Johnson Matthey
Battery Systems

Our Guide to Batteries

3rd Edition

Introduction

Welcome to the 3rd edition of 'Our Guide to Batteries'. This guide has been created with the input of our experienced team of battery professionals who are ready to assist you with your future battery requirements, whatever they may be.

Johnson Matthey Battery Systems is a leading independent provider of battery design, development and supply for demanding automotive applications, such as performance hybrids and PHEVs. We also manufacture high volumes of batteries for e-bikes, power tools and mobile technologies. Our recently formed Battery Materials group are focused on the development and manufacture of advanced materials for the battery market.

We have a market-leading technology for managing Lithium-ion batteries, delivering safe, durable performance. Our UK operation focuses on the design and manufacture of large-scale high voltage automotive grade battery systems for Electric and Hybrid Electric vehicles and batteries for mobile power products. In Poland we design and manufacture high performance battery packs for the professional cordless power tools and electric bike markets.

We are part of the Johnson Matthey group, a leading speciality chemicals company underpinned by science, technology and its people. A leader in sustainable technologies, many of its products enhance the quality of life for millions of people around the world. Johnson Matthey has five divisions: Emission Control Technologies, Process Technologies, Precious Metal Products, Fine Chemicals and New Businesses. Part of the New Businesses division, Battery Technologies comprises Johnson Matthey's R&D programmes in advanced battery materials and Johnson Matthey Battery Systems.

Contents

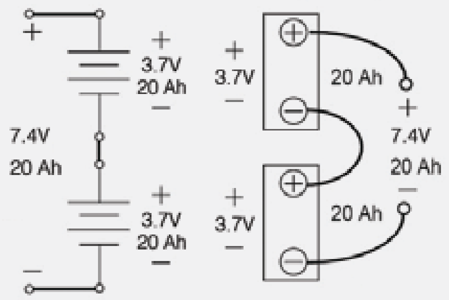
Batteries

Automotive batteries are comprised of hundreds of individual elements, of which the electrochemical cells are the vital energy storage component.

By performing detailed application analysis it is possible to select the most appropriate cell chemistry and form factor to provide the most optimised technical solution for any given application. There are many cell chemistry types and topologies available and described in detail later on page 6.

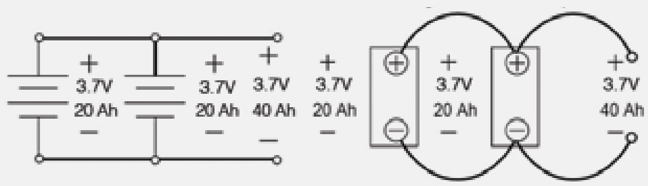
In order to build battery sub-modules and total pack solution, the selected cells will need to be connected in such a way to achieve the desired voltage and capacity for the application. The range of battery applications that can be designed spans from low-power low-energy small batteries for leisure and medical uses, to high-power high-energy larger batteries for use in electric and hybrid electric vehicles.

Series connections:
Voltages Add, Capacity is Constant



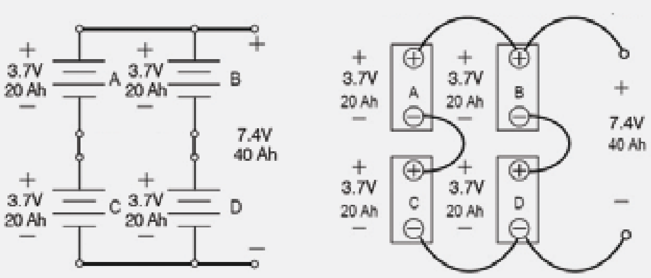
Adding cells in a series connection increases the voltage by the value of the cell. In the example above, two 3.7V cells have been added together to increase the voltage from 3.7V to 7.4V.

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 energy storage cells there are a wide range of other vital components required within the battery system architecture. Some of the key battery elements are shown below.

Cells
For automotive batteries, the most promising and attractive technological solutions utilises Li-ion cells. See section on Cells for more details (page 6).

Busbars
These are highly conductive metallic bars used to connect the cells and/or modules together electrically.

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

Battery Management System (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 (page 14). In some cases, a master and slave architecture is used for the electronics.

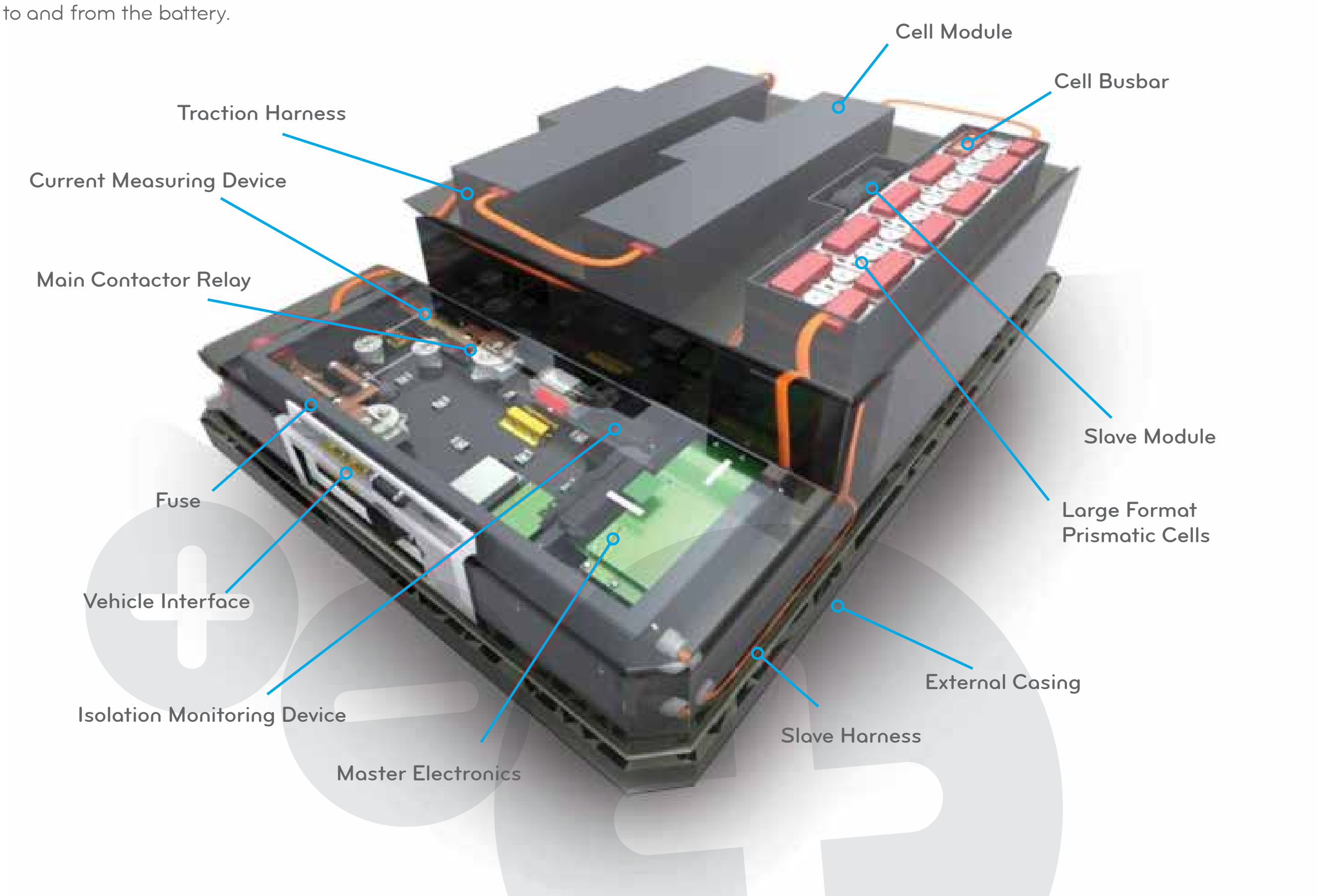
Traction cable
A high voltage and current carrying cable that interconnects the cell module strings together into a circuit able to deliver the main power to and from the battery.

Vehicle interface
A specific connection between the battery and the vehicle. Typically communication from vehicle to battery is via information transferred by CAN-BUS, an automotive standard communications protocol. Information may include parameters such as state of charge (fuel gauge), battery voltages and temperatures, etc.

Current measuring device
This allows the BMS to monitor the instantaneous current loads delivered and accepted by the battery during charge and discharge.

Isolation monitoring device
A device to check the high voltage insulation of the battery system so that any insulation issue would be detected and allow the battery to be disconnected should there be a need to make it safe.

Main contactor relays
The main high voltage switches on the battery, which turn 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. A cell can be either primary (single-use) or secondary (rechargeable).

The chemical energy of the cell contained in its active materials can be converted directly into electric energy by means of electrochemical oxidation-reduction (redox) reactions.

The electrochemical cell typically comprises of two electrodes, a positive and a negative, on which the redox reactions occur while in contact with the electrolyte. The electrodes are electronic conductors (such as a metal or carbon) or semiconductors. Current flows through the electrodes via the movement of electrons, while the electrolyte is an ionically conducting but electrically insulating charge transfer phase.

Cell potential

Cells 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).

Rechargeable cells

There are a wide variety of electrochemical cells available, these are described in more details on pages 8 to 12. The principal of operation of the electrochemical cell described here is based on Li-ion cell technology, for which many discrete chemistries exist and will be explained in detail later on page 10.

Conventional Lithium-ion cells typically operate by the principle of intercalation – in which lithium ions are incorporated into the structure of the electrode material without inducing a major structural change within it.

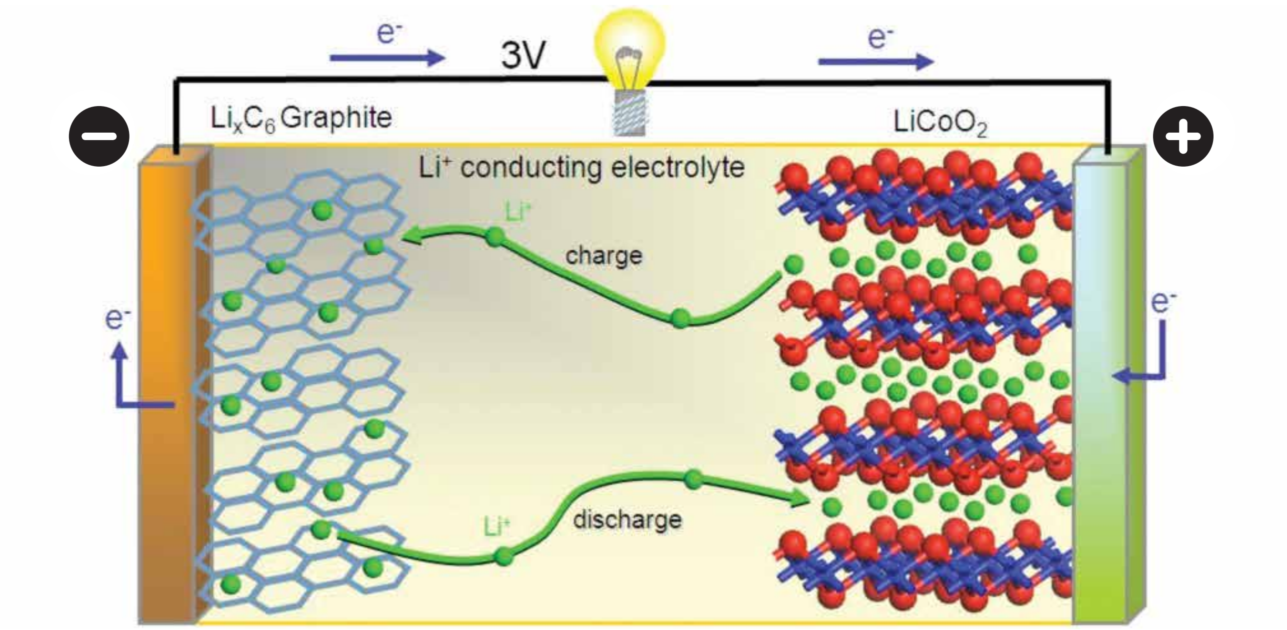
1: The negative electrode

In the discharge process, the negative electrode gives up electrons to the external circuit and is oxidised during the electrochemical reaction. A simultaneous electrochemical reaction takes place at the positive electrode. In the charge process, the negative electrode is electrochemically reduced.

Most commercial Li-ion cells currently employ a carbon/graphite based electrode. In an attempt to improve certain cell performance and capabilities the use of Silicon based negative electrodes or lithium titanate based electrodes have also be used and described in more detail on page 10.

2: The positive electrode

On discharge, the positive electrode accepts electrons from the external circuit and is reduced during the electrochemical reaction. On charge, the positive electrode is oxidised and gives up electrons. The positive electrode of Li-ion cells are usually a Lithium transition metal oxide or phosphate. Specific battery chemistries are usually named according to the material used for the positive electrode, e.g. LCO for cells containing Lithium Cobalt Oxide positive electrodes (with exception of lithium titanate negative electrode cells, termed LTO).

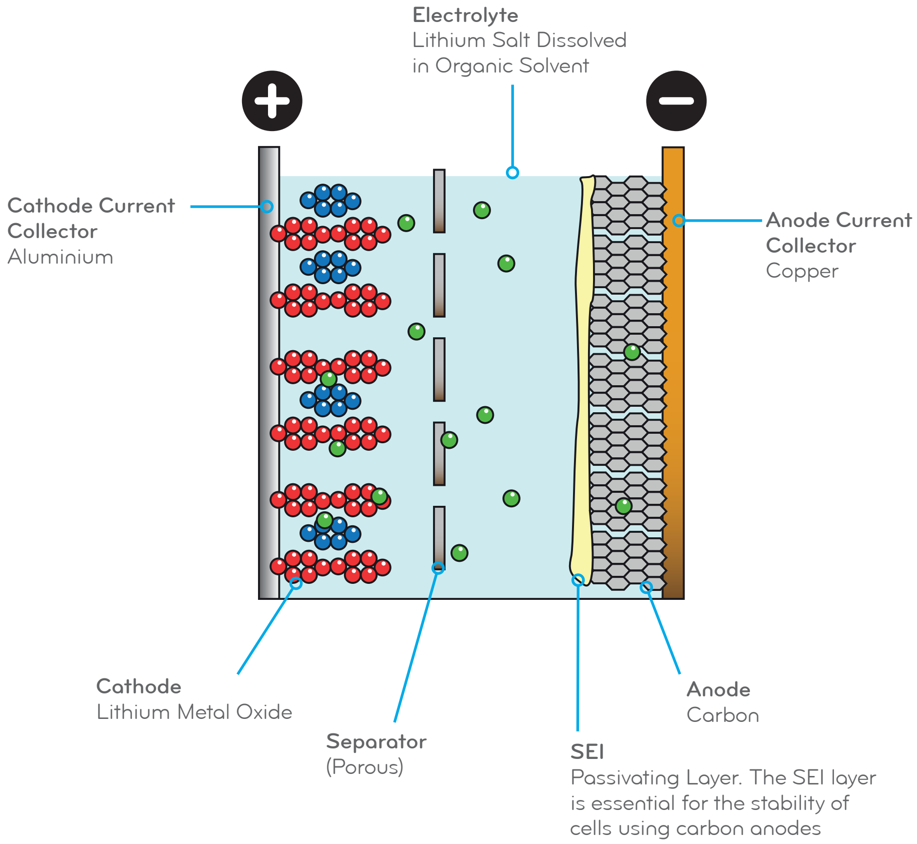


3. The electrolyte and separator

Is an ionic conductor but an electronic insulator, providing the medium for charge transfer inside the cell between the negative and positive electrodes. For Lithium-ion batteries, the electrolyte is typically a non-aqueous organic 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. The separator is mostly a microporous layer consisting of either a polymeric membrane or a non-woven fabric mat. A 'ceramic separator' has become more popular nowadays. This may be a porous mat made of ultrafine inorganic particles bonded using a small amount of binder or a conventional separator material coated with a thin layer of inorganic material. These separators have good thermal stability and exhibit zero-dimensional shrinkage and are therefore highly desirable for the development of Li-ion batteries for applications in which high safety is critical, e.g. in hybrid and electric vehicles.

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.

All solid state cells using ceramic electrolyte systems are in development with a view to eliminating any liquid phase, providing greater stability and safety whilst attempting to minimise the impact on power due to low inherent ionic transport performance.



Types of cell construction

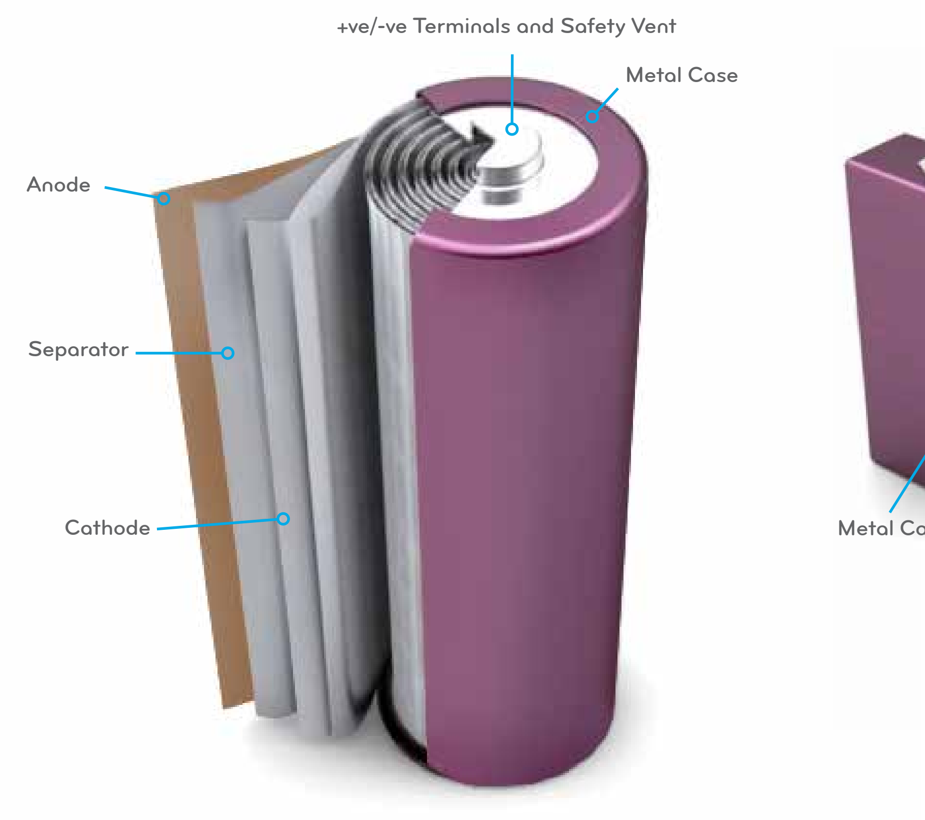
The energy storage materials and the overall cell chemistry has a large role to play in determining the overall cell performance. However, Lithium ion cells are available in a range of form factors where the cell engineering also has a role to play in influencing overall cell and therefore battery performance in the end application. The energy storage cells need engineered supports and retention systems to connect and retain them in the battery pack structure.

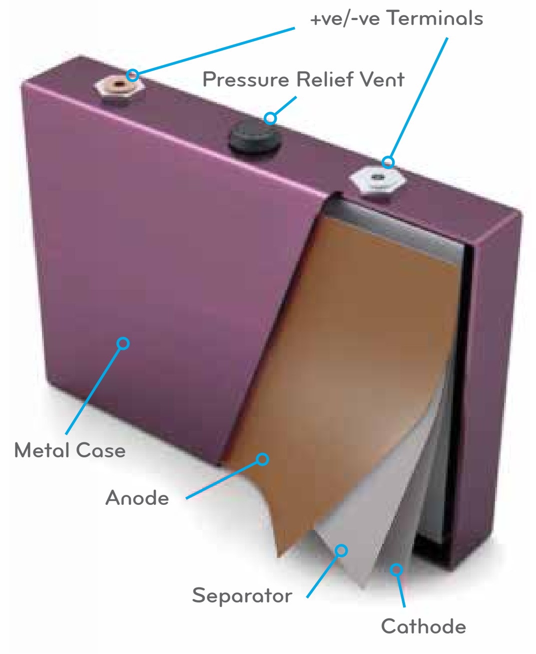
1: Cylindrical

Cylindrical metal case
The most commoditised form of lithium ion cell is that of the small cylindrical cell type. The most common variant being the 18650 format, so called due to being 18mm in diameter and 65mm long, being the most mature and used in many forms of consumer applications including laptops, power tools and E-Bikes. A wide range of 18650s are available, optimised for power and/or energy against the target applications. A degree of engineering is then required to construct a battery pack from the discrete cells taking into account interconnection and thermal management requirements. The cells may contain internal safety features such as over-temperature and pressure cut off features.

2: Prismatic

Prismatic metal case
Aluminium or steel cans are typically used as housing of prismatic lithium-ion cells. The metal case ensures structural stability, mechanical robustness and humidity protection. In addition, it allows the use of safety features such as pressure relief vents, which are not possible to be used in pouch cells. In some cases, prismatic cells may allow packaging to be more efficient than cylindrical cells because of their form factor.

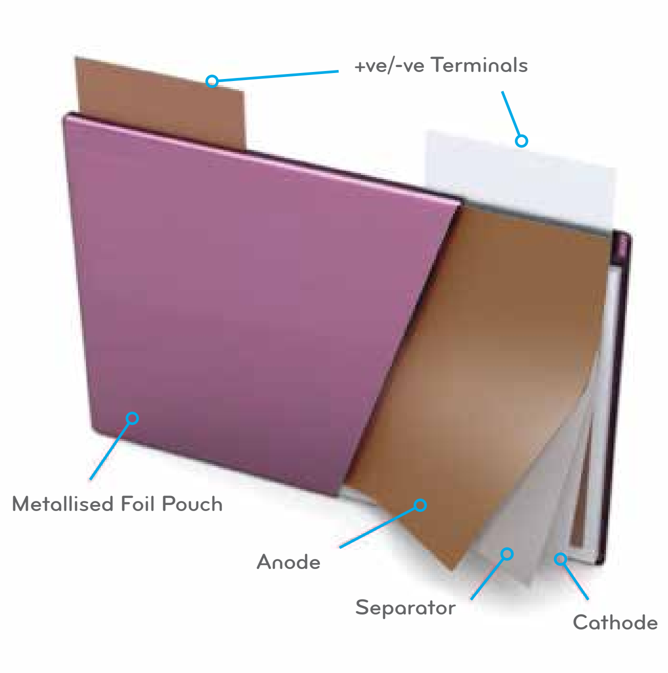




3: Pouch

Pouch cell
Pouch cells are cells where the internal electrode stack is contained within a soft plastic-aluminium package. Current collectors are welded internally to terminal tabs that protrude through seals to allow external connection.

The minimising of cell packaging material makes pouch cells attractive over metal body prismatic cells due to potentially higher energy density for the same chemistry type, but will typically require complex module structure in order to constrain and retain the cells in the pack structure. The large surface area may be beneficial for thermal management.



Variety of cell formats

Traditional battery and cell chemistries

There are a wide range of different cell chemistries that offer different voltages, power and energy performances. Lithium-ion cells have considerably greater energy density than previous chemistries, making them particularly suitable for automotive applications. They are also considered safer, less toxic, and are more 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.

Lead-acid 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 and good charge retention for intermittent charge applications.

This chemistry is used in starter batteries for internal combustion engine (ICE) vehicles. However the cell chemistry is of low energy density making Lead-acid batteries heavy for the same amount of energy compared to other cell chemistries.

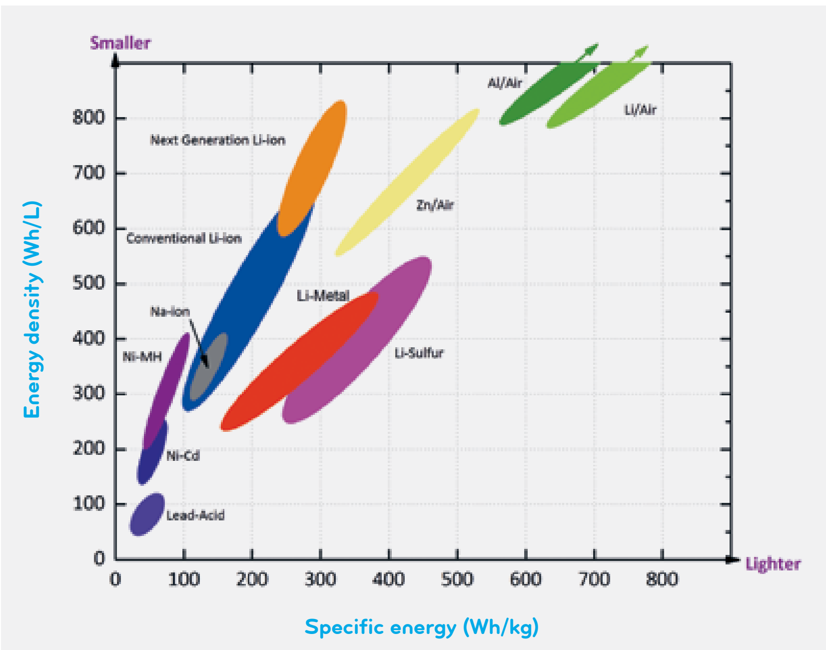
Cell components are easily recycled. Because of the irreversible physical changes in the electrodes, failure occurs between several hundred and 2,000 cycles. The main drawbacks of these batteries are their comparatively low energy density, long charging time and the need for careful maintenance.

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). It still dominates the stop-start battery and e-bike battery market. With continuous improvement and the development of the advanced Lead acid battery, it will remain competitive.

Nickel Cadmium (NiCd)

These cells use nickel hydroxide $Ni(OH)_2$ for the cathode, cadmium Cd as the anode and an alkaline potassium hydroxide for the 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 oxidised to form protons. The electrolyte is alkaline, usually potassium hydroxide.

Nickel Metal Hydride cells have higher energy density 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. It was the main choice for mild and strong hybrid electric vehicles. However, lithium-ion batteries are gradually taking the market.

Sodium Nickel Chloride (Na-NiCl)

The so-called ZEBRA battery, which operates over 270°C, utilises molten sodium tetrachloroaluminate ($NaAlCl_4$), which has a melting point of approximately 160°C, as the electrolyte. The negative electrode is molten sodium. The positive electrode is nickel in the discharged state and nickel chloride in the charged state.

The ZEBRA battery has a specific energy and power of 90Wh/kg and 150W/kg. The liquid electrolyte freezes at 157°C, and the normal operating temperature range is 270-350°C.

The b-alumina solid electrolyte that has been developed for this system is very stable, both to sodium metal and the sodium tetrachloroaluminate.

When not in use, ZEBRA batteries are typically kept molten, in order to be ready for use when needed. If shut down, the reheating process lasts 12 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. The applications include traction batteries, EVs, HEV and railway application.

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, as well as long cycle life and thermal stability for increased safety. Attention has also focused on fast charge capability as well as cost reduction, through the use of inexpensive raw materials, synthetic processes and using materials of low toxicity and environmental banality.

Research and development has focussed on many aspects of cell chemistry to improve overall performance. However, large attention has been placed on positive cathode materials development as it has a large role to play in determining overall specific energy density.

Comparison of different cell chemistries

Application	Unit of measurement	Lead acid	NiCd	NiMH	Lithium-ion
Cell Voltage	Volts	2	1.2	1.2	2.4-3.8
Specific Energy	Wh/kg	30-40	35-80	55-110	100-300
Energy Density	Wh/l	50-90	50-70	160-420	125-600+
Power Density	W/kg	100-200	100-150	100-500	500-5000
Maximum Discharge	Rate	6-10C	20C	15C	80C
Useful Capacity	Depth of Discharge %	50	50	50-80	>80
Charge Efficiency	%	60-80	60-80	70-90	>95
Self-Discharge	%Month	3-4	15-20	15-30	2-3
Temperature Range	°C	-40 to 60	-20 to 70	-20 to 65	-30 to 70
Cycle Life	Number of cycles	200-400	300-1000	500-1000	>2000
Memory Effect		No	Yes	Yes (<NiCd)	No
Micro-Cycle Tolerance		Deteriorates	Deteriorates	Yes	Yes
Robustness (Over/under Voltage)		Yes	Yes	Yes	Needs BMS

Lithium ion cell chemistries and variants

Lithium Cobalt Oxide (LCO) – *$LiCoO_2$*
Lithium Cobalt Oxide has been the most widely used positive electrode material in lithium batteries for many years, being used for laptop, mobile phone and tablet batteries. LCO cells provide moderate cycle life (<500 cycles) and energy density. However, the chemistry is less thermally stable than other transition metal oxide or phosphate chemistries under extreme abuse conditions such as cell puncture or short circuit making them more susceptible to thermal runaway conditions. These characteristics limit the use in Electric and Hybrid Electric Vehicles.

Lithium Cobalt Aluminium Oxide (NCA) – *$LiNiCoAlO_2$*
Lithium Nickel Cobalt Aluminium Oxide offers high specific energy density and reasonably good power capabilities. NCA cells are considered somewhat safer than $LiCoO_2$. NCA cells tend to have a superior life characteristic to LCO and is more commonly available in some 18650 type cells than in large format automotive cells.

Lithium Iron Phosphate (LFP) – *$LiFePO_4$*
Phosphate-based technology lithium ion materials possess improved thermal and chemical stability than oxides and are generally perceived to be a safer cell chemistry than other Lithium-ion technologies and less susceptible to thermal runaway under abuse conditions. The phosphate binds the oxygen more closely than in oxide systems providing a degree of inherent stability. Automotive lithium ion cells are also durable and stable to long term cycling.

Although Lithium iron phosphate batteries have lower energy density than Oxide systems they are typically able to support higher currents and thus suited to high power and longer life applications. They are a significant improvement over lithium cobalt oxide cells in terms of the cost, safety and toxicity.

Lithium Manganese Oxide Spinel (LMO) – *$LiMn_2O_4$*
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 rate capability. However, they suffer from lower overall capacities as a result of their spinel structure and are unstable at higher temperatures in Li-based electrolyte.

Lithium Nickel Cobalt Manganese Oxide (NCM) – *$LiNi_xCo_yMn_zO_2$*
Although no single cell chemistry currently ticks all the boxes of energy, power, cost, safety and life, the mixed metal oxide systems and in particular those based on NCM type chemistry can be optimised to give high specific energy and/or high specific power whilst being considered safer and more cost effective than LCO and LFP but with reasonable life expectation.

Lithium Titanate Oxide (LTO) – *$Li_4Ti_5O_{12}$*
These cells replace the graphite negative electrode with lithium titanate. This negative electrode material is compatible with any of the above positive electrode materials, but is commonly used in conjunction with Manganese-based materials. They offer superior rate capability and power combined with wide operating temperature range. They are considered a safer alternative to the graphite material due to higher potential vs Li/Li^+ than conventional Graphite and therefore have a degree of inbuilt overcharge protection. Also they are a 'zero-strain' insertion material that does not form a large passivating Solid Electrolyte Interface (SEI) layer with the electrolyte, thus giving rise to high coulombic efficiency and long cycle life. However, lithium titanate batteries tend to have a slightly lower energy density than graphite based systems.

Main Li-ion cell variants

	Cell level specific energy (Wh/kg)	Cell level energy density (Wh/l)	Typical power (C-rate)	Approx. safety thermal runaway onset	Typical nominal potential (V)	Typical temp. range (ambient)	Year of introduction into market
LCO	175-240	400-640	~1C	150°C	3.6	-20 to 60°C	1991
NCA (EV)	130-240	490-670	2-3C	150°C	3.6	-20 to 60°C	1999
LFP (EV/PHEV)	90-150	190-300	5C cont 10C pulse	270°C	3.2	-20 to 60°C	1996
LFP (HEV)	70-110	100-170	30C cont 40C pulse	270°C	3.2	-30 to 60°C	1996
NCM (EV/PHEV)	100-200	260-400	3C cont 6C pulse	210°C	3.7	-20 to 60°C	2008
NCM (HEV)	70-100	150-200	10C cont 40C pulse	210°C	3.7	-20 to 60°C	2008
LTO	90-130	170-230	10C cont 60C pulse	Not susceptible	2.4	-30 to 75°C	2008
LMO (EV/PHEV)	150-240	240-360	3-10C	250°C	3.8	-20 to 60°C	1996

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 be achieved with the use of new materials as well as the establishment of standardisation.

+ 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 10-15 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, and new technologies.

Improved safety: Safety is always one of the most important concerns about lithium-ion batteries. Short circuits, thermal runaway and other potential safety issues need to be prevented. The development of new electrode materials, electrolyte systems, and separator technology as well as lithium-ion cell electrolyte additives will help to improve safety. 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 development of new materials for the electrodes. Some potential replacements are outlined below.

Silicon

+ The use of silicon containing negative electrode materials is seen as an attractive route to increased cell energy density.

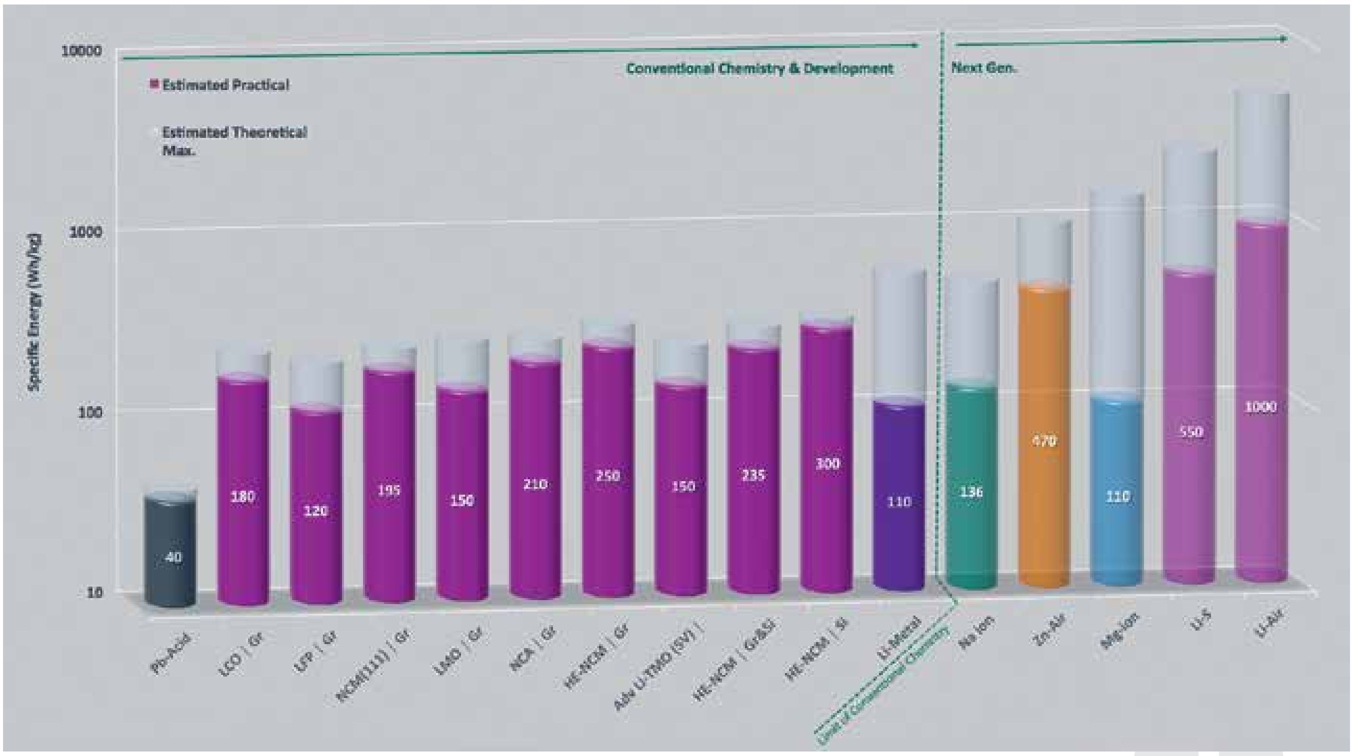
+ On charge and discharge the silicon reversibly alloys with large numbers of lithium ions. However the process typically results in a large volume expansion at particle level. This may limit cycle life if not addressed through the use of novel and stabilised electrolytes. Although only thus far considered for non-automotive consumer electronics type applications where the cycle life requirements are less challenging and used as a smaller percentage in the anode composite, going forward technology development may enable the use of such materials in larger amounts and for automotive applications to energy higher energy density cells.

HE-NCM

+ Often referred to as 'High Energy-NCM' or 'Overlithiated-NCM' these materials are composite Ni, Co, Mn-oxide based materials that contain electrochemically inactive ($Li_2M'O_3$) component, integrated with an electrochemically active ($LiMO_2$) component to provide improved structural and electrochemical stability.

+ These materials may offer a route to high energy density, high cell voltage, long cycle life as a cost effective solution.

Secondary cell technology: theoretical vs practical specific energy



Development of cell chemistries continued

Advanced high voltage Oxides and Phosphates

- One target for the next generation of Lithium-ion batteries is to increase the operational voltage, if possible into the region of up to 5V.
- Olivine-based phosphates systems ($LiMPO_4$ where M = Mn, Ni) are in development that operate at such higher voltage and are therefore able to store more energy compared to conventional materials.
- In terms of oxides there is considerable investigation of spinel, $LiNi_{0.5}Mn_{1.5}O_4$ type materials. This material may be cost effective and has attracted a wide range of interest as a 5V cathode material with high energy and high power.
- When used in conjunction with lithium titanate anode materials in full cells systems, such material combinations may offer stable and tolerant cells, exhibit very long life, improved safety as well as high power capabilities with good energy density.

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.
- Usually primary and used for hearing aids.

Lithium-Sulphur Cells

- Potentially a longer term attractive candidate for high energy EV batteries assuming some of the challenges to enabling the technology can be solved. Li-S cells are relatively stable to electrical and mechanical abuse as has good tolerance to elevated temperatures.
- The high energy density coupled with low cost nature of the materials making the technology highly attractive.
- However, many years of development have not yet solved fundamental issues of poor cycle life and self-discharge caused by the discharge products (lithium thiolate) being soluble in the electrolyte.

Lithium-Air Cells

- Although currently only at early R&D stages, lithium-air cells potentially offers 5 to 10 times the energy density of today's Lithium-ion cells.
- Attempts have been made to achieve rechargeable non-aqueous systems by the use of a porous composite carbon based electrodes with imbedded redox catalyst. Practical cells require sophisticated oxygen selective membranes that allow O_2 molecules to pass within the cell but are impervious to water and electrolyte.
- This is a fledgling technology that still requires considerable research effort to achieve a commercially-viable cell that has the efficiency to lasts the thousands of cycles required for automotive applications.

Sodium Ion Cells

- A type of battery uses sodium ions as charge carriers. Considered a low cost sustainable alternative to Lithium ion due to the abundant nature of Sodium. May only be applicable in certain types of application due to the marginally lower energy density an perceived lower rate capability than lithium-ion alternatives.
- The material chemistry and synthetic routes to manufacture energy storage devices are in principal closely related.

Other energy storage technologies

There are other available forms of energy storage for automotive and non-automotive applications. These include, but are not limited to the following alternatives:

- Flywheels – A rotor is spun at high speed to store energy mechanically in the form of rotational energy. Electrical energy converted to and from the flywheel rotor.
- Redox Flow Batteries – a rechargeable energy storage system in which all the electrochemical components are dissolved in liquid and the charge/discharge reaction occurring over a membrane.
- Fuel Cells – Electrochemical energy storage system where for automotive it is generally hydrogen based energy storage. Current commercially available fuel cell automotive vehicles include the Toyota Mirai, Hyundai Tucson and Honda FCX Clarity. Johnson Matthey is also active in the fuel cell energy storage sector, for more information please see the website below:
- JM Fuel Cells http://www.jmfuelcells.com/

Material availability

Concerns are sometimes raised about the availability of the materials necessary for the construction of large-format automotive batteries. However, the current estimates of worldwide Lithium reserves total about 13.5 million tons (or 39.5 million tons of Lithium resources). Around 0.3 kg of lithium is required per kWh of battery storage. The U.S. Geological Survey produced a reserves estimate of lithium in early 2015, concluding that the world has enough known reserves for about 365 years of current global production of about 37,000 tons per year.

Lithium can also be extracted from sea-water (seawater has an average Lithium concentration of 0.17ppm). Currently this is prohibitively expensive.

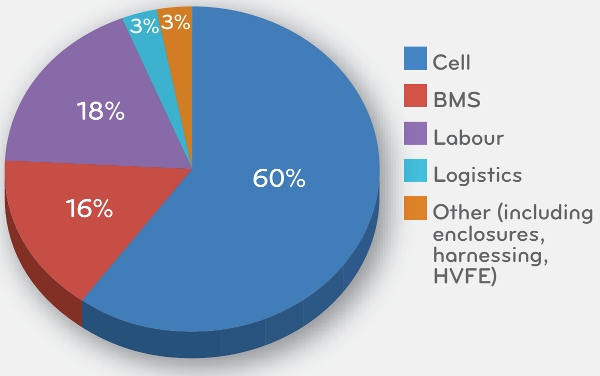
Cost of various parts

The most expensive components of an automotive battery pack is 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 also as market penetration 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.

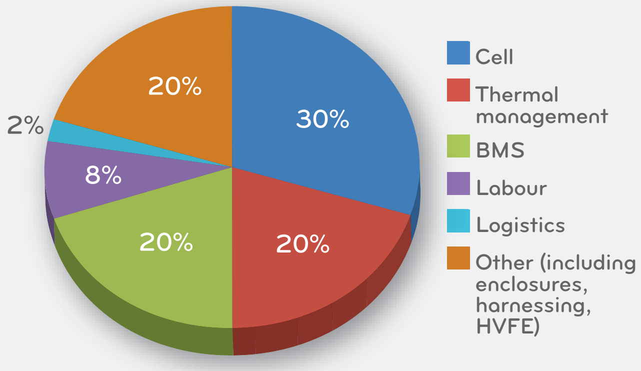
Pack cost breakdown for 25kWh EV

Whole battery pack



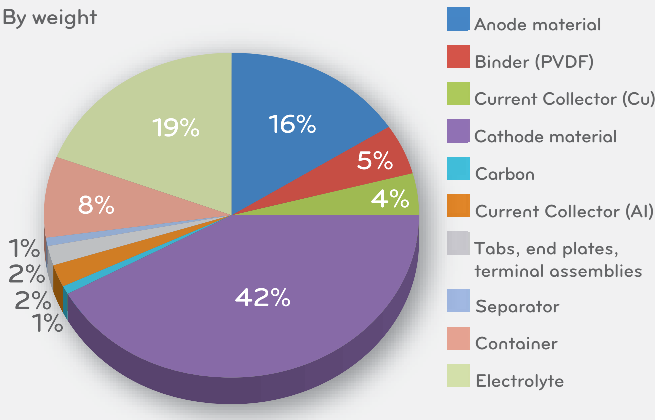
Pack cost breakdown for 10kWh PHEV

Whole battery pack



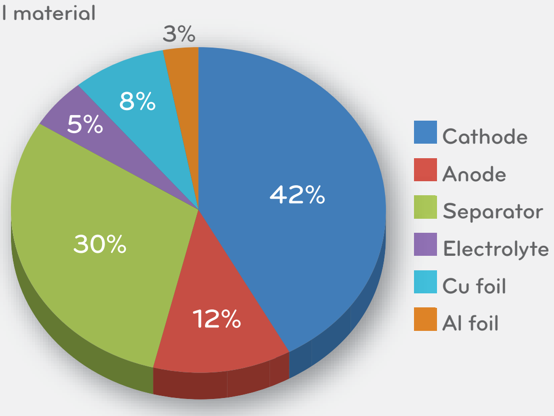
Cell material breakdown

By weight



Cell cost breakdown

Cell material



Reference: Johnson Matthey Battery Systems

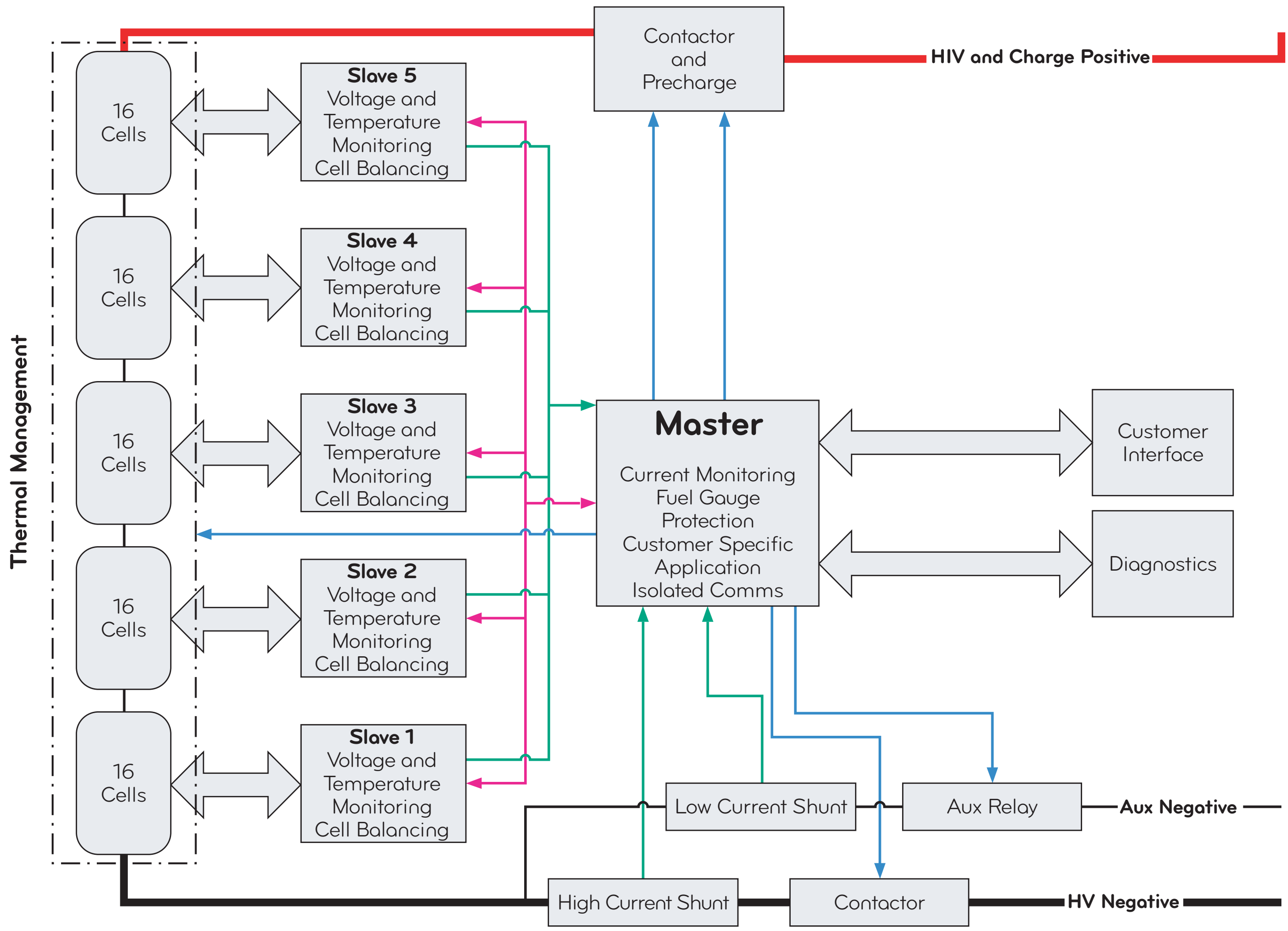
Battery Management System (BMS)

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.

Schematic of typical BMS



Safety

Abuse of the cells can cause a the cell to fail. The single cells have safety devices and the battery has a safety circuit that monitors each cell and prevents overcharging and over-discharging. 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 an ability to close its pores as a result of thermal runaway and are also designed to prevent short circuits.
+ Pressure vents to relieve excess pressure and prevent uncontrolled cell rupture in case of abuse.
+ 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 over current protection devices, switches and additionally as heaters.
+ Fuses.
+ Cell isolation to prevent event propagation.

3. BMS

+ The BMS monitors all key indicators coupled to control actions (Cooling, Power disconnect). You would expect a BMS designed for high volume automotive use to be designed to ISO26262, while for non-automotive applications the use of IEC 61508 is normally appropriate.

4. Battery installation location

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

  A well-designed BMS can optimise cycle life by preventing the overcharging and deep discharging of 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 Battery Management System 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.

Cycle life

Cycle life is the number of charge/discharge cycles a battery can perform before its capacity falls below a pre-determined percentage of its initial rated capacity. The cycle life of automotive Lithium ion batteries is in the thousands of 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 (charge or discharge rate equal to the capacity of the cell or battery divided by 1 hour): A lower C rate will increase cycle life.
+ Depth of discharge: Micro-cycles or reduced depth of discharge will increase cycle life.

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 reduce battery life; 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 that is 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 automotive Lithium-ion cells can be charged at rates equivalent to at least 1C. That means that for a 100Ah cell/battery, it would take 1 hour to charge at 100A.

Batteries can be designed specifically to accept fast charging without having a detrimental effect on the battery or cells. These battery systems may require thermal management, at added cost, mass and complexity to the system.

Certain cell chemistries are more tolerant to fast charge acceptance, e.g. Lithium Titanate Oxide (LTO). Such chemistries may carry a cost premium and lower energy density.

Automotive DC fast chargers may have a typical power of around 50kW. Charging at significantly faster rates may not always be practical. Fast charging is not always practical. Charging a 50kWh battery in 10 minutes would require a 300kW power supply. Domestic ring main power outlets deliver only 3kW. A 50 Amp high current outlet delivers about 11kW. At 11kW it would take approximately 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.

Battery exchange
Quick battery exchange is possible at dedicated battery exchange stations. This system is being adopted by some companies. However the range of vehicles that can utilise this system is limited unless all manufacturers choose to build standardised 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 and bus 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.

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 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 on the other hand do not communicate with the battery, instead following a standard charge profile. They tend to 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.

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 beforehand.

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, and 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 chargers 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.

Additional battery applications

12V/48V automotive batteries
Lithium batteries were once reserved for the race track. However, they are now becoming affordable for high-end and demanding automotive applications. These include stop/start technology, micro hybrid, mild hybrid, non-idling requirements, electric turbo charging and reconfigured packaging to assist in weight distribution.

The advantages are lead-free construction, 50% weight saving, longer life with lower total ownership costs, increased energy storage and more accurate SOC and SOH indication.

E-bike batteries
E-Bikes (also known as Electric bicycles, Electric-Assist bicycles or Pedelecs) are generally a bicycle-type frame with a battery-supplied motor to provide power to the wheels. There are considerable variations in the legislation applied to these but in general they are not required to be licensed, taxed or insured as motorised road vehicles, provided certain conditions of maximum power and/or maximum speed are met.

Lithium chemistries are much more common in these applications now. Typically, small cylindrical cells are used in 30-50V arrays, although there are also models using pouch type cells (also known as lithium polymer or li-po cells). All Lithium cells require a battery management system, which monitors battery voltage and temperature, and controls the charge and discharge currents, and usually provides a charge-gauge function. Batteries are usually mounted on the frame, either ahead of or behind the saddle tube, under the rack assembly or can be integrated into the frame of the bike. Batteries are typically easily removable for charging, although in many designs this can be carried out with the battery still installed on the bike.

Motors can be hub-mounted on the front wheel or rear wheel and also incorporated in the bottom bracket.

E-mobility batteries
Electro mobility (e-mobility) is a general term for the development of electric-powered drivetrains designed to move vehicle design away from the use of fossil fuels and harmful emissions. It encompasses the idea of smart-grids and fully connected mobile technology.

E-mobility sector as well as main stream xEV vehicles covers a wide range of products including, e-motor scooters, e-motorcycles, e-trikes, e-rickshaws, electric power wheels chairs and driverless vehicles to name a few.

These batteries can be in the range of 12V-100V and are typically designed to provide energy rather than high power. This market is expected to grow significantly in the next 5 years due to the increasing problem of pollution. Most major cities are considering zero emission zones by 2020-2025.

Stationary energy storage
Whilst this guide has mainly focused on batteries for automotive and mobile batteries, there is a very large market for stationary energy storage. This includes systems for domestic storage aimed at renewable technologies like solar power. Typically these range from 2-10kWh. Community wide systems which range from 20-100kWh and grid scale systems at 1-3MWh.

These systems are benefiting from technology generated in the automotive sector which is driving down the price of batteries due to increased volumes, increasing energy and power density as well as improving safety. There is also the opportunities to reuse cells and batteries from the demanding automotive applications in the stationary sector as will be referred to later in this guide.

48V MHEV battery

Other battery issues

Definition of end of life

In contrast to other battery technologies, such as lead acid batteries, Li-ion batteries do not suffer from 'sudden-death' failure. Instead they exhibit a gradual decrease in performance over their life. The End of Life (EOL) defined either by reduction of the original capacity, typically 20-30%, or by the increase of their internal resistance, often referred to as the impedance, which affects the battery's capability to deliver the power required, a key performance aspect for power applications.

EOL legislation

Automotive batteries are considered industrial batteries and cannot be disposed of as landfill. All battery suppliers must prove compliance with 'The Waste Batteries and Accumulators Regulations 2009'. This is a mandatory requirement, and states that manufacturers take back batteries from continuing customers for suitable disposal and recycling.

End-of-life battery recycling of EV and HEV is supported by legislation such as the battery directive (2000/66/EC), the end-of-life vehicles directive (2000/53/EC) and the European raw materials initiative (COM(2008) 699) and waste electrical and electronic equipment directive (WEEE) (2002/96/EC). Such legislation is expected to drive OEMs towards the development of a comprehensive recycling concept for EV batteries.

Recycling of Li-ion batteries

The volume of lithium-ion battery recycling is still very small, but significant amount of materials could potentially be recycled such as stainless steel, copper and aluminium, as well as the electrode material components manganese, cobalt, nickel, iron and lithium carbonate.

Currently there are two established types of processes for Li-ion batteries recycling: the pyro-metallurgical (where batteries are placed in a furnace and treated thermally), and hydro-metallurgical (where batteries are treated chemically to separate the materials).

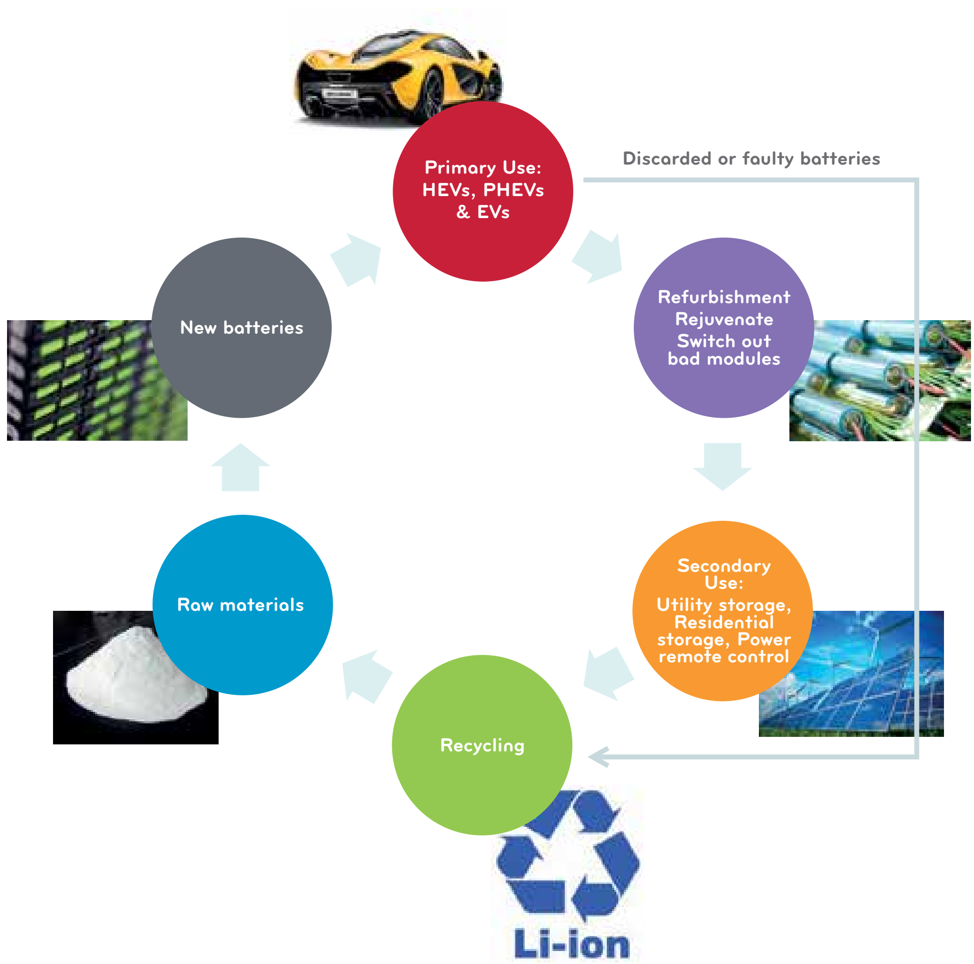
Pyro-metallurgical processes

In the pyro-metallurgical processes, Li-ion cells (or cell modules), are fed to a high-temperature shaft furnace along with a slag-forming agent that typically includes limestone, sand, and slag. The electrolyte and plastics burn to supply some of the energy for the smelting, and the valuable metals are reduced to an alloy of copper, cobalt, nickel, and iron. These metals are recovered from the alloy by leaching. The slag contains lithium, aluminium, silicon, calcium, iron, and any manganese that was present in the cathode material. It should be noted, however, that recycling of aluminium or lithium from the slag is neither economical nor energy efficient.

This process is currently operating commercially and it is economical for batteries with cathode materials containing cobalt and nickel, but not for newer designs with manganese spinel or LFP cathodes.

Hydro metallurgical processes

Hydrometallurgical processes for battery recycling involves chemical treatment of the battery materials in aqueous solutions – normally after mechanical treatment – to recover materials. Commonly, these processes involve three subsequent steps to extract and recover materials.



Other battery issues continued

Following some form of mechanical treatment, the electrode materials are leached into aqueous solution, by the use of acid or base. The solution then undergoes purification – typically by filtration, precipitation or solvent extraction – to yield a mixture of metals. The final step is then to extract the metals from the mixture; this can be achieved by a number of methods including addition of chemical reagents, precipitation and electrolysis.

The advantages of hydrometallurgical over pyro-metallurgical processes are that the recovered products are of better quality and often the energy requirements are lower. The disadvantages are that the input is more sensitive and therefore separate processes are often required for different battery chemistry variants. They are also often more expensive than pyro-metallurgical processes due to the high operational costs associated with treating waste water and solvents.

Re-use

As noted above, a battery at its EOL is not 'dead', it has simply reached a pre-defined measure of ageing, which makes it no longer compliant to the specific original application requirements. However, an EOL battery should still be able to deliver at least 70-80% of its initial capacity, and could potentially continue to be operational for a very long time when employed in a different application than originally intended.

The Battery 'Second life' represents the potential for recovering some of the original value of the battery by using it in another application, thus maximising the total life cycle value of the battery.

Potential Second Life applications include grid load levelling and renewable energy systems, as well as localised energy storage and micro-grid.

Before re-use the battery would have to be refurbished, possibly replacing some cells but reusing the housing and the electronics. Alternatively the battery re-use could apply at cell level instead of pack level. However, the costs incurred in doing this, combined with uncertain supply of end-of-life batteries, may make re-use unviable. In addition, it is likely that after five or more years' use, cell chemistry, as well as BMS technology, will have progressed such that they are of limited commercial value.

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.10/11 – Manual of Tests and Criteria (sub-section 38.3). 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, rail and road freight.

UN transportation compliance

Irrespective of which electrochemical variant of Lithium-ion chemistry is used within our battery systems it is necessary to be compliant with the UN regulations for all modes of transport (Air, Sea, Road and Rail). Although some countries and carriers will have their own, additional requirements, the UN has specified the minimum required depending on the mode of transport.

These regulations continue to be revised. Changes in law adopt the current level of knowledge and technology development, as well as using lessons resulting from the analysis of dangerous situations in transport (accidents, potential critical situations). New regulations take into account the emerging electrification of the automotive sector. This difficult topic is always supported by our specialists. This is particularly evident during the development phase of large battery systems which may need transporting to aid the development cycle. JMBS works closely with our customers and partners to ensure that we are compliant at all stages of the product life cycle, including end of life.

Glossary

Ah
The Ah or Ampere-hour is a unit of cell/battery capacity. It is the charge a battery can provide over a specified period of time, e.g. a 10Ah battery may provide 10 Amps of current 1 hour, or 5 Amps for 2 hr. etc.

Anode
The electrode of an electrochemical cell at which oxidation occurs. The negative electrode is commonly referred to as the anode.

Battery
A number of cells connected together in series and/or parallel strings along with associated electronics, sensors, thermal management and connectors.

BMS (Battery Management System)
The electronics systems that oversees battery performance and behaviour. The BMS maintains safe operation, controls the battery input and output and extends its life and durability through optimised control strategy. The BMS is key to the successful exploitation of lithium-ion battery cells.

CAN-Bus
A standard vehicle communication bus designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer.

Cathode
The electrode of an electrochemical cell at which reduction occurs. The positive electrode is commonly referred to as the cathode.

Cell
In a battery context, a cell is a discrete building block electrochemical energy storage component capable of delivering and accepting electrical energy.

C-rate
C-rate is a measure of the speed at which a battery is discharged and or charged relative to its maximum capacity. e.g. 1C for a 10Ah cell would be charge or discharge at 10A, C/2 would be 5A and 5C would be 50A charge or discharge.

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

Cycle life
The number of discharge-charge cycles the battery can experience before it fails to meet a pre-determined performance criteria. The operating life of the battery is affected by the rate and depth of cycles and strongly by conditions such as temperature, hence automotive batteries contain thermal management systems to maximise battery life.

Electrolyte
Iononically conducting and electronically insulating medium that allow ions to migrate from one electrode to the other.

EV
An electric vehicle (EV), also referred to as an electric drive vehicle, is a form of transportation that uses one or more electric machines or traction motors for propulsion.

HVFE
High voltage front end – the power management interface between the cells and the battery external power output controlled by the BMS.

kWhr
The kilowatt-hour is a unit of energy used to describe the large battery systems storage capability. A 1kWh battery would be able to deliver one thousand watts of energy over one hour of discharge.

Micro hybrids
A micro hybrid vehicle is what's called a 'start-stop system,' the internal combustion engine is automatically stopped once the vehicle comes to a complete stop and restarts when the driver engages a gear. The vehicle can also decide when to charge the battery, usually when the engine load is light. Most batteries used are lead-acid or AGM type but are moving across to Lithium to improve the life of the battery.

Mild hybrids
These are essentially conventional fossil-fuel vehicles equipped with a large electric machine (one motor/generator in a parallel configuration) allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restart quickly. Mild hybrids may employ regenerative braking and some level of power assist to the ICE, but mild hybrids do not have an exclusive electric-only mode of propulsion. A start-stop system automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling, thereby improving fuel economy and reducing emissions.

HEV
A hybrid electric vehicle (HEV) is a type of hybrid vehicle and electric vehicle that combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system (hybrid vehicle drivetrain). The presence of the electric powertrain is intended to achieve either better fuel economy than a conventional vehicle or better performance. The battery is internal and is not plugged-in to recharge. When discussing about different degree of hybridisation, it usually represents full hybrid vehicle, sometimes also called a strong hybrid vehicle, which is a vehicle that can run on just the engine, just the batteries, or a combination of both.

PHEV
A plug-in hybrid electric vehicle is similar to the hybrid electric vehicles (HEVs) on the market today, but it has a larger battery that is charged both by the vehicle's gasoline engine and from plugging into a standard electrical outlet or charge point for a few hours each day. PHEVs and HEVs both use battery-powered motors and gasoline-powered engines to get high fuel efficiency, but PHEVs can further displace fuel usage with off-board electrical energy charged at home or public charge points.

Pure EV
Also known as battery electric vehicle (BEV) or fully electric vehicle, is a type of electric vehicle (EV) that uses chemical energy stored in rechargeable battery packs. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion.

REEV
Range-Extended Electric Vehicle – a vehicle where the battery propels the vehicle and the internal combustion engine acts as a generator to recharge the battery when it is depleted (or by plugging into a charge point). By doing this the ICE can run at maximum efficiency. Typically, these vehicles have a pure electric battery range of around 30-40 miles, before the vehicle switches to the range-extender mode to continue the journey without any compromise in range. The propulsion technology is always electric.

Separator
A separator is a permeable membrane placed between a battery's anode and cathode. The function of the separator is to keep the two electrodes physically apart to prevent short circuits while also allowing the transport of ionic charge carriers that occurs on charge and discharge of the cell.

VTBM
Voltage and temperature measuring device, part of the BMS.

All figures and diagrams by Johnson Matthey Battery Systems, unless otherwise credited.

Why Johnson Matthey Battery Systems?

+ Johnson Matthey Battery Systems is a world-leading battery systems integrator. We design and manufacture battery systems for electric, hybrid and plug-in hybrid electric vehicles, as well as high volumes of batteries for e-bikes, power tools and mobile technologies. We can also offer battery solutions for stationary energy storage applications. All these include state-of-the-art battery management systems.
+ Johnson Matthey Battery Systems' 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.
+ Johnson Matthey Battery Systems continues to invest in R&D to make better batteries, improve battery technology, reduce cost and increase performance.

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

The basic information required in order to start to specify an automotive battery:

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 e.g. delivery truck, city car	–
Battery location e.g. 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

Notes

Notes

Johnson Matthey Battery Systems
Nobel Court, Wester Gourdie,
Dundee DD2 4UH
Scotland, UK
T +44 (0) 1382 618000
F +44 (0) 1382 400044

www.jmbatterysystems.com