axeon

Our Guide to Batteries

The information contained in this guide is intended to be used as an educational tool and should not be relied upon for any decisions relating to production, product development or acquisition or use of battery technology. You should consult an appropriate professional expert for advice tailored to your specific requirements.

Whilst every effort is made to ensure that the information in this guide is up to date and correct, it may nevertheless include some inaccuracies. To the fullest extent permitted by law, we shall not be liable for any direct, indirect, incidental or consequential loss or damages whatsoever arising out of or in any way connected with reliance on the contents of this guide.

Introduction

Welcome to our ‘Guide to Batteries’. We hope that you will find it a useful overview of current battery technology, particularly as it relates to the automotive industry.

Axeon is Europe’s leading provider of battery systems for electric vehicle propulsion. We are committed to providing clear knowledge and information on battery technology to all stakeholders in the sectors to promote greater understanding of how batteries can revolutionise the automotive industry.

This guide therefore includes an introduction to cell chemistry and some indications of probable future developments, as well as an overview of the Battery Management System, critical for safety and performance, and a discussion on charging.

Battery technology will play a major role in product development across all sectors of the automotive industry with the continual drive to reduce vehicle emissions. We hope this guide is useful in providing not only an explanation of current systems, but also insights into how the technology is likely to develop.

Contents

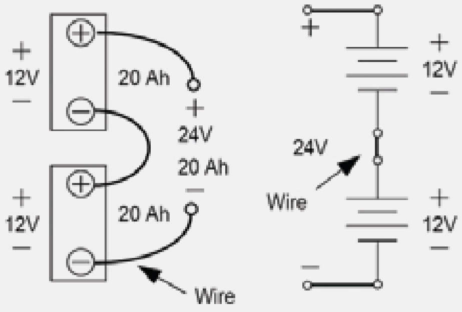
Batteries

Batteries are made up of various elements. This includes cells, which are connected together in series or parallel strings to achieve the desired voltage and capacity (amperage).

By choosing how to connect the cells, batteries can be designed for a wide range of applications, from low-power low-capacity batteries for industrial, leisure and medical uses, to high-power high-capacity batteries for use in electric and hybrid electric vehicles.

Series connection:

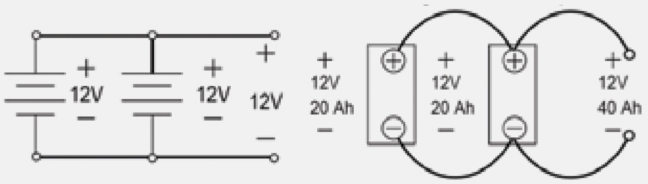
Voltages Add, Capacity is Constant



Adding cells in a series connection increases the voltage by the value of the cell. In the example above, two 12V cells have been added together to increase the voltage from 12V to 24V.

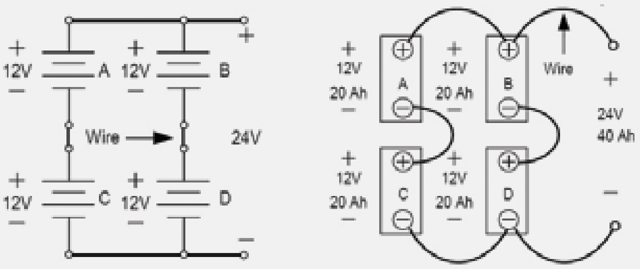
Parallel connections:

Voltage is Constant, Capacities Add



Adding cells in a parallel connection increases the capacity by the value of the cell. So in the example above two 20Ah cells have been added together to increase the capacity from 20Ah to 40Ah.

Series/parallel connections:



Combining the two methods above makes any combination of voltage and capacity possible, allowing a particular application's needs to be met.

Essential parts of an automotive battery

In addition to the cells, batteries are made up of a Battery Management System (BMS), busbars, cabling, shunts, wiring harnesses, and housing.

Cells
For automotive batteries the cells used are usually Lithium-ion. See section on Cells for more details (p8).

Busbars
These are used to connect the cells together electrically and are usually made from copper.

Wiring harnesses
Used to connect temperature and voltage sensors from the cells to the BMS.

Master and slave modules (BMS)
These are the electronics that control the battery, and collectively are known as the Battery Management System (BMS). See separate section on this for more details (p13).

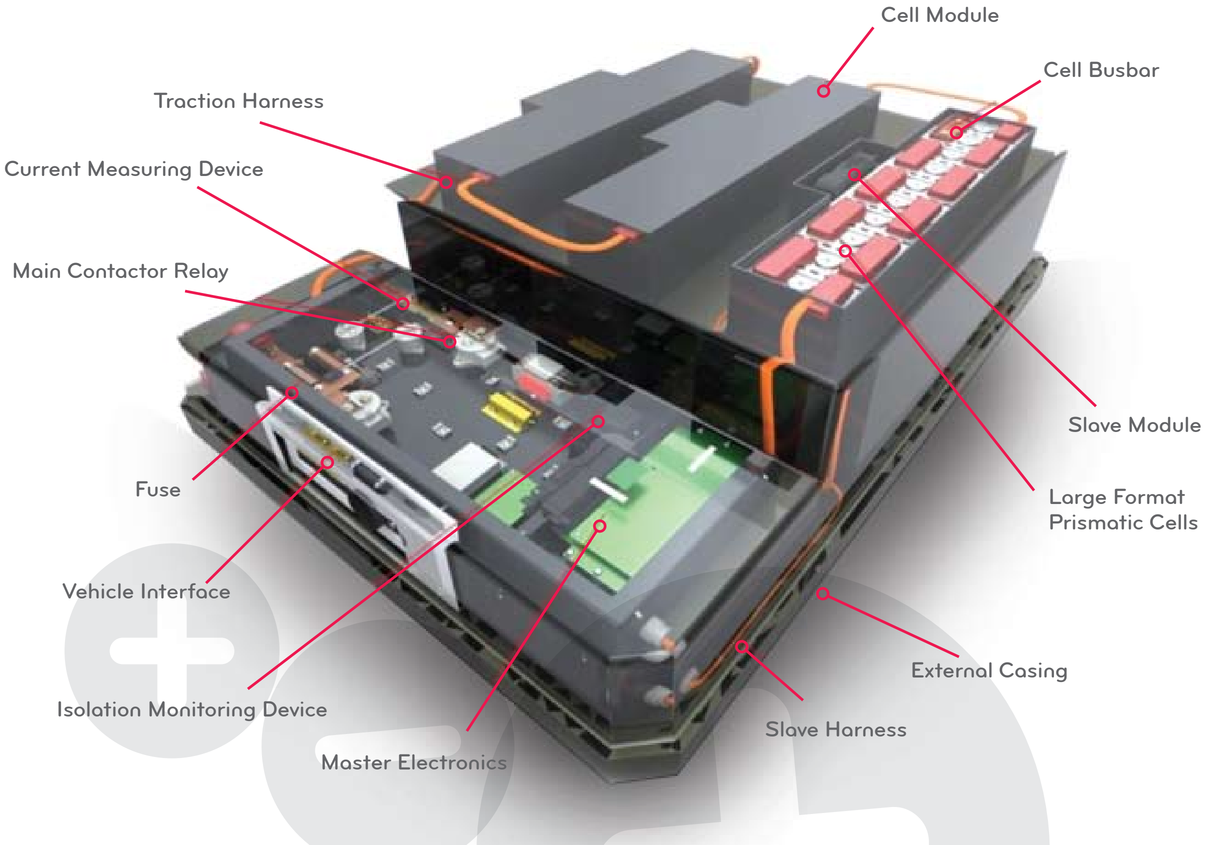
Traction cable
A high voltage and high current cable that connects the cell modules together and carries the main power round the battery.

Vehicle interface
This is a specific connection between the battery and the vehicle. Information is transferred by CAN-BUS, which is an automotive standard protocol. Typical information is state of charge (fuel gauge), battery voltage temperature and current (amps) from the battery.

Current measuring device
This measures the amount of amps during discharge and charge.

Isolation monitoring device
A safety device that checks for electrical leakage to ground. This reduces the risk of receiving a shock from the battery.

Main contactor relay
The main switch on the battery, which switches off both positive and negative connections, thereby rendering the battery safe.



What is a cell?

Cells are the building blocks of batteries. A cell is a closed power source, in which energy is stored chemically. This energy is released due to internal chemical reactions as a flow of electrons through an external circuit.

A cell can be either primary (single-use) or secondary (rechargeable). A cell is a device that converts the chemical energy contained in its active materials directly into electric energy by means of electrochemical oxidation-reduction (redox) reactions. A cell comprises a number of positive and negative charged plates immersed in an electrolyte that produces an electrical charge by means of an electrochemical reaction. On discharge, electrolytic cells convert chemical energy to electrical energy. The lithium-ion battery is known as a rocking chair or swing battery due to charge carriers shuttling back and forth between two intercalating electrodes during the charge and discharge processes.

Cell potential

In simple terms, batteries can be considered as electron pumps. The electrical (pump) pressure or potential difference between the positive and negative terminals is called voltage or electromotive force (EMF).

Cell components

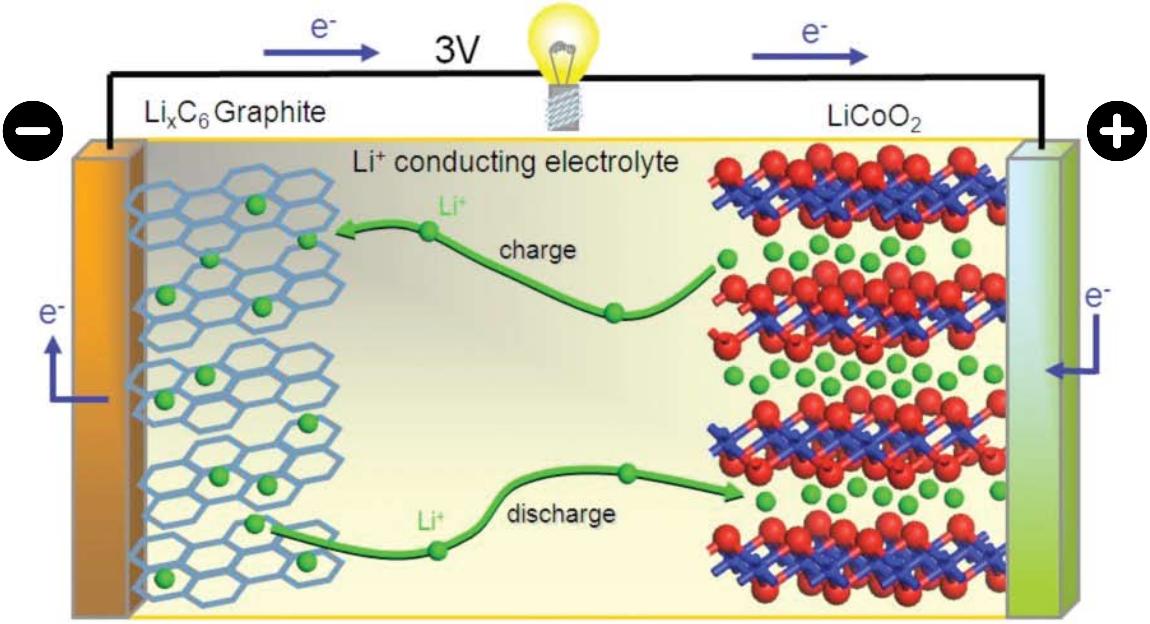
Lithium Battery cells consist of three main components:

1: The anode

On discharge, the anode (negative electrode) gives up electrons and Li^+ ions to the external circuit and is oxidised during the electrochemical reaction. Most commercial cells currently employ a carbon/graphite based electrode; however, metal or an alloy can also be used.

2: The cathode

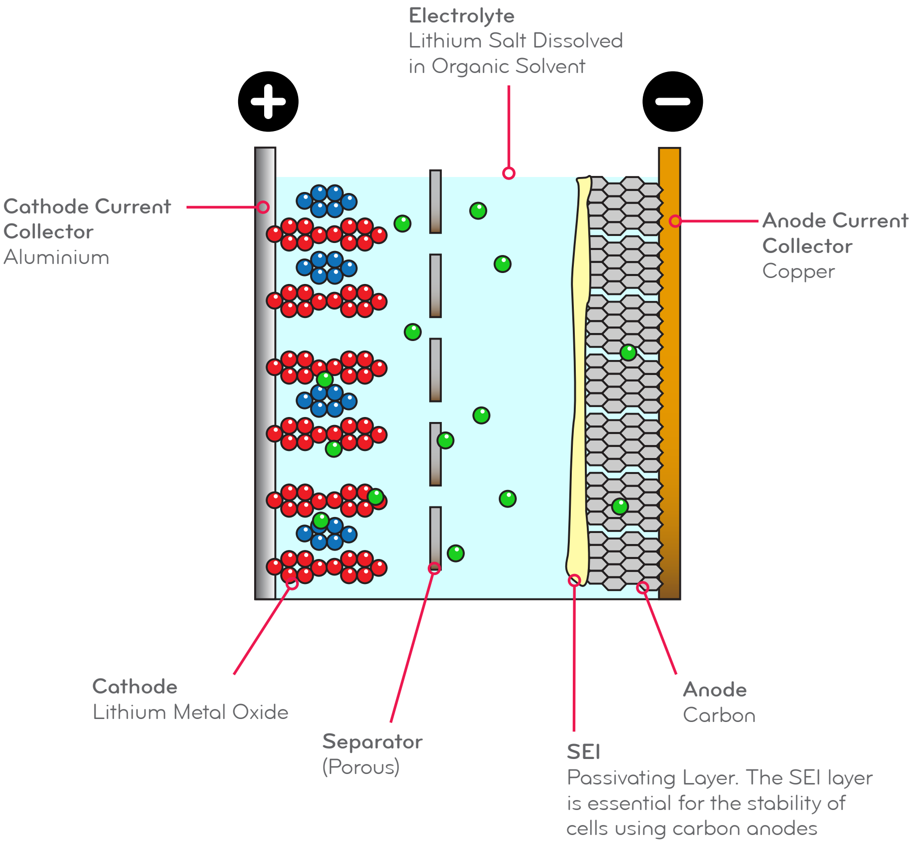
On discharge, the cathode (positive electrode) accepts electrons and Li^+ ions from the external circuit and is reduced during the electrochemical reaction. It is usually a Lithium transition metal oxide or phosphate. Specific battery chemistries are typically named according to the material used for the cathode.



3. The electrolyte

This does not take part in the chemical action. It is an ionic conductor but an electronic insulator, separating the two electrodes and providing the medium for charge transfer inside the cell between the anode and cathode. For Lithium ion batteries, the electrolyte is typically a non-aqueous inorganic solvent containing a dissolved Lithium salt, e.g. $LiPF_6$ in propylene carbonate. Within liquid electrolyte systems, a porous separator physically keeps the two electrodes apart to prevent a short circuit but provide ion diffusion channels.

Solid polymer electrolytes are less volatile, have a lower flash point and are less prone to leakage than liquid or gelled electrolytes but the cells have higher internal impedance.



The charge process
Cells are generally constructed in the discharged state. On charge, the cathode (positive electrode) material is oxidized, Li^+ ions are de-intercalated from the layered lithium intercalation host, e.g. $LiCoO_2$, passes across the electrolyte and is intercalated between the graphite layers of the anode by an electrochemical reduction reaction taking place at the anode.

The discharge process
When the cell is discharged, an oxidation reaction occurs at the anode (negative electrode), Li^+ ions are de-intercalated from the anode and migrate across the electrolyte to be re-intercalated into the cathode. Due to charge balance, the equivalent number of electrons travel through the external circuit. A simultaneous electrochemical reduction reaction takes place at the cathode and accepts electrons from the external circuit, Li^+ ions from the electrolyte, to reform the starting material. A change from electronic current to ionic current occurs at the electrode/electrolyte interface.

Lithium ion cells operate by the principle of intercalation – the reversible insertion of a guest atom into a solid host structure without inducing a major disruption of the host material.

Types of cell construction

A key component of a cell is the case. This contains the active chemicals and holds the electrodes in place. Cells can be housed in various ways.

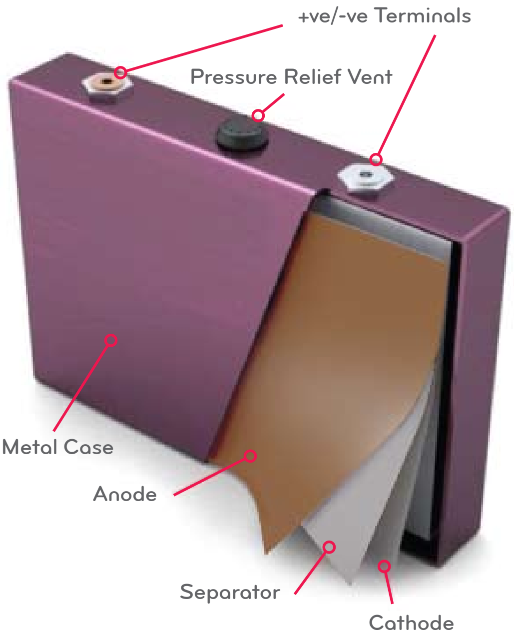
1: Prismatic

Prismatic metal case
Aluminum or steel cans are traditionally used with Li-ion cells. Prismatic Li-ion cells have high energy density. Metal cans are strong and enable good heat dissipation. Prismatic lithium cells can be packaged more efficiently than cylindrical cells because of their form factor and therefore the packing density is higher. They come in sizes up to 100 Ah.

2: Cylindrical

Cylindrical steel case
Small cylindrical cells are made in very high volumes and the price is low for standard shapes. The 18650 (18mm diameter, 650mm long) standard size cells are used on laptop batteries. For the standard size cells the battery pack must be designed around the available cell. The cells have high energy density, but the disadvantage is their bulky size and inefficient use of space. The air cavities created between cells can be used for cooling. The cells usually have an overcharge protection.

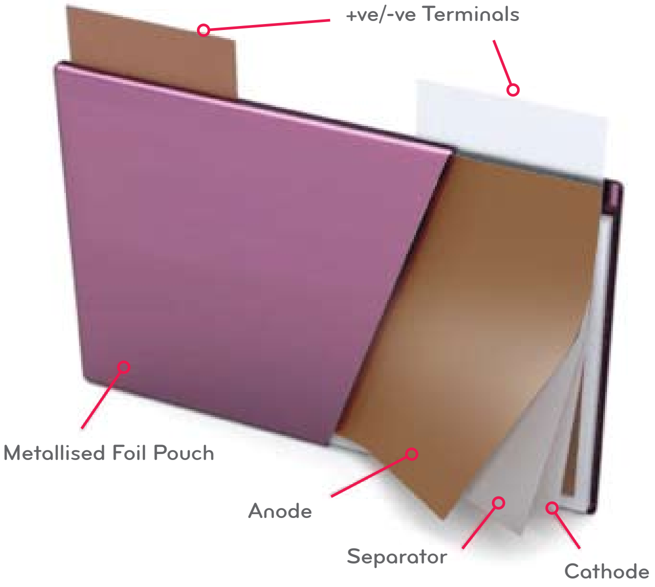
High capacity cells bigger than the standard sizes are expensive. Sizes of up to 200 Ah are available.



3: Pouch

Pouch cell

Pouch cells make the most efficient use of available space and achieve a packaging efficiency of 90 – 95%. Because of the absence of a metal can, the pouch pack has a lower weight and therefore the battery pack will have a higher energy density. Pouch cells can be produced in different forms depending on the application and manufacturers are not bound by standard cell formats. With high volume, any reasonable size can be produced economically. Lithium polymer pouch cells are increasingly being considered as alternatives to large prismatic cells for automotive applications; because their form is flexible they can be packaged more efficiently, and reduced cell packaging overheads result in high battery energy density. This cell construction uses a polymer for the electrolyte, and is thus less volatile and less prone to leakage. Due to large surface area and aspect ratio they have good heat dissipation. However, the cells have low mechanical stability and therefore more robust packaging is required.



Cell chemistries

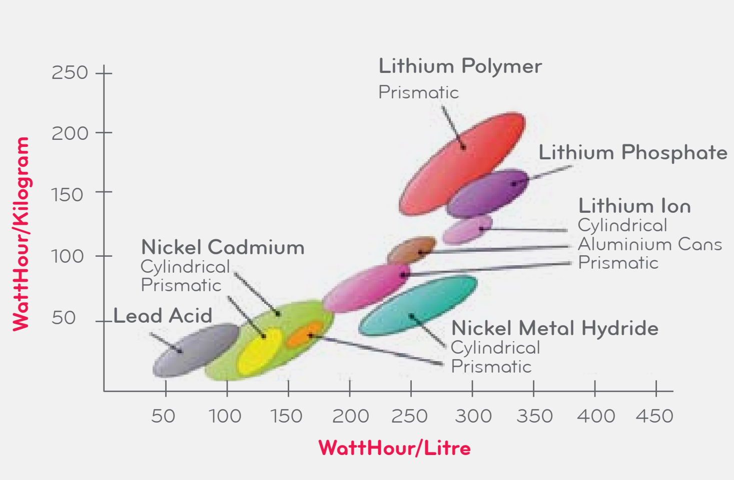
Different cell chemistries have different energy densities. Lithium-ion cells have considerably greater energy density than previously-used chemistries. This makes them particularly suitable for automotive applications. They are also considered safer, less toxic, and are more highly energy efficient with significantly longer cycle life.

Lead acid (Pb)

Lead-acid batteries are composed of a Lead-dioxide cathode, a sponge metallic Lead anode and a Sulphuric acid solution electrolyte. This heavy metal element makes them toxic and improper disposal can be hazardous to the environment. The cell voltage is 2 Volts.

This chemistry is used in starter batteries for internal combustion engine (ICE) vehicles. However, it is heavy and has poor energy density.

It is a popular low-cost secondary battery, available in large quantities and in a variety of sizes and designs, has good high-rate performance, moderately good low- and high-temperature performance, easy state-of-charge indication, good charge retention for intermittent charge applications. Cell components are easily recycled. Because of the irreversible physical changes in the electrodes, failure occurs between several hundred and 2,000 cycles. The main drawbacks of these batteries are their comparatively low energy density, long charge time and the need for careful maintenance. It is widely used in battery power for energy storage, emergency power, earlier generations of electric and hybrid vehicles (including off-road vehicles) and for engine starting, vehicle lighting, and engine ignition (SLI).



Reference: www.electropaedia.com

Nickel Cadmium (NiCd)

These cells use nickel hydroxide Ni$(OH)_2$ for the cathode, cadmium Cd as the anode and an alkaline potassium hydroxide KOH electrolyte.

Standard Ni-Cd cells use an aqueous chemical impregnation process for the fabrication of electrodes. It has been used for storing electrical energy in spacecraft since the beginning of space exploration. It has a long cycle life, good low-temperature and high-rate performance capability, long shelf life in any state of charge and rapid recharge capability. Memory effect is one of its biggest drawbacks, as is a fairly high rate of self-discharge at high temperature. As cadmium is highly toxic, its use in batteries is now banned, with the exception of medical and some military applications.

Nickel Metal Hydride (NiMH)

These cells use nickel hydroxide $Ni(OH)_2$ for the cathode. Hydrogen is used as the active element in a hydrogen-absorbing anode. This electrode is made from a metal hydride, usually alloys of lanthanum and rare earths that serve as a solid source of reduced hydrogen that can be oxidized to form protons. The electrolyte is alkaline, usually potassium hydroxide.

Nickel Metal Hydride cells have higher capacity than nickel-cadmium cells, rapid recharge capability, long cycle life and long shelf life in any state of charge. There are minimal environmental problems. However, its high-rate performance is less than that of nickel-cadmium. The poor charge retention, memory effect and higher cost anodes are the drawbacks. It has been used in computers, cellular phones and other consumer electronic applications, with the possible exceptions of high-drain power tools and applications where low battery cost is the major consideration.

Zebra – Sodium ($Na-NiCl_2$)

The so-called zebra battery, which operates at 250°C, utilizes molten sodium chloroaluminate ($Na-NiCl_2$), which has a melting point of approximately 160°C, as the electrolyte. The anode is molten sodium. The cathode is nickel in the discharged state and nickel chloride in the charged state.

The zebra battery has a specific energy and power (90 Wh/kg and 150 W/kg). The liquid electrolyte freezes at 157°C, and the normal operating temperature range is 270–350°C. The β-alumina solid electrolyte that has been developed for this system is very stable, both to sodium metal and the sodium chloroaluminate.

When not in use, zebra batteries typically require to be left on charge, in order to be ready for use when needed. If shut down, the reheating process lasts 24 hours, and then a normal charge process of 6-8 hours is required for a full charge. This is a major issue for EV customers who may not use their vehicle every day or forget to put the vehicle on charge. It is also inefficient as it consumes energy when not in use.

Lithium-ion

Lithium is attractive due to its low equivalent weight and high standard potential and has been used in rechargeable batteries to provide over three times the energy density of traditional rechargeable batteries. The field has seen significant advances in solid state chemistry in effort to improve performance further. This includes a drive for increased energy density, rate capability and the ability to provide high power, leading to high cycle life and thermal stability for increased safety. Attention has also focused on fast charge ability as well as cost reduction, through the use of inexpensive raw materials, synthetic processes and using materials of low toxicity and environmental banality.

Lithium-ion cells typically use a carbon-based anode, although lithium titanate anodes have recently become commercially available. Various compounds can be used for the cathode, each of which offers different characteristics and electrochemical performance. The electrolyte is usually a lithium salt dissolved in a non-aqueous inorganic solvent. Lithium battery technology is still developing, and there is considerable potential for further enhancements.

The energy of the battery is limited by the specific capacity of the electrodes, and the cathode in particular. Much investment and research has therefore been devoted to replacement cathode materials.

Comparison of different cell chemistries

Property	Unit of Measurement	Lead Acid	NiMH	Lithium-ion
Cell Voltage	Volts	2	1.2	3.2-3.6
Energy Density	Wh/Kg	30-40	50-80	100-200
Power Density	W/Kg	100-200	100-500	500-8000
Maximum Discharge	Rate	6 -10C	15C	100C
Useful Capacity	Depth of Discharge%	50	50-80	>80
Charge Efficiency	%	60-80	70-90	~100
Self Discharge	%/Month	3- 4	30	2-3
Temperature Range	°C	-40 +60	-30 +60	-40 +60
Cycle Life	Number of Cycles	600-900	>1000	>2000
Micro-cycle Tolerant		Deteriorates	Yes	Yes
Robust (Over/Under Voltage)		Yes	Yes	Needs BMS

Lithium variants

Lithium Iron Phosphate – $LiFePO_4$

Phosphate-based technology possesses superior thermal and chemical stability which provides better safety characteristics than those of other Lithium-ion technologies. Lithium phosphate cells are incombustible in the event of mishandling during charge or discharge, they are more stable under overcharge or short circuit conditions and they can withstand high temperatures without decomposing. When abuse does occur, the phosphate-based cathode material will not release oxygen, will not combust and is therefore much less susceptible to thermal runaway. Lithium iron phosphate cells also offer a longer cycle life (1,000 – 2,500 cycles).

Lithium iron phosphate batteries have lower energy density than cobalt, but they can support higher currents and thus greater power. They are a significant improvement over lithium cobalt oxide cells in terms of the cost, safety and toxicity.

Lithium Cobalt Oxide – $LiCoO_2$

Lithium Cobalt Oxide has been the most widely used cathode material in lithium batteries for many years; it is typically used for laptop batteries and mobile phones. It provides moderate cycle life (>500 cycles) and energy density. However, the chemistry is less thermally stable than other transition metal oxide or phosphate chemistries making it highly combustible under extreme abuse conditions: cell puncture or drawing too much current can trigger thermal runaway or even a fire. These characteristics make them unattractive for use in Electric and Hybrid Electric Vehicles.

Lithium Manganese Oxide Spinel – $LiMn_2O_4$

Lithium Manganese Oxide Spinel provides a higher cell voltage than Cobalt-based chemistries and thermally is more stable. However the energy density is about 20% less. Manganese, unlike Cobalt, is a safe and more environmentally benign cathode material due to its low toxicity. Other benefits include lower cost and higher temperature performance.

Lithium (NCM) – Nickel Cobalt Manganese – $LiNi_xCo_yMn_zO_2$

Batteries which employ lithium nickel cobalt manganese oxide are a compromise of electrochemical performance, combined with lower cost. Electrochemically the performance is superior to $LiFePO_4$ in terms of energy density. In terms of rate capability and therefore power density the electrochemical performance is better than $LiCoO_2$ but not as high as $LiFePO_4$. This chemistry is increasingly seen as a viable alternative solution to $LiFePO_4$ for high energy density packs for electric vehicles.

Lithium Titanate Oxide (LTO) – $Li_4Ti_5O_{12}$

These cells replace the graphite anode with lithium titanate. This anode is compatible with any of the above cathodes, but is generally used in conjunction with high voltage Manganese-based materials due to its high potential vs Li/Li^+ redox couple. They offer superior rate capability and power combined with wide operating temperature range. They are considered a safer alternative to the graphite anode due to higher potential and therefore inbuilt overcharge protection. Also they are a 'zero-strain' insertion material that does not form a large passivating layer with the electrolyte, thus giving rise to long cycle life. However, lithium titanate batteries tend to have a slightly lower energy density than graphite based systems.

Main Lithium variants

	Cell level energy density/ Wh/kg	Cell level energy density/ Wh/l	Durability cycle life (100 % DoD)	Price $/Wh (estimate)	Power C-rate	Safety thermal runaway onset	Potential (voltage)	Temp. range (ambient)
$LiCoO_2$	170-185	450-490	500	0.31-0.46	1C	170°C	3.6	-20 to 60°C
$LiFePO_4$ (EV/PHEV)	90-125	130-300	2000	0.3-0.6	5C cont. 10C pulse	270°C	3.2	-20 to 60°C
$LiFePO_4$ (HEV)	80-108	200-240	>1000	0.8-1.2	30C cont. 50C pulse	270°C	3.2	-20 to 60°C
NCM (HEV)	150	270-290	1500	0.5-0.58	20C cont. 40C pulse	215°C	3.7	-20 to 60°C
NCM (EV/PHEV)	155-190	330-365	1500	0.5-0.58	1C cont. 5C pulse	215°C	3.7	-20 to 60°C
Titanate vs NCM/LMO	65-100	118-200	12000	1-1.7	10C cont. 20C pulse	Not susceptible	2.5	-50 to 75°C
Manganese Spinel (EV/PHEV)	90-110	280	>1000	0.45-0.55	3-5C cont.	255°C	3.8	-20 to 50°C

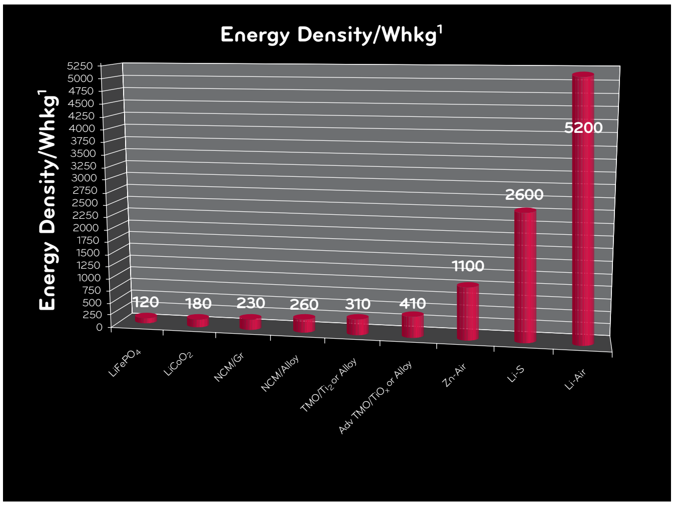
Development of cell chemistries

Future development

There are a number of challenges to be overcome relating to cell chemistry. Future battery development requires:

- Inexpensive batteries. Cheaper cells are needed; this can only be achieved with the use of new materials.
- More durable batteries. The cycle life of batteries needs to be extended, to thousands of cycles for EV batteries and tens of thousands of micro-cycles for HEV. Equally the calendar life of the battery will ideally need to mirror that of the vehicle, possibly up to 10 years.
- Energy and power density. Both need to be increased, though the relative importance of each will depend on the specific application of the battery. This can be achieved both by the use of new electrode materials and potentially also the design of the cell.

Theoretical maximum energy density of different cell chemistries



Although it is unlikely that these theoretical maximum energy densities can be achieved, huge efforts are being made to work towards them.

Chemistry development

There is considerable room for the development of new materials for the electrodes. This would offer the possibility of increasing the energy density of cells, thus making them more attractive for automotive applications. Some potential replacement cell chemistries are outlined below.

TMO/Silicon Alloy

- Silicon-Alloy materials are particularly attractive as replacements for a graphite anode, as they offer higher energy density than graphite (up to three times as much) and would be potentially much cheaper to manufacture than both soft, hard and semi-graphitised carbons.
- When used in conjunction with an advanced transition metal oxide (TMO) or even silicate-based cathodes then cells using these anode and cathode combinations have a theoretical energy density of over 300Wh/kg, depending on the exact materials used.

Zinc-Air cells

- Discharge is powered by the oxidation of zinc with oxygen from the air . Like other metal air systems the rechargeable cells use a catalyst to allow the reverse process of discharge to occur and make the cell rechargeable.
- Although they offer high energy density, the downside is slow discharge rates and low power density; in other words the energy cannot be accessed fast.

Lithium-Sulphur cells

- These have a high capacity but many years of development have not solved the main problems.
- These are very poor cycle life and self-discharge, caused by the discharge products (lithium thiolate) being soluble in the electrolyte.

Lithium-Air cells

- Although currently at the R&D stage only, lithium-air cells potentially offer 5 to 10 times the energy density of today's Lithium-ion cells.
- Recharge is achieved by the use of a porous composite carbon and catalyst positive electrode. It also requires very sophisticated membranes that allow selective oxygen molecules to pass but are impervious to water and electrolyte.
- This is a fledgling technology that has demonstrated only limited capacity retention on cycling. It still requires considerable research effort to achieve a commercially-viable cell that lasts the hundreds of cycles that are required for automotive applications.

Possible current/future cell options

	Short Term	Medium Term 3-5yrs	Long Term +5yrs
City EV	Large Format cells LFP/$LiMn_2O_4$	NCM/TMO Pouch	Silicon/ Tin-alloy Rechargeable metal air systems
Urban Delivery EV	Large Format LFP	NCM/TMO Pouch	
PHEV	NCM Pouch	NCM/TMO Pouch	
High performance HEV	Small Format LFP	Small Format LFP	Advanced Nano-material electrodes

Material availability

Concerns are sometimes raised about the availability of the materials necessary for the construction of large-format automotive batteries. However, the current estimate estimates of worldwide Lithium reserves total about 30 million tons (or 150 million tons of Lithium Carbonate). Around 0.3 kg of lithium is required per kWh of battery storage. The consensus amongst experts is that with EVs achieving 60% penetration of the new car market, these reserves would last well over a thousand years.

Lithium can also be extracted from sea-water (sea-water has an average Lithium concentration of 0.17ppm). Currently this is prohibitively expensive; however, in March 2010 the Koreans announced plans to do this commercially.

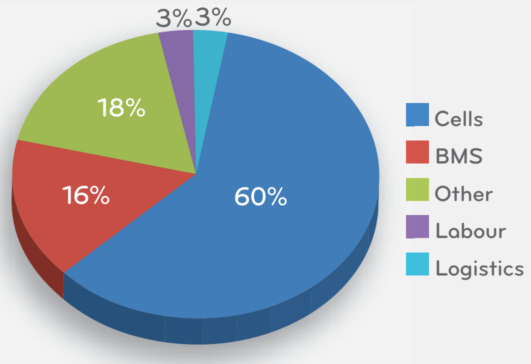
Cost of various parts

Almost two thirds of the cost of an automotive battery pack is contained in the cells, and of that, the largest component is the cathode (see diagrams below). Cost reductions are being sought by the use of inexpensive raw materials with no exotic chemical elements and by simplifying synthesis methods and at lower temperatures. Clearly as market penetration also increases, economies of scale have the potential to lead to unit cost reduction.

Cost reductions are also being sought for other components, including electronics, enclosures and the BMS.

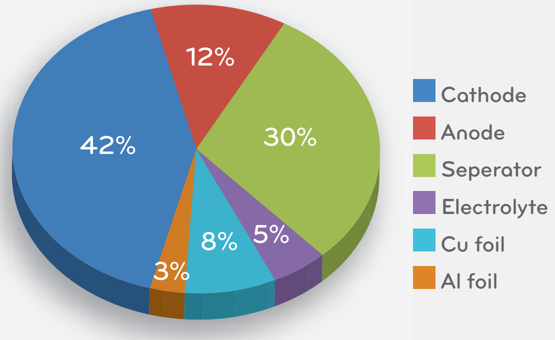
Pack cost breakdown for 25kWh EV

Whole Battery Pack



Cell cost breakdown

Cell Material Costs



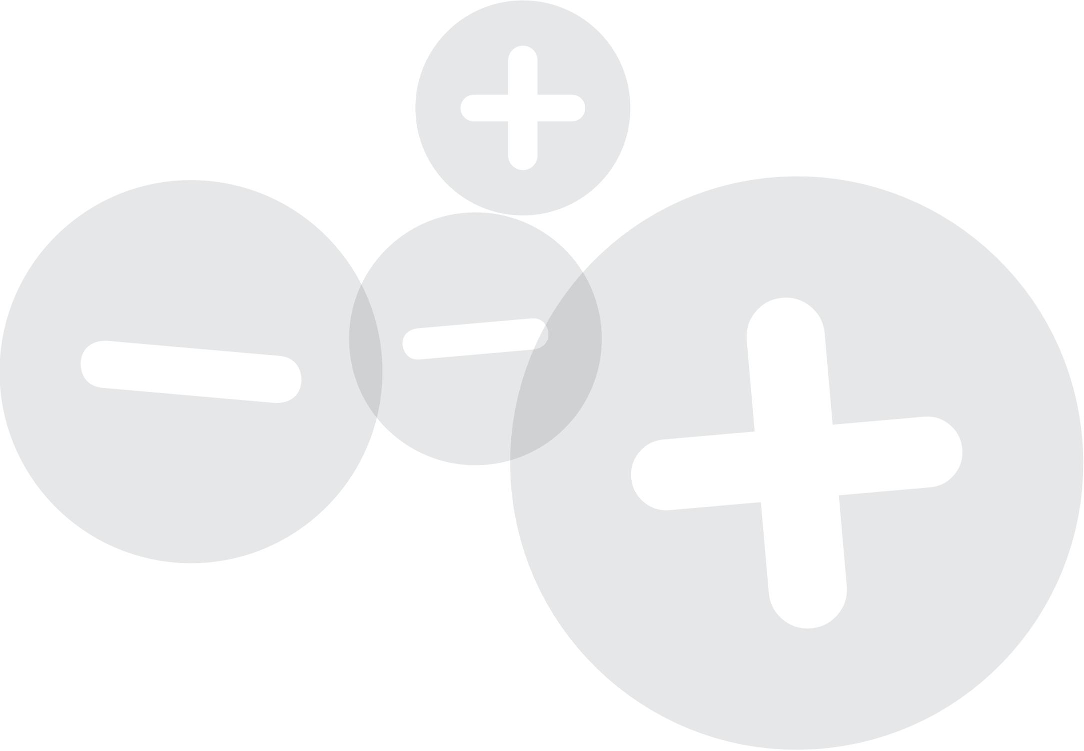
Reference: Yano Research Ltd

Battery Management System (BMS)

The Battery Management System (BMS) is an essential component within a multiple cell battery pack. It monitors the state of a battery, measuring and controlling key operational parameters, and thus ensuring safety.

The BMS has four main objectives:

+ Protect the cells and the battery from damage.
+ Prolong the life of the battery.
+ Maintain the battery in a state where it can meet the requirements of the application.
+ Interface with the host application.



Safety

Li-ion cells have high energy density so abuse of the cell can cause a thermal runaway leading to a cell fire and explosion. The single cells have safety devices and the battery has a safety circuit that monitors each cell and prevents overcharging and overdischarging. The multi-level safety system of a battery pack is described as follows:

1. Cell level safety devices:

- Current interrupt device (CID). Cells often include safety components to protect the cell from excessive internal pressure. In such a case the CID will break and electrically disconnect the cell.
- Shut down separator: The separator between anode and cathode (through which the electrolyte's ions conduct current flow) can have the ability to close its pores as a result of thermal runaway.
- Pressure vent.
- Flame retardant cover.

2. External circuit devices

- Positive Temperature Coefficient (PTC) resistors (Low power only) are resistors that exhibit an increase in resistance at a specified temperature. Such PTC-resistors are suitable for a wide range of applications, in particular including overcurrent protection devices, switches and additionally as heaters.
- Fuses.
- Cell isolation to prevent a chain reaction of cell events.

3. BMS Software

- The software monitors all key indicators coupled to control actions (Cooling, Power disconnect).
- The hardware provides a fail-safe back-up, including a switch-off in case of software failure that is set to slightly higher limits, and a battery switch-off in case the low voltage BMS power supply fails.

4. Battery installation location:

- This should be outside the passenger compartment and behind the vehicle firewall.

Cycle life

Cycle life is the number of charge/discharge cycles a battery can perform before its capacity falls below 80% of its initial rated capacity. Cycle life can also be considered as the total energy throughput during the life of the cell. The cycle life of Lithium batteries is typically at least 1,000 cycles.

There is a gradual reduction in cell performance over time due to the slow, progressive, irreversible breakdown of the active chemicals in the cell leading to loss of capacity and increased internal impedance. This is known as aging.

Cycle life is affected by different variables:

- Temperature: There is an optimum operating range of +10°C to +40°C.
- C rate (the current required to charge/discharge a cell fully in one hour): a lower C rate will increase cycle life.
- Depth of discharge: Micro-cycles or reduced depth of discharge will increase cycle life.

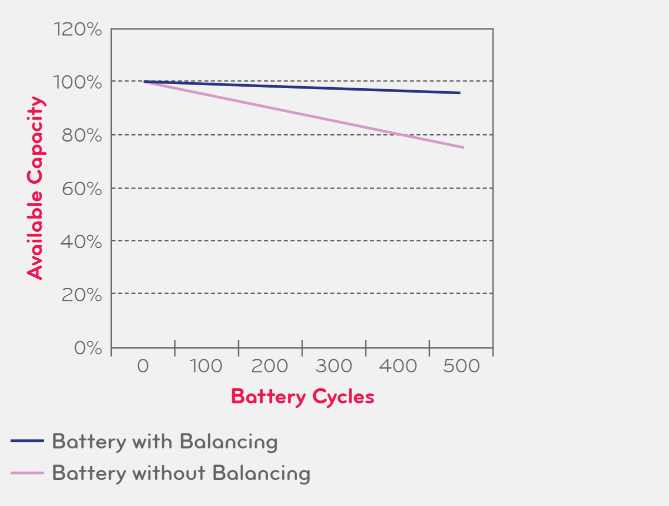
A well-designed BMS can optimise cycle life by preventing the overcharging and deep discharging the cells, which damages the cell.

Balancing

Battery packs, constructed with string(s) of high capacity cells will have an overall pack voltage equal to the average of all the cell open circuit potentials.

In an ideal pack, all cells will have very similar electrochemical performance, in terms of load profile and internal resistance. In practice this is not the case; there will always be slight variances and cells will have slightly different cell impedances. These parameters will also change with temperature, aging etc. An unbalanced cell would reach full charge sooner than others in the string causing possible premature termination of the charging process and reach end of discharge, in terms of depleted capacity and therefore low voltage, sooner than other cells within the pack. It is therefore necessary to manage cells, by balancing their state-of-charge (SOC) operational window in order to maintain optimum pack performance. An example of cell balancing is where the BMS will dynamically re-balance the pack according to a specific algorithm, selecting specific cells exhibiting characteristics by dissipating small amounts of energy in order to equalise as near as possible the cell potentials across the entire pack.

Effect of balancing on capacity



Charger basics

Charging schemes

The charger has three key functions:

- Getting the charge into the battery (Charging).
- Optimising the charging rate (Stabilising).
- Knowing when to stop (Terminating).

The charging scheme is a combination of the charging and termination methods.

Charge termination

Once a battery is fully charged, the charging current somehow has to be dissipated. The result is the generation of heat and gases, both of which are bad for batteries. The essence of good charging is to be able to detect when the reconstitution of the active chemicals is complete and to stop the charging process before any damage is done while at all times maintaining the cell temperature within its safe limits. Detecting this cut-off point and terminating the charge is critical to preserving battery life. This is particularly important with fast chargers where the danger of overcharging is greater.

Safe charging

If for any reason there is a risk of over-charging the battery, either from errors in determining the cut-off point or from abuse, this will normally be accompanied by a rise in temperature. Internal fault conditions within the battery or high ambient temperatures can also take a battery beyond its safe operating temperature limits. Elevated temperatures hasten the death of batteries; therefore monitoring the cell temperature is a good way of detecting signs of trouble from a variety of causes.

Charging times

During fast charging it is possible to pump electrical energy into the battery faster than the chemical process can react to it, with damaging results. The chemical action cannot take place instantaneously and there will be a reaction gradient in the bulk of the electrolyte between the electrodes with the electrolyte nearest to the electrodes being converted or 'charged' before the electrolyte further away. This is particularly noticeable in high capacity cells which contain a large volume of electrolyte.

There are in fact at least two key processes involved in this chemical conversion. One is the 'charge transfer', which is the actual chemical reaction taking place at the interface of the electrode with the electrolyte; this proceeds relatively quickly. The other is the 'mass transport' or 'diffusion' process in which the materials transformed in the charge transfer process are moved on from the electrode surface, making way for further materials to reach the electrode to take part in the transformation process. This is a relatively slow process which continues until all the materials have been transformed. Both of these processes are also temperature dependent.

Fast charging

Most Lithium ion cells can be charged at 1C. That means that for a 100Ah cell, it would take 1 hour to charge at 100A. 10C means a 100Ah cell can be charged at 1,000A; this would take 6 minutes to charge.

The cells typically used for EV batteries are Lithium Iron Phosphate ($LiFePO_4$) and Lithium Nickel Cobalt Manganese (NCM). These can accept at least a 1C or 1 hour charge, depending on the charger and cable infrastructure.

Batteries can be designed specifically to accept fast charging without having a detrimental effect on the battery or cells. The chemistries which accept fast charge are more likely to be Lithium Titanate Oxide (LTO). These are more expensive and have lower energy density so more of them are required to make up a battery, increasing the overall cost and size of the battery.

Off-board charger

Fast charging is not always practical. Charging a 50kWh battery in 10 minutes would require a 300 kW power supply. Domestic ring main power outlets deliver only 3 kW. A 50 Amp high current outlet delivers about 11 kW. At 11 kW it would take four and a half hours to charge the battery.

Inductive charging

Inductive charging does not require a physical connection between the vehicle and the charger or power point. Instead, electricity is transferred using an electro-magnetic field. The system works by having an inductive coil on the bottom of the vehicle and another coil located in the ground, which need to be in close proximity to each other. The main advantage is that the user does not have to plug anything in.

For vehicles on a fixed route or regular stop-start (such as buses, taxis, delivery vehicles) then the system may be useful. However, the system is only 85% efficient, there are some safety concerns and initially it is likely that the system will be more complex and expensive.

Battery exchange

Quick battery exchange is possible at dedicated battery exchange stations. This system is being adopted by some countries (including Israel and Denmark). However the range of vehicles that can use this system is limited unless all manufacturers choose to build standardized batteries, and it requires a large investment in infrastructure. Battery exchange could work for large commercial vehicles if the development of standard battery packs could be agreed between major truck manufacturers.

Charging efficiency

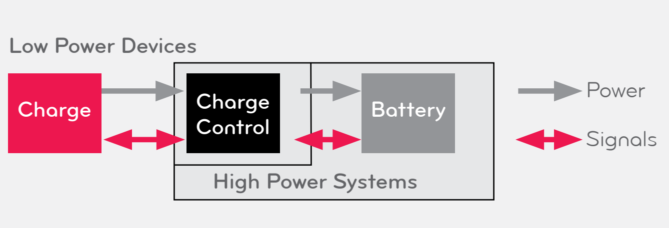
Charging generates heat and if the battery gets too hot its life is significantly shortened. Charging is typically 95% efficient, so 5% of the energy used in charging appears as heat and must be dissipated. Most of this inefficiency comes from the charging cabinet, not the cells.

Charging standardisation

It is important to ensure that the vehicle and charging infrastructure are compatible with each other. Today's standard car charging posts are in fact just electric power points, with the battery management electronics situated on the car. The industry is working on developing standard charging connectors so that vehicles can be charged at normal rates at any standard charging point.

Fast charging requires complex battery management electronics (see below), which may be too heavy to install on the vehicle and will therefore require dedicated charging sites.

Intelligent chargers



Intelligent charging involves communication between the charger and the battery to monitor the battery status. This permits faster charging by controlled working to the battery's performance limits. (Dumb chargers have arbitrary or excessive safety margins)

The charge control unit implements the charging scheme and cuts off the charger at the appropriate termination point, protecting the battery from over-charging or excessive temperature or current flow. It can also incorporate short stabilisation periods during charging to allow for the reaction gradient.

Low power portable devices usually provide the application with a dumb battery to save weight and space and put the charge controller in the charging unit.

In high power systems, safety is more important than portability and they are more likely to use dumb chargers with all the intelligence in the battery so that the battery can protect itself from user errors and abuse during both charging and discharging.

On or off-board charging?

This question causes great debate amongst most EV manufacturers when in reality it comes down to a few simple specification requirements.

1. What type of vehicle are you charging?

If it is a small city car which has a 10-20kWh battery then a single phase 13A domestic supply would be adequate. This is a relatively small device which probably will be on-board. If the battery and vehicle are larger then there are options for both on-board and off-board.

2. What charge time is required?

If a fast or rapid charge is required then even for a 10-20kWh battery, the charger will be relatively heavy and large, and it will also require higher levels of cooling. Therefore an off-board is the likely solution.

3. Is charging always done at one location or at a customer depot?

If charging is always done at the same location then an off-board charger can be considered rather than carrying the charger around.

4. Is there space on the vehicle?

Obviously if there is no available space on a vehicle then it will have to be off-board. Alternatively a smaller charger with an increased charge time may be appropriate for times when the vehicle cannot get back to base or only a 13A supply is available.

5. What is the fleet size?

For fleets of 5 or more vehicles, then there is the opportunity to share off-board chargers between vehicles so the ratio does not have to be 1 to 1 charger to vehicle. This will save money.

Installation of chargers

This applies mainly to off-board chargers but has to be considered for on-board also. Off-board chargers can be reasonably large and heavy so position and installation of the chargers is important and has to be planned before hand.

They have to be close to the vehicle (less than 3m). They also should be positioned close to the buildings power distribution circuit to reduce the length of cable. Chargers can draw very large current (415V, 3 phase, 270A per phase) so cable and installation costs can be tens of thousands of pounds and stretch the available power resources of the facility.

Chargers have to be positioned where their controls are easily reached but protected from damage by material handling equipment and vehicles. Adequate ventilation has to be provided as larger chargers require a lot of forced air cooling. Because of this they can be noisy so they should not be located in quiet areas.

On-board charges require single or 3 phase mains power to be connected to the vehicle. Appropriate plugs and sockets must be used and installed to meet current building and IEE regulations.

Other battery issues

Definition of end of life
For a cell and therefore battery, the end of life is considered to be when a battery has reached 80% of its original capacity. A driver of an EV will begin to notice that the range has reduced or more likely that the fuel gauge is closer to zero than it used to be when they finish their journey (EV drivers will not regularly drive a vehicle until it runs out of fuel).

Batteries should continue to deliver at least 80% capacity after 1,000 charge/discharge cycles, which is typically up to 100,000 miles. This would equate to 8-10 years of use.

Re-use
End-of-life batteries could have a secondary life in shorter-range vehicles, grid load levelling and renewable energy systems as well as localised energy storage and micro-grid in developing countries. This would require the battery to be re-furbished, possibly replacing some cells but reusing the housing and electronics. Alternatively the batteries could be stripped down to cell level. From that batteries could be re-manufactured using the key parts such as cells, BMS, wiring harnesses, fuses, contactors etc.

Recycling
While lead from lead acid batteries is the world's most recycled material (over 90% of all batteries), the volume of Lithium recycling is still very small. Lithium-ion cells are considered non-hazardous but they contain elements that can be recycled. These include metals (copper, aluminium, steel, manganese, cobalt and iron) as well as plastics. Several methods to limit the reactivity during recycling are currently in use, though still on a small scale. These include low temperature (-180°C) recovery, room temperature recovery in inert gases and high temperature recovery.

All battery suppliers must prove compliance with 'The Waste Batteries and Accumulators Regulations 2009'. This is a mandatory requirement, and requires that manufacturers take back batteries from continuing customers for suitable disposal and recycling.

Transport of Dangerous Goods
It is mandatory that any lithium cells used in a battery have passed the UN transportation testing standard ST/SG/AC.10/27. This comprises eight tests covering, altitude, thermal, vibration, shock, external short circuit, impact, overcharge and forced discharge. This is to ensure safety and it is essential otherwise cells and batteries cannot be legally transported.

Battery manufacturers must be fully conversant with UN transportation regulations for Lithium batteries and have approved dangerous goods signatories on site to ensure they can meet all of the transport regulations for air, sea and road freight.

Glossary

Ah
The Ah or Ampere/hour capacity is the charge a battery can provide over a specified period of time, e.g. 100Ah means the battery can provide 10 Amps for 10 hours or 100 Amps for 1 hr.

Anode
Negative electrode or terminal on a battery; the electrode of an electrochemical cell at which oxidation occurs.

Battery
A number of cells connected together in series or parallel strings.

Battery Management System
The electronics package that maintains safe operation, controls the battery and extends its life and durability. A good BMS is key to the successful exploitation of lithium-ion battery cells.

Cathode
Positive electrode or terminal on a battery; the electrode of an electrochemical cell at which reduction occurs.

Cell
A combination of two electrodes arranged so that an overall oxidation-reduction reaction produces an electromotive force.

C-rate
Used to signify a charge or discharge rate equal to the capacity of the cell or battery divided by 1 hour e.g. 1C for a 100Ah cell would be 100A, C/2 would be 50A and 5C would be 500A.

Cycle
A full charge and discharge of the battery is 1 cycle.

Cycle life
The number of cycles completed until the battery has reached 80% of its original capacity, typically 1,000-2,500 cycles.

Electrolyte
A non-metallic ionic conductor between the positive and negative electrodes of a battery.

EV
Electric Vehicle – a vehicle powered solely by electricity.

E-REV
Extended range electric vehicle – a vehicle where the battery propels the vehicle and the internal combustion engine is a back-up generator, providing hundreds of additional miles of mobility. The propulsion technology is always electric.

HEV
Hybrid Electric Vehicle – a vehicle with more than one power source, such as an electric motor and an internal combustion engine.

ICE
Internal combustion engine.

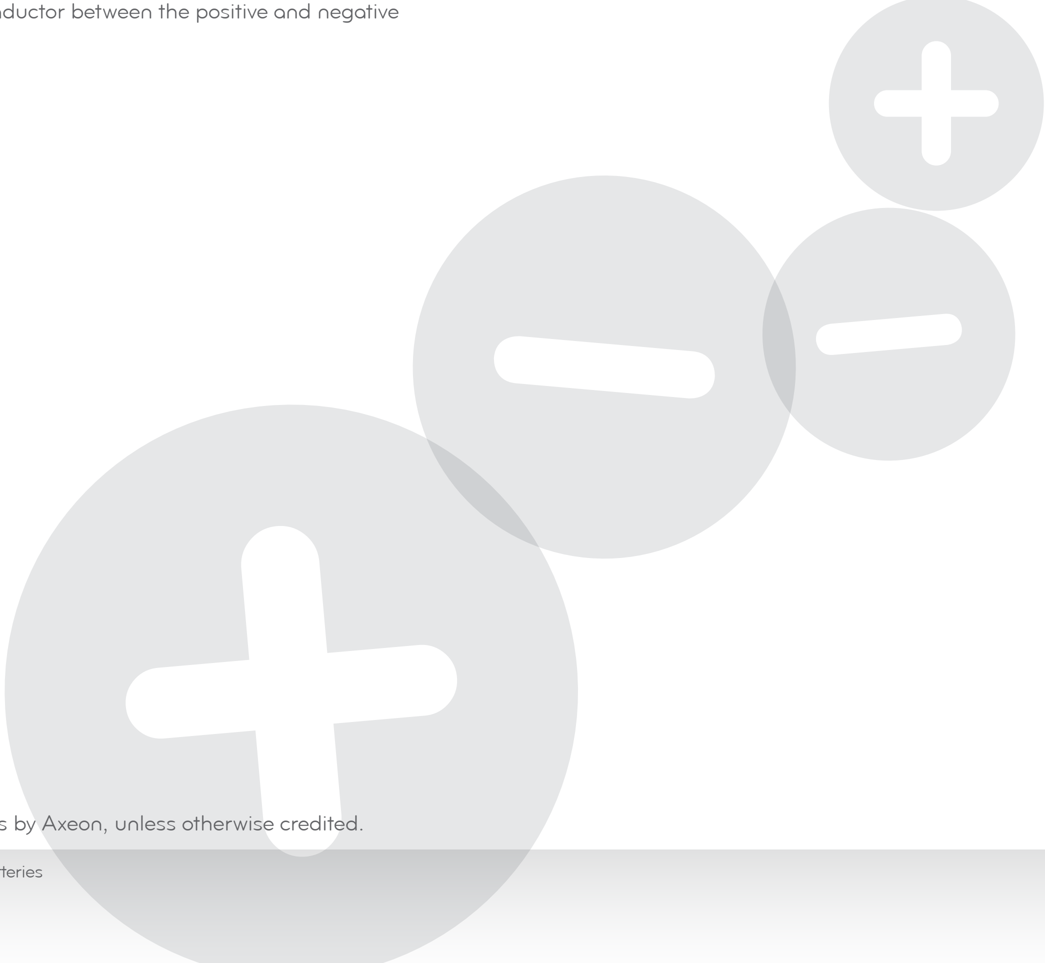
kWhr: kilowatt hour
A unit of energy equal to the work done by a power of 1,000 watts operating for one hour. This is the measure of the battery energy. This is determined by multiplying the battery voltage by the Ah capacity, e.g. a 3.2V 200Ah cell has an energy of 640Wh, whereas a 256V 200Ah battery has an energy of 51.2kWh.

Primary battery
A battery that cannot be re-charged.

PHEV
Plug-in Hybrid Electric Vehicle – a hybrid vehicle that has additional batteries that can be recharged by plugging them into an electrical outlet. The vehicle will revert to an internal combustion engine once the battery range has been used.

Secondary battery
A battery that can be re-charged.

Separator
Physical insulator between the anode and the cathode; is porous to allow ionic transfer.



All figures and diagrams by Axeon, unless otherwise credited.

Why Axeon?

- Axeon is a world-leading battery systems integrator. We design and manufacture batteries and battery management systems for three main sectors: automotive, powering clean electric vehicles; power tools, enabling new cordless tools that deliver more power with less weight; and mobile power, delivering energy for innovative new products.
- Axeon's Electric and Hybrid Electric vehicle (EV and HEV) battery and charger systems are designed and manufactured to exacting automotive standards by drawing on many years of battery experience. Currently these batteries have a range of up to 140 miles from a single charge and with stored capacity ranging from 5 kWh to 180 kWh. Vehicles powered by Axeon's batteries had by mid 2010 driven around a million miles on European and US roads.
- Axeon continues to invest in R&D to make better batteries, improve battery technology, reduce cost and increase performance.

Visit www.axeon.com for more details and to contact us to discuss your battery needs.

In order to design an automotive battery and charger, the following information is required:

Nominal Voltage	V
Maximum Voltage	V
Minimum Voltage	V
Target battery capacity in kWh	kWh
Nominal discharge current	A
Peak discharge current and duration	A sec
Nominal charge current	A
Peak charge current	A
Maximum dimensions	mm
Maximum weight	Kg
Is it EV, HEV or PHEV application	–
Vehicle Type i.e. delivery truck, city car	–
Battery location i.e. under vehicle, internal	–
Degree of waterproofness	–
Expected production volumes	–
Target price	–
What specific approvals are required	–
Is a charger required; if so, on or off board	–
Required charge time	Hr

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