How Much Lithium does a LiIon EV battery really need?

by William Tahil
Research Director
Meridian International Research
France
Tel: +33 2 32 42 95 49 Fax: +33 2 32 41 39 98 www.meridian-int-res.com

5th March 2010

Executive Summary

The adoption of Lithium Ion battery technology for Electric Vehicles continues to gather momentum. A range of figures for the quantity of Lithium required per unit battery storage capacity (kWh) have been stated. Some of these figures quote the minimum theoretical quantity of Lithium per kWh as if this is achievable in a practical device. Other figures are also unrealistically low. This briefing paper is intended to illustrate for strategic planners in the automotive industry how real world battery efficiency differs from theory and to estimate the realistic quantity of Lithium that will be required per kWh of (PH)EV battery capacity.

For realistic strategic planning purposes automobile manufacturers should model the material requirement at 2 kg to 3 kg of technical grade Lithium Carbonate per nominal kWh of PHEV battery capacity.

Current global LCE production of circa. 100,000 tonnes, if available, would therefore be sufficient for 2 to 3 million PHEV batteries of 16 kWh capacity (GM Volt class).

Introduction

The question of how much Lithium or Lithium Carbonate is required per kWh of battery storage capacity has become a matter of some importance due to the limited availability of Lithium for EV applications. Questions as to the feasibility of establishing mass production of more than a few million PHEV battery packs per year are in part met with assurances that the quantity of Lithium required per kWh is low.

For instance, in a recent report[1] to investors, Dundee Capital Markets assume a Lithium Carbonate requirement of 425 grams LCE per kWh (80 g of Lithium metal).

In a recent Reuters article[2], a claim is made that “one million tonnes of Lithium is enough to produce 395 million Chevrolet Volts (16 kWh)”, i.e. 158 grams of Lithium metal or 840 g LCE per kWh.

In a more detailed report[3] from ANL, estimates are presented varying between 113 g and 246 g of Lithium (600 g and 1.3 kg LCE) per kWh for various cathode types of batteries all with a graphite anode, with a Lithium titanate spinel anode battery having a high requirement of 423 g Li (2.2 kg LCE) per kWh.

This range of figures illustrates the difficulty that may exist in modelling LCE requirements for strategic planning purposes. This briefing paper describes the main factors that intervene in a real battery to reduce its effective capacity and recommends a realistic figure for the quantity of LCE that should be assumed to be required per kWh battery capacity.

---

[1] “Lithium Hype or Substance”, 28/10/09, Dundee Securities Corporation

[2] “Known Lithium Deposits can cover Electric Car Boom”, 11/02/10, M. Rosenberg and E. Garcia, Reuters

[3] “Lithium Ion Battery Recycling Issues”, Linda Gaines, Argonne National Laboratory, 21/5/09.

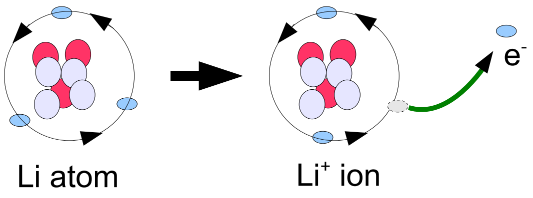
How is electricity produced from Lithium?

Let us start with a very basic description – how do the atoms of Lithium metal in a LiIon battery generate electricity?

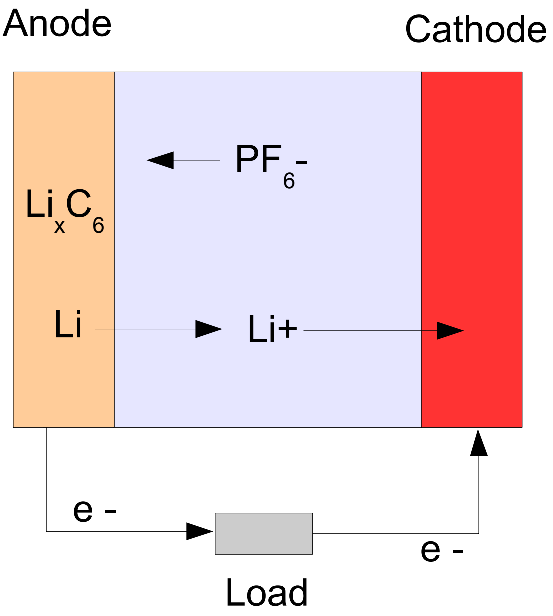
All atoms consist of a central positively charged nucleus surrounded by orbiting negatively charged electrons. The total positive charge of the nucleus and negative charge of the electrons balance each other out so the atom is neutral overall.

Electricity is the flow of electrons in an electrical circuit.

To produce electricity, the LiIon battery sets up a controlled chemical reaction in which atoms of Lithium lose one of their electrons. These electrons flow round the circuit between the two poles of the battery to drive the electrical load, i.e. the electric motor of an EV. This process of losing an electron is called *ionisation* and the resulting Lithium atom, now minus one of its electrons, is called a Lithium *ion*. The Lithium ion is now positively charged by one unit because it has lost a negative electron and so its original neutral charge has been unbalanced.



The Lithium ions then move through the electrolyte of the battery from the anode to the other electrode (the cathode) where they recombine with the electrons they originally lost which in the meantime have travelled through the outer circuit to drive the motor.



Theoretical Capacity of Lithium

We now need to consider *how much* electricity Lithium can theoretically generate.

Electrical current is measured in Amps which is proportional to the number of electrons flowing through the circuit per second. The higher the current, the higher the electron flow per second and the higher the number of Lithium atoms that must ionise and lose electrons per second, from the stock of Lithium atoms in the anode of the battery.

The theoretical charge density of Lithium metal from fundamental electrochemistry is 3.8 Ah/g. This means that if we took 1 gram of Lithium metal and could effortlessly convert it 100% into Lithium Ions, while then sending the electrons released by the Lithium through the electrical circuit to do work (drive an EV), that 1 g of Lithium could supply 3.8 A of electron current for 1 hour. Then all of the Lithium would have been converted into ions, moved to the cathode and be discharged.

If the Lithium metal is in a LiIon battery with a nominal 3.6 V voltage between the Lithium electrode (anode) and the cathode, we can then say that the *energy* delivered[4] by that 1 gram of Lithium metal would be 3.8 Ah multiplied by 3.6 V or 13.68 Watt Hours.

Therefore from a purely theoretical perspective, 1000 Watt Hours or 1 kWh of energy, the basic unit of energy we consider for EV battery storage, would require 1000 divided by 13.68 = 73 grams of Lithium metal. This equates to 385 grams of Lithium Carbonate.

The theoretical figure of 385 grams of Lithium Carbonate per kWh battery capacity is substantially less than our guideline real-world figure of 1.4 kg of Li_2CO_3 per kWh.

Why is there such a difference and why do real batteries require so much more Lithium (or Lithium Carbonate) than the theoretical amount?

Theoretical Capacity versus Reality

The first thing to consider is that the above theoretical picture assumes the Lithium metal can be converted **with 100% efficiency** into ions and free electrons in a chemical reaction using physically real electrodes, electrolytes and the other battery components.

100% efficiency can never be achieved and therefore a battery will never display 100% of the theoretical capacity of its active materials. In fact, the **theoretical capacity of a cell only applies at zero current**. As soon as current is drawn from a cell it loses “free energy” (ΔG) and capacity will fall.

A large number of factors intervene to greatly reduce the theoretical capacity of the active materials in a battery so that for the demanding application of driving an EV, batteries are between 10% and 25% efficient at delivering the purely theoretical energy they contain.

This means that a real battery will need 4 to 10 times as much active material (Lithium) per kWh as the theoretical minimum.

If we look at the theoretical specific energy of a LiIon battery, the figures widely quoted are between 400 and 450 Wh/kg. The actual specific energy achieved is between 70 and 120 Wh/kg. Therefore practical LiIon batteries are using some four times as much Lithium per kWh as the “theoretical” quantity or more.

The main factors which affect capacity are:

---

[4] The fundamental equation $\Delta G = -nFE^\circ$ means that the amount of energy ΔG that can be delivered by a galvanic cell equals the open circuit cell emf E° multiplied by the charge delivered nF; the sign is negative to show the cell releases that energy and so ends up with less energy when discharged. E° is the cell open circuit or zero current voltage which automatically falls as soon as the battery is connected to a load.

- Rate of discharge or power delivery.
- Anode material
- Cathode material
- Electrolyte
- Cycle related capacity loss
- Reaction kinetics

In addition, only the Lithium in the anode delivers energy to the load but Lithium is used in the electrolyte and cathode of the battery as well: thus extra Lithium per kWh is required in addition to the active material that makes up the kWh of stored energy.

Batteries are a trade-off between numerous variables.

Rate of Discharge

The capacity of a battery is not a constant. When we talk about the kiloWatthour capacity of a battery, this is a nominal figure usually defined at a relatively low discharge rate of C/20, which means it takes 20 hours to discharge the battery.

The more slowly a battery is discharged, the more energy in total it will supply – but it is supplying a relatively small amount of energy per unit time, i.e. its power delivery is low.

When a battery is discharged quickly at a high rate of power, its total nominal energy capacity falls – in other words it can deliver high power but for a short period of time and delivers less total energy than if it was discharged slowly.

The standard discharge rate generally used to analyse the performance of pure battery EVs is C/3 which means that at the “average” discharge rate expected for a BEV, the battery will last 3 hours. Therefore for a 32 kWh battery expected to deliver on average 3 miles range per kWh or 100 miles in total, over 3 hours, that equates to an average speed of 33 mph with the battery delivering about 10kW over that time period. Therefore if the car drives faster, the battery capacity will fall as power delivery increases and range will fall below 100 miles; conversely, if the car drives more slowly than 33 mph, it can go further than 100 miles but will obviously take longer to do so.

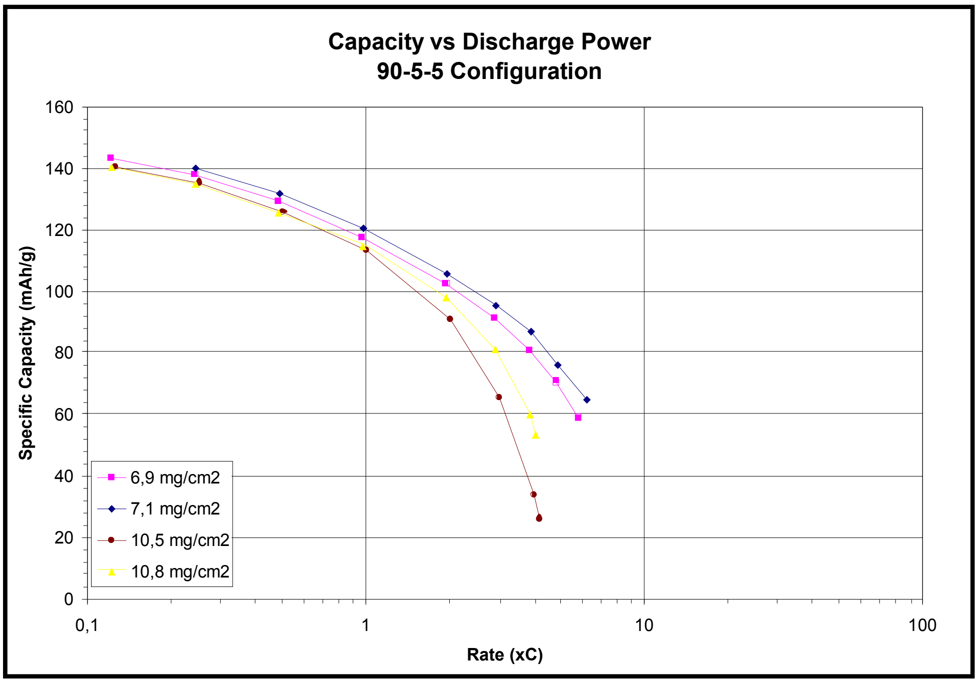
The problem is exacerbated as the size of the battery becomes smaller. The power needed to drive the vehicle at any speed remains substantially the same if the battery is smaller but the relative rate at which the battery is being discharged increases. Therefore its effective capacity falls even further due to the increased discharge rate.

Thus for a standard hybrid vehicle (HEV0) with a nominal 1.5 kWh battery, not even 5 miles range can be achieved on battery power alone because the battery capacity is so small compared to the power demand needed to drive the vehicle: a 10 kW draw at 30 mph is a discharge rate of 10 / 1.5 or about C7 which means the battery will discharge in 1/7 of an hour or say 9 minutes. So at 30 mph one would expect a range of 4 - 5 miles. The problem is that the nominal capacity of 1.5 kWh applies at C/20, not C7. C7 is a discharge rate 21 times as fast as the C/3 discharge rate on a full 32 kWh BEV battery. Thus the nominal capacity of 1.5 kWh falls even further under this higher discharge rate and the vehicle only provides 1 mile of range, not 4 or 5.

The Ragone Plot

These dynamics are illustrated with a diagram known as the Ragone plot, which is used to show how the total energy capacity of a battery declines as its speed of discharge or how much power it delivers increases.

The following graph[5] is for a Phostech Lithium $LiFePO_4$ (carbon coated) cathode, using a fairly dense cathode phosphate material (1.8 g/cm^3).



Therefore the generally quoted figures for the capacity of the $LiFePO_4$ material of 170 mAh/g are at low discharge rates of 0.1 C or less – this is a theoretical figure.

Looking at the C/3 discharge rate which might occur in a large pure EV battery, capacity falls to 130 mAh/g.

Let us take a 10 kWh PHEV battery and assume a maximum speed in EV mode of 60 mph and further assume optimistically that at that speed range of 3 miles per kWh is obtained i.e. 30 miles nominal range for complete discharge – that is discharge in 30 minutes or a 2C rate. It can be seen that capacity declines to 90-100 mAh/g or down to 55% of theoretical. Therefore the available capacity would be only 5.5 kWh and so the battery would have run out after only 15 minutes at that discharge rate.

(In a recent presentation Volkswagen assumed an average energy requirement for a Golf class EV of 320 Wh/mile and 20 kWh required for 60 miles of range, with a full 30 kWh battery at an “average” speed. Our theoretical example above is therefore not conservative).

These Ragone Plots reflect the fact that as the power draw on a battery increases, its voltage falls, analogous to the pressure in a tank of water falling more quickly if the valve is fully opened. As the voltage falls the stored energy also falls.

---

[5] Source: “Carbon Coated Lithium Iron Phosphate: Enabling large battery markets for Li-Ion Batteries”, Phostech Lithium, 21st International Seminar & Exhibit on Primary & Secondary Batteries. (We have used the high density 1.8 g/cm^3 material illustration with worse capacity vs power than the less dense 1.25 g/cm^3 material also shown in this Phostech report since Phostech stipulate the lower density material is for HEV use (lower energy density) and the high density material (and higher energy density) is for pure EV use.

Polarisation

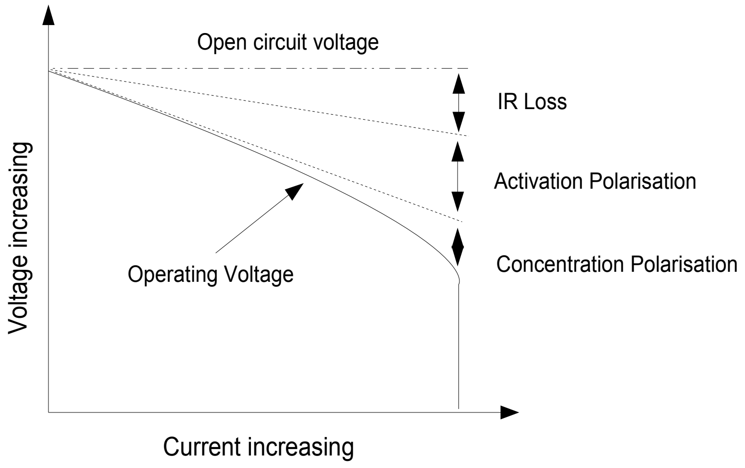
The fall in capacity shown above is due to a phenomenon which occurs at the electrodes of all batteries known as *polarisation* or *overvoltage*. These overvoltages are voltage drops due to chemical kinetics in the battery which consume part of the nominal open circuit voltage and reduce the operating voltage of the battery – i.e. the energy density falls. The reactions at the electrodes do not occur perfectly in a real battery: activation polarisation drives the electrochemical reaction at the surface of the electrodes (i.e. $Li \rightarrow Li^+ + e^-$ at the anode and $Li^+ + e^- \rightarrow Li$ at the cathode): these processes themselves consume energy (the activation energy of the chemical reactions, ionic activity coefficient etc.) In other words the Lithium atoms in the anode cannot ionise effortlessly but consume energy stored in the battery to do so.

Concentration polarisation is another effect due to differences in concentration of the reactants at the electrode surfaces which interfere with the diffusion/ migration of the ions. The higher the discharge rate, the faster the chemical reaction in the battery proceeds and there is less time for the reactants to mix: a steeper concentration gradient arises which sets up greater resistance and greater energy loss.

IR Drop or resistance polarisation is caused by the internal resistance of the cell. This causes a voltage drop (IR drop) during operation and loss of energy as waste heat.

Polarisation and IR drop is only low at very low discharge current, when the cell may then operate near the OCV and deliver most of the theoretically stored energy. At realistic discharge rates, they become significant factors and cause the discharge rate capacity loss described above.

Cell polarisation as a function of current



These polarisation effects cause losses at the electrodes which consume part of the energy and give it off as waste heat. Therefore not all of the theoretically available energy in the battery will be converted to useful energy.

While considering IR drop, it should also be remembered that $LiFePO_4$ batteries operate at lower voltage than $LiMO_2$ batteries. The OCV falls from 3.6 V to 3.3 V or even 3.2 V. This increases the *theoretical* quantity of Lithium required per kWh from 73 g to 80 g or 82 g (420 g of Lithium Carbonate) and the actual amount by at least four times that (1.7 kg Lithium Carbonate) for the anode alone.

Conductivity of the Organic Electrolyte

Because an aqueous electrolyte cannot be used with Lithium, since the Li^+ ions would simply react with it to form Lithium Hydroxide, a complex organic electrolyte of $LiPF_6$ dissolved in an organic solvent is used. This has conductivity 10 to 100 times lower than aqueous electrolytes as used in a conventional NiMH, ZnAir or PbA battery. Therefore the internal resistance of the battery is relatively high and leads to higher energy losses (IR drop) as heat is dissipated in this resistance inside the battery.

Once again the "theoretical" energy density of the Lithium metal couple by itself, 3.6 V x 3800 mAh/g = 13680 Wh/kg, is reduced.

A number of the LiIon battery packs being designed for EV use will use liquid cooling to dissipate generated heat. This would be unusual for any of the traditional aqueous chemistry batteries for which air cooling is sufficient. This increased internal heat generation is indicative of the higher internal resistance and hence higher energy losses, which translates into further reduced effective energy density compared to that theoretically available.

Other Electrolyte Factors

[This section can be omitted if desired].

In addition to the physical electrode processes we have described above, the working potential of a cell is also affected by the processes of the chemical reaction in the electrolyte.

How much the cell or battery voltage falls when a current is drawn is predicted by the famous *Nernst Equation* whose derivation we will not present here. The equation states that the actual working potential of a cell is reduced by a factor derived from the *extent* of the reaction or how far it has proceeded and the *activity* of the reactants. The further the reaction proceeds in extent, the more the voltage will drop. Interrelated with this is the activity of the reactants. Simply because Li^+ ions have entered the electrolyte from the anode, it does not mean that they will all react and move to the cathode. In a concentrated solution, the ions *interfere* with each other and reduce their overall activity thus slowing down the reaction. This is exacerbated by the low transport number for Lithium ions (see below) which means they will tend to build up near the anode causing increased interference from each other and from the increased concentration of oppositely charged PF_6^- ions.

Transport Number (Transference Number or Transfer Coefficient)

[This section goes into more detail on "concentration polarisation" and can also be omitted if desired].

To recap, the operation of the LiIon battery is often described as follows: Li atoms in the anode dissociate into Li^+ ions and electrons. The Li^+ ions migrate through the electrolyte to the cathode where they recombine with the electrons that passed through the outer circuit powering the load.

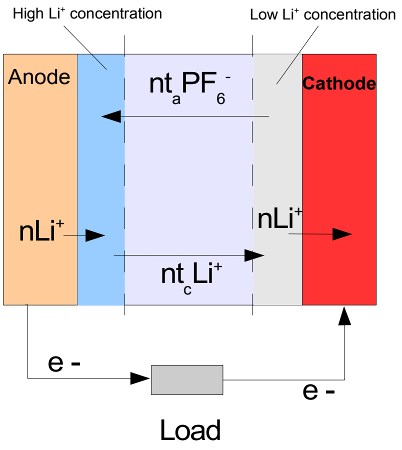
However Li^+ ions are not the only species to migrate and diffuse through the cell. The electrolyte salt is usually $LiPF_6$, which provides the electrical conductivity between anode and cathode. The salt is present in solution as Li^+ and PF_6^- ions. When Li^+ cations move into the electrolyte solution from the anode and migrate towards the cathode, PF_6^- anions in solution migrate in the opposite direction towards the anode. Therefore the total current inside the battery is carried by both Li^+ and PF_6^- ions, not just Li^+. However, only the part of the current that is carried by the Li^+ cations performs useful work (i.e. the electrons associated with those Li^+ ions in the outer circuit).

The proportion of the current that is carried by a particular ion is called the *transport number* for that ion.

The transport number for Li^+ in a typical LiIon cell using a $LiPF_6$ electrolyte salt is between 0.35 and 0.4. This means that only 40% of the total current within the battery is from the Lithium ions and 60% is from the PF_6^- anions.

In a perfect battery, the Li^+ transport number would be 1.

When it is not, it means that Li^+ ions will collect near the anode and increase the concentration of Li^+ ions in the electrolyte in the "anode compartment" near the anode. Conversely more Li^+ ions will leave the electrolyte "cathode compartment" and migrate into the cathode than enter the cathode compartment. This sets up an adverse concentration gradient in the electrolyte, with higher [Li+] near the anode than near the cathode causing concentration polarisation in the same way as a concentration cell which then absorbs part of the battery's energy and reduces its capacity. In other words, a counter voltage is set up which opposes the forward voltage of the battery.



With the transport number for the Lithium cations $t_c = 0.4$, n Lithium ions enter the anode compartment from the anode but only nt_c leave it and enter the cathode compartment, leaving a concentration build up of $n(1 - t_c)$ or 0.6n near the anode. Conversely, n Lithium ions leave the cathode compartment and are discharged as Lithium atoms in the cathode but only nt_c enter the cathode compartment, leading to a concentration deficit of $n(1 - t_c)$ or 0.6n.

Thus a concentration gradient is set up of excess Lithium ions near the anode and a reduced number near the cathode. This sets up what is known as a concentration cell but with an EMF in the *opposite* direction to the desired battery voltage.

The lower the transport number for the cation, i.e. Li^+ the greater the adverse concentration gradient that occurs.

Only when the cation transport number t_c reaches 1 is an adverse concentration gradient avoided but this cannot be achieved in practice.

The Li^+ transport number in Lithium Metal Polymer batteries is generally even lower than 0.4 due to the poor conductivity of the polymer electrolyte.

Carbon Anode

The anode material used in the majority of LiIon batteries is graphite with Lithium atoms stored within the carbon matrix. Diagrams illustrating LiIon battery operation show neat flat layers of graphite hexagons with Lithium atoms smoothly intercalating in and out between the layers. In reality graphite is disordered and imperfect creating inevitable resistance to the transport of the Lithium atoms and ions.

When highly ordered graphites are used in the anode to minimise resistance, the Lithium does not just flow in and out with no change to the potential between the anode and the cathode. Instead voltage plateaus are formed. This means that as the battery is discharged, from fully intercalated LiC_6 to $Li_{0.4}C_6$ and below, the voltage of the battery falls[6] by up to 0.3V. In other words, energy density is lost.

---

[6] See P35.18 “Handbook of Batteries”, D. Linden, McGraw Hill, 3rd Ed., 2002

In most LiIon batteries a flatter discharge profile or constant supply voltage (at a particular discharge rate) is obtained by using disordered graphites. The trade off is less efficient transport and hence higher internal energy losses.

Therefore again the “theoretical” energy density of a LiC_6 anode with one Li atom present per six Carbon atoms cannot be achieved in the real world. The “theoretical” charge density of LiC_6 is 372 mAh/g if all of the Lithium atoms in a sample could be discharged and do work. Sony's consumer battery carbon anodes provided 180 mAh/g nominal capacity at low discharge rates or less than 50% of that theoretical storage capacity.

Irreversible Capacity

When the battery is first charged and discharged, passivation layers form on the electrode surfaces as the electrolyte reacts with the electrodes. These passivation layers (SEI – Solid Electrolyte Interphase) contain Lithium that is no longer electrochemically active, i.e. it is bound up in the battery and can no longer provide useful power. This represents a permanent capacity loss when the battery is first used – so extra capacity will have to be built in to EV batteries during manufacture, requiring more Lithium, for the battery to meet its actual nominal specification.

Irreversible capacity in the anode can range between 50 and 200 mAh/g or roughly one sixth to one half of the Lithium in the anode (theoretical: 372 mAh/g) becomes permanently bound up and unusable. It can be seen therefore that the battery has to be manufactured with at least in the order of 20% excess Lithium and anodic material over “theoretical” to account for this initial loss. There are some hard carbon materials that offer even higher theoretical capacity of over 500 mAh/g to even 1000 mAh/g but they display irreversible capacity loss of over 200 mAh/g.

In general, to obtain high power, smaller carbon particle size is needed but this tends to increase irreversible capacity. In other words, smaller carbon particles mean more Lithium atoms can be intercalated because there are more spaces for Li to occupy and so higher power, more Lithium ions being formed per second, can be achieved. However, with more small spaces more Lithium becomes permanently bound up in the carbon matrix and “lost” so irreversible capacity is higher. Everything is a trade-off.

Cathode Delithiation

Irreversible capacity loss also occurs in the cathode. LiIon batteries are manufactured in the discharged state with no Lithium in the carbon anode and the $LiMO_2$ oxide or $LiFePO_4$ cathode fully lithiated. When it is charged, not all of the Lithium in the cathode will migrate to the anode but some will remain permanently bound up in the cathode. This represents another capacity loss and point of Lithium consumption.

LiMP Batteries

Lithium Metal Polymer batteries use an anode made of Lithium metal, rather than carbon intercalated with Lithium. LiMP batteries generally require up to 5 or 6 times as much Li metal in the anode than the minimum theoretical amount because of the low efficiency of the stripping and plating process on discharge and recharge. The general figure used in the industry for the practical achievable energy density of a Lithium metal anode is 960 mAh/g versus the theoretical figure of 3800 mAh/g, i.e. some four times as much Lithium metal as the theoretical amount.

LiMP is the technology favoured by Bolloré in France for their Bluecar and associated developments with Pininfarina.

Cycle Life Capacity Fade

As batteries are cycled, the internal resistance increases resulting in lower voltage and lower delivered energy. The higher the rate at which the battery is discharged on each cycle, the greater the capacity fade per cycle. In commercial $LiCoO_2$ and $LiMn_2O_4$ 18650 cells capacity can fade by 10% to 30% respectively after 500 cycles at the 1C rate at room temperature. Capacity loss per cycle increases with ambient temperature as well so this problem will be accentuated in warm climates. Cycle life of several thousand cycles is being claimed for the batteries being developed for EV applications before 80% End of Life (EOL) capacity is reached but extra capacity will have to be built into the design to compensate for capacity fade.

In fact, (PH)EV batteries are being designed so that the vehicle owner sees the same range and performance at EOL when battery capacity has fallen by 20% as he experienced at the beginning. This is achieved by not allowing full use of the installed capacity during the vehicle life, i.e. 20% of the capacity is hidden from the user. The hidden capacity is then gradually made more available as time goes on to compensate for cycle and age related capacity loss. At EOL 20% of the capacity will have been lost but this is transparent to the driver who will achieve the same range throughout vehicle life.

This strategy means that the batteries must be manufactured 25% larger than their nominal rated capacity. The Lithium requirement will increase accordingly by 25% over the nominal battery capacity.

Energy Batteries vs Power Batteries

A “power” battery is designed to release its charge quickly so that it can deliver high power, for instance to accelerate a hybrid vehicle. This is achieved by making the electrodes very thin with a large surface area so as many charge carriers as possible are close to the electrode surface. The Li atoms can then quickly ionise into the electrolyte, move to the cathode and be quickly intercalated into the cathode.

Thin coatings are also needed because of the low conductivity of the non-aqueous electrolyte (~10mS/cm) and the fact that the Li^+ ions diffuse slowly through the anode and cathode materials and electrolyte. LiFePO4 has particularly poor diffusivity.

However the specific energy of the “power battery” is low because the surface area to volume ratio is high – in effect the electrodes have very little internal volume in which to store charge since they are so thin. To increase the specific energy enough to store the much larger quantities of energy (charge) required for a PHEV or BEV, the electrodes must be made thicker and of appreciable volume to store charge. The surface to volume ratio will therefore fall and the surface of the electrode becomes less accessible to the charge carriers stored inside. **It is the volume of the electrodes that dictates storage capacity while surface area dictates maximum rate of discharge.** So by definition a power battery in an HEV optimised for discharge will have less actual energy storage in its electrodes than an energy battery with electrodes of the same surface area but greater thickness.

The drawback for the energy battery is that the thicker electrodes now present a greater impediment to transport of the Lithium ion charge carriers: they have higher internal resistance and will incur higher energy losses within the battery. Therefore even though the energy battery stores more energy overall, pro rata it loses energy efficiency in delivering that energy to the load. This is unavoidable.

Therefore as the market moves towards higher energy density LiIon batteries optimised for PHEV and BEV applications, the Lithium utilisation efficiency based on this metric will fall compared to that in power batteries and more Lithium per unit of kWh energy storage will be required than in power batteries optimised for HEV0 hybrids.

We saw in the “Ragone Plot” section how a cathode material optimised for energy storage (the Phostech 90-5-5 material) rather than power delivery is greatly affected by high rate of discharge which makes the PHEV application particularly demanding – 50% of the nominal capacity might be lost at higher road speeds.

Lithium Carbonate Purification

Another factor that must be allowed for is the processing yield to purify raw technical grade Lithium Carbonate into purified low sodium (99.95%) Lithium Carbonate required for the manufacture of batteries.

The technical grade Li_2CO_3 produced from Atacama contains about 0.04% Sodium (Na). This has to be reduced to below 0.0002% Na for use in batteries. In some cases ultra high purity 99.995% Lithium Carbonate is required.

While yields of over 80% are possible on a laboratory scale, this is more difficult to achieve industrially particularly as purity control requirements increase. 70% may be a more realistic yield figure to use.

Conclusion

This briefing paper has been intended to illustrate for a non-specialist the major real world electrochemical factors which significantly reduce the theoretical specific energy and energy density of LiIon batteries.

The main factors which reduce the theoretical capacity of a LiIon battery are:

Irreversible capacity loss: Lithium that becomes bound up in the anode and cathode and electrochemically inactive. This can be as high as 50% of the Lithium originally put into the cathode before the battery is charged for the first time.

Discharge rate: this is the major variable which reduces day to day effective capacity while the battery is in use. The Energy batteries required for PH(EV) use are more sensitive to this than power batteries and the problem is further exacerbated by using small batteries in a PHEV. Again, up to 50% of the effective capacity could be lost at medium to high speeds. Manufacturer capacity figures that only apply at low discharge rates are of little use in determining a realistic benchmark for PHEV battery capacity, for which capacity at the 1C rate at least should be used as a realistic indicator.

Cycle life capacity fade: EV batteries will be 25% larger than the nominal or useable stated capacity to allow for capacity fade.

A real world EV LiIon battery will provide nominally some 25% of the theoretical energy capacity or 70 – 120 Wh/kg instead of 410 – 450 Wh/kg. This translates into a Lithium requirement of at least 320 g of Lithium (1.7 kg LCE) per kWh of available capacity. In addition, Lithium has to be added to this for the electrolyte, irreversible capacity loss and capacity fade. EV batteries will be 25% oversized to account for capacity fade. Then allowance has to be made for processing yields of an estimated 70% from the raw technical grade Lithium Carbonate plus inevitable losses in the use of high control purity Lithium Carbonate in the manufacture of the battery components themselves. $LiMPO_4$ batteries operate at lower voltage than $LiMO_2$ and therefore induce a further increase.

If one therefore allows 400 g of Lithium (2.1 kg LCE) per battery kWh with a 70% processing yield to produce that, an initial 3 kg of raw technical grade Lithium Carbonate will be required per kWh of final usable battery capacity.

At 3 kg raw technical grade LCE per kWh, current global production of some 100,000 tonnes raw LCE would be sufficient, if available, for some 2 million 16 kWh batteries per year. Even at an optimistic 2 kg LCE per kWh assuming very high purity yields, production would be sufficient for only 3 million 16 kWh PHEV batteries per year.