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professional battery solutions

Technical Marketing White Paper

Subject:	***Portable Battery Energy Density***
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Energy Density

Cell and battery manufacturers often promote their technology and products in terms of Energy Density to demonstrate stored energy with regard to both weight and volume. Gravimetric Energy Density (*GED*) is expressed in Watt Hour per Kilogram (*Wh/Kg*) while Volumetric Energy density (*VED*) is expressed in Watt Hour per Litre (*Wh/l*). These figures are useful to battery designers and device manufacturers as they allow comparison between different battery technologies, different cell sizes and different manufacturers. It is commonly known that out of the three mainstream technologies used for portable batteries, Lithium Ion has the highest energy density with Nickel Metal Hydride in second place and Nickel Cadmium coming in third which explains the transition away from Nickel based chemistries over the past ten years. Chart 1 shows the energy density of these technologies using data gathered from commercially available data sheets.

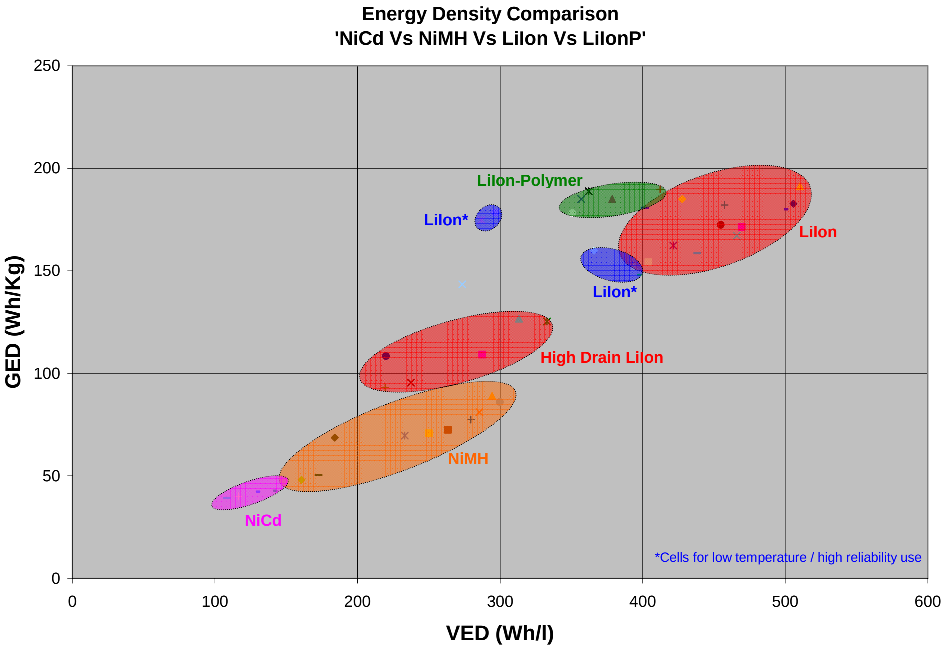


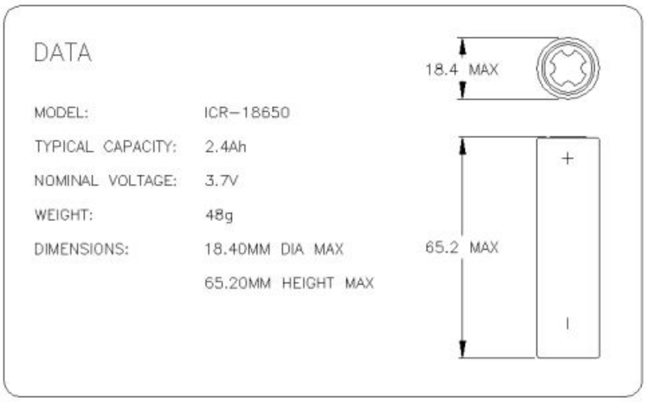
Chart 1

Lies, Damn Lies and Energy Density

Energy Density figures are much like fuel efficiency ratings for cars, they should not simply be accepted as fact without thinking more about how they are calculated and how differing usage may affect them. The first question one should ask is how the stored energy is calculated. The stored energy is a function of the cell or battery voltage and capacity, and is subject to changes in temperature, load and age. A simple estimate can be made by multiplying the cell or battery nominal voltage by the typical capacity, this gives a good 'rule of thumb' and is ideal for badge ratings or simple comparisons. For the GED and VED calculations, a manufacturer's data sheet can provide typical weight and dimensional information.

So for typical cylindrical Lithium ion cells, manufacturer's data sheets may provide basic information as shown in the following two examples:

Example 1



DATA

MODEL:	ICR–18650
TYPICAL CAPACITY:	2.4Ah
NOMINAL VOLTAGE:	3.7V
WEIGHT:	48g
DIMENSIONS:	18.40MM DIA MAX 65.20MM HEIGHT MAX

The theoretical energy is therefore Voltage (V) x Capacity (Ah) or 3.7V x 2.4Ah = **8.88Wh.**

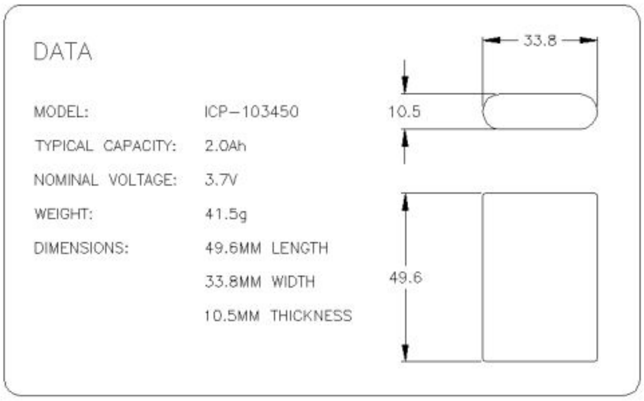
The VED:

= (1000cm^3 / Cell Volume in cm^3) x Cell Energy in Wh
= (1000cm^3) / (((Pi x R^2 in mm) x Height in mm) / 1000) x Cell Energy in Wh
= (1000cm^3) / 17.34cm^3 x 8.88Wh
= **512Wh/l**

The GED:

= (1000g / Cell weight in g) x Cell Energy in Wh
= (1000g) / 48g x 8.88Wh
= 185Wh/Kg

Example 2



DATA

MODEL:	ICP–103450
TYPICAL CAPACITY:	2.0Ah
NOMINAL VOLTAGE:	3.7V
WEIGHT:	41.5g
DIMENSIONS:	49.6MM LENGTH 33.8MM WIDTH 10.5MM THICKNESS

The VED:

= (1000cm^3 / Cell Volume in cm^3) x Cell Energy in Wh
= (1000cm^3) / 17.60cm^3 x 7.40Wh
= **420Wh/l**

The GED:

= (1000g / Cell weight in g) x Cell Energy in Wh
= (1000g) / 41.5g) x 7.40Wh
= 214Wh/Kg

High Energy

These are good numbers! 420~512 Wh/l and 185Wh~214 Wh/Kg are both attractive and are likely to turn the head of any engineer or marketing person looking at energy requirements for their latest gizmo. However things are never this simple. The number calculated from the data sheet may not translate into a similar number at a battery pack level as I will explain below.

The Effect of Rate

The energy calculated from the data sheet assumes a constant current discharge at 0.2C. (Where “C” is the capacity of the battery in Ah) The 3.7V is assumed to be the mean voltage as it drops from 4.2V (fully charged) to around 3.0V (fully discharged). Of course the dissipated energy is the ‘area under the curve’ during the discharge so to get a more accurate number it is useful to look at data from real usage. Charts 2 and 3 show the discharge curves for the 2.4Ah cylindrical ICR-18650 cell and the 2.0Ah prismatic ICP-103450 cell under constant current discharges of 0.2C, 1C and 2C*.

It can be seen that the voltage and capacity reduce as the discharge current increases resulting in a lower energy output. The actual energy output for each discharge is shown in Chart 4 and expressed as a percentage versus the theoretical energy calculations. It can be seen that the discharge at 0.2C is very close to the calculated figure, but the higher discharge rates of 1.0C and 2.0C reduce the available energy.

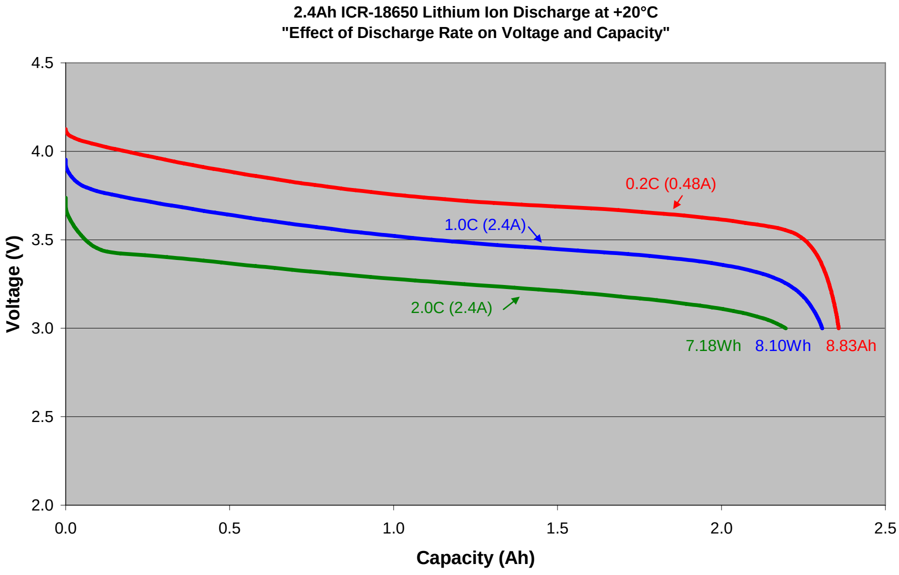


Chart 2

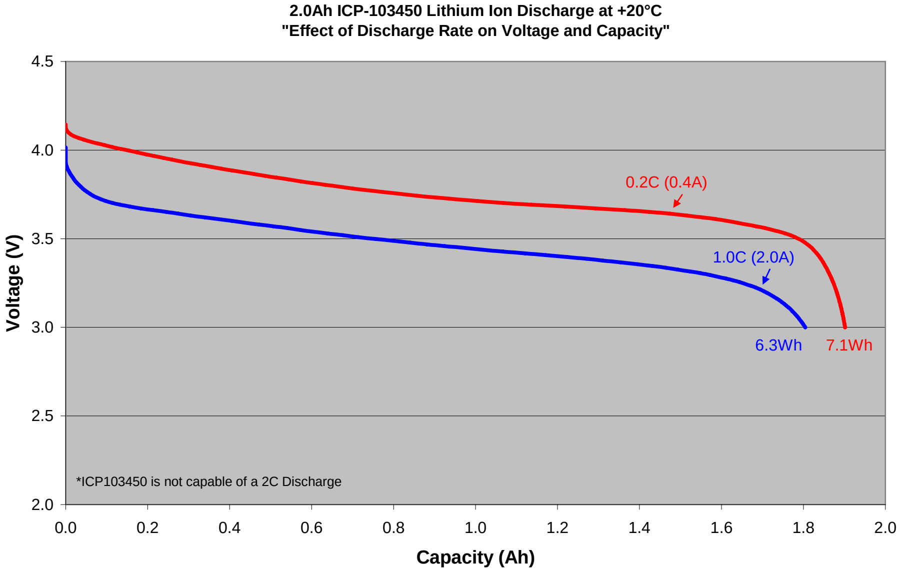


Chart 3

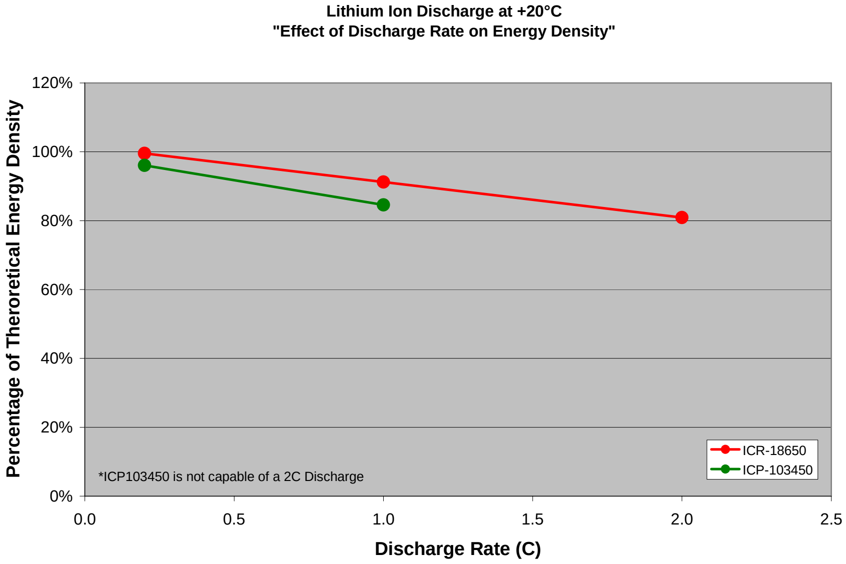


Chart 4

The Effect of Temperature

Although the commercial operating temperature range for most cells during discharge is -20°C to +60°C, data sheets usually assume operation at room temperature (+20°C) for the purposes of ‘typical voltage’ and ‘typical capacity’. Higher temperatures usually result in a slight improvement in discharge performance while lower temperatures result in a dramatic reduction in both voltage and capacity which results in a drop in energy output. While certain cell manufacturers do provide cells which are optimised for low temperature operation (for applications such as military and power tool use) the performance of most cells is poor below 0°C. Charts 5 and 6 shows the discharge performance of two cells at temperatures between -20°C and +60°C during a 0.2C discharge. Chart 7 demonstrates the energy output at each temperature as a percentage of the theoretical output at +20°C. It can be seen that the +20°C to +60°C performance is consistent but 0°C shows a marked reduction and -20°C is considerably worse. It must be noted that these tests were all conducted at a constant current 0.2C discharge. Higher rates will usually result in higher voltage drops and lower capacity/energy. Other variables should also be taken into account when determining battery performance at low temperature such as (i) I²R self heating (ii) multiple cells in close proximity to each other (iii) case thermal insulation and (iv) battery age and (v) host product heating.

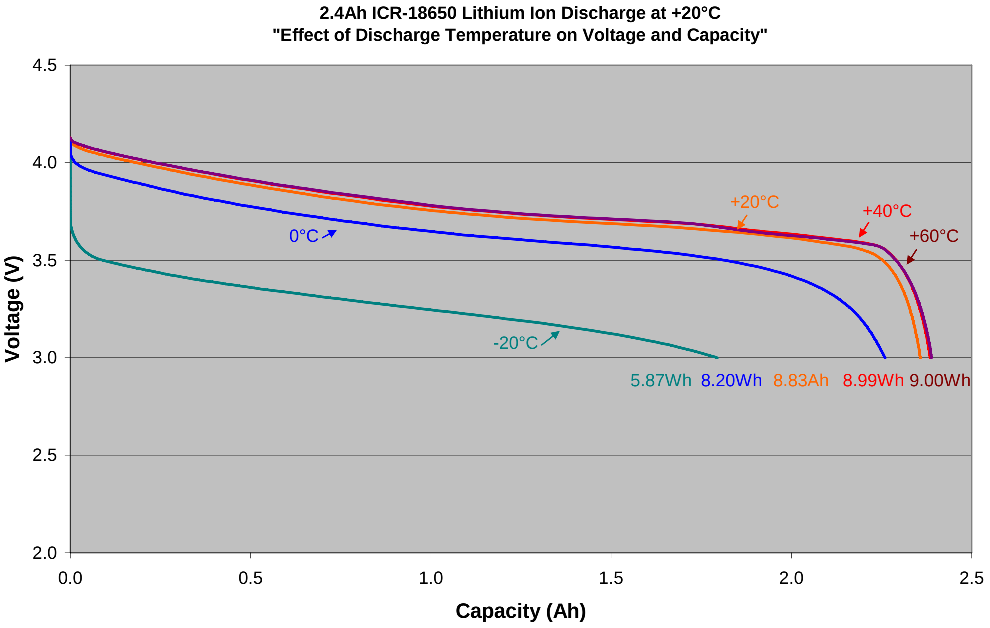


Chart 5

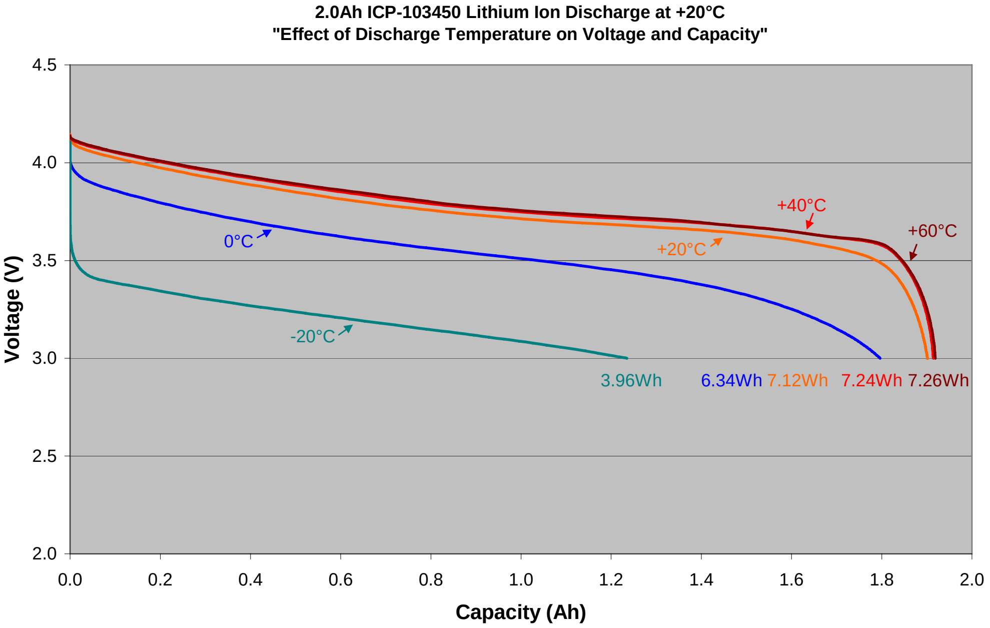


Chart 6

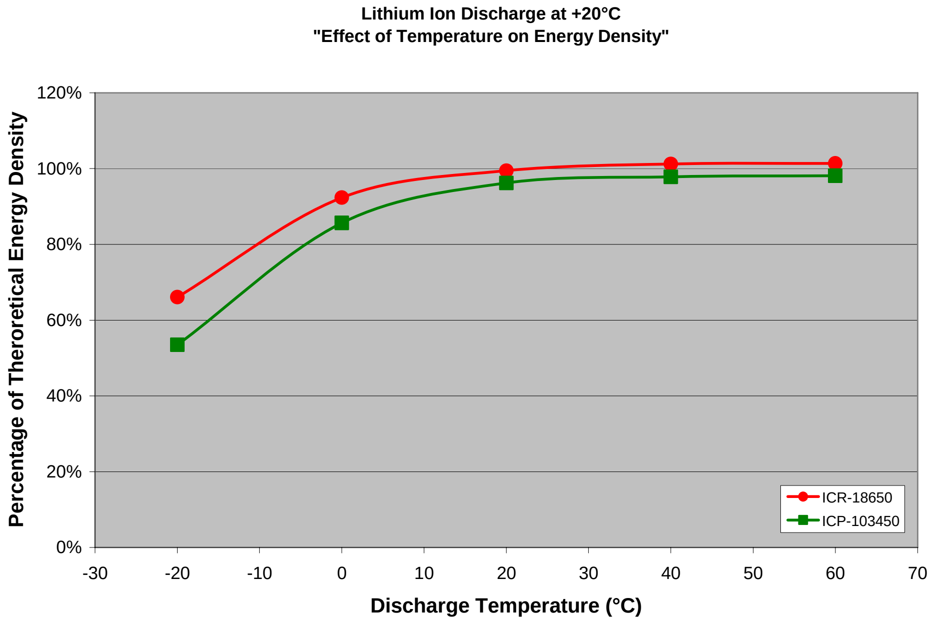


Chart 7

Effect of Age

As batteries age through cycling, their capacity and discharge voltages reduce. This reduction in available energy should not be overlooked when considering the overall energy requirements of a device over the product life cycle, especially if batteries are to be imbedded in the device. Chart 8 shows how voltage and capacity reduces for a typical Lithium ion battery over 300 cycles.

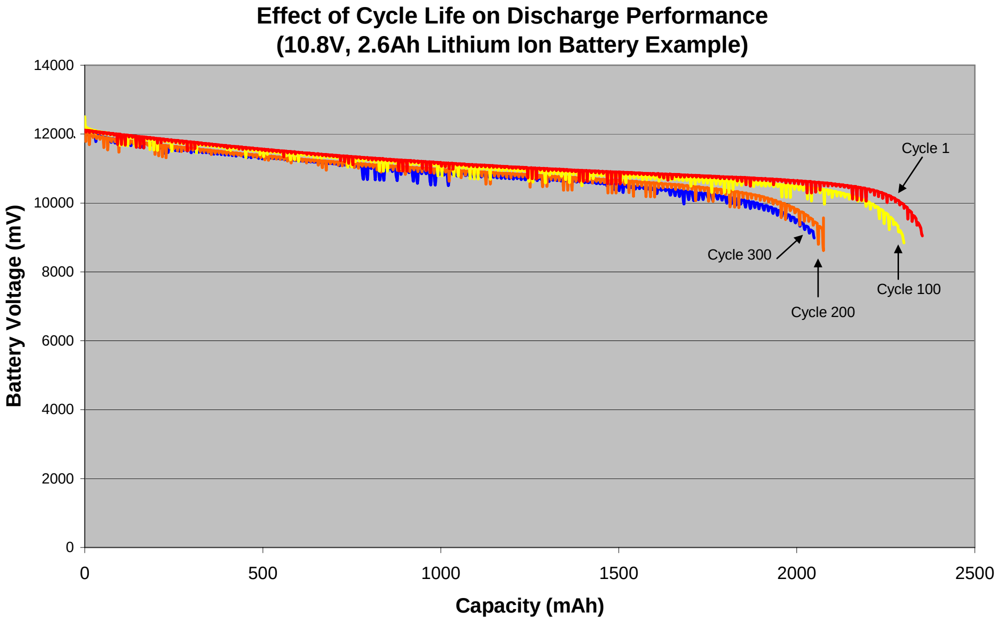
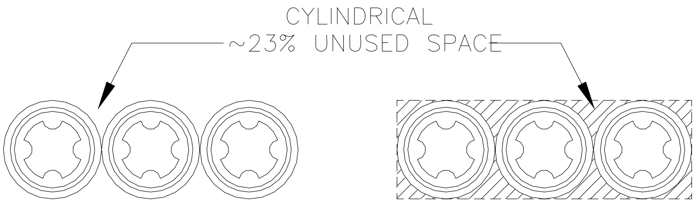
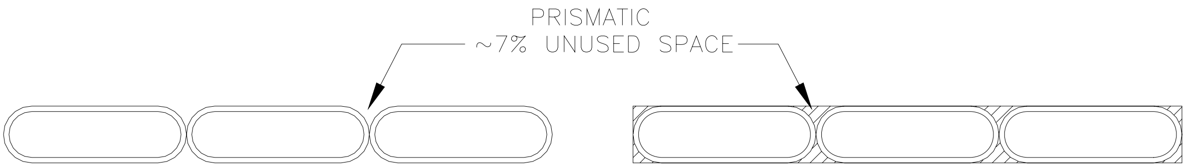


Chart 8

Battery Dimensions

The first cell in our example is cylindrical which is common in devices such as laptops and power tools. Cylinders however do not tessellate very well in flat batteries and designers will always be left with voids between the cells which do not contribute to the overall energy density of the battery pack. If the volume of a cylinder is compared with the prismatic space that it occupies it can be seen that around 27% is unused space whereas only 7% is unused when using prismatic cells.





The fact that the cells are left only touching at their tangents is however good for cell performance as heat dissipation is improved and some of these space are put to good use to contain thermal fuses and wiring, but most will be left as empty valleys.

Other components also reduce energy density such as insulation, wiring, printed circuit boards and connectors. The battery casing itself also adds to the volume and may also have additional features such to mould itself around the device. In a recent study of multi cell Lithium Ion battery packs from various manufacturers, 40% to 50% of the battery could be attributed to 'non cell' volume. This is not necessarily a bad thing as some non cell volume is absolutely necessary to the function and safety of the battery pack but it does nothing to enhance its VED figure.

Battery Weight

Cell manufacturers have done a lot of the past few years to reduce the weight of cells through the use of thin wall cans and aluminium replacing nickel plated steel cans in some cases. Electrode weight has also been reduced, and the thin aluminium and copper foils used for Lithium ion cells are a vast improvement from the heavy gauge sintered plates used in Nickel Cadmium cells. However, as with VED figures, a battery pack GED will be reduced as other components such as casing, electronics and insulation are introduced. In a recent study of multi cell Lithium Ion battery packs from various manufacturers, 20% to 30% of the weight could be attributed to 'non cell' weight.

Conclusion

Energy density figures quoted by cell and battery manufacturers needed to be treated with caution; Theoretical figures calculated from data sheets do not account for the reduced efficiency of the chemistry when used at discharge rates higher than 0.2C. The effects of temperature, especially low temperature during discharge can also have a huge impact on battery performance and the reduction in available energy over the product life must also be considered as it will also erode the energy density figure.

Taking cells and assembling them into battery packs further reduces both the Volumetric and Gravimetric energy density due to the addition of the battery assembly components and the reduction can be as high as 50% for VED and 30% for GED. This reduction must be understood when starting the product design process so that sufficient volume and weight allowance is made for the battery pack whilst still maintaining product run-time targets.

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