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. LiIon 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 must 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 Lithium available in the Earth's crust to sustain Electric Vehicle manufacture in the volumes required, based solely on LiIon 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 LiIon. 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 LiIon 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 LiIon 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 salts Lithium Carbonate and Lithium Chloride.**
- **A hard mineral called Spodumene, which is a silicate or glass of Lithium and Aluminium.**

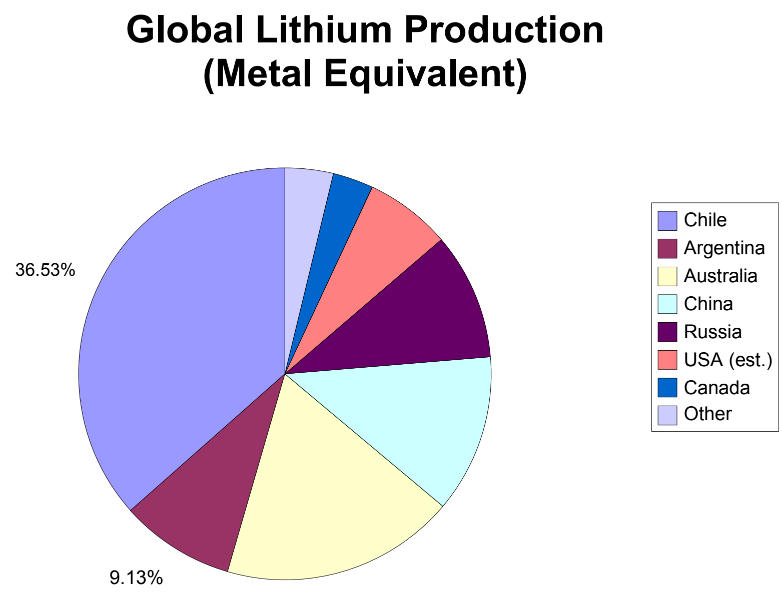
The main producers of Lithium minerals are Chile, the USA, Argentina, China, Australia and Russia.

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

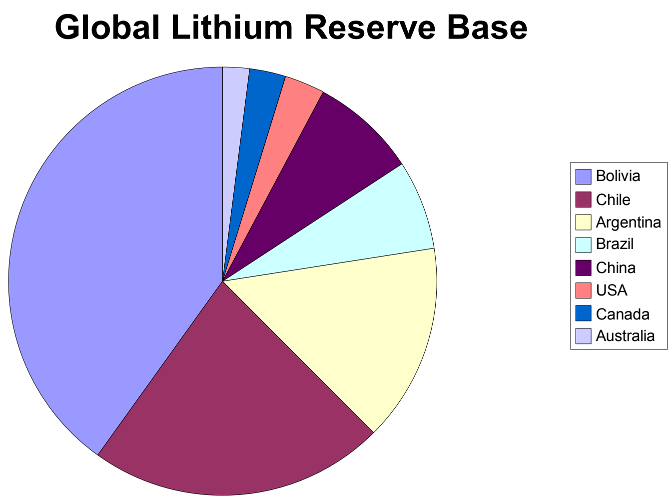
CONTAINED LITHIUM METAL PRODUCTION - 2005			
Country	2005 Production (tonnes)	Reserves (tonnes)	Reserve Base (tonnes)
United States	1,000 (est.)	38,000	410,000
Argentina	2,000	2,000,000 (est.)	2,000,000 (est.)
Australia	4,000	160,000	260,000
Bolivia	-	-	5,400,000
Brazil	240	190,000	910,000
Canada	700	180,000	360,000
Chile	8,000	3,000,000	3,000,000
China	2,700	640,000	1,100,000
Portugal	320	NA	NA
Russia	2,200	NA	NA
Zimbabwe	240	23,000	27,000
TOTAL	21,400	6.2M	13.4M
Source: USGS; MIR for US and Argentina estimates			

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 (metal equivalent) production is probably in the order of 1,000 tonnes.

The following graph shows this contained Lithium production by country.



While South America currently dominates Lithium Production, with Chile and Argentina producing 10,000 out of the world total of 21,400 tonnes, it dominates the Lithium Reserve Base even more so.



South America holds nearly 80% 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 4.2M tonnes, to which we have added an estimated 2MT for Argentina, for a total of 6.2MT. "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".

The total global "Reserve Base" of Lithium is estimated by the USGS at about 11M tonnes, to which again we have added 2MT for Argentina. 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 a rather nebulous figure – at some point these resources might become available if prices rise sufficiently, but of course the market wants the price of LiIon batteries to come down, not increase. As energy prices rise in the future, the cost of extraction and processing will not necessarily fall.

To be realistic, only the 6.2M tonnes of "Reserves" should be considered as available at the moment, plus a yet to be determined fraction of the resources in Bolivia.

If the world was to swap oil for LiIon based 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 strategic mineral while China would have a certain degree of self sufficiency.

However, in addition to these geo-political factors, in the rush to extrapolate the LiIon battery from portable electronics to EVs, two other major factors are being overlooked:

1. **Only Lithium from the Brine Lakes and Salt Pans will ever be useable 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 LiIon laptop computer battery.**

Real Lithium Availability

In this section, we will now estimate how much of the Global Reserve Base of 13.4 MT, plus the unknown deposits in Russia, could realistically be available for LiIon battery production.

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

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

To manufacture a LiIon battery, Lithium is needed for the cathode material and the electrolyte. This is obtained from Lithium Carbonate or Lithium Chloride, mostly the former. These two substances are obtained naturally only from a limited number of salt pans and salt lake deposits in Nevada, Chile and Argentina. Small scale production is just starting in China (DXC Salt Lake, Tibet) and a second extraction facility has just been opened in Argentina. The Chilean salt deposits at Salar de Atacama are the biggest producer in the world, with production of about 40,000 tonnes of Lithium Carbonate per year. The deposits in Nevada are in decline and many older Lithium deposits in the USA are now uneconomic. The last and biggest untapped reserve of Lithium salt is in the Uyuni salt pans of Bolivia, the remains of an ancient inland sea. Bolivia is said to contain Lithium reserves 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.

Bolivia has made a number of attempts to exploit these Lithium reserves. The current political situation in the country is acting as a strong disincentive for western mining companies to operate there.

Indeed, there is growing antipathy between local communities in Argentina and international mining companies. This has in effect spilled over into a social revolution in Bolivia where many foreign mineral extraction companies are seeing their assets nationalised. 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.

Global Lithium Carbonate/Chloride production is currently between 70,000 and 80,000 tonnes or 13,000 to 15,000 tonnes of Lithium metal equivalent. The other 5,000 to 7,000 tonnes of Lithium metal equivalent produced each year is contained in Spodumene which is used directly in the manufacture of ceramics and glass.

Global Lithium Carbonate Production is in the order of 70,000 to 80,000 tonnes p.a.

Spodumene is a silicate of Lithium and Aluminium. In other words – it is a glass. Before the mass market introduction of the LiIon battery, limited amounts of Lithium Carbonate were manufactured from spodumene. Today, this would be impossible on a large scale not only due to the economics but the large amount of energy required to process it. The Chinese still do produce some Lithium Carbonate from spodumene but normal economics do not apply in China and this is likely to cease when the DXC salt lake project comes on stream.

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 are known. Bolivia holds over 50% of these deposits and production has not even started.

The two biggest gaps in “Reserve Base” 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 similar brine deposits to those in Chile. Based on estimated reserves at one of these sites of 1.2 million tonnes, Argentina probably holds a similar amount of Lithium to Chile – about 2M to 3M tonnes. We have estimated these at 2MT and added them to the USGS Reserves. Russia's reserves are unknown but if we are optimistic we could put an upper limit of 5M tonnes, 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 suitable for LiIon batteries.

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 58MT of Li_2CO_3. The US salt deposits are in decline. All the other deposits can be discounted when considering their availability for batteries.

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

Exclusive dependency on Lithium Ion batteries, where the Lithium will overwhelmingly come from South America, would be like being dependent on South America for 100% of our oil supply.

Lithium Requirement

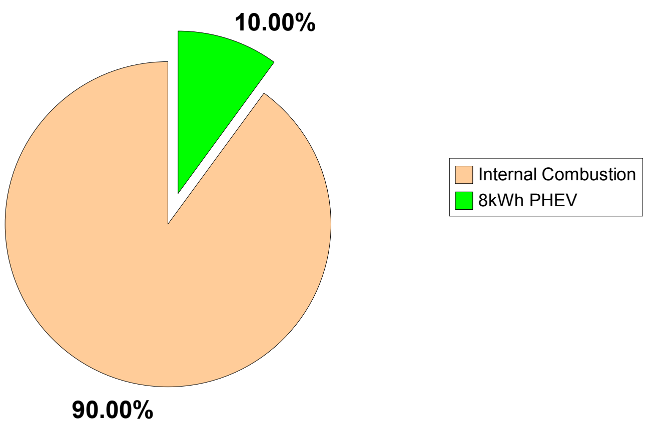
Today, some 60M cars are produced each year. If they were all PHEV20s with a small 5kWh battery[1], they could reduce current fuel consumption of "compact" type cars by up to 50%. Further developments in prioritising aerodynamics and reduced weight could improve this further. Existing LiIon batteries 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 LiIon 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 LiIon 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 LiIon batteries. Total Global Lithium Carbonate production today (which is of course already consumed by existing applications) would allow about 6 million such batteries to be manufactured – enough for 10% of vehicle production. Production of LiIon EV batteries today is insignificant, so all of the Lithium Carbonate supply for a growing LiIon 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.

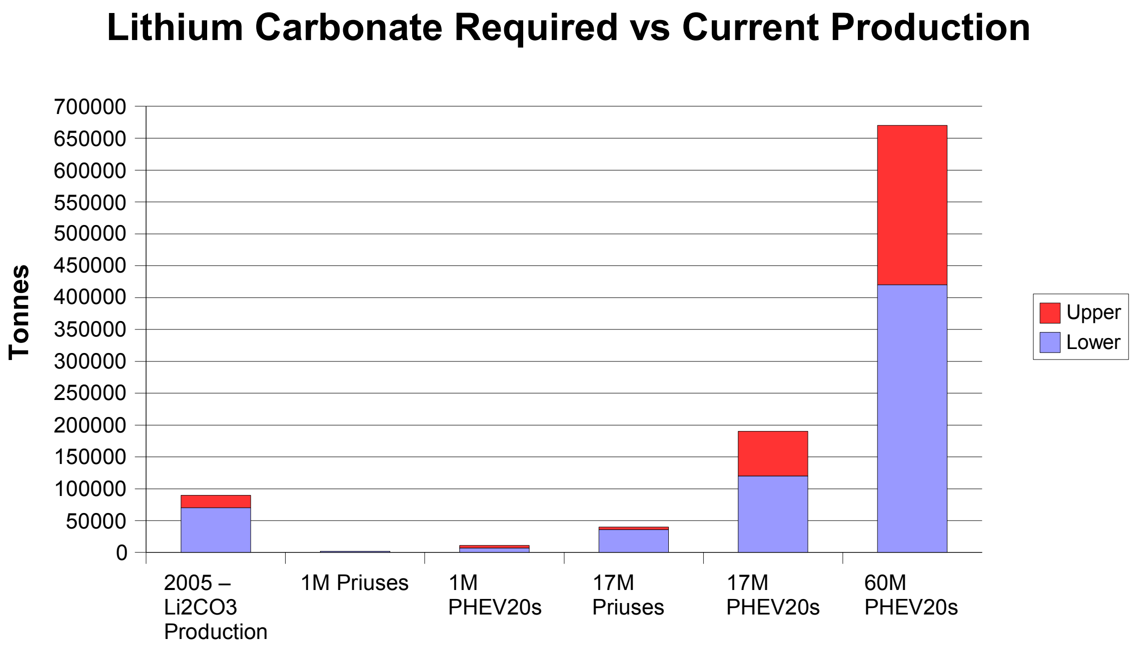
Global Automobile Production
Percentage Replaceable with 8kWh LiIon Battery
Current Li2CO3 Production



- Global Automobile Production is 60 million vehicles per year
- Current Global Lithium Carbonate Production would permit production of 6.25 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.

1 5.1kWh is the minimum battery size for a compact PHEV20 (EPRI, 1000349, Comparing the Benefits and Impacts of HEV Options, 2001)



- Lithium Carbonate Production is about 70,000 tonnes per year
- 17M existing Priuses (1.5kWh battery) would consume 35,700 tonnes of Li_2CO_3 per year
- 1M PHEV20s would consume 7,000 – 11,000 tonnes of Li_2CO_3 per year
- 17M PHEV20s would consume 120,000 – 190,000 tonnes of Li_2CO_3 per year
- 60M PHEV20s would consume 400,000 – 700,000 tonnes of Li_2CO_3 per year

A vast increase in Lithium Carbonate production will be required to convert the existing car fleet into HEV0s or PHEVs using LiIon 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 +25º C during the day and -25º 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 early 1990s, their production has reached 27,000 tonnes per year. Their competitor SCL (owned by Chemetall of Germany) produce maybe 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 12,000 tonnes of Li_2CO_3 and 5,000 tonnes of LiCl. Admiralty Resources of Australia are also just about to start production in Argentina (Salar de Rincon) and expect to reach output of 8,000 tonnes of Li_2CO_3 and 9,000 tonnes of LiCl – this could eventually double or maybe triple but that would probably be the limit. Chemetall Foote in the USA do not reveal their production but it is probably between 5,000 and 10,000 tonnes at the most and falling. Many other Lithium deposits in the USA are no longer worked. The last known Lithium Carbonate resource is in China, where Sterling Resources and a Chinese venture are supposed to be imminently starting production of two 5,000 tonne projects.

These are all fairly small scale operations in comparison with what will be required.

The potential depletion rates also give rise for concern. Even if all of Bolivia's estimated 5,400,000 tonnes of Lithium is economically extractable Lithium Carbonate or Chloride, which will not be the case, this would be only 28 Million tonnes of Li_2CO_3. 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 forseeably exceed 1 Million tonnes per year. This would be 3.6% of the Bolivian Reserve Base per year or 1.7% of the Global Li_2CO_3 Reserve Base per year.

Future Lithium Carbonate Demand could exceed 2% of the Global Li_2CO_3 Reserve Base per annum

One can see that a major logistical challenge faces us: 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, scrappage 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 LiIon 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 11% of economically viable Li_2CO_3 Reserves or Reserve Base (58MT), including Bolivia. With a more realistic projection of at least an average 10kWh battery per vehicle, over a quarter of the world's current Lithium Carbonate Reserve Base 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 LiIon battery would consume over 25% of the World's Lithium Carbonate Reserve Base

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).

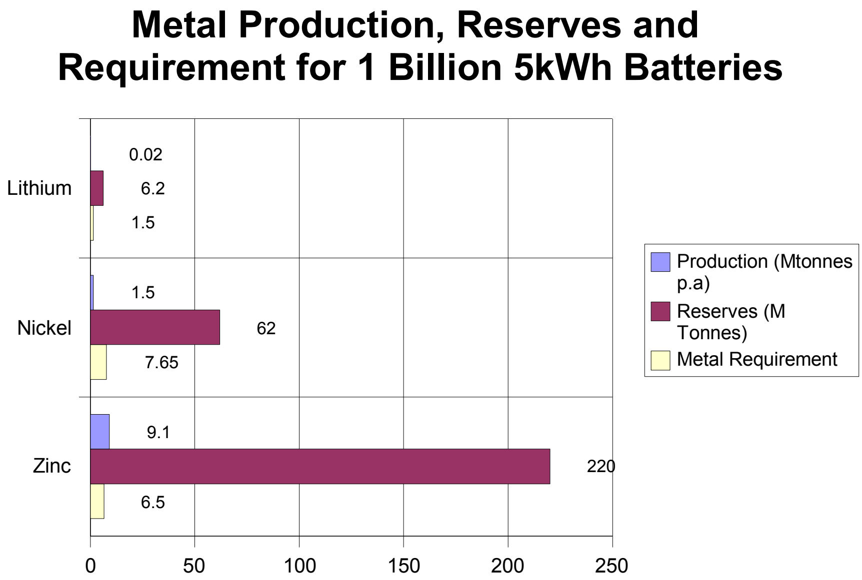
The most well known alternative to LiIon is the NiMH battery. It is rugged, proven, has high cycle life and has many years development behind it. However, it is also heavier than LiIon and very Nickel intensive: between 3 and 6 kgs of Nickel metal are required per kWh of capacity depending on the cathode 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 LiIon battery manufacturers will not use the LiCoOx cathode type in EV batteries, as used in consumer LiIon batteries, apart from the unacceptable safety of a Cobalt containing LiIon 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, Nickel and Zinc to the existing Reserves of those metals; and how much of each of those metals would be required to equip 1 billion cars with a 5kWh battery, using LiIon, NaNiCl and ZnAir technology respectively.

The Lithium position is in fact further constrained by 25% more than shown below since the resource required is Li_2CO_3, not Lithium metal.



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 Metal Requirement to Current Annual Production is 1.5 : 0.02 or 75:1.

In terms of Lithium Carbonate, the ratio is closer to 100:1 since only 75% of current Lithium production is in the form of Lithium Carbonate.

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.

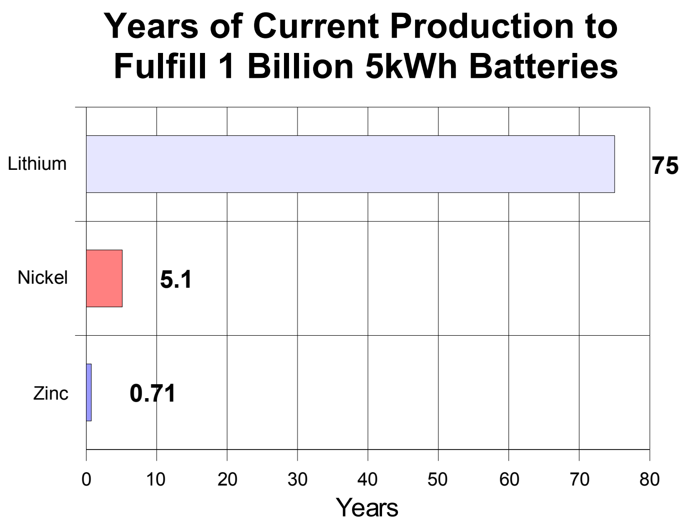
It would take 5 years at current Nickel production rates to produce enough Nickel to equip the global motor fleet with a 5kWh NaNiCl PHEV battery.

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.

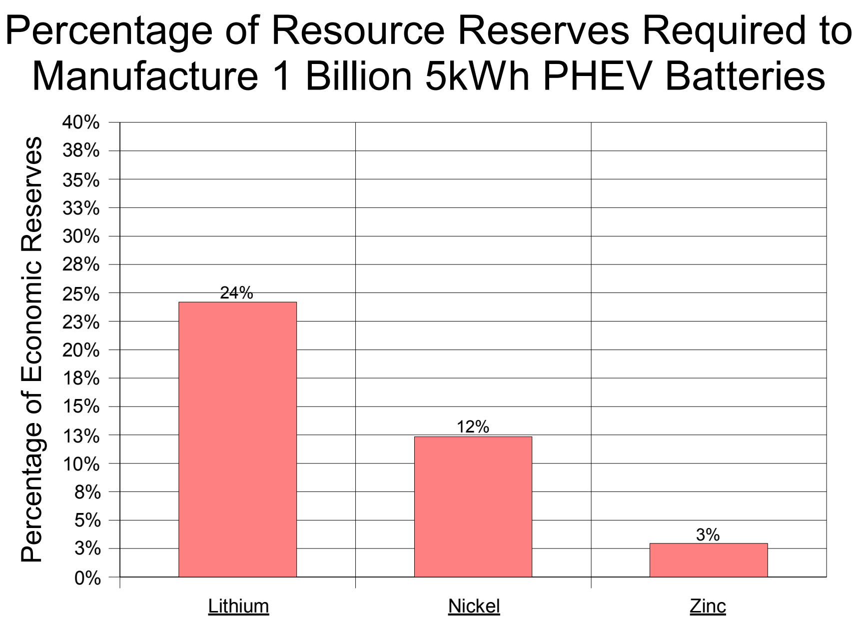
The above graph shows that 6.5M tonnes of Zinc would be required to equip the Global Motor Fleet with a 5kWh ZnAir battery. The ZnAir metal fuel cell uses 1.3kg of Zinc per kWh of capacity.

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



The scale of the logistical challenge is again self evident. If we commit to Lithium Ion batteries, it would take 75 years at current production rates to produce enough Lithium to equip the current world vehicle fleet with a 5kWh battery. In fact, it would take 100 years at current production rates to equip the global motor fleet with a 5kWh LiIon PHEV battery because only Lithium Carbonate can be used, not Spodumene. 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.



There are currently nearly 1 billion motor vehicles in the World. To equip them all with a small 5kWh PHEV battery would use up 24% of the world's existing Lithium metal reserves using LiIon batteries; 12% of the world's Nickel reserves with NaNiCl batteries; and 3% of the world's Zinc reserves with ZnAir batteries.

Again, the Lithium picture is actually worse since we have included the Spodumene resources as Lithium metal reserves in the above graph.

We stated earlier that that the Lithium Carbonate Reserve Base was 58MT and that 900M 5kWh LiIon batteries would use 11% of this – now we seem to be saying that they would use 24% of the world's Lithium

Reserves. Why the discrepancy? This is the distinction between "Reserves" and "Reserve Base". In the above graph, we have used estimated Lithium metal "Reserves" of 6.2MT, not our more optimistic estimated Li_2CO_3 Reserve Base of 58MT, to enable direct comparison with the USGS Reserves figures for Nickel and Zinc.

In comparison, the USGS Reserve Base figures for Nickel and Zinc are 140MT and 460MT respectively, compared to 62MT and 220MT of "Reserves".

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 our optimistic 11% 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 be obtained from sea water – but at what cost?

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 use[2] 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 9M tonnes of Lithium – close to the total current Reserves Base and estimated total future recoverable reserves. The Lithium Carbonate requirement would be over 42 Million tonnes, close to the total Li_2CO_3 Reserve Base of 58MT. Such a scenario is unrealistic.

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 LiIon 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 LiIon 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 LiIon 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.

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

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

60kWh capacity ZnAir unit was projected to cost only $2,000 in 1998. A unit this size would fit comfortably 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 currently have a cycle life of only 500 cycles – it remains to be seen how far this can be extended. This would however be adequate for a yearly battery replacement and still be cost effective for a PHEV battery at under $100/kWh. One company (ReVolt Technology) claims to have greatly extended the cycle life (at 100% DoD) 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.

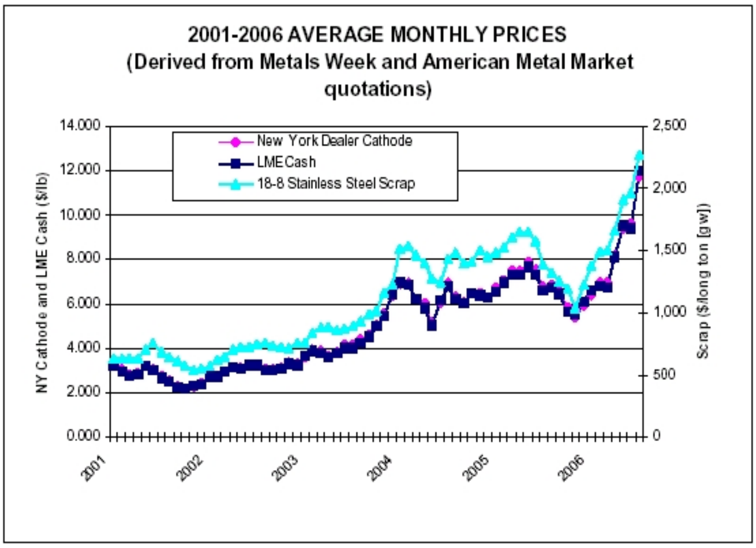
At 400Wh/kg, battery discharge could be limited to 50% to increase cycle life to well over 500 cycles.

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, one could have a PHEV40 with a 20kWh ZnAir unit using a rechargeable version of the ZnAir battery. The cycle life of these rechargeable ZnAir batteries is currently limited to about 500 80% DoD cycles, but in a hybrid car this could be limited to 50% DoD to give an effective 10kWh capacity and greatly extend the cycle life.

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 $1/kg. During 2005 and 2006 this rose to over $5/kg and apparently some Japanese LiIon battery manufacturers are now offering $10/kg or $10,000 per tonne, a tenfold increase in 2 years. This will only continue to rise as supply is limited to the few brine and salt deposits.

The projected costs for LiIon and NiMH batteries are still in the order of $300 - $450 per kWh even in high production volume. A 30kWh LiIon 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 $NaFeCl_2$ 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 300º to 250º 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 LiIon 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 Lion 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 LiIon battery have serious safety implications.

Overall, the cost and complexity of the LiIon 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 LiIon 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 LiIon technology for EV applications has not been performed.

One of the most quoted studies[3] 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 LiIon 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. 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 LiIon variants, much more rugged and stable, require simpler and cheaper control electronics and even outrank LiIon in performance terms, particularly the lower energy density LiIon cathode technologies which will be used for safety reasons - Iron Phosphate, Manganate Spinel or Layered MnO_2.

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

In parallel, research into improving the cycle life of the rechargeable ZnAir battery should be prioritised. The economics of industrialising even an existing 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.

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