Published in Applied Energy
Volume 110, October 2013, Pages 252-266
http://dx.doi.org/10.1016/j.apenergy.2013.04.005

Lithium availability and future production outlooks

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Abstract
Lithium is a highly interesting metal, in part due to the increasing interest in lithium-ion batteries. Several recent studies have used different methods to estimate whether the lithium production can meet an increasing demand, especially from the transport sector, where lithium-ion batteries are the most likely technology for electric cars. The reserve and resource estimates of lithium vary greatly between different studies and the question whether the annual production rates of lithium can meet a growing demand is seldom adequately explained. This study presents a review and compilation of recent estimates of quantities of lithium available for exploitation and discusses the uncertainty and differences between these estimates. Also, mathematical curve fitting models are used to estimate possible future annual production rates. This estimation of possible production rates are compared to a potential increased demand of lithium if the International Energy Agency's Blue Map Scenarios are fulfilled regarding electrification of the car fleet. We find that the availability of lithium could in fact be a problem for fulfilling this scenario if lithium-ion batteries are to be used. This indicates that other battery technologies might have to be implemented for enabling an electrification of road transports.

Highlights:

- Review of reserves, resources and key properties of 112 lithium deposits
- Discussions of widely diverging results from recent lithium supply estimates
- Forecasting future lithium production by resource-constrained models
- Exploring implications for future deployment of electric cars

Keywords: Peak lithium, electric vehicles, lithium production, lithium supply, resource-constrained modelling, lithium battery cars

1. Introduction

Global transports currently predominantly rely on one single fossil resource, namely petroleum that supplies 95% of the total energy used for transport [1]. In fact, about 62% of all world oil consumption takes place in the transport sector [2]. Oil prices have oscillated dramatically over the last few years, and the price of oil reached $100 per barrel in January 2008, before skyrocketing to nearly $150/barrel in July 2008. A dramatic price collapse followed in late 2008, but oil prices have at present time returned to over $100/barrel. Also, peak oil concerns, resulting in imminent oil production limitations, have been voiced by various studies [3–6]. It has been found that continued oil dependence is environmentally, economically and socially unsustainable [7].

The price uncertainty and decreasing supply might result in severe challenges for different transporters. Nygren et al. [8] showed that even the most optimistic oil production forecasts implied pessimistic futures for the aviation industry. Curtis [9] found that globalization may be undermined by peak oil's effect on transportation costs and reliability of freight. Likewise, Krumdieck et al. [10] pinpoints that current transportation planning models do not include the impacts of constrained fuel supply on private travel demand.

At present, barely 2% of the world electricity is used by transportation [2], where most of this is made up by trains, trams, and trolley busses, but an electrification of road transport, such as cars and small trucks, is commonly proposed as a way to solve the mentioned problems. Electric cars have historically provided rather short driving ranges, but new batteries based on lithium-ion technologies are capable of relatively high energy density and longer driving distances, possibly enabling a switch to electrified cars. Consequently, electrified cars using Li-ion batteries are considered to become the main option for powering electric vehicles in the coming decades [11].

A high future demand of Li for battery applications may arise if society choses to employ Li-ion technologies for a decarbonisation of the road transport sector. Batteries are at present time the second most common use, but are increasing rapidly as the use of li-ion batteries for portable electronics [12], as well as electric and hybrid cars, are becoming more frequent. For example, the lithium consumption for batteries in the U.S increased with 194 % from 2005 to 2010 [12]. Relatively few academic studies have focused on the very abundance of raw materials needed to supply a potential increase in Li demand from transport sector [13]. Lithium demand is growing and it is important to investigate whether this could lead to a shortfall in the future.

1.1 Aim of this study

Recently, a number of studies have investigated future supply prospects for lithium [13–16]. However, these studies reach widely different results in terms of available quantities, possible production trajectories, as well as expected future demand. The most striking difference is perhaps the widely different estimates for available resources and reserves, where different numbers of deposits are included and different types of resources are assessed. It has been suggested that mineral resources will be a future constraint for society [17], but a great deal of this debate is often spent on the concept of geological availability, which can be presented as the *size of the tank*. What is frequently not reflected upon is that society can only use the quantities that can be extracted at a certain pace and be delivered to consumers by mining operations, which can be described as *the tap*. The key concept here is that *the size of the tank* and *the size of the tap* are two fundamentally different things.

This study attempts to present a comprehensive review of known lithium deposits and their estimated quantities of lithium available for exploitation and discuss the uncertainty and differences among published studies, in order to bring clarity to the subject. The estimated reserves are then used as a constraint in a model of possible future production of lithium and the results of the model are compared to possible future demand from an electrification of the car fleet. The forecasts are based on open, public data and should be used for estimating long term growth and trends. This is not a substitute for economical short-term prognoses, but rather a complementary vision.

1.2 Data sources

The United States Geological Survey (USGS) has been particularly useful for obtaining production data series, but also the Swedish Geological Survey (SGU) and the British Geological Survey (BGS) deserves honourable mention for providing useful material. Kushnir and Sandén [18], Tahil [19, 20] along with many other recent lithium works have also been useful. Kesler et al. [21] helped to provide a broad overview of general lithium geology.

Information on individual lithium deposits has been compiled from numerous sources, primarily building on the tables found in [13–16]. In addition, several specialized articles about individual deposits have been used, for instance [22–26]. Public industry reports and annual yearbooks from mining operators and lithium producers, such as SQM [27], Roskill [28] or Talison Lithium [29], also helped to create a holistic data base.

In this study, we collected information on global lithium deposits. Country of occurrence, deposit type, main mineral, and lithium content were gathered as well as published estimates for reserves and resources. Some deposits had detailed data available for all parameters, while others had very little information available. Widely diverging estimates for reserves and resources could sometimes be found for the same deposit, and in such cases the full interval between the minimum and maximum estimates is presented. Deposits without reserve or resource estimates are included in the data set, but do not contribute to the total. Only available data and information that could be found in the public and academic spheres were compiled in this study. It is likely that undisclosed and/or proprietary data could contribute to the world's lithium volume but due to data availability no conclusions on to which extent could be made.

2. Geological overview

In order to properly estimate global lithium availability, and a feasible reserve estimate for modelling future production, this section presents an overview of lithium geology. Lithium is named after the Greek word "*lithos*" meaning "*stone*", represented by the symbol Li and has the atomic number 3. Under standard conditions, lithium is the lightest metal and the least dense solid element. Lithium is a soft, silver-white metal that belongs to the alkali group of elements. As all alkali elements, Li is highly reactive and flammable. For this reason, it never occurs freely in nature and only appears in compounds, usually ionic compounds.

The nuclear properties of Li are peculiar since its nuclei verge on instability and two stable isotopes have among the lowest binding energies per nucleon of all stable nuclides. Due to this nuclear instability, lithium is less abundant in the solar system than 25 of the first 32 chemical elements [30].

2.1 Resources and reserves

An important frequent shortcoming in the discussion on availability of lithium is the lack of proper terminology and standardized concepts for assessing the available amounts of lithium. Published studies talk about “*reserves*”, “*resources*”, “*recoverable resources*”, “*broadbased reserves*”, “*in-situ resources*”, and “*reserve base*”. A wide range of reporting systems minerals exist, such as NI 43-101, USGS, Crirsco, SAMREC and the JORC code, and further discussion and references concerning this can be found in Vikström [31]. Definitions and classifications used are often similar, but not always consistent, adding to the confusion when aggregating data. Consistent definitions may be used in individual studies, but frequently figures from different methodologies are combined as there is no universal and standardized framework. In essence, published literature is a jumble of inconsistent figures. If one does not know what the numbers really mean, they are not simply useless – they are worse, since they tend to mislead.

Broadly speaking, resources are generally defined as the geologically assured quantity that is available for exploitation, while reserves are the quantity that is exploitable with current technical and socioeconomic conditions. The reserves are what are important for production, while resources are largely an academic figure rather with little relevance for real supply. For example, usually less than one tenth of the coal resources are considered economically recoverable [32, 33]. Kesler et al. [21] stress that available resources needs to be converted into reserves before they can be produced and used by society. Still, some analysts seemingly use the terms ‘resources’ and ‘reserves’ synonymously.

It should be noted that the actual reserves are dynamic and vary depending on many factors such as the available technology, economic demand, political issues and social factors. Technological improvements may increase reserves by opening new deposit types for exploitation or by lowering production costs. Deposits that have been mined for some time can increase or decrease their reserves due to difficulties with determining the ore grade and tonnage in advance [34]. Depletion and decreasing concentrations may increase recovery costs, thus lowering reserves. Declining demand and prices may also reduce reserves, while rising prices or demand may increase them. Political decisions, legal issues or environmental policies may prohibit exploitation of certain deposits, despite the fact significant resources may be available.

For lithium, resource/reserve classifications were typically developed for solid ore deposits. However, brine – presently the main lithium source – is a fluid and commonly used definitions can be difficult to apply due to pumping complications and varying concentrations. Houston et al. [35] describes the problem in detail and suggest a change in NI 43-101 to account for these problems. If better standards were available for brines then estimations could be more reliable and accurate, as discussed in Kushnir and Sandén [18].

Environmental aspects and policy changes can also significantly influence recoverability. Introduction of clean air requirements and public resistance to surface mining in the USA played a major role in the decreasing coal reserves [33]. It is entirely possible that public outcries against surface mining or concerns for the environment in lithium producing will lead to restrictions that affect the reserves. As an example, the water consumption of brine production is very high and Tahil [19] estimates that brine operations consume 65% of the fresh water in the Salar de Atacama region.

Regarding future developments of recoverability, Fasel and Tran [36] monotonously assumes that increasing lithium demand will result in more reserves being found as prices rise. So called *cumulative availability curves* are sometimes used to estimate how reserves will change with changing prices, displaying the estimated amount of resource against the average unit cost ranked from lowest to highest cost. This method is used by Yaksic and Tilton [14] to address lithium availability. This concept has its merits for describing theoretical availability, but the fact that the concept is based on average cost, not marginal cost, has been described as a major weakness, making cumulative availability curves disregard the real cost structure and has little – if any – relevance for future price and production rate [37].

2.2 Production and occurrence of lithium

The high reactivity of lithium makes it geochemistry complex and interesting. Lithium-minerals are generally formed in magmatic processes. The small ionic size makes it difficult for lithium to be included in early stages of mineral crystallization, and resultantly lithium remains in the molten parts where it gets enriched until it can be solidified in the final stages [38]. At present, over 120 lithium-containing minerals are known, but few of them contain high concentrations or are frequently occurring. Lithium can also be found in naturally occurring salt solutions as brines in dry salt lake environments.

Compared to the fairly large number of lithium mineral and brine deposits, few of them are of actual or potential commercial value. Many are very small, while others are too low in grade [39]. This chapter will briefly review the properties of those deposits and present a compilation of the known deposits.

2.2.1 Lithium mineral deposits

Lithium extraction from minerals is primarily done with minerals occurring in pegmatite formations. However, pegmatite is rather challenging to exploit due to its hardness in conjunction with generally problematic access to the belt-like deposits they usually occur in. Table 1 describe some typical lithium-bearing minerals and their characteristics. Australia is currently the world's largest producer of lithium from minerals, mainly from spodumene [39]. Petalite is commonly used for glass manufacture due to its high iron content, while lepidolite was earlier used as a lithium source but presently has lost its importance due to high fluorine content. Exploitation must generally be tailor-made for a certain mineral as they differ quite significantly in chemical composition, hardness and other properties [13]. Table 2 presents some mineral deposits and their properties.

Table 1. *General characteristics of Li-bearing minerals. Amblygonite, Eucryptite, lepidolite, petalite, spodumene and zinnwaldite are pegmatites while hectorite and jadarite are more claylike minerals.*

Name	Formula	Li content [%]	Hardness [Moh grades]	Density [g/cm^3]
Amblygonite	$(Li,Na)AlPO_4(F,OH)$	3.44	5.5–6	3.0–3.1
Eucryptite	$LiAlSiO_4$	5.51	6.5	2.6–2.7
Hectorite	$Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$	0.53	1–2	2.5
Jadarite	$LiNaSiB_3O_7(OH)$	3.16	4–5	2.5
Lepidolite	$KLi_2Al(Al,Si)_3O_{10}(F,OH)_2$	3.58	2.5–3	2.8–2.9
Petalite	$LiAlSi_4O_{10}$	2.09	6–6.5	2.4–2.5
Spodumene	$LiAlSi_2O_6$	3.73	6.5–7	3.1–3.2
Zinnwaldite	$KLiFe^{2+}Al(AlSi_3)O_{10}(F,OH)_2$	1.59	3.5–4	2.9–3.0

Recovery rates for mining typically range from 60 to 70%, although significant treatment is required for transforming the produced Li into a marketable form. For example, [40, 41] describe how lithium are produced from spodumene. The costs of acid, soda ash, and energy are a very significant part of the total production cost but may be partially alleviated by the market demand for the sodium sulphate by-products [42]. The spodumene treatment chain is short, requiring roughly five days, and can be constantly productive throughout the year [13].

Table 2. *Properties for known lithium mineral deposits.*

Country	Deposit	Main mineral	Li content [%]	Estimated reserves [Mt]		Estimated resources [Mt]	
				Min	*Max*	*Min*	*Max*
Afghanistan	Helmand Basin	Spodumene	n.a	n.a	n.a	n.a	n.a
Afghanistan	Katawaz Basin	Spodumene	n.a	n.a	n.a	n.a	n.a
Afghanistan	Parun	Spodumene	1.5	n.a	n.a	n.a	n.a
Afghanistan	Taghawkor	Spodumene	1.7–2.8	n.a	n.a	n.a	n.a
Australia	Greenbushes	Spodumene	1.9	0.1	0.6	0.3	0.7
Australia	Mt Marion	Spodumene	0.65	n.a	n.a	0.02	0.02
Australia	Mt Cattlin	Spodumene	0.5	n.a	n.a	0.07	0.07
Austria	Koralpe	Spodumene	0.78	0.1	0.1	0.1	0.1
Brazil	Aracuai / Cachoeira	Petalite	n.a	n.a	n.a	0.01	0.023
Brazil	Mibra / Minas Gerais	Spodumene	n.a	0.1	0.1	0.1	0.9
Canada	Barraute / Quebec	Spodumene	0.23–0.53	n.a	n.a	0.1	0.37
Canada	Bernic Lake / Tanco	Spodumene	0.64–1.28	0.02	0.02	0.1	0.14
Canada	Big Bird / Curlew	Spodumene	1.24–1.72	n.a	n.a	n.a	n.a
Canada	English River Greenstone	Spodumene	n.a	n.a	n.a	n.a	n.a
Canada	FI	Pegmatites	n.a	n.a	n.a	0.03	0.03
Canada	Gods Lake	Spodumene	n.a	n.a	n.a	0.025	0.025
Canada	James Bay / Lithium One	Pegmatites	n.a	n.a	n.a	0.13	0.13
Canada	La Corne	Spodumene	0.52	0.1	0.2	0.1	0.4
Canada	La Motte	Spodumene	0.5	n.a	n.a	0.023	1.023
Canada	McAvoy	Spodumene	3.3–4.5	n.a	n.a	n.a	n.a
Canada	Moblan	Spodumene	1.7	n.a	n.a	0.04	0.04
Canada	Moose 2	Spodumene	n.a	n.a	n.a	0.016	0.016
Canada	Nama Creek	Pegmatites	n.a	n.a	n.a	0.01	0.01
Canada	Niemi Lake	Spodumene	n.a	n.a	n.a	0.001	0.001
Canada	Separation Rapids	Petalite	0.62	n.a	n.a	0.05	0.072
Canada	Sirmac Lake	Pegmatites	n.a	n.a	n.a	0.003	0.003
Canada	Snow Lake	Pegmatites	n.a	n.a	n.a	0.026	0.026
Canada	Thompson Brothers	n.a	n.a	n.a	n.a	0.026	0.026
Canada	Thor	Pegmatites	n.a	n.a	n.a	0.02	0.02
Canada	Violet	Pegmatites	n.a	n.a	n.a	0.01	0.01
Canada	Wekusko Lake	Spodumene	0.79	n.a	n.a	0.028	0.028
Canada	Yellowknife	Spodumene	0.66	0.1	0.1	0.1	0.13
China	Daoxian	Lepidolite	0.55	0.1	0.1	0.18	0.2
China	Gajika	Spodumene	n.a	0.3	0.3	0.56	0.6
China	Hupei	Petalite	n.a	n.a	n.a	0.042	0.042
China	Lijiagou	Petalite	n.a	n.a	n.a	0.06	0.06
China	Jaijika	Spodumene	0.6	0.2	1.2	0.2	0.5
China	Jinchuan	Petalite	n.a	n.a	n.a	n.a	n.a
China	Maerkang	Spodumene	n.a	0.1	0.2	0.2	0.5
China	Ningdu	Petalite	n.a	n.a	n.a	n.a	n.a
China	Yichun	Lepidolite	2.0	0.2	0.2	0.3	0.5
Congo	Kitotolo	Spodumene	0.6	n.a	n.a	0.8	0.8
Congo	Manono	Spodumene	0.6	1.2	1.5	1	3
Finland	Länttä	Spodumene	0.43	0.35	0.35	0.01	0.68
Mali	Bougouni	Amblygonite	1.4	n.a	n.a	0.03	0.03
Portugal	Barroso	Petalite	0.37–0.72	n.a	n.a	0.01	0.01
Namibia	Karibib	Petalite	0.93–1.4	n.a	n.a	0.012	0.15
Russia	Achivansky / Uchastok	Pegmatites	n.a	n.a	n.a	0.05	0.05
Russia	Alahinskoe	Spodumene	n.a	n.a	n.a	n.a	n.a
Russia	Belerechenskoe	Spodumene	n.a	n.a	n.a	0.05	0.05
Russia	Belo–Tagninskoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Bolchoi Potchemvarek	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Diturskoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Etykinskoe	Lepidolite	0.23–0.79	n.a	n.a	0.046	0.046
Russia	Goltsovoe	Spodumene	0.37	n.a	n.a	0.14	0.29
Russia	Knyazheskoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Kolmorzerskoe	Pegmatites	n.a	n.a	n.a	0.29	0.84
Russia	Ohmylk	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Oleniy Hrebet	Pegmatites	n.a	n.a	n.a	n.a	n.a

Russia	Olondinskoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Otboninoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Orlovskoe	Lepidolite	n.a	n.a	n.a	0.05	0.05
Russia	Pellapahik	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Podgorskoe	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Pogranichnoe	Pegmatites	n.a	n.a	n.a	0.05	0.05
Russia	Polmostundrovskoe	Pegmatites	n.a	n.a	n.a	0.1	0.4
Russia	Raduga	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Severny Vystup	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Suglugskoe	Spodumene		n.a	n.a	n.a	n.a
Russia	Tala	Pegmatites	n.a	n.a	n.a	n.a	n.a
Russia	Ulug-Tanzek	Pegmatites	n.a	n.a	n.a	0.1	0.3
Russia	Urikskoe	Spodumene	n.a	n.a	n.a	0.1	0.3
Russia	Tastyg	Spodumene	1.86	n.a	n.a	0.05	0.05
Russia	Vishnyakovskoe	Pegmatites	0.49	n.a	n.a	0.05	0.21
Russia	Voronietundrovskoe	Spodumene	n.a	n.a	n.a	0.05	0.82
Russia	Voznesenskoe	Pegmatites	n.a	n.a	n.a	0.05	0.14
Russia	Zavitinskoe	Spodumene		n.a	n.a	0.05	0.14
Serbia	Jadar Valley	Jadarite	0.84	0.4	0.5	0.9	1
Spain	Mina Feli	Lepidolite	0.5	n.a	n.a	0.005	0.005
Sweden	Järkvissle	Spodumene	0.45	n.a	n.a	0.003	0.003
Sweden	Varuträsk	Spodumene	n.a	n.a	n.a	0.001	0.001
USA	Bessemer City	Pegmatites	0.67	n.a	n.a	0.42	0.42
USA	Kings Mountain Belt	Spodumene	0.68	n.a	n.a	0.2	5.9
USA	McDermitt / Kings Valley	Hectorite	0.24–0.53	1	1.1	2	2
USA	North Carolina	Spodumene	n.a	1.2	1.6	2.6	5.5
Zimbabwe	Barkam	Pegmatites	n.a	n.a	n.a	0.22	0.22
Zimbabwe	Bikita	Spodumene	0.58–1.4	n.a	n.a	0.06	0.17
Zimbabwe	Kamativi	Spodumene	0.28	n.a	n.a	0.28	0.28
Zimbabwe	Masvingo	Spodumene	n.a	n.a	n.a	0.057	0.057
TOTAL	-	-	-	**5.57**	**8.17**	**12.814**	**30.677**

2.2.2 Lithium brine deposits

Lithium can also be found in salt lake brines that has high concentrations of mineral salts. Such brines can be reachable directly from the surface or deep underground in saline expanses located in very dry regions that allow salts to persist. High concentration lithium brine is mainly found in high altitude locations such as the Andes and south-western China. Chile, the world largest lithium producer, derives most of the production from brines located at the large salt flat of Salar de Atacama.

Lithium has similar ionic properties as magnesium since their ionic size is nearly identical; making is difficult to separate lithium from magnesium. Equation 1 describes the magnesium-lithium ratio (Mg/Li ratio) which is an important attribute of brine deposits [43, 44]. In contrast, this ratio has little impact for exploitation of lithium minerals [14, 45]. Magnesium prevents lithium chloride to be formed, which is the first step towards forming the desired end product of lithium carbonate [46]. A low Mg/Li ratio in brine means that it is easier, and therefore more economical to extract lithium. The ratio differs significant at currently producing brine deposits and range from less than 1 to over 30 [14]. The lithium concentration in known brine deposits is usually quite low and range from 0.017–0.15% with significant variability among the known deposits in the world (Table 3).

$$Mg/Li\ ratio = \frac{Number\ of\ magnesium\ ions}{Number\ of\ lithium\ ions} \qquad (1)$$

Exploitation of lithium brines starts with brine being pumped from the ground into evaporation ponds. The actual evaporation is enabled by incoming solar radiation, why it is desirable that the operation is located in sunny areas with low annual precipitation rate. The net evaporation rate determines the area of the required ponds [42]. It can easily take between one and two years before the final product is ready to be used, but certain places submitted to the effects or winter or high precipitation can take even longer. The long timescales required for production can make brine deposits ill fit for sudden changes in demand.

Table 3. *Properties of known brine deposits in the world.*

Country	Deposit	Li conc. [%]	Mg conc. [%]	Mg/Li ratio	Estimated reserves [Mt]		Estimated resources [Mt]	
					Min	*Max*	*Min*	*Max*
Argentina	Cauchari	0.062	0.18	2.84	0.5	0.5	0.9	0.9
Argentina	Diablillos	n.a	n.a	n.a	n.a	n.a	0.9	0.9
Argentina	Olaroz	0.09	0.18	2.00	0.1	0.2	0.2	0.3
Argentina	Rincon	0.04	0.34	8.50	0.3	1.4	0.5	2.8
Argentina	Salar del Hombre Muerto	0.062	0.089	1.46	0.4	0.85	0.8	0.9
Argentina	Sal de Vida	n.a	n.a	n.a	n.a	n.a	0.3	0.3
Bolivia	Salar de Uyuni	0.096	2.0	20.83	0.6	3.6	5.5	10.2
Canada	Beaverhill Lake	n.a	n.a	n.a	n.a	n.a	0.52	0.59
Canada	Fox Creek	0.01	0.1	10.00	0.3	1.3	0.5	0.5
Chile	Maricunga	0.092	0.74	8.00	0.1	0.2	0.2	0.4
Chile	Salar de Atacama	0.14	0.96	6.40	1	16.1	3	35.7
China	Dangxioncuo / DXC	0.045	0.099	0.22	0.1	0.1	0.1	0.2
China	Lake Zabuye	0.097	0.001	0.01	0.7	0.8	1.3	1.5
China	Qaidam/Qinghai/Taijinaier	0.03	1.02	34.00	0.5	1	1	3.3
India	Sua Pan	0.002	n.a	n.a	n.a	n.a	n.a	n.a
Israel	Dead Sea	0.002	3.4	1700	0.9	1.9	2	2
USA	Bonneville Salt Flats	0.004	0.04	100	n.a	n.a	n.a	n.a
USA	Brawley	n.a	n.a	n.a	n.a	n.a	1	1
USA	Great Salt Lake	0.006	0.8	133.33	0.2	0.3	0.5	0.5
USA	Salton Sea	0.022	0.028	1.27	0.3	0.5	1	2
USA	Searles Lake	0.0083	0.034	4.10	n.a	n.a	0.03	0.03
USA	Clayton Valley / Silver Peak	0.03	0.04	1.33	0.04	0.1	0.3	0.3
USA	Smackover	0.038	0.75	20.00	0.5	0.5	0.75	1
TOTAL	**-**	**-**	**-**	**-**	**6.54**	**29.35**	**21.3**	**65.32**

2.2.3 Lithium from sea water

The world's oceans contain a wide number of metals, such as gold, lithium or uranium, dispersed at low concentrations. The mass of the world's oceans is approximately $1.35*10^{12}$ Mt [47], making vast amounts of theoretical resources seemingly available. Eckhardt [48] and Fasel and Tran [36] announce that more than 2 000 000 Mt lithium is available from the seas, essentially making it an "*unlimited*" source given its geological abundance. Tahil [20] also notes that oceans have been proclaimed as an unlimited Li-source since the 1970s. The world's oceans and some highly saline lakes do in fact contain very large quantities of lithium, but if it will become practical and economical to produce lithium from this source is highly questionable.

As a useful example, one may consider gold in sea water – in total nearly 7 million metric tons (Mt). This is an enormous amount compared to the cumulative world production of 0.17 Mt accumulated since the dawn of civilization [49]. There are also several technical options available for gold extraction. However, the average gold concentration range from <0.001 to 0.005 ppb [50]. This means that one km^3 of sea water would give only 5.5 kg of gold. The gold is simply too dilute to be viable for commercial extraction and it is not surprising that all attempts to achieve success – including those of the Nobel laureate Fritz Haber – has failed to date.

Average lithium concentration in the oceans has been estimated to 0.17 ppm [14, 36]. Kushnir and Sandén [18] argue that it is theoretically possible to use a wide range of advanced technologies to extract lithium from seawater – just like the case for gold. However, no convincing methods have been demonstrated this far. A small scale Japanese experiment managed to produce 750 g of lithium metal from processing 4 200 m^3 water with a recovery efficiency of 19.7% [36]. This approach has been described in more detail by others [51–53]. Grosjean et al. [13] points to the fact that even after decades of improvement, recovery from seawater is still more than 10–30 times more costly than production from pegmatites and brines.

It is evident that huge quantities of water would have to be processed to produce any significant amounts of lithium. Bardi [54] presents theoretical calculations on this, stating that a production volume of lithium comparable to present world production (~25 kt annually) would require $1.5*10^3$ TWh of electrical energy for pumping through separation membranes in addition to colossal volumes of seawater. Furthermore, Tahil [20] estimated that a seawater processing flow equivalent to the average discharge of the River Nile – 300 000 000 m^3/day or over 22 times the global petroleum industry flow of 85 million barrels per day – would only give 62 tons of lithium per day or roughly 20 kt per year. Table 4 contains some estimated water consumption volumes. Furthermore, a significant amount of fresh water and hydrochloric acid will be required to flush out unwanted minerals (Mg, K, etc.) and extract lithium from the adsorption columns [20].

Table 4. *Estimated water requirements for an extraction capacity equivalent to 20 000 metric tons of lithium per year derived from seawater and selected salt lakes with maximum and reasonable recovery rates.*

Deposit	Li conc. [ppm]	Mg/Li ratio	Assumed 100% recovery rate [Mt of seawater]	Assumed 30% recovery rate [Mt of seawater]
Dead Sea	10	2000	2000	6 667
Great Salt Lake	400	250	50	167
Seawater	0.17	7000	118 000	392 000

In summary, extraction from seawater appears not feasible and not something that should be considered viable in practice, at least not in an imminent future. A major portion of sound scepticism should accompany all thoughts about rapid developments of large-scale Li-extraction from seawater.

2.3 Estimated lithium availability

From data compilation and analysis of 112 deposits, this study concludes that 15 Mt are reasonable as a reference case for the global reserves in the near and medium term. 30 Mt is seen as a *high case* estimate for available lithium reserves and this number is also found in the upper range in literature. These two estimates are used as constraints in the models of future production in this study.

Estimates on world reserves and resources vary significantly among published studies. One main reason for this is likely the fact that different deposits, as well as different number of deposits, are aggregated in different studies. Many studies, such as the ones presented by the USGS, do not give explicitly state the number of deposits included and just presents aggregated figures on a national level. Even when the number and which deposits that have been used are specified, analysts can arrive to wide different estimates (Table 5).

It should be noted that a trend towards increasing reserves and resources with time can generally be found, in particularly in USGS assessments. Early reports, such as Evans [56] or USGS [59], excluded several countries from the reserve estimates due to a lack of available information. This was mitigated in USGS [73] when reserves estimates for Argentina, Australia, and Chile have been revised based on new information from governmental and industry sources. However, there are still relatively few assessments on reserves, in particular for Russia, and it is concluded that much future work is required to handle this shortcoming.

Gruber et al. [16] noted that 83% of global lithium resources can be found in six brine, two pegmatite and two sedimentary deposits. From our compilation, it can also be found that the distribution of global lithium reserves and resources are very uneven. Three quarters of everything can typically be found in the ten largest deposits (Figure 1 and 2). USGS [12] pinpoint that 85% of the global reserves are situated in Chile and China (Figure 3) and that Chile and Australia accounted for 70 % of the world production of 28 100 tonnes in 2011 [12].

From Table 2 and 3, one can note a significant spread in estimated reserves and resources for the deposits. This divergence is much smaller for minerals (5.6–8.2 Mt) than for brines (6.5–29.4 Mt), probably resulting from the difficulty associated with estimating brine accumulations consistently. Evans [75] also points to the problem of using these frameworks on brine deposits, which are fundamentally different from solid ores.

Table 5. *Comparison of published lithium assessments.*

Reference	Deposits included	Reserves [Mt]	Resources [Mt]
Clarke and Harben (2009) [55]	61	n.a	39.4
Evans (1978) [56]	22*	2.0*	10.6*
Evans (2008) [42]	24	n.a	29.8
Fasel and Tran (2005) [36]	n.a	4–6	9.4–21
Grosjean et al. (2012) [13]	77	n.a	37.1–43.6
Gruber et al. (2012) [16]	103	<19.3	38.7
Kesler et al. (2012) [21]	61	n.a	30.9
Kushnir and Sandén (2012) [18]	n.a	30	n.a
Mohr et al. (2012) [15]	45	23.1	71.3
Rockwood Lithium (2012) [57]	n.a	n.a	>30
SGU (1987) [58]	n.a	8.4	n.a
SQM (2009) [27]	n.a	n.a	56.1
Tahil (2007; 2008) [19, 20]	15	4.6	19.2
USGS (1996) [59]	n.a	2.2	>12.8
USGS (1997) [60]	n.a	2.0	>12.8
USGS (1998) [61]	n.a	3.7	>12.8
USGS (1999) [62]	n.a	3.4	>12.8
USGS (2000) [63]	n.a	3.4	>12.8
USGS (2001) [64]	n.a	3.4	>12.8
USGS (2002) [65]	n.a	3.4	>12.8
USGS (2003) [66]	n.a	4.1	>13.8
USGS (2004) [67]	n.a	4.1	>13.8
USGS (2005) [68]	n.a	4.1	>13.8
USGS (2006) [69]	n.a	4.1	>13.8
USGS (2007) [70]	n.a	4.1	>13.8
USGS (2008) [71]	n.a	4.1	>13.8
USGS (2009) [72]	n.a	4.1	>13.8
USGS (2010) [73]	n.a	9.9	25.5
USGS (2011) [74]	n.a	13	33
USGS (2012) [12]	n.a	13	30
Yaksic and Tilton (2009) [36]	40	29.4	64
This study	**112**	**15**	**65**

* Only data for the western world

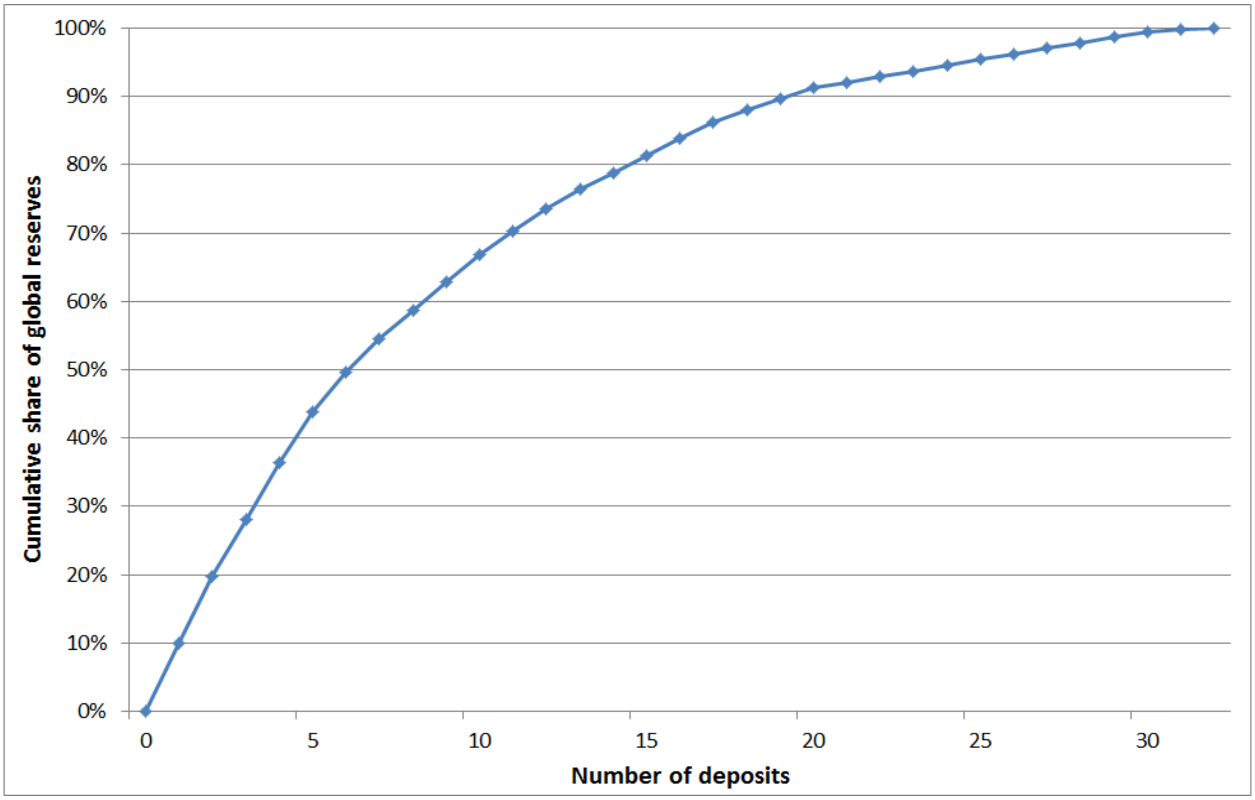

Figure 1. *Cumulative share of global reserves by deposits. The ten largest deposits contain 65% of the known reserves.*

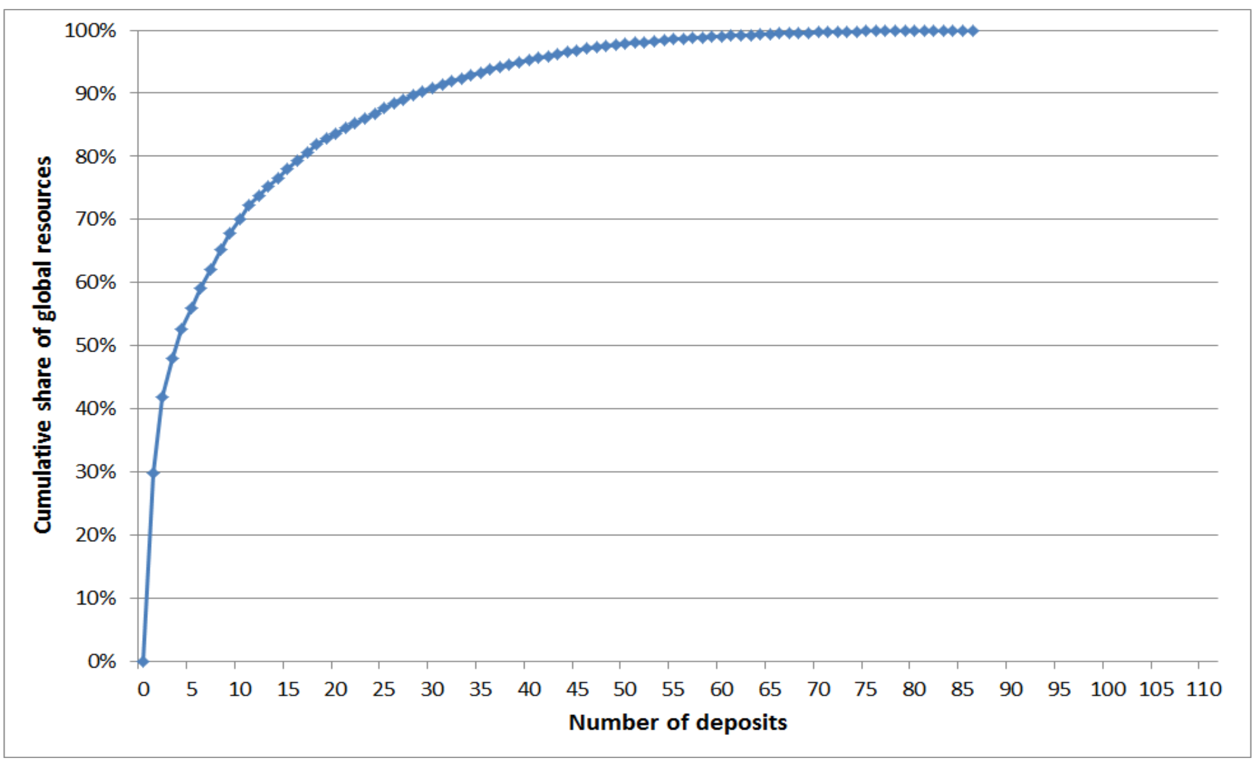

Figure 2. *Cumulative share of global resources by deposits. The ten largest deposits contain 70% of world lithium resources.*

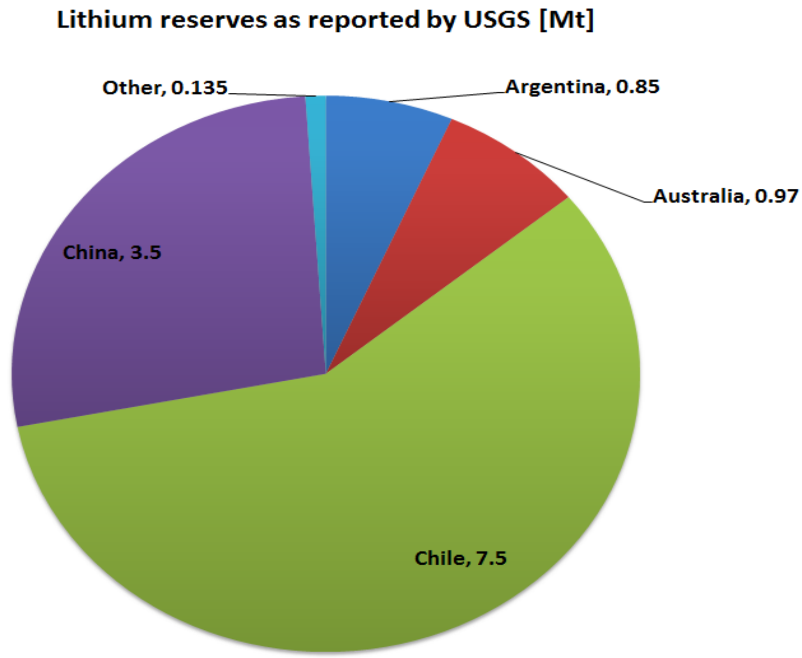

Figure 3. *Lithium reserves by country. Data source: USGS [12]*

3. Lithium production

Lithium production was very limited until 1950s, since its useful applications were poorly understood until after World War II. The U.S was the main lithium producer during the period from the 1950s until the mid-1980s. A few companies exploited hard rock minerals to produce mineral concentrates for the glass and ceramics industry. The German industry conglomerate Chemetall managed to, step by step, buy up all small dispersed mining operations and basically form a monopoly [13]. This likely generated the small but steady price increase seen from 1990 to 1996.

In 1997, lithium production changed dramatically by the emergence of brine operations in Salar de Atacama capable of producing cheap lithium carbonate [76]. The Chilean company SQM quickly became market leaders due to very low production costs, while many pegmatite mines were forced to close. Production bottlenecks in the Chilean salt lake as well as soaring oil prices lead to both dramatic price evolution containing both drops and spikes during the 2000s [13]. Since brine started to dominate the production, the average concentration of lithium metal has decreased considerably in the reported historical gross product production (Figure 4).

It should be mentioned that lithium production can be presented in somewhat different ways. Since 1967 lithium gross production is generally reported as quantities of ore together with ore concentrations from mines and lithium carbonate from brine deposits. As an example, the lithium content in lithium carbonate equivalent is 18.9 %. There are also uncertainties in the reported production. The years 1966–1967 does not include production from Africa. Considering Zimbabwe was the largest lithium producer at that time, production was probably considerably higher [74]. The lithium production in the U.S used to be publicly available, but is classified since 1954 [74]. The production of lithium in the U.S. is estimated by BGS [77] to be about 2000 tons of lithium annually since the year 2000.

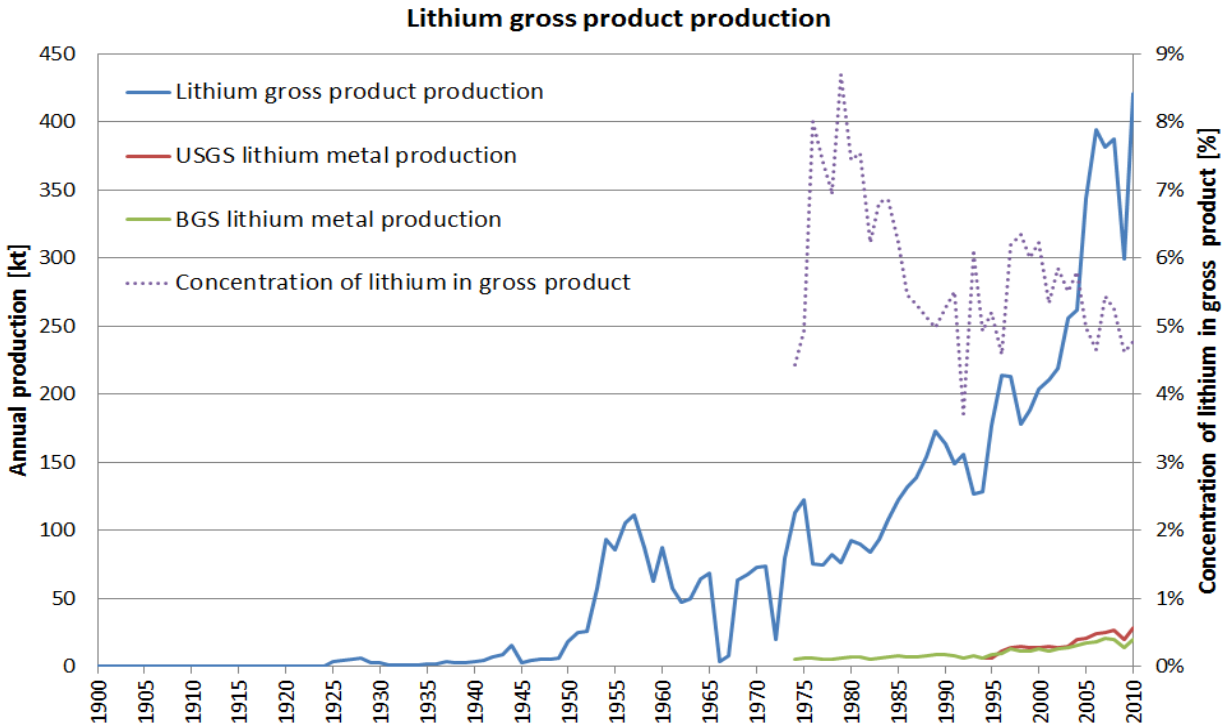

Figure 4. *World lithium production as both metal and gross product. Actual lithium metal is only a very low share of the gross product. Data for lithium metal production can only be found from 1974 from BGS [77] and 1994 from USGS [78].*

3.1 Modelling future production

Many recent papers (i.e. [13, 14, 16, and 36]) primarily consider available lithium inventory (either as reserves or as resources) and compare this with estimated future consumption volumes, without regarding possible or likely production rates. This approach is not adequate to estimate if demanded quantities will be available to society.

All metals and many other natural resources are finite resources in the sense that their deposits are limited either physically, technically or economically. Lithium is no exception from this and, consequently, future production will ultimately be limited by the amounts that are geologically, technically, and economically available. The upper limit to cumulative production, often called the ultimately recoverable resources (URR), is hard to quantify exactly and one should always keep in mind that this figure may change with time. Even though the actual URR may be unknown, or at least uncertain, it is perfectly defined to end up somewhere below the geologically occurring lithium resources. Future production is also bound by the URR as the ultimate cumulative production never can be larger than the quantity of the recoverable resource initially present. This can be boiled down into two fundamental assumptions:

(1) *For any production curve, two points on the curve are known at the outset, namely that at $t = 0$ and again at $t = \infty$. The production rate will be zero when the reference time is zero (i.e. before extraction has started) and the production rate will again be zero when the resource is fully exhausted. Between these points, production rate will pass through one or several maxima.*

(2) *The fundamental theorem of integral calculus states that if there exists a single-valued function $y = f(x)$, then the area between the curve $y = f(x)$ and the x-axis from the origin out to the distance x_1 can be expressed as A:*

$$\int_0^{x_1} y\, dx = A \tag{2}$$

If the production curve is plotted against time, the following will also hold:

$$P = \frac{dQ}{dt}, \tag{3}$$

Where dQ is the quantity of the resource produced at time dt and, from Equation 2, the area under the production curve up to any time t can now be expressed as follows:

$$A = \int_0^t P\, dt = \int_0^t \left(\frac{dQ}{dt}\right) dt = Q \tag{4}$$

where Q denotes the cumulative production up to the time t. The ultimate production can be represented on a graph of production-versus-time as the total area beneath the curve or expressed as:

$$Q_{max} = \int_0^\infty P\, dt, \tag{5}$$

If one has a suitable estimate of the available lithium resources, a family of arbitrary production curves can be drawn, where all would exhibit the common property of beginning at zero and ending at zero, and encompassing an equal area limited by available recoverable resources. Even though this framework is plausible and can be applied to all finite resources, it remains quite arbitrary as no functional form for the production curve can be obtained and applied for extrapolation.

Hubbert [79, 80] was among the first who investigated historically occurring production patterns for certain finite resources – in this case petroleum – and found that it approximated a logistic curve reasonably well, although he also discussed curves with several peaks (i.e. multicyclic behaviour). This was successfully combined with good URR estimates and used to predict the peak in US oil production in 1970. Further refinement and analysis of this methodology has been done by others [81–84].

Bardi [85] showed that mineral production almost always results in bell-shaped curves, in the same way that has been observed for petroleum. This was expanded upon by Cordell [86] using phosphorous as an example, while May et al. [87] reviewed the concept of peak minerals from both a theoretical and practical perspective. As a practical application for a solid resource, the use of logistic curves and their relatives has been shown to agree with observed coal production patterns and proved useful for forecasting [32, 33, 88]. Mohr et al. [89] also found that logistic curves agree well with real world mineral exploitation behaviour and that it could be used to portray a free-market situation with supply-demand interactions. Other curve types, such as Gaussian, Gompertz, and many other shapes, have also been used for modelling production of both liquid and solid energy sources [90].

Related approaches for lithium have already been used by Kushnir and Sandén [18] who used a logistic curve for future lithium production. However, they decided to only use the logistic curve for minerals, while not using it for brines for unclear reasons. Given the fact that functional curve fits have been shown to be plausible models for both solid and liquid products, this study will use such models for both brine and minerals. As models, the different curve types are used to reduce the dependence of the function used for fitting (Table 6). Both Gompertz and Logistic functions are actually special cases of the more general Richards model and this is described in more detail in [90].

Table 6. *Mathematical description of the models used. URR denotes the ultimately recoverable resources, k is a growth factor, t_0 is the peak year, while M is an exponent used in the Richards curve. If M < 0, the first sign is positive. If M > 0, the first sign is negative.*

Model	Functional form
Logistic	$q(t) = \frac{\text{URR}}{1 + e^{-k(t-t_0)}}$
Richards	$q(t) = URR(1 \pm e^{(\mp k(t-t_0))})^M$
Gompertz	$q(t) = URRe^{(-e^{-k(t-t_0)})}$

It is also possible to add a maximum allowed depletion rate to avoid unreasonable production rates. The *depletion rate of remaining recoverable resources*, denoted $d_{RRR,t}$, describes how fast the reserves are extracted and can be expressed as an annual percentage produced of the remaining reserves (see Equation 6).

$$d_{RRR,t} = \frac{q_t}{R_r} = \frac{q_t}{URR - Q_t} \tag{6}$$

Where q_t is the annual production at time t, R_r the remaining recoverable reserves, URR equals the ultimately recoverable resources, and Q_t the cumulative production at time t.

It is simply logistically and practically infeasible to extract all the existing resources at once, even though such an enterprise is theoretically possible. Historical experience from mining activities serves as a justification for these limits. For example, the maximum depletion rate for US copper production was 4.3% [78] and the depletion rate for South Africa's gold production was 4.1% [91]. Likewise, studies on coal production have shown typical $d_{RRR,t}$-values of around 3% [33]. Therefore, the models in this study were constrained by an allowed maximum $d_{RRR,t}$ of 5%. This helps avoiding curve fits that are mathematically correct but practically unrealistic with absurdly high depletion rates, far outside the realm of real world mineral exploitation patterns.

Unfortunately, such mechanisms are not grasped by all analysts. For example, a projection made by Wanger [92] claims that global lithium resources are likely to be depleted before 2025. This would necessitate extremely rapid depletion rates far over what has ever been seen in exploitation of other natural resources and cannot be considered realistic. In a similar way, Kushnir and Sandén [18] estimates potential maximum and minimum mine output from mineral lithium resources with a logistic curve with magnitude and time constants and an estimate of mineral reserves of 5.5 Mt. The maximum mine output grows extremely fast and peaks at an output of over 300 kt per year, as soon as around 2025. Also here, extracted volumes of this magnitude would imply largely unrealistic depletion rates.

3.2 Production model results

All models in this study were fitted to historic production data using numerical methods and least squares minimization using the URR as a constraint (Table 7). The URR includes the estimated remaining recoverable resources and the already extracted volume of lithium metal. The historical produced lithium is estimated to be 0.5 Mt, using USGS gross product data and an assumed lithium content of 6%. The model also use a constrained maximum depletion rate of remaining recoverable resources of 5 %, but should be noted that none of the models in this paper actually reaches up to depletion rates of 5 % (Figure 5 and 6).

Table 7. *Assumed URR values used in modelling*

Scenario	**Ultimately Recoverable Resources [Mt]**
Base case	15.5
High case	30.5

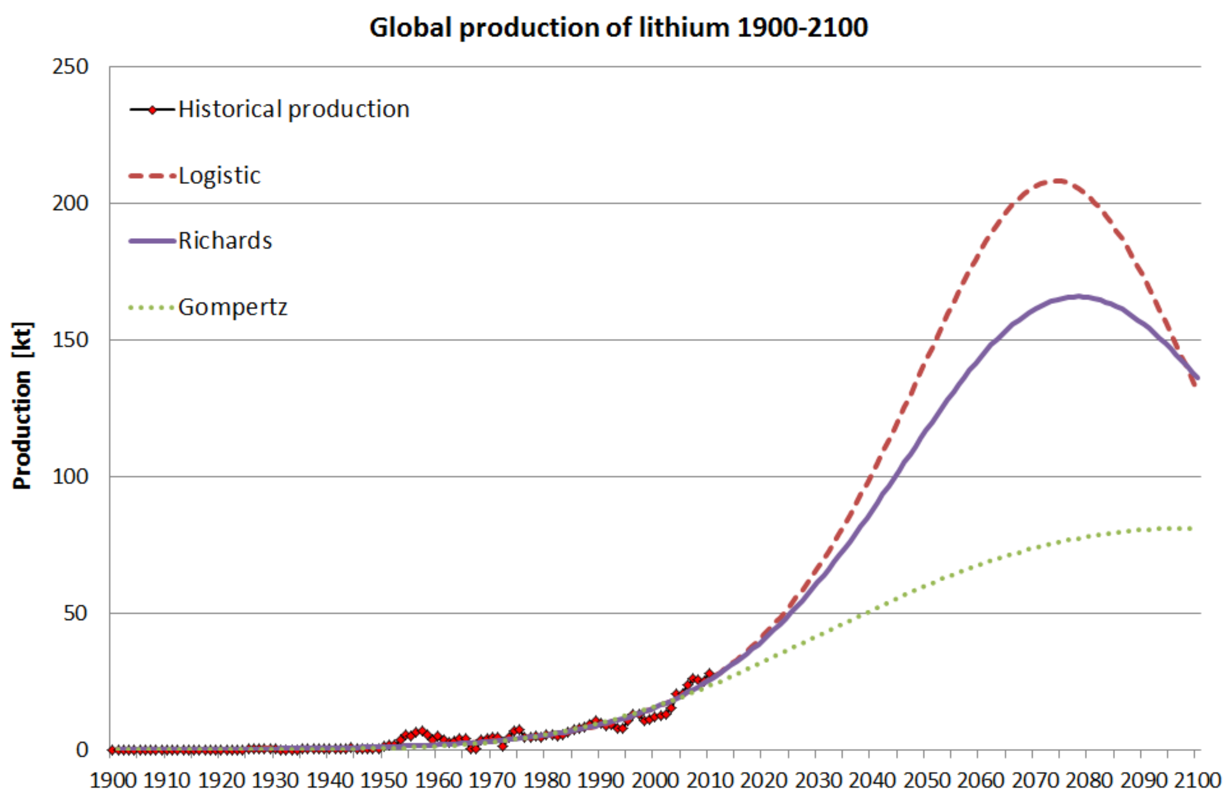

Figure 5. *Projected future lithium production in the base case. Peak production levels occur in 2074 for the Logistic model, 2078 for the Richards model, and 2098 for the Gompertz model.*

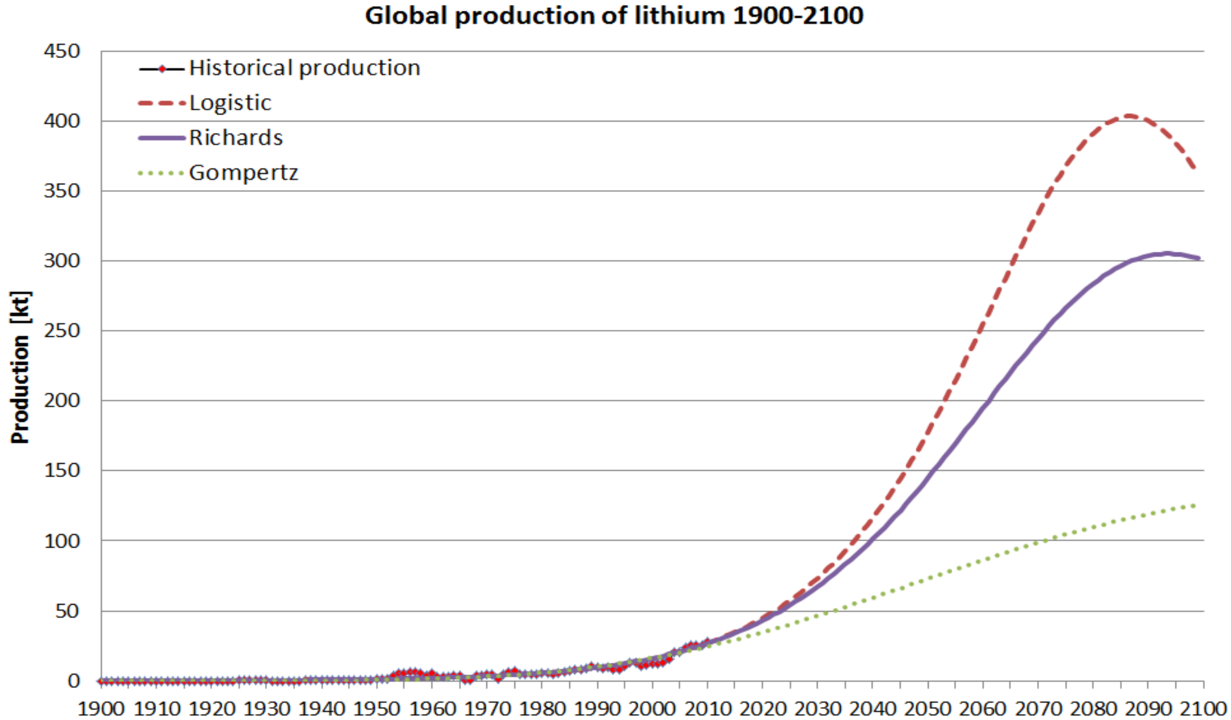

Figure 6. *Projected future lithium production in the high case. The peak production will occur in 2088 for Logistic model, 2095 for the Richards model, and by 2129 for the Gompertz model.*

The estimated peak year and maximum production for the used models can be found in Table 8. One can see that there is a significant future potential for increasing production according to all models as there is still major part of the reserves left for exploitation. The logistic and Richards models yield similar estimates in peak year (only 4-7 years difference), even though they give rather diverse maximum production volumes (26-32% difference). In contrast, the Gompertz curve places the peak year further into the future and also at a remarkably lower maximum production level. A much lower depletion rate is the main cause of this divergence.

Table 8. *Peak year and maximum production in kt of lithium for the different models and cases.*

	Base case			**High case**		
	Logistic	*Gompertz*	*Richards*	*Logistic*	*Gompertz*	*Richards*
Peak year	2074	2098	2078	2088	2129	2095
Maximum production	208	81	165	403	134	305

Mohr et al. [89] found that simple curve fitting models can be good approximations for more realistic models including supply-demand interactions. Especially the logistic model was found to be in good agreement with real world mineral exploitation behaviour. Although the Gompertz curve deviates significantly from the other models, it does not necessarily make it unreasonable. Low depletion rates are something can be caused by factors like political interventions or restricting policies. Grosjean et al. [13] highlights lithium resource nationalization (i.e. Bolivia) and the Gompertz outlooks may be seen as a possible projection of how such events may influence future production.

3.3 Recycling

One thing that may or may not have a large implication for future production is recycling. The projections presented in the production model of this study describe production of lithium from virgin materials. The total production of lithium could potentially increase significantly if high rates of recycling were implemented of the used lithium, which is mentioned in many studies.

USGS [12] state that recycling of lithium has been insignificant historically, but that it is increasing as the use of lithium for batteries are growing. However, the recycling of lithium from batteries is still more or less non-existing, with a collection rate of used Li-ion batteries of only about 3% [93]. When the Li-ion batteries are in fact recycled, it is usually not the lithium that is recycled, but other more precious metals such as cobalt [18]. If this will change in the future is uncertain and highly dependent on future metal prices, but it is still commonly argued for and assumed that the recycling of lithium will grow significantly, very soon. Goonan [94] claims that recycling rates will increase from vehicle batteries in vehicles since such recycling systems already exist for lead-acid batteries. Kushnir and Sandén [18] argue that large automotive batteries will be technically easier to recycle than smaller batteries and also claims that economies of scale will emerge when the use for batteries for vehicles increase. According to the IEA [95], full recycling systems are projected to be in place sometime between 2020 and 2030. Similar assumptions are made by more or less all studies dealing with future lithium production and use for electric vehicles and Kushnir and Sandén [18] state that it is commonly assumed that recycling will take place, enabling recycled lithium to make up for a big part of the demand but also conclude that the future recycling rate is highly uncertain.

There are several reasons to question the probability of high recycling shares for Li-ion batteries. Kushnir and Sandén [18] state that lithium recycling economy is currently not good and claims that the economic conditions could decrease even more in the future. Sullivan and Gaines [96] argue that the Li-ion battery chemistry is complex and still evolving, thus making it difficult for the industry to develop profitable pathways. Georgi-Maschler [93] highlight that two established recycling processes exist for recycling Li-ion batteries, but one of them loose most of the lithium in the process of recovering the other valuable metals. Ziemann et al. [97] states that lithium recovery from rechargeable batteries is not efficient at present time, mainly due to the low lithium content of around 2% and the rather low price of lithium.

In this study we choose not to include recycling in the projected future supply for several reasons. In a short perspective, looking towards 2015-2020, it cannot be considered likely that any considerable amount of lithium will be recycled from batteries since it is currently not economical to do so and no proven methods to do it on a large scale industrial level appear to exist. If it would become economical to recycle lithium from batteries it would take time to build a capacity for the recycling to take place. Also, the battery lifetime is often projected to be 10 years or more, and to expect any significant amounts of lithium to be recycled within this period of time is simply not realistic for that reason either. The recycling capacity is expected to be far from reaching significant levels before 2025 according to Wanger [92].

It is also important to separate the recycling rates of products to the recycled content in new products. Even if the percentage of the products is recycled at the end of the life cycle, this is no guarantee that the use of recycled content in new products will be as high. The use of Li-ion batteries is projected to grow fast. If the growth would happen linearly, in time if high recycling rates are accomplished, recycling could start constituting a large part of the lithium demand, but if the growth happens exponentially, recycling can never keep up with the growth that has occurred during the 10 years lag during the battery lifetime.

In a longer time perspective, the inclusion of recycling could be argued for with expected technological refinement, but uncertainties regarding technology development are highly uncertain. Still, most studies include recycling as a major part of future lithium production, which can have very large implications on the results and conclusions drawn. Kushnir and Sandén [18] suggest that an 80% lithium recovery rate is achievable over a medium time frame. The scenarios in Gruber et al. [16], assumes recycling participation rates of 90 %, 96% and 100%. In their scenario using the highest assumed recycling, the quantities of lithium needed to be mined are decreased to only about 37% of the demand. Wanger [92] looks at a shorter time perspective and estimates that a 40% or 100% recycling rate would reduce the lithium consumption with 10% or 25% respectively by 2030. Mohr et al. [15] assume that the recycling rate starts at 0%, approaching a limit of 80%, resulting in recycled lithium making up significant parts of production, but only several decades into the future. IEA [95] projects that full recycling systems will be in place around 2020–2030. The impact of assumed recycling rates can indeed be very significant, and the use of this should be handled with care and be well motivated.

4. Future demand for lithium

To estimate whether the projected future production levels will be sufficient, it is interesting to compare possible production levels with potential future demand. The use of lithium is currently dominated by use for ceramics and glass closely followed by batteries. The current lithium demand for different markets can be seen in Figure 7. USGS [12] state that the lithium use in batteries have grown significantly in recent years as the use of lithium batteries in portable electronics have become increasingly common.

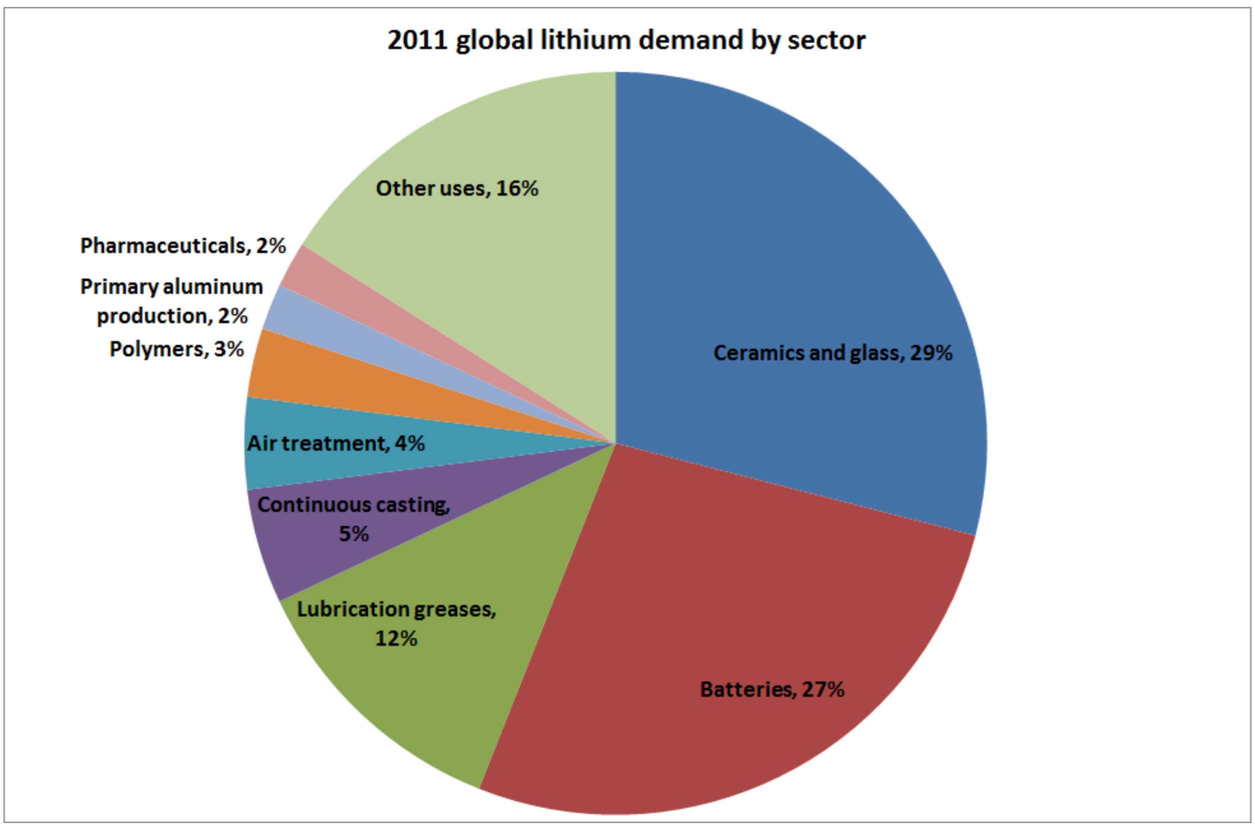

Figure 7. *Global lithium demand for different end-use markets. Source: USGS [12]*

USGS [12] state that the total lithium consumption in 2011 was between 22,500 and 24,500 tonnes. This is often projected to grow, especially as the use of Li-ion batteries for electric cars could potentially increase demand significantly. This study presents a simple example of possible future demand of lithium, assuming a constant demand for other uses and demand for electric cars to grow according to a scenario of future sales of electric cars.

The current car fleet consists of about 600 million passenger cars. The sale of new passenger cars in 2011 was about 60 million cars [98]. This existing vehicle park is almost entirely dependent on fossil fuels, primarily gasoline and diesel, but also natural gas to a smaller extent. Increasing oil prices, concerns about a possible peak in oil production and problems with anthropogenic global warming makes it desirable to move away from fossil energy dependence. As a mitigation and pathway to a fossil-fuel free mobility, cars running partially or totally on electrical energy are commonly proposed. This includes electric vehicles (EVs), hybrid vehicles (HEVs) and PHEVs (plug-in hybrid vehicles), all on the verge of large-scale commercialization and implementation. IEA [99] concluded that a total of 1.5 million hybrid and electric vehicles had been sold worldwide between the year 2000 and 2010.

Until now, nickel-metal hydride (NiMH) cells have been the dominating battery type in electrified cars. Wilburn [100] estimate that use NiMH batteries are used in 95% of all hybrid vehicles. Lithium-based cells, such as Li-ion batteries, are lighter and offer several advantages in comparison, such as higher efficiency and lower weight. Gruber et al. [16] expect Li-ion batteries to dominate future car battery implementations. Although predicting future trends is challenging, several outlooks for future development of EVs, HEVs and PHEVs have been made by agencies and analysts with widely different outcomes. In this study, the blue map scenario from IEA [101] regarding alternative vehicles is used to visualize potential demand volumes caused by Li-ion battery usage.

Both the expected number of cars as well as the amount of lithium required per vehicle is important. As can be seen from Table 9, the estimates of lithium demand for PEHV and EVs differ significantly between studies. Also, some studies do not differentiate between different technical options and only gives a single Li-consumption estimate for an "*electric vehicle*", for instance the 3 kg/car found by Mohr et al. [15]. The mean values from Table 9 are found to be 4.9 kg for an EV and 1.9 kg for a PHEV.

Table 9. *Estimates of needed lithium amounts for alternative vehicle batteries. Kushnir and Sandén [18] have a detailed description about lithium content in different batteries, and use an estimate of 160 g Li/kWh, and a 9 kWh battery for a PHEV and a 36 kWh battery for an EV.*

Reference	**EV [kg]**	**PHEV [kg]**
Falås and Troeng (2010) [102]	2.7–4.3	1.2–2.0
Gruber et al. (2012) [16]	5.1–7.7	1.5–2.3
JOGMEC (2009) [103]	2.8–5.7	1.4–3.1
Kushnir and Sandén (2012) [18]	5.8	1.4
Mean value	4.9	1.9

As the battery size determines the vehicles range, it is likely that the range will continue to increase in the future, which could increase the lithium demand. On the other hand, it is also reasonable to assume that the technology will improve, thus reducing the lithium requirements. In this study a lithium demand of 160 g Li/kWh is assumed, an assumption discussed in detail by

Kushnir and Sandén [18]. It is then assumed that typical batteries capacities will be 9 kWh in a PHEV and 25 kWh in an EV. This gives a resulting lithium requirement of 1.4 kg for a PHEV and 4 kg for an EV, which is used as an estimate in this study. Many current electrified cars have a lower capacity than 24 kWh, but to become more attractive to consumers the range of the vehicles will likely have to increase, creating a need for larger batteries [104]. It should be added that the values used are at the lower end compared to other assessments (Table 9) and should most likely not be seen as overestimates future lithium requirements.

USGS [12] claims that the lithium consumption was projected to be between 22 500 and 24 500 tonnes in 2011, similar to the figure in 2010, according to industry analysts. Figure 8 shows the span of the different production forecasts up until 2050 made in this study, together with an estimated demand based on the demand staying constant on the high estimate of 2010–2011, adding an estimated demand created by the electric car projections done by IEA [101]. This is a very simplistic estimation future demand, but compared to the production projections it indicates that lithium availability should not be automatically disregarded as a potential issue for future electric car production. The amount of electric cars could very well be smaller or larger that this scenario, but the scenario used does not assume a complete electrification of the car fleet by 2050 and such scenarios would mean even larger demand of lithium. It is likely that lithium demand for other uses will also grow in the coming decades, why total demand might increase more that indicated here. This study does not attempt to estimate the evolution of demand for other uses, and the demand estimate for other uses can be considered a conservative one.

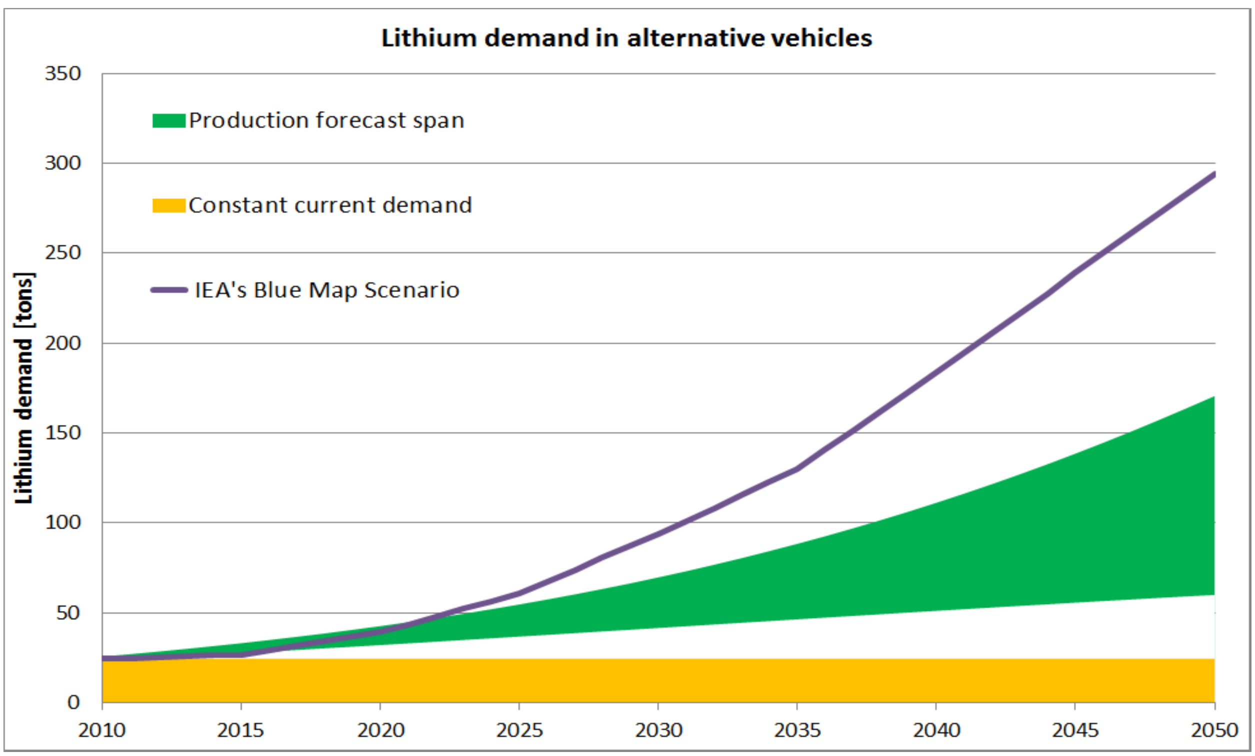

Figure 8. *The total lithium demand of a constant current lithium demand combined with growth of electric vehicles according to IEA's blue map scenario [101] assuming a demand for 1.4 kg of lithium per PHEV and 4.0 kg per EV. The span of forecasted production levels range from the base case Gompertz model to the high case logistic model.*

While the production forecasts are made over a longer period, to be able to see the estimated peak years, the demand forecast is only made towards 2050. This is done partly because we base our demand from cars totally on IEA Blue Map Scenarios, but also due to the fact that estimates of available technology used for transportation on the century level appears like more like prophesies than actual forecasts.

5. Concluding discussions

Potential future production of lithium was modelled with three different production curves. In a short perspective, until 2015–2020, the three models do not differ much, but in the longer perspective the Richards and Logistic curves show a growth at a vastly higher pace than the Gompertz curve. The Richards model gives the best fit to the historic data, and lies in between the other two and might be the most likely development. A faster growth than the logistic model cannot be ruled out, but should be considered unlikely, since it usually mimics plausible free market exploitation [89]. Other factors, such as decreased lithium concentration in mined material, economics, political and environmental problems could also limit production.

It can be debated whether this kind of forecasting should be used for short term projections, and the actual production in coming years can very well differ from our models, but it does at least indicate that lithium availability could be a potential problem in the coming decades. It should be added that these projections does not consider potential recycling of the lithium, which is discussed further earlier in this paper. On the other hand, it appears like it is highly unlikely that recycling will become common as soon as 2020, while total demand appears to potentially rise over maximum production around that date. If, when, and to what extent recycling will take place is hard to predict, although it appears more likely that high recycling rates will take place in electric cars than other uses.

As can be seen in Figure 8, it appears like the demand for lithium for electric cars at the rate proposed by the EIA [101] appears to rise over the highest of the production scenarios presented in this study, as soon as 2021, according to our assumptions. This is based on the amount of electric cars are sold as proposed in the EIA Blue Map scenario, assuming that half the cars are EVs using 4 kg of lithium and half are PHEVs using 1.4 kg of lithium while the demand for other uses than batteries for cars stays constant. The demand for other uses will very likely continue to increase as well, why the demand projection could be seen as conservative. To project future demand is highly uncertain, why this study relies on investigating if IEAs proposed electric vehicles sales can be realized according to some of our assumptions. It should be noted that the IEA Blue Map scenario only projects electric cars to make up 60% of the annual sales by 2050, why this demand projection is likely not on the high side concerning the amount of electric cars sold.

In a longer time perspective, reaching until 2050 the projected lithium demand for alternative vehicles far exceeds our most optimistic production prognoses. However, this is projections far in to the future and much can change during this time. The spread between the different production curves are much larger and it is hard to estimate what happens with technology over such a long time frame. However, the Blue Map Scenario would in fact create a demand of lithium that is higher than the peak production of the logistic curve for the standard case, and close to the peak production in the high URR case. If 100 million alternative vehicles, as projected in IEA [101] are produced annually using lithium battery technology, the lithium reserves would be exhausted in just a few years, even if the production could be cranked up faster than the models in this study. This indicates that it is important that other battery technologies should be investigated as well.

It is important to acknowledge that much can in fact happen in battery technology until 2050. Improved efficiency can decrease the lithium demand in the batteries, but as Kushnir and Sandén [18] point out, there is a minimum amount of lithium required tied to the cell voltage and chemistry of the battery. IEA [95], projects that batteries will continue to improve and that a new generation of batteries will outperform lithium-ion batteries before 2040. How likely this is, is hard to estimate, but it could have implications on the projected lithium demand in the longest time perspective until 2050. IEA [95] acknowledges that technologies that are not available today must be developed to reach the Blue Map scenarios and that technology development is uncertain. This does not quite coincide with other studies claiming that lithium availability will not be a problem for production of electric cars in the future. In the shorter perspective until 2030, it is very likely that lithium-ion technology will be the dominating battery type for EVs and PHEVs.

It is also possible that other uses will raise the demand for lithium even further. One industry that in a longer time perspective could potentially increase the demand for lithium is fusion, where lithium is used to breed tritium in the reactors. If fusion were commercialized, which currently seems highly uncertain, it would demand large volumes of lithium [36].

There are naturally arguments against the kind of modelling used for estimating future production of lithium in this study. One common argument that is often mentioned is the uncertainty of the URR. A potentially larger URR, and the fact that it could potentially grow in the future, with improving technology and rising prices, could potential give higher production rates. To investigate the importance of this, one best guess base case estimate of the URR was used, but also one that is twice this value. In the near future the projections do not differ much, even with a doubling of the URR. In a time perspective towards 2015 and 2035 a doubling of the estimated URR, reaching close to the highest current estimates, does not appear to change the production estimated with the models in a significant way. On a longer time perspective, on the other hand, a larger URR makes the peak production significantly higher.

Further problems with the lithium industry are that the production and reserves are situated in a few countries. One can also note that most of the lithium is concentrated to a fairly small amount of deposits, nearly 50% of both reserves and resources can be found in Salar de Atacama alone. Kesler et al. [21] note that Argentina, Bolivia, Chile and China hold 70% of the brine deposits. Grosjean et al. [13] even points to the *ABC triangle* (i.e. Argentina, Bolivia and Chile) and its control of well over 40% of the world resources and raises concern for resource nationalism and monopolistic behaviour. Even though Bolivia has large resources, there are many political and technical problems, such as transportation and limited amount of available fresh water, in need of solutions [18].

Regardless of global resource size, the high concentration of reserves and production to very few countries is not something that bode well for future supplies. The world is currently largely dependent on OPEC for oil, and that creates possibilities of political conflicts. The lithium reserves are situated in mainly two countries. It could be considered problematic for countries like the US to be dependent on Bolivia, Chile and Argentina for political reasons [105]. Abell and Oppenheimer [105] discuss the absurdity in switching from dependence to dependence since resources are finite. Also, Kushnir and Sandén [18] discusses the problems with being dependent on a few producers, if a problem unexpectedly occurs at the production site it may not be possible to continue the production and the demand cannot be satisfied.

5.1 Final remarks

Although there are quite a few uncertainties with the projected production of lithium and demand for lithium for electric vehicles, this study indicates that the possible lithium production could be a limiting factor for the number of electric vehicles that can be produced, and how fast they can be produced. If large parts of the car fleet will run on electricity and rely on lithium based batteries in the coming decades, it is possible, and maybe even likely, that lithium availability will be a limiting factor. To decrease the impact of this, as much lithium as possible must be recycled and possibly other battery technologies not relying on lithium needs to be developed.

It is not certain how big the recoverable reserves of lithium are in the world and estimations in different studies differ significantly. Especially the estimations for brine need to be further investigated. Some estimates include production from seawater, making the reserves more or less infinitely large. We suggest that it is very unlikely that seawater or lakes will become a practical and economic source of lithium, mainly due to the high Mg/Li ratio and low concentrations if lithium, meaning that large quantities of water would have to be processed. Until otherwise is proved lithium reserves from seawater and lakes should not be included in the reserve estimations. Although the reserve estimates differ, this appears to have marginal impact on resulting projections of production, especially in a shorter time perspective. What are limiting are not the estimated reserves, but likely maximum annual production, which is often missed in similar studies.

If electric vehicles with li-ion batteries will be used to a very high extent, there are other problems to account for. Instead of being dependent on oil we could become dependent on lithium if li-ion batteries, with lithium reserves mainly located in two countries. It is important to plan for this to avoid bottlenecks or unnecessarily high prices.

Lithium is a finite resource and the production cannot be infinitely large due to geological, technical and economical restraints. The concentration of lithium metal appears to be decreasing, which could make it more expensive and difficult to extract the lithium in the future. To enable a transition towards a car fleet based on electrical energy, other types of batteries should also be considered and a continued development of battery types using less lithium and/or other metals are encouraged. High recycling rates should also be aimed for if possible and continued investigations of recoverable resources and possible production of lithium are called for.

Acknowledgements

We would like to thank Steve Mohr for helpful comments and ideas. Sergey Yachenkov has our sincerest appreciation for providing assistance with translation of Russian material.

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