Syllabus

EV Batteries and Battery Management System: EV batteries, Lead Acid batteries – Basics, Characteristics, Lithium batteries- Basics, Characteristics, Selection of battery for EVs, Smart battery pack design, Mechanical and reliability aspects of Li Ion packs, UN38 regulation familiarity, Cell balancing in Li Ion, Battery second life and usage in BESS (energy storage systems). BMS - Global price trends, volumetric and gravimetric efficiency trends.

Introduction

A battery consists of two or more electric cells joined together. The cells convert chemical energy to electrical energy. The cells consist of positive and negative electrodes joined by an electrolyte. It is the chemical reaction between the electrodes and the electrolyte which generates DC electricity. In the case of secondary or rechargeable batteries, the chemical reaction can be reversed by reversing the current and the batter returned to a charged state.

The 'lead acid' battery is the most well-known rechargeable type, but there are others. The first electric vehicle using rechargeable batteries preceded the invention of the rechargeable lead acid by quarter of a century, and there are a very large number of materials and electrolytes that can be combined to form a battery. However, only a relatively small number of combinations have been developed as commercial rechargeable electric batteries suitable for use in vehicles. At present these include lead acid, nickel iron, nickel cadmium, nickel metal hydride, lithium polymer and lithium iron, sodium sulphur and sodium metal chloride.

Overview of Batteries

From the electric vehicle designer's point of view the battery can be treated as a 'blackbox' which has a range of performance criteria. These criteria will include:

- specific energy
- energy density
- specific power
- typical voltages
- amp hour efficiency
- energy efficiency
- commercial availability
- cost, operating temperatures
- self-discharge rates
- number of life cycles
- recharge rates

The designer also needs to understand how energy availability varies with regard to:

- ambient temperature

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- charge and discharge rates
- battery geometry
- optimum temperature
- charging methods
- Cooling needs.

However, at least a basic understanding of the battery chemistry is very important, otherwise the performance and maintenance requirements of the different types, and most of the disappointments connected with battery use, such as their limited life, self-discharge, reduced efficiency at higher currents.

Battery Parameters

1. Cell and battery voltages

All electric cells have nominal voltages which gives the approximate voltage when the cell is delivering electrical power. The cells can be connected in series to give the overall voltage required. The 'internal resistance' and the equivalent circuit of a battery is shown in Figure 1. The battery is represented as having a fixed voltage E, but the voltage at the terminals is a different voltage V, because of the voltage across the internal resistance R.

Assuming that a current I is flowing out of the battery, as in Fig. 1, then by basic circuit theory we can say that:

V=E-IR

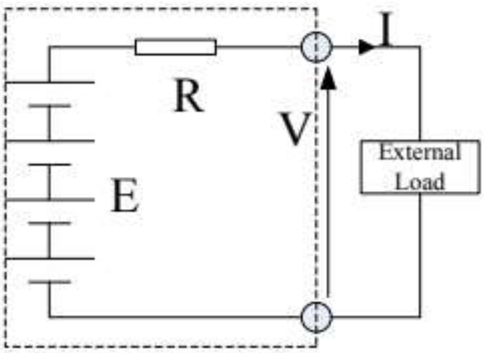

Fig. 1 Simple equivalent circuit model of a battery. This battery is composed of six cells

2. Charge (or Ahr) capacity

The electric charge that a battery can supply is clearly a most crucial parameter. The SI unit for this is the Coulomb, the charge when one Amp flows for one second. The capacity of a battery might be, say, 10Amphours. This means it can provide 1Amp for 10 hours.

3. Energy stored

The energy stored in a battery depends on its voltage, and the charge stored. The SI unit is the Joule, but this is an inconveniently small unit, and so we use the Whr instead.

Energy in Whr=V *Ahr

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4. Specific energy

Specific energy is the amount of electrical energy stored for every kilogram of battery mass. It has units of $Wh.kg^{-1}$.

5. Energy density

Energy density is the amount of electrical energy stored per cubic metre of battery volume. It normally has units of $Wh.m^{-3}$.

6. Specific power

Specific power is the amount of power obtained per kilogram of battery. It is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself.

7. Ahr (or charge) efficiency

In an ideal world a battery would return the entire charge put into it, in which case the amp hour efficiency is 100%. However, no battery does; its charging efficiency is less than 100%. The precise value will vary with different types of battery, temperature and rate of charge. It will also vary with the state of charge.

8. Energy efficiency

This is another very important parameter and it is defined as the ratio of electrical energy supplied by a battery to the amount of electrical energy required to return it to the state before discharge.

9. Self-discharge rates

Most batteries discharge when left unused, and this is known as self-discharge. This is important as it means some batteries cannot be left for long periods without recharging. The rate varies with battery type, and with other factors such as temperature; higher temperatures greatly increase self-discharge.

10. Battery temperature, heating and cooling needs

Although most batteries run at ambient temperature, some run at higher temperatures and need heating to start with and then cooling when in use. In others, battery performance drops off at low temperatures, which is undesirable, but this problem could be overcome by heating the battery. When choosing a battery the designer needs to be aware of battery temperature, heating and cooling needs, and has to take these into consideration during the vehicle design process.

11. Battery life and number of deep cycles

Most rechargeable batteries will only undergo a few hundred deep cycles to 20% of the battery charge. However, the exact number depends on the battery type, and also on the details of the battery design, and on how the battery is used. This is a very important figure in a battery specification, as it reflects in the lifetime of the battery, which in turn reflects in electric vehicle running costs.

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Lead Acid Batteries

The best known and most widely used battery for electric vehicles is the lead acid battery. Lead acid batteries are widely used in IC engine vehicles and as such are well known. However for electric vehicles, more robust lead acid batteries that withstand deep cycling and use a gel rather than a liquid electrolyte are used. These batteries are more expensive to produce. In the lead acid cells the negative plates have a spongy lead as their active material, whilst the positive plates have an active material of lead dioxide. The plates are immersed in an electrolyte of dilute sulphuric acid. The sulphuric acid combines with the lead and the lead oxide to produce lead sulphate and water, electrical energy being released during the process.

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O$$

The reactions on each electrode of the battery are shown in Fig. 2. In the upper part of the diagram the battery is discharging. Both electrode reactions result in the formation of lead sulphate. The electrolyte gradually loses the sulphuric acid, and becomes more dilute. When being charged, as in the lower half of Figure 2, the electrodes revert to lead and lead dioxide. The electrolyte also recovers its sulphuric acid, and the concentration rises. The lead acid battery is the most commonly used rechargeable battery in anything but the smallest of systems. The main reasons for this are that the main constituents (lead, sulphuric acid, a plastic container) are not expensive, that it performs reliably, and that it has a comparatively high voltage of about 2V per cell. The overall characteristics of the battery are given in Table I. The figure given in Table I of 0.022 Ω per cell is a rule of thumb figure taken from a range of good quality traction batteries. A good estimate of the internal resistance of a lead acid battery is thus:

$$R = No.\ of\ Cells \times \frac{0.022}{C_{10}}\ Ohms$$

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Table I Nominal battery parameters for lead acid batteries

Specific energy	20–35 Wh.kg−1 depending on usage
Energy density	54–95Wh.L−1
Specific power	~250 W.kg−1 before efficiency falls very greatly
Nominal cell voltage	2V
Amphour efficiency	~80%, varies with rate of discharge & temp.
Internal resistance	Extremely low, ~0.022_ per cell for 1 Amphour cell
Commercially available	Readily available from several manufacturers
Operating temperature	Ambient, poor performance in extreme cold
Self-discharge	~2% per day, but see text below
Number of life cycles	Up to 800 to 80% capacity
Recharge time	8 h (but 90% recharge in 1 h possible)

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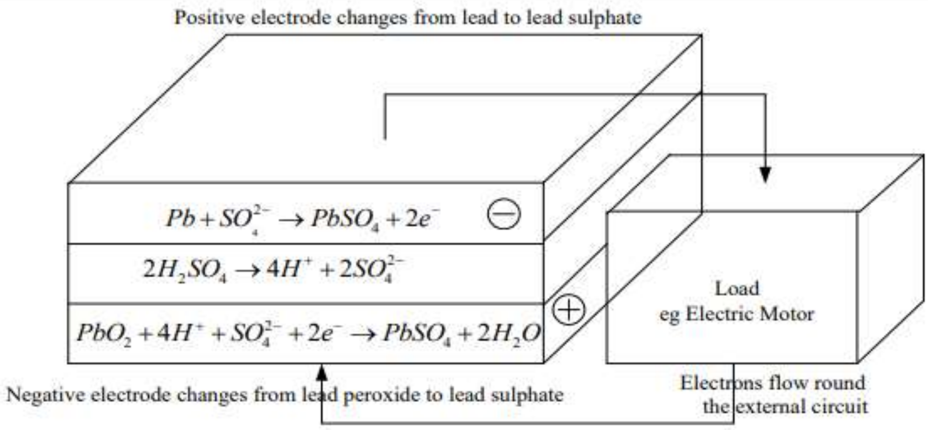
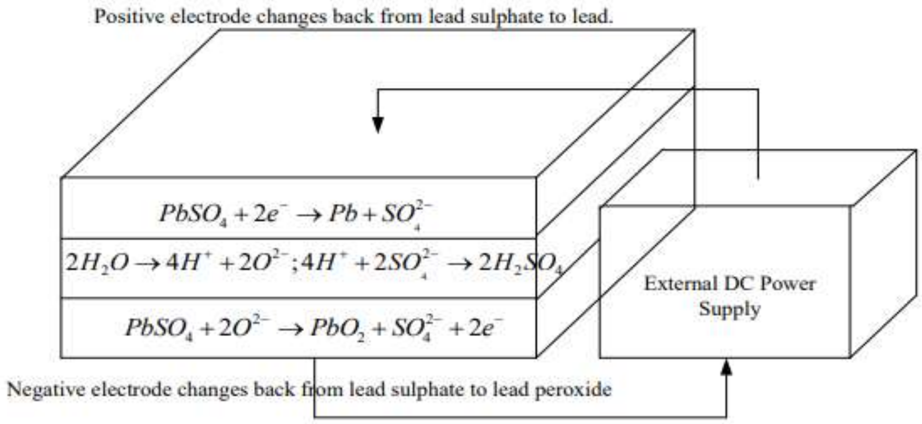


Reactions during the discharge of the lead acid battery.
Note that the electrolyte loses suphuric acid and gains water.



Reaction during the charging of the lead acid battery.

Battery charging

Charging a lead acid battery is a complex procedure and, as with any battery, if carried out incorrectly it will quickly ruin the battery and decrease its life. As we have seen, the charging must not be carried out at too high a voltage, or water loss results. There are differing views on the best way of charging lead acid batteries and it is essential that, once a battery is chosen, the manufacturer's advice is sought. The most commonly used technique for lead acid batteries is called multiple steps charging. In this method the battery is charged until the cell voltage is raised to a predetermined level. The current is then switched off and the cell voltage is allowed to decay to another predetermined level and the current is then switched on again.

Lithium Batteries

Since the late 1980s rechargeable lithium cells have come onto the market. They offer greatly increased energy density in comparison with other rechargeable batteries, though at greatly increased cost. It is a well-established feature of the most expensive laptop computers and mobile phones that lithium rechargeable batteries are specified, rather than the lower cost NiCad or NiHM cells that we have been considering earlier.

The lithium batteries are of following types:

• Lithium polymer batteries

• Lithium ion batteries

The lithium polymer battery

The lithium polymer battery uses lithium metal for the negative electrode and a transition metal intercalation oxide for the positive. In the resulting chemical reaction the lithium combines with the metal oxide to form a lithium metal oxide and release energy. When the battery is recharged the chemical reaction is reversed. The lithium is thus both a reactant and the mobile ion that moves through the electrolyte. The overall chemical reaction is:

$$xLi + M_yO_z \leftrightarrow Li_xM_yO_z$$

The lithium ion battery

The lithium ion battery was introduced in the early 1990s and it uses a lithiated transition metal intercalation oxide for the positive electrode and lithiated carbon for the negative electrode. The electrolyte is either a liquid organic solution or a solid polymer. Electrical energy is obtained from the combination of the lithium carbon and the lithium metal oxide to form carbon and lithium metal oxide. The overall chemical reaction for the battery is:

$$C_6Li_x + M_yO_z \leftrightarrow 6C + Li_xM_yO_z$$

The essential features of the battery are shown in Table II. An important point about lithium ion batteries is that accurate control of voltage is needed when charging lithium cells. If it is slightly too high it can damage the battery, and if too low the battery will be insufficiently charged. Suitable commercial chargers are being developed along with the battery.

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Table II Nominal battery parameters for lithium ion batteries.

Specific energy	90 Wh.kg−1
Energy density	153 Wh.L−1
Specific power	300 W.kg−1
Nominal cell voltage	3.5V
Amphour efficiency	Very good
Internal resistance	Very low
Commercially available	Only in very small cells not suitable for electric vehicles
Operating temperature	Ambient
Self-discharge	Very low, ~10% per month
Number of life cycles	>1000
Recharge time	2–3 h

Metal Air Batteries

The metal air batteries represent an entirely different development, in the sense that the batteries cannot be recharged simply by reversing the current. Instead the spent metal electrodes must be replaced by new ones. The metal electrodes can thus be considered as a kind of fuel. The spent fuel is then sent to a reprocessing plant where it will be turned into new 'fuel'. The battery electrolyte will also normally need to be replaced.

The aluminium air battery

The basic chemical reaction of the aluminium air battery is essentially simple. Aluminium is combined with oxygen from the air and water to form aluminium hydroxide, releasing electrical energy in the process. The reaction is irreversible. The overall chemical reaction is:

$$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3$$

The aluminium forms the negative electrode of the cell, and it typically starts as a plate about 1cm thick. As the reaction proceeds the electrode becomes smaller and smaller. The positive electrode is typically a porous structure, consisting of a metal mesh onto which is pressed a layer of catalysed carbon. A thin layer of PTFE gives it the necessary porosity to let the oxygen

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in, but prevent the liquid electrolyte getting out. The electrolyte is an alkaline solution, usually potassium hydroxide. The battery is recharged by replacing the used negative electrodes. The electrolyte will normally also be replenished, as it will be contaminated with the aluminium hydroxide. The essential characteristics of the aluminium air battery are shown in Table III. The big drawback of the aluminium air battery is its extremely low specific power.

Table III Nominal battery parameters for aluminium air batteries

Specific energy	225 Wh.kg−1
Energy density	195 Wh.L−1
Specific power	10 W.kg−1
Nominal cell voltage	1.4V
Amphour efficiency	N/A
Internal resistance	Rather high, hence low power
Commercially available	Stationary systems only available
Operating temperature	Ambient
Self-discharge	Very high (>10% per day) normally, but the electrolyte can be pumped out, which makes it very low
Number of life cycles	1000 or more
Recharge time	10min, while the fuel is replaced

The zinc air battery

The zinc air battery is similar in many ways to the aluminium air battery but it has a much better overall performance, particularly with regard to specific power which is nearly ten times that of the aluminium air battery, making it suitable for use in road vehicles. The structure is similar, with a porous positive electrode at which oxygen reacts with the electrolyte. The electrolyte is a liquid alkaline solution. The negative electrode is solid zinc. The energy from the battery is obtained by combining zinc with the oxygen in the air and forming zinc oxide. Alternatively, depending on the state of the electrodes and electrolyte, zinc hydroxide may be formed, as for the aluminium-air cell. The process is normally irreversible. The general characteristics of the battery are shown in Table IV. A few manufacturers have claimed to produce electrically rechargeable zinc-air batteries, but the number of cycles is usually quite small. The more normal way of recharging is as for the aluminium air cell, which is by replacing the negative electrodes.

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Table IV Nominal battery parameters for zinc air batteries

Specific energy	230 Wh.kg−1
Energy density	270 Wh.L−1
Specific power	105 W.kg−1
Nominal cell voltage	1.2V
Amphour efficiency	Not applicable
Internal resistance	Medium
Commercially available	A very few suppliers
Operating temperature	Ambient
Self-discharge	High, as electrolyte is left in cell
Number of life cycles	>2000
Recharge time	10min, while the fuel is replaced

Smart battery pack design

A well-designed battery pack needs to compete with petrol-based engines to appeal to customers. That’s a real challenge because electric batteries need to overcome complex issues that internal combustion engines (ICE) do not have.

Here are some common issues that can affect a battery pack’s performance:

- Cold temperatures prevent batteries from delivering their full power. Batteries operate best within a specific temperature range, which is between 68°F and 77°F (20°C and 25°C). Maintaining the right operating temperature is essential.
- Batteries lose part of their available power over time due to natural wear. EV manufacturers need to make sure that this power loss does not affect the driving experience.

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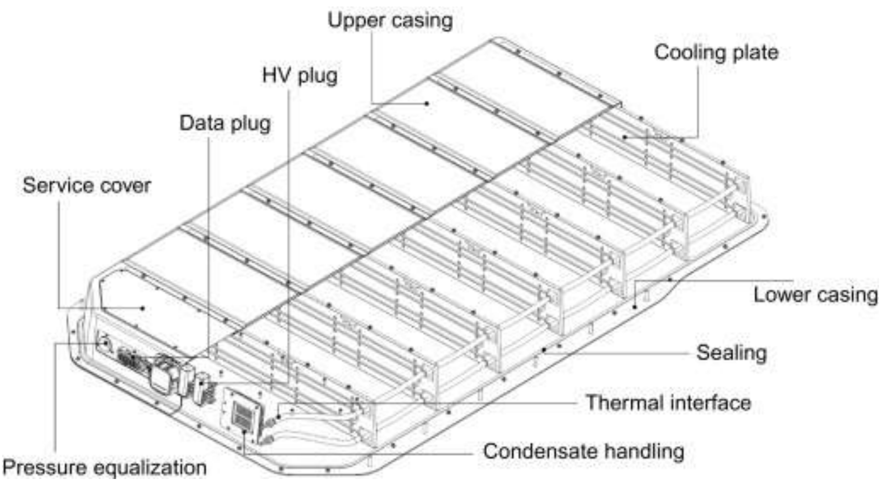
- Battery cells need to be balanced to offer optimal performance, meaning that they must all have the same voltage. Battery cells are rebalanced during charges, but they lose their ability to maintain that balance as they age. In addition, rapid charges which are gaining in popularity are challenging the balancing performance.

A battery pack is a device that stores electrical energy to provide power to an electrical system, such as an electric vehicle (EV) or an energy storage system (ESS). The energy is stored in cells that are all connected to one another in the battery pack.

To provide sufficient power, battery packs require a minimum voltage level which a single cell cannot achieve. Multiple cells are therefore connected in series to boost voltage. Some designs use small-capacity cells. To achieve the desired battery energy, cells are connected in parallel to boost capacity. Cells connected in parallel provide power as if they were a single, larger cell.

Battery packs are made of multiple, smaller sections called battery modules (or sub packs). These modules include a smaller number of cells connected in series and parallel. They are usually at a lower voltage, which is safe for handling. Modules facilitate servicing when only a few cells are defective and if they can be replaced without replacing the entire battery. EV batteries are typically made of 4 to 40 modules connected in series to one another.

The Components of a Battery Pack



A battery pack is the most expensive part in an electric vehicle. It is a complex system made of a wide range of components. Here are some of the important components.

- **Cells** are the most important components of a battery pack. The mixture of materials comprising the cell is known as its chemistry. Different battery chemistries can achieve different performances and specifications. There are two common types of cells: energy cells and power cells. There are also many variants to provide the perfect trade-off

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depending on the application. In the EV industry, the lithium-ion cell (li-ion cell) is the most common chemistry. Alternative chemistries are sometimes used, such as Nickel-Metal Hydride (NiMH), which offers a slightly better lifecycle.

- **Electrical connectors** such as busbars, wires, or other distribution conductors are used to make series or parallel connections between cells and groups of cells. These connections are typically done using ultrasonic bonding or laser welding. Busbar connections between modules can also be done mechanically using fasteners.
- **Thermal interface materials** (TIMs) such as pastes, adhesives and gap fillers are inserted between battery components to join them mechanically while improving thermal properties between surfaces. With the rise of the structural battery pack, TIMs are becoming essential components.
- The **Battery Management System** (BMS) protects cells by monitoring key parameters such as voltages, currents, and temperatures. It is responsible for cell balancing (to maintain the optimal performance of the cells at the right voltage) and communicates with several systems such as engine management and temperature control. It also includes protection devices that can shut down the battery if needed.
- The **Battery Thermal Management System** (BTMS) controls the thermal energy in the electric vehicle's powertrain and cabin, providing cooling or heating as needed to meet the battery's thermal needs and protect the cells. The BTMS includes several components such as a heat exchanger, tubes, hoses, cold plates, pumps, valves, and temperature sensors.
- The **Contactor System** is a switch controlled by the battery management system. It can cut off the electrical connection between the main battery and the high voltage bus, which delivers current to the traction motor and other high-voltage components.
- The **Housing** is a rigid enclosure that protects the battery from environmental factors such as water, dust, and salt. It helps maintain a precise temperature and electrical insulation in the battery, and it prevents damages like rust and slow shorts.
- The **Communications System** ensures communication with other components in the electric vehicle. The most used protocol is CAN bus.

The 4 Main Types of Battery Pack Designs

1. 12V Battery Packs for Accessories

With their low voltage, 12V batteries are used for low energy applications such as headlights, radio systems, and other accessories. In hybrid and petrol cars, they are used to start the engine. In electric vehicles, they are used as an energy source that can function without the main electric battery (traction battery). For example, it is used to activate the traction battery and provide power to some vital components if power has been cut off for safety reasons.

Traditionally, the most known type of 12V batteries were made using the lead-acid cell chemistry and were hence referred to as lead-acid batteries. The number of cells in these

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packs was limited to 6. The most recent 12V batteries are lithium-ion battery packs whose lithium cells offer better performance and lighter weight.

12V batteries are small and are typically placed under the hood. More recently, manufacturers have started placing them inside the trunk to improve safety, as it minimizes chances of short circuits during crashes. Since more collisions occur at the front, the battery is better protected from impacts when it is positioned at the back.

2. Hybrid Battery Packs

Hybrid batteries contain a smaller amount of energy than EV batteries and are much smaller. Still, today's hybrid batteries typically have a range between 30 and 50 miles (50 and 80 km). They can be used for most short-distance trips without having to fall back on the internal combustion engine (ICE). That's a major improvement compared to the very first models, which offered a mere 0.6 miles of autonomy (1 km).

Hybrid battery packs are built to complement the combustion engine when it is least efficient, such as when accelerating. The goal is to diminish petrol consumption as much as possible. The battery can also recharge itself by recovering wasted energy when braking (regen braking).

3. EV Battery Packs

Unlike other battery pack designs, EV batteries are full-sized batteries made to supply the entire range of the vehicle, including the traction motor and accessories. Current EV batteries offer between 20 and 130 kWh of energy and can use between 90% and 95% of that energy—a much higher percentage than other types of batteries. The Mercedes EQS is the electric car with the highest range, offering 485 miles of autonomy (780 km).

EV batteries represent a significant portion of the vehicle's weight and volume. They can weigh up to 450 kg (1000 lbs), representing one-fourth of the car's total weight. Different designs come with high voltage going from 400V to 900V. In the most recent designs, they are being integrated as part of the vehicle's structure.

4. High Performance Battery Packs

High performance battery packs are batteries designed for Formula E races. They are divided in two categories: hybrid and pure EV. They are made with composite materials to obtain an ultra-light structure. Some high-performance batteries are removable so they can be replaced during races.

Even though they are small, these batteries can deliver ultra-high power. More precisely, they can deliver several hundred kW of power, which is enough to output power for an entire neighbourhood. Their cooling system is oversized due to the aggressive power demand.

High-performance battery packs are more energy efficient than other types of batteries. For example, they can recover a larger portion of lost energy during braking (regen braking).

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SMART BATTERY PACKS

A ***smart battery pack*** provides the device with information so that it can manage its own charging, report errors, inform the device of low-charge conditions, predict remaining run-time, provide temperature, voltage, and current information, continuously self-correct to maintain prediction accuracy, and maintain its power status so that the device can conserve power intelligently. Smart battery packs can include many additional features and functionality, such as fuel gauge integration, communication protocol (I2C, SMBus, RS485, RS232 or CANBUS), cell balancing, and protection circuitry.

As all different types of equipment are becoming smaller and lighter, a custom lithium battery have the advantage of having high energy density, being light weight, wide operating temperature range, and the flexibility to use software and firmware to design the proper battery management systems (BMS) for every application.

One of the most critical parts of designing a custom battery pack is cell selection. Various chemistries are made in a wide variety of sizes, and custom battery packs offer the ability to dial in the performance of a specific cell chemistry to exactly match the performance that a device requires. A key thing to remember is that a smaller, lighter battery with the same energy density will usually cost more to produce and develop than a larger, heavier battery, which is why it is usually wise to work with an experienced custom battery pack designer before picking a specific cell technology.

Smart Battery Pack Systems Can Now Include:

- Embedded battery chargers
- Unregulated input power
- Wireless power (charging)
- System output power
- Fuel gauging
- GPIO options
- Safety circuit (PCM)
- Intrinsically safe designs
- Authentication/encryption coding
- On board charging
- High C-rate discharging
- Remote monitoring
- Integrated power management
- Custom designed ruggedized molded and metal enclosures
- Safety certifications (IEC/UL 62133, UL2054, IATA UN38.3 and others globally)
- Labeling and packaging to meet all regulations

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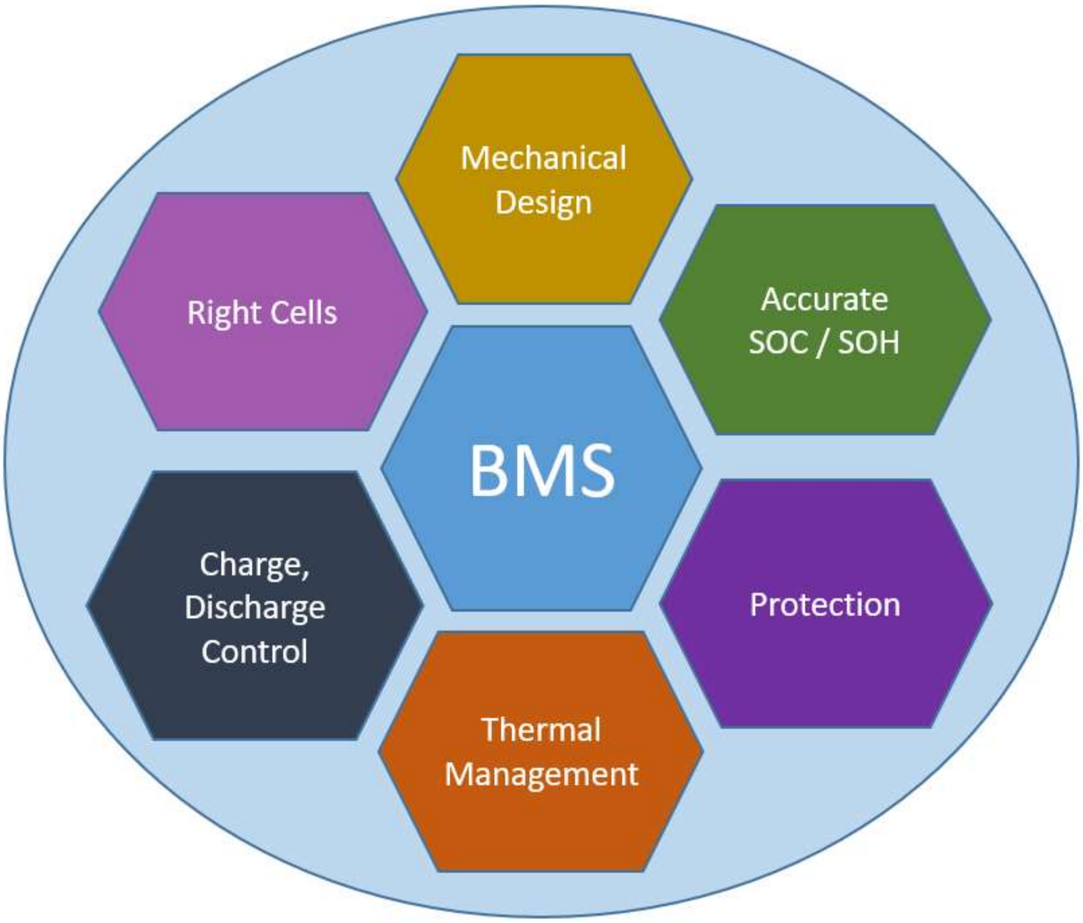
With embedded battery chargers, batteries last longer by charging them to their ideal specifications and only within proper temperature limits. Properly designed and accurate fuel gauges, batteries can be discharged to almost empty with confidence; hence, batteries do not need to be oversized making them smaller, lighter, and more dependable. GPIO interface may provide access to information or functional control you had never thought possible.



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