WHITEPAPER
THE BASICS OF BATTERY TECHNOLOGY

With global vehicle electrification, the interest and demand around batteries is increasing tremendously. Nonetheless, there are still many misunderstandings about battery technologies within this fast-growing market. The most common EV-knowledge is based on the car industry and therefore, many false assumptions are made for electric buses . To get a better understanding of the batteries and how they work, we will explain more in-depth information about battery technology.

Firstly, different **types of batteries** fit for the automotive industry will be discussed, after which one of those types, **lithium-ion batteries**, will be further explained. With the knowledge gained about lithium-ion batteries, the technology behind **LFP** and **NMC** can then be further explained. Once these topics are discussed, you will have a basic knowledge of **battery cells**. Next, we will cover how these cells are converted to a module and from a **module** to a **pack**.

We then briefly go over the functioning of these packs, how the state of charge is calculated and how they are monitored with a battery management system (BMS) within the vehicle.

BATTERY TYPES

Let's start with the basics. What exactly is a battery? A battery is a container that consists out of one or more cells in which chemical energy is converted into electricity and used to store power. There are three primary battery types that are used for electric vehicles. They are lead-acid, nickel metal hydride (NiMH), and lithium-ion batteries.

LEAD - ACID BATTERIES

Lead-acid batteries are known for their long service life. They are usually inexpensive to purchase. At the same time, they are extremely durable, reliable and do not require much maintenance. A weak point of lead batteries, however, is their sensitivity to deep discharge, meaning that the battery can be damaged. Therefore, it should always be charged to at least 20 percent.

NICKEL-METAL HYDRIDE BATTERIES (NiMH)

Nickel-metal hydride batteries offer reasonable specific energy and power capabilities. Nickel-metal hydride batteries have a much longer life cycle than lead-acid batteries and are safe and abuse tolerant. These batteries have been widely used in vehicles. The main challenges with nickel-metal hydride batteries are their high cost, heavier then others and high self-discharge and heat generation at high external temperatures, and the need to control hydrogen loss.

LITHIUM-ION BATTERIES

The costs of lithium-ion batteries are slightly higher than other batteries, but you get a lot in return. Lithium-ion batteries have a constant power output. There is very little loss of performance within the lifecycle of the battery and they perform well under high temperature situations. Another advantage of lithium-ion batteries is that they are able to recharge very quickly, and have a high power to weight ratio, meaning that they are lighter than most batteries and are therefore, ideal for mobile solutions.

MOST CHOSEN BATTERY IN THE AUTOMOTIVE INDUSTRY

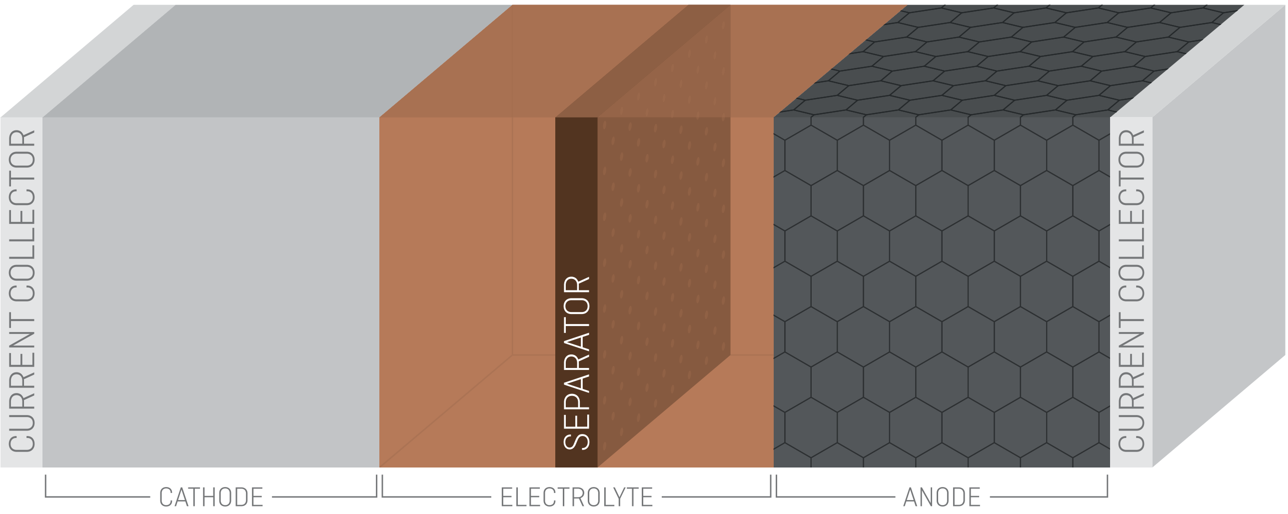
LITHIUM-ION BATTERY

For the reasons mentioned above, lithium-ion is the most commonly used battery technique within the automotive industry. A lithium-ion (Li-ion) battery is an advanced battery technology that uses lithium ions as a key component of its electrochemistry. Lithium-ion is a general technology that can be applied in different types of batteries, meaning that lithium-ion is not a battery itself, but a technique used by several battery types, such as **LFP** and **NMC** batteries. These two Li-ion batteries are the most common batteries within the automotive industry. To get a better understanding of these types of batteries, the overall lithium-ion technique needs to be explained.

TECHNOLOGY BEHIND A LITHIUM-ION BATTERY

We start by dissecting a Li-ion battery to highlight the exact chemicals in these type of battery cells. Each battery cell is composed of 3 main layers; The **Cathode**, a liquid **Electrolyte** with a Polymer membrane separator, and the **Anode**.

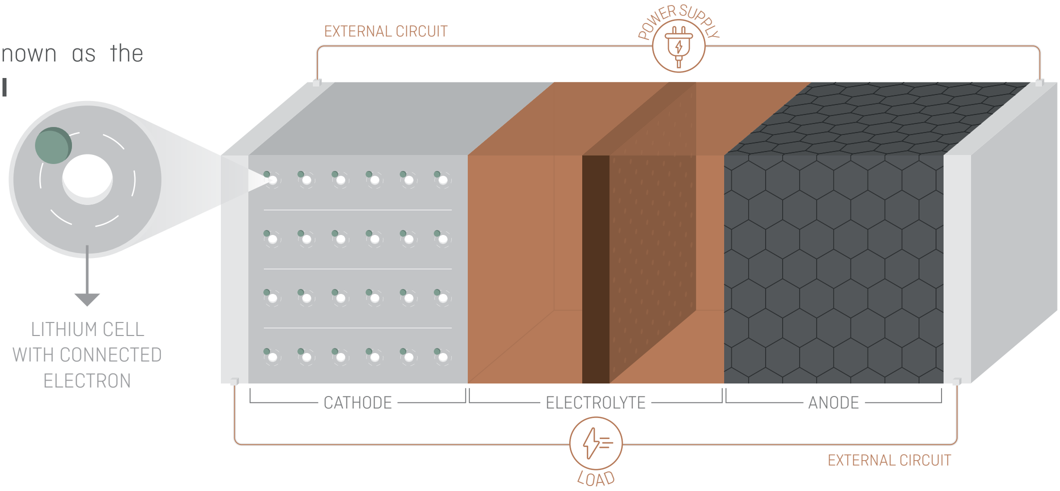
- The Cathode: consists of a positive electrode made out of aluminum foil. The additional chemical composition of this layer can vary depending on the battery type.
- Separator: a liquid Electrolyte with a Polymer Membrane as a separator for the Anode and Cathode. The Separator is made of plastic that has lots of tiny pores.
- The Anode: consists of graphite and a negative electrode made of copper foil.



Lithium, as the name lithium-ion already suggests, is situated in the battery, but the location of this chemical is depending on the state of the battery. When the battery is charged or discharged, the position of the lithium changes, meaning that the bonding from the Cathode is loosened and bonding on the anode is made.

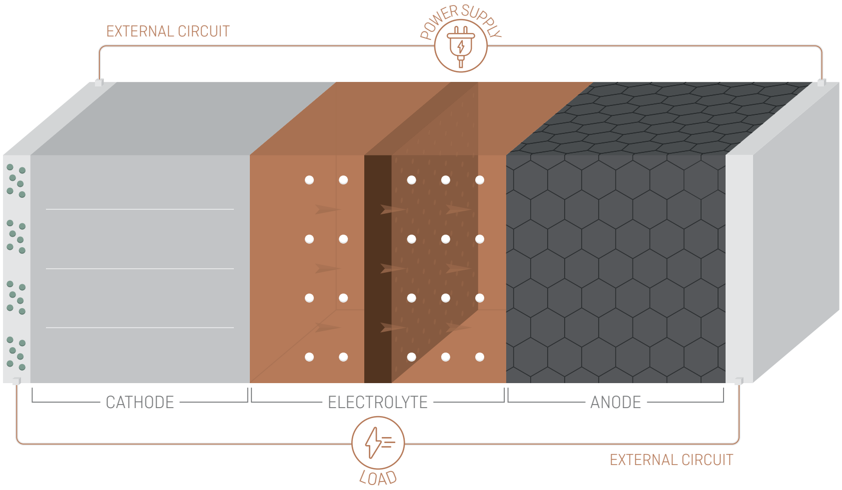
PHASE 1 - UNLOADED STATE

The cathode, also known as the **negative terminal** of the battery cell, acts as the home base for lithium. Each lithium cell positioned in the cathode possesses a single electron.



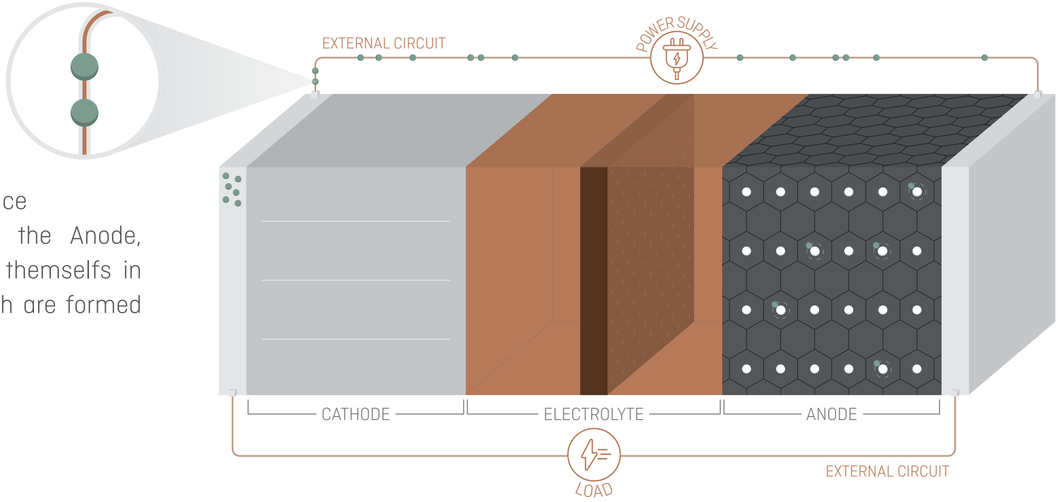
PHASE 2 - EXTERNAL POWER SUPPLY

The movement of the lithium is created by power supply. When the power supply is active, the lithium cells start traveling from the Cathode, through the liquid Electrolyte with a polymer membrane, to the Anode, also known as the **positive terminal**. While the lithium cells can travel through the polymer membrane, the electrons cannot. Therefore, the electrons get detached from the lithium cell.



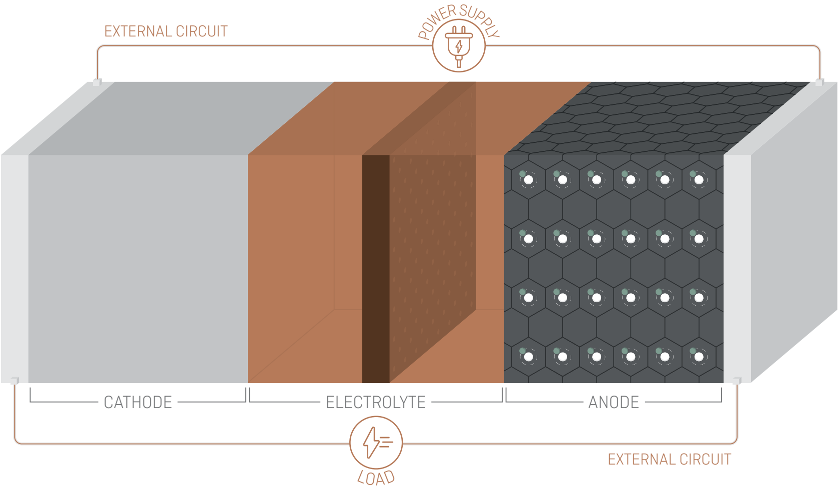
PHASE 3 - CHARGING

The electrons move towards the current collector and from there trough the **external circuit** to the Anode. Once the electrons reach the Anode, they have to situate themselves in dedicated spots which are formed by the graphite.



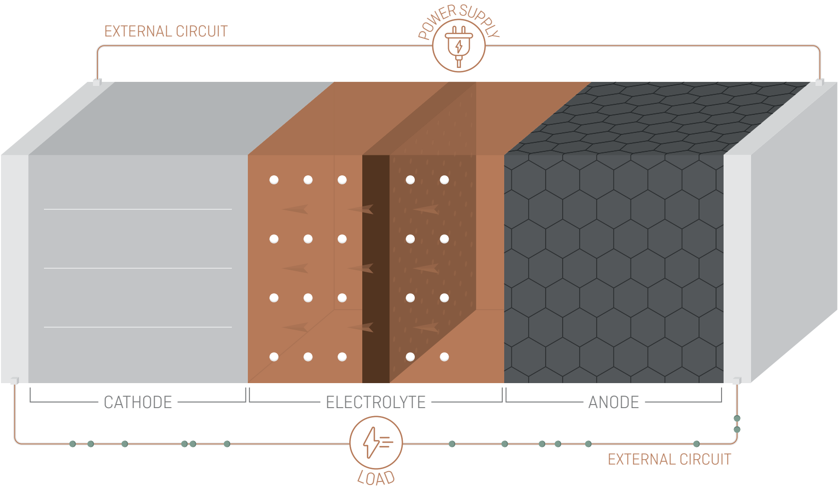
PHASE 4 - CHARGED STATE

Once all lithium-ions and electrons are situated in the Anode, the battery is in a charged state. This charged battery state in the Anode is an unstable state and once the power source is removed, the lithium-ions automatically want to get back to their stable state in the Cathode.



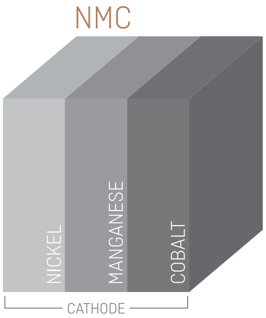
PHASE 5 - POWER TO VEHICLE

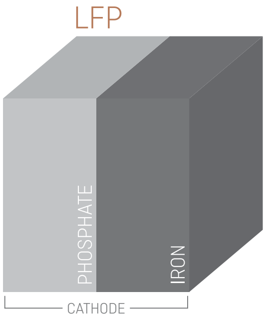
Due to this tendency, the lithium-ions move back through the electrolyte. Electrons have to return through the external circuit which is connected to the **load**. Connecting an external electrical circuit with a load in between the Anode and Cathode shall allow the electrons to move back to their stable situation. An additional switch within the electrical circuit could be added to obstruct the electrons from moving through this path, allowing the primary user to control de depletion of the battery.



Even if there is no external load connected, the electrons will slowly start moving back to the Cathode as there is always an internal load present within the batteries chemicals, thus the battery will slowly deplete over time.

TWO TYPES OF LITHIUM-ION BATTERIES

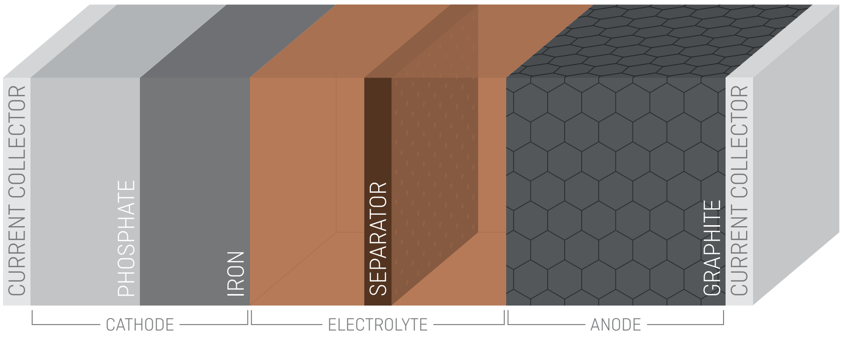




As mentioned before, lithium-ion batteries come in several types. Therefore, we will consider two different types of lithium-ion batteries that are commonly used within the automotive industry. These two types are **LFP** and **NMC**. Because both LFP and NMC Batteries are members of the lithium-ion battery family, they have many similarities. For both batteries, the displacement of lithium is the main chemical reaction within the battery. As discussed before, both batteries contain an Anode, Separator, and Cathode. For, both LFP and NMC, the chemical composition of the Separator and Anode stay the same.

The **Cathode layer** on the other hand is where the difference is made. The Cathode layer of the LFP battery contains **iron** and **phosphate**, whereas the NMC batteries contain a multi-layered cathode made of **nickel**, **cobalt**, and **manganese**.

LFP



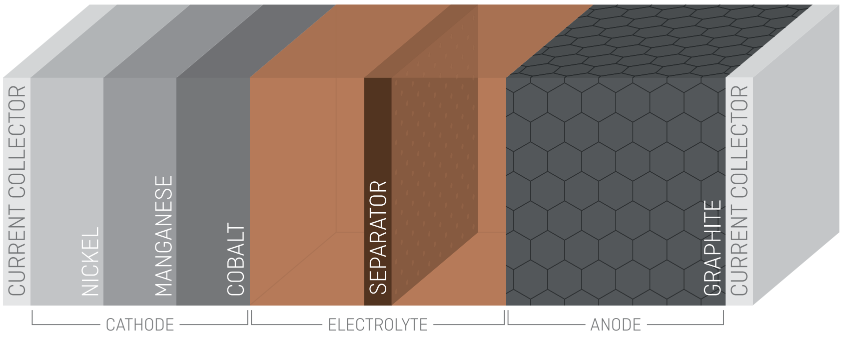
LFP is short for LiFePO4, also known as the chemical indication for **lithium**, **iron** and **phosphate**. This chemical compound forms the basis of the Cathode. One of the most highlighted features of LFP batteries is the **non-usage of cobalt**.

No cobalt or nickel is needed in the development of LFP batteries, and the materials that are used in this type of battery are very common, safe, and easy to obtain. Cobalt and nickel, on the other hand, are scarce and damaging to the environment since the mining of it is polluting the water, air, and soil. Furthermore, they can lead to health issues for those who get in contact with the material.

A second important factor of a LFP battery is that the combination of raw materials used in this battery are very **safe** and **stable**. Even at high external temperatures, or when damage is done to the battery, this type of battery remains stable and fire will not occur.

The third feature of LFP is its long life and **durability**. Lithium iron phosphate batteries live up to 5000 full cycles until end of life which is defined at 80% capacity.

NMC

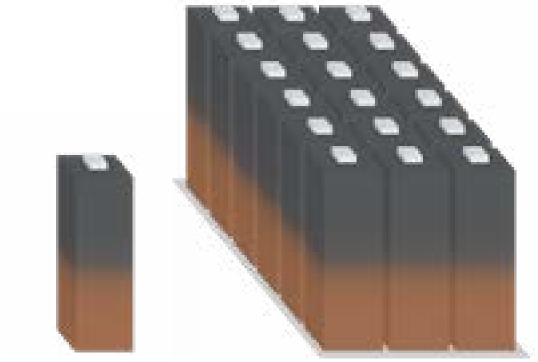


NMC, also known as the chemical indication for **nickel**, **manganese** and **cobalt.** This chemical compound also forms the basis of the Cathode. Nickel is known for its high specific energy and the manganese improves the life span. When combined, all three metals produce a cathode with a high energy density.

At the current stage, the energy density of NMC batteries is higher than that of LFP batteries. The energy density of a battery pack is also referred to as embodied energy. Energy density is the amount of energy a battery holds relative to its weight. A higher energy density is preferred because a smaller high-power battery can provide a higher output. As a result of this, the vehicle is **lighter** and therefore has a longer range, or can be equipped with less batteries for the same range.

Where LFP has a typical lifecycle of up to 5000 cycles, an NMC battery has an expected cycle life of about 2000-2500 cycles, but **degradation** sets in quickly and the full power will be lost soon after its first use. As mentioned before, the chemical compound of a NMC battery consist out of Nickel and Cobalt. Besides the fact that they are highly damaging to the environment, the composition of these raw materials are also highly sensitive. Meaning that if serious damage is done to the batteries, the chemical reaction that will occur in the battery will lead to an instant thermal runaway which causes smoke and fire.

FROM A CELL TO A MODULE



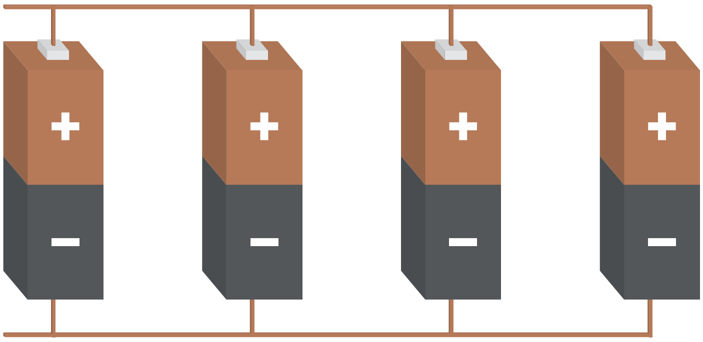
Both LFP and NMC refer to battery cells. These cells come in many shapes and forms. The battery cells are then arranged in modules to achieve serviceable units. For NMC battery, a single battery cell can supply an average of around 3,6 Volt. For LFP this is 3,2 Volt. Looking at applications such as heavy duty vehicles, the voltage of these batteries must be increased drastically to run solely on electric power.

To increase the voltage of the batteries, single battery cells need to be multiplied and combined. To do this, multiple techniques can be applied to form a battery module and pack. By placing multiple cells in a **serie** or **parallel** structure (or a mixture of both), the desired voltage, capacity or power density can be achieved.

BATTERY CELLS IN PARALLEL

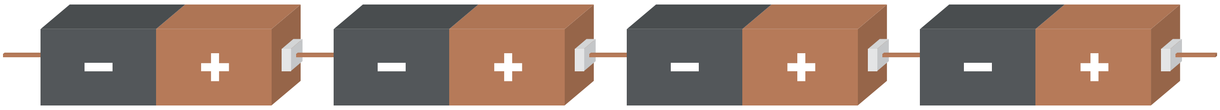
When battery cells are placed in parallel, all positive terminals of each cell, as well as the negative terminals of each cell are connected together. As a result, the **amperes** of each cell will be added together.

For example, wiring 10x 12-volt batteries with 100 Ah capacities in parallel will output 12 volts with a 1000 Ah capacity.



BATTERY CELLS IN SERIE

When battery cells are placed in series, the positive terminal of one cell is connected with the negative terminal of the succeeding cell.



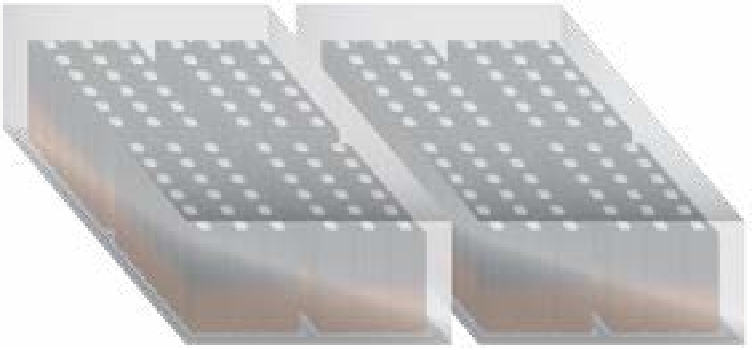
As a result, the **voltage** of each cell will be added together until the end of the series. For example: when wiring 10x 12-volt batteries with 100 Ah capacities in series, the output will be a 120 volts battery pack with a 100 Ah capacity. The main difference in wiring batteries in series vs. parallel is the impact on the output voltage and the capacity of the battery system. Batteries wired in series will have their voltages added together. Batteries wired in parallel will have their capacities, measured in amp-hours, added together. Although the available energy in both configurations is the same, wiring batteries in series provides a **higher system voltage** which results in a lower system current.

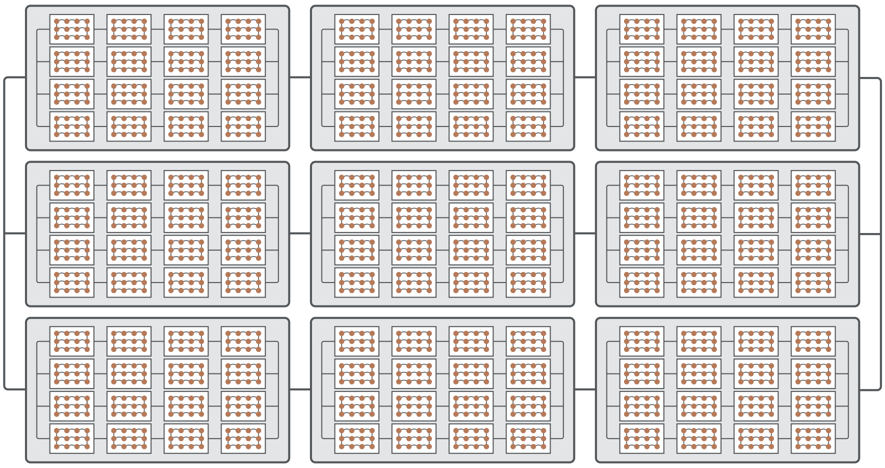
Less current means you can use thinner wiring and will suffer **less voltage drop** in the system. Larger power appliances and generation even need a minimum voltage supply to function at all. Running batteries in series is therefore required. However, a combination of both techniques is the most common solution to meet requirements in voltage and current.

FROM A MODULE TO A PACK

As mentioned before, the cells can be placed in series or parallel to form a module, Then dozens of modules can also be connected in series or parallel to form a **battery pack**.

Then multiple battery packs have to be connected to supply sufficient energy for the vehicle. The connection of these battery packs can also be done in series or parallel.





On the left, you can see a schematic representation of a **battery system** within an electrical vehicle.

Here you can see both cells and modules and then the various battery packs connected in series and parallel. How these are connected can vary per vehicle.

CHARGING

A common assumption is made about how to charge your batteries which is based on the car industry. While it is widely known that most cars should not be charged to a 100%, this is not always the case and can differ for each battery type. Where for NMC batteries, this is indeed correct, this assumption does, however not apply for LFP batteries.

To understand this better, we will take a step back, and look at the chemistry of the battery. As mentioned before, the battery charges with the movement of the electrons from the Cathode to the Anode. Within the Anode, the electrons have to find a spot to position themselves between the graphite. The more spots that are available, the faster the charging progress can go. Once most of the electrons are positioned, and the battery cell is charged to, for example 80%, it will become more difficult for the electrons to find a free spot. Therefore the charging rate will be decreased and the electrons will get more time to find a free spot. Charging of the battery will automatically stop once the first cell reaches 100%.

By decreasing the charging speed, more electrons will get the time to find a free spot. This will allow the battery to charge as much as possible before the first cell reaches 100%. Where NMC batteries are less stable, this battery is more sensitive to these movements of the electrons, and charging the cells to 100% can damage the battery. In this case, charging the battery to 90% is better. For LFP on the other hand, stability is no issue and the battery can easily be charged up to 100% which allows for full use of your battery capacity and thus, extends your range.

Besides the fact that for LFP batteries fully charging is an option, it is also highly recommended.

STATE OF CHARGE

Almost every electric vehicle shows how much remaining capacity the battery still contains. This is indicated with the State of Charge (SOC) which is an percentage comparing the remaining capacitance with the norminal capacitance of the battery. The value is calculated based on the battery behavior, and not a fixed figure. Where for NMC batteries, the SOC number is easier to predetermine, for LFP this is more difficult and may cause deviations between the real amount of energy that the battery still contains, and the percentage indicated.

To explain this, we will use figure 1 & 2. These figures show the discharge schedule of the NMC battery (figure 1) and LFP battery (figure 2).

In this figure, you see the degradation of a typical NMC battery. As you can see, it is mostly an equal decline. For these types of batteries, SOC can be estimated based on the amount of voltage the cells supply. For example,, if the voltage supply is 4 volts, a line can be drawn and the estimated battery capacity is around 80%. If the voltage supply is 3,5, the estimated SOC will be 20%. This estimation will be relatively accurate time after time.

Figure 1 - Discharge NMC battery / SOC calculation

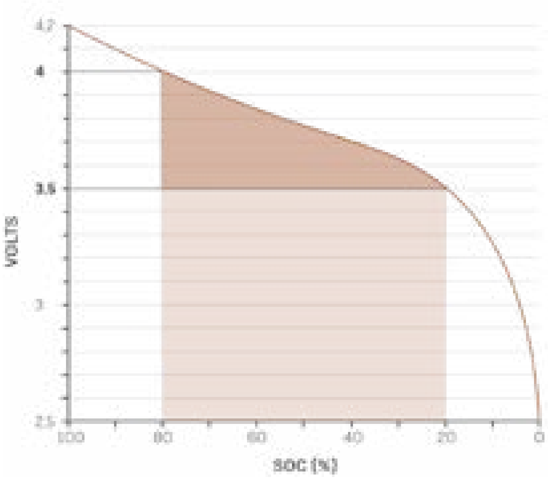
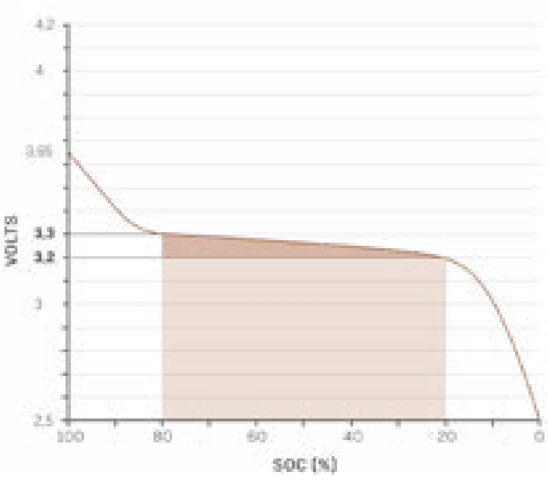


Figure 2 - Discharge LFP battery / SOC calculation



For LFP batteries, as figure 2 shows, the degradation is fairly different and the estimation of the SOC has to be done differently. Where in the beginning the voltage drops, afterwards, most of the energy will be released with an equal amount of voltage. The system does not recognize when the battery is at 20% or at 80% since the voltage supply is almost equal. As a result of this, the State of Charge cannot be estimated by the voltage supply. Instead, the estimated SOC will be based on how long the battery has been delivering almost the same amount of voltage.

However, to do this, the battery must have a fixed starting point. Therefore it is important and highly recommended to charge the LFP battery to 100%. By doing this, the battery calibrates and allows a reasonably accurate reading of the SOC. However, the SOC calculation may vary slightly to around 2% because of a unregistered deviation within the battery that, as mentioned before, occurs through the internal load. If the battery is not charged to 100%, this deviation rate can increase cumulatively.

This means that if for example, the battery is not charged to 100% for 10 days, the SOC may deviate by an additional 2% each day and thus can have a deviation of up to 20% in 10 days. In short, this means that a battery may be empty when 20% SOC is indicated.

BATTERY MANAGEMENT SYSTEM - BMS

The BMS system, also known as the Battery Management System, is an integral part of any lithium-ion battery. This system is integrated into the battery pack to ensure the optimal health and performance of each battery cell and pack.

The Battery Management System monitors individual cells in the battery pack. It then calculates how much current can safely go in (charge) and come out (discharge) without damaging the battery. The current limits prevent the source (usually a battery charger) and the load (such as an inverter) from overdrawing or overcharging the battery. This protects the battery pack from cell voltages getting too high or low, which helps increase the battery's longevity.

As mentioned before, each cell in the battery pack needs to be balanced. The BMS balances the charge across the cells to keep each cell functioning at maximum capacity. As soon as the BMS detects any unsafe conditions, it immediately shuts the battery down, to protect the battery and user.

The BMS also provides a lot of data that can be used for alternative purposes. For example, predictive maintenance can be done when the data, indicates that issues may occur in the future.

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