GLOBAL LITHIUM AVAILABILITY:
A CONSTRAINT FOR ELECTRIC VEHICLES?

by

Paul Gruber & Pablo Medina

A practicum submitted in partial fulfillment
of the requirements for the degree of
Master of Science
(Natural Resources and Environment)
at the University of Michigan
April 2010

Faculty advisors:
Professor Gregory Keoleian
Professor Stephen Kesler

Acknowledgements

We would like to thank Dr. Tim Wallington, Environmental Scientist, and Dr. Mark Everson, Risk & Uncertainty Analyst, from Ford Motor Company for their major intellectual and editorial contributions to this study.

Table of Contents

Figures

Tables

Abstract

There is disagreement on whether the supply of lithium is adequate to support a future global fleet of electric vehicles. We report a comprehensive analysis of the global lithium resources and an assessment of the global lithium demand from 2010 to 2100, assuming rapid and widespread adoption of electric vehicles.

Several estimates of global lithium resources have been published recently, and they reach very different conclusions. For this study we compiled data on 103 deposits containing lithium, with an emphasis on the 35 deposits containing more than 100,000 tonnes of lithium. For each deposit, where available, data were compiled on its location, type, area, thickness, grade, porosity, density, quantity of lithium and other recoverable products, evaporation rate (for brines), impurities, and production volume. Lithium demand was estimated under two growth scenarios for electric vehicles and other current battery and non-battery applications.

The global lithium resource is estimated to be over 38 Mt (million tonnes) while the highest demand scenario does not exceed 24 Mt. We conclude that even with a rapid and widespread adoption of electric vehicles powered by lithium-ion batteries the lithium resources are sufficient to support demand until at least 2100.

Introduction

Recognition of the adverse impacts of climate change and the importance of mitigating CO_2 emissions has led to the development of alternative vehicles that have lower CO_2 emissions than those of conventional internal combustion engine vehicles. Vehicle electrification is one strategy being pursued, and the key technologies include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Several studies have demonstrated significant reductions in life cycle greenhouse emissions for electric vehicles, relative to internal combustion engine vehicles, and greater reductions are possible through greater penetration of renewable electricity sources into the grid.[1,2,3] Major automobile companies are pursuing the development of such electrified vehicles and are considering lithium-based batteries to power them.

Lithium, the lightest solid element and a member of the alkali metal group, has a single valence electron which makes it an excellent conductor of electricity and heat.[4] Lithium has a very high energy density by weight, and it does not expand or contract when subjected to temperature changes.[5] Given these electrical and mechanical properties, lithium is used in a myriad of processes, including metal refining, organic synthesis and polymerization, and manufacture of pharmaceuticals, glass, ceramics and batteries.

Compared to nickel metal hydride batteries, the type of battery currently powering most HEVs, lithium-ion (Li-ion) batteries are lighter, 20% less bulky, and more energy efficient. In addition, for production volumes greater than 300,000 units per year, Li-ion batteries are projected to be less expensive.[6] Li-ion battery technology is attractive for future electric vehicles; but, with increasing global population and demand for battery-powered vehicles a debate regarding demand and supply of lithium has been taking place in recent years.

Tahil[7] has claimed that there is insufficient economically recoverable lithium to support a large-scale electric vehicle fleet. This claim has been refuted by Evans.[8,9] Articles by Clarke and Harben,[10] and Yaksic and Tilton[11] show lithium resources higher than the amount reported by Tahil; however, there is a 25% difference between the lithium reserve estimates offered by Clarke and Harben, and Yaksic and Tilton.

This paper assesses lithium deposits and estimates the global lithium resource. We compare this value to two scenarios for lithium demand. These scenarios take all current known uses of lithium and estimate growth in consumption between 2010 and 2100.

Lithium Supply

Research to date on supply

Several estimates of global lithium resources and reserves have been published recently, and they vary significantly as indicated in Table 1.

Table 1. World total lithium resource and reserve estimates (Mt Li).

Li Resources	Deposits Included	Reference	Li Reserves	Deposits Included	Reference
19.2	15	Tahil (2008)	**4.6**	11	Tahil (2008)
25.5	8*	USGS (2010)	**9.9**	8*	USGS (2010)
29.9	24	Evans (2008)	**29.4**	40	Yaksic/Tilton (2009)
64.0	40	Yaksic/Tilton (2009)	**39.4**	61	Clarke/Harben (2009)**

* USGS lists information by country, not deposits.
** Clarke & Harben define their estimate as "broad-based reserves."

The lowest lithium resource estimate, 19.0 Mt (million tonnes) by Tahil (2008),[12] is based on research of primary data sources and secondary meta-studies. Tahil's estimate is lower than others primarily because he only considers 15 deposits throughout the world; he also generally uses conservative estimates for the deposits' sizes than do other authors.

From 2009 to 2010, the USGS significantly increased its estimate of the world's lithium resources from 13.8 Mt to 25.5 Mt of lithium. Its estimate of reserves more than doubled, from 4.1 to 9.9 Mt.[13]

Evans (2008) produces a resource estimate of 29.9 Mt,[9] and like Tahil based this on study of primary research data and secondary meta-studies. Unlike Tahil, Evans generally used the entire deposit's volume when making his estimates, and he included 24 deposits throughout the world.

The highest resource estimate is reported by Yaksic and Tilton (2009),[11] who compiled data on 40 deposits. It is not known which studies Yaksic and Tilton used for estimating the resource at each deposit, specifically. Yaksic and Tilton applied assumptions of recovery rates listed in Table 2 to estimate "recoverable" reserves from different deposit types.

Table 2. Assumed recovery rates by deposit type (% of total Li in deposit). Source: Yaksic and Tilton, 2009.[11]

Type	Recovery rate
Brine	45%
Pegmatite	50%
Sedimentary Rock (Hectorite, Jadarite)	50%

Clarke and Harben (2009) reported the highest reserve estimate (which they call "broad-based reserves"), including 61 deposits. Clarke and Harben are independent geological and mineralogical experts and consultants; they used public and private research, communication with mining companies, and travel to lithium mine sources to compile their estimates. They claimed that deposits containing 28 Mt of the 39.4 Mt of lithium reserves are either in production currently (14.6 Mt Li) or are being developed (13.4 Mt Li).[10]

In the research to date, differences of interpretation about available data and in what can feasibly be extracted have lead to a large variation in estimates of lithium supply. The wide discrepancies between these studies are attributable to:

- different sets of deposits included in each estimate,
- differences in opinion on what constitutes the size and lithium content of the deposits,
- various methods and assumptions,
- differing understanding and use of the terms "resource" and "reserve,"
- changing estimates, as new information is obtained, including deposits' size, concentration of Li, and amenability to mining and processing.

Also, part of the reason for the discrepancies among these estimates is the lack of certified deposits. Only one of the 35 deposits we studied was compliant with National Instrument 43-101, an internationally recognized standard. A portion of Western Lithium's claim at Kings Valley was certified – 233,000 tonnes out of an estimated 2.0 Mt of lithium resource at a cut-off grade of 0.20% lithium.[14] The entire DXC deposit of 181,000 tonnes was NI 43-101 certified.[15] We expect this standard to be applied more in the future, as lithium mining companies seek to attract capital investments.

The following characteristics of the deposit determine where and when to mine: type, size, grade, density, porosity, other recoverable minerals and elements, evaporation rate (for brines), and impurities. All of these variables determine whether a deposit is, or could become, economic to exploit. Reserve and resource estimates can increase or decrease as new information becomes available and as prices change. Processing technologies will improve over time, allowing elements in newer, less concentrated, and deeper deposits to be mined.

For simplicity, and because our projection is over 90 years, we used the broadest definition of lithium supply – lithium resources – and determined the lithium resource for all deposits. As defined by the USGS, a r*esource* is the "concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible."[16]

Background on lithium

Lithium deposits are of three main types: brines, pegmatites, and sedimentary rocks. According to our analysis (see part c. "Deposit by deposit approach"), brines containing lithium make up 66% of the world's lithium resource; pegmatites make up 26% and sedimentary rocks make up 8%.

Brines

Lacustrine* brines and playa evaporites† contain lithium dissolved in solution, which was likely derived from dissolution of surrounding rocks‡ in drainage basins.[5] When brine deposits are "mined," the brine is pumped from the salt flat into shallow ponds where it is left to evaporate. As salts crystallize, the solution becomes more concentrated and is sometimes treated with soda ash and/or lime to precipitate other elements (e.g., magnesium). The presence of high levels of magnesium makes lithium extraction more costly, since additional processing steps are required.

For the most part, brine salt flats in South America, China, and Tibet are the richest lithium sources of this type. These brines are usually close to the surface and contain lithium in solution, which is easier to extract than lithium that is part of minerals in a rock. Brine deposits also contain large amounts of other useful elements, including sodium, potassium, and boron, which offset some of the costs of pumping and processing brines. Potash, which is any of several soluble potassium salts, is the main product of most brines, and lithium is generally a byproduct. Potash is mainly used as a fertilizer, and when produced from brines usually takes the form of potassium chloride.

The largest producing brine deposit in the world is the 3,000 km^2 Salar de Atacama, in northern Chile. Atacama is the highest known concentration of lithium, averaging 0.14% (or 1400 ppm) lithium, and is the world's largest producer of lithium carbonate – 40,000 and 25,000 tonnes of Li_2CO_3 in 2008 from operations owned by Sociedad Quimica y Minera (SQM) and Rockwood Holdings Inc., respectively.[9, 12] This amounts to over 12,000 tonnes of lithium metal production, close to one-half of the world's total of 25,400 tonnes of lithium (excluding U.S. production).[13] We have estimated that Atacama has a lithium resource of at least 6.3 Mt.

Bolivia's Salar de Uyuni has an average lithium concentration of 0.0532% and has yet to begin production. The popular press identifies Uyuni as the largest lithium deposit in the world; our research indicates that Uyuni is the largest known deposit, containing 10.2 Mt of lithium, or 27% of the world's lithium resource. However, geological experts note that its productive

---

* Lacustrine: referring to water, sediments, and other features of lakes.
† Evaporite: rock consisting of mineral that precipitated from evaporated water.
‡ Rock: cohesive aggregate of mineral grains.

ability will remain uncertain until further drilling is conducted and it is proven that major production and processing can deal with the high level of magnesium in Uyuni's brine.[17]

The next largest producing brine deposit is Zabuye, in China, which has an area of 243 km^2, an average lithium concentration of 0.068%, and an estimated lithium resource of 1.53 Mt. ZBY Saline reported a capacity of 7,500 tonnes of Li_2CO_3 in 2004.[18]

The brine deposit with the lowest concentration of lithium, 0.02%, that is currently producing is Silver Peak, Nevada. Silver Peak has an estimated 0.3 Mt of lithium resource. Rockwood Holdings extracted 9,000 tonnes of lithium from Silver Peak in 2008, for use in lithium chemicals. [12]

Brines are also found in deep oil reservoirs, and some of these are enriched in lithium. Best known of these are the brines in the Smackover Formation in the Gulf Coast region of the United States. These brines are estimated to contain 0.75 Mt of lithium resource at an average lithium concentration of 0.0146%, which is the lowest concentration we included in our study of lithium resource. The Smackover brines are also at depths of several thousand feet, which increases cost because of the need to pump the brine to the surface for processing (unless it is moved to the surface during oil production).[19]

The average concentrations of major brine resources are presented in Figure 1 below.

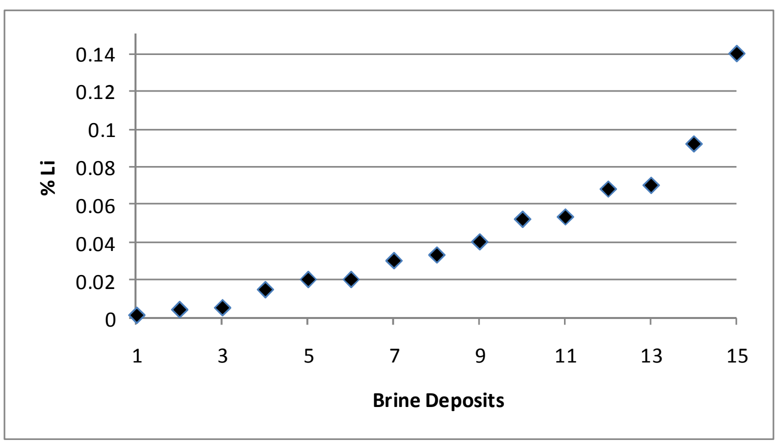

Figure 1. Average lithium concentrations of brines (1 Dead Sea, 2 Great Salt Lake, 3 Searles Lake, 4 Smackover, 5 Salton Sea, 6 Silver Peak, 7 Qaidam, 8 Rincon, 9 DXC, 10 Hombre Muerto, 11 Uyuni, 12 Zabuye, 13 Olaroz, 14 Maricunga, 15 Atacama)

<u>Pegmatites</u>

Pegmatite deposits are coarse-grained intrusive igneous rocks that formed from the crystallization of magma at depth in the crust. Pegmatites can contain recoverable amounts of lithium, boron, tin, tantalum, niobium, beryllium and other elements. Lithium in pegmatites is usually present as the mineral spodumene ($LiAlSi_2O_6$), which can be used directly in ceramics but must be processed to release lithium in a form, usually lithium carbonate, that can be used in the manufacture of batteries and other products. To produce lithium carbonate from spodumene, the material is pulverized, calcined at 1,100 degrees C, treated with sulfuric acid, dissolved in water, separated from aluminum, and precipitated with soda ash. [12]

The heating and dissolution in this process make it more expensive to extract lithium from pegmatites than to extract lithium from brines. The concentration of lithium in pegmatites is considerably higher than in brines, which offsets some of the costs. Tahil quotes Pavlovic (1992),[20] who estimated lithium carbonate production from three different deposits.

Table 3. Comparing lithium production costs (Source: Pavlovic, 1992)

Deposit	Type	Cost per kg Li_2CO_3
Bessemer City, North Carolina	Spodumene	$2.43
Silver Peak, Nevada	Brine	$1.65
Atacama, Chile	Brine	$1.10

Lithium is currently being extracted from at least 13 pegmatite deposits and more deposits are under development. The largest productive spodumene pegmatite operation is in Greenbushes, Australia. It is owned by Talison Minerals and has an estimated 560,000 tonnes of lithium resource, with an average concentration of 1.59% lithium.[21] The pegmatite deposit producing lithium with the lowest concentration is Jiajika, which has an estimated 204,000 tonnes of lithium resource, with an average concentration of 0.59% lithium.

In the U.S., Russia, and Australia, some pegmatite operations with lower lithium concentrations ceased operations when South American brine deposits came on line in the 1980s and 90s. For example, Kings Mountain, a spodumene pegmatite deposit in North Carolina with an average grade of 0.69% lithium, closed in 1991 when Chilean brine operations opened.[22] Bessemer City, an operation with similar lithium concentrations to Kings Mountain is noted in Pavlovic's table above.

The average concentrations of major pegmatite resources are presented in Figure 2 below.

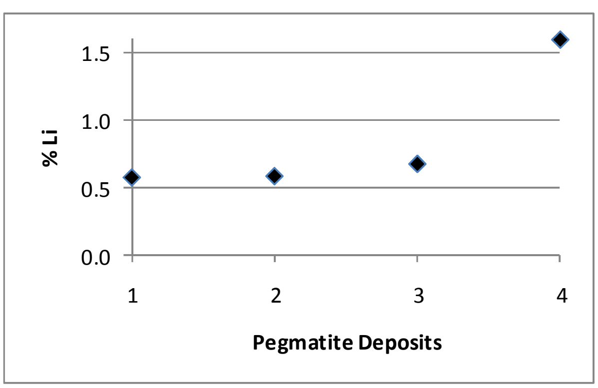

Figure 2. Average lithium concentrations of pegmatites (1 Manono & Kitotolo, 2 Jiajika, 3 Kings Mountain Belt, 4 Greenbushes)

Other Deposit Types

Lithium is also found in deposits of clay and lacustrine evaporites. In the clay deposits, lithium is part of clay minerals such as smectite, from which it must be separated by processing. The best known deposit of this type is in Kings Valley, Nevada, where deposits contain hectorite [$(Mg,Li)_3Si_4O_{10}(OH)_2$], a type of smectite that is rich in magnesium and lithium. Estimates for Kings Valley are 48.1 Mt of "indicated" resources grading 0.27% lithium and 42.3 Mt of "inferred" resources grading 0.27% lithium.[23] The Jadar Valley, in Serbia, contains lacustrine evaporite deposits containing jadarite [$LiNaB_3SiO_7(OH)$], a new mineral that is a possible source of lithium and boron.[24,25] An inferred resource of 114.6 Mt containing 1.8% Li2O has been reported for this deposit.[26] Nothing is known about the feasibility of extracting lithium from these deposits economically.

Production

While economic extraction of lithium takes into account other products and impurities, the average grade is the variable which can be compared across deposits of the same type. The lowest productive deposits for each type of deposit with lithium content are summarized in Table 4. Economically exploitable pegmatite deposits usually have higher concentrations than brine deposits.

Table 4. Grade "cut-offs."

Type	Lowest Productive Grade (%Li)	Reasoning
Brine	0.02	- Searles Lake closed at avg. 0.008% Li - Lowest content is Silver Peak, operating at avg. 0.02% Li since 1966
Pegmatite (Spodumene)	0.59	- Lowest content is Jiajika, operating at 0.59% Li - Kings Mountain closed at avg. grade of 0.69% Li - Note: Bikita and Yichun are operating and may have lower Li content, but their Li content could not be verified
Sedimentary Rock (Hectorite)	0.27	- Kings Valley being explored, avg. 0.27% Li content - Western Lithium used avg. 0.27% Li as cutoff
Sedimentary Rock (Jadarite)	0.096	- Jadar Valley being explored, avg. 0.096% Li content - No other jadarite deposits

Prices for potash and lithium determine when brine deposits become economically feasible to mine. Potash production from brines is most commonly in the form of KCl, containing 61% K_2O. According to the USGS, the average price for K_2O has increased from $200 per tonne in 2004 to a record $717 per tonne in 2008, mainly due to increased demand for fertilizers.[27]

The price of lithium carbonate (in 2008 dollars) steadily declined from around $6.50 per pound in 1954 to about $1.50 per pound in 1998, as new production sources (e.g., South America) and new extraction technologies were developed and deployed. Beginning in 2003, however, the price of lithium carbonate (in 2008 dollars) began to increase, reaching around $2.80 per pound, or $6,173 per tonne, in 2008.[11] Further increases in price would help to bring more lithium deposits on line.

Deposit-by-deposit approach

For this study we compiled data on 103 deposits containing lithium, with an emphasis on the 35 deposits containing more than 100,000 tonnes of lithium. For each site, where available, data were compiled on the deposit location, type, area, thickness, grade, porosity, quantity of lithium and other products, and production volume.

The following main assumptions were used to construct our list of the top 35 lithium deposits:

- The data used were obtained from published sources, as noted in Supplementary Information.
- We estimated lithium resources from brine deposits using the relation:

$$Lithium\ Resource = A \times T \times P \times D \times C$$

Where A = Area of aquifer, T = Thickness of aquifer, P = Porosity of aquifer, D = Density of brine, and C = Concentration of Li in brine.

- We estimated lithium resources from rock and mineral deposits using the relation:

$$Lithium\ Resource = T \times C$$

Where T = Tonnes of ore and C = Concentration of Li in ore.

- Only deposits greater than 100,000 tonnes of Li were included, with the exception of the following in Table 5, which are deposits that are currently producing:

Table 5. Producing deposits with less than 100,000 tonnes Li. Sources: Clarke/Harben, 2009;[10] Yaksic/Tilton, 2009.[11]

Deposit	Country	Type	Li Resource (tonnes Li)
Lijiagou	China	Pegmatite	53,000
Hupei	China	Pegmatite	42,000
Cachoeira	Brazil	Pegmatite	23,000
Bernic Lake	Canada	Pegmatite	19,000
Mesquitila/Guarda	Portugal	Pegmatite	10,000
Ningdu	China	Pegmatite	NA
Jinchuan	China	Pegmatite	NA
Mina Feli	Spain	Pegmatite	NA
Total:			**147,000**

- The Dead Sea, Great Salt Lake, and Searles Lake deposits were not included in the total, because the concentrations of lithium in these deposits were lower than even the poorest brines.
- When data were lacking and when several estimates existed but could not be distinguished, we chose the most conservative value.

There are many gaps in the literature, especially for poorly known deposits. Despite its weaknesses, this study is intended to be a more comprehensive tool for understanding lithium supply than currently exists in the public domain.

Lithium resource estimates

Table 6 presents our estimate of the world's top lithium deposits. All deposits listed have greater than 100,000 tonnes of lithium resource. (See Supplementary Information, "Case Studies" for a detailed description of these deposits.)

Table 6. World lithium resource, deposits greater than 100,000 tonnes Li.

Deposit	Country	Type	Resource (Mt Li)	Avg. Concentration (% Li)
Uyuni	Bolivia	Brine	10.2	0.0532
Atacama*	Chile	Brine	6.3	0.14
Kings Mountain Belt	USA	Pegmatite	5.454	0.68
Qaidam*	China	Brine	2.02	0.03
Kings Valley, NV	USA	Sedimentary Rock	2.0	0.27
Zabuye*	China	Brine	1.53	0.068
Manono/Kitotolo	Congo	Pegmatite	1.145	0.58
Rincon	Argentina	Brine	1.118	0.033
Brawley	USA	Brine	1.0	--
Jadar Valley	Serbia	Sedimentary Rock	0.99	0.0087
Hombre Muerto*	Argentina	Brine	0.8	0.052
Smackover	USA	Brine	0.75	0.0146
Gajika	China	Pegmatite	0.591	--
Greenbushes*	Australia	Pegmatite	0.56	1.59
Beaverhill	Canada	Brine	0.515	--
Yichun*	China	Pegmatite	0.325	--
Salton Sea	USA	Brine	0.316	0.02
Silver Peak*	USA	Brine	0.3	0.02
Kolmorzerskoe	Russia	Pegmatite	0.288	--
Maerking*	China	Pegmatite	0.225	--
Maricunga	Chile	Brine	0.22	0.092
Jiajika*	China	Pegmatite	0.204	0.59
Daoxian	China	Pegmatite	0.182	
DXC*	China	Brine	0.181	0.04
Olaroz	Argentina	Brine	0.156	0.07
Other (producing)*	Brazil, Canada, China, Portugal	Pegmatite	0.147	--
Goltsovoe	Russia	Pegmatite	0.139	--
Polmostundrovskoe	Russia	Pegmatite	0.139	--
Ulug-Tanzek	Russia	Pegmatite	0.139	--
Urikskoe	Russia	Pegmatite	0.139	--
Koralpa	Austria	Pegmatite	0.1	--
Mibra	Brazil	Pegmatite	0.1	--
Bikita*	Zimbabwe	Pegmatite	0.0567**	--
Dead Sea	Israel	Brine	--	0.001
Great Salt Lake	USA	Brine	--	0.004
Searles Lake	USA	Brine	--	0.005
Total			**38.33**	

*Producing

** We used the lowest estimate in the literature, though some estimates for Bikita were over 100,000 tonnes Li.

We estimate that the total lithium resource in the world is at least 38.33 Mt. The top 3 deposits – Uyuni, Atacama, and the Kings Mountain Belt – make up 57% of the world's total resource of lithium. The top 10 lithium deposits make up 83% of the world's total lithium resource and include 6 brine, 2 pegmatite, and 2 sedimentary rock deposits. Of the top 10 deposits, only Atacama, Qaidam Basin, and Zabuye are producing lithium.

Including its 8 brine deposits above 100,000 tonnes, South America represents 19.1 Mt, or 50%, of the world's lithium resource. Including its 5 brine and 5 pegmatite deposits above 100,000 tonnes of lithium, China's lithium resource accounts for 5.26 Mt, or 14% of the world's total. The U.S. accounts for 9.8 Mt, or almost 26%, of the world's lithium resource.

Production of lithium is occurring at 16 deposits (5 of which are below 100,000 tonnes lithium), whose total resource is 12.4 Mt, which is 32% of the world's total. The majority of major lithium deposits that are producing are in South America and China.

As shown in Table 7, our resource estimate of 38.3 Mt of lithium falls within Evans' (2008) and Yaksic and Tilton's (2009) estimates of 29.9 and 64.0 Mt, respectively. Both Tahil and Evans used fewer deposits. For many large deposits, including Uyuni and Atacama, Tahil used the most conservative figures for the deposits' surface area, porosity, and concentration. For example, Tahil evaluated a 20km^2 area of the Atacama deposit, but did not indicate how he estimated the resource for the highly concentrated 1,424 km^2 nucleus or the rest of the salar. Also, Tahil did not include pegmatite or sedimentary rock deposits in his estimate.

The USGS value includes lithium resources from 8 countries, whereas we used data from deposits in 15 countries.

Table 7. World total lithium resource estimates (Mt Li).

Li Resources	Deposits Included	Reference
19.2	15	Tahil (2008)
25.5	8*	USGS (2010)
29.9	24	Evans (2008)
38.3	35	This work (2010)
64.0	40	Yaksic/Tilton (2009)

* USGS (2010) only lists information by country, not deposits.

The primary differences between our estimate and Evans' were with regard to Uyuni and the Kings Mountain Belt. Evans estimated Uyuni contained 5.5 Mt, whereas we estimated a resource of 10.2 Mt. Evans reduced the lithium resource estimate for unexplored areas of North Carolina by 50%,[8] whereas we kept the originally estimate of 5.175 Mt of lithium.[28]

Yaksic and Tilton's estimate of 64.0 Mt of lithium includes a large estimate of 35.7 Mt of lithium resource for Atacama,[11] but they do not explain why this estimate is so high. If Yaksic and Tilton used the more established value of 7.0 Mt for Atacama, their world estimate would be similar to ours. Unlike Yaksic and Tilton, we did not include the Dead Sea or the Great Salt Lake as resources.

Lithium Markets and Demand

The USGS and major lithium producers report lithium use by segment starting in 2006. Data for the last three years are shown in Figure 3. Two categories (battery and others) show growth. The "other" category includes special alloy production, chemical processing, continuous casting, and pharmaceuticals. The "battery" category includes portable electronics and, more recently, vehicles. Given the scale of the application, if use in vehicles increases it is likely that the "battery" category will outpace all others.[11]

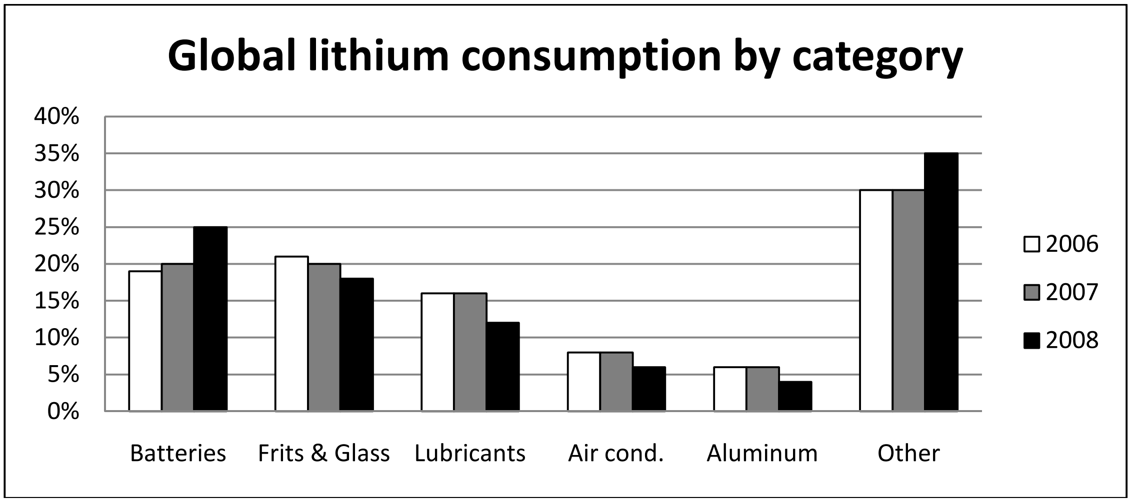

Figure 3. Global lithium consumption by category, 2006-2008

To estimate future global lithium demand and assess the possibility that lithium availability would constrain electrification of the global passenger vehicle fleet, the categories identified in Figure 3 were studied and demand was projected through 2100.

Non-battery demand forecast

Non-battery lithium demand includes uses in frits and glass, lubricants, and conditioning. We note that lithium could be substituted by other materials in these applications. In frits and glass, lithium could be substituted by sodic and potassic fluxes; in lubricants, by aluminum and calcium soaps; and lithium alloys could be substituted by engineered resins using boron, glass, and polymer fibers.[13]

In frits and glass, lithium carbonate is added to ceramics, enamels, and glass to reduce their melting point, reduce viscosity, and increase surface tension making lithium glasses suitable for ovenware.[29]

Lithium hydroxide is used in the production of greases. The addition of lithium stearates maintains the viscosity of greases at high temperatures and makes them insoluble in water. Both of these properties are important for lubricants in vehicles, aircrafts, and heavy machinery.[29]

Lithium bromide, lithium chromate, and lithium chloride are used in air conditioners operating on the absorption principle. Lithium hydroxide is also used to absorb carbon dioxide in submarines and spacecrafts.[29]

Other uses of lithium include production of organic compounds and alloys.[29] It is used as a coolant and shielding material in nuclear reactors,[29] and for the production of tritium (for hydrogen bombs and biological research.[4]) Lithium metal is used in alloys with other metals; for example, it changes the hardness of aluminum and lead, and the ductility of magnesium.[29]

Inorganic lithium compounds are employed in several applications. Lithium acetates are used in pharmaceuticals and in the production of polyesters. Lithium carbonate is added to cement to accelerate setting time and to molten salts used for electrolytic aluminum production. High purity lithium carbonate is used in pharmaceuticals to treat manic-depressive conditions.[29]

Yaksic and Tilton estimated growth rates for lithium use in the applications mentioned above. We estimated the accumulated lithium demand for the period 2010-2100, for applications other than batteries, using growth estimates from Yaksic and Tilton and current demand levels. The results are presented in Table 8. Given the possibilities of substitution by other materials, we consider the values in Table 8 to be upper limits for the likely lithium demand in these applications.

Table 8. Accumulated lithium demand estimated for non-battery uses, 2010-2100 (in tonnes of lithium).

Lubricating grease	782,962
Frits and glass	637,392
Air conditioning	283,521
Others	1,444,115
Total	3,161,260

Portable electronics battery demand forecast

Lithium metal and compounds are used as anode, cathode, or electrolyte material in batteries.[30] Lithium-based batteries are lighter, do not have a memory effect, and have a self-discharge rate lower than other chemistries.[31]

Global shipment data are available for primary (i.e., non-rechargeable) batteries between 1994 and 2008, and for secondary (i.e., rechargeable) lithium batteries between 2003 and 2007. A linear regression analysis revealed that battery shipments were strongly correlated with global GDP (correlation coefficients of 95% for primary and 99% for secondary batteries.) Hence, we estimated global demand for batteries for the period 2010-2100 based on the regression result and the Intergovernmental Panel on Climate Change (IPCC) 2010-2100 growth scenarios for future global GDP.

The IPCC identifies four world growth scenarios (A1, A2, B1, and B2) with annual GDP increasing in the ranges 2.5%-3.0%, 2.0%-2.3%, 2.5%-2.6%, and 2.0%-2.3% respectively.[32] Based on the

IPCC's minimum and maximum forecasted annual growth, two growth scenarios were explored: 2% and 3%.

Once the annual number of battery shipments was calculated, the volume of lithium required was determined assuming that all batteries are disposed of after one-year of useful life. Global recycling rates were not available; however, in the UK and Canada, disposable and rechargeable battery recycling rates are estimated to be near 5%.[33,34] This value was used to represent global recycling of portable batteries.

Lithium recovery from recycling was assumed to be 90%, a rate which is currently being achieved.[35] Although recovery is expected to increase as recycling technologies improve, we kept it constant throughout the evaluation period.

Finally, the mass of lithium used per battery was calculated assuming that all battery-related lithium use in 2008 was for primary and secondary portable batteries. SQM estimated that, in 2008, global lithium consumption was approximately 17,400 tonnes, 27% of which was used in batteries.[36] For the same year, Frost and Sullivan reported that the world total count of primary and secondary lithium batteries was 4,386 million units.[37] Hence, the average mass is 1.07 tonnes of lithium per million batteries. We assume that this ratio remains constant for the period 2010-2100. Table 9 shows our estimate of the accumulated lithium demand for portable batteries.

Table 9. Accumulated lithium demand for portable electronics, 2010-2100.

	Primary battery		Secondary Battery	
	2% GDP	**3% GDP**	**2% GDP**	**3% GDP**
Batteries [million units]	856,281	1,741,126	868,687	1,780,142
Lithium used [million metric tons]	0.92	1.87	0.93	1.91
Lithium recycled [million metric tons]	0.04	0.08	0.04	0.09
Lithium mined [million metric tons]	0.88	1.78	0.89	1.82

Vehicle battery demand forecast

As global penetration of electric vehicles (i.e., HEVs, PHEVs, BEVs) increases, so will the demand for the batteries that power them. Currently, most HEVs use NiMH batteries; but a transition to lithium-ion batteries has begun and it has been predicted that lithium-ion batteries will be used in the next generation vehicles.[38] We note that other technologies such as flow batteries, fuel cells, and ultra capacitor batteries are being explored to compete with lithium-ion batteries.[39,30] Hence, the demand values calculated below should be regarded as upper limits.

The lithium demand for vehicle batteries was estimated as follows. First, we conducted a linear regression analysis using light-duty global vehicle production for the period 1995-2008 from the Ward's 2009 Automotive Yearbook[40] and global GDP data; a 97% linear correlation was found. Second, vehicle manufacturing was estimated for 2010-2100 using two GDP growth scenarios (2% and 3%). In the 3% GDP growth scenario the annual production of light-duty vehicles increases to approximately 630 million units in 2100; this equates to the production of 42 new vehicles per-thousand-persons per year in 2100 calculated using IPCC population forecast in it A2 scenario. IPCC's A2 scenario is the one with highest population growth, reaching more than 15 billion persons in 2100. This level of global vehicle production/consumption is comparable in magnitude to the current level in the US and probably is an upper limit for likely future global production.

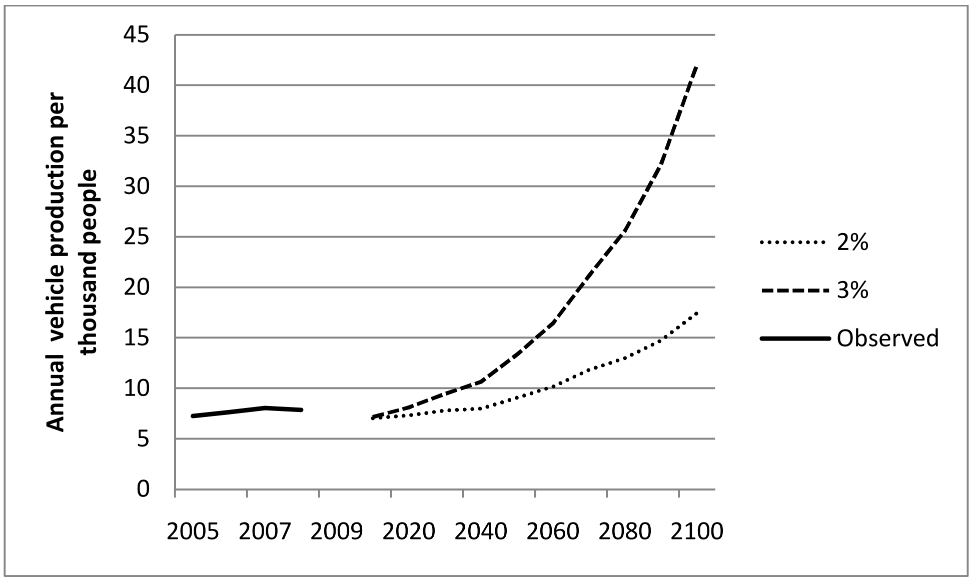

Figure 4. Global annual production of light-duty vehicles (expressed as vehicles per thousand population) versus year. The solid line is the historic data. The dashed and dotted lines are the fleets in our model for the 2% and 3% GDP scenarios discussed in the text.

Third, Credit Suisse's projection of electric vehicle penetration from 2010 to 2030 was used as the basis to estimate electric vehicle penetration through 2100. Fourth, battery life, vehicle life, and battery recycling were accounted for and the accumulated lithium use for the period 2010-2100 was estimated.

Credit Suisse projected PHEV and BEV sales for the period 2010-2030 based on total oil price, battery price, electricity costs, country subsidies, gas prices and taxes, and manufacturing capacity constraints. For HEVs, the projections were based on a country-by-country analysis of existing sales data.[41] We used the Credit Suisse data for 2010-2030. Beyond 2030 we assumed that year-over-year electric vehicle growth remained constant in the 2% GDP scenario and increased 0.5% every 10 years in the 3% GDP scenario. These growth assumptions result in 100% EV penetration in year 2083 and 2087, for 2% and 3% GDP scenarios respectively.

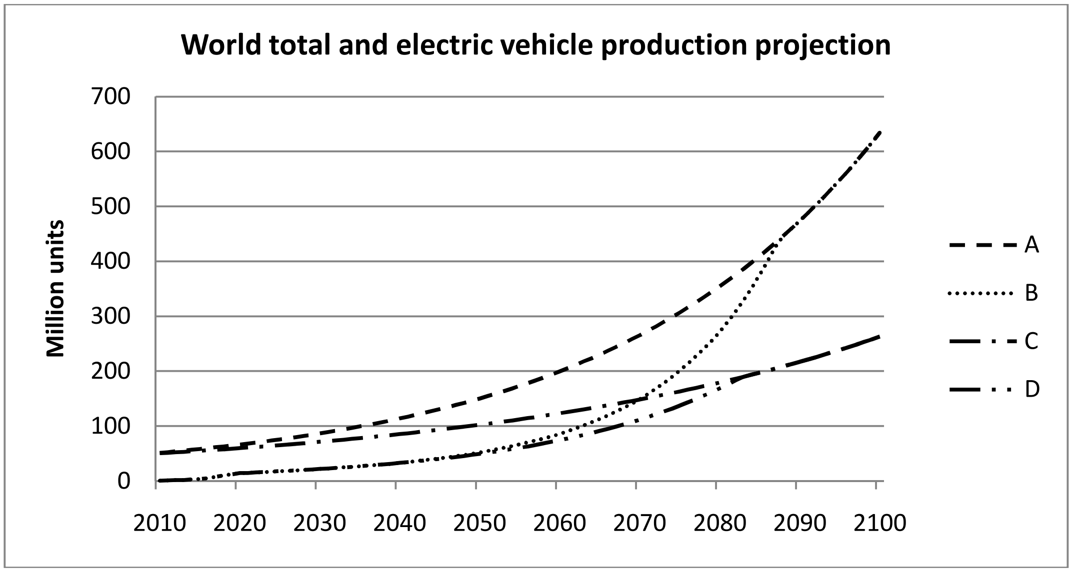

Figure 5. Global annual vehicle production (in million units) estimated for 2010-2100 for 2% and 3% GDP scenarios: A, total vehicles for 3% scenario; B, electric vehicles for 3% scenario; C, total vehicles for 2% scenario; D, electric vehicles for 2% scenario. "Electric vehicles" includes HEVs, PHEVs, and BEVs.

We compare our scenario results to IEA's 2008 BLUE Map scenario in Table 10. The penetration of EVs in the fleet in our scenario is somewhat lower than in the IEA BLUE Map scenario. The IEA scenario calculates the number of PHEVs and BEVs that must penetrate the market and lists actions that must be taken by governments, the automotive industry, the public, and other stakeholders to achieve 50% reduction in global, energy related CO_2 emission by 2050;[42] our scenario, on the other hand, is not aimed at this goal.

Table 10. Comparison of this work's vehicle projections under and IEA 2008 BLUE Map estimates.

	This work's projection (in million units)				IEA 2008 BLUE Map (in million units)	
	2%		3%			
Year	PHEV	BEV	PHEV	BEV	PHEV	BEV
2015	0.5	0.5	0.5	0.5	0.7	0.5
2020	3.0	5.0	3.0	5.0	4.7	2.5
2050	11.8	16.6	12.4	17.4	49.1	52.2
2080	48.7	49.6	78.3	80.0	-	-

To calculate the number of batteries needed we assumed that all vehicles and their batteries have 10 years of useful life. The amount of lithium required per battery was calculated according to the electric range of each type of vehicle. Consistent with estimates from a recent global energy modeling study,[43] we assume HEVs have 2 km of electric range; PHEVs, 65 km; and BEVs, 200 km. The GREET model[44] indicates that electric vehicles consume approximately 0.25 kWh/km. We consider a $\pm$20% range around this value to give 0.2-0.3 kWh/km. Hence, to provide the needed range, the batteries for HEVs, PHEVs, and BEVs need to store 0.4-0.6, 13-20, and 40-60 kWh.

Recognizing the need to avoid deep discharge and seeking to be conservative in our estimations, we add a 100% buffer for HEV and 50% buffer for PHEV and BEV batteries to provide adequate cycle life.[45] The resulting capacity requirements for HEVs, PHEVs, and BEVs batteries in our model are 0.8-1.2, 20-30, and 60-90 kWh respectively. Lithium-ion batteries have approximately 0.114 kg Li per kWh, so the lithium content of batteries in HEVs, PHEVs, and BEVs would be 0.092-0.136, 2.28-3.42, and 6.84-10.3 kg.

To account for future improvements in vehicle efficiency (e.g., weight reduction, aerodynamic and rolling resistance improvements) we adopted the assumption of Grahn et al.[43] that the vehicle energy demand will decrease by a factor of two over the century (i.e., the energy efficiency increases at a compound rate of 0.77% per year over the period 2010-2100). Hence, by 2100, HEVs, PHEVs, and BEVs would contain between 0.046-0.068, 1.14-1.71, and 3.42-5.2 kg of lithium, respectively. Seeking to calculate maximum expected lithium demand, we used the upper bound of these ranges (i.e., 0.068, 1.71, and 5.2 kg) in our calculations.

Recycling of lithium from Li-ion batteries may be a critical factor in balancing the supply of lithium with future demand. To cover this factor we draw upon estimates from several sources. The USA EPA reports that "nearly 90% of all lead-acid batteries are recycled."[46] The International Lead Management Center reports that "recycling rates for used batteries is as high as 96% in many countries."[47] With regard to lead-acid batteries, the International Lead Association states that "some countries boast 100% recycling and most others share the possibility of 100% recyclability."[48] We calculated total lithium demand and recycling volumes assuming three recycling participation rates (90%, 96% and 100%) with 90% recovery of lithium during the recycling process.[35] The results are shown in Table 11.

Table 11. 2010-2100 maximum expected lithium demand (in Mt) for electric vehicles batteries for 2% and 3% GDP growth scenarios and recycling participation at 90%, 96%, and 100%. A recovery efficiency of 90% during the recycling process was assumed.

		90%				96%				100%			
		HEV	**PHEV**	**BEV**	**Total**	**HEV**	**PHEV**	**BEV**	**Total**	**HEV**	**PHEV**	**BEV**	**Total**
2%	**Demanded**	0.29	4.79	15.52	20.60	0.29	4.79	15.52	20.60	0.29	4.79	15.52	20.60
	Recycled	0.16	2.58	9.01	11.76	0.17	2.75	9.62	12.54	0.18	2.87	10.02	13.06
	Mined	0.12	2.21	6.50	8.84	0.11	2.04	5.90	8.06	0.11	1.93	5.50	7.53
3%	**Demanded**	0.47	8.19	25.19	33.86	0.47	8.19	25.19	33.86	0.47	8.19	25.19	33.86
	Recycled	0.23	3.82	12.81	16.86	0.25	4.07	13.67	17.99	0.26	4.24	14.24	18.73
	Mined	0.24	4.38	12.38	17.00	0.22	4.12	11.53	15.87	0.21	3.95	10.96	15.13

Total demand forecast

The upper limit for lithium demand from 2010 to 2100 was calculated by aggregating the mass needed to be mined to support the demand from "non-battery", "portable electronic batteries", and "vehicle batteries" uses. In the case of vehicle use, the upper limit was calculated considering vehicle battery recycling at 90%. We expect total lithium demand to be less than 24 Mt for the period 2010-2100 (Table 12).

Table 12. Accumulated lithium demand for electric vehicles, 2010-2100 (Mt).

	2% GDP	**3% GDP**
Non-battery use	3.2	3.2
Portable battery use	1.8	3.6
Vehicle battery use	8.8	17.0
TOTAL	**13.8**	**23.8**

Conclusion

The lithium demand model shows that the accumulated amount of lithium required for the period from 2010 to 2100 could be between 14 and 24 Mt when recycling participation is at its lowest (90%), based on 2% and 3% growth scenarios. This upper limit for lithium demand is significantly below the 38 Mt of lithium resource. We conclude that lithium availability will not constrain the electrification of the automobile during the present century.

The resource estimate we calculated, 38.33 Mt, will change as new information becomes available. Limited primary data were available to evaluate all the deposits with the same level of scrutiny. Also, seven of the top 10 deposits are not under production, and two new types of deposits, Kings Valley (hectorite) and Jadar Valley (jadarite), have never been operated economically before. With the demand for lithium batteries, we are entering a new lithium exploration era; new brine, spodumene, and other types of deposits will be discovered. Many deposits, like Coipasa near Uyuni, are being explored. Some of these deposits might not be economically exploitable now, or ever; some may produce unforeseen amounts of lithium. Further exploration of current and potential lithium deposits, especially if these studies are NI 43-101 certified, will help produce improved estimates of the world's lithium resources.

Actual lithium demand could differ significantly from the projections used in this study. It could be lower if new or existing materials are more efficient or cheaper to use, thus providing the basis to substitute lithium use. It could be higher if lithium starts to be used in applications that we did not foresee in this work.

Several highly uncertain factors influence demand. Growth ratios used to calculate lithium use in frits, lubricants, air conditioning, and other applications could be lower or higher than the real growth rates observed in the future. Annual global GDP growth for the period 2010-2100 could be less than 2% or more than 3%, thus affecting our estimates for the number of portable batteries and vehicle batteries manufactured. Our demand for battery use would also be affected by recycling participation and recovery factors being different to what we assumed in this work.

Despite these limitations, this study provides a comprehensive repository of data and estimates on lithium supply and a transparent set of parameters used for projecting demand. It also provides a context for interpreting and comparing results from previous investigations. Furthermore, we hope this research facilitates future studies examining the adequacy of this unique resource.

Appendices

Case Studies of Lithium Deposits

We estimated and summed the lithium resource of 43 deposits throughout the world to arrive at the world's total lithium resource of at least 38.33 Mt (million tonnes). The deposits we chose have been discussed heavily in the literature and have each been estimated to contain more than 100,000 tonnes of lithium. We also included deposits which have less than 100,000 tonnes of lithium but are currently producing.

Salar de Uyuni

Bolivia's Salar de Uyuni has a total surface area of 9,000 to 10,500 km^2. [22] It contains a layer of halite that has abundant pores containing a brine that is enriched in lithium, potassium, magnesium, and boron. Concentrations of lithium in this brine reported in the literature range from 80 ppm[22] to 4,700 ppm. [12]

Uyuni is the world's largest potential source of lithium, though it is not currently producing. The Bolivian government and its state mining company, Comibol, control the rights to Uyuni. A pilot mining and processing project was started in May 2008.

Recent estimates for Uyuni's lithium content range from 0.6 to 9.0 Mt (Figure 6). Tahil's estimate is the most conservative, at 0.6 Mt. A number of estimates, by Anstett el al,[49] Garrett, [22] Clarke and Harben,[10] Yaksic and Tilton,[11] and Evans (2008),[8] are between 5 and 5.5 Mt. Evans (2009)[50] and Risacher and Fritz[51] round out the top end of the range, at 8.9 to 9 Mt.

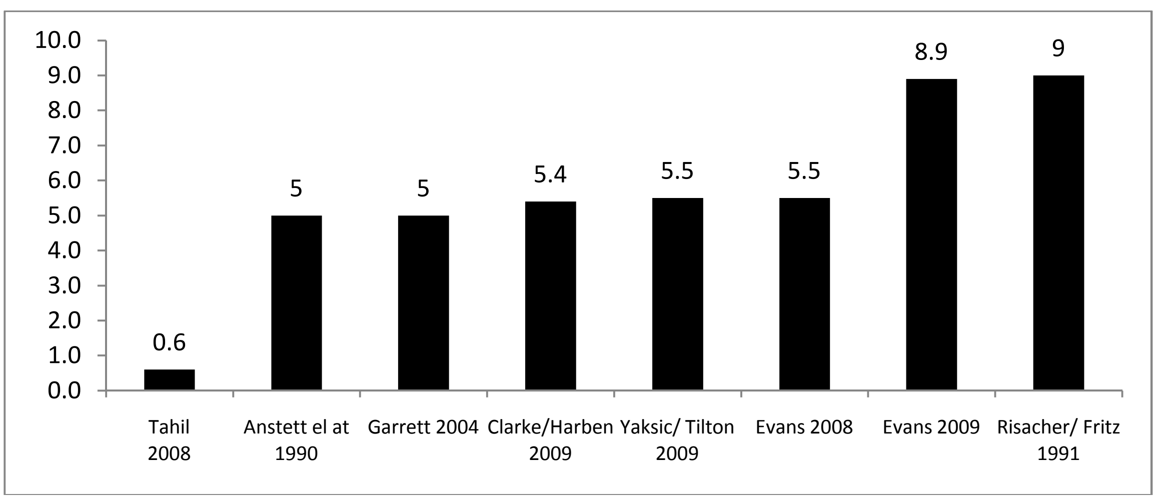

Figure 6. Estimates of lithium reserves (Mt Li) in the Uyuni salar.

Resource Formula & Data

We estimated resources of lithium in the Salar de Uyuni using the relation:

$$Lithium\ Resource = A \times T \times P \times D \times C$$

Where A = Area of aquifer, T = Thickness of aquifer, P = Porosity of aquifer, D = Density of brine, and C = Concentration of Li in brine

Data used in this estimate were obtained from published sources as noted in Table 18. Use of this formula was complicated by the fact that the aquifer's thickness and concentration of lithium varied dramatically, both vertically and horizontally, across the aquifer.

The most comprehensive source of primary information on Uyuni's lithium resource (Risacher and Fritz[51]) contains detailed data on the thickness, density, and concentrations of lithium in the aquifer. It is based on data from 138 samples of brine taken at depths ranging from 1 cm to 10 m from 40 drill holes across the salar (Table 19). An additional 26 samples were taken from drill holes in the southeastern part of the salar, at depths ranging from 1 to 180 cm (Figure 7).[51] These data were used to construct iso-concentration maps (Figure 8), although it is clear that there is considerable variation from place to place in lithium concentration.

A: Based on the maps provided by Risacher and Fritz, we estimated the area of the surface of the salar at **8,876 km^2**. We also assumed that the aquifer spanned the entire salar. Our estimate of surface area is lower than estimates in the literature, which ranged from 9,000 km^2 [8] to 10,500 km^2.[22] A majority of those investigating lithium availability, including Kunasz,[52] Risacher and Fritz,[51] and Tahil,[12] estimated that the salar's surface is 10,000 km^2. In 2009, Evans increased his estimate from 9,000 to 10,000 km^2.[50] Warren[53] and Banks[54] made specific estimates of 9,654 and 10,085 km^2 respectively, though we could not find information for how these figures were calculated.

T: There is disagreement in the literature on the thickness of the aquifer. The aquifer is non-uniform, with some layers of silt separating layers of porous salt. Kunasz estimated it was 15 to 20 m thick but admitted that this range was based on "Meager subsurface data."[55] Garrett produced a different picture: "The Salar's average depth is 121 m, and it has a 0.1-20 m thick salt mass (average 3-6m) in its central area in the form of 11 porous (20-30% void space) halite beds separated by layers of mud and sand."[22] Risacher and Fritz reported that "The salt crust has a maximum thickness of 11 m… [and] is made of layered porous halite with little amount of fine-grained gypsum and filled with an interstitial brine. It is underlain by impermeable lacustrine sediments."[51] We used Risacher and Fritz's estimates of thickness from 40 drill holes (Table 19), which are based on the samples from the field and are the most conservative in the literature. The deepest samples at each of the 40 drill holes ranged from 1 to 10 m.[51] The average of the deepest samples from all drill holes was **5.07 m**.

P: Unlike at Atacama, where porosity decreases with depth, the porosity of Uyuni's aquifer is not obviously zoned vertically. Ericksen et al. first reported porosity of 20 to 30% based on field work.[56] Risacher and Fritz estimated a porosity of 30 to 40%, averaging about 35%, based on field studies.[51] Risacher and Fritz stated:

"The salt crust is composed of alternating layers around 10 cm thick of hard halite and crumbly crystal aggregates. Due to this texture, the average porosity of the whole crust is very difficult to estimate. Several determinations could only be made on hard samples, which led to rather low values: 20-30%. The porosity of the friable layers is likely to be significantly higher, around 40-50%. Therefore, we have assumed an average porosity of 30-40% for the whole crust."[51]

For this study, we applied an average porosity of **35%**.

D: Risacher and Fritz reported density values for each sample.[51] The average of densities from drill holes across the entire salar was **1.217 g/cc**, which we used in our estimate. Risacher and Fritz used a very similar figure, 1.22 g/cc, in calculating their estimate.[51]

C: Uyuni has undergone just one intense evaporation cycle, which may explain why it has lower concentrations of lithium than Atacama, which has undergone many cycles.[52] As Table 13. Estimates of average Li concentration across the Salar de Uyuni. shows, estimates of concentration of lithium varied in the literature, from 0.0187% lithium[53] to 0.052%.[10]

Table 13. Estimates of average Li concentration across the Salar de Uyuni.

Risacher/Fritz 1991	Kunasz 2006	Garrett 2004	Evans 2008	Evans 2009	Yaksic/Tilton 2009	Clarke/Harben 2009	Warren 2010
0.045%*	0.025%**	0.0349%	0.035%	0.045%	0.040%	0.052%	0.0187%

*Estimated based on data available.
**Partial cation chemical analysis.

Kunasz indicated that the range of lithium concentrations in Uyuni was 100 to 700 ppm.[55] Garrett reported a range of 80 to 1,150 ppm.[22] Tahil cited 500 to 4,700 ppm.[12] We used the data provided by Risacher and Fritz, because they were the most comprehensive. The average concentrations at the 40 drill holes ranged from 110 ppm (0.011% Li) to 2,190 ppm (0.219% Li) (Table 19). The average of all concentrations from 138 samples across the entire salar was **0.0532% lithium**.

We noted that nine drill holes had average concentrations of lithium below 0.03%. The lowest lithium-containing brine reserve, Nevada's Silver Peak, produces lithium at average concentrations between 0.01 and 0.03% lithium. Based on Risacher and Fritz's maps,[51] Uyuni's western region and its eastern-central edge, which total approximately 2,675 km^2, might not have economically recoverable lithium (Figure 7 and Figure 8) at current lithium prices. However, our study estimates lithium availability through 2100; since we do not know the potential for technological improvements in extraction over this long time period, we included these areas of lower concentration in our estimate for the total lithium resource.

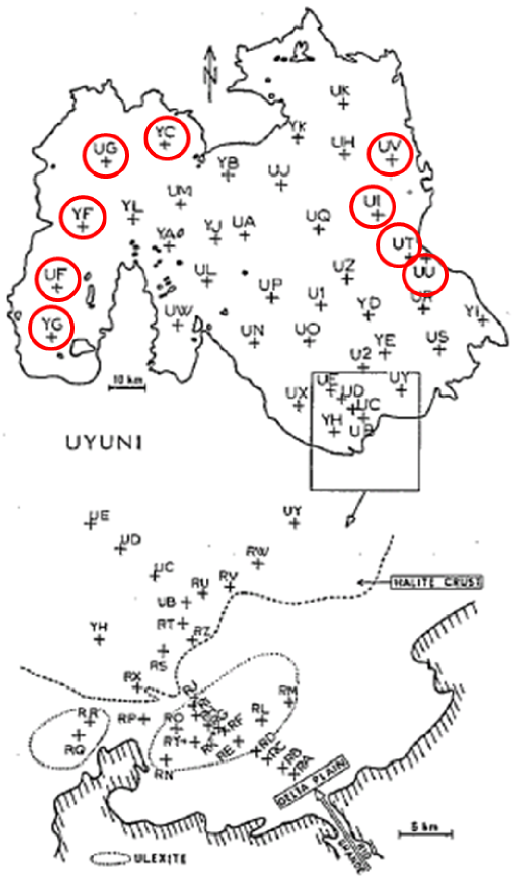

Figure 7. Drill Holes on the Salar de Uyuni, average concentrations below 0.03% circled in red (adapted from Risacher and Fritz 1991).

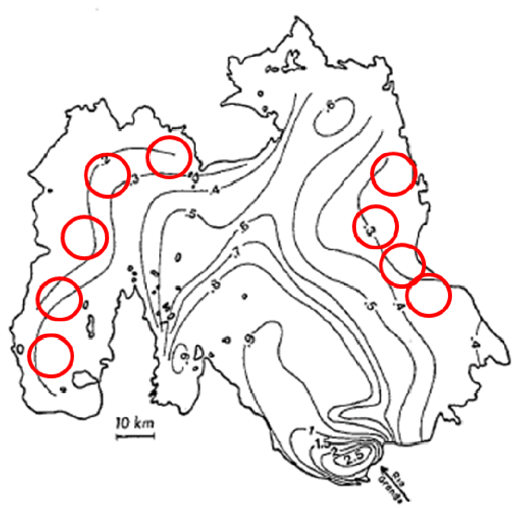

Figure 8. Average Li concentration isopleth map of Uyuni (g/L), average concentrations below 0.03% circled in red (adapted from Risacher and Fritz 1991).

Uyuni has high concentrations of magnesium, an impurity which adds cost to the processing of lithium. Kunasz noted, "In systems with high Mg:Li ratios, the phase chemistry prevents the formation of lithium chloride brine unless the magnesium is removed at the start of the process...The exceedingly high Mg:Li ratio has prevented the development of the Salar de Uyuni (and the Great Salt lake) as an economic source of lithium."[55] According to Evans however, "In the early 2000's after the evaluation of the very large brine deposits in the Qaidam Basin in Northwest China, a technical breakthrough was achieved in the processing of brines with a high magnesium content."[8] For the purposes of this study, we assumed that removing this impurity was possible across the salar.

Results

The total amount of lithium **resources in Uyuni is 10.2 Mt** (Table 14). Since no company is currently producing lithium and no information was found to indicate that estimates in the salar are NI 43-101 compliant, we cannot estimate the lithium reserves.

Table 14. Data and Estimate of the Lithium Resource within the Salar de Uyuni.

Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Avg. Density (g/cc)	Avg. Grade (Li)	Resource (Mt)
8,876	5.07	35%	1.217	0.0532%	**10.2**

Lower Estimate

Tahil's estimate of 0.6 Mt of lithium reserves was based exclusively on the southeastern edge of Uyuni, which has the highest concentrations of lithium; Tahil used a surface area of 200 km^2 (Table 15).

Table 15. Tahil's Reserve Estimate

Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (ppm Li)	Reserve (Mt)
200	3.5	35%	1.2	2,000	0.588

Tahil states, "As with the Salar de Atacama, expanding production outside a central high concentration epicentre (the Rio Grande lagoon region) will result in steeply diminishing returns." [12] Profitability may be affected by drilling relatively shallow holes across a very large area, but the reserves above 0.03% lithium might be economically exploitable. Further information is needed to understand what parts of Uyuni can be considered reserves.

Middle Estimates

Ballivian and Risacher calculated Uyuni's lithium reserves at 5.5 Mt, based on an area of 9,000 km^2 and an average concentration of 0.035% Li.[57] Several authors offer reserve estimates around this value, even though Risacher and Fritz later revised the estimate to 9.0 Mt based on more detailed survey data.[51] The other author's estimates from 5.0 to 5.5 Mt were calculated based on the 1981 study, with differing values of aquifer thickness and porosity like the ones below (Table 16).

Table 16. Middle-Range Estimate of Li Reserves for Uyuni.

Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (ppm Li)	Reserve (Mt Li)
9,000	~5-8	~20-35%	1.2	0.035%	5-5.5

Higher estimates

Our estimate of 10.2 Mt is comparable to Risacher and Fritz's estimate of 9.0 Mt[51] and Evan's (2009) value of 8.9 Mt.[50] Risacher and Fritz may have used a very similar way of calculating the lithium reserve as we calculated the resource, except they reported the volume of brine. Table 17 shows the formula variables, including a concentration of 0.045% lithium, which they may have used to reach 9.0 Mt.

Table 17. Risacher and Fritz's (1991) Average Values

Volume of brine (m3)	Avg. Porosity	Density (g/cc)	Avg. Grade (ppm Li)	Reserve (Mt Li)
16.5×10^9	35%*	1.22	0.045%	9.0

*Included in calculation for volume of brine.

Conclusion

Our estimate of the salar's total lithium resource is reasonable, since there could be increasing concentrations of lithium below the depths surveyed, which would result in even more lithium reserves. More detailed analysis of the porosity and concentration at more drill sites is needed, since these are highly variable parts of the lithium equation.

Table 18. Uyuni Data.

	Ericksen et al. 1977[56]	Kunasz 1979[52]	Anstett el al 1990[49]	Risacher and Fritz 1991[51]	Banks et al 2004[54]	Garrett 2004[22]	Kunasz 2006[55]	Evans ("Know Limits") 2008[73]	Evans ("Abun-dance2")2008[9]	Tahil 2008[12]	Evans 2009[50]	Yaksic/ Tilton 2009[11]	Clarke/ Harben 2009[10]	Warren 2010[53]
Area of Salar (km2)		10000		10000	10085	9000-10500		9000	9000	10000	10000			9654
"Epicenter" (km2)				276						276				
Halite thickness (m)		15-20				0.1-20	15-20			2-11				
Aquifer thickness (porous halite) (m)										2-11				
Porosity (%)	20-30%			30-40%						35%				
Concentration (%Li)				0.045%?		0.0349%	0.025%	0.035%			0.045 %	0.040%	0.052%	0.0187%
Magnesium/ lithium					21.77			22/1	22/1	18.6/1		19		
Reserve (Mt)			5	9		5		5.5	5.5	0.6	8.9	5.5	5.4	
Resource (Mt)										5.5				

Table 19. Uyuni Data from 40 drill holes, concentrations below 0.03% Li in red (adapted from Risacher and Fritz51)

Drill Hole	Sample	Depth of sample (cm)	Porosity	Density	Li (g/l)	%Li	Avg. %Li per drill hole
1	UA	15	35%	1.211	0.412	0.0340	0.0594
	UA	80		1.220	0.770	0.0631	
	UA	200		1.226	0.812	0.0662	
	UA	400		1.226	0.812	0.0662	
	UA	600		1.228	0.826	0.0673	
2	UB	10	35%	1.247	1.780	0.1427	0.1999
	UB	100		1.242	2.560	0.2061	
	UB	250		1.246	2.790	0.2239	
	UB	400		1.248	2.830	0.2268	
3	UC	5	35%	1.227	1.460	0.1190	0.0837
	UC	100		1.220	0.888	0.0728	
	UC	250		1.222	0.868	0.0710	
	UC	400		1.223	0.881	0.0720	
4	UD	10	35%	1.224	1.310	0.1070	0.0785
	UD	100		1.220	0.888	0.0728	
	UD	250		1.222	0.819	0.0670	
	UD	400		1.223	0.819	0.0670	
5	UE	5	35%	1.226	0.708	0.0577	0.0579
	UE	100		1.224	0.708	0.0578	
	UE	250		1.224	0.708	0.0578	
	UE	400		1.221	0.708	0.0580	
6	UF	30	35%	1.212	0.339	0.0280	0.0280
	UF	110		1.211	0.339	0.0280	
7	UG	15	35%	1.209	0.254	0.0210	0.0227
	UG	95		1.211	0.266	0.0220	
	UG	270		1.213	0.303	0.0250	
8	UH	10	35%	1.212	0.315	0.0260	0.0387
	UH	100		1.211	0.351	0.0290	
	UH	300		1.219	0.463	0.0380	
	UH	500		1.220	0.488	0.0400	
	UH	700		1.223	0.489	0.0400	
	UH	900		1.222	0.513	0.0420	
9	UI	15	35%	1.212	0.303	0.0250	0.0250
	UI	100		1.212	0.303	0.0250	
	UI	1000		1.213	0.303	0.0250	
10	UJ	15	35%	1.211	0.339	0.0280	0.0464
	UJ	100		1.217	0.584	0.0480	
	UJ	300		1.218	0.560	0.0460	
	UJ	700		1.223	0.575	0.0470	
11	UK	10	35%	1.215	0.413	0.0340	0.0554
	UK	100		1.223	0.685	0.0560	
	UK	200		1.228	0.688	0.0560	
	UK	400		1.229	0.688	0.0560	
12	UL	20	35%	1.218	0.805	0.0661	0.0679
	UL	100		1.219	0.805	0.0660	
	UL	250		1.216	0.840	0.0691	
13	UM	17	35%	1.205	0.277	0.0230	0.0518
	UM	100		1.216	0.559	0.0460	
	UM	400		1.222	0.672	0.0550	
14	UN	16	35%	1.219	0.868	0.0712	0.0781
	UN	100		1.220	0.916	0.0751	
	UN	300		1.225	0.979	0.0799	

15	UO	9	35%	1.208	0.471	0.0390	0.0733
	UO	100		1.220	0.784	0.0643	
	UO	500		1.231	0.937	0.0761	
16	UP	17	35%	1.218	0.756	0.0621	0.0764
	UP	100		1.220	0.930	0.0762	
	UP	500		1.225	0.944	0.0771	
17	UQ	17	35%	1.204	0.313	0.0260	0.0342
	UQ	100		1.208	0.399	0.0330	
	UQ	450		1.210	0.411	0.0340	
	UQ	800		1.211	0.424	0.0350	
18	UR	15	35%	1.205	0.217	0.0180	0.0302
	UR	100		1.207	0.314	0.0260	
	UR	450		1.207	0.338	0.0280	
	UR	800		1.215	0.413	0.0340	
19	US	9	35%	1.201	0.276	0.0230	0.0338
	US	100		1.209	0.314	0.0260	
	US	450		1.216	0.389	0.0320	
	US	800		1.224	0.465	0.0380	
20	UT	15	35%	1.209	0.278	0.0230	0.0243
	UT	100		1.203	0.277	0.0230	
	UT	450		1.208	0.266	0.0220	
	UT	800		1.210	0.327	0.0270	
21	UU	20	35%	1.206	0.350	0.0290	0.0252
	UU	350		1.211	0.291	0.0240	
	UU	700		1.214	0.316	0.0260	
22	UV	10	35%	1.208	0.242	0.0200	0.0200
	UV	100		1.208	0.242	0.0200	
	UV	500		1.208	0.242	0.0200	
23	UW	22	35%	1.226	1.030	0.0840	0.0683
	UW	100		1.228	0.784	0.0638	
24	UX	90	35%	1.226	1.130	0.0922	0.0949
	UX	300		1.228	1.180	0.0961	
25	UY	16	35%	1.208	0.254	0.0210	0.0392
	UY	100		1.213	0.340	0.0280	
	UY	300		1.220	0.500	0.0410	
	UY	600		1.216	0.511	0.0420	
26	UZ	12	35%	1.211	0.484	0.0400	0.0483
	UZ	100		1.218	0.536	0.0440	
	UZ	450		1.222	0.599	0.0490	
	UZ	800		1.220	0.598	0.0490	
27	U1	12	35%	1.215	0.701	0.0577	0.0741
	U1	400		1.226	0.895	0.0730	
	U1	800		1.228	0.930	0.0757	
28	U2	13	35%	1.212	0.640	0.0528	0.0691
	U2	100		1.219	0.750	0.0615	
	U2	200		1.221	0.791	0.0648	
	U2	300		1.222	0.826	0.0676	
	U2	400		1.226	0.909	0.0741	
	U2	500		1.228	0.916	0.0746	
	U2	600		1.228	0.895	0.0729	
29	YA	17	35%	1.207	0.435	0.0360	0.0443
	YA	100		1.210	0.557	0.0460	
30	YB	11	35%	1.202	0.144	0.0120	0.0405
	YB	100		1.208	0.338	0.0280	
	YB	500		1.213	0.534	0.0440	
31	YC	12	35%	1.202	0.120	0.0100	0.0179

	YC	100		1.204	0.229	0.0190	
32	YD	9	35%	1.203	0.229	0.0190	0.0513
	YD	100		1.209	0.496	0.0410	
	YD	450		1.217	0.621	0.0510	
	YD	800		1.218	0.670	0.0550	
33	YE	8	35%	1.205	0.193	0.0160	0.0522
	YE	100		1.213	0.509	0.0420	
	YE	450		1.247	0.673	0.0540	
	YE	800		1.226	0.661	0.0539	
34	YF	23	35%	1.202	0.0722	0.0060	0.0113
	YF	200		1.203	0.144	0.0120	
35	YG	15	35%	1.211	0.521	0.0430	0.0226
	YG	100		1.201	0.228	0.0190	
36	YH	1	35%	1.260	2.460	0.1952	0.2079
	YH	100		1.246	2.590	0.2079	
	YH	250		1.245	2.590	0.2080	
37	YI	8	35%	1.207	0.362	0.0300	0.0365
	YI	100		1.208	0.399	0.0330	
	YI	450		1.209	0.411	0.0340	
	YI	800		1.210	0.484	0.0400	
38	YJ	17	35%	1.204	0.301	0.0250	0.0560
	YJ	100		1.211	0.545	0.0450	
	YJ	400		1.222	0.743	0.0608	
39	YK	1	35%	1.204	0.325	0.0270	0.0477
	YK	100		1.207	0.410	0.0340	
	YK	400		1.216	0.584	0.0480	
	YK	700		1.220	0.634	0.0520	
40	YL	22	35%	1.201	0.156	0.0130	0.0330
	YL	100		1.209	0.375	0.0310	
	YL	400		1.209	0.423	0.0350	
Avg.		**507***	**35%**	**1.217**	**0.652**	**0.5323**	
Avg.						**0.0688****	

*Average of lowest samples at each drill hole.

**Average of all concentrations above 0.03% lithium.

Salar de Atacama

The Salar de Atacama, in northern Chile, is a 3,000 km^2 desert salt basin and the world's largest producer of lithium. Atacama's salt nucleus, in the southern half of the salar, is a layer of halite (salt) with an area of around 1,400 km^2 and a thickness of around 360 m in the center of the basin. In the uppermost 30 to 40 m of the halite layer, there are abundant pores between the halite crystals. This porous zone is referred to as an aquifer, and it contains a very saline solution called brine that contains from 900 ppm to 7,000 ppm of lithium, the world's highest known concentrations in brines of this type.[8, 55] Brine outside of this nucleus has lower but still important concentrations of lithium, up to 1,000 ppm.[55]

Two companies, Sociedad Quimica y Minera (SQM) and Rockwood Holdings, Inc., extract lithium from this brine. SQM has a claim of ~820 km^2 and two operations in the nucleus.[12] It currently produces lithium from its southwestern operation. Rockwood has a claim of ~137

km^2 and one operation in the southeast, part of which is devoted to lithium extraction. A buffer zone of around 100 km^2 separates the two companies' claims.[8]

Recent estimates for reserves of lithium contained in the aquifer range from 1.0 to 7.25 Mt (Figure 9). Tahil estimates that the aquifer contains 1.0 Mt of lithium.[12] SQM estimates that their claim contains 6.0 Mt of lithium reserves.[8] Including SQM's and Rockwood's claims, the buffer zone, and a "portion of the area to the north of the nucleus" containing 400,000 tonnes of lithium, Evans estimates that the salar contains a total of 7.0 Mt of lithium reserves.[9] Yaksic and Tilton also accept this estimate.[11] Clarke and Harben have a slightly higher value of 7.25 Mt but provide no information on why they increased the estimate.[10]

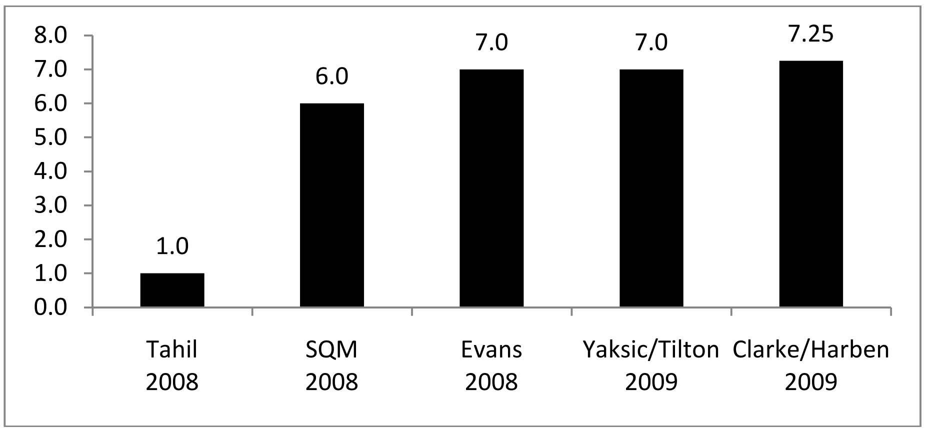

Figure 9. Estimates of lithium reserves (Mt Li) in the Atacama salar.

Resource Formula & Data

The following relation was used to estimate the lithium resource in the Salar de Atacama:

$$Lithium\ Resource = A \times T \times P \times D \times C$$

Where A = Area of aquifer, T = Thickness of aquifer, P = Porosity of aquifer, D = Density of brine, and C = Concentration of Li in brine

Information is needed on the area of the aquifer and its thickness to calculate its volume. The porosity of the aquifer is needed to understand how much brine the aquifer contains. The density for the brine corrects for the fact that it is heavier than pure water. The concentration of lithium in the brine is needed to determine the overall amount of lithium in the aquifer. The data used in this formula were obtained from published sources as noted in Table 23 and the following discussion.

A 1978 survey by CORFO and Foote Mineral Company identified five isopleths for concentration of lithium in the aquifer.[55] According to this survey, a large part of the aquifer has concentrations of more than 1,000 ppm, with progressively smaller zones having higher concentrations (Figure 10). We estimated the area of each of these (Table 21). Zone 1 has concentrations above 4,000 ppm and the smallest area, approximately 7 km^2. Zone 2 has concentrations between 3,000 and 4,000 ppm and an area of 21 km^2. Zone 3 has concentrations between 2,000 to 3,000 ppm and an area of 94 km^2. Zones 4 and 5 have the largest areas, approximately 651 km^2 each, and concentrations of 900 to 1,000 ppm and 1,000 to 2,000 ppm, respectively. The areas for Zones 4 and 5 were difficult to estimate but appeared to be of comparable size, and the same value was used for both.

A: We focused our study on the nucleus of the salar, which has been surveyed and holds the highest concentrations of lithium. Based on Kunasz's maps of Atacama, we estimated the area of the surface of the salt nucleus to be **1,424 km^2** (Figure 10). The aquifer spans beyond the nucleus; it is present underneath the entire 3,000 km^2 surface area of the salar.[9] Our estimate of the surface area of the nucleus is closest to Kunasz's estimate of 1,400 km^2.[55] Other estimates for the area include 1,100 km^2 (Warren 2010) and 1,700 km^2.[22,53]

T: The thickness of the halite body ranges from around 360 m in its center to 40 m near its southern borders;[55] however, we are only concerned with the aquifer – the porous part of the halite body, which contains the lithium-bearing brine. The aquifer consists of the top 35 m of the halite body, and only the top 30 m section has high transmissivity.[12,55] If the aquifer is lens-shaped, its center would have a thickness of 30 m and its edges a thickness of 0 m, with **an average of 15 m** across all zones. This average value was used in our estimate.

P: Porosity of the aquifer decreases substantially with depth. According to Garrett, the porosity of the aquifer decreases from 30% for the top 0.5 m to 5% at a depth of 25 m (Table 20) and averages 18%.[22] Other estimates include 10% for the upper 30 m of the nucleus, by CORFO and 4.4% at a depth of 40 meters for SQM's claim area, by Hydrotechnica.[12] We have used the **18%** value estimated by Garrett.

Table 20. Porosity decreases with depth at Atacama.

Depth (m)	Porosity
0 – 0.5	30%
0.5 – 2	20%
2 – 25	15%
25 – 35	5%
> 35	0%

Source: Garrett 2004

D: The brine has a density of **1.2 g/cc**, according to Tahil.[12] No other information on the density of the Atacama brine was found, but 1.2 g/cc is the value used for other South American brines (see Uyuni, Rincon, and Hombre Muerto case studies).

C: Average lithium concentrations for each zone were calculated by averaging lithium concentrations for the upper and lower concentration contours for each zone. Based on these ranges the average lithium grades for each zone are 5,500, 3,500, 2,500, 1,500, and 950 ppm for Zones 1 through 5, respectively (Table 21). The weighted average of these concentrations, by area of each zone, is **0.14%**, which is equivalent to the average concentration for the entire aquifer cited in the literature.[9,55]

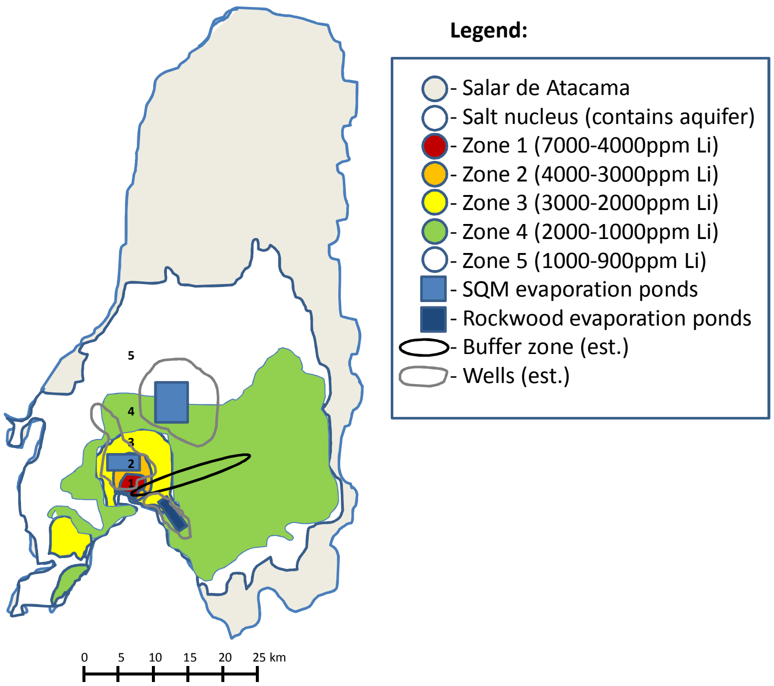

Figure 10. Map of Atacama showing location variations in concentration of lithium in the brine.

All authors agree that the Atacama brines have a low ratio of magnesium to lithium; therefore, impurity is not a burdensome factor in processing. All authors also agree that Atacama's high rate of evaporation makes concentration of lithium in brine pools easier than in other, less arid regions. Neither of these factors needs to be taken into account when calculating the lithium resources in Atacama's aquifer, but they would need to be considered to evaluate the costs of processing lithium reserves.

Results

Applying the data from above into the formula, the estimated resource for the Salar de Atacama's nucleus is **6.3 Mt of lithium** (Table 21). We recognize that the nucleus has a large area with high concentrations of lithium and that certain parts might be classified as reserves. However, no information was found to indicate that any part of the Atacama area contains reserves that are NI 43-101 compliant, or equivalent.[§]

The following table presents the hierarchy of resources present in the nucleus.

[§] National Instrument 43-101 is an internationally recognized mineral resource classification standard. It is comparable to the Joint Ore Reserves Committee (JORC) Code.

Table 21. Data and Estimate of the Lithium Resource within the Atacama Salt Nucleus.

Zone	Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (ppm Li)	Resource (tonnes)
1	7	15.0	18%	1.2	5,500	124,740
2	21	15.0	18%	1.2	3,500	238,140
3	94	15.0	18%	1.2	2,500	761,400
4	651	15.0	18%	1.2	1,500	3,163,860
5	651	15.0	18%	1.2	950	2,003,778
Total	**1,424**					**6,291,918**

Using the same methods, but an average porosity of 10% based on CORFO's original estimate, the total estimated lithium resource in Atacama's nucleus is 3.5 Mt. As this estimate demonstrates, the aquifer's porosity is a sensitive variable.

Lower estimate

Tahil used an estimate of 40 m for the aquifer's thickness and CORFO's porosity figure of 10% to calculate reserves for Zones 1 and 2.[12] Tahil used a thickness of 40 m, although in his summary he stated: "Lithium is only found in the top 35 metres of the Salar de Atacama."[12] Tahil did not calculate reserves for Zones 3, 4, and 5; however, satellite images of Atacama reveal that SQM and Rockwood are extracting brine from these zones. They might be processing lithium from these zones already; if not, they already have the wells drilled and could begin processing lithium in the future, since the concentrations of lithium present are attractive (Figure 10). SQM, which is already producing potash from its northernmost plant in the aquifer, can likely begin concentrating lithium when there is enough demand.

Table 22. Tahil's Reserve Estimate for Zones 1 and 2.

Zone	Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (ppm Li)	Reserve (tonnes)
1	8	40.0	10%	1.2	4,000	150,000
2	20	40.0	10%	1.2	3,000	288,000
Total	**28**					**438,000**

Tahil cited porosity figures for the southern edge of the nucleus of between 0.43 and 5.25% (from Garrett, 2004),[12] but it is unclear if these figures were used to calculate the reserve for this region. Tahil also mentioned the work of the UK consultancy, Hydrotechnica, which calculated a "mean effective porosity of the Salar de Atacama in the upper 40m of SQM's 820km^2 claim area" of 4.4%.[12] Tahil reported that this would reduce the lithium reserves for Zones 1 and 2 to just 200,000 tonnes.[12]

For his overall estimate, Tahil states: "With a 50% recovery factor and taking into account the reality from studying the [Li] contour map that only the higher concentration areas of the salar might be exploited, the upper limit to Recoverable Reserves cannot exceed 1.0MT."[12] Tahil does not state how he evaluated the reserves beyond Zones 1 and 2.

Higher estimates

Our estimate of 6.3 Mt of lithium in the nucleus is comparable to Evans's estimate of 7.0 Mt and Clarke and Harben's estimate of 7.25 Mt for the entire salar.[9,10] Specific information is not available on how Clarke and Harben made their estimate, but Evans estimated the overall reserves across the salar by summing "the Chemetall [Rockwood] claims, the SQM claims, the buffer zones between them and a portion of the area to the north of the nucleus."[9] Evans's 7.0 Mt value includes 6.6 Mt for the nucleus and 400,000 tonnes of lithium reserves for the area to the north of the nucleus.[8] It is not clear what specific information was used for these sums. As Evans points out, a Chilean company plans to produce 200,000 tpa of potash from a region north of the nucleus.[9] There is a possibility that this company, or others, might set up operations to extract lithium.

Conclusion

Our estimate of the salar's total resources of lithium is conservative, since brines with concentrations as high as 1,000 ppm are present outside the salar's nucleus.[55] Silver Peak, in Nevada, has the world's lowest lithium concentration for a brine deposit that is producing, ranging from 0.01 to 0.03% lithium.[9] Applying this same lithium concentration outside of Atacama's nucleus, which has a minimum concentration of 0.09%, a portion of the salar above the nucleus has lithium that might be extracted economically. It is unknown how much lithium is available above the nucleus. We can only report what we know; the total **lithium resource in Atacama is greater than 6.3 Mt.**

Table 23. Atacama Data.

	Kunasz (2006)[55]	Kunasz (1989)[58]	Warren (2010)[53]	Garrett (2004)[22]	Tahil (2008)[12]	Evans ("Know Limits"2008)[73]	Evans ("Abundance2" 2008)[9]	Yaksic/ Tilton (2009)[11]
Area of Salar (km2)	3,000			3,000	3,500	3,000	3,000	
Area of nucleus (km2)	1,400		1,100	1,700	1,000-1,400	1,400		
Halite thickness (m)	40-360	up to 390		up to 800				
Aquifer thickness (porous halite) (m)	35	30	35	35	35	40	40	
Porosity (%)			18%	18%	10%			
Concentration (%Li)	0.14%	0.15%		0.15%		0.14%	0.14%	
Reserve (Mt)					1.0	6.9	7.0	7.0
Resource (Mt)	4.3	4.6			3.0			35.7

Kings Mountain Belt

The Kings Mountain Belt, in North Carolina, contains spodumene pegmatite ($LiAlSi_2O_6$) deposits. The largest of these is the Kings Mountain deposit, now owed by Rockwood Holdings Inc, a subsidiary of Chemetall Foote Corporation. The next largest lithium pegmatite deposit in the area is Cherryville, first mined by the Lithium Corporation of America. Major recovery of lithium from Kings Mountain began in the 1960s but ceased in 1984 when South American brine deposits came on line; according to the USGS the mine officially closed in 1991 and the plant was dismantled in 1994. [22] In 2009 Rockwood received $28.4 million from the U.S. government "to expand and upgrade the production of lithium carbonate at the company's Silver Peak, Nevada, site and add the production of very high purity lithium hydroxide to the company's Kings Mountain, North Carolina, facility."[59] Rockwood is not producing lithium carbonate with North Carolina.

Lithium reserve and resource estimates for the Kings Mountain belt were reported by Kesler (1978), based on the 1976 National Research Council Panel on Lithium, to include:

- Cherryville deposit: 22.6 Mt containing 0.65% Li (146,900 tonnes Li content)
- Kings Mountain deposit: 18,900,000 Mt containing 0.7% Li (132,300 tonnes Li content)
- Unexplored deposits: 750 Mt containing 0.69% Li (5.175 Mt Li content).[28]

Kesler estimated a total of **5.454 Mt of lithium resources** in the Kings Mountain Belt, which we used for this study.

The cost of extracting lithium from ore is much higher than extracting from brines. Tahil quotes Pavlovic, who estimated lithium carbonate production from three different deposits.

Table 24. Comparing lithium production costs (Source: Pavlovic[20])

Deposit	Type	Cost per kg Li_2CO_3
Bessemer City, North Carolina	Spodumene	$2.43
Silver Peak, Nevada	Brine	$1.65
Atacama, Chile	Brine	$1.10

Qaidam Basin

The Qaidam Basin, also known as Tsaidam Basin,[60] occupies the northwestern part of China's Qinghai province on the Plateau of Tibet.[60] The basin has an area of 34,700 square miles and contains 37 lakes, of which 28 are considered salt lakes located at an average elevation of 9,150 feet over sea level.[61] Lakes in the basin are characterized by higher Mg/Li ratios and lower Li concentration than lakes in the rest of the Qinghai-Tibet Plateau.[62] High Mg/Li ratios had been a hindrance to lithium extraction; however, in 2004, Blue Star Changsha Design and Research Institute demonstrated the feasibility of commercial production of lithium carbonate with a new technology to treat these high-Mg content brines.[63]

Reserves estimates for deposits in the Qaidam Basin range from 1 to 3.1 Mt. An important reason for the difference is that Garret (Tahil references Garret's figure) and Evans give resources estimates for one lake only; whereas Clarke and Harben, and Yaksic and Tilton give estimates for three lakes and the whole basin, respectively. Another reason for the difference might be the lack primary of data available and the fact that some articles use significantly different spellings for the translation of lakes' names. This is an issue we faced while completing this analysis and one that Evans cited as a reason for the reduced reliability of the Chinese reserve estimates he presents. [8]

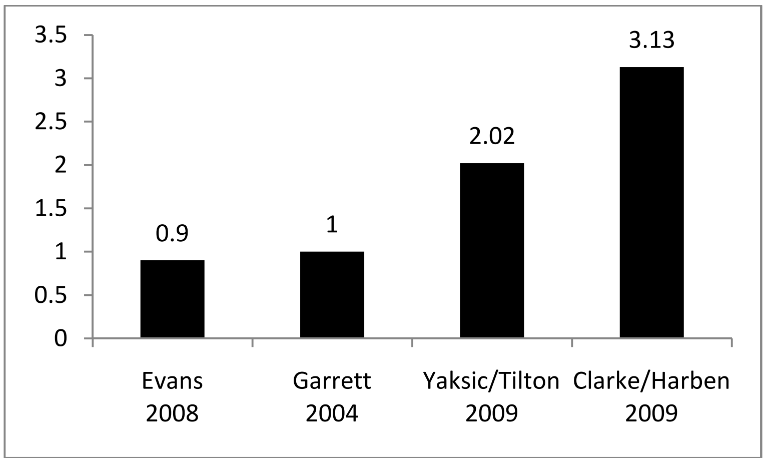

Figure 11. Estimates of lithium reserves (Mt Li) in the Qaidam basin, China.

We focus our analysis on lakes Xitai, Dongtai, and Chaerhan which are the same as those considered in the estimates by Garret (2004), Clarke and Harben (2009), and Evans (2008). Yaksic and Tilton do not specify which lakes are being considered in their 2.02 Mt estimation.

There are no data publicly available to support an independent estimate of lithium reserves of Chaerhan Lake. Instead, we use the reserve estimates published by Qinghai Salt Lake Industry. This company is extracting lithium from the Chaerhan Lake deposit and says it has proven reserves of 8 Mt of lithium chloride,[64] equivalent to 2.6 Mt of lithium.

Xi Taijnar Lake (also spelled Xitaiji'er and Xitai)[10,65] has an area of 82.4 km^2. Lithium is being extracted from Xitai Lake by Qinghai Guoan, a subsidiary of CITIC Guoan Information Industry Co. Ltd. Qinghai Guoan Co's plant has a 5,000 tpa Li_2CO_3 capacity and is projected to expand to 30,000 tpa.[10]

Dong Taijnar Lake (also spelled Dongtai)[10] has an area of 116 km^2. Lithium extraction in Dongtai is being done by Qinghai Salt Lake Industry, whose plant has a 3,000 tpa Li_2CO_3 capacity and is projected to expand to 20,000 tpa.[10]

The hydrochemistry of both lakes is very similar. For example, brines at Xitai contain 29.03 (mg/L) of Li^+ and those at Dongtai contain 22.91.[62] No information on the lithium concentration in Xitai's brine was available; but, given Xitai and Dongtai similar hydrochemical characteristics, it was assumed that both brines are identical. Dongtai's intercrystal brine has a concentration of 638 (mg/L) and its surface brine has a concentration of 117 (mg/L) of Li. [62] Depth of surface brine is approximately 0.3 meter and 0.6 meter for Xitai and Dongtai, respectively.[61]

Lithium content in surface brine was calculated multiplying surface brine's depth, Li concentration, and the lakes' area. Thus,

$$\begin{aligned}\text{Xitai}_{Surface\ Li} &= 82.4[km^2] \times 0.3[meter] \times 117\left[\frac{mg}{L}\right] \\ &= 2{,}892[tonnes] \\ \text{Dongtai}_{Surface\ Li} &= 116[km^2] \times 0.6[meter] \times 117\left[\frac{mg}{L}\right] \\ &= 8{,}143[tonnes]\end{aligned}$$

No data were available to determine the thickness of intercrystal brines. So, instead of assessing lithium reserves, we calculated what thickness the brine should have in order to contain the reserves quoted in previous estimates (Figure 11). Then, we evaluated whether this thickness makes sense. In other words,

$$\begin{aligned}Thickness &= \frac{Reserve_{Intercrystal}}{A \cdot P \cdot C} \\ &= \frac{Reserve_{Total} - Reserve_{Surface}}{A \cdot P \cdot C}\end{aligned}$$

Garret says Qinghai Lake has 1,000,000 tonnes of lithium reserve; when citing Garret, Tahil says Qinghai is the same as Taijinaier Lake. [12] We assumed Taijinaier is another spelling for Taijnar and that this word is used to describe both lakes: Xitai and Dongtai. We also assumed Taijnar's brine porosity is similar to Salar de Atacama's. Applying the formula,

$$\begin{aligned}Thickness_{Garret} &= \frac{1[M\ tonnes] - (2{,}892 + 8{,}143)[tonnes]}{(82.4 + 116)[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} \\ &= 49[m]\end{aligned}$$

Clarke & Harben give reserve estimates for each lake separately. The brine thickness for each lake would have to be,

$$\begin{aligned}Thickness_{Clarke\&Harben_{Xitai}} &= \frac{502\ [k\ tonnes] - 2{,}892[tonnes]}{82.4[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} \\ &= 59[m]\end{aligned}$$

$$\begin{aligned}Thickness_{Clarke\&Harben_{Dongtai}} &= \frac{1.3\ [M\ tonnes] - 8{,}143[tonnes]}{116[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} \\ &= 109[m]\end{aligned}$$

Like Garret, Yaksic & Tilton do not break down reserve estimates between the lakes and give a total for Taijnar. With this value, brine thickness would have to be,

$$Thickness_{Yaksic\&Tilton} = \frac{260[k\ tonnes] - (2{,}892 + 8{,}143)[tonnes]}{(82.4 + 116)[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} = 12[m]$$

Similarly, Evans presents aggregated reserves for Taijnar lakes; accordingly,

$$Thickness_{Evans} = \frac{940[k\ tonnes] - (2{,}892 + 8{,}143)[tonnes]}{(82.4 + 116)[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} = 46[m]$$

Table 25 presents a summary of the thicknesses calculated above. For comparison, the Salar de Atacama brine has an average thickness of 15 meters. Given that the aquifer thickness calculated from the Yaksic and Tilton estimate comes close to this value, we will use their reserve estimate of **2.02 Mt of lithium** for the Qaidam basin.

Table 25. Summary of calculated brines thickness.

	Thickness (in meters)			
Deposit	Garret	Clarke&Harben	Yaksic&Tilton	Evans
Taijnar	49	-	12	46
Xitai	-	59	-	-
Dongtai	-	109	-	-

Kings Valley, Nevada

Kings Valley, Nevada is a hectorite clay deposit being explored by Western Lithium Corp. The company estimates its lithium resource, for one of its five lenses, totals 240,000 tonnes.[66]

Western Lithium has an NI 43-101 compliant report for one lens of 2,889 hectares (about 26 km^2), out of the five lenses.[14] This report was based on surveying of 70 drill holes by Tyree Surveying Company, Albuquerque, New Mexico and Desert Mountain Surveying Company, Winnemucca, Nevada for Chevron Corp. in 1980. It determined that the PCD lens owned by Kings Valley contains 86.4 Mt of ore and an average lithium concentration of 0.27%.[14] This equates to a lithium resource of over 233,000 tonnes of lithium, consistent with the value above.

Chevron inferred a resource of over **2.0 Mt of lithium** for all five lenses, based on its surveying in the 1980s. This is the value we used in our study.

Zabuye Salt lake and DXC

Zabuye (also spelled Zhabuye[8, 12] and Zabuye Caka[67]) and DXC (also spelled Dangxiongcuo[10] and Damxung Co[67]) salt lakes are located in the southwestern region of the Tibet Plateau, a region in which lakes with high lithium content and low Mg/Li ratios predominate.[62]

Reserve estimates for deposits in these two lakes range from 1 to 1.7 Mt. With the exception of Garrett, who only gives reserves for Zabuye, there seems to be little difference among the other authors with regards to lithium reserves. All authors say Zabuye's brine contains 1.53 Mt of lithium. DXC's brine contains 140,000 tonnes according to Clarke and Harben, and Yaksic and Tilton; and 170,000 tonnes according to Evans.

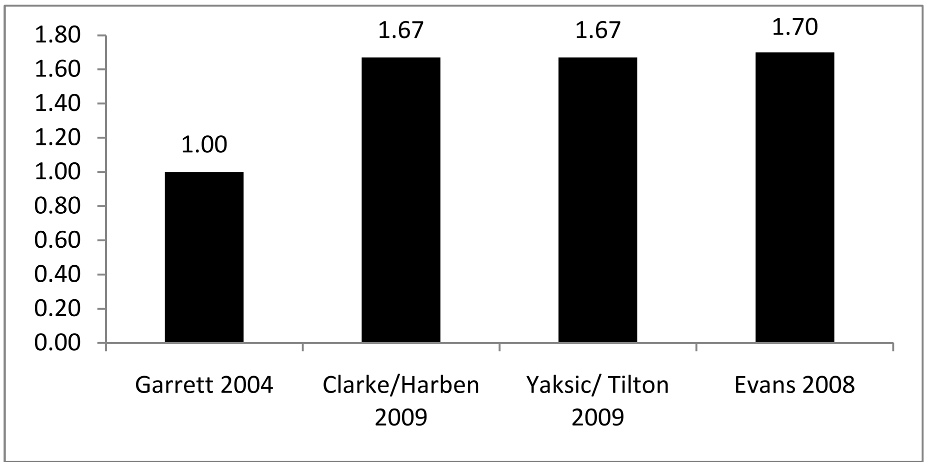

Figure 12. Estimates of lithium reserves (Mt Li) in the Zabuye and DXC deposits, China.

Zabuye consists of two lakes (South and North Zabuye) connected by a channel.[67] South Zabuye has an area of 145 km^2 and presents intercrystal and surface brine; North Zabuye's area is 98 km^2 and only presents surface brine. [67] Lithium concentration is 1,413 (mg/L) in South Zabuye's intercrystal brine, 896 (mg/L) in South Zabuye's surface brine, and 1,527 (mg/L) in North Zabuye's surface brine.[62] Zabuye Caka's mean depth is 70 (cm).[68] Lithium is being extracted from Zabuye by ZBY Saline with reported capacity of 7,500 tonnes of Li_2CO_3 in 2004.[18]

Lithium content in surface brines at Zabuye was calculated multiplying surface brine's mean depth, Li concentration, and the lakes' area. Thus,

$$\begin{aligned} \text{North Zabuye}_{Surface\ Li} &= 98[km^2] \times 0.7[meter] \times 1527 \left[\frac{mg}{L}\right] \\ &= 104{,}750[tonnes] \\ \text{South Zabuye}_{Surface\ Li} &= 145[km^2] \times 0.7[meter] \times 896 \left[\frac{mg}{L}\right] \\ &= 90{,}940[tonnes] \end{aligned}$$

No data were available to determine the intercrystal brine's porosity or thickness. We assumed porosity is equal to Salar de Atacama's and, instead of assessing lithium reserves, we calculated what thickness the brine should have in order to contain the reserves quoted in previous estimates (Figure 11). Then, we evaluated whether this thickness makes sense.

$$Thickness = \frac{Reserve_{Intercrystal}}{A \cdot P \cdot C} = \frac{Reserve_{Total} - Reserve_{Surface}}{A \cdot P \cdot C}$$

$$Thickness = \frac{1.53\,[M\ tonnes] - 197[k\ tonnes]}{243[km^2] \cdot 16\% \cdot 638\left[\frac{mg}{L}\right]} = 24[m]$$

This thickness (i.e., 24 meters) is reasonable when compared to Salar de Atacama's average aquifer thickness of 15 meters. Hence, we consider the **1.53 Mt of lithium resource** estimated for Zabuye by Clarke and Harben (2009), Yaksic and Tilton (2009), and Evans (2008) to be a sensible value.

DXC Lake's lithium resource is being exploited by Tibet Saline Lake Mining High-Science & Technology Co., a joint venture between Sterling Group Ventures and Zhong Chuan. [69] Production capacity is 5,000 tonnes of Li_2CO_3 capacity annually.[10]

DXC Lake has an area of 55.5 km^2 and an average depth of 7.6 meters.[70] Its brine lithium concentration is 430 (mg/L).[71] With this information, the lithium resource was calculated.

$$\mathrm{DXC}_{Surface\ Li} = 55.5[km^2] \times 7.6[meter] \times 430\left[\frac{mg}{L}\right] = 181{,}300[tonnes]$$

The value for lithium resource calculated above is higher than reserve estimates published by all the authors represented in Figure 11. It is also higher than 748,490 tonnes of Li_2CO_3, or 141,600 tonnes of lithium, with is DXC's average reserve of Li_2CO_3 as certified by the Ministry of Land and Resources of China.[71]

We used our estimate of **181,300 tonnes of lithium resource for DXC**.

Manono and Kitotolo, Katanga province, Congo

Kitotolo (also spelled Kitolo) is a spodumene deposit in Congo. Kesler (1978) reported reserves of 120,000 tons of ore containing 0.6% Li (contained Li of 720,000 tons) and an additional resource of 400 Mt of ore containing 0.6% Li for a contained Li of 2.4 Mt.[28] More recently Clarke and Harben estimate that Manono contains 835,000 tonnes and Kitotolo contains 310,000 tonnes of lithium resources, for a total resource estimate of **1.145 Mt** of lithium, which is the value we used.[10]

Salar de Rincon

The Salar de Rincon is a 250[72] to 280 km^2 [8] playa in a closed basin in northern Argentina, about 130 km north of Salar del Hombre Muerto.[7] Brine in the salar has an average lithium concentration of 330ppm.[73]

Compared to other playas on the Altiplano, Rincon has lower concentrations of lithium and a higher magnesium to lithium ratio. Since 1999, Admiralty Resources has sampled brines in the salar; by 2007 it had drilled 7 production wells and established a 1:100 scale pilot facility.[72] Admiralty sold the rights to Rincon to the Sentient Group in December 2008. Sentient plans to produce KCl, Na_2SO_4 and NaCl, in addition to lithium, which will be a byproduct. [12] Its pilot plant produced 12 tonnes of Li_2CO_3 in 2008,[74] and information on additional production is not available.

Most experts estimate Rincon's lithium reserves to be about 1.4 Mt, based on Admiralty's own reporting of proved and probable lithium reserves. As with other deposits, Tahil produces a more conservative estimate of 0.25 Mt of lithium (Figure 13).

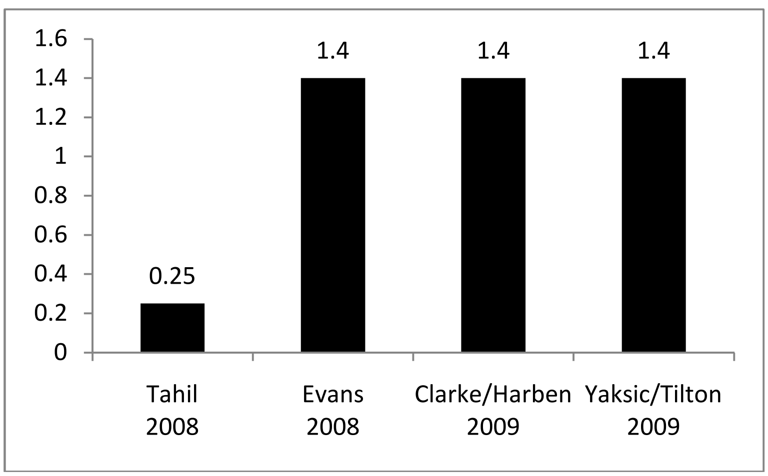

Figure 13. Estimates of lithium reserves (Mt Li) in the Salar del Rincon.

Resource Formula & Data

The following relation was used to estimate the lithium resource in the Salar del Rincon:

$$Lithium\ Resource = A \times T \times P \times D \times C$$

Where A = Area of aquifer, T = Thickness of aquifer, P = Porosity of aquifer, D = Density of brine, and C = Concentration of Li in brine

The data used in this formula were obtained from published sources as noted in Table 27 and the following discussion. There was no comprehensive source of primary data available other than Admiralty's estimates.

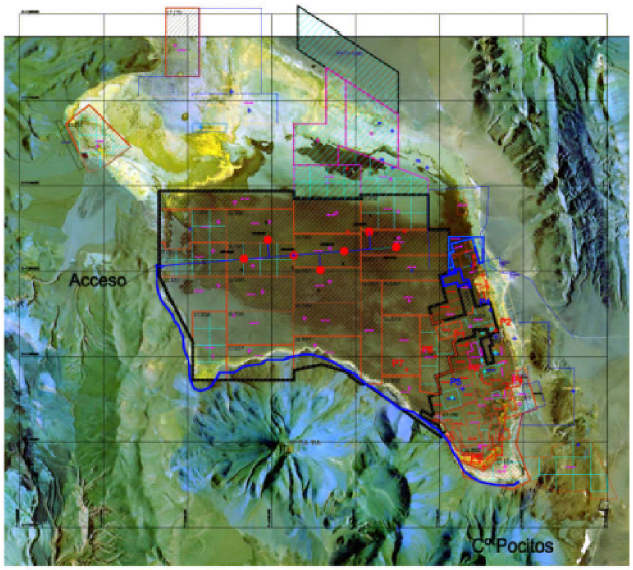

Figure 14. Admiralty's 2006 proposed site plan for the Salar del Rincon (Source: Admiralty 2006).

A: The surface area of the salar is **250 km^2**.[72] Admiralty has surveyed large sections of the salar and has drilled 7 production wells in the center of the salar in a west-east direction (Figure 14).

T: Admiralty has surveyed large sections of the salar and has drilled seven production wells in the center of the salar in a west-east direction (Figure 14). Industrial Minerals magazine reported in 2007 that Rincon's brine zone averages 40 m in thickness and has a maximum thickness of 60 m.[72] Assuming the aquifer is lens-shaped, the center has a maximum thickness of 60 m, and the edges have a thickness of 0, the average thickness is **30 m**.

P: Industrial Minerals reported in 2007, based on preliminary hydrological testing, that the average porosity of the aquifer was approximately 23%. Tahil reported that a consultant to Admiralty, Pavlovic, estimated porosity at 8 to 10%, based on similar salars in the area.[12] Admiralty reported a porosity of 38%, based on the presence of large cavities of brine within the halite. Five of the seven wells that Admiralty drilled have average porosities of 38%; the remaining 2 wells have low porosities of 4.7 and 8%.[12] Assuming these wells will yield similar amounts of lithium, the average porosity from these seven wells is **30%**, which is the value we used in our estimate.

D: In absence of information on this brine, we used the average density of **1.2 g/cc** that was used for estimates at Atacama and Hombre Muerto.

C: Estimates of average lithium concentration fell within a tight range. Evans, Tahil, and Clarke and Harben all used 0.033% lithium. Yaksic and Tilton used a higher value of 0.04% lithium. We used the more conservative value of **0.033% lithium**.

Results

Applying the data from above into the formula results in an **estimated resource of 1.1 Mt of lithium** in the Salar del Rincon (Table 26).

Table 26. Data and Estimate of the Lithium Resource within the Salar del Rincon.

Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (%Li)	Resource (tonnes)
250	40	30%	1.2	0.033%	1,118,000

Tahil reported that Admiralty estimated its proven reserves at 911,000 tonnes (+/- 53,000) and its probable reserves at 492,000 tonnes (+/- 72,000).[12] In other words, Admiralty believes it has proven 54% of its reserves. As with other deposits, Rincon does not have production of lithium and has not been rated NI 43-101 compliant. So, these values are not reported here as reserves.

Evans, Clarke and Harben, and Yaksic and Tilton's estimates are based on Admiralty's reports. Admiralty may have reached its estimate of 1.4 Mt with higher values for area, thickness, and/or porosity than ours. For example, applying an area of 280 km^2, and increasing the porosity to 31 or 32% would result in a 1.4 Mt lithium resource estimate.

Tahil's estimate of 250,000 tonnes of lithium reserves is also based on Admiralty reports, but Tahil applies a porosity of 10%, and then discounts the resulting resource estimate by 50% to reach his reserve estimate.

Table 27. Rincon data from the literature.

	Industrial Minerals Exposure 2007	Evans ("Abun-dance2" 2008)	Evans ("Abun-dance1 2008)	Hallgarten & Company 2008	Tahil (2008)	Clarke/ Harben 2009	Yaksic/ Tilton 2009
Area of Salar (km2)	250						
Area of nucleus (km2)			280				
Aquifer thickness (porous halite) (m)	40						
Porosity (%)	~23%				8-10% OR 38%		
Concentration (%Li)		0.033	0.033		0.033	0.033	0.04
Magnesium/ lithium			8.6/1		8.6/1		
Reserve (Mt)		1.40	1.86	1.4	0.25	1.4	1.4
Resource (Mt)					0.5		

Brawley

The Brawley geothermal brine is to the south of the Salton Sea and shares many of the same characteristics, though it is smaller. Clarke and Harben estimate it contains a lithium resource of **1.0 Mt**;[10] although no further data is on the deposit is provided.

Jadar Valley

The Jadar Valley, in Serbia, contains lacustrine evaporite deposits containing jadarite ($LiNaB_3SiO_7(OH)$), a new mineral that is a possible source of lithium and boron.[24, 25] The jadarite deposit occupies an area of almost 5 km^2. The only primary data available on this deposit is from Rio Tinto, which completed an "Order of Magnitude study" to estimate Jadar's lithium resource in January 2009.[75] Using Rio Tinto's recent data, the following formula was used to calculate the lithium resource in the Jadar Valley:

$$Lithium\ Resource = T \times C$$

Where T = Tonnes of ore and C = Concentration of Li in ore.

T: The amount of ore present in the region of interest, the Lower Jadarite Zone, is 114.6 Mt.[75]

C: The average concentration of lithium in this ore is 1.8% Li2O[**].[75]

This equates to a resource of around **990,000 tonnes of lithium**, which we used for our study. Rio Tinto has conducted a feasibility study, which proposes extracting 1 Mt of ore per year, from which lithium carbonate and boric acid would be produced.[75]

According to Clarke and Harben, Jadar's resource totals 957,000 tonnes of lithium and has a lithium concentration of 0.096%.[10] Clarke and Harben do not provide information on how they made this estimate. Evans estimated the lithium tonnage at 850,000 tonnes, based on other data from Rio Tinto.[8] These estimates, based on slightly older information, are comparable to ours.

Salar de Hombre Muerto

The Hombre Muerto salar is a 565 km^2 playa in Argentina with a 280 km^2 salt nucleus in its southeast section.[8, 22] The salar contains brines with concentrations ranging from 190 to 900ppm lithium.[22] Compared to Atacama and Uyuni, Hombre Muerto has lower concentrations of lithium but also very low levels of magnesium, which can cause problems in processing of brines to extract lithium.

[**] Li_2 (metal) = Li_2O * 0.481

FMC Corp. obtained the rights to Hombre Muerto from the Argentinean government in 1995,[73] and Kunasz estimated that its lithium reserves will last 75 years.[22] FMC has been producing lithium chloride at Hombre Muerto since 1997,[76] although it has had difficulties producing lithium carbonate.[12, 22]

Recent estimates for Hombre Muerto's lithium reserves range from 0.4 to 0.850 Mt.

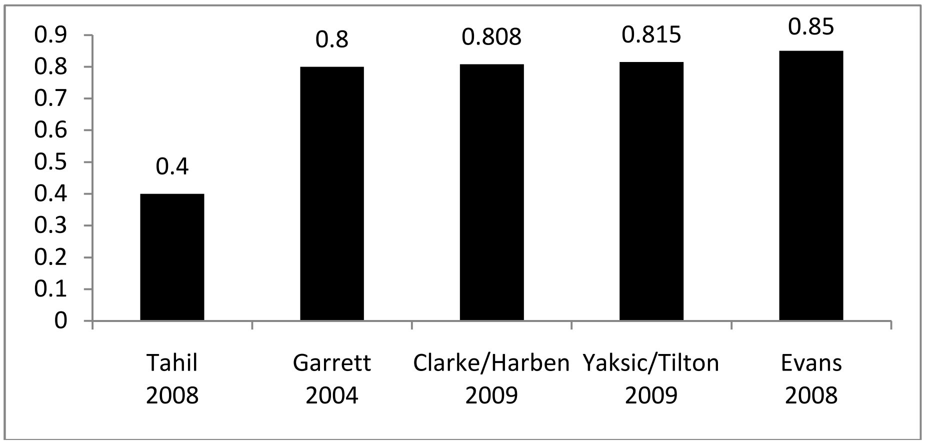

Figure 15. Estimates of lithium reserves (Mt Li) in the Salar del Hombre Muerto.

Resource Formula & Data

The following relation was used to estimate the lithium resource in the Salar del Hombre Muerto:

$$Lithium\ Resource = A \times T \times P \times D \times C$$

Where A = Area of aquifer, T = Thickness of aquifer, P = Porosity of aquifer, D = Density of brine, and C = Concentration of Li in brine

The data used in this formula were obtained from sources as noted in Table 30 and the following discussion. Garrett (1998) compiled data from one source of primary data: Authors Nicolli, Suriano, Mendez, and Peral's 1982 study[77] consisted of 100 drill holes to depths of 0.2 to 1 m (most of which were 0.7 to 0.9 m) and 1 additional hole of 15 m, of which samples at 0.5 m intervals were taken.[78] Data from 35 of the 100 drill holes are profiled in the Figure below and in Table 31. .

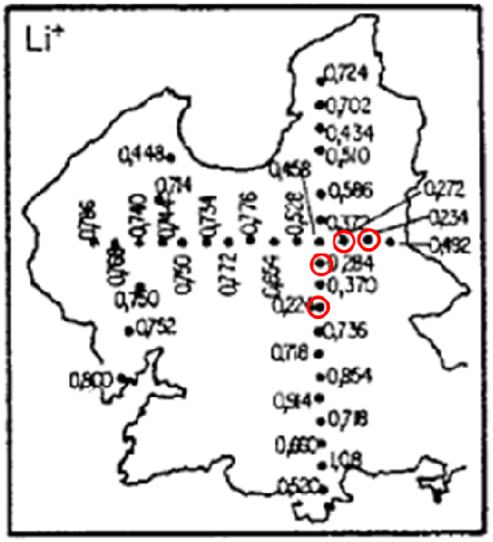

Figure 16. Li brine analysis (g/L) across the Salar del Hombre Muerto; concentrations below 0.03% Li are in red (Adapted from Garrett[22]).

A: The surface area of the salar is **565 km2**.[22] Because high concentrations of lithium were found across the entire salar, this was the surface area we used for our estimate.

T: Nicolli et al[77] drilled 100 holes to depths of up to 1 m. Garrett used this information to report an average thickness of **15 m**, which we used for this study.

P: Based on Nicolli et al's report, Garrett assumed a porosity of around **15%**,[22,78] which we used for this study.

D: In the absence of measurements of density, we used an average density of **1.2 g/cc**, which is similar to that at Uyuni where do have information.

C: Estimates of lithium concentration fell within a tight range (Table 28). Both Warren[53] and Clarke and Harben[10] reported 0.052%, which was also quoted by Garrett.[22] Yaksic & Tilton[11] and Evans[8] have higher values but do not report how these were calculated. Tahil noted that FMC extracts lithium from an area (its size is not disclosed) that has a concentration of 650 ppm lithium.[12] For our estimate, we used Garrett's average lithium concentration of **0.052%**, which is based on Nicolli et al's 100 samples from the top 1 m of the aquifer plus the additional samples from the 15 m hole. Garrett noted that the 15 m hole "had almost the same analyses for all of the 0.5-m intervals, but packers were not used to isolate the samples."[78] Recognizing that we lack better data from more holes to at least 15 m depths, we used 0.052% as the best known estimate.

Table 28. Estimates of lithium concentration in the Salar del Hombre Muerto.

Warren 2010	Clarke/Harben 2009	Garrett 2004	Yaksic/Tilton 2009	Evans 2008	Evans 2009
0.052%	0.052%	0.052%	0.060%	0.062%	0.064%

Results

Applying the data from above into the formula results in an estimated **resource of 0.8 Mt of lithium** in the Salar del Hombre Muerto (Table 29).

Table 29. Data and Estimate of the Lithium Resource within the Salar del Hombre Muerto.

Area (km^2)	Avg. Aquifer Thickness (m)	Avg. Porosity	Density (g/cc)	Avg. Grade (%Li)	Resource (tonnes)
565	15	15%	1.2	0.0521%	794,786

This figure is not reported here as lithium reserve, as no information was found to indicate that measurements meet the requirements for NI 43-101 certification.

Tahil calculated Hombre Muerto's reserves based on the 280 km^2 salt nucleus, whereas we used the surface area of the entire salar to calculate resources. As Figure 16 shows, there were high concentrations across the salar.

Table 30. Hombre Muerto data.

	Warren (2010)[53]	Evans (2009)[50]	Garrett (2004)[22]	Evans, "Know Limits" (2008)[73]	Evans, "Abundance2" (2008)[9]	Evans, "Abundance" (2008)[8]	Clarke/ Harben (2009)[10]	Tahil (2008)[12]	Yaksic/ Tilton (2009)[11]
Area of Salar (km2)			565						
Area of nucleus (km2)				280		280			
Elevation (m)				4000		4000			
Halite thickness (m)	40-50		>50	70	70				
Aquifer thickness (porous halite) (m)	15		15						
Porosity (%)	15%		15%						
Concentration (%Li)	0.052%	0.064%	0.0521%	0.0620%	0.062%		0.0520%	0.022-0.1%	0.0600%
Mg/Li				1.37/1					
Reserve (Mt)			0.8	0.85		0.85	0.808	0.4	0.815
Resource (Mt)								0.8	
2008 Production (tonnes Li)							3,300		

Table 31. Hombre Muerto survey data; concentrations in red are below 0.03% Lithium cutoff (adapted from Garrett 2004).

Drill Hole	Li (g/l)	Grade (%Li)		Drill Hole	Li (g/l)	Grade (%Li)
1	0.448	0.0373		20	0.724	0.0603
2	0.786	0.0655		21	0.702	0.0585
3	0.769	0.0641		22	0.434	0.0362
4	0.75	0.0625		23	0.51	0.0425
5	0.752	0.0627		24	0.586	0.0488
6	0.8	0.0667		25	0.372	0.0310
7	0.714	0.0595		26	0.284	0.0237
8	0.74	0.0617		27	0.37	0.0308
9	0.744	0.0620		28	0.224	0.0187
10	0.75	0.0625		29	0.718	0.0598
11	0.772	0.0643		30	0.854	0.0712
12	0.734	0.0612		31	0.914	0.0762
13	0.776	0.0647		32	0.718	0.0598
14	0.654	0.0545		33	0.66	0.0550
15	0.528	0.0440		34	1.08	0.0900
16	0.458	0.0382		35	0.52	0.0433
17	0.272	0.0227			**Average**	**0.05201**
18	0.234	0.0195			**Max**	**0.0900**
19	0.492	0.0410			**Min**	**0.0187**

Smackover Formation

Smackover is a set of oilfield brines in Texas, Arizona, Oklahoma, North Dakota, and Wyoming and a potential source of lithium.[19] Clarke and Harben[10] and Evans[8] report a resource of 750,000 tonnes; it is unclear, however, if this value is based on Collins' and Dow's average lithium concentrations of 146 ppm[19] and 170 ppm,[79] respectively. Garrett[22] and Yaksic and Tilton[11] estimate the brines contain 1.0 Mt. No one is mining any of the oilfield brines for lithium; however, they may be potential source of lithium in the future. We used the more conservative value of **750,000 tonnes of lithium resource** for our study.

Other Chinese mineral deposits

Clarke and Harben, Yaksic and Tilton, and Evans give resource estimates for several Chinese deposits (Table 32).

Table 32. Other Chinese lithium mineral resources (in thousand tonnes).

Deposit (Province)	Clarke and Harben	Yaksic and Tilton	Evans
Gajika	-	560	-
Yichun (Jiangxi)	325	-	-
Maerkang (Sichuan)	224	220	80-225
Daoxian (Hunan)	125	-	125

The authors named in Table 32 do not say how the resource estimates were calculated and we were unable to find primary data on them. In the interest of contrasting resource figures, below we quote a few websites' claims regarding particular deposits; we chose the more conservative estimates from the table above.

Gajika

"CITIC Guoan Lithium Sci. & Tech. Co., Ltd is a sole sub-company of CITIC Guoan Group. It owns the […]Gajika Mine, which is estimated to have 1,266,000 tons of reserve as counted by lithium oxide."[80]

1,266,000 tonnes of Li_2O are equivalent to approximately **591,000 tonnes of lithium**. Yaksic and Tilton report a lower value of 560,000 tonnes of lithium, which is comparable.

Yichun

Limited information is available on Yichun's lithium resource. One source indicated that the lepidolite deposit contains 1.1 Mt of Li^2O.[81] 1.1 Mt of Li_2O are equivalent to approximately 513,000 tonnes of lithium. Due to a lack of detailed information on this deposit, we used the more conservative value of **325,000 tonnes of lithium** reported by Clarke and Harben.[10]

Maerkang

"SICHUAN SHENG NI KEI GUO RUN XIN CAI LIAO CO.,LTD. is a sole sub-company of CITIC Group. It owns Maerkang spodumene mine which is estimated to have 483,000 tons of reserve as counted by lithium oxide."[82]

483,000 tonnes of Li_2O are equivalent to approximately **225,000 tonnes of lithium**. We used this value which is similar to estimates by Clarke and Harben, and Yaksic and Tilton.

Daoxian

Sterling Group Ventures stated that "On September 15, 2003, a letter of intent was signed with Dao County of Hunan Province of China to develop the Daoxian lithium – rubidium property… The exploration works completed include 5,284 meters of drilling and 4,366 m^3 of trenching. The property is estimated to contain 0.39 Mt of Li_2O."[83]

It is unclear from Sterling Group's report what is the concentration of Li2O or lithium metal in the deposit.

390,000 tonnes of Li_2O are equivalent to **182,000 tonnes of lithium**, which we used for this study. Clarke and Harben, and Evans both use the value 125,000 tonnes of lithium, which is comparable.

Greenbushes

Greenbushes is a spodumene pegmatite located in Western Australia; Talison Minerals Party Limited mines tantalum and extracts lithium as a byproduct.[12] In 2009, Talison estimated a lithium **resource of 560,000 tonnes**, which we used for this study; this is based on a 35.5 Mt ore body, with an Li_2O concentration of 3.31%.[21] Clarke and Harben gave an estimate of 1.5 Mt of lithium[10] and Yaksic and Tilton gave an estimate of 255,000 tonnes of lithium. [11] Tahil notes that production of lithium carbonate ceased in 1998, when SQM began production at Atacama. [12]

Beaverhill Lake Formation (Leduc Aquifer)

The total resource for the Leduc aquifer is an estimated 567,690 tons, according to the Alberta Geological survey, which is **515,000 tonnes**; this value, which was used for this study, is lower that Clarke and Harben's value of 589,000 tonnes.[10] High concentrations of lithium are only found between 2,700 and 4,000 m depths. [84]

Salton Sea

This geothermal brine in southern California's Salton Sea area contains lithium in a 17 km^2 region, as well as potash, zinc, boron, and lead. The brine is currently used as a source of geothermal power, and a pilot project consisting of solar ponds to concentrate the lithium from the electric plant's effluent has been established; but no effort has been made to process the lithium. [22] According to Evans, the brine has an average lithium concentration of around 200 ppm, [8] which is consistent with an analysis by Maimoni of 8 wells whose concentrations ranged from 117 to 245 ppm.[85] Evans does not specify the volume of brine, but it is estimated to contain 316,000 tonnes of lithium, based on a 20-year life and throughput of 16,000 tpa of lithium. [8] According to Garrett, the brine contains 100 to 400 ppm and the lithium reserves are estimated to be 1.0 Mt, [22] although the source of information for this calculation was not provided. Maimoni estimated that 31,000 to 65,000 tonnes of lithium could be recovered per year from these 8 wells.[85] The average of these amounts, over 20 years, is 960,000 tonnes of lithium. Additional information could not found detailing the lithium in the Salton Sea, so for this study we used the conservative estimate of **316,000 tonnes of lithium resources**, though we acknowledge that the resource could be as much as 960,000 tonnes.

Silver Peak (Clayton Valley)

Silver Peak is a 50 km^2 [12] to 83 km^2 [86] salt basin consisting of stratified layers of "fine-grained sediment and halite, some volcanic ash layers, and some tufas" in Nevada.[55] Kesler estimated the lithium content at Silver Peak to be 77,300 tonnes in 1976.[28] Rockwood, owned by Chemetall, has been producing lithium materials from Silver Peak since 1966.[76] Its brines vary from 100 to 300 ppm of lithium,[8, 55] and its remaining lithium reserves are estimated at 40,000 tonnes.[8] Tahil reports that its brines were 118,000 tonnes in 1992 and have an average concentration of 200 ppm; Chemetall produces 9,000 tpa of lithium, to augment their lithium supply from Hombre Muerto, for lithium chemicals.[12] Most production comes from a volcanic ash layer that exists beneath the entire basin, though additional aquifers have been identified and used.[55]

Clayton Valley's evaporation rate of 900mm per year is 25% of Atacama's,[12] which means the Clayton operation requires larger evaporation ponds and takes longer to concentrate the lithium. Dillard and McClean estimated a lithium resource of 382,000 tonnes in 1991.[87] Tahil adjusted this estimate to **300,000 tonnes of lithium** in 2008 to account for additional lithium extracted.[12]

Russian deposits

Nine Russian deposits are estimated, by Clarke and Harben, to have greater than 100,000 tonnes of lithium resources,[10] but limited information is available on these deposits. Evans quotes Roskill Information Services, which identifies 6 large deposits. None of these deposits produces lithium carbonate currently. We chose the most conservative estimate for each Russian deposit above 100,000 tonnes to include in our study.

Table 33. Russian lithium deposits (thousand tonnes of lithium)

Deposit	**Clarke/ Harben 2009**	**Evans 2008**
Kolmozerskoe	<844	**288**
Polmostundrovskoe	**139** – 278	144 – 288
Ulus (or Ulug)-Tanzek	**139** – 278	144 – 288
Goltsovoe	**139** – 278	144 – 288
Urikskoe	**139** – 278	144 – 288

Maricunga

Maricunga is a brine resource in Chile and is not being mined. Yaksic and Tilton reported a value of **220,000 tonnes** of lithium reserves for this deposit, at an average 0.092% concentration.

Jiajika

Jiajika is a spodumene-bearing pegmatite deposit located in Sichuan Province, China. On September of 2003, Sterling Group Ventures signed a 30-year mining joint venture agreement with Sichuan Province Mining Ltd. to develop the deposit with a 240,000 tpa initial capacity; the joint venture was terminated on March 2006.[88] Evans says the mine is owned by Sichuan Mineral Industry. [8] Jiajika resource estimates range from 6,000 to 480,000 tonnes (Figure 11).

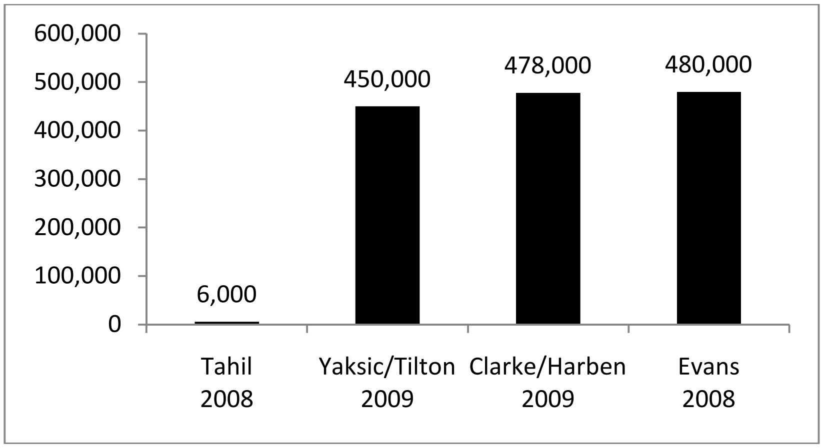

Figure 17. Estimates of lithium resources (tonnes Li) in the Jiajika deposit.

Jiajika has an area of 62 km^2 and contains 498 pegmatite veins, of which 78 are judged to have economic potential.[89] Vein number 134, the largest vein, was explored in 1992 by Sichuan Province's Geological Brigade No. 108, with 25,691 meters of drilling and 55,155 meters of trenching.[90] The exploration showed that vein 134 has a length of 1,055 meters, depth of 200 meters, average width of 55 meters, and average grade of 1.398% lithium oxide (Li_2O). [91] Primary source data were available only for vein 134; thus, our resource estimation for Jiajika only considers this vein. Using a density of 2.7 (tonnes/m^3) for the pegmatite rock, the lithium resource is estimated as follows.

$$\begin{aligned} Jiajika_{Resource\ Li_2O} &= Vein'svolume \times Rock's\ density \times grade \\ &= (1{,}055 \times 200 \times 55)[m^3] \times 2.7 \left[\frac{tonnes}{m^3}\right] \times 0.01398 \\ &= 438{,}040[tonnes] \end{aligned}$$

Lithium oxide contains 46.7% lithium; hence, Jiajika's lithium resource is

$$Jiajika_{Resource\ Li_2} \boldsymbol{\sim 204{,}000[tonnes]}$$

Salar de Olaroz

The Salar de Olaroz, in Argentina, is a 140 km^2 salt lake. [8] According to Orocobre Limited, which owns the rights to develop 118 km^2 of the salar: "Within the top 55m from [the] surface, an inferred resource of 1.5 Mt of lithium carbonate equivalent and 4.1 Mt of potash has been estimated by independent consultants Geos Mining."[92] This equates to a resource of approximately 280,000 tonnes of lithium. Orocobre also states that the average porosity of the brine is 6 to 8% to a depth of 40 to 50 m and that the average concentration is twice that of Rincon's.[92] Assuming the aquifer is lens-shaped, the average thickness of the aquifer would be 22.5 m. Using this variable, and assuming a density similar to other Altiplano salars, we calculated a resource of 156,000 tonnes of lithium.

Table 34. Data and Estimate of the Salar de Olaroz.

Area (km^2)	**Avg. Aquifer Thickness (m)**	**Avg. Porosity**	**Density (g/cc)**	**Avg. Grade (%Li)**	**Resource (tonnes)**
118	22.5	7%	1.2	0.07%	156,114

Geos Mining must have used a greater average thickness in its estimate; a thickness of 40 m would produce an estimate of 280,000 tonnes. Other estimates include 325,000 tonnes by Yaksic and Tilton, who quote an average concentration of 0.07% lithium, [11] and Tahil, who used an average porosity of 10%.[12] Clarke and Harben quote 560,000 tonnes at an average concentration of 0.09% lithium.[10] The calculations for these estimates are not provided.

We used our more conservative estimate of **156,000 tonnes** of lithium resource for this study.

Mibra

Mibra is a spodumene deposit in Brazil, which is not being mined. It is operated by Companhia Industrial Fluminense, which extracts tantalum and, as a byproduct, lithium.[93] Clarke and Harben estimated a resource of **100,000 tonnes** of lithium, though the average lithium concentration is not reported.[10]

Koralpa (or Koralpe)

Koralpa is a spodumene deposit in Austria and has been surveyed to a depth of 450 m. It is not being mined, but its estimated **lithium resource is 100,000 tonnes**, which we used for this study. [8, 11]

Bikita, Masvingo

Bikita is a spodumene deposit in Zimbabwe. Bikita Minerals Ltd. is currently producing about 700 tonnes of lithium per year.[10] Bikita contains an estimated 56,700[11] to 168,000 tonnes[94] of lithium, and an average average concentration of 4% LiO_2.[95] We used the more conservative value of **56,700 tonnes** for this study.

Searles Lake, California

The lithium resource for Searles Lake was below 100,000 tonnes of lithium and was not used in our study. Kesler estimated a probable lithium reserve of 23,700 tonnes of lithium, with an average concentration of 0.005% lithium. [28]

Dead Sea

Israel's Dead Sea has an estimated lithium resource of 2.0 Mt but very low concentrations of lithium – just 0.001% Li according to Garrett[22] and 0.002% according to Yaksic and Tilton.[11] Tahil adds that it has an astronomically high Mg:Li ratio of 2000:1. [12] Due to these factors, and the fact that great volumes of water would have to be processed in order to produce lithium, the Dead Sea is not a foreseeable resource of lithium, so we did not include it in this study.

Great Salt Lake

The Great Salt Lake has an estimated 520,000[8] to 526,000 tonnes[11, 22] of lithium resource, and a low average lithium concentration of around 0.004%.[11, 12] Due to this low average concentration and the vastness of the lake, enormous volumes of water would have to be processed in order to produce lithium. We do not include this deposit in our list of resources.

Active Deposits with less than 100,000 tonnes of lithium resource

The following deposits are producing but are estimated to contain less than 100,000 tonnes of lithium resource each:

Table 35. Producing deposits with less than 100,000 tonnes Li.

Deposit	**Country**	**Type**	**Li Resource (tonnes Li)**	**2008 Production (tonnes Li)**	**Data source**
Lijiagou	China	Pegmatite	53,000	NA	Clarke
Hupei	China	Pegmatite	42,000	NA	Clarke/Harben
Cachoeira	Brazil	Pegmatite	23,000	14	Clarke/Harben
Bernic Lake	Canada	Pegmatite	19,000	300	Clarke/Harben; Yaksic/Tilton
Mesquitila/Guarda	Portugal	Pegmatite	10,000	110	Clarke/Harben; Yaksic/Tilton
Ningdu	China	Pegmatite	NA	NA	Clarke/Harben
Jinchuan	China	Pegmatite	NA	NA	Clarke/Harben
Mina Feli	Spain	Pegmatite	NA	NA	
Total (known):			**147,000**	**424**	

Lithium demand.

GDP

Observed global GDP was obtained from the World Bank statistics database. The World Bank reports GDP in 2000 dollars. The IPCC's growth scenarios, on the other hand, use GDP in 1990 dollars. Accordingly, in the regression analysis we used GDP in 1990 dollars. We converted World Bank figures to 1990 dollars using a 0.76 conversion factor.[96]

Table 36. World GDP in 1990 and 2000 dollars.

Year	GDP (trillion 2000 dollars)	GDP (trillion 1990 dollar)
1995	27.17	20.65
1996	28.09	21.35
1997	29.13	22.14
1998	29.79	22.64
1999	30.74	23.36
2000	32.00	24.32
2001	32.48	24.69
2002	33.10	25.15
2003	33.98	25.82
2004	35.37	26.88
2005	36.61	27.82
2006	38.08	28.94
2007	39.52	30.03
2008	40.31	30.64

Global lithium consumption by category

Table 37. USGS annual lithium use per category.

	2006	2007	2008
Batteries	19%	20%	25%
Ceramics and glass	21%	20%	18%
Lubricant greases	16%	16%	12%
Pharmaceuticals and polymers	9%	9%	7%
Air conditioning	8%	8%	6%
Primary aluminum production	6%	6%	4%
Other	21%	21%	28%

Data used in the construction of this table was obtained from the *Mineral Commodity Summaries* found on the USGS *Lithium Statistics and Information* website http://minerals.usgs.gov/minerals/pubs/commodity/lithium/

Non-battery demand forecast - Calculations

In its 2008 annual report, SQM says that world total lithium carbonate consumption was approximately 92,000 tonnes. This is equivalent to 17,405.41 tonnes of lithium metal, as calculated below.

$$\begin{aligned} \frac{Li_2}{Li_2CO_3} &= \frac{2\cdot 7}{2\cdot 7+12+3\cdot 16} \\ &= \frac{14}{74} \\ &= 0.189 \\ 92{,}000\ [tonnes\ Li_2CO_3] &= 0.189 \times 92{,}000[tonnes\ Li_2] \\ &= 17{,}405\ \ [tonnes\ Li_2] \end{aligned}$$

On the same report SQM says that of this lithium mass, approximately 12% was used in lubricants; 17%, in frits and glass; 6%, in air conditioning; 4%, in aluminum production; and 34%, in other applications. Proportional lithium metal mass allocated per use is shown in Table 38.

Table 38. 2008. Total lithium metal use and per category use.

Total 2008	17405.41	tonnes	
Lubricating greases	12%	2088.649	tonnes
Frits and glass	17%	2958.919	tonnes
Air conditioning	6%	1044.324	tonnes
Aluminum	4%	696.2162	tonnes
Other	34.00%	5917.838	tonnes

Yearly lithium demand, allocated per activity, was calculated using Yaksic and Tilton estimated growth rates. Results are shown on Table 39.

Table 39. Non-battery 2010-2100 global lithium metal consumption.

	Demand (in tonnes)					
Year	Lubricants	Frits and glass	Air conditioning	Aluminum	Other	Total [M mt]
2010	2303	3139	1151	696	6401	0.01369
2011	2418	3233	1209	696	6657	0.014213
2012	2539	3330	1269	696	6923	0.014758
2013	2666	3430	1333	696	7200	0.015325
2014	2799	3533	1399	696	7488	0.015916
2015	2939	3639	1469	696	7787	0.016531
2016	3086	3748	1543	696	8099	0.017172
2017	3240	3861	1620	696	8423	0.01784
2018	3402	3977	1701	696	8760	0.018536

2019	3572	4096	1786	696	9110	0.019261
2020	3679	4178	1840	661	9292	0.019651
2021	3790	4261	1895	628	9478	0.020053
2022	3904	4347	1952	597	9668	0.020467
2023	4021	4433	2010	567	9861	0.020893
2024	4141	4522	2071	539	10058	0.021331
2025	4266	4613	2133	512	10260	0.021782
2026	4393	4705	2197	486	10465	0.022246
2027	4525	4799	2263	462	10674	0.022723
2028	4661	4895	2331	439	10888	0.023213
2029	4801	4993	2400	417	11105	0.023716
2030	4945	5093	2424	-	11327	0.023789
2031	5093	5195	2449	-	11554	0.02429
2032	5246	5298	2473	-	11785	0.024803
2033	5403	5404	2498	-	12021	0.025326
2034	5566	5512	2523	-	12261	0.025862
2035	5732	5623	2548	-	12506	0.02641
2036	5904	5735	2574	-	12757	0.02697
2037	6082	5850	2599	-	13012	0.027542
2038	6264	5967	2625	-	13272	0.028128
2039	6452	6086	2652	-	13537	0.028727
2040	6646	6208	2678	-	13673	0.029204
2041	6845	6332	2705	-	13809	0.029691
2042	7050	6459	2732	-	13948	0.030188
2043	7262	6588	2759	-	14087	0.030696
2044	7480	6720	2787	-	14228	0.031214
2045	7704	6854	2815	-	14370	0.031743
2046	7935	6991	2843	-	14514	0.032283
2047	8173	7131	2871	-	14659	0.032834
2048	8418	7274	2900	-	14806	0.033397
2049	8671	7419	2929	-	14954	0.033973
2050	8758	7456	2958	-	15103	0.034275
2051	8845	7493	2988	-	15254	0.034581
2052	8934	7531	3018	-	15407	0.034889
2053	9023	7569	3048	-	15561	0.0352
2054	9113	7606	3078	-	15716	0.035514
2055	9204	7644	3109	-	15874	0.035832
2056	9296	7683	3140	-	16032	0.036152
2057	9389	7721	3172	-	16193	0.036475
2058	9483	7760	3203	-	16355	0.036801
2059	9578	7798	3235	-	16518	0.03713

2060	9674	7837	3268	-	16683	0.037462
2061	9771	7877	3300	-	16850	0.037798
2062	9868	7916	3333	-	17019	0.038136
2063	9967	7956	3367	-	17189	0.038478
2064	10067	7995	3400	-	17361	0.038823
2065	10167	8035	3434	-	17534	0.039171
2066	10269	8076	3469	-	17710	0.039523
2067	10372	8116	3504	-	17887	0.039878
2068	10475	8156	3539	-	18066	0.040236
2069	10580	8197	3574	-	18246	0.040598
2070	10686	8238	3610	-	18429	0.040963
2071	10793	8279	3646	-	18613	0.041331
2072	10901	8321	3682	-	18799	0.041703
2073	11010	8362	3719	-	18987	0.042078
2074	11120	8404	3756	-	19177	0.042457
2075	11231	8446	3794	-	19369	0.04284
2076	11343	8489	3832	-	19562	0.043226
2077	11457	8531	3870	-	19758	0.043616
2078	11571	8574	3909	-	19956	0.044009
2079	11687	8616	3948	-	20155	0.044407
2080	11804	8660	3987	-	20357	0.044808
2081	11922	8703	4027	-	20560	0.045212
2082	12041	8746	4067	-	20766	0.045621
2083	12162	8790	4108	-	20974	0.046033
2084	12283	8834	4149	-	21183	0.04645
2085	12406	8878	4191	-	21395	0.04687
2086	12530	8923	4233	-	21609	0.047294
2087	12655	8967	4275	-	21825	0.047723
2088	12782	9012	4318	-	22043	0.048155
2089	12910	9057	4361	-	22264	0.048592
2090	13039	9102	4404	-	22487	0.049032
2091	13169	9148	4449	-	22711	0.049477
2092	13301	9194	4493	-	22939	0.049926
2093	13434	9240	4538	-	23168	0.050379
2094	13568	9286	4583	-	23400	0.050837
2095	13704	9332	4629	-	23634	0.051299
2096	13841	9379	4675	-	23870	0.051765
2097	13979	9426	4722	-	24109	0.052236
2098	14119	9473	4769	-	24350	0.052711
2099	14260	9520	4817	-	24593	0.053191
2100	14403	9568	4865	-	24839	0.053675

Portable electronics battery demand forecast – Calculations

Table 40. Annual battery total world shipment, as reported by Frost and Sullivan.

Year	Battery shipment in million units	
	Primary battery	Secondary battery
1994	620	-
1995	690	-
1996	840	-
1997	1020	-
1998	1170	-
1999	1170	-
2000	1074.4	-
2001	1150.5	-
2002	1247.8	-
2003	1372.8	1349.4
2004	1517.9	1456.5
2005	1671	1596.1
2006	1846.9	1756.1
2007	2030	1938.9
2008	2237.5	-

Primary battery – Linear regression on 1990 GDP

Table 41. Linear regression statistics. Primary battery shipment and global GDP.

Regression Statistics	
Multiple R	0.976126
R Square	0.952822
Adjusted R Square	0.94889
Standard Error	101.5485
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2499196	2499196	242.3556	2.54E-09
Residual	12	123745.2	10312.1		
Total	13	2622941			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-2113.8	224.7793	-9.40388	6.93E-07
GDP (constant 1990 US$)	1.37E-10	8.81E-12	15.56778	2.54E-09

Global manufacturing of portable primary battery was calculated using the expression below. GDP must be expressed in million 1990 dollars, to obtain battery manufacturing in million units.

$$Primary\ Battery_{Year\ n} = -2{,}113.8 + 1.37 \cdot 10^{-10} \cdot GDP_{Year\ n}$$

Secondary battery – Linear regression

Table 42. Linear regression statistics. Secondary battery shipment and global GDP.

Regression Statistics	
Multiple R	0.996598
R Square	0.993208
Adjusted R Square	0.990945
Standard Error	22.35479
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	219247.2	219247.2	438.7257	0.000238
Residual	3	1499.209	499.7364		
Total	4	220746.4			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-2323.99	188.5318	-12.3268	0.00115
X Variable 1	1.41E-10	6.75E-12	20.94578	0.000238

Global manufacturing of portable secondary battery was calculated using the expression below. GDP must be expressed in million 1990 dollars, to obtain battery manufacturing in million units.

$$Secondary\ Battery_{Year\ n} = -2{,}323.99 + 1.41 \cdot 10^{-10} \cdot GDP_{Year\ n}$$

Annual primary and secondary battery manufacturing

GDP figures in Table 36 were extrapolated at 2% and 3%, the resulting scenario annual GDP was used on *Primary* and *Secondary* battery equations above to calculate global manufacturing for the period 2010-2100.

Vehicle battery demand forecast - Calculations

Table 43. Ward's Automotive Yearbook 2009, Light-duty vehicle. Global manufacturing, in units.

Year	Car manufacturing
1995	35,954,083
1996	36,845,782
1997	39,427,759
1998	37,445,313
1999	38,885,715
2000	39,866,023
2001	39,242,955
2002	41,215,063
2003	41,782,241
2004	42,494,575
2005	44,112,912
2006	46,577,235
2007	49,344,591
2008	50,025,457

Table 44. Linear regression statistics. Light-duty global vehicle manufacturing and global GDP.

Regression Statistics	
Multiple R	0.97225
R Square	0.945269
Adjusted R Square	0.940708
Standard Error	1079234
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.41E+14	2.41E+14	207.2557	6.21E-09
Residual	12	1.4E+13	1.16E+12		
Total	13	2.55E+14			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	7518637	2388901	3.147321	0.008417
GDP (constant 1990 US$)	1.35E-06	9.37E-08	14.39638	6.21E-09

Global manufacturing of light duty vehicles was calculated using the expression below. GDP must be expressed in million 1990 dollars, to obtain vehicle manufacturing in million units.

$$Vehicle_{Year\ n} = 7.52 \cdot 10^{6} + 1.35 \cdot 10^{-6} \cdot GDP_{Year\ n}$$

This equation and GDP from Table 36 (extrapolated at 2% and 3%) were used to estimate global light-duty vehicle manufacturing for the two scenarios considered in this work.

The Excel workbook, which can be found on the CD accompanying this document, used to calculate vehicle battery demand automatically calculates lithium demand when vehicle life, battery life, recycling participation, and recycling recovery are changed. All these variables can be modified on the “Main Variables” worksheet.

Automatic calculation is achieved by a series of auxiliary tables found on the “Aux calculation tables” worksheet.

References

1 Kromer, M. A. and Heywood, J. B. “A Comparative Assessment of Electric Propulsion Systems in the 2030 US Light-Duty Vehicle Fleet.” SAE Technical Paper Series. Massachusetts Institute of Technology. 2008.

2 Samaras, C. and Meisterling, K. “Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy.” Environ. Sci. Technol. 2008, 42, 3170-3176.

3 Stephan, C. and Sullivan, J. “Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles.” Environ. Sci. Technol. 2008, 42, 1185–1190.

4 Encyclopedia Britannica. “Lithium.” (2010). Encyclopedia Britannica Online, retrieved January 10, 2010.

5 Kesler, S. E. “Mineral Resources, Economics and the Environment.” 1994. pgs. 273, 310-311.

6 Snyder, K. A., Yang, X. G., and Miller, T. J. “Hybrid Vehicle Battery Technology - The Transition From NiMH to Li-Ion.” Society of Automotive Engineers Technical Paper. 2009-01-1385.

7 Tahil, W. “The trouble with lithium.” Meridian International Research. January, 2007

8 Evans, R. K. “An Abundance of Lithium.” March 2008.

9 Evans, R. K. “An Abundance of Lithium: Part Two.” July 2008.

10 Clarke, G.M. and Harben, P.W., "Lithium Availability Wall Map." June 2009.

11 Yaksic, A. and Tilton, J. E. "Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium." Resources Policy, 2009.

12 Tahil, W. “The Trouble with Lithium 2. Under the Microscope.” Meridian International Research, May 29, 2008.

13 Jaskula, B. “Lithium.” Mineral Commodity Summaries. U.S. Geological Survey. January, 2010.

14 Western Lithium Corp. “Kings Valley Project NI 43-101 Technical Report: Preliminary Assessment and Economic Evaluation Humboldt County, Nevada.” Issue date: Jan. 22, 2010 http://www.westernlithium.com/static/userfiles/kvreports/Western_Lithium_PAEE_Final-full_report.pdf. Accessed March 25. 2010.

15 Tribe, N. “Qualifying Report for Dangxiongcuo Salt Lake Deposit.” http://www.sterlinggroupventures.com/dxcreport/dxcreport.htm. Accessed 3/21/2010.

16 U.S. Geological Survey. “Appendix C: A Resource/Reserve Classification of Minerals.” 2009. Based on U.S. Geological Survey Circular 831, 1980.

17 TRU Group Inc. Lithium Consultants. “Bolivia pins hopes on lithium electric vehicles.” www.usatoday.com/tech/world/2009-03-02-bolivia-lithium_N.htm. Accessed Dec. 12, 2010.

18 Shenzhen ZBY Lithium Trading Co. www.zabuye.com.cn/com/zby/main.php?sLAN=en. Accessed 3/21/2010.

19 Collins, A. “Lithium abundances in oilfield waters.” U. S. Geological Survey Professional Paper, Report: P 1005, pp.116-123, 1976.

20 Pavlovic, P.. “La Industria del Litio en Chile.” 1992.

21 U.S. Geological Survey 2007 Minerals Yearbook. July 2009.

22 Garrett, D. “Handbook of lithium and natural calcium chloride: their deposits, processing, uses and properties.” Elsevier Academic Press, 2004.

23 Western Lithium Corporation. www.westernlithium.com/project/ Accessed March 29, 2010.

24 Stanley, C. et al. “Jadarite, LiNaSiB3O7(OH), a new mineral species from the Jadar Basin, Serbia.” Eur. J. Mineral. 19: 575-580., 2007.

25 Obradovic, J., Djurdjevic-Colson, J., and Vasic, N. “Phytogenic lacustrine sedimentation oil shales in Neogene from Serbia, Yugoslavia.” Journal of Paleolimnology 18: 351-364, 1997.

26 Rio Tinto. www.riotinto.com/whatweproduce/17056_inferred_resource_at_jadar_lithium_project.asp Accessed March 29, 2010.

27 Jasinski, S. M. “Potash.” Mineral Commodity Summaries, U.S. Geological Survey. 2008-09.

28 Kesler, T.L. “Raw lithium supplies: Mining Engineering.” March 1978, p. 283-284.

29 Ullmann’s Encyclopedia of Industrial Chemistry. “Lithium and Lithium Compounds.” Wiley-VCH Verlag GmbH & Co. Online article published June 15, 2000; accessed January 7, 2010.

30 Frost & Sullivan. “Energy Storage and Generation for Portable Power.” Frost.com. 2008.

31 Winter, M. and Brodd, R. “What are Batteries, Fuel Cells, and Supercapacitors?” Chemical Reviews, vol. 104, no. 10. American Chemical Society. 2004.

32 Nakicenovic, Nebojsa. et al. “Special Report on Emissions Standards” Intergovernmental Panel on Climate Change, 2001.

33 Woodbank Communications. “Electropaedia - Battery and Energy Technologies.” www.mpoweruk.com/recycling.htm. Accessed June 2009.

34 Rechargeable Battery Recycling Corporation. “The Challenge of Calculating Portable Rechargeable Battery Recycling Rates.” March 2008. www.call2recycle.org/doc_lib/ISP%20Appendix%2006.pdf. Accessed June 2009.

35 Advanced Automotive Battery & EC Capacitor Conference. "Poster presentations." 2009.

36 SQM. “Annual Report. 2008.”

37 Frost & Sullivan. “World Primary Lithium Battery Markets.” 2008

38 Frost & Sullivan. “World Hybrid Electric and Electric Vehicle Lithium-ion Battery Market.” September 2009.

39 Frost & Sullivan. “Automotive and Transportation Technology Alert. D890-00-33.” November 2009.

40 Ward's Automotive Yearbook 2009, Ward's Automotive Group, Southfield MI, 2009, ISBN 978-0-9105-89-26-0

41 Jobin, L. et al. “HEV and EV projections” Credit Suisse. 2009.

42 International Energy Agency. “Technology Roadmap. Electric and plug-in hybrid electric vehicles.” OECD/IEA 2009.

43 Grahn, M. et al. “Fuel and technology choices for passenger vehicles in achieving stringent CO2 targets: connections between transportation and other sectors.” Environ. Sci. Technol., 2009, 43, 3365-3371.

44 Wang, M., 1999, “GREET 1.5 - Transportation Fuel-Cycle Model,” ANL/ESD-39, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, version 1.8c.0, March 23, 2009.

45 Miller, T.J., private communication, 2010.

46 Environmental Protection Agency. “Battery Recycling.” www.epa.gov/osw/conserve/materials/battery.htm. Accessed October 2009.

47 Wilson, B. “Recycling Used Lead Acid Batteries – A Model Life Cycle Approach.” 13th Asian Battery Conference, International Secondary Lead Conference. www.ilmc.org/Presentations/ABC/Recycling%20Used%20Lead%20Acid%20Batteries;%20A%20Model%20Life%20Cycle%20Approach.pdf. Accessed February 2010.

48 International Lead Association. “Lead Recycling.” www.ila-lead.org/lead-information/lead-recycling. Accessed February 2010.

49 Anstett, T., Krauss, U., Ober, J., and Schmidt, H. “Lithium.” Int. Strat. Min. Invest. Summ. Rept., U.S. Geol. Survey Circular 930-I, 28, 1990.
50 Evans, R. “Equating Bolivian lithium.” Industrial Minerals. July 16, 2009.
51 Risacher, F. and B. Fritz. “Quaternary geochemical evolution of the salars of Uyuni and Coipasa, Central Altiplano, Bolivia.” Chemical Geology. Elsevier Science Publishers, 1991.
52 Kunasz, I. “Lithium in Brines.” Fifth Symp. Salt, N. Ohio Geol. Soc. 1, 1979.
53 Warren, J.K. “Evaporites through time: Tectonic, climatic and eustatic controls in marine and nonmarine deposits” Earth Science Reviews, 2010.
54 Banks, D., Markland, H., Smith, P., Mendez, C., Rodriguez, J., Huerta, A., and Saether, O. “Distribution, salinity and pH dependence of elements in surface waters of the catchment areas of the Salars of Coipasa and Uyuni, Bolivian Altiplano.” Journal of Geochemical Exploration 84, 2004.
55 Kunasz, I. “Lithium Resources.” Industrial Minerals and Rocks, 2006.
56 Ericksen, G., Vine, J., Ballón A., R. “Lithium-rich brines at Salar de Uyuni and nearby salars in southwestern Bolivia” U.S. Dept. of the Interior, Geological Survey, 1977.
57 Ballivian, O., and Risacher, F. “Los Salares Altiplano Boliviano” O.R.S.T.O.M. Paris, 1981.
58 Kunasz, I. and F. Ide Y. “Origin of Lithium in Salar de Atacama, Northern Chile.” Earth Sciences Series, 1989.
59 Chemetall. “Chemetall awarded $28.4 million in Stimulus Funds for the Production of Advanced Materials for Lithium Ion Batteries in the U.S.” News Release. August 10, 2009.
60 Encyclopedia Britannica. “Qaidam Basin.” Encyclopedia Britannica Online. Accessed March 16, 2010.
61 Shengsong, Y. “The Hydrochemical Features of Salt Lakes in Qaidam Basin.” Chinese Journal of Oceanology and Limnology. 1986, volume 4, number 4.
62 Zheng, M. and Liu, X. “Hydrochemestry of Salt Lakes of the Qinghai-Tibet Plateau, China.” Aquatic Geochemestry, 2009, pp. 293-320.
63 China Chemical Reporter. “Major Breakthrough in the Technology of Extracting Lithium from Salt Lake Brine.” January 16, 2004.
64 Qinghai Salt Lake Industry. www.qhyhjt.com/group/about.asp?type=%BC%AF%CD%C5%B8%C5%BF%F6&stype=%C6%F3%D2%B5%BC%F2%BD%E9&xz=1. Accessed 3/19/2010.
65 China Business Daily News. “Potential Value for Lithium Mining in Qinghai Exceeds RMB 30 billion.” November 25, 2002.
66 Western Lithium Corp. www.westernlithium.com/project. Accessed: March 25, 2010.
67 Zheng, M. “An Introduction to Saline Lakes on the Qinghai-Tibet Plateau.” Kluwer Academic Publishers. 1997.
68 The mineral and locality database. “Zabuye (Zhabuye) Salt Lake (Chabyer Caka), Zhongba Co., Xigazê (Rikaze; Shigatse) Prefecture, Tibet Autonomous Region, China.” www.mindat.org/loc-3257.html. Accessed 3/21/2010.
69 Sterling Group Ventures, Inc. “Home page – Introduction.” www.sterlinggroupventures.com/index.html. Accessed 3/21/2010.
70 Sterling Group Ventures, Inc. “DXC - General Characteristics.” www.sterlinggroupventures.com/dxc2.html. Accessed 3/21/2010.
71 Sterling Group Ventures, Inc. “DXC - Exploration.” www.sterlinggroupventures.com/dxc5.html. Accessed 3/21/2010.
72 Industrial Minerals. Exposure. “Salar del Rincon Lithium.” July 2007.
73 Evans, R. “Know Limits.” Industrial Minerals, July 2008.

74 Ecclestone, C. “Rincon Lithium” Hallgarten & Company. June 24, 2008.

75 Rio Tinto. “Inferred resource at Jadar lithium project.” www.riotinto.com/whatweproduce/17056_inferred_resource_at_jadar_lithium_project.asp Accessed: March 24, 2010.

76 Jaskula, B. USGS, "Estimated World Mine Production of Lithium, 2008" 2009 conference presentation.

77 Nicolli, H., Suriano, J., Mendez, V., and M. Gomez. “Salmuercas ricas en metals alcalinos del salar Hombre Muerto, Catamarca, Argentina.” 5th Argentinean Geological Congress. Minutes 111: 187-204. Bs.As.

78 Garrett, D. “Borates: handbook of deposits, processing, properties, and use.” Elsevier Academic Press, 1998.

79 Dow Chemical. “Lithium Recovery by Alumina-Ion Exchange.” Lee, J. and W. Bauman. 1984.

80 BusinessPatrol.com. “Citic Guoan Lithium Sci Tech Ltd.” www.businesspatrol.com/directory/Site-Citic-Guoan-Lithium-Sci-Tech-Ltd,8074.html. Accessed March 25, 2010.

81 Qi,L. “Himfr.com Reports Jiangxi Nonferrous highlight the effect of industrial clusters.” www.articleblast.com/E-Commerce_and_Online_Businesses/General/Himfr.com_Reports_Jiangxi_Nonferrous_highlight_the_effect_of_industrial_clusters/. Accessed March 23, 2010.

82 SICHUAN SHENG NI KEI GUO RUN XIN CAI LIAO CO.,LTD. “About Us.” nikeiguorun.lookchem.com/About.html. Accessed March 25, 2010.

83 Sterling Group Ventures. “Sterling Group Acquires Lithium Deposits in China.” www.sterlinggroupventures.com/pdf/prjan_21_2004.pdf. Published January 22, 2004. Accessed March 25, 2010.

84 Resource Estimates of Industrial Minerals in Alberta Formation Waters. Alberta Geological Survey, Jan. 31, 1995 http://www.ags.gov.ab.ca/publications/OFR/PDF/OFR_1995_01.PDF. Accessed: March 27, 2010.

85 Maimoni, A. “A Cementation Process for Minerals Recovery from Salton Sea Geothermal Brines.” Lawrence Livermore Laboratory, University of California. Manuscript date: January 26, 1982.

86 Davis, J., Friedman, I., Gleason, J., “Origin of the lithium-rich brine, Clayton Valley, Nevada.” US Geological Survey Bulletin 1622, 131–138, 1986.

87 Dillard, G., and S. McClean. “Cyprus Mineral Taps a Unique Treasure.” Rocky Mountain Pay Dirt. September, 1998.

88 Sterling Group Ventures, Inc. “10-k SEC Filing.” August 28, 2009.

89 Sterling Group Ventures. “JIAJIKA - Topography Map.” www.sterlinggroupventures.com/jiajika4.html. Accessed March 24, 2010.

90 Sterling Group Ventures. “JIAJIKA – Geological Works.” www.sterlinggroupventures.com/jiajika3.html. Accessed March 24, 2010.

91 Sterling Group Ventures. “Jiajika Lithium Reserve Confirmed by Independent Consulting Firm (December 13, 2004).” http://www.sterlinggroupventures.com/prdec_13_2004.html. Accessed March 24, 2010.

92 Orocobre. “Olaroz Lithium Project.” [http://www.orocobre.com.au/Projects_Olaroz.htm] Accessed: March 24, 2010.

93 Tantalum International Study Center. “Tantalum – Raw Materials and Processing.” http://tanb.org/tantalum. Accessed: March 27, 2010.

94 Kennedy, B. “Surface mining.” Society for Mining, Metallurgy, and Exploration (U.S.), p. 94-96, 1990.

---

95 Industrial Minerals. “Bikita continues petalite mining in Zimbabwe.” February, 2009.
96 U.S. Bureau of Labor Statistics. “Inflation Calculator.” http://data.bls.gov/cgi-bin/cpicalc.pl