energy Agency (IEA) in May 2019 shows that the global electric car fleet is increasing at a rapid rate. In 2018 it exceeded 5.1 million, 2 million more than in 2017 (Bunsen et al. 2019). IEA estimates the lithium amount used in batteries for EVs sold in 2018 to be about 11 kt. In a scenario based on the announced policy ambitions[130], the IEA estimates the world annual demand for lithium to increase to around 155 kt by 2030. In a scenario with higher EV uptake[131] the annual world demand for lithium in 2030 will be more than twice as high, i.e. exceeding 300 kt.

[130] Global EV sales reach 23 million and the stock exceeds 130 million vehicles in 2030.

[131] Scenario under the assumption that EVs will reach a 30% market share for all modes except two-wheelers by 2030. EV sales and stock nearly double by 2030 reaching 43 million and more than 250 million respectively.

These estimates of future demand for lithium for EV'S are three to six times higher than the current (2017) world production of lithium of about 50 kt (WMD 2019).

The comparison of the projected lithium demand with the current levels of supply (36.5 kt of Li in 2016) suggests that in the years ahead the supply of lithium has to expand substantially to cover the demand from all end-use sectors, as well as to avoid shortages that may hinder the projected transition to electric mobility. Significant expansions in production capacity have been already announced for the coming years or commissioned recently, and the world output is expected to rise strongly in short to medium term (USGS 2018)(M Schmidt 2017). However, the future availability of lithium depends on many factors which will determine the demand/supply balance such as the prevailing prices, the discovery rate of economically exploitable deposits and investments made in their development, the progress in lithium recycling and battery design, substitution by solid-state batteries etc. (Christmann et al. 2015).

Table 75: Qualitative forecast of supply and demand for lithium

Materials	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Lithium	x		+	+	+	+	+	?

14.2.3EU trade

It is difficult to obtain data for the trade of lithium-containing minerals due to the aggregation of trade statistics and the lack of a specific trade code for lithium ores and concentrates. The EU imports of lithium concentrates are estimated at 868 tonnes of Li content on an annual basis over 2012-2016. The data refers to exports of spodumene concentrates from Australia to the EU, assuming a 5% Li_2O content. It is also assumed that Australia is the only sourcing country of EU imports of lithium ores and concentrates. Because lithium minerals currently extracted and imported in the EU are used directly in glass and ceramics production, it is reasonable to consider that no export of ores and concentrates of lithium is taking place from the EU.

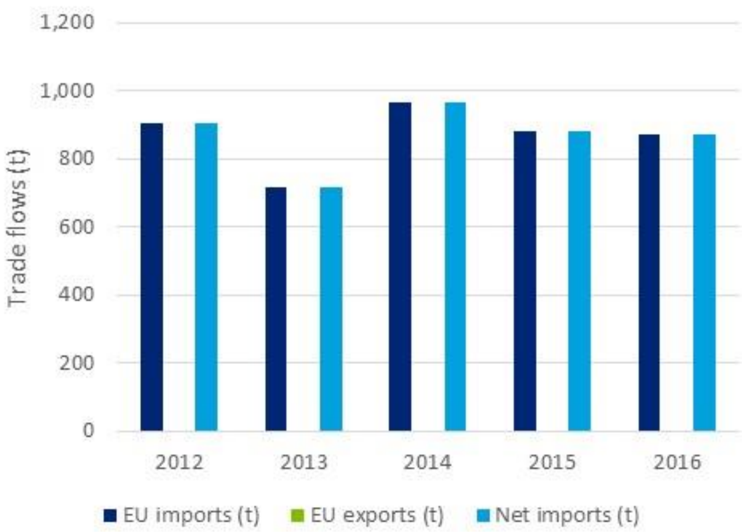


Figure 172: EU trade flows for lithium ores and concentrates. Data from (CRM validation workshop 2019)

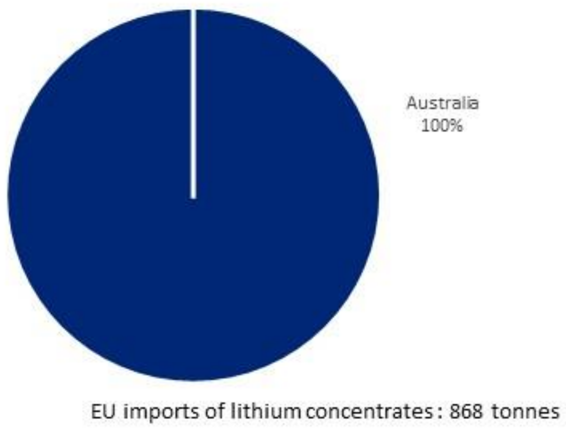


Figure 173: EU imports of lithium ores and concentrates. Data from (CRM validation workshop 2019)

On average, between 2012 and 2016, the EU imports of processed lithium compounds are estimated at 3,100 tonnes of lithium contained in processed/refined materials. According to (ESTAT Comext 2019), the EU imports of processed lithium compounds consist annually of about 135 kt of lithium carbonates (HS 283691) and 30 kt of lithium oxides and hydroxides (HS 282520) in gross weight. Lithium carbonate accounts for 83% of the total EU imports of refined lithium compounds in Li content, and lithium hydroxide accounts for the remaining 17% of total imports. The largest share by far (78%) of imports came from Chile, and 8% from the US (ESTAT Comext 2019). Imports of lithium carbonate and lithium hydroxide decreased in 2014 by 25% compared to those of 2012 but increased from 2014 to 2016 by 47%. The EU import reliance is 100%.

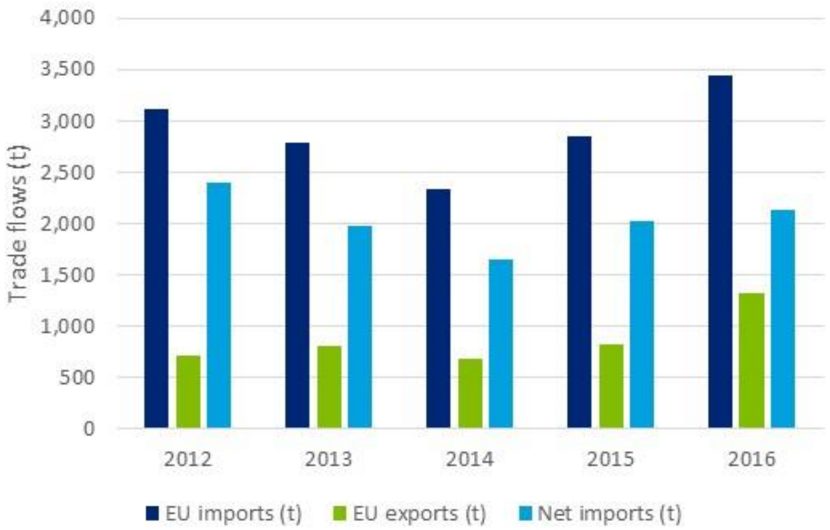


Figure 174: EU trade flows for refined lithium compounds (lithium carbonate and lithium hydroxide). Data from (ESTAT Comext 2019)

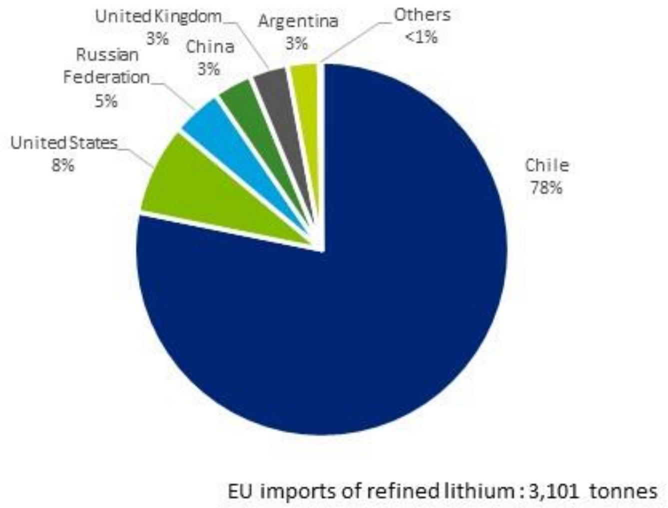


Figure 175: EU imports of refined lithium compounds. Data from (ESTAT Comext 2019)

A trade agreement is in force since 2005 with Chile, the dominant producer of lithium worldwide. In addition, the EU and the four members of Mercosur (Argentina, Brazil, Paraguay and Uruguay) have reached on June 28th a political agreement for a trade agreement (European Commission 2019a); Argentina is the world's second exporter of lithium carbonates (see Figure 169) and within the top-5 producing countries worldwide (see Figure 183).

14.2.4Prices and price volatility

Lithium is traded in many forms, including lithium spodumene concentrate, lithium carbonate technical-grade and battery-grade, lithium hydroxide and others. Each type is priced differently depending on product quality and specifications required (e.g. lithium content, purity) (BGS 2016), (BRGM 2012), (M Schmidt 2017). For example, according to data from S&P (S&P Global Market Intelligence 2019b), battery-grade lithium carbonate was priced 13% higher than technical-grade lithium carbonate in the period January 2018 to July 2019.

Lithium commodities are not traded in international exchange markets, and prices are established through direct negotiations between primary producers and processors or users (M Schmidt 2017). Lithium prices are mainly negotiated in long-term contracts; smaller quantities are traded on spot markets where spot prices can vary significantly and be more volatile fromprices in long-term contracts (DERA 2018)(M Schmidt 2017)(BGS 2016). Prices for various products are not available to the general public (BGS 2016) (BRGM 2012).

The long-term trend of lithium prices can be approximated by the US unit value of apparent consumption (Figure 176). Lithium prices followed a moderate downward trend in the 1990s from about USD 5,000 to USD 4,200 per tonne. In 2001 prices dropped considerably to around USD 1,500 per tonne and remained stable until 2005, due to rising supply from South American brines and the general depreciation in the prices of raw materials in the period 2002-2003 (BRGM 2017). From 2006 to 2009, lithium prices recovered as a result of increased demand from China and for Li-ion batteries in portable electronic devices (BRGM 2017). Not surprisingly, prices declined in 2009 due to the reduced demand caused by the global economic recession towards the end of 2008 (BGS 2016). However, they did subsequently recover and remained stable from 2012 to 2014.

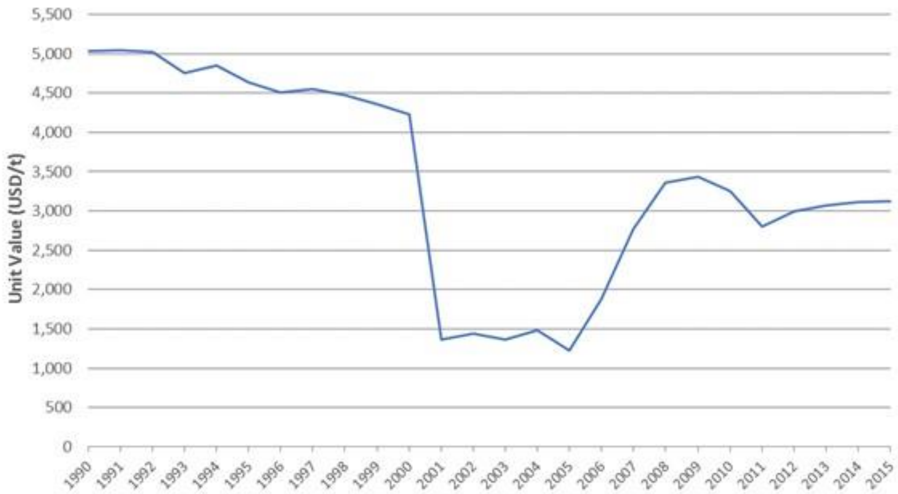


Figure 176. Trends in lithium pricing in the United States (indexed to the 1998 unit value[132]), yearly average (in USD/tonne of lithium). Data from (USGS 2017)

Lithium prices rose significantly from the mid-2015 onwards, reflecting the very dynamic market developments in electromobility and industry's expectations for a sharp rise for demand in the future. Consequently, prices on the lithium market nearly increased four times within three years, reaching historical peaks (DERA 2017), (DERA 2018). In particular, the global average price of lithium carbonate was around EUR 4,150 per tonne (USD 5,170/tonne) at the end of 2014, and it rose by 270% to EUR 15,500 per tonne (USD 18,900/tonne) in March 2018. The increase in prices has been more acute in China, as the result of a temporary shortage of imported mineral concentrates from Australia (USGS 2018). However, since the beginning of 2018, a steady downward trend for lithium prices is observed (Figure 177). The global average price of lithium carbonate has dropped by 42% to EUR 9,115 (USD 10,313/tonne) per tonne in July 2019 in comparison to March 2018. The trend for lithium hydroxide, which is priced at a premium in comparison to lithium carbonate, has been similar (see Figure 177). The price of lithium hydroxide in China reached USD 23,000 per tonne in May 2018, whereas in July 2019 almost halved to USD 12,125 per tonne. According to market experts, the decline of lithium prices is the result of the ongoing influx of lithium supply from new projects into the market, led by Australia, combined with weaker than expected demand in China for BEVs, the world's top electric vehicle market (CRU 2019), (Fastmarkets MB 2019).

[132] The unit value in the US is defined as the estimated value of apparent consumption of one tonne of lithium

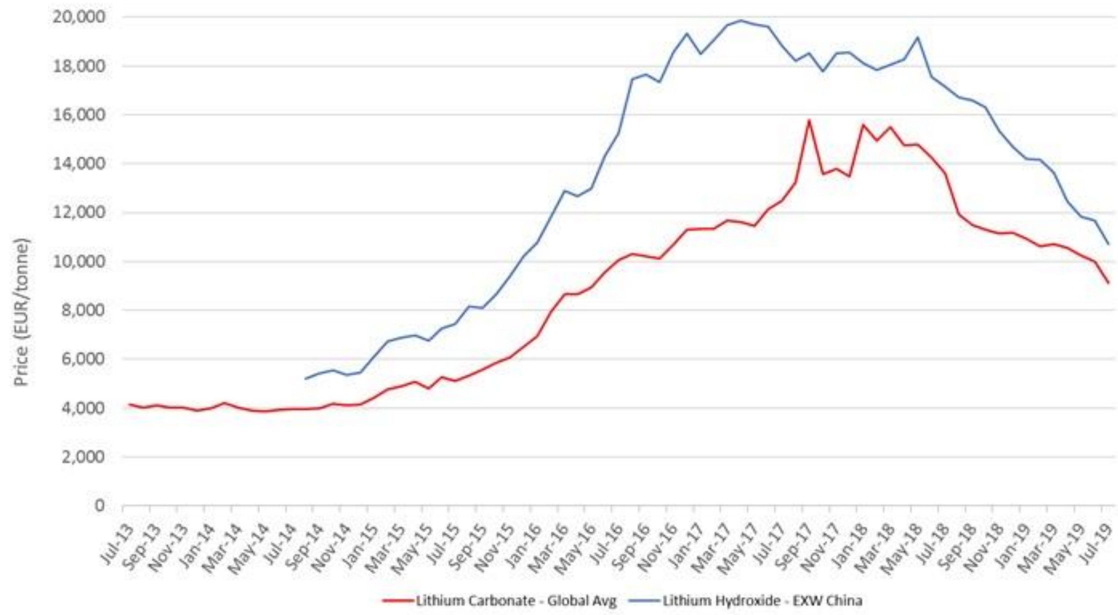


Figure 177: Lithium carbonate (global average) and lithium hydroxide monthly price trend (CIF Europe) (EUR/tonne). Data from (S&P Global Market Intelligence 2019b)

14.3 EU demand

14.3.1 EU consumption

The EU consumed annually about 3,225 tonnes of lithium in various end-uses on average over 2012-2016. The EU apparent consumption is estimated at approximately 997 tonnes of Li content for lithium concentrates, and 2,228 tonnes of lithium content for refined lithium compounds. The net import reliance as a percentage of apparent consumption is calculated at 87% for lithium concentrates and 100% for refined lithium.

14.3.2 Uses and end-uses of lithium in the EU

Lithium's unique properties have resulted in many and diversified commercial applications. In 2015, the manufacture of rechargeable batteries was the main application of lithium accounting for 37% of global lithium demand. Other global markets for lithium products were ceramics, 13%; glass ceramics, 12%; lubricants, 8%; glass, 5%; polymer production, 5%; continuous casting fluxes, 5%; air treatment, 2%; non-rechargeable batteries 2%; and other uses, 11% (BGR 2017).

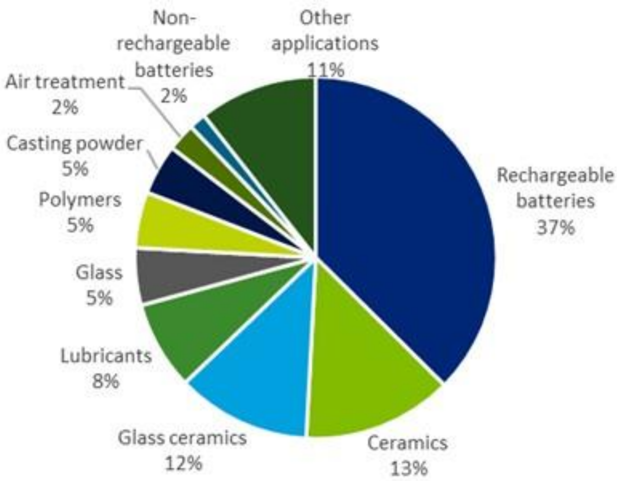


Figure 178: Global end uses of lithium in 2015. Data from Roskill (BGR 2017)

Contrary to the global context, the most significant demand market for lithium in the EU is the glass and ceramics industries, making up 66% of total demand in 2012 (BIO Intelligence Service 2015).The EU production of Li-ion batteries was limited (Patrícia Alves Dias et al. 2018), (Roskill 2019). The shares of lithium use in the EU are provided in Figure 179.

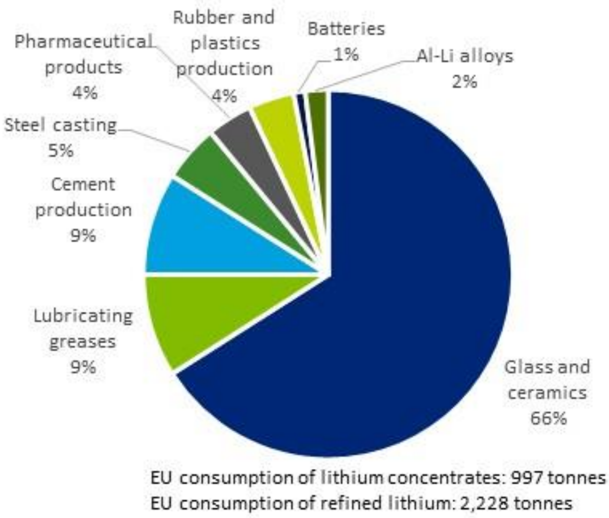


Figure 179: Lithium uses in the EU[133] in 2012 (BIO Intelligence Service 2015), and EU consumption of lithium (average 2012-2016).

The relevant industry sectors are described using the NACE sector codes in Table 76.

[133] Finished products manufactured in the EU and other uses of Li in the EU manufacturing industry

Table 76: Lithium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector, average between 2012 to 2016 (Eurostat 2019)

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	Examples of 4-digit NACE sectors
Glass and ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2311-Manufacture of flat glass; C2312-Shaping and processing of flat glass; C2313-Manufacture of hollow glass; C2319-Manufacture and processing of other glass, including technical glassware; C2340- Manufacture of other porcelain and ceramic products
Lubricating greases	C20 - Manufacture of chemicals and chemical products	105,514	C2059 - Manufacture of other chemical products n.e.c.
Cement production	C23 - Manufacture of other non-metallic mineral products	57,255	C2351- Manufacture of cement; C2369- Manufacture of other articles of concrete, plaster and cement
Steel casting	C24 - Manufacture of basic metals	55,426	C2410 Manufacture of basic iron and steel and of ferro-alloys C2452- Casting of steel
Pharmaceutical products	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	80,180	C2110 Manufacture of basic pharmaceutical products; C2120 Manufacture of pharmaceutical preparations
Rubber and plastics production	C22 - Manufacture of rubber and plastic products	75,980	C2219- Manufacture of other rubber products
Batteries and products containing batteries	C27 - Manufacture of electrical equipment	80,745	C2720- Manufacture of batteries and accumulators
Al-Li alloys	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products n.e.c.

The diverse applications of lithium can be divided into two broad categories, i.e. technical and chemical.

14.3.2.1 Technical applications

Technical-grade concentrates are used, with spodumene concentrates as the dominant input; lepidolite and petalite concentrates are used in lower quantities. Lithium carbonate is preferred when quality and other factors exclude the use of mineral concentrates. The technical applications of lithium are grouped in two categories categories:

- *Glass and Ceramics*. In glassmaking, a small amount of lithium oxide (Li_2O) added as a flux to glass melts reduces melting temperature (usually by as much as 25 °C) and lowers viscosity, which results in production cost savings as energy use is reduced by 5-

10% (Christmann et al. 2015). Besides, glassware containing lithium is characterised by low thermal expansion and increased hardness. Glasses treated with lithium in the form of lithium concentrates which contain silica and alumina – important in many glass formulations – and low Fe_2O_3 content on avoiding undesirable discolouration in the products, contain between 0.1 and 0.7% Li_2O (M Schmidt 2017). In alumina-silicate glass ceramics, lithia addition to the formulation to approximately 3-5% Li_2O (M Schmidt 2017) produces a hardened product with nearly zero thermal expansion, able to withstand high temperatures and thermal shocks from sudden temperature changes. Applications include cookware, induction cooktops, safety glasses, fireplace windows, laboratory equipment, telescoping lenses etc. In the ceramics industry, lithium is added as a fluxing agent, in the form of concentrated ore or lithium carbonate, in concentrations from 0.15% up to 2.5% (M Schmidt 2017), to reduce baking temperature and time and improve finishing characteristics and thermal shock resistance of porcelain enamels and glazes, as well as to produce tiles with increased mechanical strength and low thermal expansion.

- *Casting powders.* Lithium in either carbonate or mineral form is used as an additive in mold flux powders for the continuous casting of steel, which is applied in 90% of global crude steel production, ensuring improved molten steel flow without casting defects.

14.3.2.2 Chemical applications

A wide variety of lithium-containing products is commercially available. Their uses are listed below (BGS 2016), (M Schmidt 2017), (Hocking et al. 2016), (BRGM 2012):

- *Batteries.* Lithium is one of the most attractive materials for batteries due to its high electrochemical potential combined with the lowest mass. Lithium carbonate and lithium hydroxide are the principal lithium compounds for the production of cathode materials.

In non-rechargeable (or primary batteries) batteries, metallic lithium is used for the anode. These batteries are more expensive than most of other types of disposable batteries like alkaline batteries but are superior concerning operational lifetime, size, stability and durability. Primary lithium batteries are employed in various household applications (e.g. calculators, cameras and watches) and medical devices (e.g. heart pacemakers).

In rechargeable batteries, lithium is present in the electrolyte and the cathode of lithium-ion rechargeable batteries. The advantages of lithium-ion batteries compared to other battery types are outstanding energy and power density as well as long lifetime and cycle life. In the electrolyte, lithium salts (e.g. lithium-perchlorate ($LiClO_4$) are used together with organic solvents. In the cathode, several lithium-ion chemistries are currently in commercial use with a wide performance range and cost. The prevailing cathode compositions are NMC (lithium-nickel-manganese-cobalt oxide), LCO (lithium-cobalt oxide), LFP (lithium-iron phosphate), LMO (lithium-manganese oxide) and NCA (lithium-nickel-cobalt-aluminium oxide).

Li-ion batteries are applied in a range of end-uses, while new applications still emerge. The largest market has been portable electronic devices such as mobile phones, laptops, tablets, digital cameras, etc., corresponding to 65% of total Li demand for batteries (M Schmidt 2017). Beyond consumer electronics, lithium-ion chemistry has become firmly established as the reference for the emerging electric vehicle (EV) sector, in particular for full-battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). In 2015, electric mobility accounted for almost 31% of total Li use in batteries (M Schmidt 2017). Furthermore, Li-ion batteries have found use in cordless heavy-duty power tools and medical devices (e.g. hearing aids). Finally, Li-on batteries have the potential to be utilised in off-grid and grid-connected energy storage systems.

- *Lubricating greases.* Lithium is an additive to multi-purpose, high-performance lubricants. Lithium hydroxide monohydrate or lithium carbonate is mixed and heated with fatty acids to produce "lithium soap" grease, a thickening agent which is combined within the lubricant's final formulation to ensure that lubrication properties are maintained over a wide range of temperatures and extreme load conditions. Lithium grease is one of the most commonly used types of lubricating grease due to its cost-efficiency, excellent water resistance and effectiveness over a wide temperature range. Lithium grease usually accounts for 6-15% of the final product; approximately 70% of all industrial lubricants produced globally contain lithium, typically at concentrations of 0.2 to 0.3% (Hocking et al. 2016).

- *Pharmaceutical products*. Some lithium-based compounds, including lithium carbonates, are used as antidepressants and mood stabilisers in the treatment of specific psychiatric disorders such as bipolar disorder, depression and other nervous problems. As lithium is being ingested, purity is essential.
- *Primary aluminium production.* Lithium carbonate or lithium bromide addition to the cryolite bath during aluminium smelting reduces the melting point, thus with benefits in energy consumption, carbon cathode degradation and fluorine emissions.
- *Aluminium alloys.* Metallic lithium is alloyed with aluminium to produce lightweight Al-Li and Al-Cu-Li alloys for the manufacture of specific parts in the aerospace industry where a combination of lightweight and high strength is required.
- *Polymer production.* Organolithium compounds such as butyl-lithium serve as catalysts or initiators for the manufacture of synthetic rubber products (e.g. styrene-butadiene, polybutadiene), commonly used in the manufacture of car tyres.
- *Air treatment.* Lithium bromide and lithium chloride are among the best available hygroscopic substances for absorbing water; as a result, these salts found use as a desiccant to dehumidify the moist air, for example in large-scale air conditioning or air drying systems. Also, lithium hydroxide and lithium peroxide are used in scrubbers in enclosed environments (i.e. mining, space and submarine applications) to remove CO_2 from the air.
- *Other applications.* Lithium and other lithium-based compounds are present in smaller quantities in a broad range of minor applications such as:
  - *Electronics*. Lithium niobate is used in optics and telecommunications;
  - *Nuclear*. The ^{6}Li and ^{7}Li isotopes have applications in nuclear weapons and nuclear reactors;
  - *Textiles*. Lithium acetate and lithium hydroxide are additives in textile dying;
  - *Cement*. Lithium carbonate accelerates the hardening process of quick setting alumina cement;
  - *Fireworks*. Lithium nitrate generates a red colour in fireworks;
  - *Rockets*. Lithium metal and lithium hydrides are employed as high-energy additives in rocket propulsion;
  - *Water treatment*. Lithium hypochlorite is used in swimming pool cleaning products;
  - *Welding*. Lithium chloride is used as a flux in welding or soldering.

14.3.3 Substitution

Substitution for lithium compounds is possible in many applications such as batteries, glass and ceramics, and greases (USGS 2019). However, there is often little incentive to use the available substitutes instead of lithium because of the relatively low lithium's price and the stability of its supply (BGS 2016).

In rechargeable batteries, a wide range of non-lithium types are available on the market, such as nickel-cadmium (NiCd), nickel-metal hydride (NiMH) and lead-acid batteries, with different advantages and disadvantages compared to lithium-ion types. Generally, the Li-ion battery is progressively replacing nickel batteries due to its better performance, particularly where a high-energy density and lightweight is required (Evans 2014). Lithium has become the preferred material for portable equipment and electric vehicle batteries (BRGM 2012), (Evans 2014). Nickel-metal hydride (NiMH) batteries compete with Li-ion batteries with good performance for energy storage and hybrid electric vehicles (HEV) (Tercero et al. 2015), (Graedel et al. 2015b). However, lithium batteries are more and more replacing such nickel batteries and most HEVs marketed today use Li-ion batteries (Harvey 2018), (ProSum 2019). There are no substitutes foreseen in the short to mid-term that can replace the role of lithium in rechargeable batteries for electric vehicles and energy storage systems. In the longer term, lithium batteries may even replace traditional lead-acid car batteries for starting, lighting and ignition (SLI), leading to much higher demand (Ferg, Schuldt, and Schmidt 2019).

In primary batteries, zinc is the main substitute to replace lithium as anode material in the cell (Graedel et al. 2015b), as well as calcium, magnesium, and mercury (Bradley et al. 2017).

Sodium and potassium fluxes can be used instead of lithium in ceramics and glass manufacturing (Peterson 2017), but with a loss of performance, as they do not improve the thermal shock resistance to the same degree as lithium fluxes (Evans 2014).

Alternative formulations with polyurea, calcium and aluminium soaps, can substitute for lithium stearates in lubricating greases (Saruls 2017)(Bradley et al. 2017).

In electronics, lanthanum and gallium are substitutes for lithium tantalite in electronics used in surface acoustic wave filters for sensors (Tercero et al. 2015). In air conditioning and dehumidification systems, substitution with ammonia/water systems is possible but with reduced performance (Graedel et al. 2015b). For primary aluminium production and continuous casting, sodium is a potential substitute (Graedel et al. 2015a). Composite materials consisting of boron, glass, or polymer fibres in engineering resins can be used in place of aluminium-lithium alloys (Bradley et al. 2017). Finally, no substitutes exist for the applications of pharmaceuticals and polymer production (Graedel et al. 2015b).

In the criticality assessment, substitution was assessed for glass and ceramics, and lubricating greases. The rest of the applications were not evaluated due to less than 10% share in total end uses.

On a scale of 0 to 100[134], (Graedel et al. 2015b) assessed the substitutability of lithium to 41.

14.4 Supply

14.4.1 EU supply chain

The lithium flows through the EU economy are shown in Figure 180.

[134] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

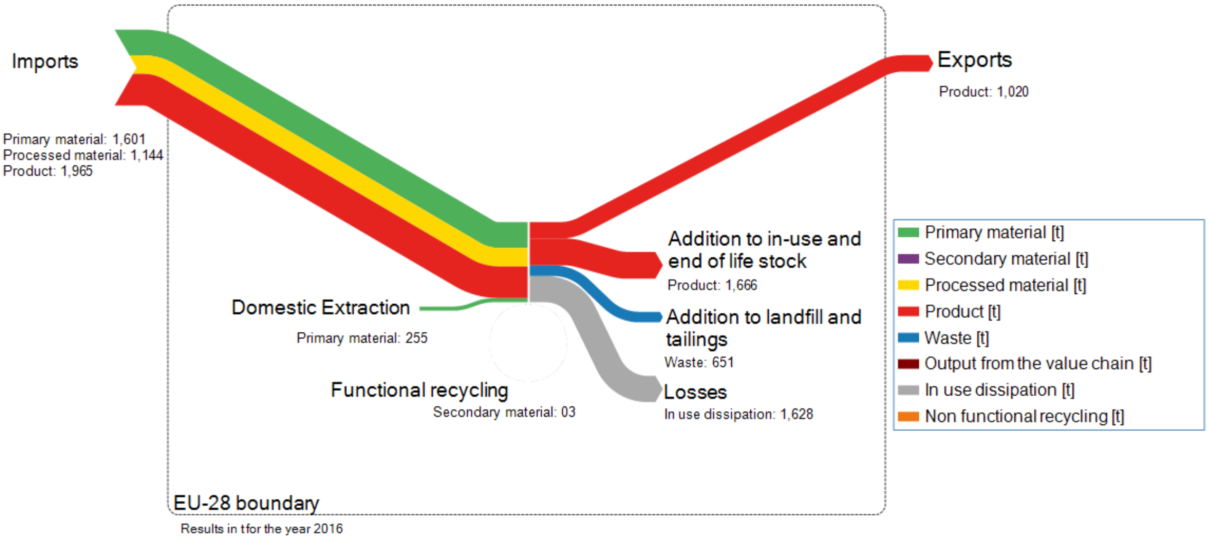


Figure 180: Simplified MSA of lithium flows in the EU. 2016 (MSA 2019)

14.4.1.1 EU sourcing of lithium ores and concentrates

Lithium is currently extracted in Portugal in the form of lepidolite and marketed as Li-rich feldspars used by the ceramics industry. Six mining sites were registered as active in 2017 at the Guarda (Alvarrões), Braga (Gondiães) and Villa Real (Alijó, Lousas, Mina do Barosso) districts (Dinis P. and Horgan S 2018). The annual production over 2012-2016 averaged to about 24,000 tonnes of lepidolite minerals (BGS 2019).

Since 2011, production from Spain is not included in statistics published by common sources such as the British Geological Survey's World Mineral Statistics, World Mining Data or the United States Geological Survey. However, there are reports that Li-containing minerals were extracted in Spain at about 8 kt tonnes per year of gross weight in the 2011-2014 period for use in the ceramics industry (Regueiro y González-Barros 2016), while the French Geological Survey reports a small production of lepidolite concentrates in Spain of 100 tonnes in LCE content in 2015 (BRGM 2017). In addition, small quantities of lithium are produced in the form of Li-rich mica concentrates as a co-product of kaolin mining at Échassières, France for use in the glass industry, but production is also not published by mine statistics providers. The estimated output in 2015 was 15 kt of concentrates at a grade of 1.8% of Li_2O(BRGM 2017d).

The annual EU sourcing of lithium ores and concentrates is estimated at about 980 tonnes of lithium content averaged over 2012-2016. Under the HS or CN nomenclature, lithium ores and concentrates are grouped with many other commodities in the code HS 260790 "Other ores and concentrates, not elsewhere specified", therefore disaggregated imports data are not available in Eurostat Comext database. However, the imports of lithium ores and concentrates were estimated at 868 tonnes of Li according to data provided by (CRM validation workshop 2019). The data refers to exports of spodumene concentrates from Australia to the EU, assuming a 5% Li_2O content. It is also assumed that Australia is the only sourcing country of EU imports of Li ores and concentrates. Import reliance is 87%.

Figure 181 shows the EU sourcing (domestic production + imports) of lithium concentrates.

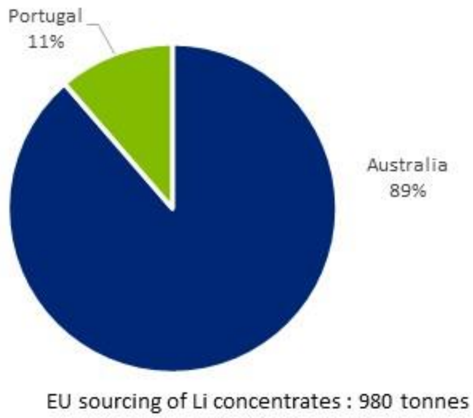


Figure 181: EU sourcing (domestic production + imports) of lithium concentrates, average 2012-2016. Data from (WMD 2019), (CRM validation workshop 2019)

14.4.1.2 EU sourcing of refined lithium

No metallurgical processing of chemical-grade lithium concentrates is taking place in the EU. Downstream lithium compounds such as butyl-lithium, lithium chloride, and lithium metal are produced at Langelsheim in Germany by Albemarle from imported lithium carbonate (Albemarle 2019)(USGS 2018).

Therefore, the EU is entirely reliant on imports of refined lithium, i.e. carbonates and hydroxides (import reliance of 100%). The principal supplier of the EU for refined lithium compounds is Chile (78% of total EU sourcing).

Figure 182 presents the EU sourcing (domestic production + imports) of lithium compounds (carbonates and hydroxides).

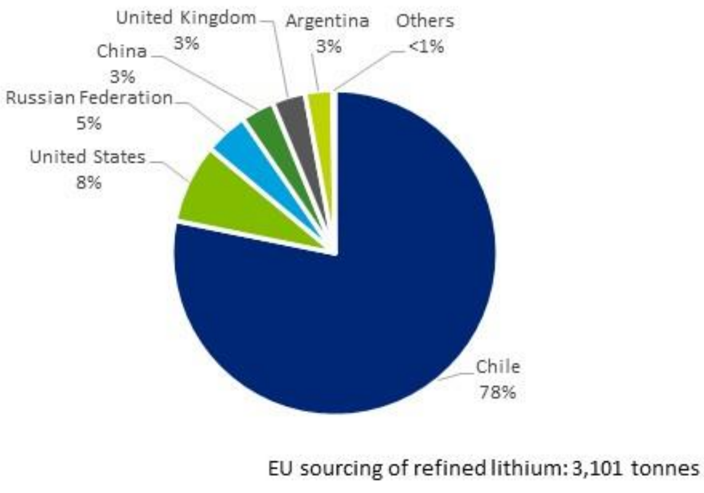


Figure 182: EU sourcing (domestic production + imports) of refined lithium compounds, average 2012-2016. Data from (ESTAT Comext 2019)

14.4.1.3 Supply of recycled lithium

The majority of end-uses of lithium are dissipative. Lithium is either not available for recycling at all, or extremely hard to be recovered. Only lithium embedded in batteries is available for recycling.

Recycling of Li-ion batteries is carried out by specialised companies, with a total processing capacity for all battery types of more than 40,000 tonnes of batteries (Table 77). Valdi in France has the largest capacity at 20,000 tonnes/year of various types of batteries. Umicore's plant in Hoboken, Belgium, with a total annual capacity of 7,000 tonnes for all battery types, enables the treatment of around 250,000,000 mobile phone batteries, 2,000,000 E-bike batteries, 200,000 HEV batteries and 35,000 EV batteries (Patrícia Alves Dias et al. 2018). Duesenfeld in Germany set up a plant with a capacity of 3,000 tonnes of Li-ion batteries in 2018 (Roskill 2019). Accurec in Germany recycles annually 1,500-2,000 tonnes of Li-ion batteries, while AkkuSer in Finland treats 1,000 tonnes of Li-ion batteries annually (Lebedeva, Di Persio, and Boon-Brett 2017). With a large share of the global recycling capacity located in Europe, it is likely that in the future, EU recycling facilities will expand their processing capacities and attract significant volumes from abroad (Patrícia Alves Dias et al. 2018). Table 77 presents the facilities undertaking recycling of Li-ion batteries in the EU.

Table 77: Overview of plants with the capacity to recycle Li-ion batteries. Data from (Patrícia Alves Dias et al. 2018)(Roskill 2019)

Company	Country (location)	Battery types	Annual capacity (tonnes of all battery types)
Valdi (Eramet)	France (Commentry)	Various including Li-ion	20,000
Umicore SA	Belgium (Hoboken)	Li-ion, NiMH	7,000
Accurec GmbH	Germany (Mulheim, Krefeld)	NiCd, NiMH, Li-ion, Li primary	6,000
Akkuser Oy	Finland (Nivala)	NiCd, NiMH, Li-ion, Zn alkaline	4,000
Duesenfeld GmbH	Germany (Wendeburg)	Li-ion	3,000
SNAM	France (Saint Quentin Fallavier)	NiCd, NiMH, Li-ion	300
Eurodieuze (SARPI)	France (Dieuze)	Li-ion	200
Recupyl SA	France (Grenoble)	Li-ion, Li primary	110
Total			40,610

Umicore Battery Recycling has announced lithium recovery from the slag fraction of its pyrometallurgical process on an industrial level (Hagelüken 2018). Also, Recupyl in France patented a hydrometallurgical recycling process enabling Li recovery on an industrial scale (Lebedeva, Di Persio, and Boon-Brett 2017). Lastly, Duesenfeld applies a patented technology for recycling Li-ion batteries, developed within the frame of the research project Lithorec II, allowing lithium recovery of at least 85% combining mechanical processing with subsequent hydrometallurgical processing (Duesenfeld 2019). Recovery of lithium is planned at the Accurec facility in Germany after a planned investment in thermal deactivation and treatment of spent lithium batteries, which will make it one of the most significant lithium recycling locations globally (Recharge 2018). No information is available from other recycling facilities in the EU on current industrial-scale lithium recovery.

14.4.2Supply from primary materials

14.4.2.1 Geology, resources and reserves of lithium

Geological occurrence: Estimates for the average lithium content in the Earth's crust range from 16 to 20 ppm (BGS 2016) (Rudnick and Gao 2014), but lithium abundance ranges from about 30 ppm in igneous rocks to approximately 60 ppm in sedimentary rocks (Evans 2014). According to (Rudnick and Gao 2014), the abundance of lithium in the upper crust is 24 ppm. Lithium also occurs in various types of brines, as well as in seawater at an average concentration of 0.18 ppm (BGS 2016).

Because of its high reactivity, lithium does not occur in elemental form in nature, but in the form of compounds as silicates in igneous rocks, in some clay minerals and generally as chloride in brines (Evans 2014). There are more than 100 known minerals that may contain lithium, but few with enough lithium content to be economical to extract (BGS 2016). Two distinct deposit types are identified from which lithium can be extracted; brine deposits in which the average lithium grade is about 0.1% Li_2O, and hard-rock deposits where lithium generally grades from 0.6 to 1.0% Li_2O hosted by various Li-bearing minerals (Gautneb et al. 2019).

Continental brine deposits contain substantial lithium resources. These brines are formed in enclosed basins where inflowing surface and underground water with a medium content of dissolved solids from surrounding weathered rocks become mineral-rich due to evaporation on high ambient temperatures (Evans 2014). Economic Li deposits of brines mainly occur in areas where arid climate and high evaporation has resulted in further lithium enrichment (0.04-0.15% Li average grade) originating from weathered Li-bearing source rocks; these deposits are usually associated with salt lakes or salt pans (BGS 2016). Likewise, economically viable concentrations of lithium are found in geothermal and oilfield brines where lithium extraction has been demonstrated as a by- or co-product of existing operations, although not yet on a commercial scale (BGS 2016) (Bradley et al. 2017).

Brine resources are mostly found in South American countries – Chile, Argentina and Bolivia – in an area known as the "Lithium Triangle", which contains half of the world's lithium resources and 70% of global reserves at the end of 2018. Bolivia hosts the most abundant lithium brine resource in the world (Salar de Uyuni); however, it has not been exploited until 2016, but action has been undertaken in this direction. Currently, most lithium extraction from brines comes from the Salar de Atacama in Chile; other significant brine-based deposits are located at Salar del Hombre Muerto and Salar de Olaroz in Argentina. Brine operations in South America accounted for 55% of global lithium supply in 2016. Other brine deposits, though of generally lower grade, are located in the USA (e.g. Silver Peak) and China (e.g. Qinghai province).

In hard-rock deposits, lithium-bearing minerals are generally associated with granitic pegmatite deposits. Pegmatites are coarse-grained igneous rocks formed at the late stages of magmatic crystallisation. Even though pegmatites are relatively common, lithium-rich pegmatites are rarely found, and may also contain minerals of tantalum, caesium, beryllium or tin (Bradley et al. 2017) (BGS 2016).

Spodumene ($LiAlSi_2O_6$) is the most important and abundant of lithium-bearing minerals hosted by granitic pegmatites. Lepidolite ($KLi_2AlSi_4O_{10}F_2$) and petalite ($LiAlSi_4O_{10}$) are other common lithium minerals of economic importance found in pegmatite intrusions. Amblygonite ($LiAl(PO_4)(F,OH)$) and eucryptite ($LiAlSiO_4$) occur in smaller quantities and are of lower economic significance. The world's largest lithium-rich pegmatite deposit and operating mine is Australia's Greenbushes in Western Australia, in which spodumene reserves grade up to 3.9% Li_2O. Other important hard rock deposits are located in North Carolina, USA, at Manono-Kitolo in the Democratic Republic of Congo, at Bikita in Zimbabwe and Tanco in Canada. Hard rock lithium deposits around the world are currently mined in Australia (spodumene), China (spodumene and lepidolite), Brazil (spodumene), Portugal (lepidolite) and Zimbabwe (petalite and spodumene). (Bradley et al. 2017) (BGS 2016)

Finally, two types of lithium ore deposits occurring in different geological settings than pegmatites – lithium clays and lithium zeolites – have been recognised. The lithium-bearing clay deposits (hectorite, $Na(Mg,Li)_3Si4O_{10}(OH)_2$) identified in the United States, Mexico and Morocco, and the lithium zeolite deposit at Jadar in Serbia containing the recently discovered mineral of jadarite ($LiNaSiB_3O_7(OH)$), are under evaluation for future lithium extraction (Bradley et al. 2017) (BGS 2016).

The spatial distribution of geological occurrences in Europe shows a strong clustering highlighting lithium potential of the Variscan belt of south and central Europe (Gautneb et al. 2019). Lithium deposit types can be broadly classified to:

- *high-grade* Li deposits, represented by Li-rich lithium-cesium-tantalum pegmatites such as Wolfsberg in Austria, San Jose in Spain, Rapasaari in Finland and Sepeda in Portugal, rare metal granites such as Beauvoir in France, and atypical stratiform deposits such as Jadar in Serbia;
- *medium-grade* Li deposits, represented by hydrothermal greisens such as Cinovec in Czechia, Li-bearing quartz veins such as Argemela in Portugal;
- *other types.*

Global resources and reserves[135]: Worldwide lithium resources have increased significantly in recent years on account of continuing exploration. The United States Geological Survey estimates the global resources of lithium at the end of 2018, at about 62 million tonnes of contained Li (USGS 2019). The largest identified lithium resources worldwide are located in Argentina (14.8 Mt, 24%), Bolivia (9 Mt, 15%), Chile (8.5 Mt, 14%), Australia (7.7 Mt, 12%), United States (6.8 Mt, 11%) and China (4.5 Mt, 7%). The world's reserves of lithium are estimated at 14 million tonnes in Li content, with the most significant reserves held by Chile, Argentina, Australia and China (USGS 2019d) (see Table 78).

[135] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of lithium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template, which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

Table 78: Global reserves of lithium in 2018. JRC elaboration based on data from (USGS 2019) and industry announcements for the EU[136]

Country	Lithium Reserves (in tonnes of Li)	Percentage of the total (%)
Chile	8,000,000	56
Australia	2,700,000	19
Argentina	2,000,000	14
China	1,000,000	7
Czechia	104,000	<1
Germany	94,000	<1
Zimbabwe	70,000	<1
Brazil	54,000	<1
Portugal	53,000	<1
Finland	36,000	<1
United States	35,000	<1
Austria	25,000	<1
World total (rounded)	14,200,000	

EU resources and reserves*:* Table 79 and Table 80 present available data on EU lithium resources and reserves based on the ongoing progress of exploration and mine development projects.

Table 79: Lithium resources data in the EU

Country	Classification	Quantity (million tonnes of ore)	Grade (%Li_2O)	Reporting code	Reporting date	Source
Austria	Measured	2.86	1.28	JORC	03/2018	(European Lithium Ltd 2018)
	Indicated	3.44	1.08			
	Inferred	4.68	0.78			
Czechia	Measured	-	-	JORC	11/2017	(European Metals Ltd 2017b)
	Indicated	372.4	0.44			
	Inferred	323.5	0.39			
Finland	Historic Resource Estimates	0.15	0.83 (Li)	None	12/2017	(FODD 2017)
	Measured	1.21	1.24	JORC	05/2018	(Keliber Oy 2018)
	Indicated	8.26	1.15			
	Inferred	0.53	1.08			
France	Measured	0.023 (Li_2O content)	NA	None	12/2018	(Gloaguen et al. 2018)
	Indicated	0.069 (Li_2O content)	NA			
	Inferred	0.443 (Li_2O content)	NA			
Germany[137]	Inferred	13.726 km^3	181 mg/l (Li)	JORC	12/2019	(Vulcan Energy Resources 2019)

[136] (Deutsche Lithium GmbH, 2018)(Dinis P. and Horgan S, 2018)(European Lithium Ltd, 2018)(European Metals Ltd, 2017a) and (Keliber Oy, 2018) for Germany, Portugal, Austria, Czechia and Finland respectively

[137] Geothermal Brine

Country	Classification	Quantity (million tonnes of ore)	Grade (%Li_2O)	Reporting code	Reporting date	Source
Germany	Inferred	25	0.45	JORC	12/2017	(Lithium Australia 2017)
Germany	Measured	18.51	0.78	NI 43-101	10/2018	(Deutsche Lithium GmbH 2018)
	Indicated	17	0.73			
	Inferred	4.87	0.76			
Ireland	Historic Resource Estimates	0.57	1.5	None	01/2015	(Minerals4EU 2019)
Portugal[138]	Measured	6.6	1.10	JORC	04/2019	(Savannah Resources Plc 2019b), (Lepidico Ltd 2019), (Dakota Minerals 2017), (PANNN 2017)
	Indicated	15.6	0.82			
	Inferred	32.07	0.91			
Spain	Measured	-	-	JORC	05/2018	(Infinity Lithium Ltd 2018)
	Indicated	59	0.63			
	Inferred	52.2	0.59			
Sweden	Historic Resource Estimates	0.6	0.45 (Li)	None	07/2017	(FODD 2017)
		0.4	0.12 (Li)		12/2017	

Table 80: Lithium reserves data in the EU

Country	Classification	Quantity (Mt of ore)	Grade (%Li_2O)	Li(kt)[139]	Rep. code	Rep. date	Source
Austria	Proved	4.32	0.69	14	JORC	03/2018	(European Lithium Ltd 2018)
	Probable	3.12	0.75	11			
Czechia	Proved	-	-	-	JORC	06/2017	(European Metals Ltd 2017a)
	Probable	34.5	0.65	104			
Finland	Proved	1.14	1.12	6	JORC	05/2018	(Keliber Oy 2018)
	Probable	6.26	1.02	30			
Germany	Proved	16.5	0.66	51	NI43 -101	05/2019	(Deutsche Lithium GmbH 2019)
	Probable	14.7	0.63	43			
Portugal[140]	NA	10.7	1.06	53	NA	2018	(Dinis P. Horgan S 2018)

[138] Ongoing exploration and mine development projects Mina do Barosso, Alvarrões, Sepeda and Argemela.
[139] Rounded values
[140] Total reserves of the existing mining concessions

14.4.2.2 Exploration and new mine development projects in the EU

Mineral exploration activities targeting lithium are in progress across the EU. The recent developments for projects having reached a more advanced stage are listed below:

- *Austria.* At the Wolfsberg spodumene deposit, total lithium mineral reserves and resources reported in April 2018 under the JORC Code amount to 7.5 million tonnes (0.71% Li_2O average grade) and 11 million tonnes (1.00% Li_2O average grade) respectively. A pre-Feasibility study is completed. (European Lithium Ltd 2018);
- *Czechia*. JORC compliant total lithium resources estimate of the Cinovec deposit are announced in November 2017 to be almost 700 million tonnes (0.42 % Li_2O average grade), making it the largest lithium deposit in Europe. Lithium is present in the lithium-bearing mica of zinnwaldite ($KLiFeAl(AlSi_3)O_{10}(F,OH)_2$. A preliminary feasibility study has been completed, and the definitive feasibility study is ongoing. (European Metals Ltd 2017b);
- *Finland*. JORC compliant estimates of total resources for spodumene deposits in pegmatites have been announced in February 2019 to be 9.5 million tonnes at 1.16% Li_2O average grade. Total reserves are estimated at 7.4 million tonnes at 1.04 % Li_2O average grade. This figure is cumulative for six distinct deposits in the area, i.e. Syväjärvi, Rapasaari, Länttä, Outovesi, Emmes and Leviäkangas. The definitive Feasibility study (covering operations in the above depositsas a single project) is completed and updated (Keliber Oy 2018) (Keliber Oy 2019);
- *Germany*. Total lithium resources of the Zinnwald deposit reported under NI 43-101 requirements are approximately 40 million tonnes at 0.76 % Li_2O, as of October 2018 (Deutsche Lithium GmbH 2018). Lithium mineralisation is represented by the zinnwaldite lithium mica. A feasibility study is concluded (May 2019) and mineral reserves account for 31.2 million tonnes at 0.65 % Li_2O average grade (Deutsche Lithium GmbH 2018). In addition, an inferred lithium mineral resource of 25 million tonnes grading 0.45 % Li_2O at the Sadisdorf project is announced (December 2017) based on re-analysis and re-interpretation of historical drilling data (Lithium Australia 2017); Last but not least, vast JORC-compliant lithium resources were announced in December 2019 to be contained in geothermal brines at the Vulcan lithium brine project in the Upper Rhine valley of Germany. Total inferred mineral resources are estimated to 2.484 million tonnes of lithium, at a lithium brine grade of 181 mg/l Li (Vulcan Energy Resources 2019);
- *Portugal.* According to information published in September 2017 by the Portuguese Lithium Working Group (Lithium Working Group, 2017) based on reports by operating mining companies, total resources in Portugal were estimated at approximately 30 million tonnes at an average grade of 0.81 % Li_2O (Lithium Working Group, 2017). However, as exploration and mine development projects are in progress, JORC compliant lithium resources of the active projects are estimated at the end of 2018 to be about 43 million tonnes at an average grade of 0.88 % Li_2O. In particular:
  - The latest (May 2019) JORC compliant update of the overall mineral resource estimate of the ongoing spodumene mine development project Mina Do Barroso in northern Portugal amounts to 27 million tonnes at 1.06 % Li_2O (Savannah Resources Plc 2019b). A Feasibility study is on track (Savannah Resources Plc 2019a);
  - The JORC compliant mineral resource estimate for the ongoing exploration project in the Alvarrões lepidolite mine is 5.9 million tonnes at 0.87 % Li_2O (April 2019). Advanced exploration by drilling has been completed (Lepidico Ltd 2019);
  - Exploration is also underway in the Sepeda deposit. The last available (February 2017) JORC compliant mineral resource estimate is 10.3 million tonnes at 1.0% Li_2O. A scoping study has been finalised (Dakota Minerals 2017);
  - Exploration works are ongoing in the Argemela tin-lithium project (Patricia Alves Dias 2018). In 2012, JORC-compliant mineral resources were estimated to be 11.1 million tonnes grading 0.21 % Li (PANNN2017).
- *Spain*. The San Jose deposit, where lithium is hosted mainly in lithium-mica minerals, holds in total 111 million tonnes of JORC compliant estimated resources at an average grade of 0.61 % Li_2O average grade, as announced in May 2018. A Feasibility study is underway (Infinity Lithium Ltd 2018).

Moreover, the Jadar lithium-borate deposit in Serbia, discovered by Rio Tinto in 2004, represents a massive lithium deposit. Lithium is hosted by the previously unknown borosilicate mineral jadarite. The deposit contains 136 million tonnes of ore at a grade of 1.9% Li_2O that is equivalent to about 2.6 Mt of Li_2O. The pre-feasibility study is on-going for a mine and processing facility, and production could commence by 2023-2024 (Rio Tinto 2018), (Rio Tinto 2017), (Gautneb et al. 2019).

14.4.2.3 Lithium extraction

Conventional drill and blast mining techniques for hard rock lithium ores are applied in open-pit or underground mines. Once extracted, the ore is crushed and ground in the beneficiation facility at or close to the mine site. The Li-bearing minerals can then be liberated from gangue minerals via various physical separation methods taking advantage of differences in their properties, e.g. screening and gravity separation, heavy-media separation, optical sorting. Different separation processes produce a concentrate with differing levels of lithium oxide (Li_2O, also known as lithia) content. In some cases, the concentrated ore has to be further upgraded by removing entrained minerals; froth flotation for separating micaceous minerals and magnetic separation when paramagnetic minerals are present, are techniques commonly applied. Finally, the wet concentrate is filtered, dried and marketed (BGS 2016).

Hard-rock lithium concentrates need to be further refined for value-added applications. A typical concentrate, suitable for downstream lithium carbonate and other lithium compounds production, generally contains between 6-7% Li_2O ("chemical-grade concentrate"). Higher grade spodumene concentrates, with a lower level of impurities such as iron (i.e. less than 0.1% Fe_2O_3), are known as "technical-grade concentrates" and can be directly consumed in mineral form by manufacturing industries (e.g. glass and ceramics) without going through any refining process (Hocking et al. 2016).

In brine-based operations, lithium-rich brine is pumped to the surface from underground reservoirs/aquifers by a series of wells or boreholes and is concentrated by solar evaporation in a succession of artificial ponds. Lime is added to precipitate impurities. It takes 9-12 months or even more to achieve a concentrate that is both enriched in lithium and depleted in other elements. The concentrated liquor from the last pond is then transferred to processing plants for the production of lithium compounds (BGS 2016). The end products derived from brine operations can be used directly in value-added applications.

14.4.2.4 World and EU production of lithium

As an annual average over the period 2012-2016, the global production of lithium was about 68,190 tonnes of Li_2O content (WMD 2019), which corresponds to approximately 31,680 tonnes on contained metal terms or 168,600 tonnes of LCE (lithium carbonate equivalent). Lithium is currently extracted in Australia, China, Zimbabwe, Portugal and Brazil from hard rocks, whereas in Chile, Argentina, China and USA lithium is extracted from brines (BGS, 2016). Chile is the most important producer (37%), followed by Australia (33%), China (12%) and Argentina (11%) (see Figure 183). In 2015, around 50% of lithium supply came from lithium brines, approximately 45% from hard-rock spodumene ores, while other lithium minerals accounted for 5 to 10% (Hocking et al. 2016).

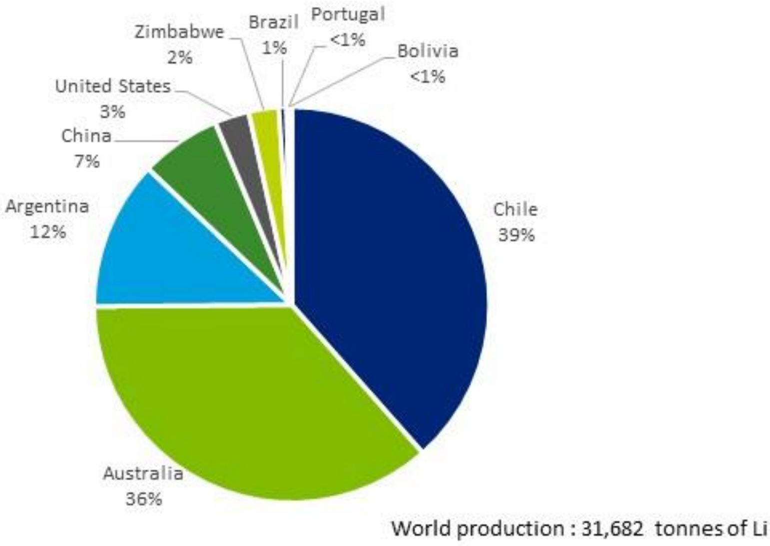


Figure 183: Global mine and brine production of lithium, in Li content. Average for the years 2012-2016. Background data from (WMD 2019)

In the EU, about 128 tonnes of lithium were extracted annually (average over 2012-2016) in Portugal in the form of lepidolite.

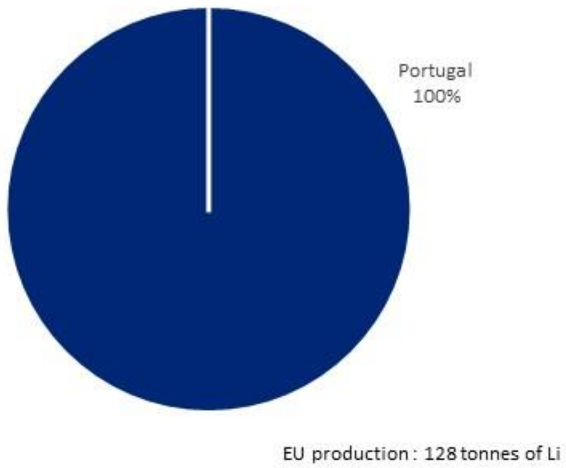


Figure 184: EU production of lithium ores and concentrates, in Li content. Average for the years 2012-2016. Background data from (WMD 2019)

14.4.3Processing/Refining of lithium

A variety of lithium compounds that can be produced in processing plants including lithium carbonate, lithium hydroxide, lithium chloride, lithium bromide, lithium metal, butyllithium. Lithium carbonate is the precursor of most other lithium compounds in the refining stage.

In brine operations, processing methods vary considerably depending on the overall chemistry. In the basic process, the concentrated Li-rich brine (around 6,000 ppm Li) is treated with sodium carbonate to precipitate lithium carbonate slurry. A pure lithium carbonate product is obtained after filtering, washing, and drying. Potassium, magnesium and boron salts (e.g. KCl) may be recovered as co-products. Lithium chloride and lithium hydroxide can be produced via different processing routes.

The chemical-grade mineral concentrates undergo additional processing in refining plants to produce a variety of lithium chemicals or lithium metal. Different metallurgical methods are applied to recover lithium from its ores; the most commonly used for spodumene is the acid leaching process. Other refining processes include the autoclave carbonate leaching and the lime leaching method.

The acid leaching process involves high-temperature calcination of the concentrate at about 1,100 °C to improve the solubility of spodumene in acids, followed by acid digestion at 200-250 °C with sulphuric acid. Lithium from spodumene forms lithium sulphate, which is soluble in water; thus, a downstream water leaching step produces a solution of lithium sulphate. Impurities are removed by filtration, precipitation, and ion-exchange techniques. Finally, the recovery of lithium from the liquor is carried out by adding a carbonate donor like sodium carbonate (Na_2CO_3) at 80-100 °C to precipitate insoluble lithium carbonate (carbonation step). The purity of lithium carbonate can be improved by a series of re-dissolution/precipitation/ion exchange steps to achieve up to 99.9% grade. Industry-grade lithium carbonate generally has a purity of 98.5-99.0%, while battery-grade lithium carbonate must have a higher purity of at least 99.5%.

For the production of lithium hydroxide, in the typical processing route of acid leaching and before the carbonation step, the aqueous liquor after removal of impurities may undergo electrodialysis to produce a lithium hydroxide solution, and crystallisation to form a high-purity lithium hydroxide product. Alternatively, lithium hydroxide is produced by a chemical reaction between lithium carbonate and calcium hydroxide.

Lithium chloride is mainly produced in brine operations, also by treating lithium carbonate with hydrochloric acid. Lithium bromide is produced by lithium carbonate after treatment with hydrobromic acid. Lithium metal is obtained by electrolysis of lithium chloride and potassium chloride mixture, in the form of ingots, rods, foils, granules, and powders. Finally, butyl-lithium and other organolithium compounds are produced from lithium metal.

14.4.3.1 World and EU production of refined lithium

There are no publicly available statistics on the production of refined lithium. China hosts the majority of the world's lithium refining facilities from hard-rock minerals, and Chile the most of the world’s capacity from brine operations. The global capacity and world production of refined lithium compounds (Li carbonates and Li hydroxides) in 2015 was reported to be about 41,628 tonnes and 26,716 tonnes respectively.

The production of refined lithium compounds in the EU is negligible (Draft lithium MSA 2019).

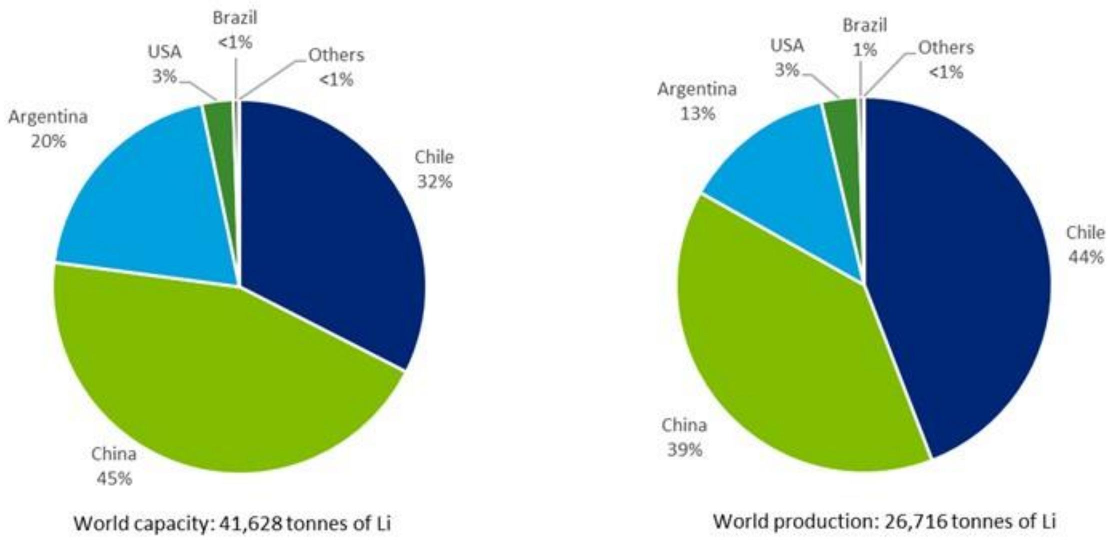


Figure 185: World production and world capacity of processed lithium in 2015, in lithium content. Data from (M Schmidt 2017)

14.4.4Supply from secondary materials/recycling

Lithium recycling has long been insignificant because of dissipative end-uses (e.g. lubricating greases, metallurgy), not functional recycling (e.g. glass and ceramics)), or reusable end-uses (such as catalysts) (BIO Intelligence Service 2015), (BGS 2016). The only waste flow with lithium recycling potential is spent Li batteries (Nogueira 2017).

Recycling of lithium-ion batteries, which is a complex and costly process hindered by the wide variety of chemistries and battery formats, has attracted much attention during the last years due to the constantly increasing significance of Li-ion batteries, especially in the rapidly growing electric vehicle sector. At the same time, regulatory instruments already applicable in the EU, such as Directive 2000/53/EC (End-of-Life Vehicles Directive), Directive 2012/19/EU (Waste Electrical and Electronic Equipment Directive), and Directive 2006/66/EC (Batteries Directive), aim to achieve a high level of recycling for waste Li-ion batteries in electric vehicles and electronic equipment.

Nowadays, the recovery of lithium from batteries is technically feasible, but until 2017 industrial-scale recycling was considered not cost-effective in comparison with primary supplies. As a result, the main focus of Li-ion battery recycling plants has been the recovery of cobalt, nickel, and copper, which have a higher economic value than lithium (BGS 2016). At a global scale, only a minor amount (20 tonnes in 2016) of Li recovery is reported from secondary sources (BRGM 2017). Nevertheless, given the recent introduction of EVs on the European market, and taking into account the average lifetime of EV components (estimated to be approximately ten years), a significant number of EVs have not yet reached end-of-life (European Commission 2018a).

Hydrometallurgical recycling methods of end-of-life Li-ion batteries enable recovery of lithium as a lithium carbonate precipitate. Instead, in pyrometallurgical processes, lithium remains in the slag, which can be used as a construction material (non-functional recycling) (BGS 2016), or further processed by hydrometallurgical methods to recover lithium.

Recycling of Li-ion batteries has the potential to create a continuous and secure secondary stream of lithium supply for the EU in the future (Blagoeva et al. 2016), under conditions that will make it economically attractive e.g. higher lithium prices, market of scale.

According to (BIO Intelligence Service 2015) no recycling of lithium is taking place in the EU, therefore the end-of-life recycling input rate (EOL-RIR) is 0%. Lithium employed in the glass and ceramics industry is used up in the production process and cannot be recycled (Christmann et al. 2015).

14.5 Other considerations

14.5.1 Environmental and health and safety issues

Lithium metal is highly reactive and flammable in its elemental form, even potentially explosive; it cannot be stored in air or water. Nevertheless, it is not found in nature in elemental form and its compounds are non-flammable (Bradley et al., 2017) (BGS, 2016).

Lithium is neither an environmental nor a human health concern at ambient conditions (Bradley et al. 2017). Lithium salts have neurological and psychiatric medical properties. Only some mixed arsenic-lithium substances are restricted (Annex XVII) under the REACH regulation (ECHA 2019).

A supply risk, associated with a very high risk of exposure to natural hazards (Bündnis Entwicklung Hilft 2019), and high water stress (World Resources Institute 2019) is identified in Chile, the leading supplier globally.

14.5.2 Contribution to low-carbon technologies

Lithium is a key material for hybrid and electric vehicles as most hybrid electric vehicles (HEVs), and all plugin hybrid electric vehicle (PHEVs) and battery electric vehicles (BEVs) marketed today use Li-ion batteries (Harvey 2018). In addition, Li-ion batteries are employed in energy storage systems for renewable energy (M Schmidt 2017).

Another contribution to the transport sector is the use of novel, low-density Al-Li alloys for aircraft building which provide weight reduction and improve fuel economy (Marscheider-Weidemann et al. 2016).

14.5.3 Socio-economic issues

The level of governance in countries supplying lithium to EU is medium to high. Only a minor share of the global supply (3%) derives from a country (Zimbabwe) with deficient governance level and conflict risk (World Bank 2018).

14.6 Comparison with previous EU assessments

The assessment has been conducted using the same methodology as for the 2017 list. In the current assessment, the supply risk has been analysed separately at the mine, and the processing stage. In the processing stage, the materials analysed were lithium carbonate and lithium hydroxide. It has to be noted that in the 2017 assessment, a ‘hybrid’ approach was applied due to lack of data, i.e. production data from mines and brines were used for the calculation of the global HHI, and trade data for the most important lithium compounds (lithium carbonate and lithium hydroxide) for the calculation of the EU HHI. The results of the current and earlier assessments are shown in Table 81.

Table 81: Economic importance and supply risk results for lithium in the assessments of 2011, 2014, 2017, 2020 (European Commission 2011-2014-2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
Lithium	5.6	0.7		5.5	0.6		2.4	1.0		3.1	1.6

The results of the older assessments are not comparable due to the introduction of a revised methodology in the 2017 assessment. In particular, the economic importance appears reduced in the 2017 assessment as the value-added considered in the 2017 criticality assessment corresponds to a 2-digit NACE sector rather than a 'megasector' (which was used in the 2011 and 2014 assessments).

In the current assessment, the Supply Risk indicator (SR) was calculated using both the HHI for global supply and EU supply as prescribed in the revised methodology. The assessment results reveal that the processing stage has a higher supply risk (SR=1.64) compared to the extraction stage (SR=1.33). The overall supply risk for lithium is considered for the stage with the highest score, i.e. SR=1.64 (rounded to 1.6). The supply risk results are not directly comparable to the 2017 assessment, as a different approach was applied for the definition of the value-chain stages. However, for the components of the supply risk which are comparable, it is noted a slightly higher supply risk for the global HHI of lithium ores and concentrates due to the moderate increase of the world production share that the top-2 producing countries hold (i.e. Chile and Australia).

Also, the Economic Importance indicator (EI) is higher in the current assessment compared to the 2017 exercise. The main reason is that the application 'Lubricating greases' is allocated more appropriately to the NACE 2-digit level sector 'C20 - Manufacture of chemicals and chemical products', instead of the sector 'C19 - Manufacture of coke and refined petroleum products' as in the 2017 exercise. The increase in the EI indicator is also affected to some extend by the results scaling step[141], as the value-added of the largest manufacturing sector in the current assessment is lower because it corresponds to 27 Member States (i.e. excluding UK), whereas in the 2017 assessment it was related to EU28.

14.7 Data sources

Data published by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress were used for the production at the extraction stage ('World Mining Data'). Statistical data for refined lithium production is not available. Information published by the German Minerals Resources Agency (DERA) for the year 2015 was used to approximate the global supply risk; therefore, the results for the global HHI of refined lithium production are not based on a 2012-2016 average, but only on the year 2015.

Trade data for refined lithium compounds were sourced from Eurostat's Comext database. Trade data for lithium concentrates are not available in the Harmonised System or in the Combined Nomenclature system of trade codes. The reason in that lithium ores and concentrates trade iare reported in combination with other commodities under code HS 260790 for "Other ores and concentrates, not elsewhere specified". However, data concerning spodumene exports of Australia to the EU were provided by industry expert (for code HS 253090) after the SCRREEN workshop, and these were used in the

[141] The results are scaled by dividing the calculated EI score by the value of the largest manufacturing sector NACE Rev. 2 at the 2-digit level and multiplied by 10, in order to reach the value in the scale between 0-10.

assessment. EU exports were considered as non-existing, as it was assumed that all domestic production of ores and concentrates, as well as all imports, is consumed domestically. Trade data for lithium in other forms than lithium carbonate and hydroxide (e.g. Li chloride, Li bromide, butyllithium, lithium metal) are also not accounted separately by trade statistics; therefore, these compounds were not considered in the EU sourcing of refined lithium.

The EU MSA study of lithium published in 2015 was the source for the distribution of end use sectors and for the EOL-RIR.

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