

Lithium market research – global supply, future demand and price development



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ABSTRACT

Ensuring the supply of strategic metals is crucial for the growth of industrialised countries. One of these strategic metals is lithium, which is used in a variety of high tech product and everyday objects. In this study the lithium market is analysed including areas of application, drivers of demand as well as lithium price development. A demand forecast up to 2020 is given in four different scenarios, including the increasing demand in electric mobility, forced by political driven influences. To meet the growing demand of lithium huge lithium projects are planned or under construction. The projects are summarised with a completion up to 2020 and a capacity of more than 20,000 t lithium carbonate equivalents (LCE).

1. Introduction

Lithium is an essential metal with widespread applications in next generation technologies, such as energy storage, electric mobility and cordless devices. Lithium compounds, however, are also used in a far wider spectrum, e.g. glass, enamel and ceramic industry, lubricating greases, pharmaceutical products or aluminium production [1]. Because lithium cannot be substituted in most applications, a steady increase of 8–11% in annual demand is anticipated [2,3]. Furthermore, the increasing production of electric cars has been predicted to be a major driver in growing lithium demand. Since 2000 the global lithium production for use in batteries has increased by approx. 20% per annum, amounting to 35% of the overall lithium consumption in 2015 [4,5].

The most important lithium compound for the production of tradable products is Li_2CO_3 , with a total quantity of 46% in 2015. Of minor, yet growing importance is LiOH (19%). These two lithium compounds cover approx. 2/3 of the market.

Within this context lithium find widespread application in secondary batteries (rechargeable batteries) as cathode materials (e.g. LiFePO_4 , LiCoO_2 , LiMn_2O_4 , $\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$) as well as in primary batteries (single-discharge batteries) as anode materials. Current research activities for lithium based cathode [6] or anode materials [7,8] vary, but confirm the preferred use of lithium for energy storage in the future.

Rising lithium demand requires an extensive knowledge of raw

material situation as well as the current and future lithium supply and demand. This also presupposes detailed information of industrial applications of important lithium compounds as well as potential substitutes for lithium.

These market trends are crucial not only for the lithium key users and producers but also for scientists with a lithium research background. Current detailed studies are mostly published in commercial reports (e.g. Roskill's "Lithium: Global Industry Markets and Outlook") and therefore are ordinarily unavailable for scientists [9]. Though commercial studies are truly well-researched, there exists a wide spectrum of scientific reports, which have not been compiled yet for an in-depth study. This study aims at not only covering scientific progress, but also discussing the market and price development. In view of increasing global demand, additional planned lithium projects up to 2020 will be summarised.

2. Methods

The following chapters provide an overview, how global supply and demand influence the market price of lithium. Especially core industrial applications are evaluated based on a state-of-the-art literature review. A demand forecast for 2020 is created considering lithium substitutes in different applications. The underlying demand scenarios are primarily based on trend extrapolations for different areas of application (Fig. S1 Supporting Information) as well as the Information of Roskill's "Lithium - Market Outlook to 2017". In

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addition, an electric vehicle (EV) scenario shows the recent market development in electric mobility, driven by political influences. Combined with higher environmental standards for lithium extraction from brine deposits, short term bottlenecks in supply are likely to occur. Overall, the domestic exploration and extraction activities by the individual lithium consuming countries highly depends on the future price development. In the last section, the price of lithium carbonate (Li_2CO_3) is analysed using data of Consumer Price Index (CPI) 1990–2015 considering the US inflation rate.

3. Fundamentals of supply and demand

3.1. Supply

When assessing lithium supply, a distinction is made between reserves and resources. In addition, lithium production volume and the impact of recycling have to be considered.

3.1.1. Reserves and resources

Resources are confirmed and estimated deposits, whereas reserves are defined as known deposits only. According to USGS, estimated reserves of more than 14 mill. t are available. Resources are considerably greater and are reported to amount to approx. 34 mill. t. In 2014, the global lithium production reached roughly 32,000 t, corresponding to 170,000 t LCE [5].

In fact, the theoretical static range of lithium reaches 435 years. Hence, lithium supply can be held at a sufficient level. Fig. 1 shows the geographical distribution of global lithium resources. Almost 60% are found in South America, especially Chile, Bolivia and Argentina.

Approx. 4.4 mill. t Li are located in North America (USA, Canada) and further 5.4 mill. t Li in China. The European lithium deposits (approx. 1.2 mill. t Li) on the other hand represent only roughly 3.5% of worldwide resources.

Two types of lithium deposits have to be distinguished: brine deposits and lithium ores. The most important brine for lithium extraction is the Salar de Atacama in Chile (6.3 mill. t Li). An even greater brine deposit is the Salar de Uyuni in Bolivia (10.2 mill. t Li). The altitude (3,650 m), a quite low average lithium content of 320 ppm and less favourable climatic conditions for industrial concentration activities, are some reasons which till present have stood against a large-scale lithium production [11–13].

Presently, the most important Li-containing deposits are igneous rocks (3.9 mill. t Li). These pegmatites in particular contain the minerals spodumene, lepidolite, petalite and zinnwaldite. The greatest lithium ore deposit is the Greenbushes spodumene mine, Australia

(0.85 mill. t Li) [12]. Deposits are found in the USA, China, Zimbabwe, Russia or Canada and Europe as well. Important European lithium deposits are located in Germany/Czech Republic (0.16 mill. t Li) and Serbia (1.0 mill. t Li).

3.1.2. Production volume

The production volume is shown in Fig. 2, which includes the world-produced amount of lithium, with exception of the United States.

The global production of lithium rose steadily from 1995 to 2008 starting at around 40,000 t and reaching close to 140,000 t, whereby the first significant quantitative decrease happened in 2009, the year of the economic crisis. Subsequently, for the next five years the production volume increased by 70%.

3.1.3. Recycling

Due to huge lithium primary reserves and resources, which can be exploited at rather low cost, lithium from secondary sources had no significant impact on the total supply so far. Currently, the proportion of recycled lithium is less than 1% [14].

Indeed, some scenarios agree on the importance of lithium recycling, predicted to attain relevance in about 2030 and is forecasted to substitute up to 25% of the supply in 2050 [15]. The greatest potential lies in recycling lithium containing batteries. However, the methods presently employed, such as the pyrolytic VAL'EAS process (Umicore NV/SA, Belgium) or low-temperature separation (TOXCO Inc., USA), aim at recovering particularly cobalt and nickel [16,17].

A battery recycling company, which recover lithium as well, is the Accurec Recycling GmbH (Mülheim an der Ruhr, Germany) with an annual recycling quantity of 4,000 t/a spent batteries. By combining pyrolytic and hydrometallurgical process steps, lithium carbonate (Li_2CO_3) is recovered in addition to the high-priced metals [18]. Further industrial lithium recycling processes are carried out by AEA Technology Group plc (Harwell, United Kingdom), by Batrec Industrie AG (Wimmis, Switzerland) as well as by Recupyl S.A.S., (Domène, France). In addition, a host of further lithium recycling processes are published, with the aim of an economically viable lithium recycling [19,20]. However, these approaches have not yet been scaled up on a commercial scale. Engaging in intensified recycling activities to access lithium as a secondary resource is a viable option for securing the long-term supply.

3.2. Demand

Lithium has a wide range of applications. The majority of the

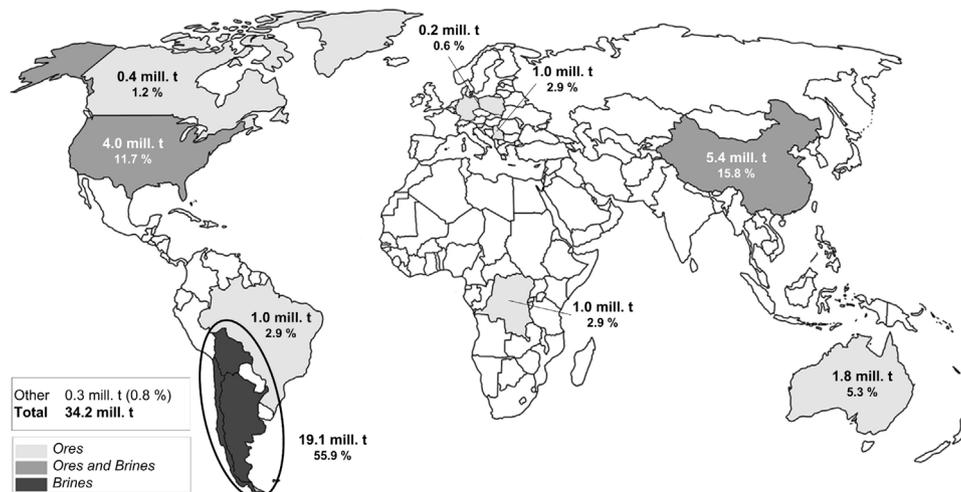


Fig. 1. Geographical distribution of global lithium resources [5,10].

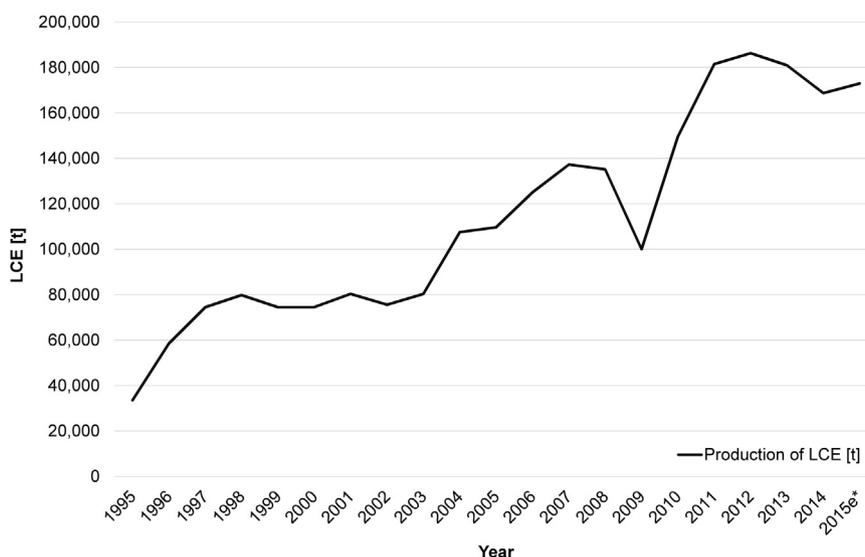


Fig. 2. Global, annual production of lithium (excluding US) (USGS 1995–2016).

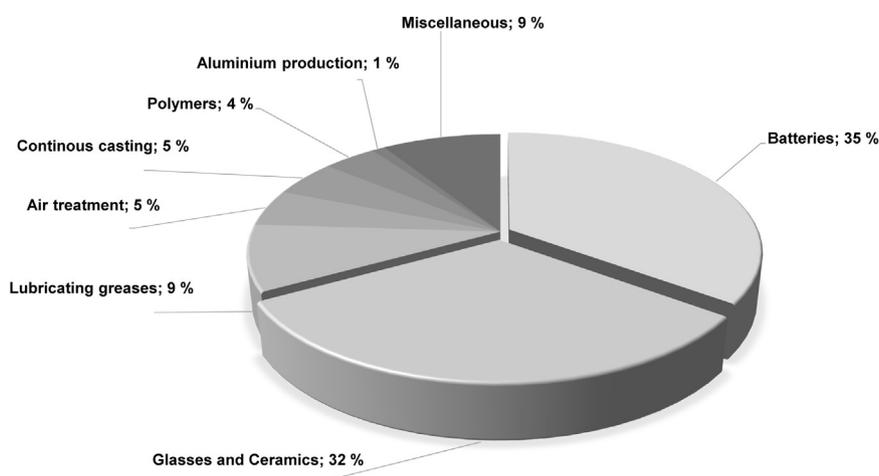


Fig. 3. Application areas of lithium (2015) [5].

annually extracted lithium (35%) is consumed in batteries, followed by glass and ceramic applications (32%). Other important applications include lubricants with a share of 9%, continuous casting as well as air treatment with 5% each, polymer production with 4% and aluminium production with 1%. Further industrial applications (9%) are among others, sanitisation, organic synthesis, construction, pharmaceuticals, alloys and alkyd resins such as other minor end uses. (Fig. 3) [5].

The demand of the major industrial applications for lithium is analysed subsequently. Estimates of the average growth in each field of application are based on recent economic developments.

I. Batteries

Primary batteries (single-discharge batteries) have lithium metal as an anode. They profit from a high charge density, low weight and long life, but suffer high costs per unit. They can provide voltages from 1.5 to 3.7 V. After use, they are disposed of.

In secondary batteries (rechargeable batteries) lithium compounds served as electrode material. Lithium is essential for producing the electrolyte and the two electrodes [21]. For production, typically lithium hydroxide (LiOH), lithium carbonate (Li_2CO_3) and several salts are employed. Yet, the exact lithium amount, which is consumed in the battery industry, is hard to estimate, because only a few reliable sources exist. Roskill 2012, for instance, reports that the data on the demand for

rechargeable batteries is only available for Japan [22], while the by far dominant Chinese market is more or less a black box.

II. Glasses and ceramics

With a 32% share of total production in 2016, glasses and ceramics are the second largest lithium market. Addition of lithium improves various product properties of glasses and ceramics, e.g. it increases the mechanical strength and decreases the shrinkage of fine ceramics. Furthermore, lithium can reduce the required heating temperatures, thus shortens cycle times and increases output quantities. Li_2CO_3 is mainly used as a flux in the manufacturing process of ceramic glazes and porcelain enamels for coating the ceramic body [21,22].

In the glass industry, lithium improves the colourfastness as well as gloss and among others the resistance. Additionally, spodumene concentrate may also be used as a flux in glazes, typically in conjunction with other lithium minerals, especially lepidolite, amblygonite and petalite. A lithia (Li_2O) content between 4.0 and 7.25 wt.-% results in reducing the melting temperature and thus in energy savings of the production process [23]. The produced lithia glazes also have a higher chemical resistance, a lower number of air entrapment and a lower viscosity, resulting in a lower number of rejects [21,22].

III. Lubricating greases

Greases can be subdivided into conventional and complex

Table 1

Calculated lithium demand (Basic scenario) forecast and share in 2020 for different applications.

	<i>Demand LCE 2015 [t]</i>	<i>Share 2015 [%]</i>	<i>Demand LCE 2020e* [t]</i>	<i>Share 2020 [%]</i>
Batteries	53,629	35	76,673	34
Glasses and Ceramics	60,549	32	86,717	38
Lubricating greases	13,840	9	14,507	7
Polymers	8,650	4	2,315	1
Air conditioning	8,650	5	5,325	2
Aluminium	1,730	1	0	0
Continuous casting	10,380	5	18,478	8
Other	15,570	9	22,235	10
Sum	172,998	100	226,250	100

greases. Lithium greases are prepared by mixing a lithium soap and lubricating oils. This mixing takes place usually by applying heat and pressure. The use of soap greases are advantageous, since maintaining lubricating properties over a high temperature range and providing a good resistance to water [21,22].

IV. Air treatment

Lithium bromide (LiBr) is used as an absorbent in chloro-fluorocarbon (CFC) free, industrial absorption chillers. Lithium chloride (LiCl) is also used in industrial dehumidification and drying equipment. Lithium and lithium peroxide are used to remove carbon dioxide (CO₂) from the air in closed systems such as submarines and spacecrafts [21,22].

V. Continuous casting

Li₂O is a melting agent, which is added to metallurgical casting fluxes either in the form of LiOH or Li₂CO₃. It reduces melt viscosity improving the flow rate in continuous casting. In traditional metal casting sets, lithium is part of the melting sand to reduce the thermal expansion coefficient to reduce distortion and deformation of the casting [21,22].

VI. Polymers

The organic lithium compound *n*-butyl lithium is used as an initiator in polymerisation reactions for production of inorganic styrene-butadiene rubber (SBR) and polybutadiene rubber (BR). *n*-Butyllithium, and smaller amounts of *sec*-butyl lithium catalyse reactions. In polymer synthesis they serve to obtain polymers with thermoplastic properties. SBR is the most commonly produced synthetic rubber which is used mainly for production of tires [21,22].

VII. Aluminium production

Li₂CO₃ is an electrolyte additive in molten aluminium. It increases electrical conductivity of the bath and reduces the melting point as well. This way metal throughput is increased and fluorine emissions are reduced. Roughly 1% of annual lithium demand is estimated to be spend on the production of aluminium [21,22].

VIII. Miscellaneous applications

In addition to the core industrial applications, lithium is used in a wider spectrum. In organic synthesis, lithium compounds are used mainly for production of pharmaceuticals, flavours and fragrances, as well as producing a variety of organic intermediates. In construction and design, Li₂CO₃ is used e.g. to accelerate the setting time of cementitious systems such as alumina cement and alumina Portland cement mixtures. The use of lithium in alloys occurs superficially for Al-Li and Mg-Li alloys. The Mg-Li alloy is the lightest, versatile material that is commercially available. In electronics, lithium niobate (LiNbO₃) and lithium tantalate (LiTaO₃) wafers serve for the production of microchips. One key application is the automotive sector (keyless access or

tire pressure monitoring systems). Finally, there are some minor end uses, where lithium is needed in very small quantities e.g. fireworks [22].

4. Results and discussion

4.1. Demand forecast in 2020

Currently, substitution potential for lithium compounds is chiefly seen for batteries, ceramics, greases and manufactured glasses [5]. The use of these substitutes depends to a large extent on raw material prices. New inventions and developments, which use substitutes, typically need five to seven years for being established. Next to the substitutability of lithium, there are increasing demands in some applications. The forecast in this study is based on a specially created trend exploration, in which requirements for each segment of lithium consumption is conducted. The basis for the analysis are demand values for the individual areas of lithium applications from USGS starting in 2007. The calculated forecast values are represented in the following in a “Basic scenario” with demand and share of lithium by field of application (Table 1). Furthermore, an Optimistic and a Pessimistic scenario are shown (Table 2). The Optimistic scenario is based on a likely economic scenario and assumes that lithium demand will develop in a positive way. The Pessimistic scenario presumes that lithium demand will develop in accordance with global projected goods growth. This annual growth rate is estimated at 2–3% [2,3]. Following, the requirements of the main application areas are evaluated and estimated below.

Table 1 shows the demand of 2015 in lithium carbonate equivalents (LCE) and the predicted requirements for 2020. In accordance with the Mineral Commodity Summaries of USGS, the estimated lithium demand per year and application area from 2007 to 2016 is used in order to allow for a better comparison with existing data.

In the following, areas of application for lithium are analysed individually. For the Basic scenario, the average annual growth rates from the linear trend analysis are given. For the Optimistic scenario, latest developments are taken into account. Therefore, forecast values are verified with values from a market analysis of industry trends [22]. The Pessimistic scenario is not listed in the individual analysis, because it based on the assumption, that demand development of lithium is oriented on global growth. The Pessimistic scenario is modelled on the global annual economic growth of 2.5%.

I. Batteries

According to the Basic-scenario forecast, lithium demand for batteries will significantly rise by approx. 34% until 2020, which corresponds to an annual average growth rate of about 7%. In fact, future demand for lithium depends on various factors. Primary lithium batteries for example can be stored for long time and they are often used for military purposes. It is probable that

Table 2

Comparison of lithium demand growth scenarios in 2020 for different applications.

<i>Application</i>	<i>Optimistic 1 [%/a]</i>	<i>Basic 2 [%/a]</i>	<i>Pessimistic 3 [%/a]</i>
Batteries	12	6	2.5
Ceramics and Glass	10	8	2.5
Lubricating greases	1	–1	2.5
Air treatment	0	–5	2.5
Polymers	–5	–16	2.5
Continuous casting	12	12	2.5
Aluminium	5	0	2.5
Miscellaneous	10	10	2.5

primary batteries are being more and more replaced by secondary batteries. In the field of secondary batteries, the demand is likely to increase due to the growing number of electrified drives. Besides Tesla, other major vehicle manufacturers have promoted the production of electric and hybrid vehicles. According to Financial Times Tesla's Gigafactory will require 24,000 t LiOH·H₂O (~21,000 t LCE) per annum [24]. Additionally, unsaturated markets of electronic devices in India and China are boosting demand, too. Because of the high amount on batteries in both cordless devices and electrified drives, the Optimistic scenario considers the basic-scenario demand to double. In the Optimistic scenario, a rise in demand of 12% is assumed.

For batteries, there is no evidence of exponential growth in lithium demand from 2007–2015 (Fig. S1 Supporting Information). The growth considers the continuous increasing lithium demand in portable electronics in the last decade. In addition, the derived scenarios were determined without actual politically driven influences.

In 2016, electric mobility is particularly forced by many countries (e.g. China, USA, Germany) [25] so that the demand forecast even in the Optimistic scenario could be too low. Because of actual discussions to ban combustion engines in 2030, e.g. in California, USA or in Germany [26], a fourth scenario (EV scenario) shows the development of lithium demand caused by electrified drives. In principle, electric vehicles are subdivided into hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV). Actually, the majority of HEV uses nickel metal hydride battery technology. Only PHEV and BEV are completely based on Li-ion technology [27]. The used lithium ratio per vehicle PHEV to BEV is about 1:10 [28]. The estimation in "EV-scenario" based on barriers, such as insufficient coverage with charging stations in many countries or the limited range of BEV and the limited usage of raw materials as well [29].

A view on battery electric vehicles shows a wide range of battery performance. For example, the Chevy Volt by General Motors with 16.5 kW h has a significant smaller battery compared to the Tesla Model S with 70–85 kW h. For a performance of 6 kW h a lithium consumption of 1 kg is required [28]. This corresponds to a share of 5.32 kg LCE. For a BEV, a mean energy density of 50 kWh is assumed (8.5 kg Li or 45.25 kg LCE). For PHEV vehicles a mean energy density of 5 kW h is assumed, which corresponds to a demand of 0.85 kg Li or 4.52 kg LCE respectively [28]. Because of the high volatility in market, many different estimates have been published. The forecasts for 2020 differ very strongly. The estimates show a strong spread between 7.5 and 9 mill. electric vehicles in 2020 [30–32].

In the EV scenario, we assume that approx. 9 mill. electric vehicles will be registered in 2020 [32]. Frost and Sullivan expected that BEV has a share of 1.3% (1,365,000 units). The share of PHEV will be about 1.6% (1,680,000 units). In addition, the share of HEV (5.6%, 5,880,000 units) is not considered as a lithium demand driver, since even until 2020 the majority of batteries is based on nickel metal hydride [27].

With a mean energy density of 50 kW h for BEV and 5 kW h for PHEV respectively, this corresponds to a lithium demand of about 62,000 t LCE (BEV) and about 8,000 t LCE (PHEV). In sum, an additional lithium demand of 70,000 t LCE is required until 2020 for the EV scenario.

II. Glasses and Ceramics

For the market of glasses and ceramics, an increase of about 49% compared to 2015 is predicted. That represents an average annual increase of almost 8% shown in the Basic scenario. The use of lithium to reduce melting temperatures strongly depends on the price of raw material. Because of large markets in Europe and Asia, a higher than average growth is expected, too. Due to

the high volatility of commodity prices, it is assumed that real, annual growth rates vary widely. If commodity prices are high, demand declines and vice versa. In the Optimistic scenario, a growth of 10% per year is estimated.

III. Lubricating greases

The Basic scenario for lubricating greases show a consolidation of the market until 2020 by approx. 4%. Primarily, high performance greases are used in aircraft and motor vehicles. If the lithium price rises highly, substitutes such as urea are consumed instead of LiOH. If rising commodity prices are required, an annual fall in demand of 1% is assumed in Basic scenario. Kline & Company confirmed the contraction of the market and they estimated 0.6% growth per year for European market. For the Optimistic scenario, Kline Group estimates a growth of annual 0.2% for Europe lubricant demand [33]. In the Optimistic scenario, a growth in global demand of 1% is assumed for lubricating greases.

IV. Air treatment

In the field of air treatment, a decline of 24% until 2020 is predicted in Basic scenario. This is caused by an annual reduction of about 5% in the field of dehumidification. Demand for LiBr particular in the area of absorption cooling is assumed to be steady. The demand for Li₂CO₃ in the field of dehumidification declines because of new materials and new technological development. The use of lithium hydride (LiH) or lithium peroxide (Li₂O₂) for air purification occupies a niche, wherein the demand is also assumed to be constant. Due to the uncertain data situation, for the Optimistic scenario a steady lithium demand is estimated (growth rate 0%/a).

V. Polymers

From 2007, demand of lithium for polymers is decreased. In this field, an average decrease of approx. 16% per year is calculated for the Basic scenario. Trinseo forecasts in context of growing global trade of Styrene-Butadiene Rubber (SBR) an increase in demand of about 6.6% per year [34]. Due to the fact that on average 3 kg lithium per ton SBR is assumed, the demand of lithium will increase only slightly [22]. For the Optimistic scenario, we assume a decrease of 5% per annum because the trend analysis shows a negative coefficient of determination (67%).

VI. Continuous casting

The forecast value for the Basic scenario of continuous casting applications (78%) corresponds to an annual average growth of about 12%. Due to the increase in the throughput and the improved properties of final products, an increase in demand can be assumed. To operate the continuous casting process economically, lithium must be used. Because of the opaque data situation about the casting metals market, it is assumed, that demand in the Optimistic scenario is equal to the Basic scenario (12%/a).

VII. Aluminium production

The demand of lithium for production of aluminium for 2020 is negative as well. Lithium additives for the production of aluminium are mainly used to improve melting efficiency. In this area Li₂CO₃ is used in only 12% of aluminium smelters [35]. An analysis of demand in recent years shows that the consumption of Li₂CO₃ has steadily decreased. This is partly due to high raw material prices and to the increased use of substitutes. The Basic scenario forecast shows that requirement of lithium decreases to 0% until 2020. An estimation based on increasing demand for aluminium predict a 5.1% growth per year in the market until 2020 [36]. Therefore, in the Optimistic scenario a rise of 5% per year is assumed, since the application of lithium offers several advantages in aluminium production.

VIII. Miscellaneous applications

For the category "miscellaneous applications", e.g. organic

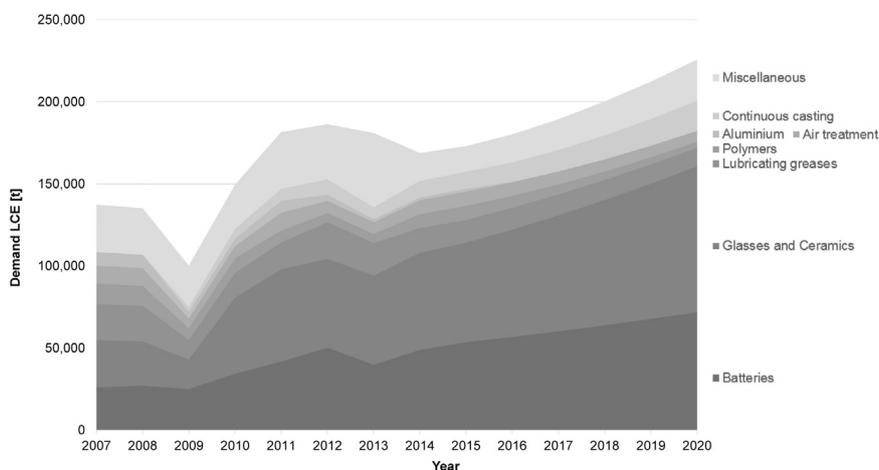


Fig. 4. Lithium demand 2007–2020 with estimated values 2016–2020 (Basic scenario).

synthesis, pharmaceutical and electric applications, a growth of 43% until 2020 has been determined. The average annual growth rate of 10% in this Basic scenario mainly affects the field of lightweight construction, which indicates a strong increase in demand. Owing to the multitude of application areas in this category, the growth rate of 10% is assumed for the Optimistic scenario too. Another reason is the use of lightweight material in automotive applications to extend the range of electric vehicles.

A summary of the results in the application areas is given below (Table 2).

In the Basic scenario, an annual average lithium growth of 6% per annum is predicted. The coefficient of determination (Fig. S1 Supporting Information) of batteries, glasses and ceramics as well as Continuous casting is more than 90%, which means, that the trend is highly unbiased. Lubricating greases, air treatment, polymers and aluminium tend to have a negative annual growth. Due to their small amounts, the influence on annual demand is low. Miscellaneous applications show a high volatility, what results in the lowest coefficient of determination of all application fields. Fig. 4 shows the cumulative total demand for lithium per application field from 2007 to 2020. The values 2016–2020 are calculated in a forecast (Basic scenario). For this calculation, an annual lithium demand of around 230,000 t LCE in 2020 is predicted.

For the Optimistic scenario, a total annual lithium growth rate of

around 9% is predicted. In the field of glasses and ceramics, there is a reciprocal relationship between price and quantity. The required amount of lithium increases only, if the price remains relatively stable. With about 270,000 t LCE in 2020, the Optimistic scenario shows an annual average increase of 19,000 t/a LCE.

The Pessimistic scenario assumes that lithium demand will rise by 23,000 t LCE by 2020. This scenario is considered likely if the economic realities change only slightly. In addition, the Pessimistic scenario is probable as well, if revolutionary developments for example new inventions in batteries (e.g. lithium-air batteries, lithium-sulphur batteries, fuel cells) replace current technologies in the battery market.

Fig. 5 shows the described scenarios for development of lithium demand until 2020. The conclusion of the Optimistic scenario is a raise in demand of 95,000 t LCE until 2020. This represents an annual increase of 19,000 t LCE. The Basic scenario shows an increase of about 56,000 t LCE until 2020, which corresponds to an annual demand of 11,000 t LCE. The Pessimistic scenario regarded as the worst-case shows an increase of about 23,000 t LCE until 2020, which constitutes an annual demand of about 4,500 t LCE.

Due to current economic developments, the market volume of battery applications, glasses and ceramics as well as casting metals will increase. Most probably, lithium demand will grow in ranges between Basic and Optimistic scenario (6–9%/a).

In addition to lithium (especially in the EV scenario), cobalt has to be considered as a primary constraint of the market as well. The

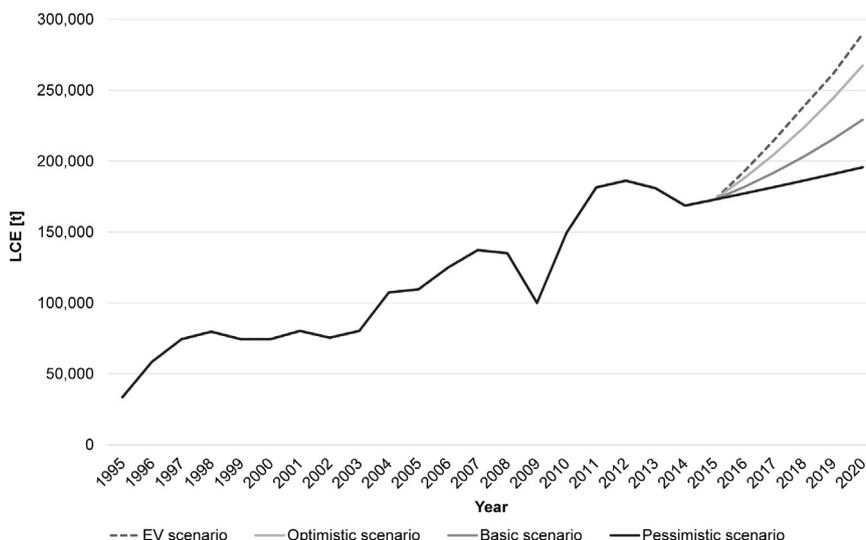


Fig. 5. Scenarios for the development of lithium demand until 2020.

demand for cobalt is expected to grow by 70% until 2020, compared to nickel (4%) and manganese (2%) [37]. Hence, a shortage in cobalt supply may have a negative impact on the lithium demand.

Cobalt is used for production of cobalt compounds, mainly cobalt (mixed) oxides, whereby a high amount of which is consumed in battery production. Worldwide, China is the main consumer for cobalt. Nearly 75% are processed by the battery sector [38]. The high demand for cobalt is one reason for the scepticism towards widespread use of lithium-ion batteries in electric mobility [39]. Global reserves are 7.1 mill. t, of which 3.4 mill. t are located in the Democratic Republic of the Congo and 1.1 mill. t in Australia [38]. In the forthcoming years, demand for refined cobalt is expected to increase rapidly up to 110,000 t/a in 2030 and 190,000 t/a in 2050. The forecasts show no shortage in supply until 2050, if the supply situation in Africa remains unchanged [40].

Overall, the highest surge in lithium demand (approx. 117,000 t LCE until 2020) is calculated for the EV scenario. To meet the rising demand, a number of lithium projects are currently planned or under construction.

4.2. Additional lithium projects up to 2020

Present global lithium projects or expansions with an estimated completion up to 2020 and a production capacity $\geq 20,000$ t/a are listed below in Table 3. The annual production volume of these projects will be approx. 100,000 t Li_2CO_3 , about 50,000 t $\text{LiOH}\cdot\text{H}_2\text{O}$ (44,000 t LCE) and up to 25,000 t LCE spodumene concentrate.

The projects encompass brines in Argentina (Cauchari-Olaroz project, Salar de Vida) and the largest global lithium deposit in Bolivia (Salar de Uyuni) as well as lithium production from ores in Australia (Greenbushes, Mt. Marion) and Canada (Whabouchi).

The listed projects with a planned production volume of approx. 169,000 t LCE would be sufficient to cover the demand for EV scenario in 2020. In addition, smaller new projects or expansions could raise the lithium supply in 2020 as well.

In addition to the envisaged plants up to 2020, a large number of further lithium projects have been recently investigated at various stages. For instance, lithium recovery from important European minerals, such as jadarite (Jadar, Serbia) and zinnwaldite (C í novec/Zinnwald, Czech Republic/Germany).

The largest known European lithium ore deposit is located in Jadar with a volume of approx. 3 mill. t Li_2O (125.3 mill. t, averaged lithium content 3.9 wt.-% Li_2O) in form of the mineral jadarite, $\text{LiNaSiB}_3\text{O}_7(\text{OH})$ [12,49]. At present, the deposit is about to be exploited towards its suitability as lithium resource.

The most important zinnwaldite, $\text{K}(\text{Li,Fe,Al})(\text{AlSi}_3)\text{O}_{10}(\text{OH,F})_2$ deposit comprises approx. 347,000 t Li_2O [10,50]. SolarWorld AG [51], as well as the joint venture by Lithium Australia NL and European Metals Holdings Ltd., intend to establish lithium production on an industrial-scale [52,53]. In 2011, Solar World started exploration and elaboration of a feasibility study for lithium mining (Germany), whereas Lithium Australia plans a plant for lithium extraction from

tailings (Czech Republic).

4.3. Price development

Lithium is used to improve several product properties in different fields of application, which indicates that lithium is hard to replace in a considerable number of production processes. Lithium is primarily used to increase the quality of products and for saving costs, for example by reducing the melting point. Fig. 6 shows the price history of lithium starting from 1990 to 2015.

Up to 1995, lithium supply was stable and demand grew slowly. With the market entry of SQM, higher supply resulted in rapidly falling trade prices. From 1999 to 2002 prices as well as demands stagnated because of the Asian economic crisis and the recession in North America. In the period from 2002 to 2007, Chinese economy grew strongly, which results in higher demand of lithium and higher trade prices. After 2008, lithium demand dropped in immediate response to the economic crisis. Shortly after, the price reached its lowest point in 2010. The price recovered subsequently, to a level of 6,900 USD/t by the end of 2015. This represents an increase of 56% within five years.

4.3.1. Market price analysis

According to forecasts, global lithium demand will increase significantly. The price for Li_2CO_3 has raised substantially since 2010. In fact, markets have witnessed Li_2CO_3 prices increase by approx. 15% since November 2015. In September 2016, it amounted to 7,200 USD/t [55,56]. Concerns of some authors, who potential see a price jump to 25,500 USD/t no later than 2020 [57] already have become reality in China: In February 2016 the spot price was up to 22,900 USD/t *tg*- Li_2CO_3 (technical grade, > 99.0%) [58].

As a reaction, there are three major issues under discussion, which are believed to most strongly affect lithium price formation, both in China and for long-term contracts:

I. Analysts estimate a declined future lithium liquidity in the Chinese spot market.

Firstly, a strongly increased domestic lithium demand in China is observed, especially due to electric mobility. The Chinese government supports purchasing of electric vehicles, particularly in metropolitan areas. Compared to 2014, in 2015 three times the volume of electric cars (188,000 units) were sold [59].

Secondly, China is highly dependent on imports of Australian spodumene ore. Hitherto, spodumene concentrate is exported in large quantities from Australia to China for glasses ceramics and battery production. At present, Albemarle Corporation plans to process more spodumene concentrate to lithium compounds like Li_2CO_3 or LiOH directly in Australia, thus contributing to market scarcity for spodumene concentrate in China [60].

II. Concentration of the world lithium market.

As a consequence of the takeover of Rockwood Lithium GmbH (former Chemetall) by Albemarle Corporation Inc., approx. 90% of the world lithium market is ruled by three global players: SQM,

Table 3
New lithium projects and planned expansions up to 2020.

Country	Deposit/Company	Resource	Product	Capacity	Completion	Source
Argentina	Cauchari-Olaroz/Lithium Americas & SQM	9.14·10 ⁸ m ³ 630 mg/L	Li_2CO_3	40,000 t	2019 ^a	[21,41]
Argentina	Salar de Vida/Galaxy Resources	7.2·10 ⁸ m ³ 787 mg/L	Li_2CO_3	25,000 t	2017	[21,42]
Australia	Greenbushes/Tianqi Lithium	70.4 mill.t 2.58 wt.-% Li_2O	$\text{LiOH}\cdot\text{H}_2\text{O}$	24,000 t	2018	[12,43]
Australia	Mt. Marion/Neometals	60.5 mill.t 1.36 wt.-% Li_2O	Spodumene concentrate	20,000–25,000 t LCE	2016	[44,45]
Bolivia	Salar de Uyuni/Comibol	22.0 mill. t Li_2O	Li_2CO_3	30,000 t	2018	[12,46,47]
Canada	Whabouchi/Nemaska Lithium	27 mill.t 1.53 wt.-% Li_2O	$\text{LiOH}\cdot\text{H}_2\text{O}$, Li_2CO_3	27,645 t, 3,267 t	2018	[21,48]

^a Estimated

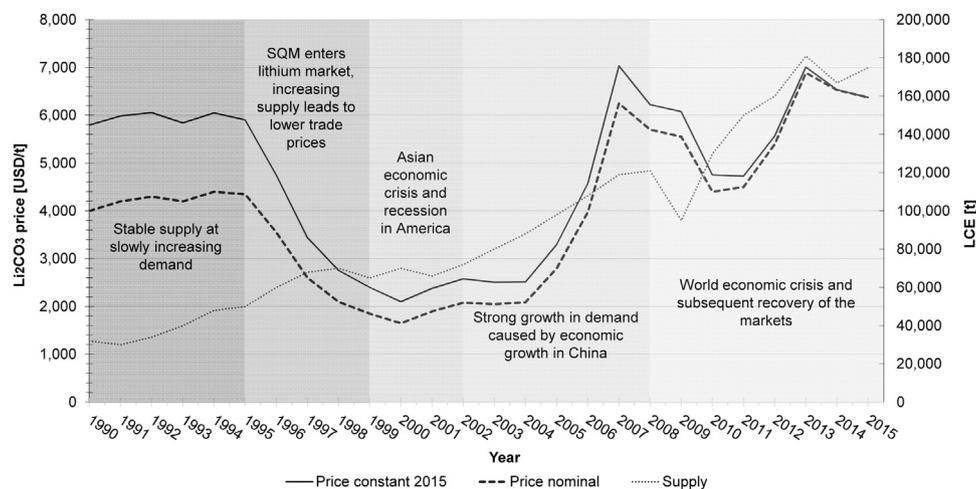


Fig. 6. Lithium price history 1990–2015 [5,22,54].

American FMC Lithium, Albemarle Corporation [61,62].

III. Political and ecological conflicts in South America.

The steadily increasing production volumes give rise to political conflicts, specifically in Chile. The Chilean SQM produced 39,500 t LCE in 2014, which is about 28% of global production [63]. However, environmental regulation limits the total capacity until 2030 to 200,000 t LCE. If the output of 2014 were projected onto the next years on the same scale, this limit would be reached in 2023. However, this estimation does not consider production increases which are highly likely to occur [64]. Concerns have been raised regarding an increase of lithium output quota, as the current activities are regarded critically by environmental stakeholders. At present, there are concerns that evaporation processes for lithium brines may locally result in groundwater pollution. In addition, emissions from transport vehicles and lithium containing dust are regarded as constituting a severe challenge to ecosystems and human sanity [65].

5. Summary

Lithium is an essential metal with widespread applications, e.g. batteries, glasses and ceramics, lightweight materials, lubricating greases, casting alloys and polymers. In fact, lithium is not a rare element, since estimated reserves of more than 14 mill. t Li (static range 435 years) and resources of approx. 34 mill. t Li are available. Most probably, lithium demand will increase in a range between 6%/a (Basic scenario) from about 173,000 t/a LCE in 2015 to 230,000 t/a LCE and 9%/a (Optimistic scenario) to approx. 270,000 t LCE in 2020. Greatest demand drivers are applications in primary (anode materials) and secondary (cathode materials) batteries (6–12%/a) and ceramics and glasses (8–10%/a). By considering political driven influences on electric mobility, an EV scenario respected a strong increase in lithium demand for batteries (70,000 t LCE additional consumption up to 2020). To meet the rising demand up to 117,000 t LCE until 2020 new lithium projects are currently planned or under construction. These projects with an annual production volume $\geq 20,000$ t LCE will be able to extract 169,000 t LCE per year and consequently should meet the requested demand.

Besides the increasing demand it has to take also into account that,

- world lithium market is concentrated on three global players,
- recycling had no significant impact on total supply so far, and
- lithium deposits are concentrated on a small number of countries,
- the price for Li_2CO_3 is raised since 2010 and expected to increase in short- to medium-term future as well, and
- the battery market depends on several influence parameters,

particularly political decisions, raw materials or new battery technologies, which makes it difficult to give a reliable forecast of the lithium market beyond 2020.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.ensm.2016.11.004>.

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