

The Trouble with Lithium

Implications of Future PHEV Production for Lithium Demand

by

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Executive Summary

Lithium Ion batteries are rapidly becoming the technology of choice for the next generation of Electric Vehicles - Hybrid, Plug In Hybrid and Battery EVs. The automotive industry is committed increasingly to Electrified Vehicles to provide Sustainable Mobility in the next decade. Lilon is the preferred battery technology to power these vehicles.

To achieve required cuts in oil consumption, a significant percentage of the world automobile fleet of 1 billion vehicles will be electrified in the coming decade. Ultimately all production, currently 60 Million vehicles per year, will be replaced with highly electrified vehicles – PHEVs and BEVs.

Analysis of Lithium's geological resource base shows that there is insufficient economically recoverable Lithium available in the Earth's crust to sustain Electric Vehicle manufacture in the volumes required, based solely on Lilon batteries. Depletion rates would exceed current oil depletion rates and switch dependency from one diminishing resource to another. Concentration of supply would create new geopolitical tensions, not reduce them.

The alternative battery technologies of ZnAir and NaNiCl are not resource constrained and offer potentially higher performance than Lilon. Research and industrialisation of Electrified Vehicles must also prioritise these alternative battery technologies.

The Rise of Lithium

The world is embracing the Lithium Ion battery as its answer to mobile electrical energy storage needs. All other technologies are being more or less swept aside by the attraction of the potentially high energy density of Lithium based batteries.

The Lithium Ion battery has brought great improvements for portable electronic devices. Longer run time is still desired for laptop computers, but the Lithium battery now provides acceptable run times for most hand-held devices. The high cost of Lilon batteries is still a drawback and accounts for the continuing presence of NiMH batteries in the market.

As the reality of Peak Oil sinks in further, the apparent high performance of the Lilon battery is being carried over into the future of transportation mobility – the Electric Vehicle in all its variants: EV, PHEV and HEV0.

But is this enthusiasm justified? And could we not be swapping dependence on one depleting natural resource – oil – for another?

Analysis shows that a world dependent on Lithium for its vehicles could soon face even tighter resource constraints than we face today with oil.

Lithium Production and Resources

Global Production of Lithium containing minerals today is about 20,000 tonnes of contained Lithium metal. The two main mineral sources are:

- **Brine Lakes and Salt Pans which produce the soluble salt Lithium Chloride.**
- **A hard mineral called Spodumene, which is a silicate or glass of Lithium and Aluminium.**

The main producers of Lithium minerals are Chile, the USA, Argentina, China, Australia and Russia.

The following table shows the amount of Lithium metal equivalent contained in the Lithium mineral production from the main producing countries.

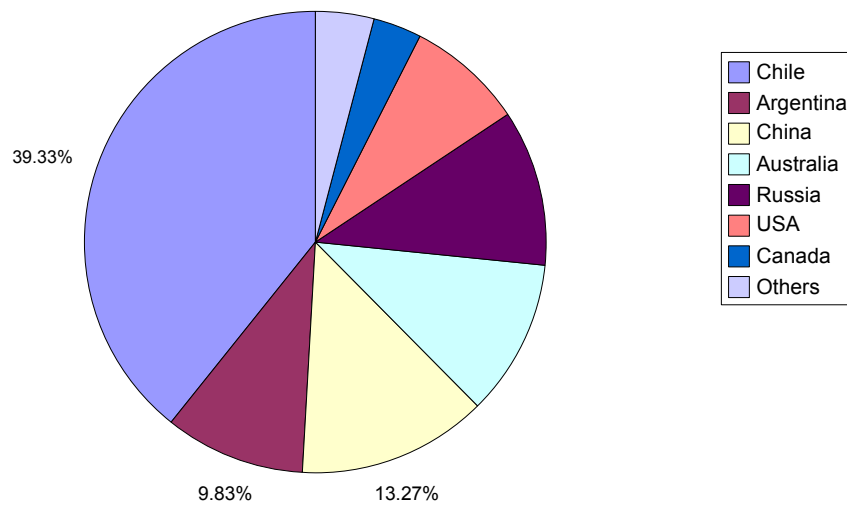
CONTAINED LITHIUM METAL PRODUCTION - 2005			
Country	2005 Production (tonnes)	Reserves (tonnes)	Reserve Base (tonnes)
United States	1,700 (MIR)	38,000	410,000
Argentina	2,000	1,000,000 (MIR)	2,000,000 (MIR)
Australia	2,240 (MIR)	160,000	260,000
Bolivia	-	2,700,000 (MIR)	5,400,000
Brazil	240	190,000	910,000
Canada	700	180,000	360,000
Chile	8,000	1,500,000 (MIR)	3,000,000
China	2,700	1,100,000 (MIR)	2,700,000 (MIR)
Portugal	320	NA	NA
Russia	2,200	NA	NA
Zimbabwe	240	23,000	27,000
TOTAL	20,340	6.8M	15.0M
<i>Source: USGS and MIR where indicated</i>			

The USA does not disclose how much Lithium it produces, but consumption was estimated to be 3,000 tonnes in 2005, up 50% from 2004. US Lithium Carbonate production in 2002 was in the order of 9,000 tonnes.

USGS data for Argentina, Australia, Bolivia, Chile and China has been amended by MIR in light of other data. This is discussed below.

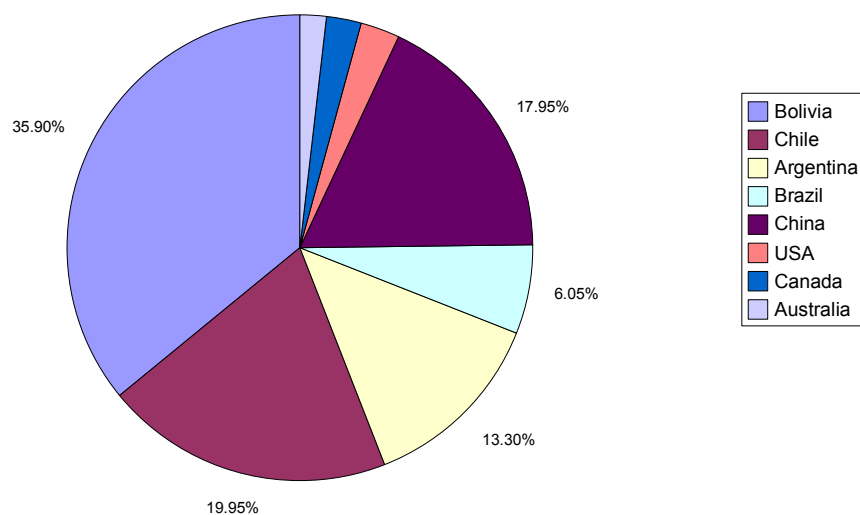
The following graph shows this contained Lithium production by country.

Global Lithium Production (Metal Equivalent)



While South America currently dominates Lithium Production, with Chile and Argentina producing 10,000 out of the world total of about 20,000 tonnes, it dominates the Lithium Reserve Base even more so.

Global Lithium Reserve Base



South America holds 75% of the known Global Lithium Reserve Base

Reserves vs Reserve Base

It is important to understand the distinction between “Reserves” and “Reserve Base”. The USGS estimate that Global Lithium Reserves today are in the order of 4.2M tonnes, to which we have added an estimated 1.5MT for Argentina and 2.7MT for Bolivia, but subtracted 1.5MT from their Chile estimate, to give a total of 6.8 MT. “Reserves” are defined by the USGS as follows:

“Reserves. That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials”.

“Reserves” are therefore what one can realistically expect to produce, using existing economically viable techniques.

The total global “Reserve Base” of Lithium is estimated by the USGS at about 11M tonnes, to which we have added 2.0MT for Argentina and another 1.6MT in China. Reserve Base is defined as follows:

“Reserve Base. That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources).”

“Reserve Base” is therefore the geological resource, not what is economically recoverable. At some point these resources might become available if prices rise sufficiently, but of course the market wants the price of Lilon batteries to come down, not increase. As energy prices rise in the future, the cost of extraction and processing will not necessarily fall.

We will discuss other often cited potential Lithium sources such as Seawater later in this paper.

If the world was to exchange oil for Lilon based battery propulsion, South America would become the new Middle East. Bolivia would become far more of a focus of world attention than Saudi Arabia ever was. The USA would again become dependent on external sources of supply of a critical strategic mineral while China would have a large degree of self sufficiency.

However, in addition to these geo-political factors, in the rush to extrapolate the Lilon battery from portable electronics to EVs, a number of other factors are being overlooked:

- 1. Only Lithium from the Brine Lakes and Salt Pans will ever be usable to manufacture batteries: the Spodumene deposits can play no part in this.**
- 2. An HEV or PHEV battery is 100 times as big as the largest Lilon laptop computer battery.**

Lithium Production and Real Availability

In this section, we will present an overview of how Lithium is currently produced and estimate how much of the Global Reserve Base of 15MT, plus the unknown deposits in Russia, could realistically be available for Lilon battery production in future.

The first point is that not all Lithium mineral deposits are created equal. There are two major types of deposit: a hard silicate mineral called Spodumene; and Brine Lake or Salt Pan deposits that contain Lithium Chloride.

Only the second of these is economically and energetically viable for Lilon batteries.

Lithium Chloride Production

To manufacture a Lilon battery, Lithium is needed for the cathode material and the electrolyte. This is obtained from **Lithium Carbonate** (Li_2CO_3) which in turn is now produced from naturally occurring Lithium Chloride. Lithium Chloride is currently produced in volume from only three salt lake deposits in the world in:

- Nevada (Silver Peak or Clayton Lake)
- Chile (Salar de Atacama)
- Argentina (Salar de Hombre Muerto).

All of these lakes contain a mixture of salts in varying proportions – chlorides and sulphates of sodium, potassium, calcium, magnesium, boron and lithium.

The process used to obtain Lithium Carbonate is known as the Lime Soda Evaporation process. In brief, the salty water is pumped out of the lake into a series of shallow ponds and left to evaporate for 12 to 18 months. Different salts crystallise out at different times as the solution becomes more concentrated. At one point it is treated with lime to remove the magnesium. Finally, the initial volume of water is reduced to produce a relatively concentrated Lithium Chloride brine (6% Lithium at the Salar de Atacama). This solution is then treated with soda ash (sodium carbonate or washing soda) to precipitate out insoluble Lithium Carbonate. 1.8 times as much soda ash is required as Lithium Carbonate. With low initial Lithium concentrations, variants of this process are used with absorption membranes or sulphate precipitation. Sulphate precipitation requires higher final concentration of the Lithium brine.

Solar Evaporation Pond



In addition to the three lakes already in use, production is now starting to gear up in China at the Zhabuye and Taijinaier Salt Lakes. A second extraction facility has also just (January 2007) been opened in Argentina (Salar del Rincon). Production will reach the market in late 2008.

The Lithium salt deposits at Salar de Atacama in Northern Chile are the biggest producer in the world, with production of about 40,000 tonnes of Lithium Carbonate per year.

The Salar de Hombre Muerto in Argentina encountered production difficulties in the early 2000s but this seems to have been rectified. Production is now at about 12,000 tonnes of Li_2CO_3 and 6,000 tonnes of LiCl per year.

The deposits in Nevada are in decline and many older Lithium deposits in the USA are now uneconomic. About 9,000 tonnes of Li_2CO_3 are produced in the USA per annum.

Global Lithium Carbonate production is currently 75,000 tonnes or 14,000 tonnes of Lithium metal equivalent. The other 6,000 tonnes of Lithium metal equivalent produced each year is contained in the mineral Spodumene which is used directly in the manufacture of heat resistant ceramics and glass.

Global Lithium Carbonate Production is in the order of 75,000 tonnes p.a.

With the capacity increases announced by the industry, Global Lithium Carbonate Production should double to 150,000 tonnes per year by 2010. The maximum production forecast is as follows.

GLOBAL Li₂CO₃ PRODUCTION		
	(tonnes)	
	2006	2010
Argentina	12,000	30,000
Bolivia	-	-
Chile	41,000	55,000
China	13,000	60,000
	(from minerals)	
USA	9,000	8,000
TOTAL	75,000 tonnes	153,000 tonnes

Production is concentrated in the hands of only 3 companies outside China: SQM, FMC Lithium and Chemetall GmbH. Admiralty Resources of Australia are just entering the market in addition.

Lithium Chloride Production - Future Issues

The last and biggest untapped reserve of Lithium salt in the world is in the Salar de Uyuni salt pans of Bolivia, the remains of an ancient inland sea. Bolivia is estimated by the USGS to contain Lithium resources of 5,400,000 tonnes or nearly 50% of the global Lithium metal reserve base and an even higher percentage of the Lithium salt reserves. Another estimate has put the Bolivian resource as high as 9MT.

Bolivia has made a number of attempts in the past to exploit these Lithium resources. These have all foundered for political reasons. The current political situation in the country is acting as a strong disincentive for western mining companies to operate there. A social revolution is under way in Bolivia and many foreign mineral extraction companies are seeing their assets nationalised, notably in the Oil and Gas industry. The historical exploitation of mineral resources by foreign firms with what is considered to be insufficient benefit to Bolivian society in return is a major political issue in the country. In both Chile and Bolivia, the Lithium resources are considered to be a National Asset. In the current climate, the Bolivian government may not permit the wholesale industrialisation of the Uyuni salt flats, a unique and ancient ecosystem, just to provide motive power to the developed world. They certainly will not do so without requiring a much greater financial return than previously.

It would take at least 5 years for the first Lithium Carbonate product to reach the market after an agreement was concluded to develop it. Contract negotiations would add to this timescale.

There is also growing antipathy between local communities in Argentina and international mining companies. Friction with the FMC facility at Hombre Muerto has been reported.

In Chile, there is continuous friction between the local communities and the mining companies over water rights. Mining already consumes 65% of the water in the Salar de Atacama region. The Salar is an important tourist destination, receiving over 50,000 visitors year round according to the United Nations Millennium Ecosystem Assessment. The Salars or salt lakes of the Andean Altiplano are home to unique species of fauna, including the famous pink flamingoes.

Ecological and environmental considerations will not be ignored in the future when considering development of these mineral resources. Chile recently passed a new environmental protection law¹, which requires all future mining developments to be subjected to an environmental impact assessment beforehand. All of the existing mining projects in the country can also be reviewed under this law and would have to be brought into conformity if found wanting. Citizens have the right to bring a judicial environmental review action against any existing mineral extraction operation.

SQM's brine extraction facility employs 300 people. Therefore a large expansion in brine extraction will not bring a great direct benefit to the region in terms of employment.

Spodumene

We will now examine the other main type of Lithium deposit found in concentrated form – Spodumene. Spodumene is a silicate of Lithium and Aluminium. In other words – it is a glass. Until 1997, most of the Lithium Carbonate produced was obtained from Spodumene. The entry of SQM onto the market in 1997 with large volumes of cheap brine produced carbonate led to a price crash and the Spodumene producers left the market. Sons of Gwalia of Australia commenced Li_2CO_3 production from Spodumene in 1996, with a 5,000 tpy capacity facility but ceased in 1998. Technical problems were also encountered from the beginning with separation of the Aluminium content.

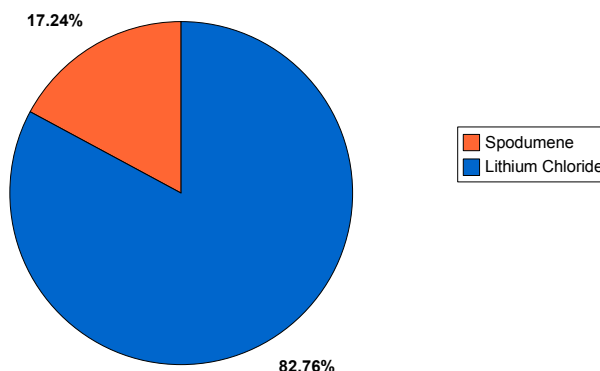
Today, this process would be uneconomic on a large scale not only on financial grounds but also due to the large amount of energy required to process it. In 2002 the Chinese were still producing some 13,000 tonnes of Lithium Carbonate from domestic and imported Spodumene but this will diminish as low cost Li_2CO_3 comes onto the market from the domestic salt lakes. One reason the Chinese have decided to develop the salt lakes is to eliminate dependence on Lithium mineral imports.

To produce Li_2CO_3 from Spodumene, the mineral is put through the following process:

- Grinding to a powder
- Calcining at 1100 °C
- Treatment with sulphuric acid at 250 °C
- Solvation with water to extract Lithium Sulphate
- Separation of Aluminium Sulphate
- Precipitation of Li_2CO_3 with soda ash

The graph below shows that the Spodumene deposits comprise a relatively small part of total Lithium reserves. Less than one fifth of the Lithium in the world (in relatively concentrated deposits) is found in the form of Spodumene or other hard rock minerals.

Lithium Metal Reserve Base
Spodumene vs Lithium Chloride



¹ Chilean Environmental Law No. 19,300

Therefore when we consider the future availability of Lithium we can only rely on the salt deposits. These will be limited to South America and China – no others of any significance are known. Bolivia holds over 50% of the global deposits and the start of production is not even officially in planning.

Ultimately Recoverable Reserves

We will now evaluate how much Lithium Carbonate is ultimately economically recoverable.

The two biggest gaps in the USGS Reserve Base and Reserves estimates are for Russia and Argentina. Russia is a vast country and Argentina of course shares a long border with Chile. Argentinian Lithium production now comes from two sites near the Chilean border which are more dilute brine deposits than those in Chile. Based on an estimated reserve base at one of these sites of 0.5 million tonnes, Argentina holds a significantly smaller amount of Lithium to Chile – about 1M to 2M tonnes. We have estimated these at 2MT and added them to the USGS Reserve Base. Russia's reserves are unknown but if we are optimistic we could put an upper limit of 5M tonnes, largely in the form of hard rock mineral Spodumene deposits. This would give a total Ultimate Global Reserve Base in the order of 20M tonnes of Lithium, but the Russian Spodumene deposits will not be economically suitable for Lilon batteries. Even if they were, geo-political factors mean that they could not necessarily be relied upon.

Looking back at the table, we can optimistically estimate the Global Lithium Salt Reserve Base as 2MT for Argentina, 3MT for Chile, 5MT for Bolivia and 1MT for China – 11MT contained Lithium in total or about 58MT of potential Li_2CO_3 . The US salt deposits are in decline. The relatively small hard rock mineral deposits can be discounted when considering their availability for batteries.

Global Lithium Salt Reserve Base is estimated to be 58MT of Li_2CO_3 .

This is the Li_2CO_3 Reserve Base – but how much is recoverable?

Let us consider the characteristics of the known Lithium Salt Lakes in more detail. The following table compares the chemical composition of the most important Lithium Brine resources in the world.

The first row shows the Percentage by Weight of Lithium in each brine.

The second row shows the ratio of Magnesium to Lithium in each brine.

	CHEMICAL COMPOSITION OF LITHIUM BRINE LAKES									
	Salar de Atacama	Salar de Hombre Muerto	Salar de Rincon	Salar de Uyuni	Clayton Valley USA	Great Salt Lake	Zhabuye Salt Lake China	DXC Salt Lake China	Taijinaier Salt Lake China	Sea Water
Lithium Content (%)	0.15%	0.062%	0.033%	0.035%	0.023%	0.004%	0.12%	0.04%	-	0.000017%
Mg/Li Ratio	6.4	1.37	8.61	18.6	1.43	250	Low	0.22	-	7000
Height AMSL	2,300m	3,700m	3,700m	3,653m	-	-	4,422m	4,475m	-	0m
Recoverable LCE	8MT	4MT	1.2MT	14.3MT	0.25MT	-	4MT	0.4MT	1.4MT	-
Source: "Evaluation of the Potential of the Salar del Rincon Brine...", Report by Consulting Geologist Mr Pedro Pavlovic to ADY, Dec. 2004; Sterling Group Ventures Inc.; Other Sources										

Based on the Process Recovery Factor at the Salar de Atacama of 40-42%, a Recovery Factor of 50% has been applied, to give a total realistic Lithium Carbonate production potential from these economically recoverable resources of 33.55MT.

Total Global Li_2CO_3 Ultimate Recoverable Reserves are ~ 35MT

If any addition is made to these Ultimately Recoverable Reserves, it will be in China or Tibet but the dominant position of South America, particularly Bolivia, is evident.

Exclusive dependency on Lithium Ion batteries, where the Lithium will overwhelmingly come from South America, would be like being dependent on South America for 80% of our oil supply.

The ratio of Magnesium to Lithium is a critical factor. If the level of Magnesium in the brine is too high, the evaporation rate is slowed down and Lithium yield reduced too much.

It is evident why the Salar de Atacama is the world's leading Lithium salt producer. It has a very high Lithium concentration which more than makes up for the rather high Mg:Li ratio. Production is carried out in locations where the concentration reaches over 3000ppm or 0.3% by weight. In other locations, the concentration of Lithium [Li] falls to 1000ppm. The climate is ideal for achieving high rates of evaporation. The Atacama desert is the driest place in the world, with strong winds. The evaporation rate is in excess of 3,600mm per year.

Total process recovery efficiency is 40-42%, so some 40% of the Lithium resource in the Salar is recovered with present techniques. The rest is re-injected back into the Salar.

The Salar de Hombre Muerto², over the border in Argentina, has only half the Lithium concentration of the Salar de Atacama but is helped by a lower Mg:Li ratio. FMC Lithium use a proprietary extraction process to produce LiCl there, but they still purchase additional Li_2CO_3 from SQM. Evaporation is also lower at 2,700mm per year, due to the higher elevation.

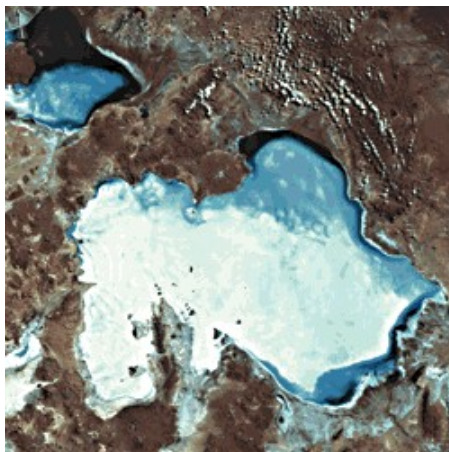
Operations have just started at Salar del Rincon, also in Argentina, 130 kms north of Hombre Muerto. This is a much less attractive resource than the preceding two, due to the even lower Lithium concentration and higher Mg:Li ratio. Admiralty Resources (ADY) are having to use a more specialised Lithium extraction process there. With Li resources of 0.48MT in the Salar del Rincon, ADY state that production of 20,000 tpy of LiCl could be sustained. Recovery factor will be 50% at best, giving total possible production from the Salar of 1.27MT of Li_2CO_3 . Admiralty Resources have presented this as 1.2MT of Lithium Metal, but in fact it is Li_2CO_3 .

Another factor is that both of these Argentinian resources are at over 3,700m altitude compared to 2,300m for Salar de Atacama. This reduces the evaporation rate to 70% of that at the lower level, increasing production time still further.

The above table also shows the problem with the Salar de Uyuni in Bolivia. This has the largest Lithium resources in the world but unfortunately, a very high Mg:Li ratio. It is also situated at a higher elevation than the Salar de Atacama. This makes it economically uncompetitive at the present time – extraction costs would be higher and production more time consuming.

² One report puts the Lithium resource in place at Hombre Muerto as only 130kT or 0.6MT LCE.

Satellite Picture of the Salar de Uyuni, Bolivia



Another factor that is not generally appreciated is that nearly all Lithium Carbonate production in the world is secondary to the main product of the extraction facility. In the case of the Salar de Atacama, SQM's main business is extraction of Potassium Chloride (KCl) and Potassium Sulphate (K_2SO_4). In 2001, SQM produced 21,000 tonnes of Li_2CO_3 – and 650,000 tonnes of KCl and 150,000 tonnes of K_2SO_4 from the salar. This large multi-commodity operation reduces the Lithium production costs greatly and makes it very competitive. The same applies to the Salars in production in Argentina and in Nevada. Only Sociedad de Químicos Litio (SCL), owned by Chemetall, were engaged in exclusive extraction of Lithium from the Salar de Atacama before SQM entered the market. The latest operation at Salar del Rincon is only economically viable as a multi-commodity extraction, due to its low lithium content, but the main bulk products produced will be KCl, Na_2SO_4 and common salt.

In the case of the two main Spodumene deposits, the Greenbushes Mine in Australia and the Lac du Bonnet mine in Canada are both primarily tantalum operations. Spodumene is only a secondary resource and sales of this mineral for ceramics are a minor secondary operation at both of these mines.

China

China is now rapidly increasing its production of Li_2CO_3 from brines. There are three main Salt Lake deposits of interest at the moment:

- The Taijinaier Salt Lake in the Qaidan Basin, Qinghai Province, North of Tibet
- The Dangxiongcuo (DXC) Salt Lake in South West Tibet
- The Zhabuye Salt Lake in Western Tibet

In August 2005, production of 5,000 tpy of Li_2CO_3 from the Zhabuye Salt Lake was started. The Chinese say this will increase in the long term to 20,000 tpy of sustained production. This salt lake is in a very remote region at an altitude of 4,400m or 14,500 feet. Evaporation rates are therefore lower than at the Chilean or Argentinian lakes. Apparently, Li_2CO_3 occurs naturally, crystallising on the shores of the lake, which is remarkable.

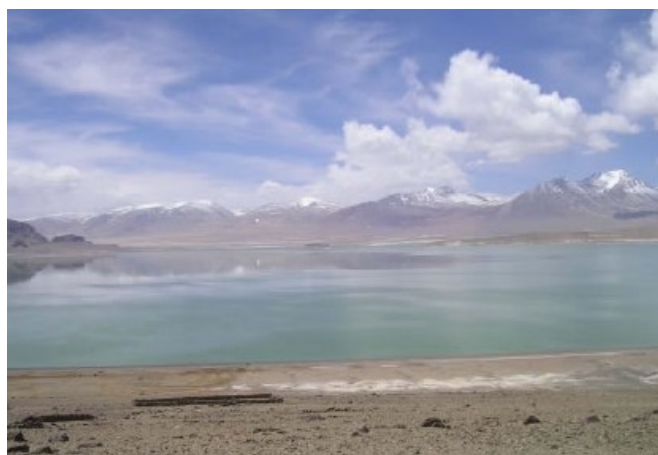
The Qaidan basin is said to be the largest Lithium resource in China. This region, north of Tibet, was once a vast lake. It now contains some 33 salt lakes. Pilot production of LiCl and Li_2CO_3 (500 tpy) from the Taijinaier salt lake was started in 2004 and full scale production is now gearing up. The CITIC Guoan Scientific and Technical Co. officially inaugurated a 35,000 tpy capacity Li_2CO_3 plant in Golmud, Qinghai Province on the 11th January 2007. It will certainly take some years for production to reach this figure, but if correct, this makes the facility the largest Li_2CO_3 plant in the world – ahead of SQM's 28,000 tpy plant at Salar del Carmen near Antofagasta.

CITIC Guoan hold a large stake in MGL, the largest Chinese manufacturer of $LiCoO_x$ cathodes for Lilon batteries.

The DXC Salt Lake in central Tibet has a Lithium concentration of about 400mg/l or 0.04% and a Mg:Li ratio of only 0.22. Extraction is attractive from that perspective, but the lake is quite a small resource, containing

only 1MT of LiCl. With a recovery efficiency of 50%, the total Lithium Carbonate production that could be expected from the lake would be in the order of 400,000 tonnes. The lake is also 4,400m above sea-level and over 400 miles from the nearest rail head by rough gravel roads³. The Canadian company Sterling Group Ventures are considering exploiting this resource with a 5,000 tpy facility.

DXC Salt Lake, Tibet



Another factor that has to be considered in these brine extraction operations is that it is a liquid resource. In Chile, after concentration in the solar ponds, the Lithium Brine is pumped into tankers and transported 250kms by road to a separate plant. In this plant it is treated with soda ash to precipitate out solid Lithium Carbonate. The transportation of the Lithium Brine by tanker, which is only 6% Lithium by weight, is a very significant inefficiency in the process. ADY in Argentina will be undertaking the same operation, tankering the brine to a production facility near a railway 50kms away.

In the case of these very remote Tibetan resources, either soda ash will have to be trucked in to the lake or the liquid brine will have to be transported by tanker to another facility.

Seawater

During the 1970s, the feasibility of extracting Lithium from Seawater was studied, to power a future nuclear fusion infrastructure.

Seawater has an average Lithium concentration of 174mg/l or 0.17 ppm: less than one ten-thousandth of the level in the Salar de Atacama (1000 – 3000ppm). Magnesium is one of the most common ions in seawater at 1.2g/l. The Mg:Li ratio is therefore nearly 7000:1. With a solar evaporation pond system, even disregarding the extremely high Mg:Li ratio, thousands of times more land area would be required to evaporate sea water to produce the same amount of Lithium than is used in the existing Salt Lake operations. More specialised absorption – selective extraction processes are then applied. Electrolysis methods have also been developed, which would of course require electrical power.

The financial and energy cost of these methods would be many times higher than existing methods and their feasibility on a large scale is unknown. To even consider basing the automotive industry on such a hypothetical future scenario is impractical and unrealistic.

³ Qualifying Report for Dangxiongcuo Salt Lake Deposit Nyima County Tibet, China. N. Tribe & Associates Ltd., 20/5/06.

Lithium Requirement

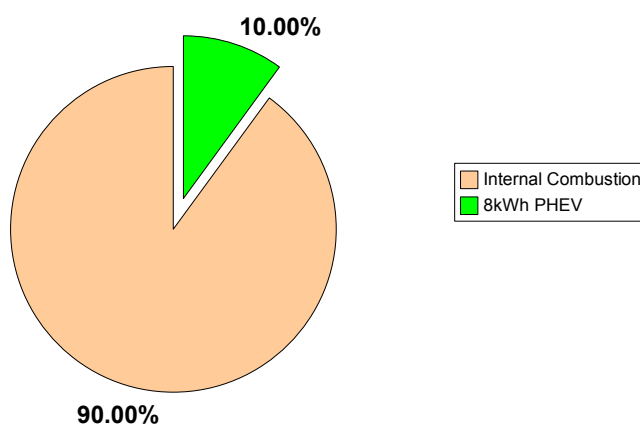
Today, some 60M cars are produced each year. If they were all PHEV20s with a small 5kWh battery⁴, they could reduce current fuel consumption of “compact” type cars by up to 50%. Further developments in prioritising aerodynamics and reduced weight could improve this further. Existing Lilon/LiMP “Energy Batteries” for EVs require about 0.3kg of Lithium metal equivalent per kWh, in the form of Lithium Carbonate. The total amount of Lithium metal required to make 60M PHEV20s with a small 5kWh Lilon battery would therefore be 90,000 tonnes – nearly 5 times current global Lithium production.

However, in Lithium Carbonate (Li_2CO_3) terms the position is worse. A Lilon “Energy” battery requires between 1.4 and 1.5kg of Li_2CO_3 per kWh of capacity. Therefore 60M PHEV20s with a 5kWh battery would require at least 420,000 tonnes of Li_2CO_3 per year – 6 times current production.

A Full Sized SUV requires a larger 9.3kWh battery to become a PHEV 20. This would use nearly 3kg of Lithium or 13kg of Li_2CO_3 per car.

A 5kWh battery is in fact marginal. In reality, at least 8kWh of capacity would be needed to assure 20 – 30 miles all electric range for a compact sized vehicle. The PHEV conversions of the Toyota Prius currently being offered by a number of independent companies in the USA use 9kWh Lilon batteries. Total Global Lithium Carbonate production today (which is already consumed by existing applications) would allow about 6 million such batteries to be manufactured – enough for 10% of vehicle production. Production of Lilon EV batteries today is insignificant, so all of the Lithium Carbonate supply for a growing Lilon EV battery industry will have to come from new Lithium Carbonate production. 60 million 8kWh batteries would consume 670,000 tonnes of Li_2CO_3 per year – nearly 10 times current production.

**Global Automobile Production
Percentage Replaceable with 8kWh Lilon Battery
Current Li_2CO_3 Production**

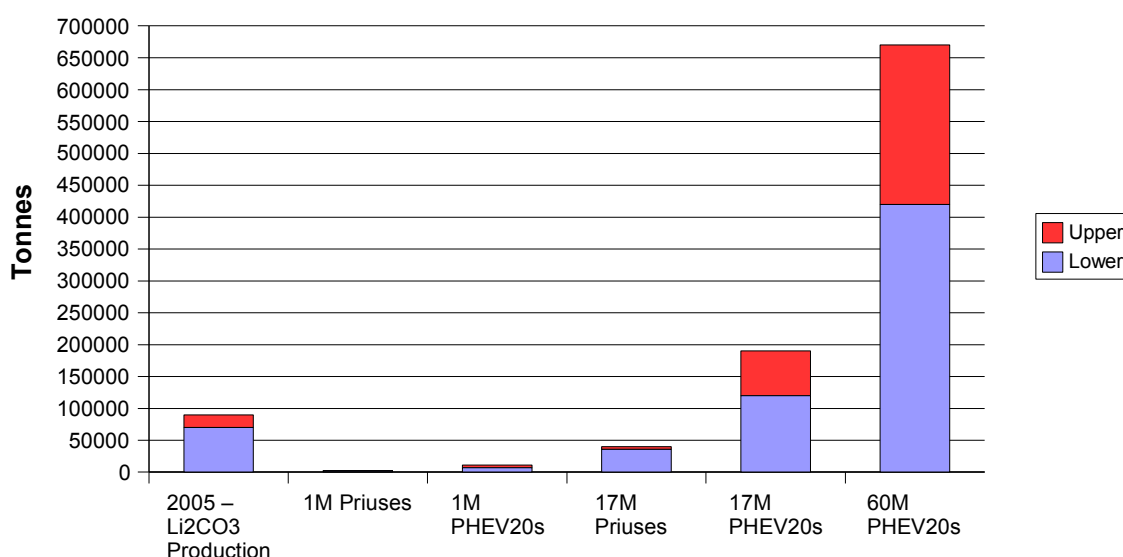


- Global Automobile Production is 60 million vehicles per year
- Current Global Lithium Carbonate Production would permit production of 6.5 million PHEV20 batteries per year
- Conversion of Global Automobile Production to PHEV20-30s would require 400-700 kilotonnes of Lithium Carbonate per annum, 6 - 10 times existing global Lithium Carbonate production.

In the USA, some 17M Light Vehicles are sold each year. The following graph shows the impact on Li_2CO_3 requirements of increasing demand for the existing Prius Hybrid and a compact PHEV20. The upper and lower demand limits for the PHEV20 are based on either a 5kWh or 8kWh battery.

⁴ 5.1kWh is the minimum battery size for a compact PHEV20 (EPRI, 1000349, Comparing the Benefits and Impacts of HEV Options, 2001)

Lithium Carbonate Required vs Current Production



- Lithium Carbonate Production is about 75,000 tonnes per year
- 17M existing Priuses (1.5kWh battery) would consume 35,700 tonnes of Li₂CO₃ per year
- 1M PHEV20s would consume 7,000 – 11,000 tonnes of Li₂CO₃ per year
- 17M PHEV20s would consume 120,000 – 190,000 tonnes of Li₂CO₃ per year
- 60M PHEV20s would consume 400,000 – 700,000 tonnes of Li₂CO₃ per year

A vast increase in Lithium Carbonate production will be required to convert the existing car fleet into HEV0s or PHEVs using Lilon batteries. GM's recently announced "Volt" series hybrid PHEV40 with a 16kWh battery would double the above requirements. Pure BEVs with a minimum 30kWh battery would multiply the above requirements by a factor of 4 to 6.

The overwhelming majority of this production will have to come from the Altiplano of Bolivia, Chile and Argentina. This is a remote mountainous region, situated over 3000 metres above sea level, where temperatures fluctuate between +25° C during the day and -25° C at night. There is no infrastructure – road, railways, telephone or electrical power. Billions of dollars of investment over a period of a decade would be required to build up production and transport facilities.

The largest producer of Lithium Carbonate at the moment is SQM of Chile. Since operations started in the late 1990s, their production has reached 27,000 tonnes per year. They have stated that production will increase to 40,000 tpy by 2008. Their local competitor SCL (owned by Chemetall of Germany) produce some 14,000 tonnes per year. Over the border in Argentina, FMC Lithium produce Lithium from brines at Salar de Hombre Muerto and relations with the local population are not at their best. Production is estimated to be around 20,000 tpy of LiCl, used to produce 12,000 tonnes of Li₂CO₃ and 6,000 tonnes of LiCl finished product. Admiralty Resources of Australia are also just about to start production in Argentina nearby (Salar del Rincon) and expect to reach output of 8,000 tonnes of Li₂CO₃ and 9,000 tonnes of LiCl. Chemetall Foote in the USA do not reveal their production but it is probably around 9,000 tonnes and falling. Many other Lithium deposits in the USA are no longer worked.

The last known Lithium salt resource is in China, where CITIC Guoan inaugurated a Li₂CO₃ production facility in January 2007 with a reported ultimate capacity of 35,000 tonnes per year. This level of production is unlikely to be reached for some time. Another 5,000 tpy Li₂CO₃ plant started operations in August 2005 at the Zhabuye Salt Lake in Western Tibet, with a stated ultimate capacity of 20,000 tpy. Sterling Resources are in the very preliminary stages of developing a possible 5,000 tpy operation at the remote DXC Salt Lake.

Global Production of Li₂CO₃ will therefore reach in the order of 150,000 tpy by 2010 and maybe up to 200,000 tpy from these existing resources. After that, attention will have to turn to Bolivia.

The potential depletion rates give rise for concern. With still growing car demand and the inevitable pressure for larger battery capacity as oil production falls, notwithstanding better Lithium utilisation in future batteries, required future production of Li_2CO_3 could foreseeably exceed 1 Million tonnes per year. This would be in the order of 3% of the Global Li_2CO_3 Recoverable Reserves per year.

**Future Lithium Carbonate Demand could exceed 3% of the
Global Li_2CO_3 Recoverable Reserves per annum**

At 1 Million tonnes per year, Lithium Carbonate production would be depleting the realistically producible reserves of 35MT by nearly 3% per year. As production from the lakes continues, the concentration of Lithium remaining will fall, leading to diminishing returns as time goes on. For instance, the concentration of Lithium in Clayton Valley has fallen from 350mg/l in the 1960s to 230mg/l today.

One can see that a major logistical challenge lies ahead: converting the car industry to produce HEVs and PHEVs, increasing battery manufacturing capacity and increasing Lithium Carbonate production by an order of magnitude to over 600,000 tonnes per year – not taking into account future growth in demand for automobiles from China and India, which could increase demand by yet another order of magnitude.

Of course, unlike oil, Lithium is recyclable. As with Lead Acid batteries a closed recycling circuit would have to be implemented to ensure recycling of used Lithium batteries. After some years, scrapping of old cars as they are retired could start to make a significant contribution to new build batteries. But 100% recovery will never be possible and growth in automobile demand will continue.

The World Automobile Parc currently stands at about 900M vehicles. If they all used a 5kWh Lilon battery, they would contain 6.3M tonnes of Lithium Carbonate – and the fleet is growing all the time. 6.3M tonnes is in the region of at least 18% of economically viable Li_2CO_3 Reserves, including Bolivia. With a more realistic projection of at least an average 10kWh battery per vehicle, 36% of the world's recoverable Lithium Carbonate Reserves would be consumed. 10KWh is still a small battery – even if 20kWh was achieved with the same Lithium utilisation, Lithium consumption will be at unsustainable levels.

**To equip the World Automobile Parc with a 10kWh Lilon battery would
consume over 35% of the World's Producible Lithium Carbonate Reserves**

Before recycling can be considered, a certain amount of Lithium will have to be extracted to equip the world vehicle fleet with batteries. That quantity is an unrealistically high percentage of the world's Ultimately Recoverable Reserves of Lithium.

Market Distortion

Some 20% of current Li_2CO_3 production or 15,000 tonnes is used in batteries, which is the fastest growing sector of demand. Laptop computer and mobile phone sales are growing on average by 20% per annum and by 50% - 70% p.a. in some countries. Demand for Li_2CO_3 from ceramics, lubricants and aerospace Al-Li alloys is also growing. Demand for Li_2CO_3 from the portable electronics sector will therefore have doubled, at least, by 2010 to over 30,000 tpy.

It is evident that the introduction of even quite modest numbers of PHEVs into service equipped with Lilon batteries will have a significantly distorting effect on the Li_2CO_3 market. In effect, 1 million PHEVs with a 10kWh battery will use as much Lithium Carbonate as is consumed by the entire electronics sector today. The entire growth in production capacity planned by 2010 – which is already an unprecedented doubling in production from initiation in 2003 – would supply only 5 million such PHEVs. That growth in production from 75,000 to 150,000 tonnes has not been planned on the basis of automotive demand, but for electronics and other applications, except perhaps by the Chinese. The Chinese production is not destined for export but for domestic battery production.

Commercial Vehicle Demand

The above analysis has only considered the Light Duty Vehicle sector, mostly comprised of private automobiles. This is the sector receiving most attention from the automotive industry, although a quiet revolution is underway in the Public Transit sector in the USA. The majority of US cities are now replacing their public buses with hybrid vehicles, mostly series hybrids. The NYCT Authority will have over 800 series hybrid buses in operation. These vehicles use lead acid batteries and achieve a modest 10% improvement in fuel consumption over a conventional vehicle.

In view of the vital importance of Road Haulage to the modern economy, the effects of potential PHEV battery demand from the Road Transport and Haulage sector must also be considered. In fact, it should be prioritised. In 2004, US trucks and buses consumed 2.67 Mb/d of oil, compared to 8.4Mb/d for LDVs.

In 2003, the US DoT estimated that there were 2.245M of the heaviest combi-trailer trucks in the USA, travelling 138 billion vehicle miles with a total fuel consumption of 27 billion gallons. This represents an average fuel efficiency of 5.1mpg. Each vehicle travelled on average over 60,000 miles per year, or five times the US average for an LDV.

The heaviest Class 8 vehicles can reach a weight of 36 tonnes. Average distance travelled is 80,000 miles per year for these largest vehicles.

How large a battery would such vehicles require? The ultimate requirement – for a fully battery powered truck, would be so high that it is beyond consideration here. 1000 kWh would not be unreasonable, but would be weight prohibitive with Lilon batteries. If we consider that the Fuel Consumption of these vehicles is six times as high as a medium passenger car, then pro-rata we could envisage that a Heavy Class 7 or 8 truck would travel in the order of 0.5 miles per kWh of electrical energy. These trucks are driven at least five times as far as an average passenger car per year. A 300kWh battery, 30 times as large as that in a PHEV automobile, might allow 150-180 miles All Electric Range (AER). We will assume they are equipped with a smaller 200kWh Lilon battery to give only 100 miles AER.

In 2004, new registrations of Class 7 and 8 trucks in the USA stood at 285,000 units. Equipped with a 200kWh battery, the total Lithium Carbonate requirement would be 80,000 tonnes. This is equal to the total Global Lithium Carbonate production in 2006.

Total registrations of Class 3 trucks and above (5 tonnes or more) in the USA in 2004 were 574,000 units. The smallest of these have an average fuel consumption of 10.5 miles per USG, falling to 5.7mpg for Class 8 trucks weighing 33,000lbs or more. Therefore, for 100 miles AER, a minimum battery size of 100kWh ranging up to 200kWh would be required.

US TRUCK REGISTRATIONS 2004				
CLASS	Registrations	mpg	Min. kWh	Li ₂ CO ₃ (tonnes)
Class 8 >33,000 lbs	202,000	5.7	200	56,560
Class 7 26-33,000 lbs	83,000	6.4	180	21,000
Class 6 19.5-26,000 lbs	76,000	7.0	160	17,000
Class 5 16-19,500 lbs	41,000	7.9	140	8,000
Class 4 14-16,000 lbs	65,000	8.5	120	11,000
Class 3 10-14,000 lbs	107,000	10.5	100	15,000

To equip all of the 574,000 Class 3 and above trucks sold each year in the USA with a 100 – 200kWh battery would consume 128,000 tonnes of Li₂CO₃ – 70% more than existing global production.

To equip the existing US Class 7 and 8 fleet of 2.245M vehicles with a modest 200kWh Lilon battery would require 627,000 tonnes of Lithium Carbonate. This is 1.8% of Global Ultimately Recoverable Reserves.

To equip the US Class 7 and 8 Road Haulage Fleet with a 200kWh Lilon battery would consume 1.8% of the World's Producible Lithium Carbonate Reserves

Conclusion

We have seen that to supply the 17M LDVs sold in the US each year with a PHEV20-30 battery would consume 200,000 tonnes of Li_2CO_3 . To equip the half a million or so trucks sold in the US each year with a very small PHEV battery would consume an additional 130,000 tonnes of Li_2CO_3 . Worldwide, 10 million Commercial Vehicles are sold each year. With a 100kWh battery, these would consume 1.4MT of Lithium Carbonate – double the requirement from the 60M automobiles sold each year of some 700,000 tonnes.

When Commercial Vehicles are taken into account, the potential annual Lithium Carbonate requirement would triple to over 2MT. This would be a depletion rate of 6% of Ultimately Recoverable Reserves per year.

With batteries larger than 200kWh, the weight even with Lilon technology becomes prohibitive. Given the vital importance of Road Haulage, efforts to reduce fuel consumption by trucks should be an absolute priority. Lilon technology faces severe resource constraints in meeting automobile requirements, let alone twice the demand from the Commercial Vehicle sector. Another battery technology with much higher energy density will be required to provide reasonable levels of energy storage at acceptable weight for heavy trucks.

Technology Resource Comparison

In this section, we will examine the resource requirements of the three most important alternative battery technologies: the Nickel Metal Hydride battery (NiMH), the Sodium Nickel Chloride battery (NaNiCl) and the Zinc – Air battery or fuel cell (ZnAir).

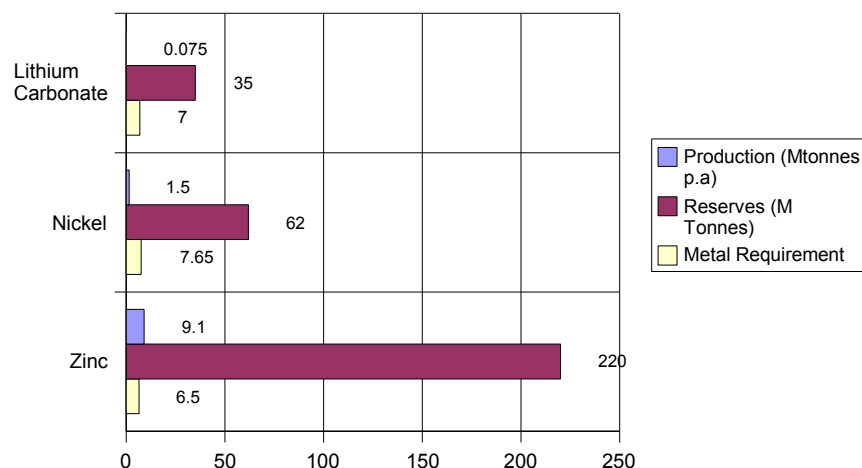
The most well known alternative to Lilon is the NiMH battery. It is rugged, proven, has high cycle life and has many years development behind it. However, it is also heavier than Lilon and very Nickel intensive: between 3 and 6 kgs of Nickel metal are required per kWh of capacity depending on the cathode type. It also requires Cobalt. Cobalt is an extremely expensive strategic metal and production is limited. Total global production of Cobalt in 2005 was about 50,000 tonnes. There is certainly insufficient Cobalt to mass produce large NiMH batteries for a global sized fleet of HEVs, PHEVs or EVs. The lack of Cobalt as well as its high price is another reason Lilon battery manufacturers will not use the LiCoO_x cathode type in EV batteries, as used in consumer Lilon batteries, apart from the unacceptable safety of a Cobalt containing Lilon cathode for an EV battery.

Two other battery technologies exist which could provide “Sustainable Mobility” in a world without oil, without the same resource constraints. These are:

- The “Zebra” Sodium Nickel Chloride battery
- The Zinc Air battery and Fuel Cell

The following graph compares the existing production of Lithium Carbonate, Nickel and Zinc to the existing Reserves of those materials; and how much of each of those materials or metals would be required to equip 1 billion cars with a 5kWh battery, using Lilon, NaNiCl and ZnAir technology respectively.

Metal Production, Reserves and Requirement for 1 Billion 5kWh Batteries



By setting a global minimum ultimate requirement to equip 1 billion motor vehicles with a small 5kWh PHEV battery, we can see the relative resource impact of each technology.

Lithium

It can be seen that the ratio of Lithium Carbonate Requirement to Current Annual Production is 7 : 0.075 or nearly 100 to 1.

Nickel

Global Nickel production in 2005 was 1.5M tonnes, 70% of which is used for the production of stainless steel. The Reserve Base is quite large – 140M tonnes in land based resources alone, of which the USGS consider 62M tonnes as currently exploitable Reserves. Extensive deposits of Nickel rich Manganese nodules on the sea bed are potentially available in addition to this – some are already economically viable.

The above graph shows that 7.65M tonnes of Nickel would be required to equip the Global Motor Fleet with a 5kWh Zebra NaNiCl battery. Twice that amount of Nickel or over 15M tonnes would be required if NiMH batteries were used.

It would take 5 years at current Nickel production rates to produce enough Nickel to equip the global motor fleet with a 5kWh NaNiCl PHEV battery.

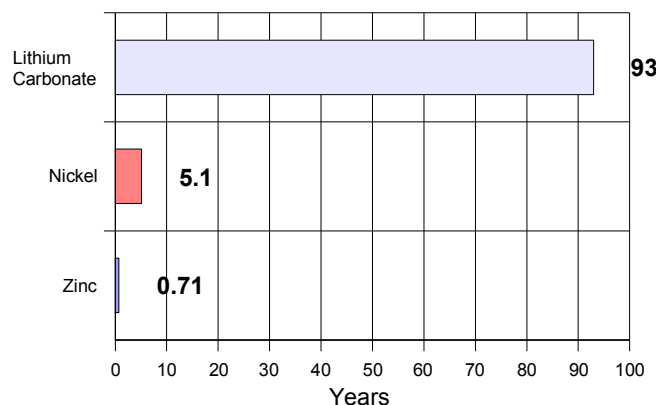
Zinc

Global Zinc production in 2005 was 9.1M tonnes, most of which is used in the galvanising of steel. Reserves are 220M tonnes and the total Reserve Base is estimated to be over 1.4 billion tonnes. Zinc production ranks fourth in the world, after iron, aluminium and copper.

The above graph shows that 6.5M tonnes of Zinc would be required to equip the Global Motor Fleet with a 5kWh ZnAir battery. The ZnAir metal fuel cell uses 1.3kg of Zinc per kWh of capacity.

If we compare these metal resource requirements to the existing production (Requirement to Production Ratio) we obtain the following graph.

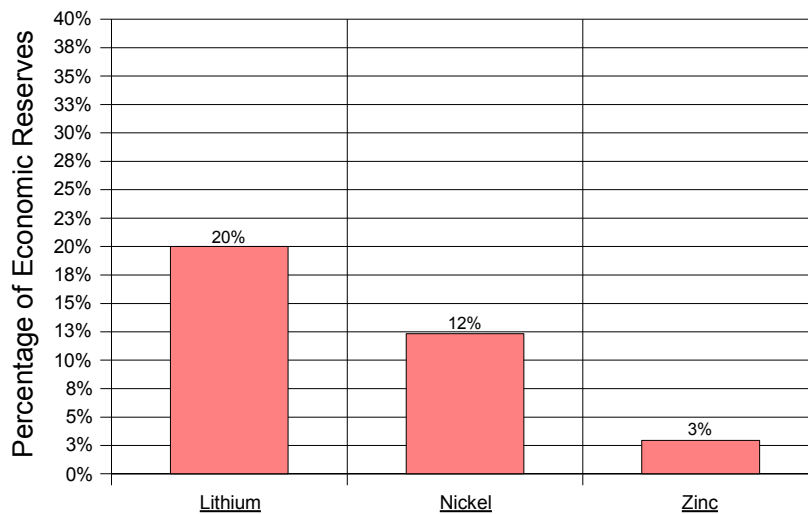
Years of Current Production to Fulfill 1 Billion 5kWh Batteries



The scale of the logistical challenge is again self evident. If we commit to Lithium Ion batteries, it would take 93.3 years at current production rates to produce enough Lithium to equip the current world vehicle fleet with a 5kWh battery. 5 years of existing Nickel production would be required if Zebra NaNiCl batteries are used and less than nine months' Zinc production with ZnAir.

We now compare the battery technologies in terms of the percentage of available resources that they would consume.

Percentage of Resource Reserves Required to Manufacture 1 Billion 5kWh PHEV Batteries



There are currently nearly 1 billion motor vehicles in the World. To equip them all with a small 5kWh PHEV battery would consume at least 20% of the world's existing Lithium metal salt reserves using Lilon batteries; 12% of the world's Nickel reserves with NaNiCl batteries; and 3% of the world's Zinc reserves with ZnAir batteries.

In addition, the USGS Reserve Base figures for Nickel and Zinc are 140MT and 460MT respectively, compared to 62MT and 220MT of "Reserves". We have estimated the Li_2CO_3 Reserve Base at 60MT.

If we compare the resource footprint in terms of these higher Reserve Base figures, the percentage of the Nickel Reserve Base required falls to 5.3% and to 1.4% for Zinc – potentially as low as 0.5% of the Zinc reserve base – compared to 12% of the Li_2CO_3 Reserve Base.

There is uncertainty in any estimate and comparison – but what this shows beyond doubt is that there are orders of magnitude difference in the availability and production of Nickel and Zinc compared to Lithium. In addition, while there are no other Lithium Salt deposits known in the world, extensive Nickel and Zinc deposits are known that could be added to the Reserve Base for these metals. Lithium can in theory be obtained from sea water – but only by using untried, untested technologies that have not been developed beyond the laboratory scale. They are certainly not economically competitive with present methods.

A 5kWh battery will become too small as time progresses. As oil supply declines steeply after 2010, even a 50% reduction in fuel consumption will become insufficient. Ultimately the world will have to use⁵ pure BEVs or highly electrified vehicles which will require at least a 30kWh battery to give a range of 120 miles. Even if this energy capacity is doubled by doubling the utilisation of Lithium, that would still only provide a range of 240 miles and would still use 6 times as much Lithium as a current 5kWh battery. 1 billion BEVs with a current technology 30kWh battery or a future “double energy density” 60kWh battery would use 8M tonnes of Lithium – over half of the total current Lithium metal Reserves Base. The Lithium Carbonate requirement would be over 42 Million tonnes, 35% more than economically recoverable Li_2CO_3 reserves and two thirds of the total Li_2CO_3 Reserve Base of 60MT. Such a scenario is unrealistic.

The above scenarios have not taken into account the 140 million trucks and commercial vehicles in the world which will require significantly larger batteries.

In 1995, the 650M Light Duty Vehicles (LDVs) in the world consumed 19Mb/d of oil. Trucks consumed 12Mb/d. There are now over 850M LDVs and 140M HGVs in use. Each HGV will require a battery at least 10 times as large as that in an automobile, if not 20 times as large. The ultimate resource requirement from Commercial Vehicles will be double that of LDVs.

Analysis

Without some sort of real energy breakthrough (such as “Zero Point Energy”), we can see that future mobility is likely to become much more constrained than it is today. The cost in mass production of Lilon batteries is expected to be quite high - \$350/kWh. The battery alone will therefore add \$2,000 to \$3,000 to the cost of a car for a PHEV20.

The Zebra NaNiCl battery has an energy density for the complete battery package including control electronics of 120Wh/kg. This is superior to any of the automotive Lilon batteries currently available, particularly the new safe cathode technologies that must be used for automobiles: iron phosphate, manganate spinel or layered MnO_2 . The Zebra battery also uses much less Nickel per kWh than NiMH: only 1.53kg per kWh versus 3 to 6 kg per kWh for NiMH.

The Zebra battery promises to be much more affordable than Lilon in high volume at potentially \$150/kWh. An 8kWh unit would therefore cost the end user only \$1,200.

The case for the Zinc Air battery is also compelling. There are three types of ZnAir technology:

- The “Refuellable” ZnAir Fuel Cell
- The “Mechanically Rechargeable” ZnAir Fuel Cell
- The Electrically Rechargeable ZnAir Battery

First, the energy density is well over 200Wh per kg of battery weight for existing mechanically rechargeable “Zinc Fuel Cell” designs. Commercially available ZnAir “button” cells exhibit an energy density of over 400Wh/kg.

Secondly, the cost of ZnAir would be by far the lowest of all the battery technologies. An end user price below \$100/kWh may not be unrealistic.

⁵ We will not discuss here the many deficiencies of Hydrogen Fuel Cell technology.

The US company Metallic Power spent some years in the late 1990s trying to commercialise a refuellable ZnAir fuel cell. The “battery” could be refuelled much like a car with a liquid slurry of electrolyte and Zinc. A 60kWh capacity ZnAir unit was projected to cost only \$2,000 in 1998. A unit this size would fit into a mid-size car or even a compact. Mechanically rechargeable ZnAir units of this capacity, in which the anodes are physically replaced, are undergoing trials in China in taxis and smaller units are widely used in scooters.

Rechargeable Zn Air batteries have historically had limited cycle life of perhaps 350 cycles, due to change in shape and loss of capacity of the anode during use. Nickel Zinc batteries, in which the anode chemistry is identical, are now commercially available⁶ with a stated cycle life of over 500 cycles. Therefore Zn Air should also now be able to match that. 500 cycles would be adequate for a yearly battery replacement and still be cost effective for a PHEV battery at under \$100/kWh. One company (ReVolt Technology) also claims to have greatly extended the cycle life with an energy density of over 400Wh/kg. The Zinc anodes could also be designed for easy replacement (like the existing mechanically rechargeable designs) and recycled. The latest design from Electric Fuel does not require special dendritic zinc anodes, which removes the need for specialised regeneration plants. This special infrastructure was the main economic barrier to adopting the ZnAir fuel cell: without it, the existing industrial Zinc recycling infrastructure can be used, greatly reducing the cost of replacement Zn anodes.

Global Zinc production stands at 9.1M tonnes per annum. Reserves are 220M tonnes and the Reserve Base is 460M tonnes. Zinc is widely used throughout society for all manner of applications. A well established zinc recycling industry already exists. Zinc is by far the cheapest and most available of these three metals (excepting Iron of course in an NaFeCl version of the Zebra battery).

Rechargeable ZnAir batteries with an energy density of 300 - 400Wh/kg of battery weight have been demonstrated. A great advantage is that the cathode is the air itself, greatly saving battery weight. When the battery is recharged, the oxygen consumed during discharge is released back into the atmosphere and of course no Carbon Dioxide is produced.

At 400Wh/kg, battery discharge could be limited to 50% to increase cycle life to well over 500 cycles.

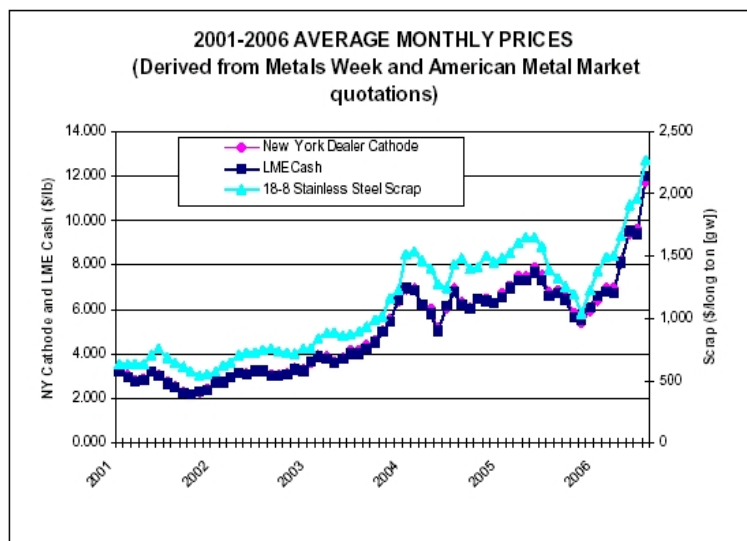
Therefore, given these cost and resource factors, it may in fact make much more sense for fleet operators to adopt the mechanically rechargeable or refuellable ZnAir fuel cell type systems, where they can install their own “recharge” infrastructure. Alternatively, as a Plug in Hybrid, a PHEV40 could be designed with a 20kWh ZnAir unit using a rechargeable version of the ZnAir battery. The cycle life of these rechargeable ZnAir batteries may be limited to 500 cycles at present, but in a hybrid car discharge could be limited to 50% DoD to give an effective 10kWh capacity and extend the cycle life.

6 Powergenix Inc., Ni Zn Technology

Cost Comparison

Many non-ferrous metals are continuing to set new price records every month. This could be a sign that Peak Oil is starting to impact energy costs for extraction, refining and transportation of metals. In August 2006, Nickel reached \$33,000 per tonne on the LME – 3 times the level of November 2005 and twice the level of June 2005. The price has become much more volatile since 2004. Zinc by contrast was trading at about \$1,300 per tonne in 2005 – still a significant increase from \$900 per tonne in 2004 but still less than a tenth the price of Nickel.

This graph shows the evolution in Nickel prices since 2001.



Lithium is not a traded metal but raw Lithium Carbonate was until recently valued at about \$3/kg. During 2005 and 2006 this rose to over \$5/kg and apparently some Japanese Lilon battery manufacturers are now offering \$10/kg or \$10,000 per tonne, a threefold increase in 2 years.

The projected costs for Lilon and NiMH batteries are still in the order of \$300 - \$450 per kWh even in high production volume. A 30kWh Lilon battery would therefore cost at least \$9,000: prohibitive for the mass market.

If Nickel prices continue to rise, the Nickel in the Zebra battery can be largely replaced with Iron to make an NaFeCl₂ battery – iron and common salt. The cell potential falls from 2.58V to 2.35V, i.e. there is a 9% reduction in energy density but operating temperature can also be reduced from 300° to 250° C. Unlimited quantities of this type of battery could be cheaply produced. Since 1998, the Zebra has used a 4:1 Ni:Fe mix.

The Zebra technology is projected to have an end user price of \$100 - \$150 in medium volume. This would put a 30kWh unit at \$3,000 - \$4,500 with the potential for further cost decrease in higher volume. Even at \$30,000 per tonne the cost of nickel is not the major factor – manufacturing costs are the driving factors.

The Metallic Power ZnAir fuel cell was expected to cost \$2,000 for a 60kWh unit in 1998. The ZnAir battery uses even less Zinc per kWh than the Zebra uses Nickel and the price of Zinc is less than a tenth that of Nickel.

Another major cost advantage of the Zebra and ZnAir technologies are their design and engineering simplicity. They do not depend on advanced, expensive to fabricate nano-materials with relatively involved battery designs, along with the complex Lilon electronic control system required for thermal management and prevention of over-charge and over-discharge.

The basic Zebra and ZnAir technologies were developed in the 1960s. They use classical chemistry, straightforward assembly and engineering and are very rugged and safe. They tolerate overcharge and overdischarge without significant degradation in performance or safety. Unlike the Lilon battery, the Zebra

battery can sustain a high number of cell failures and then only performance is affected, due to the increased internal resistance, not safety. Cell failures in the Lilon battery have serious safety implications.

Overall, the cost and complexity of the Lilon battery, even with the safer iron phosphate and manganese cathodes, cannot be justified in face of the existing alternatives: NaNiCl and ZnAir.

Conclusion

The world has become enamoured with the Lilon battery. While this may be sustainable for portable electronics goods, it is not sustainable for EV applications. A balanced scientific and economic analysis concerning the sustainability of Lilon technology for EV applications has not been performed.

One of the most quoted studies⁷ into material availability for a future Electric Vehicle fleet is that carried out by Bjorn Andersson and Inge Rade of Chalmers University. The study has been quoted to show that there is sufficient Lithium in the Earth's crust to power 12,000 million EVs with Lilon Manganese based batteries. In fact, there is a very wide range of uncertainty in Andersson and Rade's estimates: they estimate the figure could be as low as 200 million – in other words, there is a factor of 60 between their upper and lower estimates. There are currently some 900 million cars and commercial vehicles on the road worldwide.

Andersson concludes (P35):

“At least seven out of nine assessed battery technologies have a potential of more than one billion vehicles, but the constraints could materialise at a level that is at least one order of magnitude lower. We can not be sure that any of the assessed battery technologies could provide power for a fraction of a future vehicle demand that exceeds 10%. In addition, a successful diffusion is likely to create conflicts between preservation of local environments threatened by mineral exploitation and a secured supply of metals for electric vehicles.”

Andersson and Rade did not include the ZnAir technology in their evaluation.

From a resource and industrial point of view, as well as battery performance, the EV and PHEV industry should focus its battery strategy on the ZnAir and Zebra NaNiCl / NaFeCl battery technologies. Unlimited quantities of the NaFeCl battery could be manufactured from Iron and Common Salt (with a reduced Nickel content). For practical purposes there are no resource constraints on the use of ZnAir technology either. These technologies are far cheaper and simpler than the various Lilon variants, much more rugged and stable, require simpler and cheaper control electronics and even outrank Lilon in performance terms, particularly the lower energy density Lilon cathode technologies which will be used for safety reasons - Iron Phosphate, Manganate Spinel or Layered MnO₂.

Production of rechargeable batteries for PHEVs and EVs should be prioritised now with the Zebra battery, which can provide raw performance superior to Lilon today.

In parallel, research into improving the cycle life of the rechargeable ZnAir battery should be prioritised. The economics of industrialising even an existing 350-500 cycle ZnAir rechargeable battery of over 200Wh/kg energy density should be studied. The payoff is the commercialisation of a 400Wh/kg battery with multi-year life priced at under \$100/kWh.

These factors – Performance, Safety, Cost, Simplicity, Industrial Availability as well as the very significant Geostrategic and Environmental Protection implications of dependence on Lithium - should make the ZnAir and NaNiFeCl batteries the prime choice for meeting the urgent need to reduce the consumption of oil immediately at all costs or face the consequences of a meltdown in civilisation.

⁷ Material Constraints on Technology Evolution: The Case of Scarce Metals and Emerging Energy Technologies, D. Phil Thesis, 2001