BATPOWER
Preparation of the VET sector on battery energy transition

Project Nr.: 2024-1-SK01-KA220-VET-000256192

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Module 1– Introduction

Aim of the Module	This introductory unit familiarises students with the fundamental concepts of battery energy and electric vehicle (EV) technology. It covers the various types of energy storage and highlights the pivotal role of batteries in modern electrification. Learners are given a broad overview of battery technology (Battech) – what it encompasses, why it is significant in the transition to clean energy, and key technological aspects such as cell chemistry, energy density, safety, and applications. The module also presents an introduction to electric vehicles, describing core components (electric motors, inverters, battery packs, control systems, charging infrastructure) and how these elements work together. A special focus is placed on the relationship between EV systems and battery technologies, illustrating how advances in battery tech enable EV development and vice versa. The approach balances theory with practical examples in accessible language, preparing learners for the more detailed **Battery Components** module to follow.
Target	Trainers, teachers, and educators of BatTech
Pre-requisites	Basic science knowledge (physics fundamentals) and familiarity with general workshop safety (proper use of simple tools, PPE, basic electrical safety practices).
EQF Level	5 EQF
Methodology	Learning will be activity-based with short theoretical explanations supported by practical demonstrations and visual aids. Concepts are introduced with simplified

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	reasoning and real-world analogies to ensure accessibility. Students might examine sample battery cells or EV component mock-ups, watch video demonstrations of EV systems, and participate in guided discussions. Emphasis is placed on a hands-on feel where possible (for example, observing how a small battery can power a motor) alongside visuals like schematics or diagrams.
Evaluation	Evaluation methods mirror those of the subsequent module, adapted to the introductory content. Short quizzes and oral questions will check understanding of key concepts (such as identifying types of energy storage or naming EV components). Simple practical tasks may be used – for instance, learners might be asked to identify and label components on an EV diagram or compare the energy storage methods used in different devices. Instructors will observe participation in discussions and any hands-on activities to ensure learners can apply concepts (e.g. explaining how a battery powers a motor) and follow safety instructions.

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Module title	Battery Technology and EV Fundamentals
Workload	2 teaching hours, 12 studying hours

Battery Technology Overview

What is "Battech"? Battery technology (often abbreviated as **Battech**) encompasses the science, engineering, and innovations related to batteries and energy storage devices. This field covers everything from the **electrochemistry** inside a single battery cell, to the design of battery packs and Battery Management Systems, to manufacturing methods and even recycling of batteries at end-of-life. In this overview, we highlight a few key areas of Battech: cell chemistry, energy density, safety, and applications.

Cell Chemistry: This refers to the chemical composition and reactions that a battery uses to store and release energy. Different cell chemistries yield batteries with different characteristics. For example, a **lithium-ion cell** typically uses a lithium-based oxide or phosphate at the cathode and carbon (graphite) at the anode. Lithium-ion has become the leading battery chemistry today because it offers a great balance of high energy density, good longevity, and decent safety when managed properly. Other chemistries include **lead-acid** (uses lead and lead oxide with a sulfuric acid electrolyte), **nickel-metal hydride**, and emerging technologies like **lithium polymer**, **solid-state batteries** (which replace liquid electrolyte with solid electrolyte for improved safety and energy density), or **flow batteries** (which store energy in liquid electrolytes in external tanks – useful for large stationary storage though too heavy for vehicles). Each chemistry has advantages and use cases: for instance, flow batteries can be very useful for long-duration energy storage on the grid (since you can just use bigger tanks for more energy), whereas solid-state batteries promise higher safety (non-flammable) and possibly higher energy per kg, making them an exciting area of research for future EVs.

Energy Density: This is a crucial performance metric for batteries – essentially how much energy a battery can hold in a given weight or volume (often expressed in Watt-hours per kilogram or per liter). A higher energy density means a lighter and/or smaller battery can provide the same amount of power, which is especially important for mobile applications like electric vehicles (where weight and space directly affect range and performance). Modern lithium-ion batteries have a high energy density compared to older types; this has been "pivotal in enabling the electrification of transport" because a lighter battery means an electric car can drive further on a charge without being impractically heavy. Learners might recall the example of early EVs or portable devices that had limited range/battery life – improvements in energy density have continuously pushed those limits forward. For instance, maximizing energy density is essentially trying to **"have a small, lightweight battery that stores as much electric energy as possible"**. This involves materials research (finding electrode materials that can pack more ions) and clever

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engineering (efficient packaging of cells, minimal unused space, etc.). However, increasing energy density can sometimes trade off with other factors like **battery lifespan** or **stability**, so Battech aims to improve density while maintaining safety and cycle life.

Safety: Safety is absolutely paramount in battery technology. Batteries store a lot of energy in a compact form, which, if released uncontrollably (for example, due to a short circuit or damage), can lead to fires or explosions – a phenomenon often related to what is called **thermal runaway** in lithium-ion cells. As a result, modern battery systems incorporate multiple safety features. At the cell level, chemistry choices (like adding stabilizing additives, using less reactive materials) help make cells more robust. Battery packs are built with physical protection, cooling systems, and electronic monitoring. The **Battery Management System (BMS)** is a critical piece of safety equipment – it monitors each cell's voltage, temperature, and overall pack health, and can take action (shutting down the pack, balancing cells, controlling cooling) if something is out of spec. According to industry experts, "*safety is priority number one for the battery industry*" and new technologies plus better monitoring are making batteries a very safe way to store energy. For example, if one cell in an EV battery starts to overheat or fails, a well-designed pack will isolate that cell and prevent a chain reaction, so the whole vehicle isn't affected. Key safety considerations learners should be aware of include: avoiding overcharging (too high voltage can trigger reactions), avoiding deep discharging (which can destabilize cells), temperature control (batteries should not get too hot or too cold – more on this below), and protection from physical damage. Many EV battery packs are equipped with **cooling systems** (liquid coolant or air cooling) to remove excess heat, as keeping cells at a happy temperature greatly extends life and safety. There are also mechanical safeguards like **fuses** (which blow if too much current flows) and **contactors** (big switches that can disconnect the battery when the car is off or if there's a fault). In short, Battech isn't just about storing more energy – it's about doing so **reliably and safely**. As battery technology advances, a lot of focus is on making batteries **even safer**, whether through new materials that are less flammable (such as solid electrolytes) or smarter BMS algorithms that can predict and prevent failures.

Batteries are incredibly versatile and their technology is tailored to different uses. In this module we emphasize two big applications: **electric vehicles** and **energy storage for renewables/grid**, because these are central to the energy transition. In electric vehicles, batteries must be relatively lightweight, able to deliver high power (for acceleration), and withstand many charge/discharge cycles over years of driving. They also face stresses like vibrations, wide temperature ranges (a car might be in freezing winter or hot summer conditions), and need to be safe in the event of

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accidents. The typical solution today is a lithium-ion pack, as it meets these needs well. For grid or **stationary storage** (like a battery bank for a solar farm or a home battery system), weight and energy density are less critical (you don't have to carry the battery around), but cost, lifespan, and safety are key – these batteries might charge and discharge every day to balance renewable energy. Interestingly, older or alternative chemistries can find a place here (for example, some communities use large lead-acid or sodium-sulfur battery banks, and flow batteries are used in some renewable energy storage projects because they can last for thousands of very deep cycles). Other notable applications include **portable electronics** (phones, laptops – ultra lightweight and safe batteries are needed), **industrial machines**, **aviation and marine** (where new battery tech is enabling electric airplanes or ships for short distances), and **emergency backup** (batteries in hospitals or data centers that provide instant power if the grid fails). The breadth of applications drives the diversity in battery technology – for instance, an electric bus might use a different battery chemistry optimized more for longevity and cost (maybe LFP – lithium iron phosphate – known for safety and long life) whereas a high-performance sports EV might use a chemistry that maximizes energy and power even at the expense of some cycle life. In any case, all these applications benefit from the continuous improvements in Battech. As batteries get cheaper, more durable, and higher capacity, we see wider adoption: more EVs on the road, more homes with battery storage, and innovative uses like **vehicle-to-grid** systems (where EVs can even send power back to the grid when needed).

Significant achievements like the dominance of lithium-ion batteries (due to their superior energy density and falling cost), and the expectation of soaring demand for batteries in transport and energy sectors, underline how pivotal Battech is today.

Electric Vehicle Basics

Electric vehicles (EVs) are a transformative application of battery technology. In an EV, the traditional components of a gasoline or diesel car are replaced or supplemented by electrical ones. At its core, an **all-electric vehicle** (also called a battery electric vehicle, BEV) uses an **electric motor** instead of an engine, and a **traction battery pack** instead of a fuel tank. Because it runs entirely on electricity stored in batteries, an EV has **no exhaust pipe** – it produces zero tailpipe emissions. This is a key environmental benefit. Also, EVs don't carry fuel in the usual sense; there is no petrol/diesel, fuel pump, or fuel lines. Energy is delivered to the vehicle by **plugging it in** to a power source (the electrical grid via a charger) rather than filling up at a gas station.

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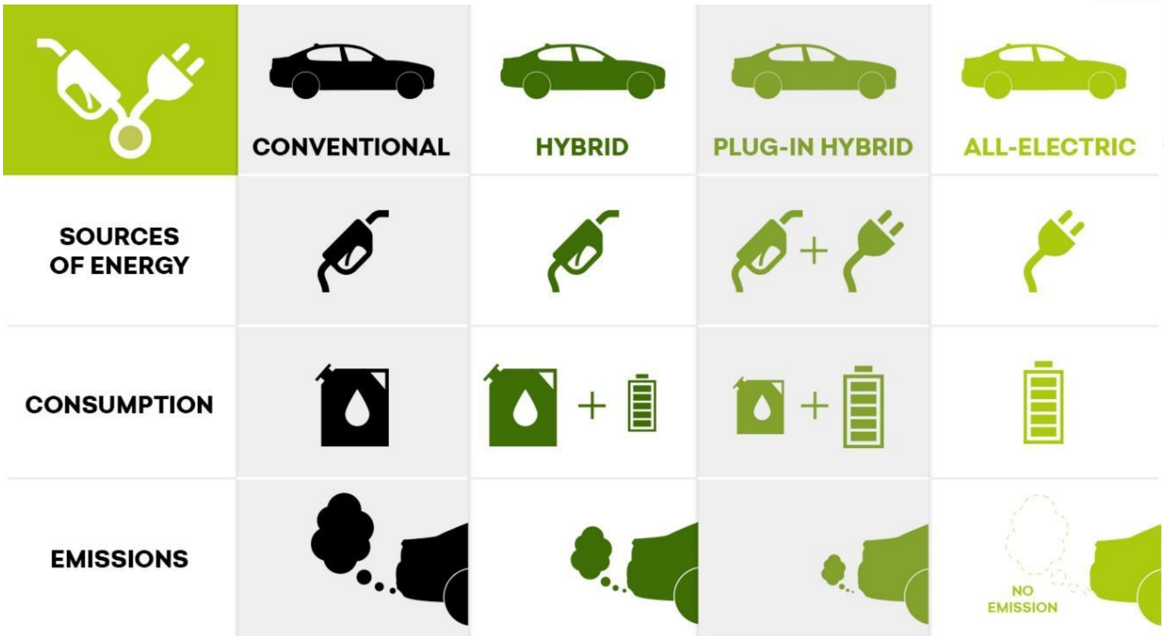
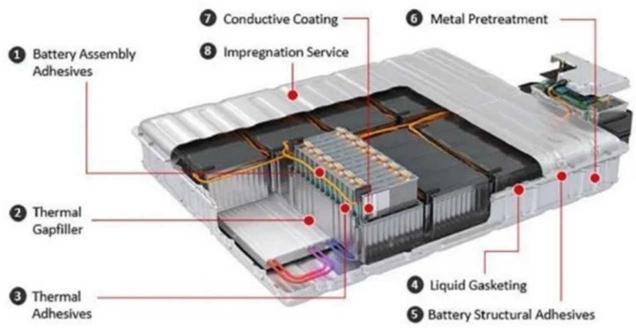


From a user's perspective, driving an EV can feel both very familiar and notably different. Familiar, because you still have a steering wheel, brakes, etc., and you use it largely the same way to get from point A to B. Different, because EVs are very quiet (no engine noise), have instant torque (leading to quick acceleration from stop), and require charging which takes longer than a fuel fill-up (though much of charging can be done while the car is parked, like overnight at home). EVs also have fewer moving parts in the powertrain – no multi-speed gearbox in most cases, no exhaust system, no complex fuel injection system – which can reduce maintenance needs.

Let's break down the major components that make an electric vehicle work. In a typical battery-electric car, you will find these key elements:



Traction Battery Pack: Often just called "the battery," this is a large assembly of battery cells (usually lithium-ion) that stores the energy to drive the vehicle. It's analogous to the fuel tank in a conventional car – it holds the energy, except in electrical form. Many EV battery packs are flat and wide, mounted in the

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floor of the vehicle to save space and improve stability (lower centre of gravity). The capacity of this battery (measured in kWh, kilowatt-hours) determines how far the car can go on a charge – essentially the EV's range. For example, an EV with a 50 kWh battery might go roughly 250-300 km on a single charge, whereas one with a 100 kWh battery might double that (range varies with efficiency, driving conditions, etc.). As a rule, **more battery capacity = longer driving range**, but also more weight and cost, which is why EV design is a balance – you can't just put an enormous battery without considering those downsides. Manufacturers strive to increase the energy density of batteries so that range can be extended without making the battery physically larger or heavier.

Electric Traction Motor: This is the component that converts electrical energy from the battery into mechanical energy (motion) to turn the wheels. Most EVs use **AC electric motors** (often three-phase AC motors like induction or permanent magnet synchronous motors). Since the battery provides DC power, the motor actually works in tandem with an inverter (next component) to run. The electric motor in an EV plays the role of the engine in an ICE (internal combustion engine) car. However, it has some great advantages: it's typically much simpler (fewer parts), very efficient (often 90%+ efficiency converting electricity to motion, compared to ~20–30% efficiency of an ICE converting fuel to motion), and as mentioned, provides instant torque – meaning the motor can deliver power to the wheels very quickly, which is why even modest EVs often feel zippy. Another big difference is that an electric motor is reversible: it can also act as a generator. This is used in **regenerative braking** – when the EV slows down or goes downhill, the motor can switch to generator mode, converting the vehicle's kinetic energy back into electrical energy to **recharge the battery** on the fly. In a conventional car, that kinetic energy would just turn into heat in the brakes and be wasted; EVs can recapture some of it, improving efficiency.

Power Electronics Controller (Inverter): This unit can be thought of as the "brain" and muscle of the powertrain's electrical side. Its primary job is to take the DC power from the battery and convert it into AC power of the appropriate voltage and frequency to drive the electric motor. This conversion is performed by a device

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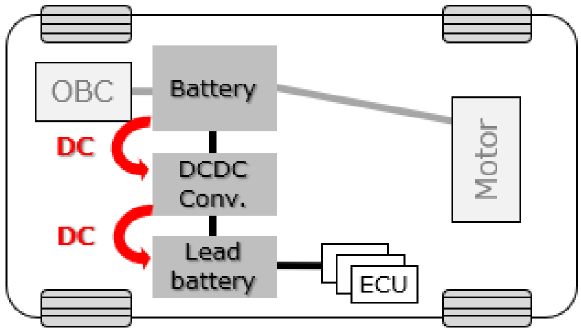
called an **inverter** (since it inverts DC to AC). The inverter doesn't just provide a static output; it actively controls the AC waveform to adjust the motor's speed and torque.



In simpler terms, pressing the accelerator pedal in an EV sends a signal to the power electronics controller, which then delivers more power from the battery to the motor (by adjusting the electrical frequency and current appropriately), causing the motor to spin faster and with more force – thus accelerating the car. Likewise, easing off the accelerator or applying the brake will signal the controller to reduce or even reverse power flow (for regen braking). The power electronics also usually include a **DC/DC converter** to step down the high voltage of the main battery (hundreds of volts) to a low voltage (around 12V) to power lights, radio, and other accessories, similar to how an alternator works in an ICE vehicle. In many EV architectures, the inverter, DC/DC converter, and sometimes the charger control are integrated into a single unit or closely housed, often referred to as a **motor controller** or **electric power control unit (EPCU)** in some literature. Without the inverter and controller, the battery's raw power would not be usable by the motor in a controlled way, so this component is absolutely critical.

Vehicle Control Unit (VCU) and BMS: Modern vehicles have multiple electronic control units. In EVs, a central **Vehicle Control Unit** often orchestrates the overall operation – it's like the supervisory computer that ensures the motor, inverter, battery, and other systems work in harmony. The **Battery Management System (BMS)** is a dedicated control unit for the battery pack. While students will learn more about BMS in the next module, in brief, the BMS monitors each cell's condition (voltage, temperature, etc.), manages charging and discharging limits, balances cells, and communicates with the rest of the vehicle to ensure the battery is used safely and efficiently. If the BMS detects something unsafe (like an overheating cell), it can request the inverter to reduce power or can disconnect parts of the pack. The VCU takes driver inputs and other data (like vehicle speed, etc.) and coordinates everything – for example, if you put the car in "Eco" mode, the VCU might tell the power electronics to limit power to improve range, or if the battery is very low, it might reduce available motor power to conserve energy. **Control systems** in an EV

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thus refer to both the electronic hardware and the software algorithms that manage the power flow, state of charge calculations, thermal management (cooling pumps and fans for the battery/motor), and even things like traction control (preventing wheel slip by adjusting motor torque). These systems ensure the EV operates smoothly, efficiently, and safely without requiring the driver to manage those details.

Charging System (Charge Port and Onboard Charger): Since an EV needs to be plugged in to recharge, the vehicle is equipped with a **charge port** – this is the socket where you connect a charging cable (from a home charger or public charging station). The **onboard charger** is the hardware inside the car that takes incoming AC electricity (from the grid) and converts it to DC to charge the battery. It also communicates with the charging station to negotiate how much current can be drawn, and monitors the battery during charging (often working closely with the BMS to not overcharge the cells). In practice, when you plug in an EV, the electricity goes through the charge port to the onboard charger, which feeds it into the battery at a rate that the battery can safely handle. Many EVs can charge on standard AC (which might take several hours for a full charge) or use **DC fast charging** through special high-power stations – in the latter case, the current is fed directly to the battery bypassing the onboard AC charger (since the station provides DC, effectively performing the conversion outside the car). Nonetheless, the vehicle's systems still manage the charging process to protect the battery. Charging infrastructure is a critical piece of the EV puzzle: it ranges from home wall chargers (typically 3–7 kW power, AC) to public Level 2 chargers (similar power levels, AC) and fast chargers (DC, anywhere from 50 kW up to 250+ kW in the latest stations).

The EV has to accommodate all these by having the appropriate port (for example, a **Type 2** or **CCS Combo** port in Europe, a **CCS1** in the US, etc., sometimes an additional CHAdeMO port for certain vehicles or the Tesla proprietary port in older Teslas). From the learner's perspective, the key point is that an EV is designed to **accept electricity from an external source** efficiently and safely, and this is enabled by the charge port and onboard power conversion electronics.

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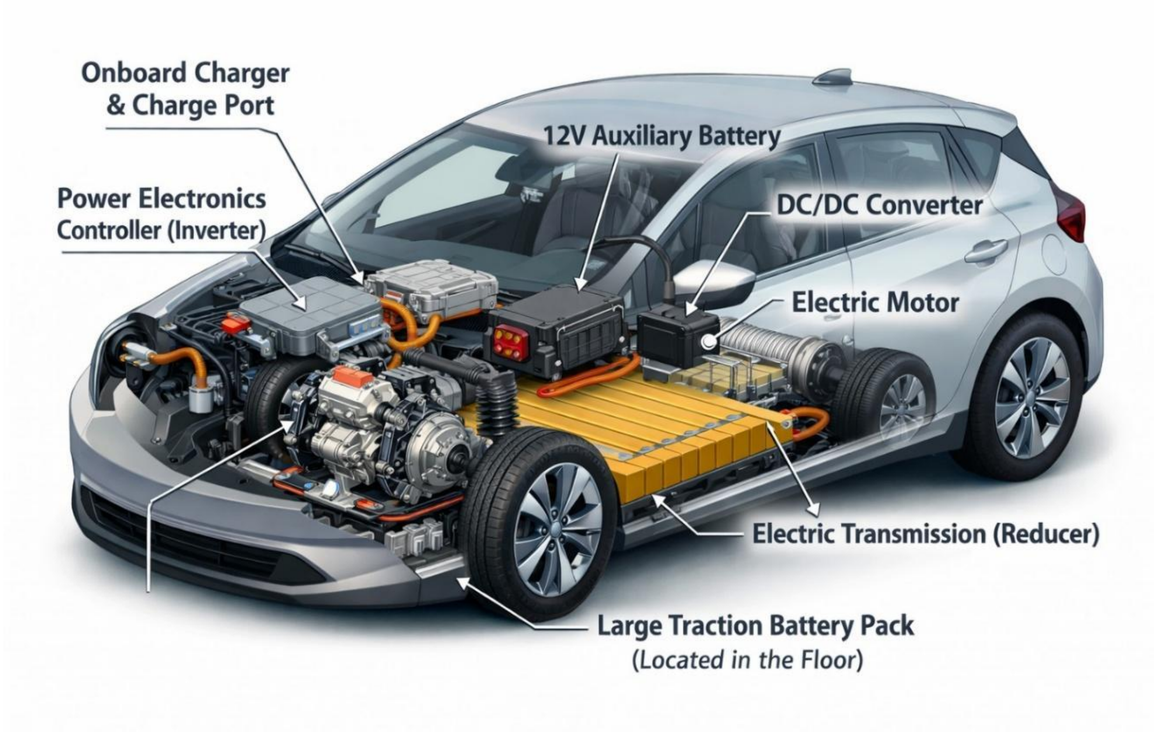
Other Supporting Systems: EVs also include a **thermal management system** (pumps, radiators, sometimes chillers or heaters) to keep the battery, motor, and electronics in their optimal temperature ranges. For instance, batteries can become less efficient or charge slower if they are too cold, and can be damaged if too hot, so many EVs actively cool or heat the battery as needed. Some EVs have a battery heating system to improve performance in winter, ensuring the battery stays within ideal temperature for effective charging and use.



Additionally, EVs have all the normal automobile components like brakes (often with antilock systems integrated with regen braking logic), steering, suspension, etc., but those are beyond our current scope.

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In summary, an electric vehicle simplifies some aspects of vehicle design (fewer moving parts in the drivetrain) but comes with new components centered around managing electric power. For a VET learner, it's useful to correlate each EV component to its traditional counterpart and function: - The **battery pack** is like the fuel tank (energy source), except it delivers electricity instead of petrol. - The **electric motor** is like the engine, converting energy into motion, but it does so with electricity and can also reverse to generate electricity when slowing down. - The **inverter/controller** is somewhat analogous to the engine control unit plus transmission in effect – it controls power flow and adjusts the form of power to suit the motor and driving needs, effectively dictating how the "throttle" from the driver translates to motion.

The **BMS** and vehicle control electronics are like the oversight systems ensuring everything runs within safe and optimal parameters, akin to how an ICE car has an ECU that manages engine timing, fuel mixture, etc., and various sensors. The **charging system** replaces the act of fueling; the car must intake electric energy, which introduces new concerns (charging time, connector standards, etc.) but also new conveniences (you can charge at home and you generally start each day with a "full tank" if you charge overnight).

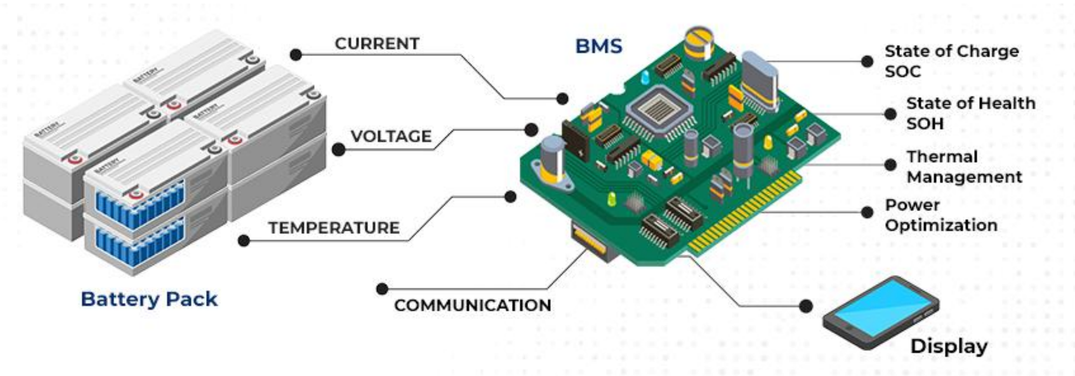

Figure 8 BMS

Illustrative example: Consider a scenario of driving an EV in city traffic. You press the accelerator lightly – the VCU signals the inverter to feed a small amount of AC power to the motor, and the car glides forward silently. When you hit a steady cruise, the motor might only draw minimal power to overcome drag. Now the traffic light turns red – you press the brake. The control system engages regenerative braking: the motor starts acting as a generator, resisting rotation and converting your car's kinetic energy back into electricity, which the inverter channels into the battery. You slow down and come to a stop, having recovered, say, a small percentage of

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energy that would have been wasted as heat in a normal car's brakes. As you wait, the car makes almost no noise; the only active sounds might be a faint hum of a cooling fan if the electronics need cooling. The light goes green, and you accelerate briskly – the EV leaps forward due to the instant torque of the electric motor. You notice it's a chilly day; thankfully the car's battery has a thermal management system that kept it warm, so performance and regenerative braking aren't compromised. This simple journey underlines how the EV's components work seamlessly: the battery provided the energy, the inverter and motor translated that into motion efficiently, and then even recaptured some energy during braking – all orchestrated by control systems to ensure smoothness and safety.

For now, the takeaway is that an electric vehicle is fundamentally an **electro-mechanical system** where batteries and power electronics are as crucial as engines and fuel systems were in the past.

EV Systems and Battery Technology

One of the first questions about an EV is, *"How far can it go on a charge?"* The answer hinges directly on battery technology. As mentioned, higher battery capacity (measured in kWh) typically means more range. However, simply using a bigger battery has downsides: more weight, higher cost, and more space taken. This is why improving the **energy density** of batteries is so critical for EVs – it allows more energy without proportional weight/size increases. Early generation EVs, say around 2010, might have had a 24 kWh battery pack (like the first Nissan Leaf) and a range of roughly 130 km. A current model EV of similar size might have a 60 kWh pack and 400+ km range, but maybe only 30-40% heavier pack, not 2.5 times heavier, thanks to better energy density. Automotive engineers constantly watch battery technology developments (such as new cell chemistries or packaging techniques) because an improvement of even, say, 5% in energy density could translate to either a few more kilometers of range or a few kilograms saved. Conversely, if an EV design calls for a certain range (maybe for a marketing target), that will dictate how large of a battery (with current tech) is needed, which then affects vehicle weight distribution, chassis design, etc. We can see that **battery tech sets the envelope** for EV range and designers must work within that or wait for tech improvements.

Beyond just energy, batteries also have limits on how much **power** they can deliver or accept at once (power is the rate of energy flow, in kW). A sports car EV that accelerates 0-100 km/h in 3 seconds demands very high power from the battery for short bursts. This requires a battery chemistry and design that can output high current without voltage dropping too much or overheating. Manufacturers might use

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special high-power cells for such EVs or more cells in parallel to share the load. The relationship here is that if battery tech doesn't allow high power output, the EV's acceleration will be slower. Similarly, for larger vehicles (like electric trucks or buses), delivering sustained high power (for climbing hills, etc.) means the battery must be capable of that output. Improvements in battery internal design (like lowering internal resistance) directly translate to better performance for EVs. On the flip side, regenerative braking is about **power input** to the battery – how quickly can the battery absorb energy when you slow down. If the battery can't take it fast enough, the EV's system will divert some energy to friction brakes instead (wasting it as heat). Modern EV batteries and BMS are getting better at this, allowing stronger regen (which drivers feel as more aggressive deceleration when lifting off the accelerator, and more energy captured).

EV owners care about how long their battery will last (in terms of years and km before noticeable range loss or needing replacement). This is an area where the EV system (especially the BMS and cooling) and battery tech work together closely. For example, fast charging an EV (especially in heat) can stress the battery and degrade it faster. So car companies manage this by both improving battery chemistry (some newer chemistries handle fast charge better) and by controlling charging via software (the car might slow down the charge rate if the battery gets too hot). Likewise, if a particular cell chemistry has a known weakness (say it degrades if charged to 100% frequently), the manufacturer might instruct the BMS to only charge to 80-90% in normal use to prolong life, or advise customers to do so. The **thermal management system** in an EV – cooling/heating the battery – is there to keep the battery in the optimal range for longevity. If battery tech improves to be more robust (like solid-state batteries might not degrade as fast in heat), then maybe future EVs won't need as elaborate cooling, or can allow more aggressive fast charging with less impact on life. Right now, typical EV batteries can last well over 1500-2000 charge cycles before significant degradation, meaning many can go 200,000+ km retaining perhaps 80% of their original capacity (varies by model). This is already suitable for many users, but the interplay is clear: better battery tech (in terms of cycle life) reduces the need for battery replacements and bolsters consumer confidence in EVs. Many EV makers give battery warranties (e.g. 8 years or 160,000 km for ~70% capacity) – essentially a promise tied to battery tech capability.

As discussed, battery safety is crucial. EVs are designed with crash safety in mind: the battery pack is placed in a protected area (often within a reinforced floor structure) to avoid punctures in accidents. The vehicle's overall safety system (airbags, disconnects) includes special measures for the battery. For example, if a

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severe crash is detected, the pyrotechnic fuses or contactors will typically isolate the battery to reduce risk of shorts or fires. This is a case where the **EV's system design** is adapted around battery characteristics – lithium-ion batteries can combust if the pack is severely damaged, so the car is built to minimize that possibility. Also, as battery tech evolves with safer chemistries (like LFP is known for being thermally more stable than some other lithium-ion chemistries), EV makers might choose those for entry-level cars where extreme range isn't needed but extra safety tolerance is welcome. We see a synergy: cars may use one battery tech vs another depending on what they value (safety, cost, performance, etc.). High-end performance EVs often use NMC or NCA lithium cells for high energy in a small package, while some standard-range models use LFP cells which are heavier for the same energy but very safe and have long cycle life. Each choice influences the vehicle – weight distribution, cost and even software (BMS algorithms differ per chemistry).

EV adoption depends on charging infrastructure, which in turn somewhat depends on battery capabilities. For instance, early EVs with smaller batteries could get by with slower charging (because their batteries couldn't take very high currents safely, and also they didn't need as much energy per charge). As battery tech improved, allowing for larger capacities and also the ability to accept faster charging (some modern batteries can charge at over 200 kW, adding ~300 km of range in 20 minutes under ideal conditions), the infrastructure is now racing to provide those high-power chargers along highways. There's a push-pull: if batteries didn't improve, we wouldn't need 350 kW chargers; but because batteries are now capable (and drivers want faster pit stops), the tech and infrastructure co-evolve. Students should understand that "*charging an EV*" is not only about the charger – the battery itself largely dictates how fast it **can** charge. The BMS will often limit charging rate at certain states of charge or temperatures to protect the battery. Some newer battery technologies claim the potential for ultra-fast charging (e.g., special electrode designs that can be charged to 80% in 10 minutes without damage). If those materialize, EV systems (from the grid to the car's cooling system) will adapt to handle the higher power transfer. In essence, improvements in battery tech (like fast-charge capabilities) directly enhance the practicality of EVs by reducing charging downtime, which is a key factor for consumer acceptance.

The fact that EVs carry large batteries influences vehicle design significantly. Many EVs are built on "skateboard" platforms where the floor is filled with battery modules. This gives a lot of design freedom for the cabin (no need to accommodate a driveshaft tunnel or engine bay, unless it's used for cargo/frunk). However, it also means the car's structure must account for a heavy slab of weight below – which

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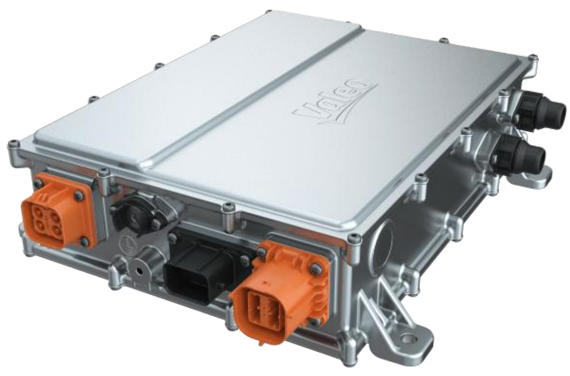
actually is beneficial for handling (low center of gravity) but can be challenging for suspension tuning. As battery tech evolves to possibly lighter or differently shaped batteries (some companies experiment with structural batteries that form part of the car's frame, or with different cell form factors that can pack more efficiently), car designs may further change. For example, if solid-state batteries allow 50% more energy in the same space, future EVs could either offer much longer ranges or, alternately, could achieve the same range with a physically smaller battery, potentially making the vehicle lighter and cheaper, or freeing up space for other uses. We mention this to illustrate that studying EV systems isn't static – it's closely tied to battery advancements. A mechanic or engineer working with EVs has to keep an eye on battery tech trends, because what's inside the vehicle will change as batteries improve.

Figure 9 Location of the battery in the EV

It's worth noting how EV popularity is feeding back into battery technology progress. Demand for EVs has led to massive investment in battery manufacturing (gigafactories being built) and research (governments and companies pouring funds into next-gen batteries). This surge helps improve battery tech further (scale brings down cost, research yields better chemistries), which in turn makes EVs even more attractive (cheaper, longer range, etc.). From a bird's-eye view, batteries and EVs are evolving together rapidly in this decade. For learners at EQF 5, it's important to grasp the trajectory: past decade saw lithium-ion become dominant with big cost drops; the coming years



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promise even greater production and possibly new chemistries (like lithium-iron-phosphate gaining ground for its cost and safety, solid-state on the horizon). EV systems will adapt to whatever makes the best battery – for instance, if one day we have sodium-ion batteries (cheaper but heavier) for stationary storage, EVs might stick with lithium variants for better weight, etc. The key is that you can't fully separate the study of electric vehicles from the study of batteries.

Practical focus – what does this mean for a technician or student? It means that to work with EVs, one must understand at least the basics of battery behavior. For example, an EV technician should know that if a car is performing poorly in cold weather, part of the reason might be the battery's reduced capability at low temperature and that the vehicle's battery heater or management might be at work. If an EV owner complains that fast charging slowed down at 80% charge, a knowledgeable explanation is that the BMS is tapering current to avoid overcharging the lithium-ion cells (a normal behavior). If someone is evaluating different EV models, understanding that one car's battery is 75 kWh and another's is 50 kWh and how that affects range and possibly power output is crucial. Also, safety protocols are heavily related to the battery – e.g., knowing how to safely disable a high-voltage system before servicing an EV, or how to respond if an EV battery is suspected to be overheated or damaged (such as after a collision), are all grounded in understanding battery tech.

Finally, consider an example scenario highlighting EV-battery interplay: **towing or hauling with an EV.** Towing a trailer causes much higher energy draw (like going up a steep hill continuously). An EV's range can drop significantly in this situation. Why? Because the motor is doing more work and pulling more power from the battery. The battery drains faster, and if it gets too warm, the vehicle might even limit power to protect it. In extreme cases, continuous high discharge can heat the battery and the BMS might step in to reduce output or ramp up cooling. This is not unlike a traditional car's engine heating up under load and the cooling system engaging. The difference is that in an EV, both the **energy source and the powerplant** produce heat that must be managed (battery and motor/inverter heating). Manufacturers may advise against heavy towing in very hot weather or may include extra thermal headroom for the battery in vehicles intended for such use. This shows how the intended *use case* of the EV (a system consideration) affects battery requirements (tech consideration).

In conclusion, the success of an electric vehicle is fundamentally linked to its battery. The phrase "EV systems and battery technology" could almost be reversed – without advanced batteries, modern EV systems as we know them wouldn't exist. As you

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continue to more advanced modules, keep in mind this big picture: improvements in battery technology (higher capacity, lower cost, faster charging, better safety) directly translate to more capable and accessible electric vehicles. And conversely, the challenges faced in EV applications (needing more range, handling quick recharge, ensuring safety over a million kilometers in a truck, etc.) are the driving questions that battery technologists are trying to answer. This symbiotic relationship will define the pace of the ongoing transportation revolution.

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Learning Reflection: At this point, you should be able to articulate why a breakthrough in battery chemistry (say a new type of cell that is much cheaper or more energy dense) would matter so much to EVs, or explain to someone why "batteries are the key to sustainable transport and energy" in practical terms. Electric vehicles provide a very tangible and exciting context to apply battery knowledge, and as a future technician or engineer, you'll likely witness and contribute to rapid developments in both these fields.

Evaluation Reminder: Be prepared to identify EV components and their functions and discuss how they relate to the battery. For instance, you might be asked in a quiz: "What does an inverter do in an EV and why does the battery need it?" or "How does cold weather affect an EV's battery and what does the vehicle do to compensate?" Such questions connect the dots between the battery tech and the overall electric vehicle system – exactly what this module has aimed to introduce. With this foundational understanding, you will be well-equipped to dive into the specifics of battery components and safe handling in the next module.

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Module 2 – Battery Components

Aim of the Module	This competence unit will focus on providing trainers with a solid understanding of the structure, composition, and operation of the main components that make up a battery system. It covers cell chemistry, module and pack configuration, battery management systems, and safety devices, highlighting their role in electric vehicles and stationary energy applications. The aim is to enable trainers to interpret technical documentation, explain functional principles, and guide learners in recognising and handling battery components safely and effectively.
Target	Educators (teachers and trainers)
Pre-requisites	Participants should possess a basic background in electrical or mechanical engineering, electronics, or industrial automation. Familiarity with energy systems and vehicle technology is recommended but not mandatory.
EQF Level	EQF 5
Methodology	The module follows a competence-based and blended learning approach, combining short theoretical inputs with practical demonstrations and digital learning tools. Case studies from industry and guided discussions support the link between technical content and teaching practice. Participants are encouraged to apply the acquired

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	knowledge through simulations, collaborative tasks, and reflection on classroom implementation.
Evaluation	Evaluation focuses on both knowledge and practical application. Trainers are assessed through short tests, observation during exercises, and a brief teaching activity proposal. Feedback and self-assessment tools, aligned with the project's quality assurance framework, ensure consistency and continuous improvement in learning outcomes.

Contents	Basic electrical engineering
	On-board electronic networks
	Battery components
	Procedure and assembly
Module title	Battery Components
Workload	2 teaching hours, 10 studying hours

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Electrical circuits

An electrical circuit is a closed path through which electric current can flow. It consists of a voltage generator, conductor cables (usually copper wires, but also silver and aluminium) for the passage of electrons, and a user (such as a light bulb, motor, etc.) that converts electrical energy into another form, such as light or movement. A switch can be inserted to open or close the circuit, interrupting or allowing the flow of current. A very important component for safety is the fuse, which breaks in the event of excessive current flow, thus protecting the circuit and the component.

The basic components of an electrical circuit:

1. Power supply (e.g. battery)
2. User (e.g. light bulb)
3. Switch (e.g. push button)
4. Cables
5. Protective fuse (A)

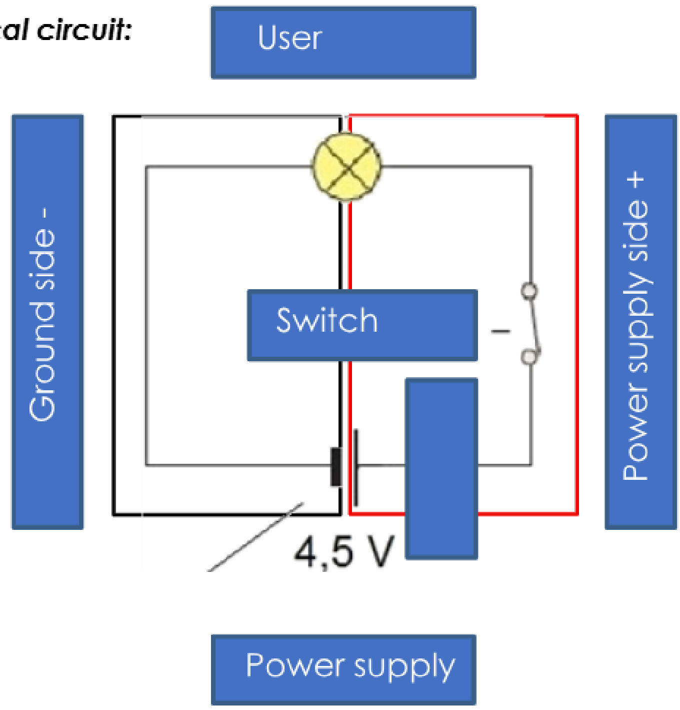

Figure 11: The basic components of an electrical circuit

N.B.: An electrical diagram only shows us how the various components are connected. It does not provide any information about the function of the components themselves, nor about the wiring layout. The colours/colour codes and sections of the wiring in the vehicle must correspond to those indicated on the wiring diagram.

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Main electrical quantities

1. Voltage – Volt (V): potential difference between the two poles of a generator
2. Current – Ampere (A): amount of current passing through the circuit in 1 second
3. Resistance – Ohm (Ω): how much current a user (e.g. light bulb) absorbs in order to function
4. Capacitance – Ampere-hour (Ah): amount of current passing through the circuit in 1 hour
5. Power – Watt (W): electrical work flow in 1 second
6. Energy – Wh: electrical work flow in 1 hour

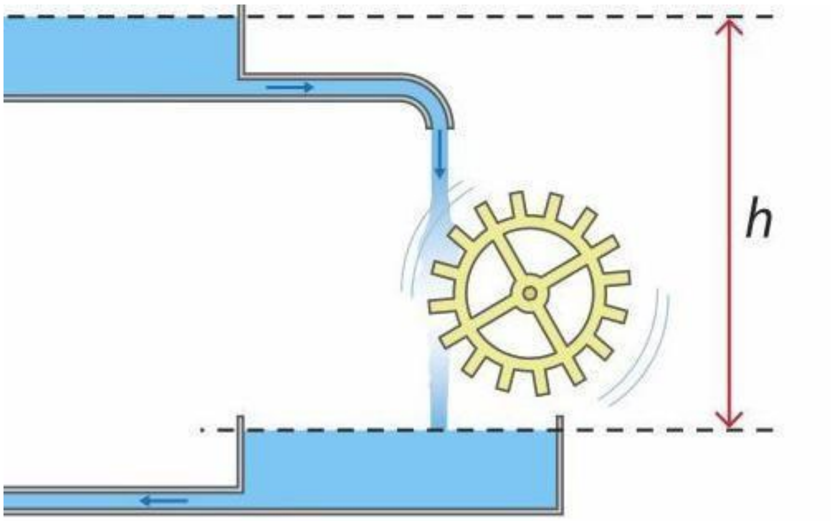

Figure 12: Cascade similarity

We can compare an electrical circuit to a hydroelectric power generation. Voltage (SI unit of measurement: VOLT - V) is the height, the difference in height between the two points of the cascade. The greater the difference in height, the greater the voltage. The lower point represents the (-), Ground, while the upper point represents the positive (+). The positive and negative poles of a battery are called the cathode and anode, respectively.

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Current (SI unit of measurement: AMPERE - A) is comparable to the flow of water between the two points of difference in height. In an electrical circuit, current consists of the orderly flow of electrons through the conductor. There are two directions of current: the actual direction, which goes from the anode to the cathode, and the conventionally used and measured direction, which is the opposite, i.e. from the cathode to the anode.

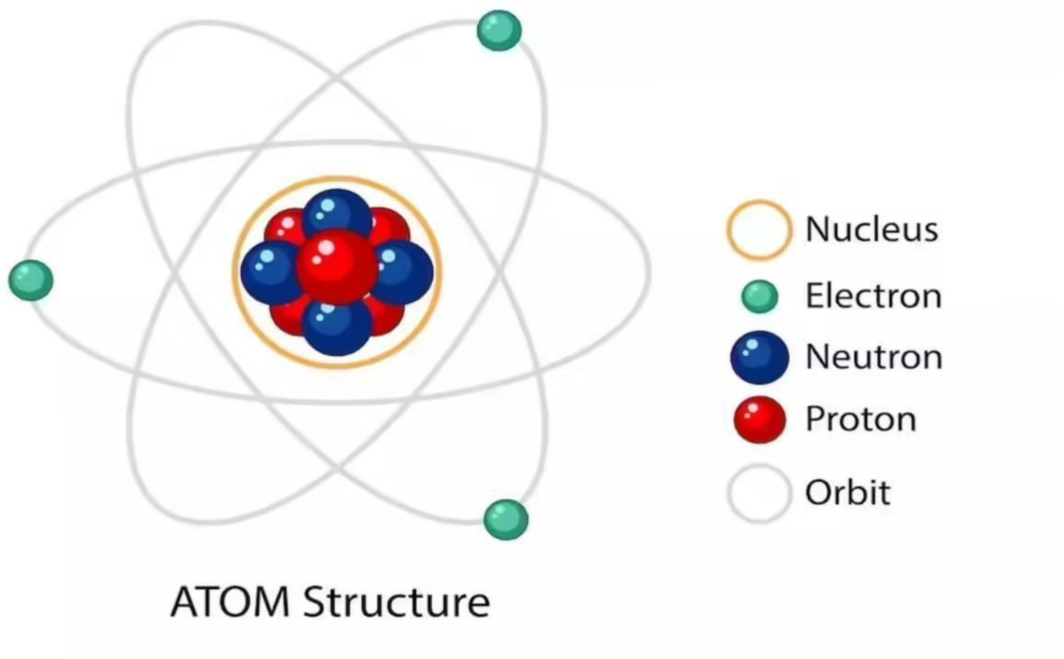

Figure 13: The structure of an atom

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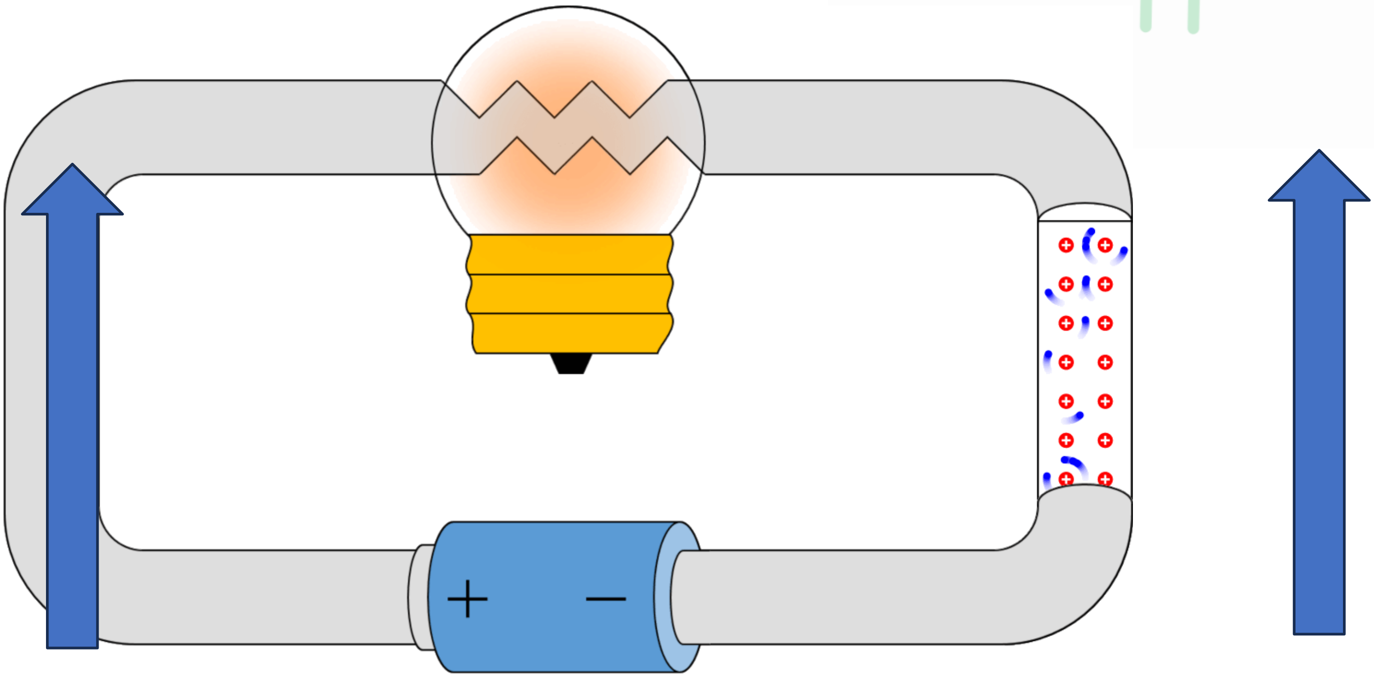

Conventional direction

Real direction

Figure 14: Electric directions

Resistance (SI unit of measurement: OHM - Ω) represents the resistance that a user offers to the passage of current. In this case, the impeller.

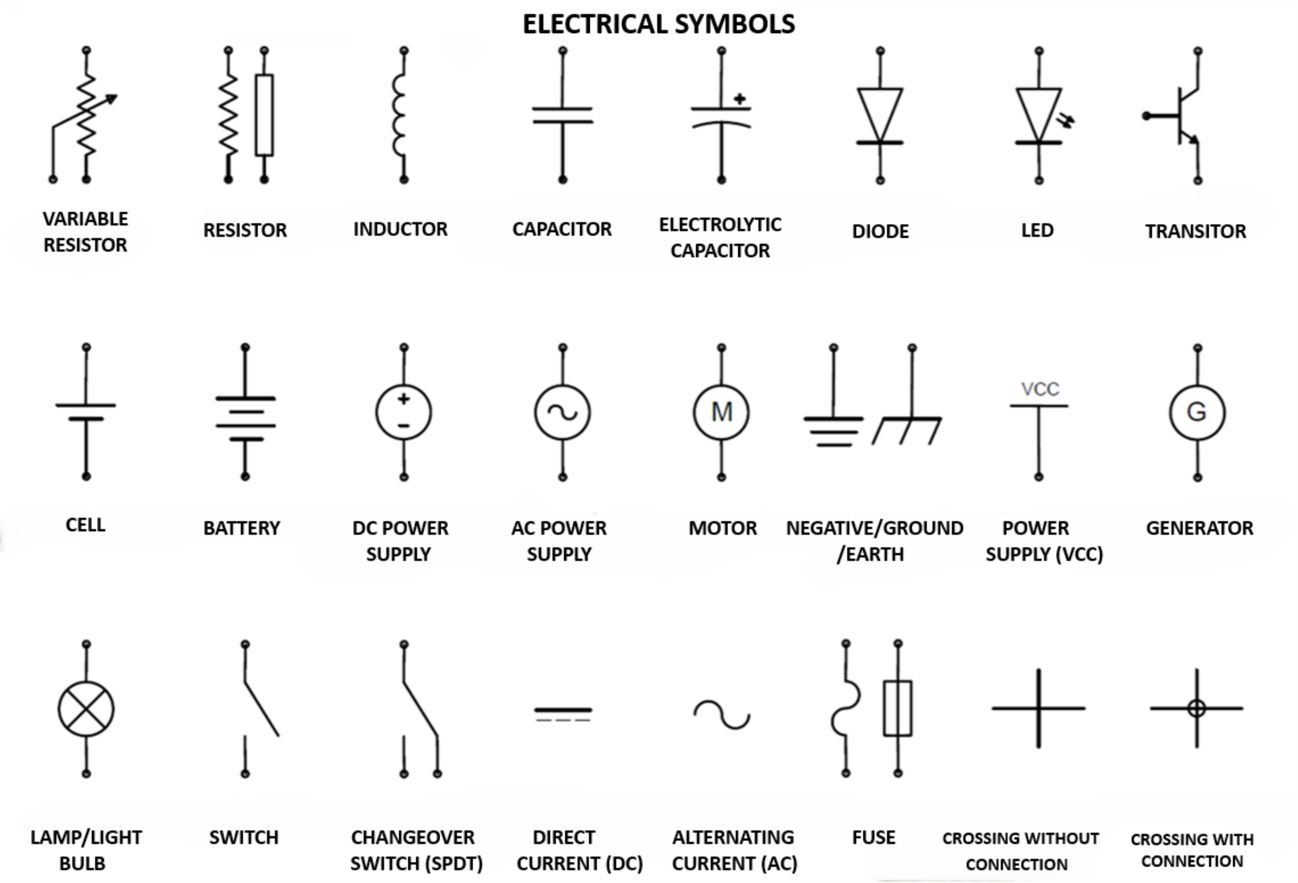

Figure 15: Electrical Symbols

Ohm's law:

1. Voltage (V) = Current (A) x Resistance (Ω) The inverse formulas are: A = V/Ω and Ω = V/A
2. Resistivity of a material = material constant x (Length/area in mm2)
3. Power Watt (W)= V x A
4. Energy (Wh) = V x Ah

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Multimeter – clamp meter and their use

A multimeter and clamp meter are used to measure electrical quantities.

NB: it is very important to check that the instrument's range of values is suitable for the values to be measured. E.g.: to measure the voltage on full hybrid batteries, you need a category 3 multimeter and a clamp up to 1000 A DC.


Figure 16: Ammeter Clamp

The ammeter clamp is used to take an indirect measurement of the current by measuring the magnetic field generated by the passage of current in the cable itself.

Figure 17: Multimeter

With the multimeter:

- Voltage: with the circuit switched on, under voltage, with the probes parallel to the load.
- Current: with the circuit switched on, in Current mode, with the probes in series (e.g. both on the + line, or both on the - line)

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	- Resistance: with the circuit not powered, placing the probes parallel to the user

N.B.: When measuring voltage, it is important to measure both the battery voltage and the voltage actually reaching the user. In fact, although wiring is conductive, it never has a resistance of exactly 0.00Ω, but will always have a minimum amount of resistance.

The difference between battery voltage and user voltage is called VOLTAGE DROP, and must not exceed 0.6 V.

Example: Voltage measured between + and – of the battery: 12.5V. Voltage measured at the user terminals:

12.1V. Voltage drop: 0.4V, correct value.

Direct and alternating current

There are two types of current:

1. Direct: indicated by the letters DC
2. Alternating: indicated by the letters AC. It can be single-phase or three-phase

The batteries on board the vehicle operate on DC,

while the electric traction motors operate on three-phase AC. There is an inverter that converts DC to AC and vice versa. It is called an AC-DC converter.

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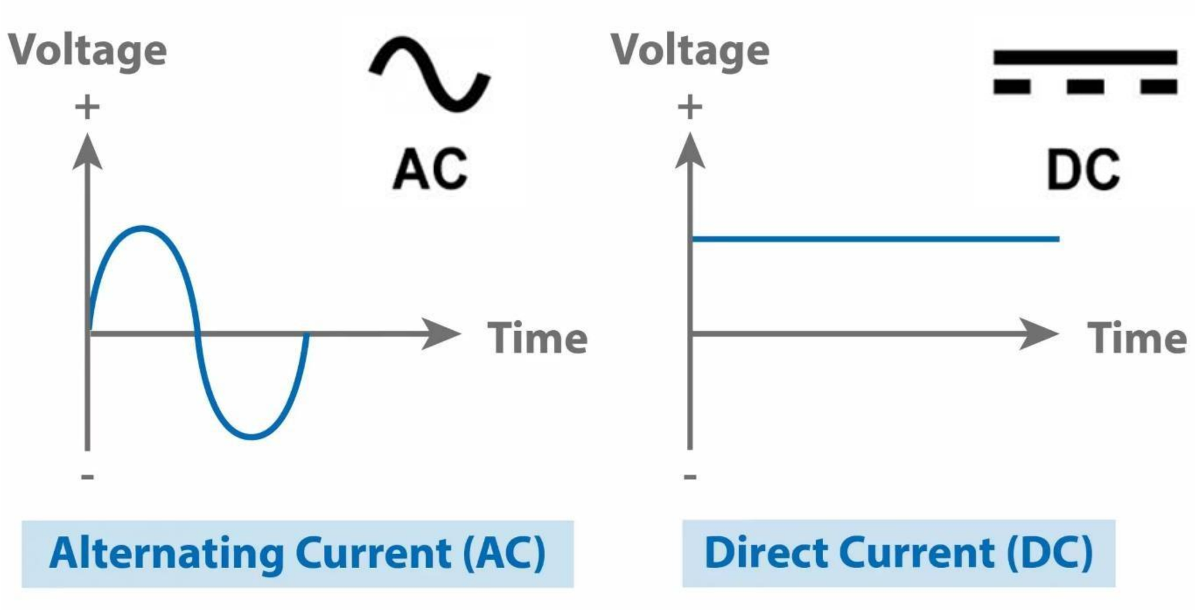

Figure 18: Alternating and Direct Current

Connection of two resistors/users:

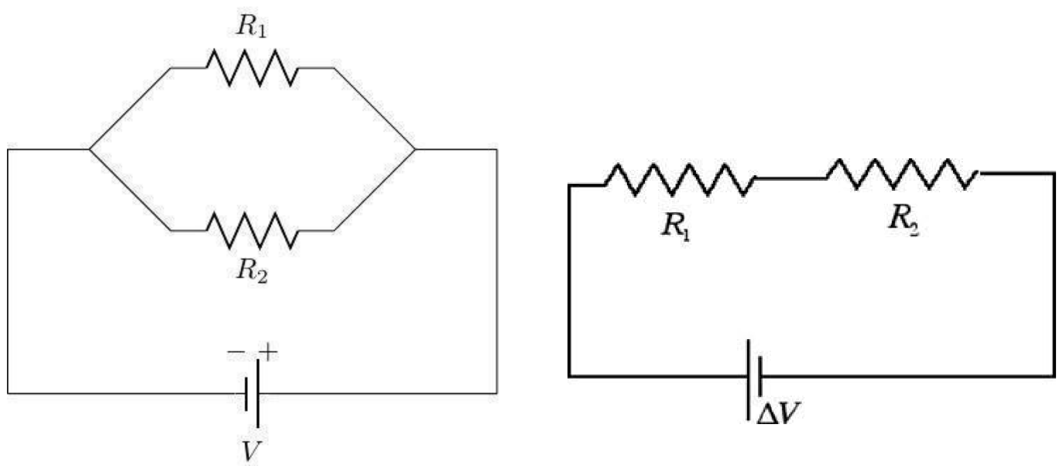

Figure 19: Resistors

In parallel (1): one next to the other. In series (2): one after the other.

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On board the vehicle, the resistors are connected in parallel: if one of them breaks (burns out), the others can continue to function. Example: rear lights, indicator lights.

In the case of resistors in series, on the other hand, sensors are based on measuring the variation in voltage between two resistors, one fixed reference and the other variable depending on the parameter being measured (e.g. temperature). These sensors are called 'voltage dividers', the best known of which is the NTC temperature sensor.

Calculation of the sum of resistances:

1. In parallel: Total resistance = (R1 x R2) / (R1 + R2)
2. In series: Total resistance = R1 + R2

Relays

These are components of electrical circuits that allow a circuit with higher currents to be controlled by activating a low-current circuit. The advantages are: safety, as the switch we operate is in the low A circuit. Reduced bulk, as we will only bring small section cables into the passenger compartment. The relay is located near the 12V battery.

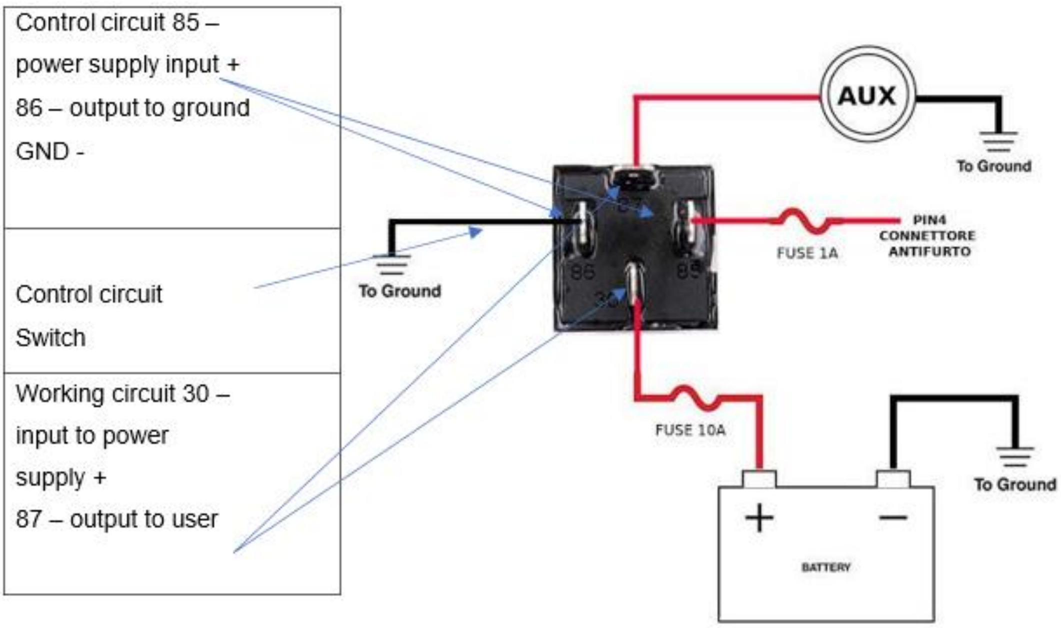

Figure 20: Circuits and relays

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On-board electronic networks

An electronic network always consists of three basic components:

1. Sensors: components that "capture" a physical quantity (e.g. temperature, pressure, rotation speed) and convert it into an electrical signal, voltage (volts), which is sent to the control unit. This electrical input signal is called Input.
2. The ECU, which receives inputs from the sensors, processes them by comparing them with reference values already stored in its memory (ROM and RAM, for example), and then sends an output signal (in volts) to the actuators. This signal is called the output.
3. Actuators: components that receive an output from the ECU and convert it into work; examples include engine injectors, airbag pyrotechnic charges and electric motors.

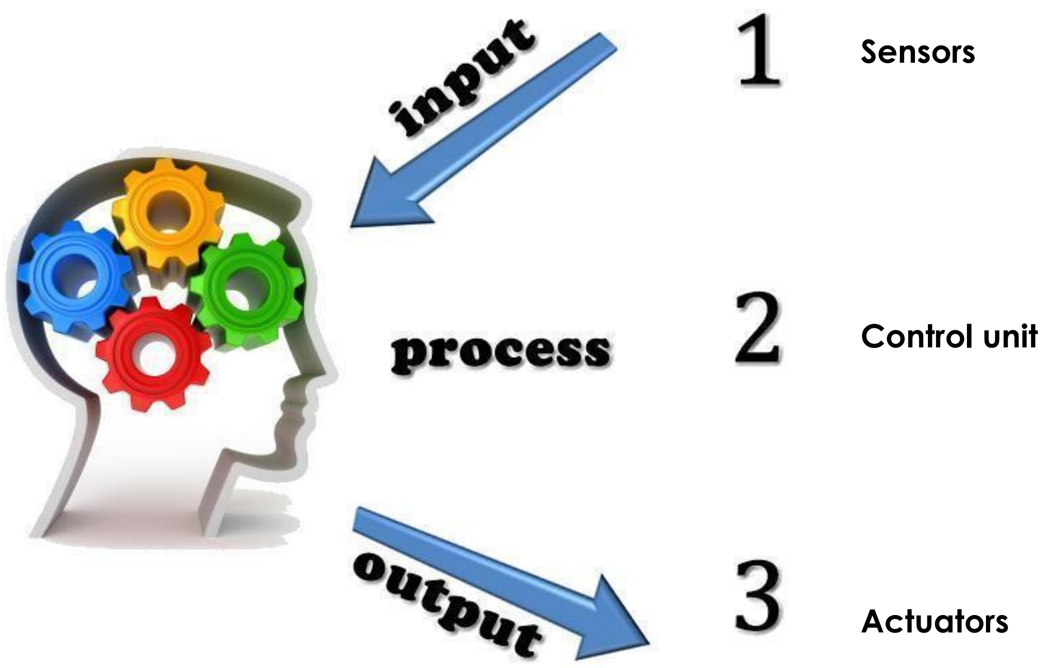

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Figure 21: How electronic networks work

The ECUs therefore receive, process, compare and produce only voltage signals. In fact, they are "very powerful voltmeters". The signals coming from the sensors (powered by the ECU itself at 5V) are usually in the 0-5V range, while the commands for the actuators can reach up to 40-60V (e.g. injectors). The ECU itself 'takes care' of lowering or raising the voltage levels, relative to the nominal 12V battery supply.

A local network consisting of sensors, ECUs and actuators, in which the ECU itself always has control, is called a 'MASTER-SLAVE' network, in which the control unit is the Master, while the sensors and actuators are slaves.

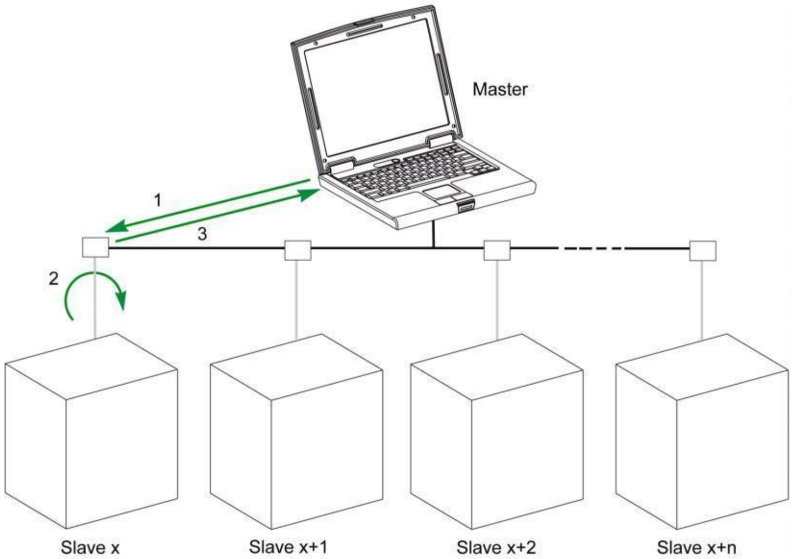

Figure 22: Local networks

Within this type of programming, "every time there is a command, there must be at least one feedback control". An example is the command for the engine liquid cooling fan, which remains on as long as the NTC temperature sensor transmits the value corresponding to the desired temperature reduction in V.

Analogue and Digital Signals

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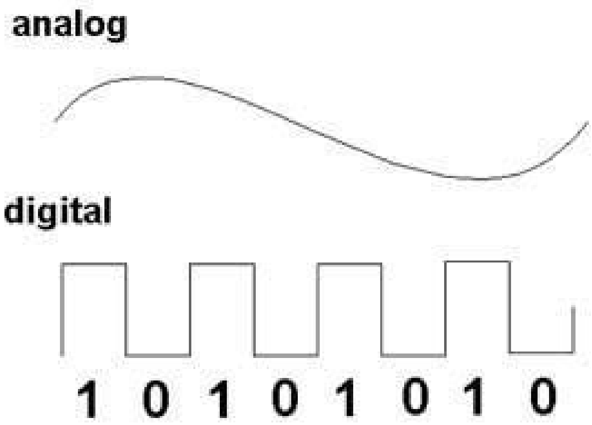

Figure 23: Signals

The transmission of a voltage signal as a function of time can be of two types:

1. Analogue: a signal that varies gradually between its minimum and maximum values.

2. Digital: which has only two values, ON or OFF. Each individual value is called a bit, which can be dominant (1) or recessive (0). Square wave signals are called PWM.

A sequence of 8 bits is called a byte, and can transmit 256 pieces of information, or 2^8

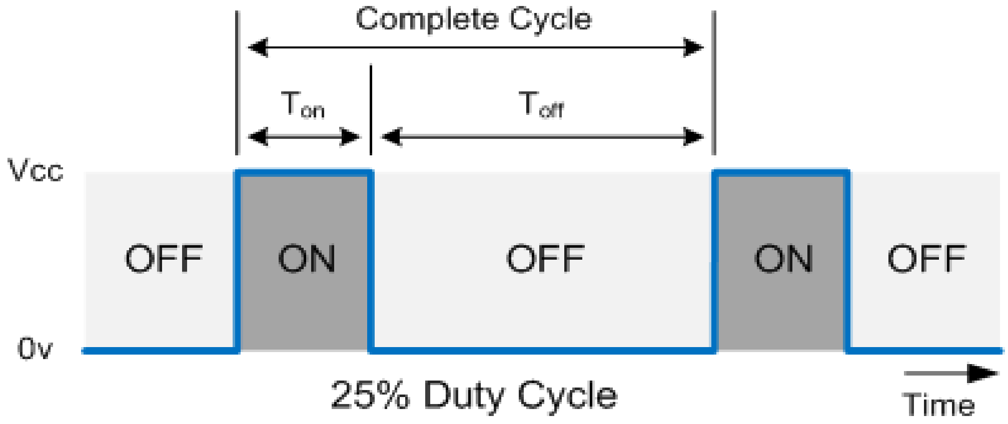

Figure 24: Cycles

To measure a PWM signal, a complete cycle must be taken and "transformed" into a percentage. By definition, a complete cycle will be 100%. Within this, it is necessary to measure, again in %, how long the signal is 'on' and how long it is 'off'. The percentage of

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time that the signal is "on" is called the duty cycle, or DC. It must always be defined when working with PWM.

To switch from analogue to digital, a special converter is required, which can be integrated into the sensor body or into the control unit.

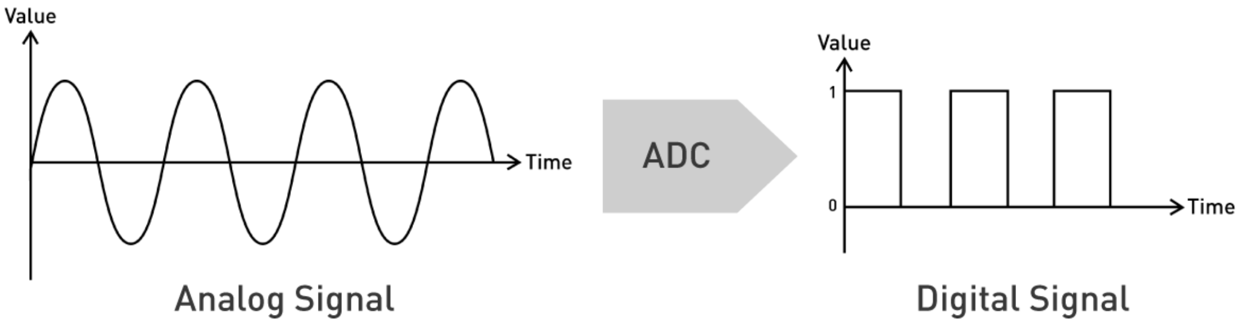

Figure 25: Analog vs Digital signals

The computing power of a microprocessor is evaluated based on several factors, but the most common are clock speed (measured in GHz) and the number of cores. Other important parameters include FLOPS (floating point operations per second), architecture and the efficiency of individual cores, which together determine the actual capacity of the processor to perform calculations.

1. Clock speed (GHz): Indicates how many processing cycles the processor can perform per second; a higher value corresponds to greater theoretical speed.

2. Number of cores: Represents the number of independent processing units on a single chip. A multicore processor can handle multiple tasks simultaneously, improving productivity.

3. FLOPS: Measures the floating-point operations that the processor can perform per second and is a crucial parameter for scientific and complex calculations.

4. Architecture: The design of the processor affects its efficiency. A newer CPU based on a more modern architecture may be faster than an older one with a higher clock speed, as it handles operations more efficiently.

CAN-BUS networks and communication protocols

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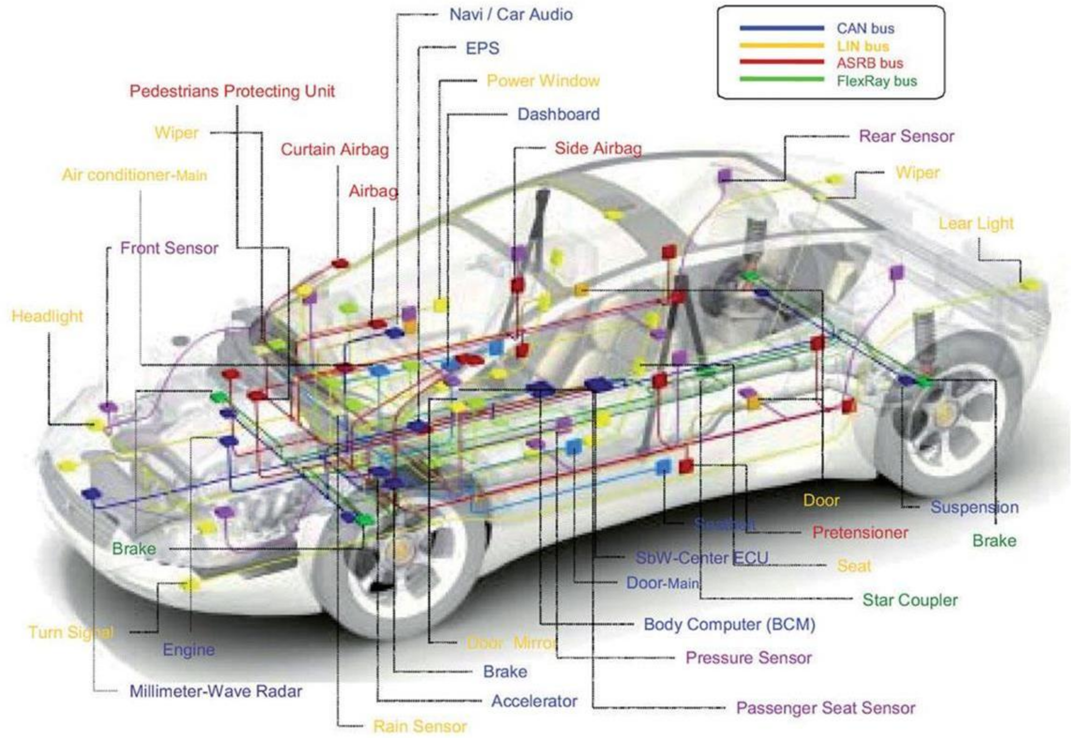

Figure 26: visual representation of CAN-BUS networks and communication protocols

With the increase in the functions managed by individual local networks (e.g. engine, ABS, airbags), it became necessary to connect them so that they could operate in an integrated manner.

The first CAN-BUS protocols in cars date back to the early 1990s, with the aim of integrating the various local networks. This is a communication protocol between control units that uses digital serial data buses. It has its own design features, such as:

1. It consists of two twisted cables, CAN-H and CAN-L, respectively, in order to minimise interference caused by electromagnetic fields.

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Figure 27: Red electric cable

When there is no communication, CAN-H and CAN-L are both powered at 2.5V each.

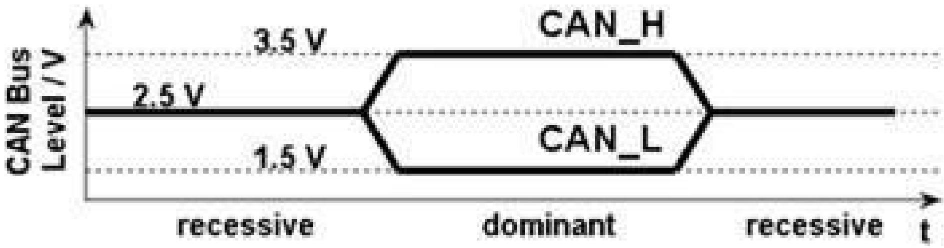

Figure 28: CAN

2. Mirroring of the CAN-BUS frame signal: when communication is active, the voltage on CAN-H rises from 2.5 to 3.5V, while on CAN-L it drops from 2.5V to 1.5V. Difference between H and L: 2V.

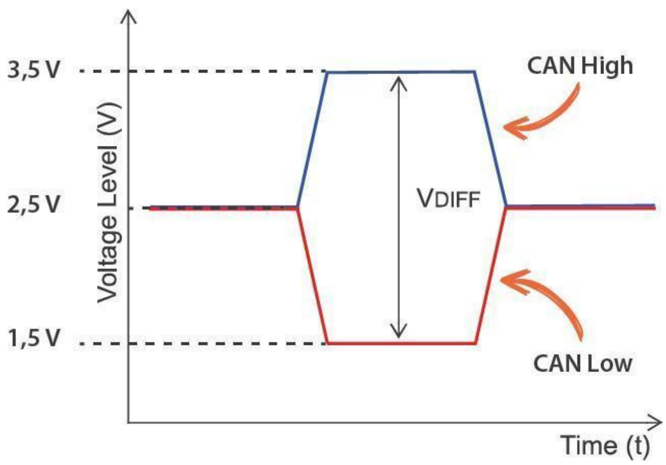

Figure 29: Voltage levels in CAN

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3. Arbitration logic: as it is a serial system, only one message passes through a CAN network at a time. Priority is established each time by the sequence of the first 12 bits: whoever has the highest priority passes first.

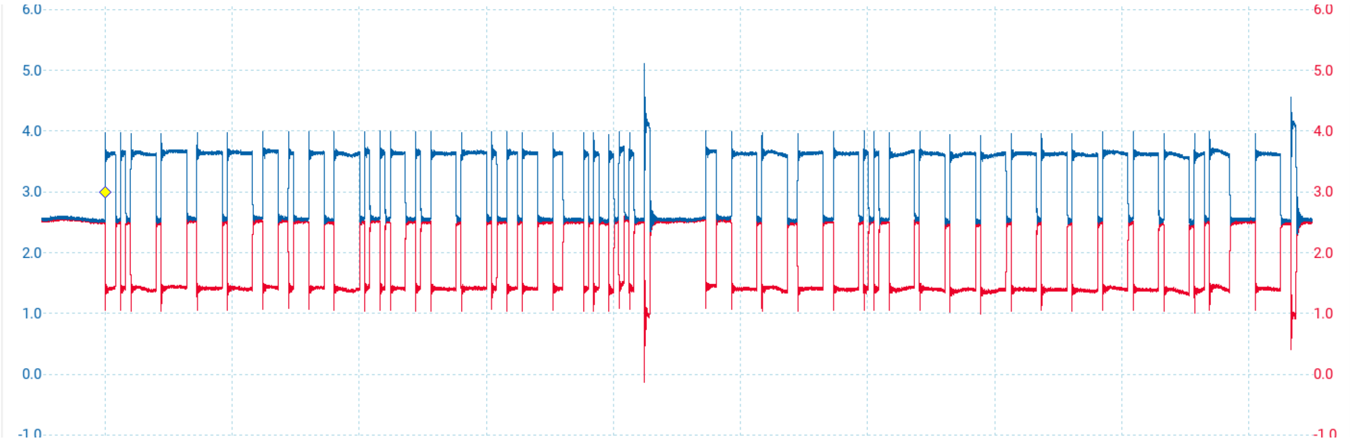

Figure 30: Visualisation of arbitration logic

4. There are two terminal resistors at the ends of the two cables, both 120Ω/each, mounted in parallel, resulting in 60Ω.

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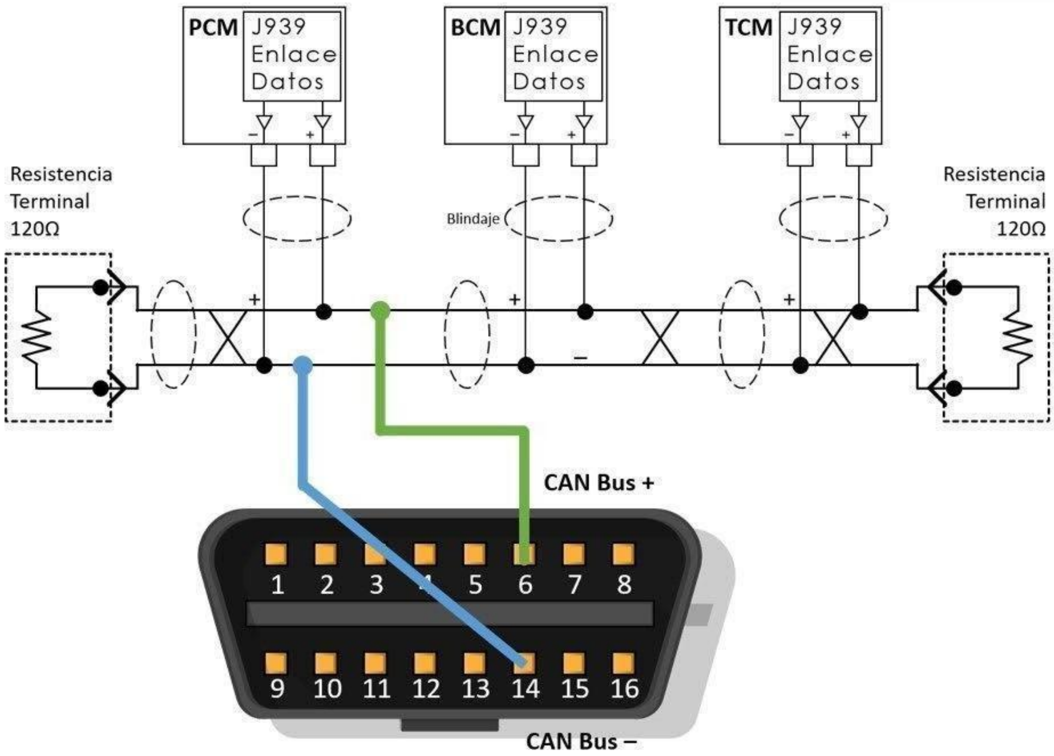

Figure 31: CAN Bus

5. All control units are connected to the main CAN line in parallel.
6. This is a MULTI-MASTER programming model, in which the priority between the control units can change depending on the circumstances. For example, if the engine ECU and ABS ECU are connected, in normal driving conditions, messages sent by the engine ECU will have priority, while the opposite will be true in the event of emergency braking. The control units therefore operate on two "levels": the local M/S network to manage their individual parameters, and the CAN M/M network to communicate and manage parameters/situations at the vehicle system level.
7. The pins relating to the CAN-BUS network are always in positions 6 and 14 of the EOBD socket. From here, it is possible to see a signal transmission using an oscilloscope.

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8. In almost all CAN schemes, all lines converge at an interface control unit, the Gateway, to which the EOBD socket is connected.

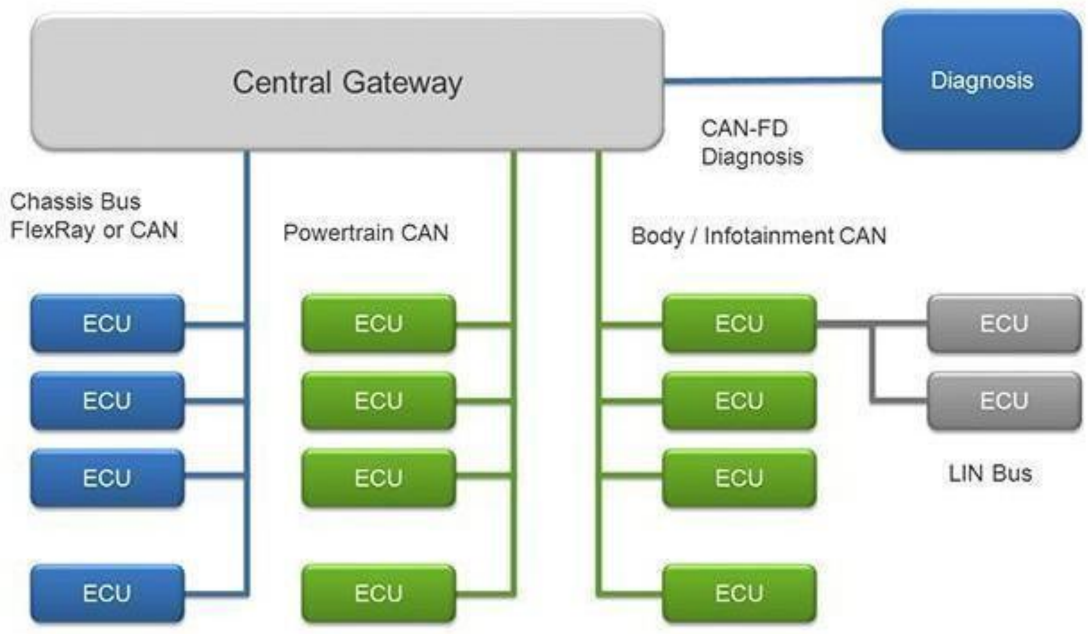

Figure 32: Can scheme

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9. Each CAN line is dedicated to a specific function, e.g. powertrain, chassis, comfort, and communication between the different CAN lines is possible by passing the message through the gateway control unit.

10. Data communication speed (bit rate): 1 Mbit/sec

Other communication protocols:

With the increase in both the number and specificity of on-board vehicle functions, it has become necessary to diversify the types of communication protocols.

The main ones are:

1. LIN BUS
2. Flex-Ray
3. Ethernet

LIN BUS

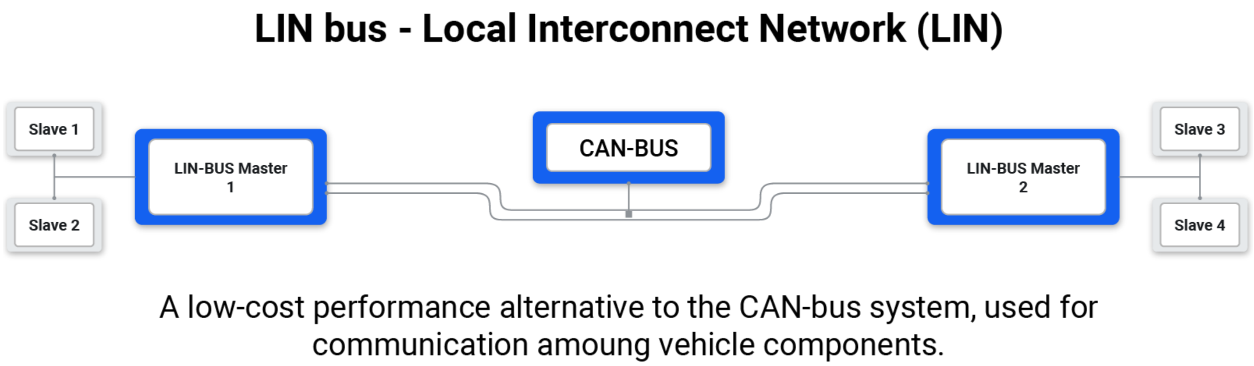

Figure 33: LIN bus

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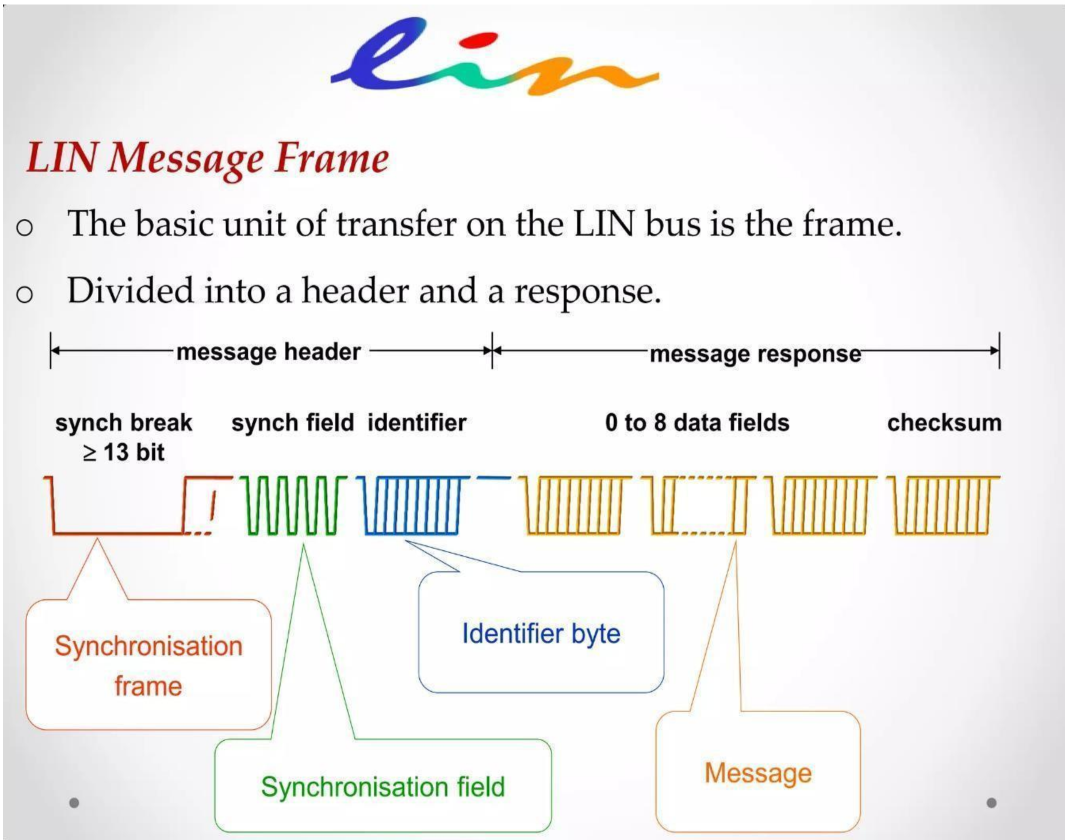

Figure 34: LIN message frame

Main features:

1. Secondary network to the CAN-BUS, with the aim of connecting users, such as windscreen wiper motors, which can be controlled via the LIN network.
2. Single-wire
3. Master-Slave. The Master control unit is positioned in series with a CAN control unit. In the event of a failure of the latter, communication with the entire LIN network is also interrupted.
4. Slaves can be sensors, actuators, but also secondary control units.
5. Value range: Dominant bit: 0V – Recessive bit: 12V
6. Data transmission speed (bit rate): 20Kbit/sec

FlexRay

The FlexRay protocol is a deterministic, high-speed serial communication bus designed primarily for critical applications in the automotive sector. It was developed to overcome the limitations of the CAN-BUS protocol. Each Flex-Ray line has a maximum of four control

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units, mounted in parallel. For each line there are two 94Ω terminal resistors, mounted in parallel, for a resultant of 47Ω.

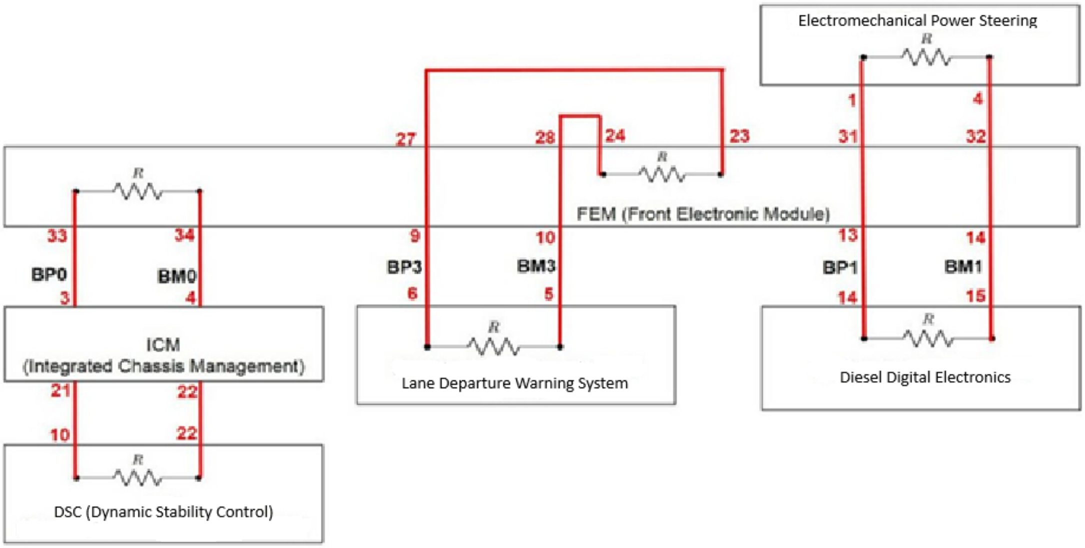

Figure 35: FlexRay protocol visualisation

Main features

1. Deterministic: The most important aspect of FlexRay is its *time-triggered* nature. This means that data transmission occurs at predefined times, ensuring that each node in the network has a precise time slot for communication. This ensures consistent and reliable data delivery, which is essential for systems that require very precise reaction times.

2. Hybrid architecture:

   A. Static segment: Based on time-division access, it assigns each node a fixed, predefined time slot for sending critical messages. This ensures deterministic data delivery.

   B. Dynamic segment: Works similarly to CAN, allowing the transmission of non-critical, low-priority messages based on events. Access to the bus is contested, but with a mechanism that ensures that all nodes are given a chance to communicate.

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3. Fault tolerance: FlexRay supports redundant communication through the use of two independent channels. If one channel fails, the system can continue to operate on the other, improving reliability, a key feature for safety systems.

4. Synchronisation: The FlexRay network is based on a shared clock that ensures synchronisation between all nodes, guaranteeing that each node communicates in its pre-determined turn. FlexRay.

5. Bitrate: 10 Mbit/sec

Some examples of use:

- Active safety systems (e.g. ABS, ESP) Advanced driver assistance systems (ADAS) Engine and chassis control systems Adaptive suspension systems
- Electronic steering and braking systems (x-by-wire)

Ethernet

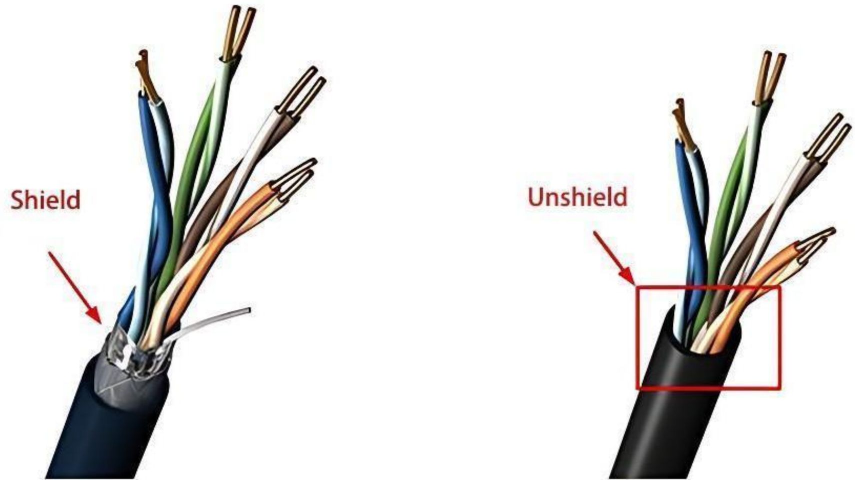

Figure 36: Ethernet cable

Ethernet works by using physical cables to connect devices to each other and to a local network. Each connected device is equipped with a network interface card (NIC) that has a unique address called a MAC (Media Access Control) address. When a device sends data, it transmits it in the form of packets that contain, among other things, the MAC address of the destination device. Only the device with the matching MAC address will accept and process the packet.

First developed in the early 1970s, Ethernet technology has constantly evolved to increase data transmission speeds. The most common versions and their speeds are:

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1. Ethernet: 10 Mbps
2. Fast Ethernet: 100 Mbps
3. Gigabit Ethernet: 1 Gbps
4. 10 Gigabit Ethernet: 10 Gbps

In the automotive sector, Automotive Ethernet is a specific, adapted version of the standard technology. It was introduced to meet the ever-increasing bandwidth requirements in modern vehicles, especially for advanced driver assistance systems (ADAS), cameras, infotainment and control systems. Unlike the FlexRay protocol, which is deterministic and optimised for real-time communication in critical systems, Automotive Ethernet focuses on high transmission speeds for large volumes of data.

Differences between Ethernet and FlexRay

1. Protocol: Ethernet is based on contended access (typically with CSMA/CD protocol in older versions, but not in modern switched connections), while FlexRay is deterministic (time-triggered).
2. Speed: Ethernet offers a potentially much higher speed (up to 40 Gbps with Cat 8 cables), while FlexRay has a lower limit (10 Mbps).

HV battery components

N.B.: The data provided below are indicative. For different models and features, ALWAYS STRICTLY FOLLOW THE PROCEDURES SET OUT IN THE LATEST UPDATED TECHNICAL DOCUMENTATION PROVIDED BY THE MANUFACTURER OF THE VEHICLE IN QUESTION! All components, such as cables and connectors, that operate at high voltage are ***orange*** *in colour.*

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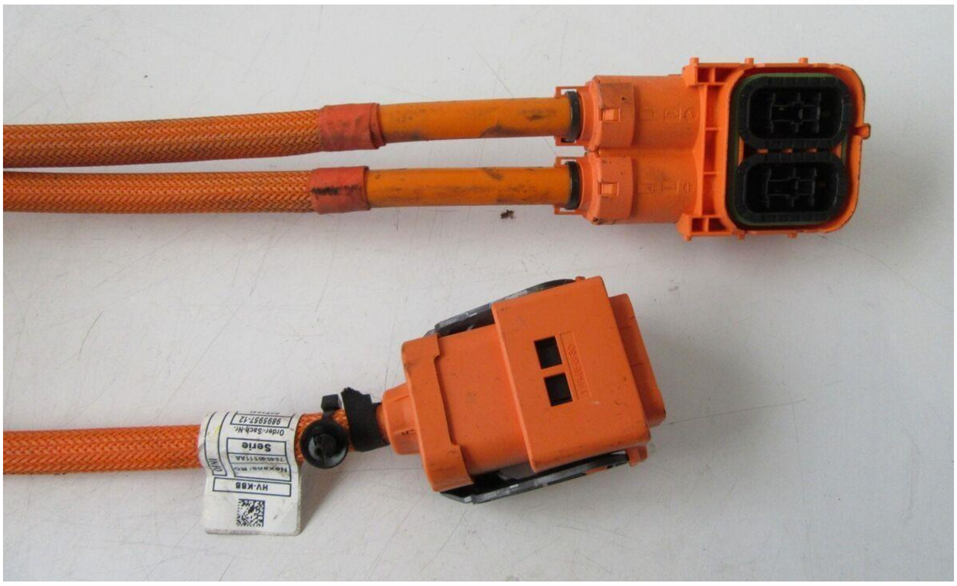

Figure 37: Orange cable

A traction battery consists of the following main components:

1. The cells, which are the actual elements that supply energy. We could call them the 'batteries'.
2. The modules, which enclose the cells
3. The contacts
4. Connectors and safety devices
5. Electronic control and management components
6. the air conditioning system, liquid-based in the most efficient batteries
7. The battery pack, which contains everything

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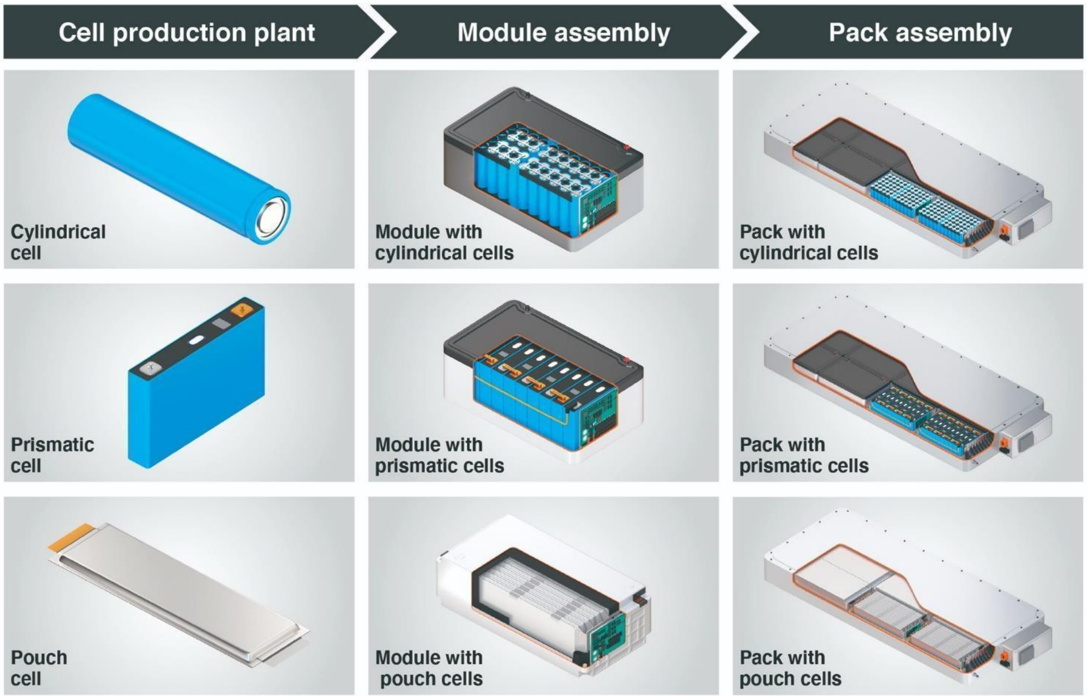

Figure 38: Battery components

Cells

These are the active element, i.e. they supply energy to high-voltage systems. Currently, lithium is used as the electrolyte for ion exchange, graphite is used to construct the negative pole, known as the anode, while the type of other elements may vary; there are two main technologies in use:

A. LFP iron phosphate

B. Nickel – Manganese – Cobalt (or, as an alternative to the latter, Aluminium), known as NMC

LFP batteries are safer, longer-lasting and more economical, with greater tolerance to full charge and a lower environmental impact, but they have lower energy density and suffer from poorer performance at low temperatures. NMC batteries, on the other hand, offer higher energy density (and therefore greater range), faster charging and better performance at low temperatures, but they are more expensive, less durable and present a greater risk of overheating.

It should be noted, in this regard, that battery packs are mostly liquid-cooled, so as to have accurate control over operating temperatures.

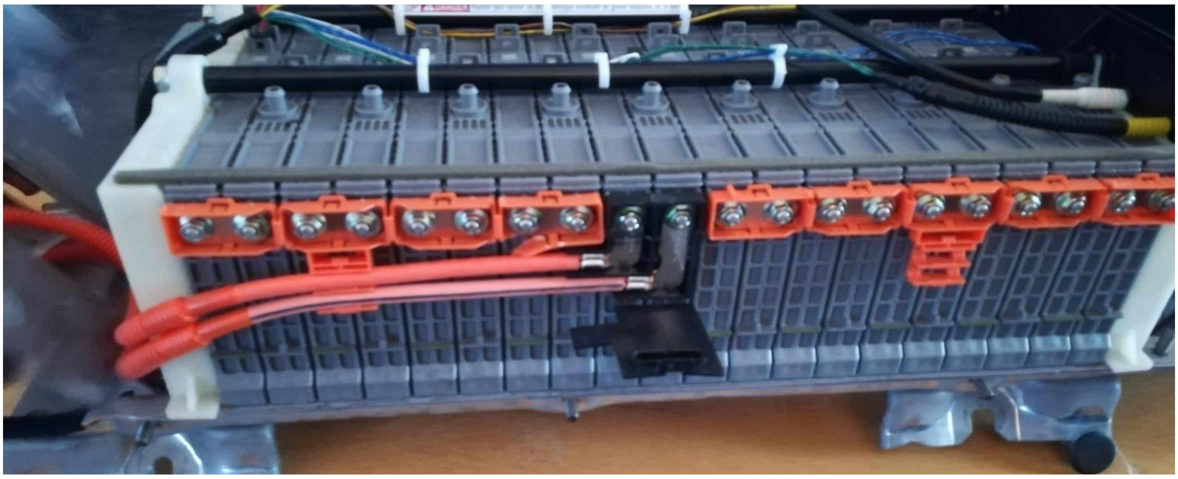

Figure 39: Real battery visualisation

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Feature	**LFP (Lithium Iron Phosphate)**	**NMC (Nickel-Manganese-Cobalt)**
Energy density (*)	Lower (90 – 130 Wh/kg)	Higher (190 – 260 Wh/kg)
Safety	Higher, more thermally stable	Lower, more sensitive to heat
Lifespan	Very high (3,000–4,000 cycles)	Lower (1,500 - 2,000 cycles)
Performance at low temperatures	Poor, loses a lot of capacity	Good, maintains bettercapacity
Recharging	They tolerate 100% charge, but recharge more slowly in cold weather	Preferably charge between 20-90% (not 100%), faster charging even at low temperatures
Cost and environment	Cheaper and more environmentally friendly (no cobalt or nickel)	More expensive and with greater environmental impact (use of cobalt and nickel)
Typical applications	Cars, stationary applications (e.g. photovoltaics)	Cars, high-performance vehicles

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(*) This is a very important figure because it represents how much energy can be "loaded" per kg of battery.

Other parameters that must be considered are:

- Nominal voltage (V). On average, this is around 4V
- Capacity (Ah). This can vary depending on the type of cell, from 70Ah to 160Ah. However, this parameter is rapidly evolving, and therefore the values given are indicative

Energy is obtained from the product of these two quantities, using the formula: Wh = V x Ah

Modules

These are the 'containers' for the cells, as well as the control unit for their parameters (e.g. average voltages, temperatures), connection wiring, safety resistors and connectors between the different cells inside it. Most manufacturers use laser-welded modules that cannot be opened. If even one component fails, the entire module must be replaced. On the other hand, however, this solution guarantees greater sealing, greater safety and improved torsional resistance.

Some manufacturers, however, have opted for designs that can be opened and repaired if a failure occurs.

Three quick questions:

1. How many cells are enclosed within a module?

There is no fixed number, but it varies approximately from 15 to 30 depending on the V and Ah characteristics of the cells themselves.

2. How are they connected to each other? Only in series, or mixed, series and parallel.

3. How do the two types of connections differ?

A. In parallel: + is connected to + and – to –, as shown in the figure on the left. This will add up the Ah, while the V remain unchanged.

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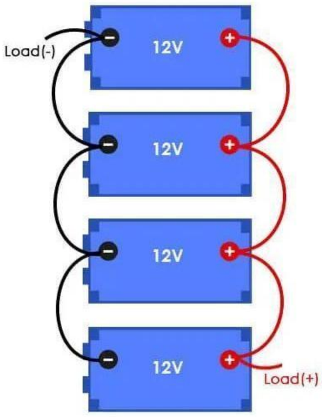
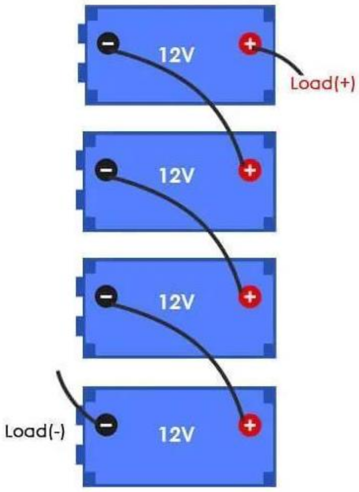
B. In series: connect the + of one cell to the – of another, as shown in the figure on the right: in this case, the V will increase, while the Ah will remain unchanged.

An example: two cells of 4V and 100 Ah each:

A. In parallel: Total: 4V and 200 Ah; Energy produced: 800 Wh



B. In series: Total: 8V and 100 Ah; Energy produced: 800 Wh



So, what's the difference? The available energy remains the same: in the first case, we will have more autonomy, thanks to the Ah; in the second, more performance, thanks to the V.

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4. What does the abbreviation, for example, 1S3P indicate? How are the cells connected to each other:

   A. 1 x 3 = 3, total number of cells

   B. 3P: Number of cells connected in parallel.

   C. 1S: number of cells connected in series

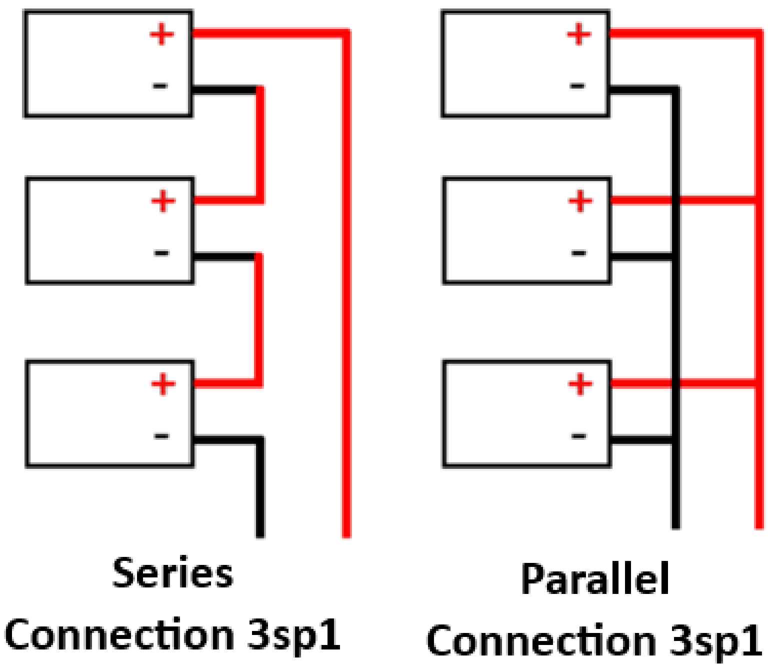

Figure 40: Series and Parallel connections visualisation

The modules also contain a control unit for parameters such as average voltages and temperatures, connectors, resistors used to balance the voltage between the different cells, + and – connectors for connecting the module, and any liquid cooling plates.

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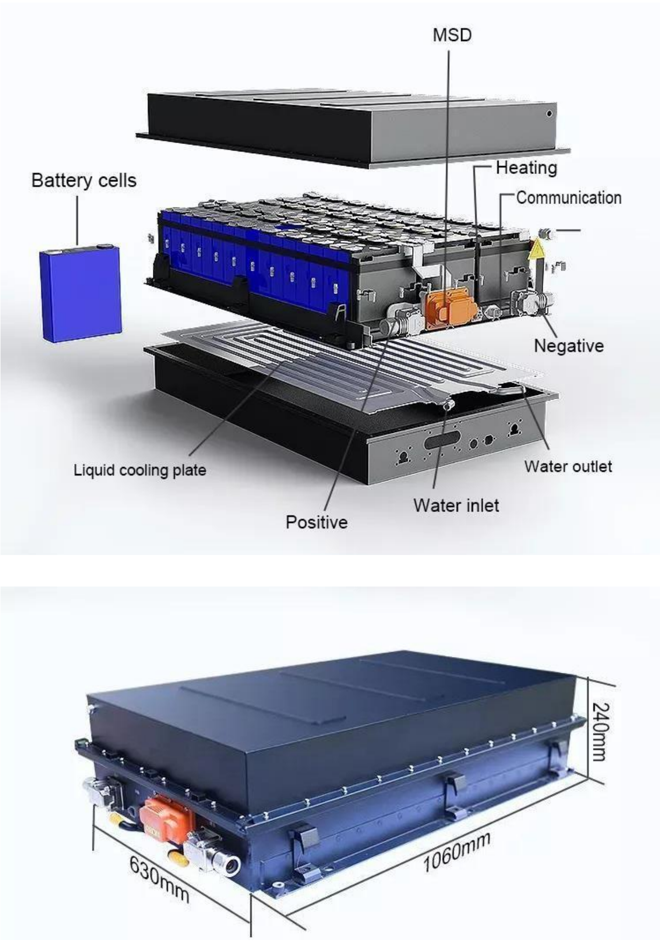

Figure 41: Battery components and measures

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Battery pack:

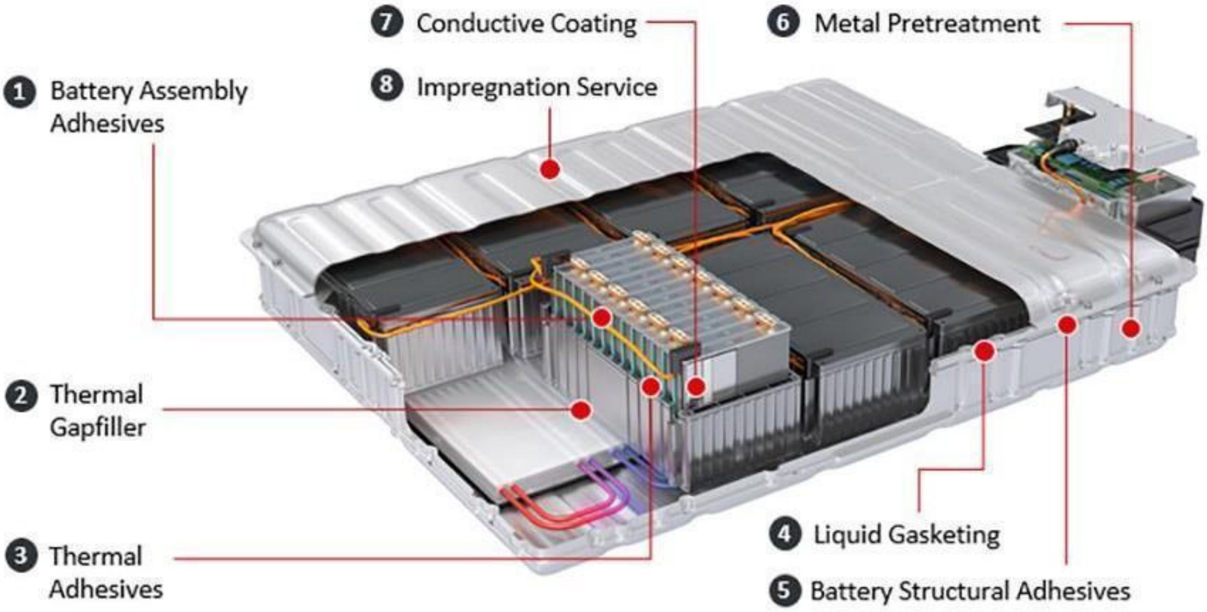

Figure 42: Battery pack components

A battery pack casing can take different forms depending on the application. We can divide the functions of the casing into these categories:

1. Mechanical
2. Electrical
3. Thermal
4. Safety
5. Production
6. Transport

Mechanical

1. Mechanical position

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2. Sealing / Ingress protection
3. The IP classification system consists of two digits. The first digit represents the degree of protection against the intrusion of solid objects, while the second digit represents the degree of protection against the intrusion of liquids.
4. Seal design
5. Impact protection
6. Crush protection
7. Choice of materials: many different materials are used for battery pack casings.
8. Vibration insulation

Electrical

1. HV connection sockets
2. HV protection
3. HV insulation
4. Surface distance and air distance – High-voltage circuits can discharge through a gap, which can be in the air or on a surface. Therefore, it is important to design according to the correct standards.
5. Protective screen against electric discharges and temperature rise

Thermal

1. Environmental thermal insulation: heating and cooling require a lot of energy
2. Most battery cells operate correctly in the temperature range from 0 °C to 35 °C. However, in many applications, they need to operate at sub-zero temperatures and up to much higher temperatures.

Depending on extreme environmental conditions, battery cells may need to be heated and/or cooled.

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3. Furthermore, the operation of each individual cell varies with temperature. This means that temperature gradients within cells can have a significant effect on performance and lifespan. This concept can be extended to cells with different temperatures within the battery pack.

Safety

1. Containment of gases emitted from cells
2. Pressure equalisation vs. pressure relief: Pressure equalisation, commonly known as 'breathing', aims to maintain pressure balance within a battery enclosure due to environmental or altitude variations.
3. Fire containment in the event of thermal runaway
4. Electrical protection

Production

1. Base positioning and orientation
2. Frame assembly
3. Seal application
4. Leak test
5. Labelling: a battery pack requires labels that define its nature and indicate warnings regarding its safe handling and use. Requirements depend on the market and type of pack

Transport

Safe transport packaging

Connectors

There are a large number of connectors inside a battery pack. These will be low-voltage (LV) power/signal connectors and high-voltage (HT) connectors.

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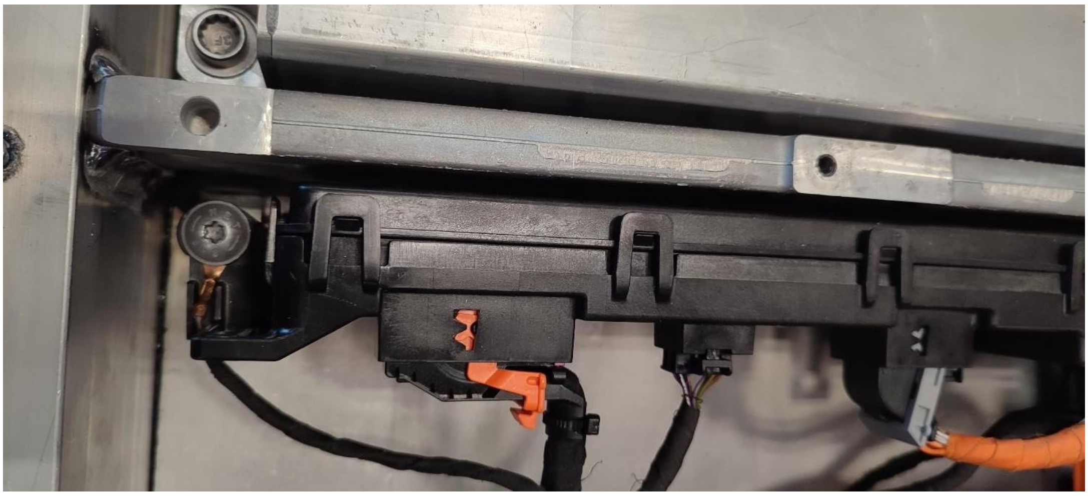

Figure 43: Battery connectors

Bolted joints

Bolted joints are common within HT battery packs.

Figure 44: Bolted joints

There are a few aspects to consider:

1. Joint strength
2. Material compatibility
3. Thermal cycles

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4. Corrosion
5. Vibrations
6. Torque resistance
7. Tool access

Bolted joints are commonly used to connect solid busbars to modules, contactors or other busbars.

What does HVIL (High Voltage Interlock Loop) mean?

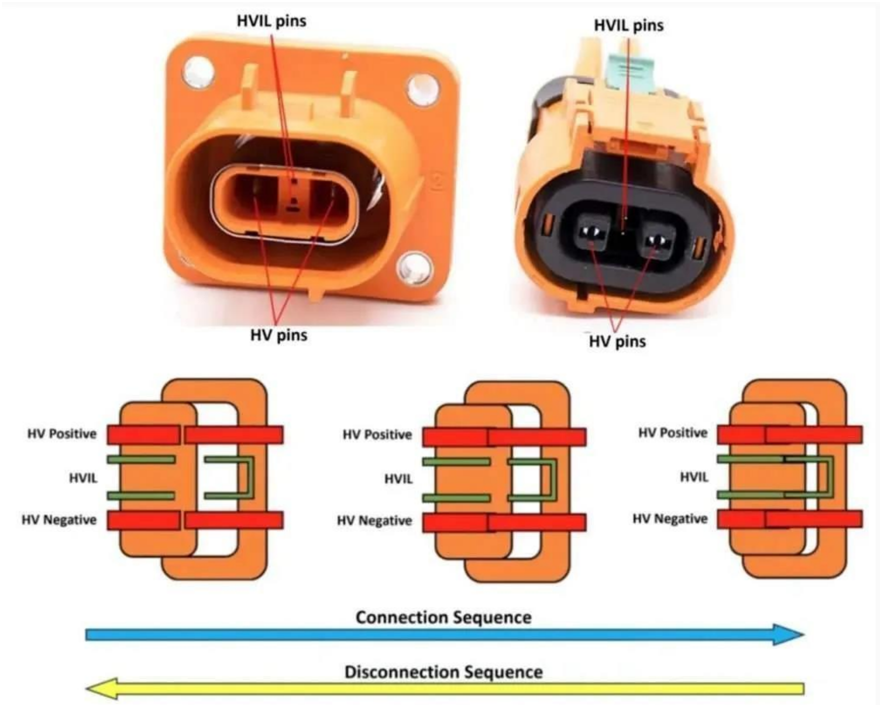

Figure 45: HVIL pins

1. Safety in electric vehicles: HVIL is a fundamental safety system in electric and hybrid vehicles.
2. Operation: It uses a separate low-voltage circuit to monitor the integrity of the high-voltage system.
3. Purpose: It protects people from accidental contact with high-voltage components during maintenance, repair and even during an accident.

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4. Mechanism: If a high-voltage component is disconnected or damaged, the low-voltage circuit is interrupted. This causes the high-voltage system to shut down immediately, while also sending an alarm to the driver.

5. Components: The HVIL circuit connects critical components such as the battery, motors, wiring and connectors, ensuring that the entire system remains safe and intact. Protects technicians during maintenance and repair operations. Standards such as IEC 61851 and ISO 26262 require the use of HVIL.

BMS – Battery Management System

Figure 46: Battery management process

The battery management system (BMS) monitors the battery pack and communicates its status to the outside world. An introduction to the BMS provides a general overview and system connections.

The battery management system (BMS) is the hardware and software control unit of the battery pack. It exchanges data via CAN-BUS or Ethernet with the rest of the vehicle, both input and output, and is powered by 12V.

It is a key component that measures cell voltages, temperatures and battery pack current. It also detects insulation faults and controls the contactors and thermal management system.

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The battery management system protects the operator of the battery-powered system and the battery pack itself from overcharging, over-discharging, overcurrent, cell short circuits and extreme temperatures.

The BMS must control and report various key functions using algorithms. These include:

1. State of charge (SoC)
2. Certified energy status (SOCE)
3. State of power (SoP)
4. State of capacity (SoQ)
5. State of energy (SoE)
6. State of health (SoH)
7. State of function (SoF)
8. Resistance status (SoR)
9. Contactor control
10. Cell balancing
11. Temperature estimation
12. High voltage insulation
13. Operating limit protection
14. Diagnostics
15. Fallback mode
16. Recording
17. Remaining useful life (RUL)

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BATPOWER
Preparation of the VET sector on battery energy transition

18. Safety diagnostics

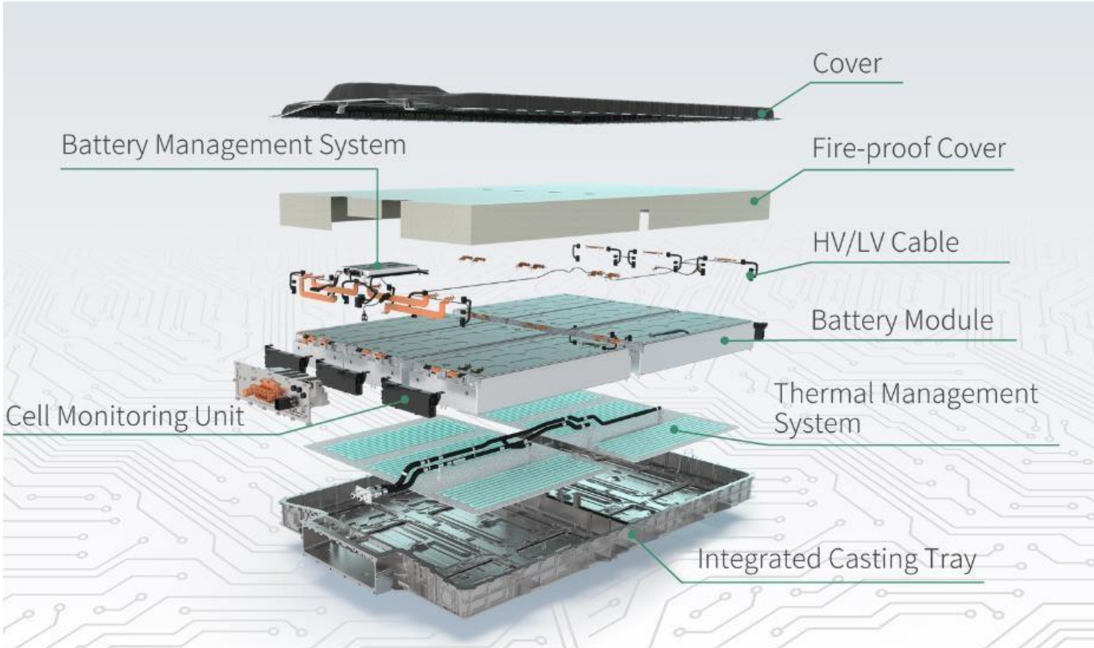

Figure 47: Battery assemby

Procedure and assembly

N.B.: As in the previous chapter, the data provided below are indicative. For the various models, ALWAYS STRICTLY FOLLOW THE PROCEDURES SET OUT IN THE LATEST UPDATED TECHNICAL DOCUMENTATION PROVIDED BY THE MANUFACTURER OF THE VEHICLE IN QUESTION! IN ITALY, THE VARIOUS LEVELS OF QUALIFICATION REQUIRED TO WORK ON HIGH-VOLTAGE SYSTEMS ARE SET OUT IN LEGISLATIVE DECREE 81/2008 AND IN STANDARD CEI 11-27 REV. 5

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Figure 48: Safety zone

The procedure for diagnosing and intervening on one or more components of a battery pack varies depending on the characteristics of the battery itself, as well as on the provisions of the various manufacturers.

We can list some explanatory points.

1. Battery classification: sequence of operations, both using diagnostic tools and sensory checks (e.g. odours, visible liquid leaks), aimed at verifying that the battery pack is safe and does not present any safety risks or critical issues, such as increased temperatures, fire hazards or electrolyte leaks. Three levels:

   A. Normal: can enter the workshop

   B. Critical: Removed from the workshop, placed in a designated area and put into "quarantine".

   C. Dangerous, as in point B, and call the fire brigade

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N.B.: For points B and C, contact the manufacturer's technical support service

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2. Diagnostic reading of any fault codes and value locks, such as:
   A. Voltages/temperatures of individual cells
   B. Average voltages/temperatures
   C. Maximum and minimum voltages/temperatures of individual cells
   D. Insulation resistance of the battery pack itself
   E. Total battery voltage
3. Guided procedure for de-energising via diagnostic tool: this opens/disconnects a safety switch which in turn opens the two maxi relays (one on the + contact and the other on the - contact) located inside the battery pack, between the modules and connectors that supply power to the HV components in the vehicle. This removes the voltage downstream of the battery pack. The two relays are controlled by the BMS via a dedicated 12V line; when the power supply is removed, the two maxi relays open.

Figure 49: Safety lock

4. If it is necessary to disconnect the HV connection cables outside the battery pack to the inverter, charging socket and other HV components, proceed as specified by the manufacturer.
5. If all the requirements of the previous point are met, you can proceed with disconnecting the HV cables and then measure in particular:

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A. The electrical insulation of the battery pack to the bodywork

B. The seal to check that there are no leaks or vents to/from the battery pack

6. At this point, once the coolant has been drained from the system, the battery pack can be removed from the vehicle so that it can be opened and worked on

Figure 50: Real-life battery pack

Figure 51: Battery dismantling process

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7. If a module needs to be replaced, before inserting the new one into the pack, you will need to:

   A. Spread a conductive paste on the base on which the module will rest, in order to maximise heat exchange with the air conditioning fluid in the cavity below

   B. Using a special device, balance the module to the required voltage value. This operation, which can take up to a few hours, is very important as incorrect balancing can lead to significant reductions in terms of range in kilometres.

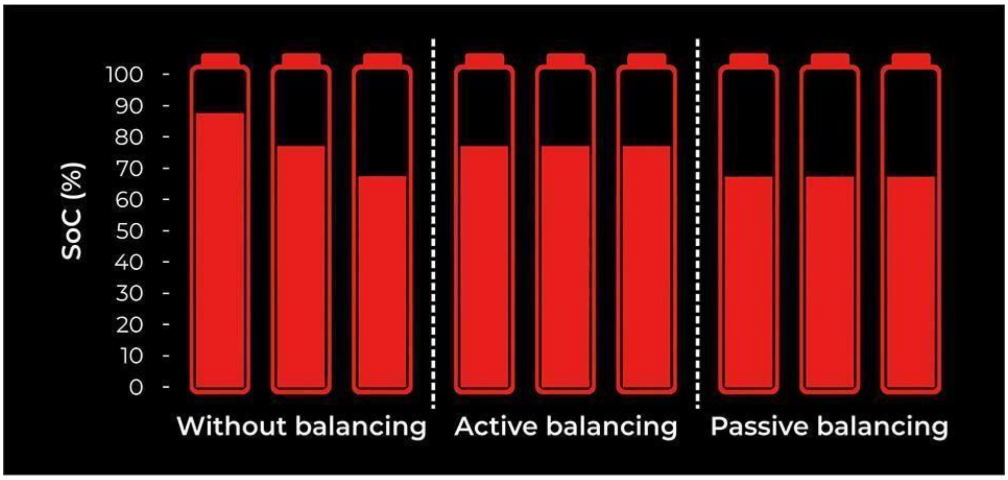

Figure 52: Battery balancing

8. Once the sequence of operations and checks has been completed, proceed with re-energising the battery pack, control and verification measurements, closing and sealing the battery pack, re-assembly and connections on the vehicle, filling the air conditioning liquid circuit, re-energising and starting up the vehicle.

N.B.: FOR ALL SEQUENCES OF OPERATIONS, ALWAYS STRICTLY FOLLOW THE PROCEDURES SET OUT IN THE LATEST UPDATED TECHNICAL DOCUMENTATION PROVIDED BY THE MANUFACTURER OF THE VEHICLE IN QUESTION!

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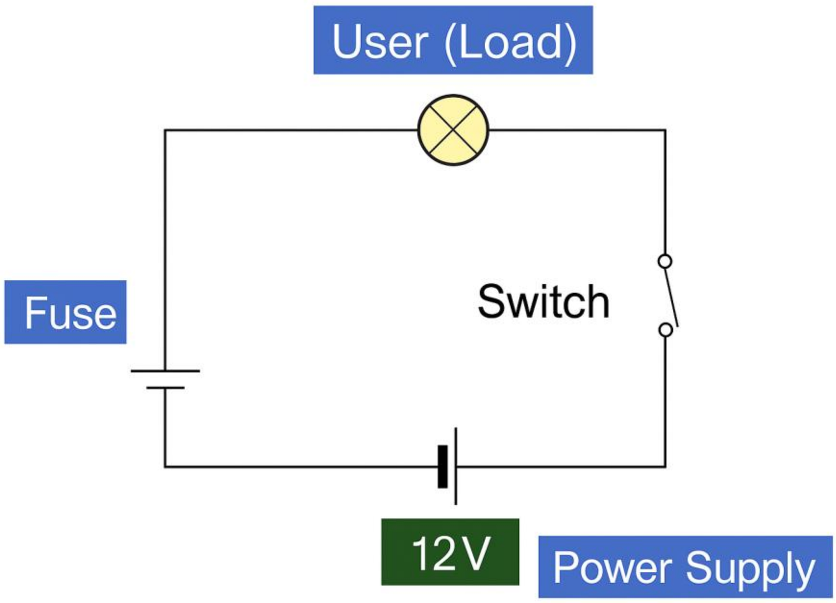
Exercises

1) Construct a basic electrical circuit using a 12V battery, an H7 lamp, a switch, and a properly rated fuse.



With the multimeter, measure in the operating circuit:

a) Battery voltage, actual voltage at the user, and voltage drop: this value must be less than 0.7V.
b) Voltage drop on the supply line and on the ground line: these two values must be respectively less than 0.3V each.
c) Voltage across the switch: with the circuit open (12V) and closed (0V).

Using the clamp ammeter, measure the current flowing through the circuit and calculate the power using W = V × A.

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With the circuit switched off, measure the resistance (Ω) of the ground line: it must be less than 0.2Ω.

---

2) In the circuit described in point 1, insert a 5Ω resistor in series and measure:

a) Total circuit voltage
b) Voltage across the lamp: a resistor in series will cause a significant voltage drop at the user, compromising its operation.

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3) In the circuit described in point 1, insert a second lamp in series and measure:

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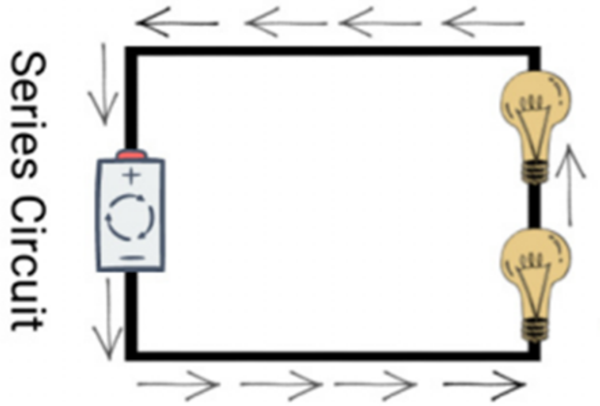
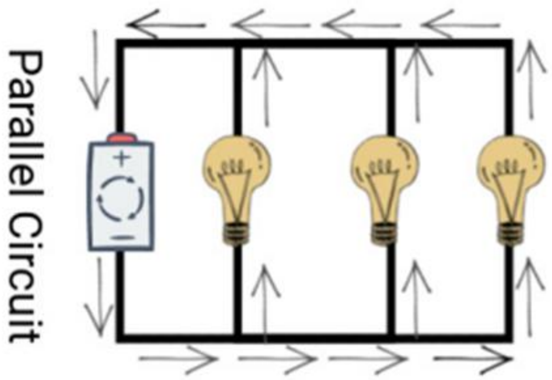


a) Total circuit voltage
b) Voltage across both lamps: for two identical users in series, the voltage divides equally between them.
c) Current with the clamp ammeter: it will be the same at any point in the circuit.

---

4) In the circuit described in point 1, insert a second lamp in parallel and measure:

a) Total circuit voltage
b) Voltage across both lamps: for two users in parallel, the same voltage drop applies to both.
c) Current with the clamp ammeter: it will be divided between the two users, and the sum of currents within the node equals zero (Kirchhoff's law).



---

5) Build a relay circuit following the diagram below:

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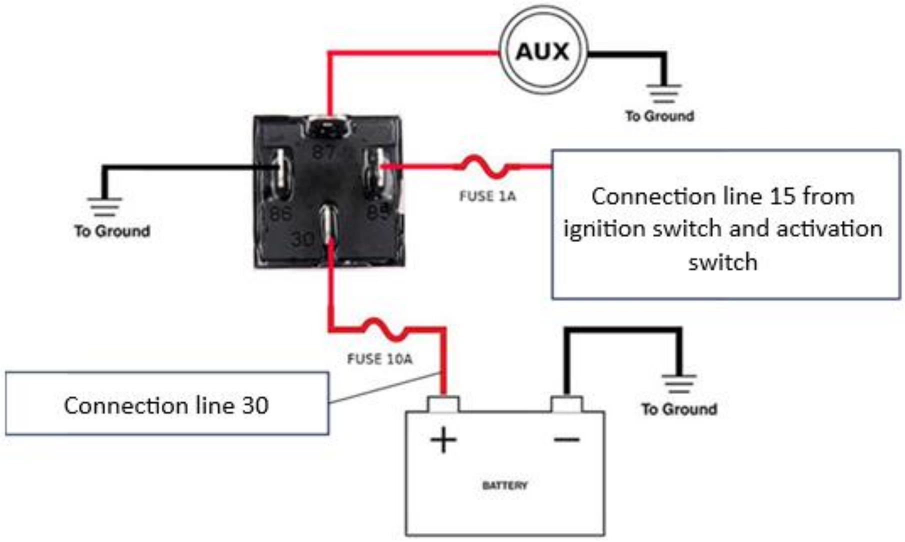
a) Use an H7 lamp or preferably an electric motor (e.g. fan motor) as the user; size the protective fuses properly.
b) With an ignition key block, power the control circuit from line 15, while the working circuit is powered from line 30 (direct positive).
c) The user will activate only after line 15 and the switch are both engaged.
d) Measure the voltage drop across the user.



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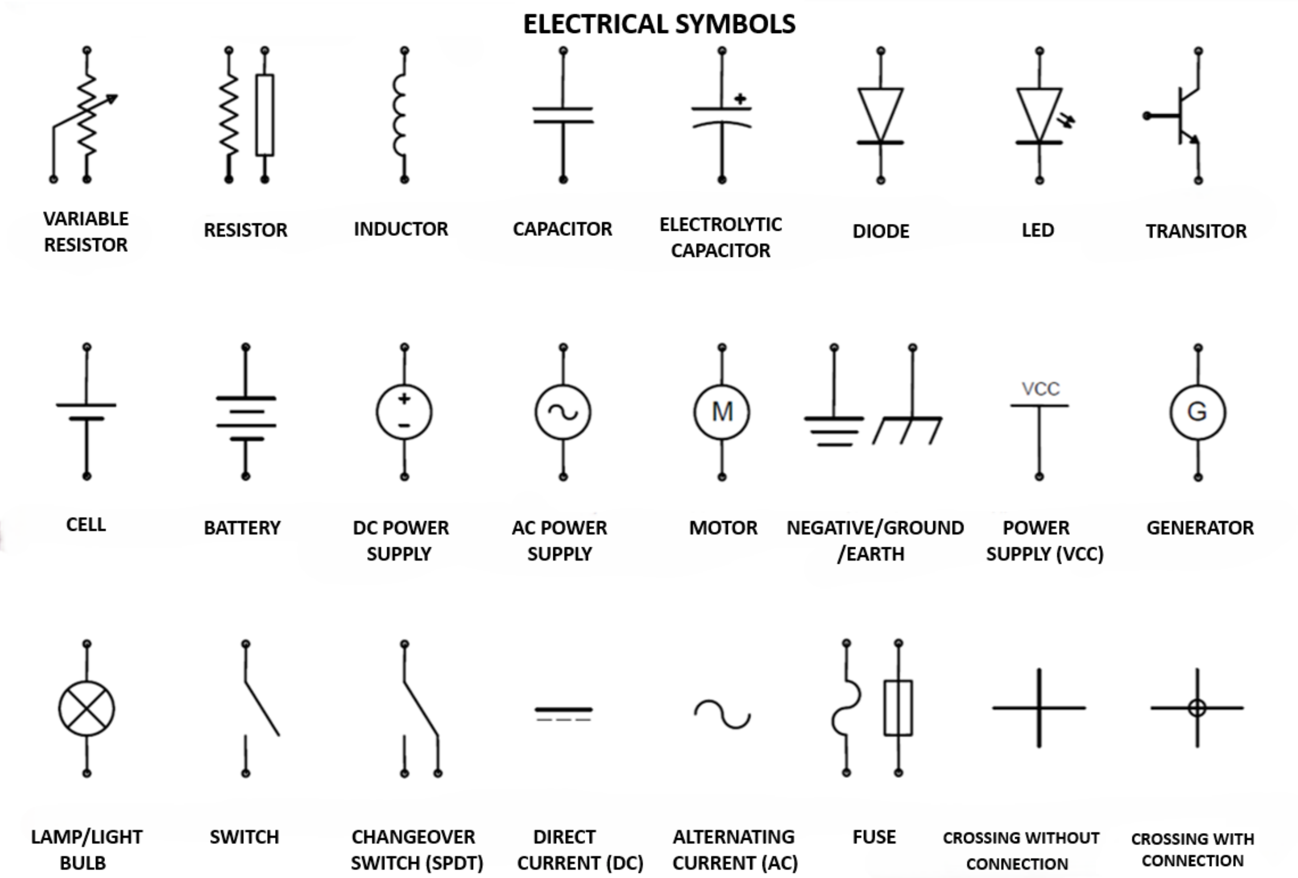

Oscilloscope

(For more details on use, refer to the links in the last page)

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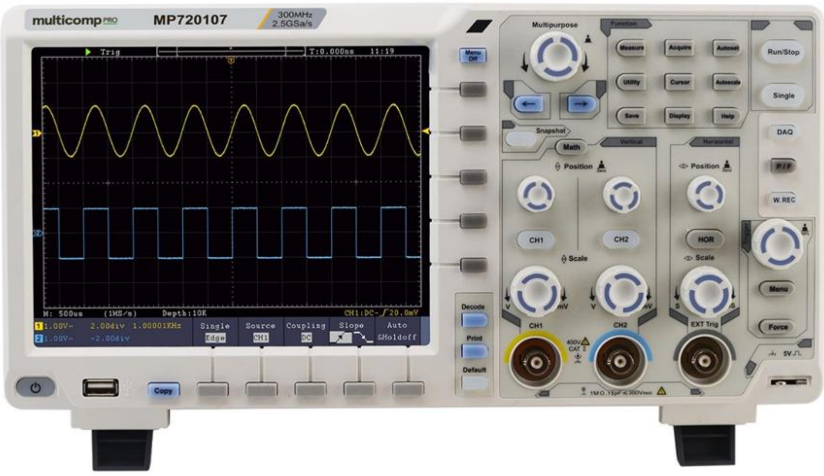
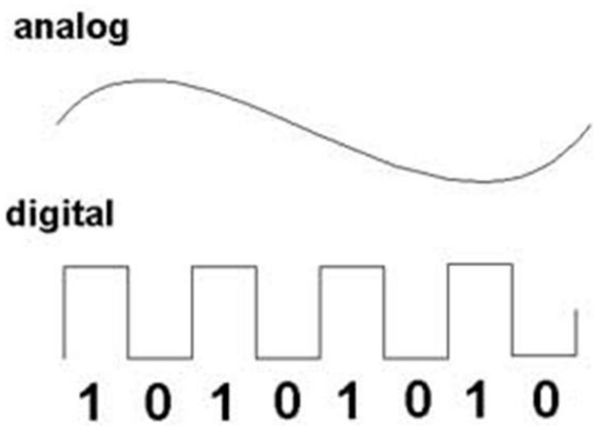


The correct use of an oscilloscope, preferably at least two-channel, is very important to determine the behaviour of voltage signals (Volts) as a function of time. Signals can be either graduated (analog) or on–off (digital).



Proper setup includes:

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a) Time scale adjustment
b) Voltage range selection
c) Trigger setting

Probe placement:

a) Red probe: parameter to measure (e.g., sensor connector)
b) Black probe: vehicle ground

It is possible to read signals from both sensors and actuators, such as:

a) Engine coolant temperature sensor
b) Accelerator pedal sensor
c) Crankshaft speed sensor
d) Phase sensor
e) Knock sensor
f) Injectors
g) Throttle body PWM control
h) Ignition coils

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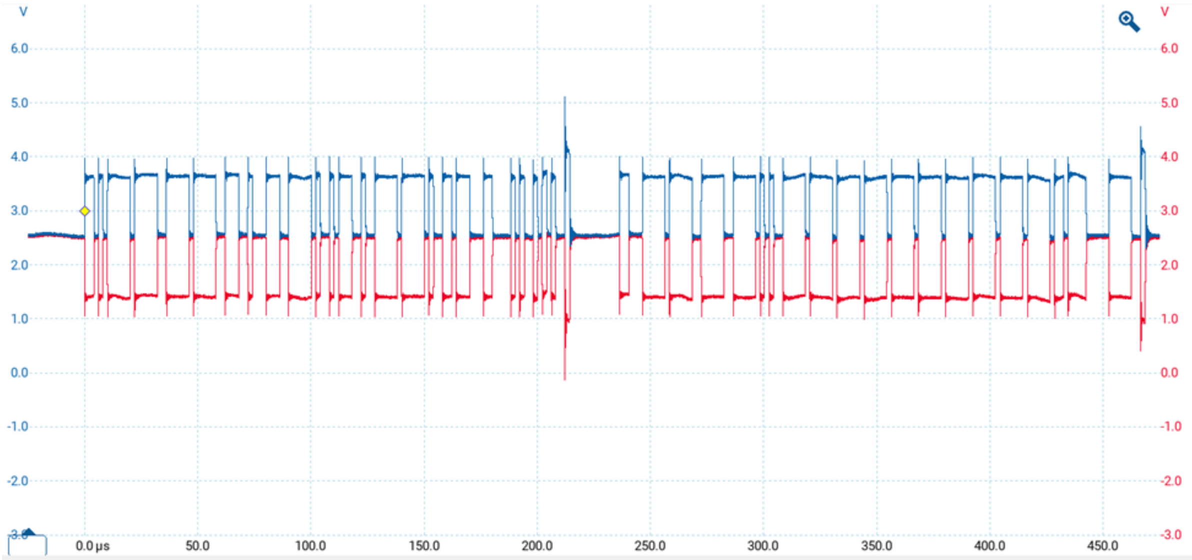
CAN-BUS

(For more details, refer to the links in the last page)

Using a two-channel oscilloscope, connect both red probes respectively to pins 6 and 14 of the EOBD port, and both black probes to vehicle ground, to visualize the CAN-BUS signals in the vehicle's electronic networks.



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For exercises

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Module 3 – Battery Charging and Recharging

Aim of the Module	This module explains how battery charging works in automotive applications, focusing on electric vehicles (EVs). It covers the *charging chain* (from the electrical grid through the charger into the vehicle's battery pack), charging methods (*AC vs DC charging*), key parameters (voltage, current, temperature), the typical *CC/CV charging profile*, the role of the *Battery Management System (BMS)*, thermal management needs, typical charging limitations, and safety risks.
Target	Teachers, trainers, educators of Battery technology
Pre-requisites	Basic electricity concepts: voltage (V), current (A), resistance (Ω), power (W), energy (Wh). Basic EV components: what a battery pack is, where the charging port is, what a charger does (and high-voltage safety principles). Ability to read simple electrical diagrams and graphs (for understanding charging curves and system schematics).
EQF Level	3–4 (with optional deeper technical notes for advanced learners)
Methodology	

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Evaluation	Evaluation methods mirror those of the subsequent module, adapted to the introductory content. Short quizzes and oral questions will check understanding of key concepts (such as identifying types of energy storage or naming EV components).

Contents	**Introduction to Battery Charging** **Charging Methods and Strategies** **The Charging Process and Key Parameters** **Role of the Battery Management System (BMS) in Charging** **Safety Aspects of Battery Charging**
Module title	Battery Charging and Recharging
Workload	4 teaching hours, 15 studying hours

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Glossary of Acronyms

AC – Alternating Current (electric grid power that oscillates in polarity).

DC – Direct Current (one-directional current; what the battery actually stores).

Ah (Ampere-hour) – Unit of electric charge (e.g. battery capacity rating).

Wh / kWh (Watt-hour / kilowatt-hour) – Unit of energy (common for battery energy content).

kW (kilowatt) – Unit of power (rate of energy transfer).

BEV – Battery Electric Vehicle (fully electric, no combustion engine).

PHEV – Plug-in Hybrid Electric Vehicle.

EVSE – Electric Vehicle Supply Equipment (general term for charging station or charger interface).

EVSE (AC) – AC charging equipment that supplies AC to the vehicle's onboard charger.

EVSE (DC) – DC fast charging station that supplies DC power directly to the vehicle battery.

OBC – On-Board Charger (the AC→DC converter built into the vehicle for AC charging).

ICCPD – In-Cable Control and Protection Device (the "control box" often seen in portable Mode 2 charging cables).

CC/CV – Constant Current / Constant Voltage (the two-phase lithium-ion charging method).

SOC – State of Charge (how full the battery is, typically given as a percentage).

SOH – State of Health (measure of battery condition relative to new, often in percentage of original capacity).

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BMS – Battery Management System (electronic system that monitors and manages the battery pack).

HV / LV – High Voltage / Low Voltage (in vehicles, the traction battery is HV; 12V systems are LV).

RCD – Residual Current Device (safety device to prevent electric shock by detecting leakage currents).

RPT / BPT – Reverse Power Transfer / Bidirectional Power Transfer (concepts where the vehicle can supply power back to the grid or another load).

REESS – Rechargeable Energy Storage System (formal term for the vehicle's rechargeable battery system, used in regulations).

UN 38.3 – A UN standard (Section 38.3 of UN Manual of Tests) defining tests for lithium battery safety for transport.

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1. Introduction to Battery Charging

1.1 Charging is an Energy Transfer Process (not just "plugging in") – Charging an EV battery means transferring electrical energy from an external source (the grid or charging station) into the vehicle's battery pack, where it is stored as chemical energy. Unlike filling a fuel tank with liquid fuel, a battery cannot accept energy at an arbitrary rate. Charging is constrained by several factors that limit how fast we can safely push energy into the cells, including:

- **Electrical limits:** Each cell has a maximum voltage it should not exceed, and the pack has maximum current limits.
- **Chemical limits:** There are limits to how fast lithium ions can move and intercalate into electrodes without causing damage or side reactions.
- **Thermal limits:** High current causes heating; the battery can only dissipate heat so fast. If it overheats, safety is compromised.

These limits mean charging **must be controlled** by electronics – you cannot just "dump" power in quickly without consequences. The battery is an electrochemical system, and if charging is too aggressive (too high current or pushing voltage too far), side reactions accelerate, the battery ages faster, and safety risks increase (e.g. plating of lithium metal or gas generation).

In summary: **Charging is an energy management process.** A controlled charging system ensures that at all times: - No cell exceeds its safe **voltage** limit (to avoid overcharge), - The **current** stays within safe levels (to avoid overheating and lithium plating), - The battery's **temperature** remains in an acceptable range, - Any faults (like a bad connection or internal cell issue) are detected in time to stop the process.

1.2 Battery Pack Structure: Cell → Module → Pack – An EV battery pack is not a single big cell; it's made of many individual cells connected together to meet the vehicle's power and energy requirements. Cells are typically grouped into modules, and modules are assembled into the full pack. The pack also includes support systems: - **Battery cells:** The fundamental electrochemical units providing voltage and capacity. Cells can be cylindrical, prismatic, or pouch type. - **Module:** A group of cells (often in series and/or parallel) in a physical frame with monitoring electronics. Modules provide a convenient subsystem (e.g. a module might be

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~50V). - **Pack:** The full battery assembly in the vehicle. The pack may contain dozens of modules to reach the desired total voltage (hundreds of volts in modern EVs). The pack includes the **BMS** electronics, main **contactors** (high-voltage switches), **fuses** and current sensors for safety, a **cooling system** (liquid coolant channels, pumps, etc., or other thermal management), and a sturdy mechanical housing often with crash protection features.

During charging, if it's an AC charger, the vehicle's **on-board charger (OBC)** converts AC from the grid to DC for the battery. If it's a DC fast charger, the conversion to DC is done off-board and DC power is delivered directly to the pack. In both cases, the BMS inside the pack supervises the process: it monitors cell voltages and pack conditions and communicates with the charger to **throttle the charging** as needed to protect the cells. Essentially, the vehicle **requests** only as much current/voltage as it can safely handle.

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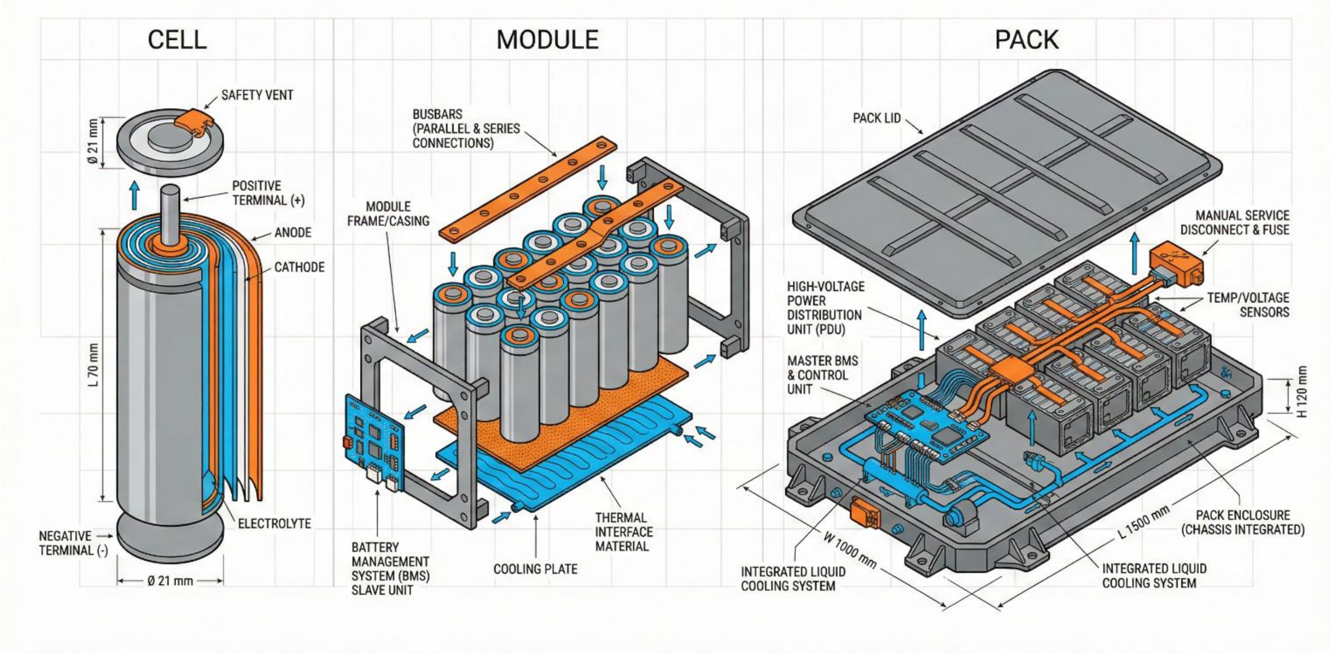

Figure 11 Schematic of an EV battery pack, composed of cells grouped into modules, with a BMS monitoring the cells and controlling contactors

Automotive Practice – Why Battery Packs Use Many Cells: EV packs use many small cells to achieve high voltage and capacity. For example, a pack might have ~400 V and tens of kWh of energy. It's impractical to build a single cell at 400 V, so instead manufacturers connect many low-voltage cells in series (to increase voltage) and parallel (to increase amp-hour capacity). This is why EV battery packs are modular. The downside is each cell must be managed – if any one cell is pushed beyond limits, it can fail. That's a key job of the BMS: *keep all those cells balanced and happy.*

1.3 The Essential Language of Charging: Capacity, Energy, Power – Before going deeper, it's important to clarify three fundamental terms which are often confused:

- **Capacity (Ah):** In battery context, capacity refers to electric charge (in ampere-hours) a battery can hold or deliver. 1 Ah means a current of 1 A can flow for 1 hour (idealized). For example, a cell might be rated 50 Ah. In EV discussions, we more often use energy in kWh (since energy is what determines range), but capacity in Ah is still used at cell/module level.

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- **Energy (Wh or more commonly kWh):** This is the total work the battery can do – effectively, how "full" of energy it can get. Energy (in Wh) = Voltage (V) × Charge (Ah). EV batteries are usually described by their energy: e.g. a "60 kWh battery pack" can store about 60 kWh of energy (not all may be usable due to buffers). Energy is what correlates with vehicle range.

- **Power (W or kW):** Power is the rate of energy transfer – how fast energy is delivered or taken in. In charging, power tells us the *speed* of charging. For example, a **7 kW** AC charger is relatively slow (overnight charging), whereas a **150 kW** DC charger is fast (can add a lot of range in minutes). Power is roughly the product of current and voltage (P = V × I). Higher power means more energy per unit time.

A simple but very useful relationship:

$$\textit{Energy} = \textit{Power} \times \textit{Time}.$$

If power is constant, you can estimate charging time as Time = Energy added / Power. *In real EV charging, power is not constant (it often tapers down at high SOC, as we'll see), but this formula gives a rough estimate*. For example, if you need to put 20 kWh into the battery and the charger can supply 10 kW, it will take about 2 hours (20/10 = 2). If the charger is 50 kW, the same energy would theoretically take ~0.4 hours (~24 minutes), *assuming the battery can accept the full 50 kW the whole time*.

Automotive Practice – "kW" vs "kWh" in Conversations: EV drivers talk about charger speed in kW (power) and battery size in kWh (energy). For instance, "My car has a 60 kWh battery and I usually charge at a 7 kW station at work." This makes sense: the battery's kWh tells you how far you can go (range potential), while the charger's kW tells you how quickly you can refill that energy. A large battery (high kWh) doesn't charge any faster by itself – it's the kW of the charger and the car's acceptance rate that matter. For example, even a 100 kWh battery charged on a 3.6 kW home charger will take many hours; conversely a small 20 kWh battery can charge in an hour if you have a 20 kW charger (again if the battery can take that power).

1.4 Why Lithium-Ion Charging Must Be Controlled – Lithium-ion batteries have well-defined safe operating limits. In use, they must stay within a **safe voltage window**. If

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voltage goes too low (deep discharge), the cell can be permanently damaged (this is more a concern when *discharging*); if voltage goes too high (overcharge), it can cause unwanted chemical reactions, gas evolution, and is **dangerous**, greatly accelerating ageing and risking thermal runaway. Therefore, charging systems **never** intentionally exceed the maximum charge voltage of the cells (typically 4.2 V for many chemistries, though newer chemistries can be a bit higher). The BMS will cut off charging if any cell hits the max voltage.

Additionally, lithium-ion cells can only accept charge at a limited rate. If you try to force charge **too fast**, several things happen chemically: - Lithium ions cannot intercalate into the anode graphite fast enough, which can cause them to plate as metallic lithium on the surface – permanently damaging the cell and creating a safety hazard. This is especially a risk at low temperatures (charging a Li-ion below ~0 °C can cause lithium plating and must be avoided). - Side reactions (like electrolyte decomposition) accelerate at high rates and high voltages, consuming active materials and producing heat and possibly gas. - The cell's internal resistance causes heating (I^2R losses). High current = much more heat (since heat ~ current^2).

In short, lithium-ion batteries *must* be charged in a controlled way with proper limits on voltage, current, and temperature. **Overcharging or charging under unsafe conditions can lead to thermal runaway**, where the cell's internal temperature skyrockets and it can vent or catch fire. Even if not that extreme, aggressive charging significantly reduces battery life by causing chemical degradation.

This is why every EV has a BMS and why charging stations and vehicles communicate: to ensure the charging stays within safe limits at all times. As a basic rule, **the battery itself (via the BMS) decides how much current to accept**, and the charger will respect those limits to protect the battery.

2. Charging Methods and Strategies

Not all charging is equal. We classify EV charging by **how the current is delivered** (AC or DC) and by **power level** (slow, fast, ultra-fast). The different methods have implications for the vehicle hardware and the charging speed.

2.1 AC Charging (Onboard Conversion) – With AC charging, the power from the grid is AC (alternating current, e.g. your household or workplace supply), and it is converted to DC **inside the vehicle** by the **On-Board Charger (OBC)**. The EV's OBC

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is essentially a rectifier/inverter device that takes the AC input and outputs a controlled DC current/voltage to charge the battery. Key points about AC charging:

- The **charging power is typically limited by the vehicle's OBC capacity** and the available AC source. Many EVs have OBCs rated around 6–11 kW (some up to 22 kW for higher-end or commercial EVs). Even if you plug into a very high-capacity wall box, the car cannot charge faster than its OBC allows on AC.
- AC charging is common for **home, workplace, and destination charging** (hotels, parking garages, etc.). These are places where the vehicle can charge for longer duration (several hours), so moderate power is acceptable.
- AC charging is often considered "battery-friendly" because the power levels are moderate (not extremely high current), causing less stress and heat on the battery. The OBC's output is tightly controlled by the BMS.
- It's worth noting AC chargers come in different "Levels" or modes (Mode 2, Mode 3, etc., referring to portable EVSE vs installed EVSE). In Europe, a common interface is the Type 2 connector for AC charging; in the US, the J1772 connector.

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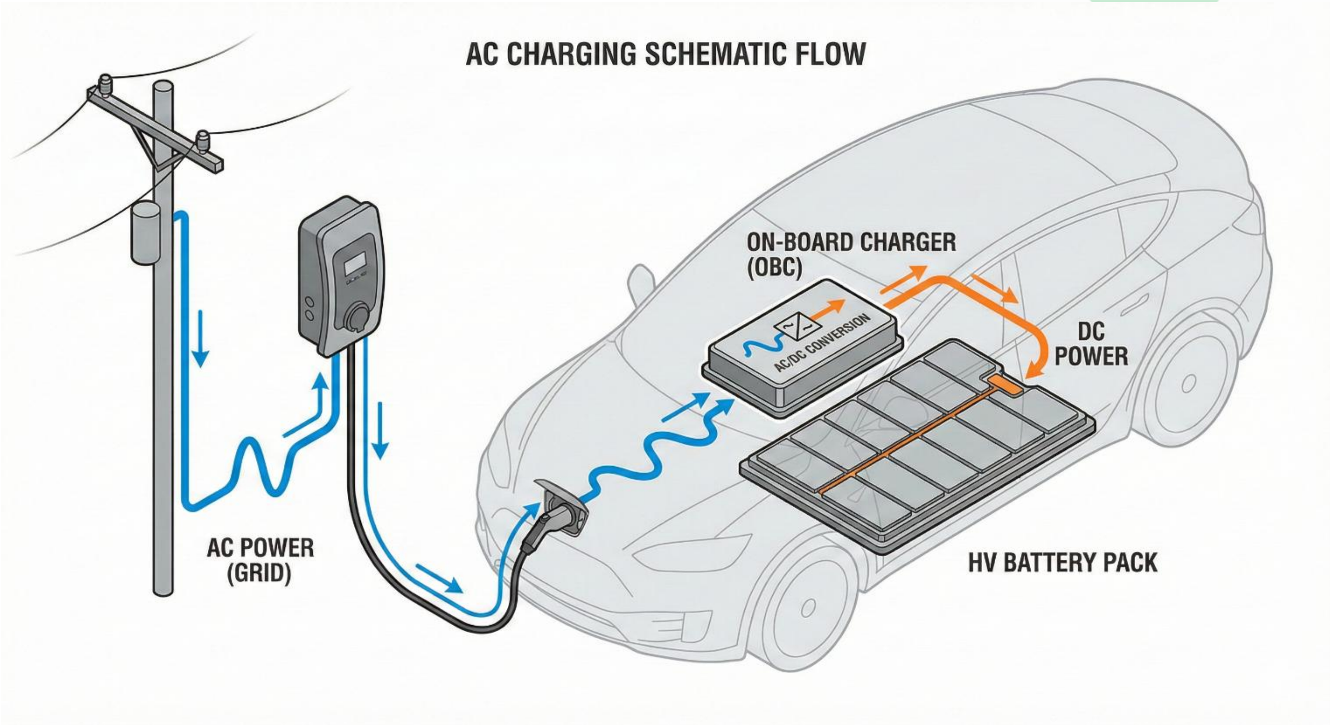


The BMS communicates with the OBC to regulate current.)

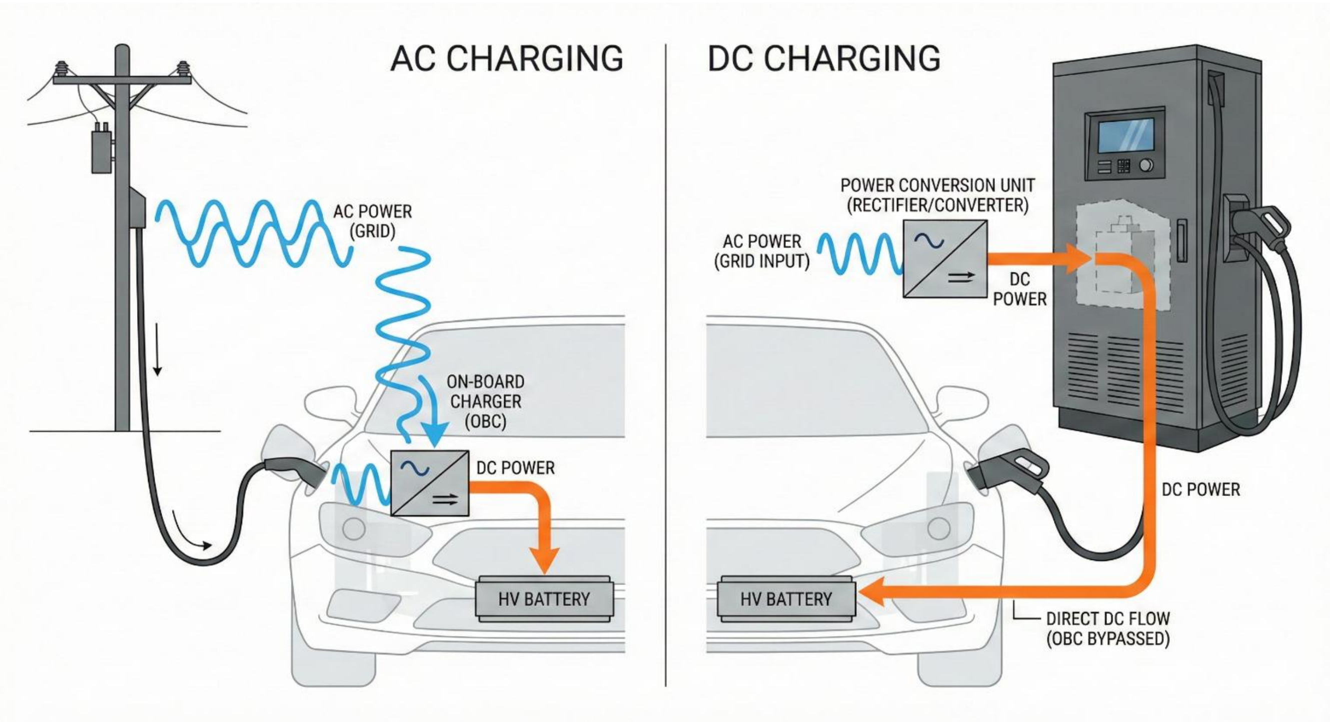
2.2 DC Fast Charging (Offboard Conversion) – With DC charging, the conversion from AC (grid) to DC is done by the **charging station itself (off-board)**. The station then supplies regulated DC power directly to the vehicle's battery through the charging port. In this case, the vehicle's onboard charger is bypassed (in fact, for DC charging the OBC simply steps aside and the BMS directly talks to the station). Key points about DC charging:

- **Much higher power** is possible than AC, because the off-board charger can be very powerful (50 kW, 150 kW, even 350+ kW in some ultra-fast chargers) and it's not limited by the vehicle's small onboard converter. Instead, the limitation becomes the battery's ability to absorb charge and the cooling system.

- DC fast charging is used for **quick pit-stop charging** – e.g. along highways, commercial charging hubs – where you want to recharge a significant amount in 15–40 minutes. It's crucial for long-distance travel in EVs.

- Even though the station can output high power, the vehicle **will still protect itself**: the BMS communicates the maximum allowed voltage and current to the station, so the battery is never over-stressed. In essence, the car "requests" a certain DC current and the charger provides it. As the battery fills up, the car will request less and less current (that's the tapering we observe).

- High-power charging generates a lot of heat in the battery and also in the charging cable and connector. Fast charging stations often have thick, liquid-cooled cables to handle currents of 200–500 A safely. The vehicle's thermal management (coolant pumps, fans) will usually kick on to manage battery temperature during a fast charge.



The vehicle's BMS communicates with the station to set current/voltage limits, ensuring the battery is not overcharged. The station handles converting AC to DC at the correct level.

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AC vs DC Summary: AC charging uses the **vehicle's converter** – it's generally slower (commonly 3 to 22 kW) but convenient and widely available; DC charging uses a **station's converter** – it can deliver much higher power (50+ kW) directly to the battery. AC is typically used for daily charging where time is less critical (and it's gentler on the battery), while DC is used when you need a lot of energy quickly (with more strain and heat to manage). The EV's charge port and connector standards differ: AC charging often uses single/three-phase connectors (Type 2, etc.), while DC fast charging uses specialized connectors (like CCS Combo, CHAdeMO) with additional pins for high-current DC.

Automotive Practice – Onboard vs Offboard Charger: Why not put a 150 kW charger onboard every car? The reason is **size, cost, and weight**. A 150 kW AC→DC converter would be huge and expensive to include in each vehicle. Instead, cars have moderate OBCs (affordable, small), and for fast charging the expensive power electronics are pooled in the off-board stations that serve many vehicles. Additionally, high-power conversion generates heat – easier managed in a big station than tightly in a car. This is why DC chargers are large boxes (often with active cooling) and cables that can be liquid-cooled, whereas AC charging cables are light and thin. The vehicle carries only what it needs for normal charging and relies on infrastructure for the occasional high-power need.

2.3 "Slow" vs "Fast" Charging: What Changes in the Battery? – The distinction between slow and fast charging is essentially the **charging current** and thus power. When we charge faster: - The **charging current (Amps)** is higher. For example, "slow" might be 16 A, whereas "fast" could be 250 A or more. - Higher current causes proportionally higher **I^2R losses** (heat generation inside the battery). If current doubles, resistive heating quadruples. This is why fast charging heats the battery significantly more than slow charging. - The electrodes (anode and cathode) experience **greater stress** at high current. Lithium ions have to diffuse quickly; if they can't all intercalate smoothly, it can cause localized plating or other degradation. - **Faster ageing**: Frequent high-C-rate charging tends to wear the battery out faster (higher internal resistance growth, capacity loss over cycles).

However, fast charging is not necessarily "bad" if the battery is designed for it and conditions are controlled. High-quality EV batteries are engineered to handle high rates *within certain SOC and temperature ranges*.

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To safely fast charge, you need: - **Precise control** of current and voltage (the charger/BMS must strictly follow the charging curve), - **Proper temperature management** (e.g. the pack should be within its optimal temperature window, often around 25–40 °C for fast charging; not too cold and not overheating), - **Battery chemistry and design that supports high C-rate** (some cell designs are made for power and can charge much faster without damage, whereas others optimized for energy might not handle fast charge as well). For instance, newer cells or those with advanced electrolyte additives can better tolerate rapid charge.

In summary, fast charging puts more strain on the battery, but EV manufacturers mitigate this through BMS algorithms and thermal controls. It's a trade-off: convenience vs. battery stress. *Occasional* fast charges are fine; doing it every day might accelerate wear.

2.4 Why Charging Power Drops at Higher SOC (the "Taper") – Most EV drivers notice that charging is really quick when the battery is low (e.g. 10% to 50% fills up fast), but slows down drastically above ~70–80% state of charge. This is expected behavior due to the lithium-ion **CC/CV charging profile** and cell chemistry: - As the cell approaches its maximum voltage (~4.2 V for many cells), the charger must switch from constant-current to **constant-voltage**. In the CV phase, the BMS will **taper the current down** to avoid exceeding the max voltage. - At high SOC, the **concentration of lithium in the anode is high**, and pushing more in becomes harder without raising voltage. The cell's internal resistance and polarization cause the voltage to climb quickly near full charge, so current must be reduced to not push it over the limit. - High SOC is also when side reactions are more likely (because voltage is high). By reducing current, we minimize stress. - Practically, this means the last 10–20% takes a long time. For example, an EV might charge at 150 kW from 10% to 50%, then gradually ramp down, and by 80–90% SOC it might only be charging at 30 kW or less. The **power tapers off** to protect the battery.

This is why EV route planning often suggests not charging to 100% at fast chargers unless you absolutely need the extra range – it's much slower beyond 80-90%. Stopping earlier and continuing your trip (or moving to a slower charger for the top-up) can save time overall.

Automotive Practice – The Last 20% Takes Longer. If you're road-tripping with an EV, a common strategy is to fast charge only up to ~80% SOC, then drive to the next

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station, rather than waiting for 100%. Going from 80% to 100% could easily double the charging time, because the car is trickling charge by the end. For example, an EV might go 10%→80% in 30 minutes, but need another 30 minutes to go 80%→100%. Unless you need the full range, it's more time-efficient to unplug earlier. Also, holding the battery at 100% is not ideal for long-term life (batteries prefer to dwell at middle SOCs if possible – but that's more about usage patterns).

3. The Charging Process and Key Parameters

When charging a battery, we control and monitor primarily three parameters: **voltage, current, and temperature**. These are the key inputs/outputs of the battery during charge. Additionally, internal values like cell resistance and the battery's state of charge/health matter for deeper understanding. Let's break down each:

3.1 Voltage – The "Ceiling" Not to Exceed – Every lithium-ion cell chemistry has a maximum charging voltage (for example ~4.2 V for NMC/Graphite cells, ~3.65 V for LFP/Graphite cells, etc.). This voltage corresponds to the full charge of the cell. Charging beyond this threshold risks triggering undesirable chemical reactions: - Exceeding the max voltage **accelerates ageing** (the electrolyte oxidizes more, the cathode structure can degrade). - It can cause **plating of lithium** on the anode (as the anode potential goes too low relative to lithium metal potential when pushing more charge). - It can lead to **gas generation** (electrolyte breakdown releasing gases) and **swelling** of the cell. - In extreme cases, over-voltage can cause a cell to go into **thermal runaway** (especially if no BMS cut-off, which is why BMS is always there to prevent this).

So, in a charging system, we treat the battery voltage limit as a hard ceiling. The charger will **hold the pack voltage at a maximum level** in the final phase of charge (constant voltage phase), and let the current taper off. The BMS monitors each cell group (series string) in the pack; if one cell group hits the max before others, the BMS can request a reduction or perform **cell balancing** (bleeding off a little charge from the full cells) to even things out. The goal is that no cell in the pack goes over its safe voltage.

In practical terms: When you see that your EV charging slows down a lot at ~4.1–4.2 V per cell (which is around 80–100% SOC depending on chemistry), it's the system respecting the voltage limit.

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3.2 Current – The "Throttle" of Charging Speed – Charging current (measured in Amps) is essentially how fast we are pumping electrons into the battery. It directly affects charging power (Power = Voltage × Current). If voltage is roughly constant during bulk charge, then more current = more kW into the battery (faster charge). However, high current: - Increases **heat** dissipated (losses ∝ I^2R). For example, going from 100 A to 200 A is a fourfold increase in heating in resistive elements. - May exceed what the battery's diffusion processes can handle, as discussed (leading to possible plating or stress). - Often necessitates **active cooling** to carry away heat.

A simple example to illustrate current vs power: Imagine an EV pack around 400 V. Charging at 100 A gives 400 V × 100 A = **40,000 W** (40 kW). At 250 A, the power is 400 V × 250 A = **100 kW**. So higher current is the path to faster charging – but only if the battery and charger can handle it safely.

The BMS will set a maximum allowable current based on conditions (e.g., it might say "I can take 200 A right now" to the charger, and as things change it might lower that limit). Conditions that affect allowable current include cell temperatures, cell voltage (at high SOC the allowed current is reduced), and cell health.

Charging current is like the "speed lever" – within the safe voltage limit, we use as high a current as the battery and thermal system allow to charge quickly. Then as we reach the voltage ceiling, we let current gradually drop (this is the CC→CV transition discussed above).

In summary: **Voltage limits ensure safety, current settings control speed.** During most of the charge (when SOC is low to mid), the system operates at maximum allowed current (constant current phase). Then near the end, it operates at maximum voltage (constant voltage phase) and current falls off.

3.3 Temperature – The Key Limiter for Fast Charging – Lithium-ion batteries have an *optimal temperature range* for operation (often around 20–40 °C for charging). Outside this range, performance and safety are impacted: - At **low temperatures** (below ~10 °C, and especially below 0 °C), lithium ion movement in electrolyte is sluggish. The anode's ability to accept lithium is reduced. Forcing high current when cold can cause lithium plating and permanent damage. Thus, EV BMS will usually severely limit charging current when the battery is very cold, or even prevent fast charging entirely below 0 °C until the battery warms up. - At **high temperatures**

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(above ~45–50 °C inside the cell), the chemical reactions accelerate, which ages the battery faster. Also safety margins decrease – a hot cell is closer to thermal runaway if something goes wrong. So the BMS will also taper charging if the battery is getting too hot. Generally, fast charging might be disallowed above a certain temperature to avoid pushing an already hot battery.

Because temperature is so crucial, EVs incorporate **thermal management systems**:
- *Battery cooling*: Most modern EVs have liquid cooling for the pack. During a fast charge, you will often hear coolant pumps and fans – the car is actively removing heat from the cells to keep them in the optimal range so it can sustain high current.
- *Battery heating/preconditioning*: In cold climates, EVs may *heat the battery* before or during charging. Some cars even use navigation data – if you set a fast charger as your destination, the car will heat the battery en route so that when you arrive the battery is warm enough to accept a high charge rate. This "preconditioning" ensures you don't have to charge at a crawl due to a cold battery. - *If limits are reached*: The BMS could reduce current to prevent further heating, or in extreme cases pause charging if something is out of bounds.

The optimal battery temperature for fast charging is often around 25–35 °C. Manufacturers publish acceptable charging temperature ranges (e.g. maybe 0 °C to 50 °C, but with reduced speeds at the extremes). Charging when the pack is extremely cold (like -10 °C) can be not only slow but harmful – some owners manual explicitly say "Do not charge below 0 °C" unless the car can warm the battery.

Thermal Influence Example: If you try to DC fast charge in winter and the car hasn't warmed its battery, you might see initially a very low power (because the BMS is protecting the cold battery). Once the battery warms up either through self-heating or heating system, the power may increase. Conversely, if a battery gets too hot,

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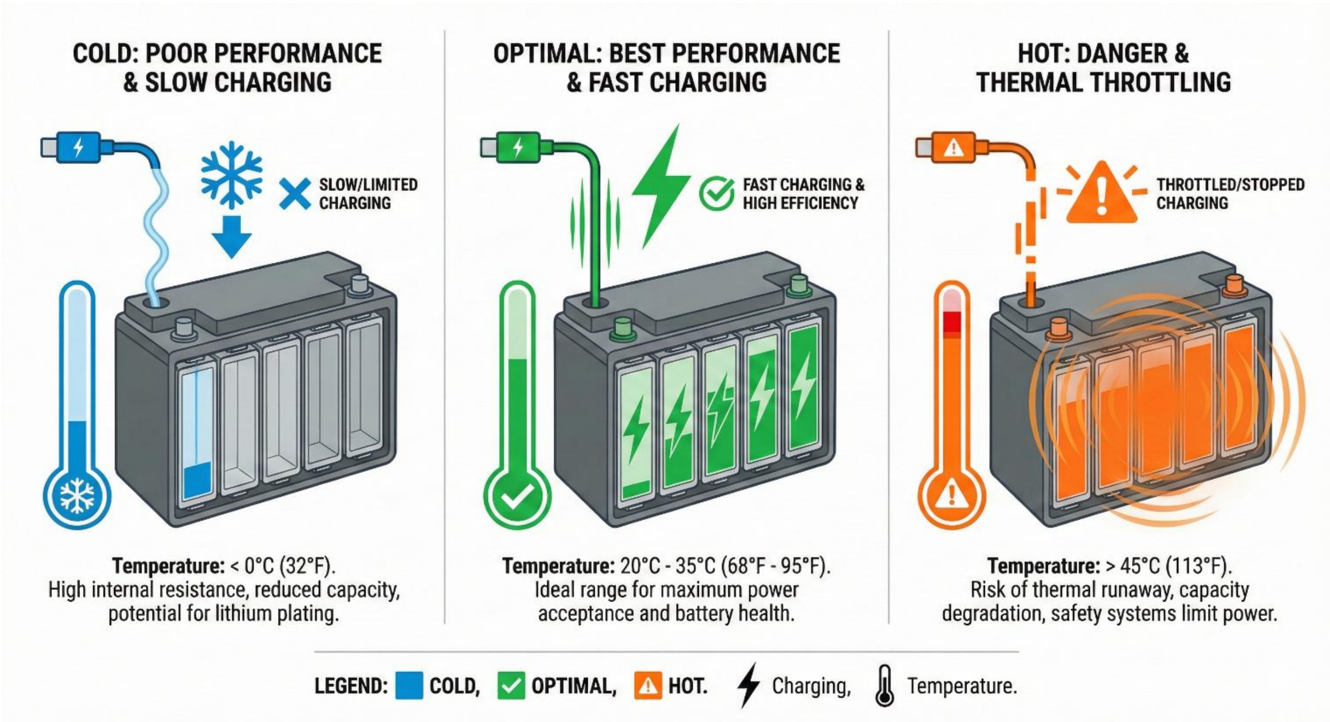
the car might throttle down the current. Temperature is always being monitored and actively managed during charging.

4: Temperature vs Charging – *a simplified "traffic light" analogy:* A battery at *low temp* (e.g. below 0 °C) has a red light for fast



charging (not safe to charge fast – current must be very low). At *moderate temp* (e.g. 20 °C), green light – charging can proceed at max rate. At *high temp* (e.g. >45 °C), yellow/red light – charging should slow or stop to avoid pushing the battery into an unsafe zone. (EVs aim to stay in the green zone by cooling or heating as needed.)

3.4 Internal Resistance and Why Fast Charging Heats the Battery – No battery is ideal; each cell has an **internal resistance** (also called impedance). When current flows through the cell, this resistance causes a voltage drop and dissipates energy as heat *inside the cell*. A very simplified formula for heat generation is:

- **Heat (power loss) ≈ $I^2 \times R_{internal}$**.

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This shows why high current is so challenging: If you double the current (I becomes 2I), the heat generated increases by four times (since $(2I)^2 = 4I^2$). For example, if a cell has an internal resistance of 0.01 Ω and you charge at 10 A, the heating is $10^2 * 0.01 =$ **1 W** (not much). If you charge at 100 A, heating is $100^2 * 0.01 =$ **100 W** (per cell!). In a pack of hundreds of cells, that's a huge heat load to manage.

This is why cables and connectors also get hot at high currents – they too have some resistance (hence heavy cables or even liquid cooling are used to reduce R and remove heat). In the battery, heat can cause temperature to rise quickly if not actively cooled.

Thus, **fast charging necessitates robust thermal management**: not only to protect the cells, but also to prevent things like connectors from melting. The concept of internal resistance also ties into **efficiency** – some energy is lost as heat. At higher currents, the percentage lost to heat is larger, meaning ultra-fast charging can be a bit less energy-efficient (you're paying a small "heat tax").

Automotive Practice – Why Do Fast Chargers Have Thick Cables? High current causes significant resistive heating in the charging cable and connectors. To keep them from overheating, DC fast chargers use very thick cables (to lower resistance) and often include active cooling (pumping coolant through the cable). For example, a 350 kW charger might carry ~500 A – without cooling, the cable would be heavy, stiff, and still get very hot. With liquid cooling, the cables can be manageable and kept within safe temperature limits.

3.5 State of Charge (SOC) and State of Health (SOH) – These are battery state estimates computed by the BMS that influence charging:

- **State of Charge (SOC)** is essentially the BMS's estimate of what percentage of the battery's usable charge remains (0% = empty, 100% = full). It's not a directly measurable quantity – it's estimated from things like:
- **Coulomb counting:** tracking how much current flows in/out over time.
- **Voltage lookup:** when the battery is rested, the open-circuit voltage correlates to SOC for a given chemistry.

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- **Models and adaptive algorithms:** the BMS may refine SOC by combining methods and adjusting for temperature, aging, etc.

SOC is used to decide charging limits (e.g. as SOC→100%, switch to CV). Also, many EVs display SOC to the user as the "battery percent".

- **State of Health (SOH)** indicates how the battery's condition compares to when it was new. Typically SOH is reported as a percentage of original capacity (and sometimes also accounts for internal resistance increase). For example, SOH = 90% might mean the battery can hold 90% of the energy it did when new. BMS estimate SOH by observing capacity fade over cycles and resistance rise. There is no single standard method, but it often involves:

- Periodic capacity tests (some BMS do subtle long-term measurements, or use full charge/discharge data).

- Tracking of coulombs and voltage behavior over time.

- The BMS might also infer SOH from how the voltage responds to known current (internal resistance).

SOH matters for charging because an aged battery with higher internal resistance will heat up more for the same current, and might not handle fast charge as well. Some EVs reduce charging power as the battery ages to protect it. Also, SOH is used in range prediction (lower SOH = less range).

In practice, if a battery is older (lower SOH): - It might reach the voltage limit faster during charge (because of capacity fade, a given amount of charge raises voltage more). - It likely generates more heat at high current (due to increased resistance). - Fast charging might be **slower** on an aged battery because the BMS will taper current sooner to avoid stress.

So, *charging performance can degrade with battery age*. For example, a 5-year-old EV might not charge as quickly from 10–80% as it did when new, especially in the later part of the range, due to these factors (and manufacturers often update charge profiles to be gentler as batteries age).

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3.6 CC/CV Charging Explained (Constant Current / Constant Voltage) – Almost all lithium-ion batteries (including EV batteries) are charged using a **CC/CV** profile: - **Phase 1: Constant Current (CC)** – The charger supplies a fixed current (often the maximum the battery can accept). During this phase, the battery's voltage rises as it charges. This is the fast-charging part where the bulk of the energy is filled. The cell voltage gradually approaches the maximum limit. - **Phase 2: Constant Voltage (CV)** – Once the cell (or pack) voltage reaches the predefined charge limit (e.g. 4.2 V per cell), the charger switches to holding that voltage constant. Now the current is no longer fixed – it starts to **taper down** as the battery's internal chemical equilibrium approaches full charge. The battery naturally draws less current when held at max voltage. This phase slows down the closer you get to 100% SOC, because the current eventually falls to a trickle.

Why have a CV phase? Because if you tried to keep pushing high current at the top of charge, the voltage would exceed safe limits – essentially you'd be overcharging. The CV phase ensures you **complete the charge safely**, topping up the last few percent without overshooting voltage. It also allows lithium ions time to fully intercalate into the anode structure, reducing stress.

In the CV phase, charging **terminates** either when current falls below a certain tiny threshold (like C/50 or so) or a timer or other cutoff says the cell is full enough (different BMS have different end-of-charge criteria, often when current tapers to ~0.05 C or similar).

A typical lithium-ion charging curve looks like this: - From 0% up to perhaps ~70-80% SOC: **constant current**, battery voltage rises roughly linearly. - Around 80% SOC (depending on chemistry), voltage reaches 4.2 V (or the set limit). Now **constant voltage** begins at 4.2 V, and current starts dropping off exponentially. - By 100% SOC, current has dropped to a very low value (essentially zero net charge current, just enough to maintain the terminal voltage).

This is illustrated in **5** below: the red line (voltage) increases until it hits the max (dotted line), then stays flat; the blue line (current) is flat initially (CC phase) then

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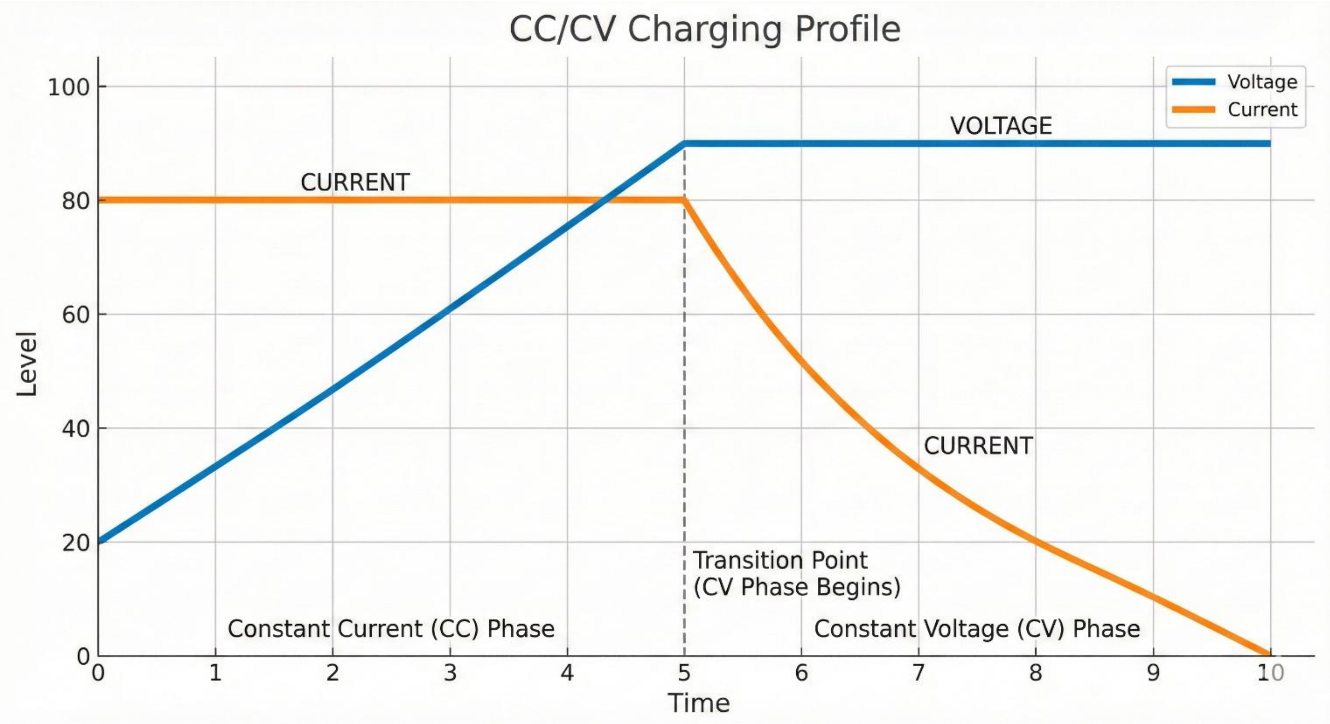
declines during CV; the green line (capacity % or SOC) climbs quickly then levels off as it approaches 100%.



During CC, charging is most efficient and fast – the battery takes in charge readily. During CV, the current taper means diminishing returns (lots of time for little charge). That's why, as mentioned, EV fast charging is usually quoted in terms of how quickly you can go from, say, 20% to 80%. The last 20% is slow.

Key takeaways of CC/CV: - CC phase = maximize use of charger/battery capability (fast fill). - CV phase = gentle finish to avoid overcharge, ensure cell balancing, and prolong life. - You cannot speed up CV phase by using a bigger charger – it's limited by the battery's chemistry. For instance, even on a 350 kW charger, an EV might only draw 50 kW at 80% and 20 kW at 90% SOC, etc.

4. Role of the Battery Management System in Charging

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The **Battery Management System (BMS)** is the "brains" of the battery pack. It is absolutely critical during charging for safety and longevity. During charging, the BMS has three major tasks: 1. **Measurement:** Continuously measure key battery parameters (voltages, currents, temperatures, etc.). 2. **State estimation:** Compute derived values like SOC (state of charge) and SOH (state of health) based on those measurements and models. 3. **Control/Protection:** Enforce limits (current, voltage, temperature), take action if something goes out of bounds (e.g. stop charging, cool the battery), and manage cell balancing and other functions.

In essence, the BMS makes sure the battery stays within safe operating area at all times. Let's detail some BMS functions relevant to charging:

4.1 Measurements During Charging – A BMS typically measures: - **Cell voltages:** Usually not every single cell (if many in series, they measure groups or every cell in some designs), to ensure no cell exceeds the safe voltage. They often have a precision voltage sense IC that can read each series cell's voltage. - **Pack current:** Using a shunt resistor or Hall effect sensor, the BMS monitors the current flowing in/out of the pack. During charging, this is the charge current. - **Temperatures:** Multiple temperature sensors (thermistors) are placed at various points in the pack – between cells, on module surfaces, coolant outlets, etc. The BMS watches these to prevent overheating and to know if the pack is too cold to charge fast. - **Isolation monitoring:** In EV packs, the BMS often includes an insulation monitor that checks that the high-voltage system is still isolated from the car's chassis (no leakage developing). This is a safety measure – if a fault appears during charging (like water intrusion causing a short), the BMS can detect it. - **Contactor status:** The BMS controls high-voltage contactors (big relays) that connect the battery to the outside circuits. It will verify that contactors are functioning (e.g. measuring voltage on both sides). - **Any fault indicators:** The BMS might also monitor for signs of internal cell faults (voltage irregularities) or external faults (like input power quality).

All these measurements feed into the BMS's decisions. For example, if any cell's voltage hits the limit, the BMS will tell the charger to reduce current or stop. If any sensor shows > some temperature threshold, it might initiate cooling or throttle current.

4.2 Protection Functions During Charging – The BMS implements a host of protection limits, such as: - **Over-voltage protection:** If a cell goes above its max voltage, BMS

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will stop or severely reduce charging. It may try to bleed that cell down via balancing resistors if possible. - **Over-current protection:** If the charge current is above safe level (perhaps due to a charger fault or communication error), the BMS can open contactors to stop the current or send a command to the charger to stop. - **Over-temperature protection:** If the battery gets too hot during charge, BMS will request current reduction or shut off charging. Likewise, if battery is below a low-temp threshold for charging, the BMS may prevent fast charging or any charging until the battery is warmed. - **Under-temperature lockout:** Many BMS will not allow charging below e.g. 0 °C or will drastically limit current, because of the plating risk. - **Cell imbalance or anomaly detection:** If one cell group's voltage is rising much faster than others (indicating it's full or there's an imbalance), the BMS might reduce current earlier or flag a fault. - **Hardware safety checks:** The BMS also has redundant hardware (voltage limits, etc.) that will blow fuses or open contactors as a backup if the primary controls fail.

If a protection limit is reached or a fault is detected, the BMS can take actions such as: - Telling the charger via communications to ramp down or stop. - Opening the pack's contactors (this is like an emergency disconnect – used if something is really wrong or charger isn't listening). - Activating cooling systems (turning on pumps, fans) or if too cold, activating heaters (if available). - In less critical situations, just logging a warning and reducing charge rate.

Modern BMS are quite sophisticated – they often have multi-level protections (soft limits vs hard trips). For example, at 45 °C maybe just limit current (soft limit), at 50 °C trigger a cooldown and warning, at 55 °C hard-stop the charge.

4.3 Cell Balancing – Ensuring All Cells Finish Together – Cell balancing is an important function especially towards the end of charging. Because in a series string, the weakest cell (highest voltage) limits the whole pack. If one cell is at 4.2 V and others are at 4.0 V, the charger must stop because of that one cell – leaving others undercharged. To prevent this outcome over time, BMS perform **balancing**, typically when near full charge: - **Passive balancing:** The most common method. The BMS uses tiny resistors to bleed off charge from cells that reach full voltage before others. Essentially it bypasses a little current around the "full" cells, allowing the others to catch up. This dissipates energy as heat (hence "passive"). It usually occurs near top-of-charge when currents are low and cells are trickle-charging. - **Active balancing:** A more complex approach (less common in production EVs currently)

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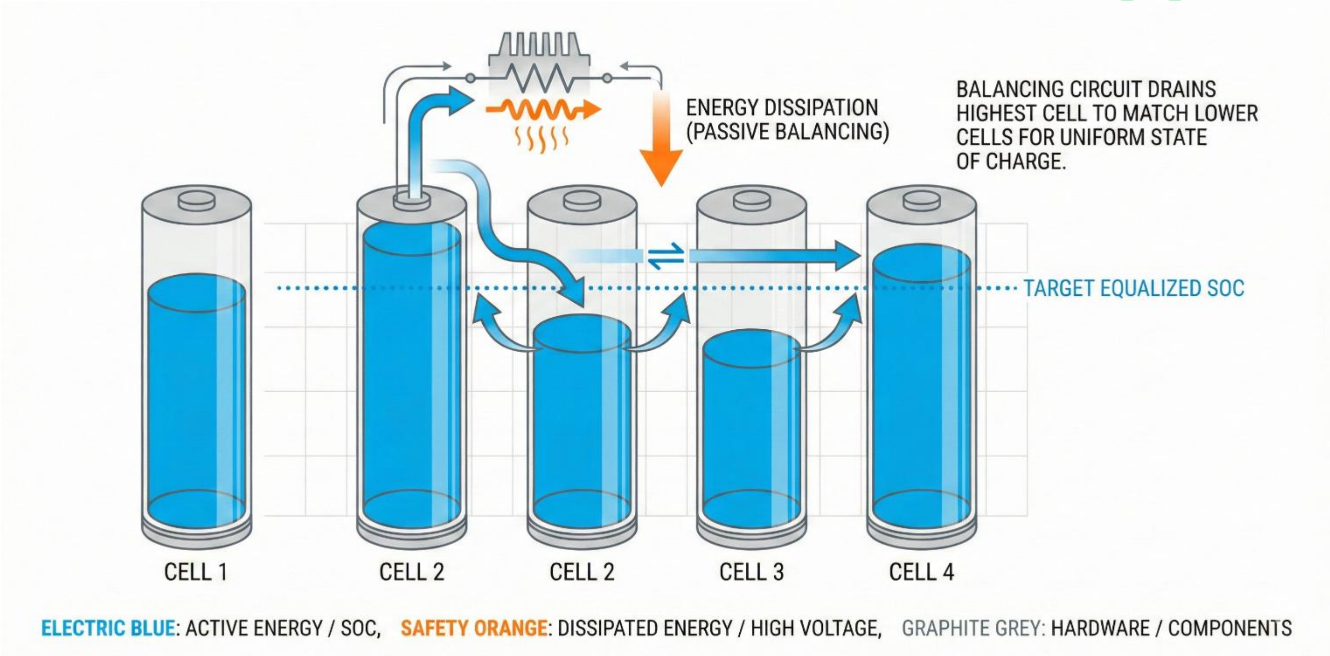

where energy is shuttled from high-charge cells to low-charge cells (using capacitors or converters). This can balance without wasting energy, but it's more expensive and intricate.

Balancing ensures that over many cycles, cells remain at roughly equal capacity utilization. Typically BMS will balance when SOC is high (cells nearly full) because that's where small differences in capacity show up as voltage differences. This is another reason charging slows near 100% – some of the current is going into balancing bleed resistors and the BMS might even hold at a CV for extra time to top balance.

A well-balanced pack can be charged to 100% maximizing range. A poorly balanced pack would either overcharge some cells or have to stop early. BMS balancing prevents one cell from becoming a chronic bottleneck.

In summary: **Balancing = longevity and capacity optimization.** It is especially relevant during the CV phase of charging – BMS might extend the CV phase slightly to balance cells at the top. Users typically won't notice, except perhaps that the last 1-2% takes a bit longer as balancing completes.

4.4 Charging Communication and Control Loop – In advanced charging (especially DC fast charging), there is a communication handshake between the vehicle (BMS)

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and the charging station (EVSE). The sequence, simplified, is: 1. **Plug in** – The EVSE and vehicle establish a connection. Safety checks ensure the connection is secure (some EVSE lock the connector). The EVSE might send a low current pilot signal to detect the car. 2. **Identification and readiness** – The car's BMS/module communicates its presence, possibly via a protocol (like PLC for CCS, or CAN, etc.). They agree on basics (the standard, max available current from station, etc.). 3. **BMS sends charging limits** – The vehicle continuously communicates how much voltage and current it wants. For example, "I am a 400 V pack, I need 380 V at 200 A now." As the charge progresses, it might update: "Now I need 400 V but can only take 100 A," etc. This is usually done many times per second. 4. **Charger regulates output** – The EVSE then provides the requested current up to the requested limits. It will monitor its own output and not exceed what the car asks for (and also not exceed what it can supply or what cable temperature allows). 5. **Feedback loop** – The BMS monitors the battery's response (voltage, temp). If things change, it adjusts its request. For instance, if the battery warms up too much, BMS might lower the current request. 6. **Charge termination** – When the BMS determines the battery is full (current tapered to end-of-charge or SOC ~100%), it will tell the EVSE to stop. Then contactors open and the station shuts down power. Usually some protocol ensures there is no arcing (the EVSE will only disconnect when current is zero and contactors open).

All of this happens automatically and is largely invisible to the user. Standards like **ISO 15118 / DIN 70121** (for CCS) or the CHAdeMO protocol define this in detail. Essentially, the car is in control of the charge it receives (which is good because only the car truly knows the battery's condition). The charger is like a smart power source that obeys the car's commands within its own safety envelope.

Even in AC charging, there is communication (a simpler pilot signal in modes 2/3 that tells the car how much current it can draw from the outlet). The BMS/OBC then only pulls that much.

In summary: **The charger and BMS form a closed-loop control** – measuring and adjusting in real time to safely charge the battery at optimal speed.

Automotive Practice – Battery Preconditioning for Fast Charge: Some EVs, as mentioned, will precondition (heat or cool) the battery when you set a fast charger as your destination. For example, a Tesla or Porsche may intentionally warm the pack to ~30°C by the time you arrive at a Supercharger station. The reason

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is to ensure the battery can take the full high current right away, **improving charging time and reducing stress**. If the pack were cold, the BMS would limit current and you'd have a slower session. This is an example of smart integration between navigation, thermal system, and BMS to enhance user experience and protect the battery.

5. Safety Aspects of Battery Charging

Charging EV batteries involves high electrical power and a large energy storage device – this carries inherent risks if not managed properly. Safety considerations span **electrical safety**, **thermal safety**, and **chemical safety**. Here we outline the main hazards and safety practices.

5.1 Electrical Hazards (High Voltage and High Current) – EV battery packs have high voltages (typically 300–400 V, sometimes up to 800 V in newer EVs). The currents during fast charge can be hundreds of amps. The key electrical hazards are:

Electric shock: Direct contact with high voltage could be fatal. Even the AC mains (230 V or 120 V) can be dangerous; EV pack voltages are far higher. Thus, the charging system is designed so that users never directly interface with live conductors – everything is insulated. Connectors are designed to not expose pins until mated, and the BMS will not close contactors to connect the battery until a safe handshake is done. A device called an **RCD** (residual current device) is often installed in charging circuits to detect any leakage current to ground and cut off power, preventing shock.

Arc flash / short-circuit: If a high current path is suddenly interrupted or shorted, it can create an arc (a plasma discharge). For example, if someone were to unplug under load (which is prevented by the EVSE's interlocks) or if there's a short between the DC terminals, an arc flash could occur causing burns or fire. To mitigate this, connectors have interlock signals – the system stops current flow before the connector unlocks. Also, the pack contactors open immediately if a severe short is detected.

Overheating of connectors or cables: If a charging plug is damaged or not fully inserted, or if a cable has an internal fault, resistance can cause heat. A poor connection can lead to a hot plug that could even melt or burn (in worst cases). This is why *charge plugs have temperature sensors* (some DC fast charge handles monitor pin temperature and will tell the car to ramp down current if it gets too hot).

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Battery overcurrent/overcharge: As covered, if the charger were to malfunction and pump excessive current or not shut off, the BMS and pack fuses act as safety. The BMS would open contactors for overcurrent or overvoltage. There are also often **charge relays** on the input of the OBC for AC charging that only close when appropriate.

Safety design features in charging systems include:

You'll notice EV charge connectors are fully shrouded; you cannot touch live pins. For DC connectors, the vehicle inlet locks the connector in place during charging so it can't be pulled out mid-session.

Many EVs have a small wire loop in the charge port that immediately signals the BMS if the latch is pressed or connector is tampered; it will cut power.

The EVSE checks that the ground connection is good before allowing any current (in AC charging). The EV's BMS checks isolation resistance of the pack to chassis continuously – if it drops (indicating a possible short to chassis), it will error out.

The battery pack has fuses that will blow in case of severe overcurrent (like a short circuit). Some packs have "pyrofuses" (pyrotechnic disconnects) that can trigger via a signal (for example, in a crash or if a serious fault is detected) to isolate the battery instantly.

For AC charging, the station often has a device that detects if any current is "leaking" out of the intended circuit (like into a person or a stray path) and cuts power within milliseconds.

Technicians are trained to *always de-energize and isolate the HV system* before working on it, and users are advised not to use charging equipment that is damaged or if the vehicle reports a fault.

5.2 Thermal Hazards and Thermal Runaway – Lithium-ion batteries are sensitive to temperature. While charging, as discussed, they generate heat. But the most dangerous failure mode is thermal runaway: a chain reaction where the battery uncontrollably overheats.

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During thermal runaway: - An initial trigger (like severe overcharging, an internal short in a cell, external heat or fire, or mechanical damage) causes the cell temperature to rise. - At elevated temperature, exothermic reactions occur in the cell (the electrolyte can decompose, electrode materials can react). These reactions release more heat. - If that heat isn't removed, it further raises the cell's temperature, causing even more violent reactions (e.g. the separator can melt, leading to internal short and rapid energy release; the electrolyte can boil and vent flammable gases). - This can lead to the cell venting with flame – essentially it can catch fire or even burst. - The danger is that one cell's thermal runaway can heat neighboring cells, causing **propagation** – a chain reaction through the module or pack.

Thermal runaway is **rare** under normal charging conditions – it is usually caused by severe abuse or critical failures. Overcharging (charging well beyond 100% SOC or beyond 4.3 V per cell) can induce it by causing internal temperatures to skyrocket. Charging a damaged cell (internal short) could also trigger it. Loss of cooling during an ongoing fast charge could allow heat to build to dangerous levels, though systems are designed to shut down if cooling fails.

Warning signs and prevention

- The BMS and charger are designed to never let the cell reach those trigger conditions (hence all the limits). For example, *overcharge protection is paramount* – no charger should ever exceed the voltage limit, as that is a known trigger for thermal runaway.

- If a cell starts to fail internally, one might observe swelling or rapid temperature increase. Packs often have thermal sensors at multiple points to catch any abnormal heating.

- Workshops are taught never to charge a battery that is known to be damaged or swollen.

- Charging should also be halted if abnormal signs appear (smell, smoke, hissing sound – indicating venting).

Although EV fires make dramatic news, it's important to note they are *extremely* infrequent per billion miles compared to gasoline fires. But the industry takes even the rare events very seriously, hence robust standards and tests (UN 38.3 transport

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tests, etc.) require that batteries can withstand certain abuse without fire, and containment measures are in place.

If thermal runaway does occur in a cell: - Modern packs try to *contain it*. They may have fire-resistant barriers between cells or modules. Some have vents to direct flames out of the passenger cabin area. - **Firefighting** such a battery is difficult; large amounts of water are generally used to cool the remaining cells to stop propagation. Specialized firefighting guidance exists for different EV models.

Figure 16 Thermal runaway chain – a diagram might show: “Trigger (e.g. overcharge) → Heat → cell venting and fire → heat spreads to next cell → etc.” along with noting safety systems like thermal propagation barriers or vents that mitigate it.

In workshop context, **thermal runaway prevention** means: - Never bypass the BMS or “trick” it during charging. - Follow proper procedures for damaged batteries (don’t charge them, isolate and call appropriate handlers). - Ensure cooling systems are working (e.g. if an EV’s cooling system is not functional, do not fast charge it until fixed). - Use the specified chargers – do not improvise with unapproved equipment.

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5.3 Chemical Hazards (Electrolyte, Gas, Smoke) – Lithium-ion cells contain flammable electrolyte (typically a mixture of organic solvents like carbonates) and other chemicals. Under normal operation, these chemicals are sealed inside the battery. But if a battery is **damaged or mishandled**, chemical hazards can emerge: - **Electrolyte leakage:** The liquid electrolyte can leak out if a cell is ruptured. It is typically toxic and flammable. It can cause skin and eye irritation or chemical burns. One component often used, $LiPF_6$ salt, can produce **HF (hydrofluoric acid)** upon contact with moisture – a highly corrosive and dangerous acid in even small quantities. - **Gas release:** If a cell vents (through the safety vent due to overpressure), it releases a mix of gases. These can include combustible gases like hydrogen, methane, CO, ethylene, as well as toxic gases. The vented gas may have a sweet solvent smell or acrid odor. It can be dangerous to breathe and of course can ignite. Swollen battery packs (especially pouch cells) indicate gas build-up inside – a clear red flag. - **Fire and smoke:** The smoke from a battery fire contains various combustion byproducts (including HF, phosphorus oxides, etc.) and is very irritating or harmful to inhale. Direct contact with the smoke can cause respiratory issues.

What are warning signs of impending failure? During charging, if you notice any of the following, treat it very seriously: - **Swelling of the battery or components:** This often means gas build-up inside cells. It's a strong warning of internal cell failure or overcharge. A swelling battery should be taken out of service. - **Hissing or venting sounds:** This indicates gas is venting. The charging should be stopped *immediately* and the area cleared since flammable gas might be present. - **Burning smell or solvent smell:** If you detect unusual odors (sweet chemical smell, or something like nail-polish remover or burnt plastic), it could be electrolyte venting or overheating. Assume something is wrong. - **Smoke or glow:** Obviously, any smoke or signs of charring = emergency; power off and follow emergency protocols (use of fire extinguisher, calling fire services). - **Unexpected overheating:** If the battery or area around it is becoming much hotter than the charging rate would suggest (e.g. lukewarm is normal during fast charge, but if you feel parts that are *hot* to the touch or see thermal warnings on the dashboard), that's a sign to stop.

If something "feels wrong" during charging (excessive heat, smell, etc.), the safe course is: 1. **Stop charging** – disconnect power (stop the charge session via the station or vehicle controls; *do not just yank the cable* if under load). 2. **Evacuate and ventilate** – Keep distance from the vehicle. If indoors, ventilate the area because of potential flammable/toxic gas. 3. **Notify professionals** – Call appropriate safety

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personnel (firefighters if fire risk, or facility safety team). They are trained for battery incidents. 4. **Do not touch** the battery or car if there's any sign of thermal runaway (you can risk chemical exposure or shock if insulation is compromised). 5. If safe to do (no immediate fire), you can use an IR thermometer from a distance to monitor if temperatures continue rising, but only if trained and with PPE.

Workshops often have an emergency response plan for EV battery incidents: including Class ABC or D fire extinguishers, lots of water, sand or firefighting blankets, etc. However, prevention is the first priority: *do not charge a battery that has known damage or that was involved in an accident without proper inspection.*

Automotive Practice – If in Doubt, Do Not Charge!

Technicians are taught that if a high-voltage battery shows any anomaly (e.g. after a crash, or any sign of leakage/swelling), it should be isolated and not charged or used. If a customer brings a car with a bulging battery case or strong odors, the response is to safely quarantine the vehicle and contact specialists. The worst thing is to put energy into a compromised battery. Safety first – it's better to tow the vehicle to a safe area than risk an incident in a closed workshop.

5.4 Safe Handling and Charging Procedures

To ensure safety, both the **technology** and the **people** must do their part. We covered the technology's role (BMS, charger interlocks, etc.). Now, some best practices for humans when charging or handling EV batteries:

- Avoid any mechanical damage to the battery pack. Do not drop batteries or subject them to impact. A crushed cell can short internally and later lead to fire.
- When the service panel is open or battery exposed, never place tools or wear jewelry that could cause a short. A simple short across terminals can be catastrophic at high voltage.
- Keep water away from charging equipment (unless it's specifically rated for rain, etc.). Ensure charge connectors are free of corrosion or debris. Water intrusion can cause short circuits (though EVSE have ground fault detection to stop it).

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- In a workshop, when working around batteries, use insulated gloves, eye protection, etc., as needed. When just plugging in an EV, generally PPE isn't required for the user because of the safety design, but a technician working on the battery must use appropriate gear.
- Using incompatible or jury-rigged charging setups is dangerous. Always use a charge cord or station that meets the standards for that vehicle. Homemade adapters or modifications can bypass safety handshakes.
- Do not leave a vehicle charging in an enclosed space unattended for long periods *unless* it's an installation designed for it with safety systems (most home chargers are fine to leave overnight, but say charging a battery on a bench in a lab – you'd supervise that). EVs have many safety layers, so an owner can normally leave the car charging in a garage – but the area should be ventilated and clear of flammable materials around the charging spot just in case.
- If a battery did overheat or vent, it should be considered hazardous waste until properly dealt with. Fire services often have to cool a battery for hours after a fire to ensure it doesn't reignite. A battery that vented may still have energy and could reignite hours or days later (thermal runaway can sometimes reoccur if not fully cooled – known as *re-ignition*).

In sum, treat an EV battery with respect: high voltage, chemical energy, and flammable electrolyte demand careful handling. The built-in systems will do their job, and we must do ours by following manufacturer guidelines and standard electrical safety protocols.

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5.5 Safety Data Sheets (SDS) and Hazard Labels (CLP/GHS) – Because EV batteries involve chemical substances (especially in cases of leakage or during manufacturing/repair when you might handle chemicals like electrolyte, solvents, adhesives), it's important for educational completeness to know how to quickly interpret hazard information

Safety Data Sheets (SDS): These are detailed documents (mandated by regulations like EU REACH) that any hazardous chemical or mixture must have, outlining hazards, first aid, firefighting measures, handling/storage, PPE, etc. For batteries, one would look at SDS for things like the electrolyte or any chemicals used in battery repair (e.g. potting compounds). Under EU rules (Regulation (EU) 2020/878 updating REACH Annex II), SDSs have a standardized 16-section format. Key sections for quick info are: - Section 2: Hazards Identification (will list the hazard classifications and pictograms, e.g. flammable, corrosive). - Section 4: First Aid Measures (how to treat exposure). - Section 5: Firefighting Measures (what to use if it catches fire, and hazards from fire). - Section 7: Handling and Storage (safe practices, incompatibilities). - Section 8: Exposure Controls/PPE (what personal protective equipment to use, e.g. gloves type). - Section 10: Stability and Reactivity (what conditions to avoid, e.g. "keep away from moisture"). - Section 14: Transport Information (if relevant, classification for shipping).

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For instance, the electrolyte might have Section 2 saying: “Flammable liquid, Category 2; Skin irritant; Specific Target Organ Toxicity if inhaled” with pictograms of flame and exclamation mark. Section 8 would say wear nitrile gloves and goggles when handling leaks. If you have an SDS handy, you can quickly answer: *Is this chemical extremely dangerous or just mildly? What do I do if someone is exposed?* etc.

- **Hazard labels (CLP/GHS):** These are the diamond-shaped pictogram labels on chemicals. For a battery or cell, you may see labels for **flammable** (flame icon), **irritant** or **harmful** (exclamation mark), **corrosive** (if it can leak corrosive fluid, though Li-ion electrolyte is usually not strongly corrosive except the HF aspect), and possibly **explosive** (if extreme heating can cause explosion). Also, a common one for batteries is the **“flammable gas”** or **pressurized gas** if applicable.

- Each label comes with a **signal word**: “Danger” or “Warning” depending on severity.

- **Hazard statements** (H-phrases) that briefly describe the nature of hazard (e.g. “H225: Highly flammable liquid and vapor” or “H314: Causes severe burns”).

- **Precautionary statements** (P-phrases) like “P280: Wear protective gloves/eye protection...” or “P370+P378: In case of fire: use water spray to extinguish” etc.

For lithium-ion batteries specifically, regulatory labels often include the **“lithium battery” handling mark** for transport (which is a separate thing indicating it’s a lithium battery and shouldn’t be mishandled). In the EU, the new Battery Regulation also has requirements for labeling state of health, etc., but that’s beyond our scope.

Why this matters in practice: If an EV battery is damaged and leaking, an SDS for the electrolyte can tell you how to clean it up safely and what personal protection to use. Also, workshops should store any chemicals (like battery coolant, cleaning solvents) with proper labels so that anyone can see at a glance the main hazards.

5.5.1 Quick Guide to Using an SDS: In a vocational setting, students should know how to quickly navigate an SDS. If a teacher hands an SDS of $LiPF_6$ electrolyte to a student and asks, “What are the main hazards and what PPE do we need to handle a spill?”, the student should flip to: - Section 2: look at hazard class and pictograms (maybe flammable, irritant). - Section 8: see recommended PPE (e.g. Nitrile gloves, respirator

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if poor ventilation). - Section 4: first aid in case of contact (e.g. flush with water if on skin, etc.). - Section 5: firefighting (maybe says use CO_2 or water, and that fumes are toxic). - Section 7: handling/storage (e.g. keep tightly closed, inert atmosphere, etc., though for end-users not as relevant). - Section 10: stability (e.g. avoid water to prevent HF formation).

In other words, you **don't need to read an SDS top-to-bottom for immediate concerns** – jump to the sections that answer your question at hand.

5.5.2 Interpreting Battery Hazard Labels: If you see a label on a battery or chemical: - A **flame pictogram** means it's flammable – keep it away from ignition sources. - An **exclamation mark** might mean it's an irritant or harmful – avoid contact or inhalation. - A **corrosion pictogram** (acid spilling on hand) means it can burn skin/eyes – wear proper protective gear. - The **health hazard silhouette** (person with star on chest) means long-term health effects (like carcinogen or specific organ toxicity). - **Gas cylinder** means compressed gas inside (cells can have pressurized electrolyte, but that pictogram is more for gas cylinders). - **Exploding bomb** means explosive (not usually on batteries, except maybe under extreme conditions).

For lithium battery shipments, often a label with a battery icon and flame is used to warn of risk of fire if damaged – that's a transport label.

Automotive Practice – Scenario: You are handling a small battery module that has a minor leak after an accident. What do you do?
- Look at any labels on the module: you see a pictogram of flame (so electrolyte is flammable) and exclamation mark (irritant). Signal word "Warning". Hazard: "Flammable liquid. Irritating to skin/eyes. Harmful if inhaled." Precautions: "Keep away from flames. Use in well-ventilated area. Wear gloves and eye protection."
- From this, you know: don't allow sparks near the leak, ventilate the area (maybe turn on fume extraction), put on your chemical-resistant gloves and goggles, and then clean up the leak with appropriate absorbent. Dispose of waste as hazardous. This quick info can all be gleaned from the hazard label/SDS.

- Additionally, you recall $LiPF_6$ can form HF, so you double-check Section 5 and 8 of SDS: it says use rubber gloves, and if contact with liquid occurs, wash thoroughly. It also says firefighters should wear SCBA because of HF fumes. This informs you to be

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cautious of inhalation – maybe wear a vapor mask while cleaning if ventilation is poor.

By understanding these safety communications, instructors and students can ensure they handle battery-related chemicals with respect and caution.

5.5.3 Safety in the Workshop: Checklist

When dealing with EV batteries or any high-voltage system in practice, a few golden rules: - **Only work when authorized and trained.** HV systems should only be serviced by qualified personnel. - **De-energize when working on the vehicle's electrical system.** Use the service disconnects, verify no voltage with a meter. - **Use insulated tools.** Even if system is off, an accidental short with a normal tool can be dangerous. - **Never charge a damaged battery.** If a vehicle has been in a severe accident and the pack is suspected of damage, let professionals handle it (they might discharge it or remove it). - **Monitor charging areas.** A charging EV in a shop should ideally be in an area with smoke detection and someone periodically checking. Consumer EV charging (home, public) is extremely safe, but a workshop may have multiple vehicles, etc., so extra vigilance doesn't hurt. - **Emergency readiness:** Have a Class ABC fire extinguisher (or class D if recommended by manufacturer) accessible near the charging area, have spill kits for electrolyte (gloves, goggles, baking soda for neutralizing if needed, absorbent pads). - **Dispose of batteries properly:** Even small cells (like from laptops) should be recycled, not tossed in trash. For EV packs, follow regulations – they are usually returned to manufacturers or specialized recyclers. There are also legal requirements to mark and ship them properly (UN 38.3 testing, etc., as mentioned in Annex).

By following these practices and respecting the BMS and charging protocols, charging operations can be done **safely** and effectively. EV charging can be as routine and safe as pumping gas – just with a different set of precautions and awareness.

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Module 3 Recap – Key Points

- **Charging = controlled energy transfer**: You can't rush it beyond what the battery chemistry allows. The BMS and charger work together to keep it safe.
- **AC vs DC charging**: AC uses the car's onboard charger (slower, up to ~22 kW). DC fast charging uses powerful external chargers (much faster, e.g. 50–300 kW) and feeds DC directly to the battery. AC is common for daily use, DC for long trips.
- **CC/CV profile**: Lithium batteries charge first at constant current (fast fill) then at constant voltage (topping off)]. That's why last few percent is slow.
- **Limits**: Voltage limits prevent overcharge; current is limited to manage heat and avoid plating; temperature must be within range (battery may heat or cool itself to assist).
- **BMS**: The guardian – monitors every cell's voltage, pack current, temperatures. It will adjust charging, balance cells, and protect against any faults. It effectively decides how the charger should behave to keep things safe.
- **Safety**: Use proper equipment, watch for warning signs (heat, smell, swelling), and never compromise on safety interlocks. The systems in place (insulation, interlocks, RCD, fuses) are there because HV batteries, if mishandled, can be very dangerous. But with correct handling, EV charging is very safe – incidents are extremely rare per millions of charges.
- **Practical tip**: When teaching or working with students, do some demos like measuring how temperature rises with faster charge (if you have a battery lab setup), or show a cell's voltage curve during CC/CV. Also, possibly show an example of an SDS for a battery chemical so students get used to hazard information.

Finally, emphasize environmental health: properly recycle batteries. There are many initiatives worldwide because end-of-life battery handling is both a challenge and opportunity (recovering valuable materials). As professionals, students should cultivate an attitude of **safety and responsibility** with these advanced energy storage systems.

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Self-Check Questions (Module 3): *(Try these to reinforce your understanding.)*

1. Explain the difference between **energy (kWh)** and **power (kW)** in the context of EV charging. Why do EV batteries have a kWh rating but charging stations are rated in kW?
2. Why must lithium-ion batteries be charged in a controlled manner? Name at least three reasons (think electrical, chemical, thermal).
3. Compare AC charging vs DC charging. Where is the AC-to-DC conversion done in each case, and what typical power levels are they used for?
4. What is the **CC/CV charging profile**? Describe what happens to current and voltage in each phase.
5. Why does charging typically slow down as the battery gets above ~80% SOC?
6. What does "C-rate" mean (e.g. 1C, 2C charging)? If a battery is charged at 2C instead of 1C, what effect does that have on charging time and heat generation?
7. List at least four types of measurements a BMS monitors during charging.
8. What is **cell balancing** and why is it especially done near full charge?
9. Give three examples of electrical hazards when charging high-voltage batteries and one design feature for each that mitigates the hazard.
10. Describe at least three warning signs during charging that would indicate you should stop the process immediately.
11. A battery needs to store 20 kWh of energy and the charging system is 85% efficient. How much energy must be drawn from the charger to achieve this? *(Hint: consider the losses.)*

(Answers are provided in the instructor's guide.)

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MODULE 4 – Chemical Components of Lithium-Ion Batteries and Safety Considerations

Module Overview: This module dives into the *chemical makeup* of lithium-ion batteries used in EVs and connects the battery chemistry to safety issues. Learners will gain an understanding of the main battery components – **anode, cathode, electrolyte, separator, current collectors**, plus minor but important components like **binders and additives** – and how these work together. We will outline the basic working principle (how lithium ions and electrons move during charge/discharge), compare common automotive battery chemistries (such as **NMC**, **LFP**, **NCA**), and explain what the **Solid Electrolyte Interphase (SEI)** layer is. Then we'll discuss major chemical and thermal hazards: flammability of materials, gas generation, what causes **thermal runaway** at the chemistry level, etc. Finally, we address safety practices for handling batteries (especially in workshops or during transport/storage), including the use of Safety Data Sheets (SDS) and hazard labeling for battery materials.

Target Group: Secondary VET students (17–19 years) in automotive or technical programs – especially those who will handle or service battery systems.

EQF Level: 3–4 (core concepts with deeper technical notes for advanced learners)

Learning Objectives

After completing *Module 2*, the learner will be able to:

- Identify the **main chemical components** of a lithium-ion cell (anode, cathode, electrolyte, separator, current collectors, etc.) and explain each of their functions.
- Describe how a lithium-ion battery **stores and releases energy** during charge and discharge, tracing the movement of lithium ions vs electrons.

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- Compare common automotive lithium-ion **chemistries** (like NMC, LFP, NCA) in terms of practical traits: energy density, cost, safety, lifespan, etc.
- Explain the purpose of the **SEI layer** on the anode, including how it forms and how it both protects and impedes the battery.
- Recognize key **chemical and thermal hazards** of Li-ion batteries (flammable electrolyte, risk of thermal runaway, toxic output when failing) and explain the underlying reasons these hazards occur.
- Apply basic **safety rules** for handling and storing batteries and for responding to suspected battery damage (including using hazard labels and SDS information effectively

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Key Concepts and Glossary

- **Anode** – The negative electrode when the battery is discharging (usually graphite in EV batteries). Lithium ions intercalate into it during charge.
- **Cathode** – The positive electrode during discharge (commonly a lithium metal oxide or phosphate, e.g. NMC, NCA, LFP). It's the source of lithium ions and largely sets the battery's voltage.
- **Electrolyte** – The ionic conductor inside the cell (typically a liquid organic solvent with dissolved $LiPF_6$ salt). It allows lithium ions to move between anode and cathode but is not electronically conductive.
- **Separator** – A thin porous membrane that physically separates anode and cathode (preventing short circuits) while letting ions pass through its pores.
- **Current Collectors** – Thin metal foils that carry electrons to and from the electrodes: usually copper foil for the anode and aluminum foil for the cathode.
- **Intercalation** – The process where lithium ions insert into the layered structure of an electrode (like "sliding in between" graphene layers in graphite).
- **(Solid Electrolyte Interphase)** – A microscopically thin layer that forms on the anode surface from electrolyte decomposition. It is electrically insulating but Li^+-conductive. It protects the anode from further reaction but can grow and increase resistance over time.
- **NMC / NCA / LFP** – Short names for common cathode chemistries:
    - NMC: Lithium Nickel Manganese Cobalt Oxide,
    - NCA: Lithium Nickel Cobalt Aluminum Oxide,
    - LFP: Lithium Iron Phosphate (chemical formula $LiFePO_4$).
- **Lithium Plating** – Undesirable deposition of metallic lithium on the anode (happens if charging too fast or at low temp, when Li^+ can't intercalate into graphite quickly enough).

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- **Thermal Runaway** – A self-accelerating, uncontrolled heating of the battery leading to fire or explosion. Caused by exothermic reactions once a certain temperature threshold is exceeded.
- **Flammability** – The tendency of a material to catch fire. Li-ion electrolyte is typically flammable. Some cathodes (like those with high nickel) release oxygen when hot, feeding fire.
- **Gas generation** – The formation of gases (like CO_2, CO, H_2, etc.) inside a cell, usually due to electrolyte decomposition (can occur if the cell is overcharged, overheated, or at end of life).
- **Swelling** – Expansion of a cell (especially pouch cells) due to gas generation or other factors. It's a warning sign of internal problems.
- **Contamination** – Presence of unwanted substances (moisture, metal particles, etc.) in a cell. Moisture can react with $LiPF_6$ salt to form HF acid*[33]*; metal particles can pierce the separator and cause shorts.
- **Moisture sensitivity** – Lithium battery components like $LiPF_6$ electrolyte react with water to produce HF. Also, battery cells must be made in dry rooms because moisture can react with electrode materials.
- **SDS (Safety Data Sheet)** – Document that provides information on the hazards of a chemical and instructions for safe handling, first aid, firefighting, etc.
- **CLP/GHS pictograms** – Standard hazard symbols (red diamonds) used globally to label chemicals (e.g. flame for flammable, corrosion for acids, skull for toxic, etc.).

Now, let's start from the ground up: the basic structure of a lithium-ion cell.

1. Basic Chemical Structure of Lithium-Ion Batteries

1.1 What "Battery Chemistry" Means in Practice – When we talk about a battery's *chemistry*, we refer to the specific materials used in the electrodes and electrolyte, which determine its performance characteristics. In EV contexts, this isn't just abstract – the chemistry affects: - **Charging speed & limits:** e.g. some chemistries

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can charge faster or at lower temps than others. - **Operating temperature range:** e.g. LFP is known for better thermal stability (less risk of runaway) than some high-Ni chemistries. - **Energy density & range:** e.g. NCA has very high energy per weight, giving longer range, whereas LFP has lower energy density (heavier for the same kWh) but perhaps longer cycle life. - **Longevity (cycle life):** e.g. LFP often endures more cycles than NMC/NCA (there are LFP packs rated for 2000+ cycles). - **Safety behavior:** e.g. LFP is more stable and less prone to thermal runaway (can tolerate higher temp before runaway), whereas high-energy chemistries store more energy and can release it more violently if mishandled. - **Cost and raw materials:** e.g. NMC/NCA use cobalt (expensive, ethically sourced issues), NCA uses nickel heavily, LFP uses no cobalt or nickel (cheaper materials like iron, phosphate – and abundant).

So, "chemistry" directly affects EV design choices (range vs safety vs cost trade-offs). For example, an automaker might choose LFP chemistry for an entry-level model to maximize safety and lifespan at lower cost (with an acceptable range), while using NMC for a long-range model where energy density is paramount.

1.2 Main Components of a Lithium-Ion Cell (Functions & Safety Links) – A typical EV cell has the following components:

- **1.2.1 Anode (Negative electrode during discharge):** In almost all modern Li-ion EV cells, the anode active material is *graphite*, a form of carbon. Sometimes a bit of silicon is added to graphite to increase capacity (since silicon can store more lithium, but it swells on lithiation). The anode is where lithium is inserted during charging (so the anode is rich in lithium when charged).

- **Function:** Provide a host for lithium ions (via intercalation) when the battery is charged, and release lithium ions during discharge (when powering the car). Essentially, during discharge, lithium leaves the anode and travels to the cathode.

- **Why graphite?** It has a layered structure (graphene sheets) where Li^+ can slip between layers. It's relatively stable and can undergo many cycles. Pure metal lithium as an anode would hold more energy but is not stable for recharge (it would dendrite/short easily). Graphite hits a sweet spot of capacity (~350 mAh/g theoretical) and stability.

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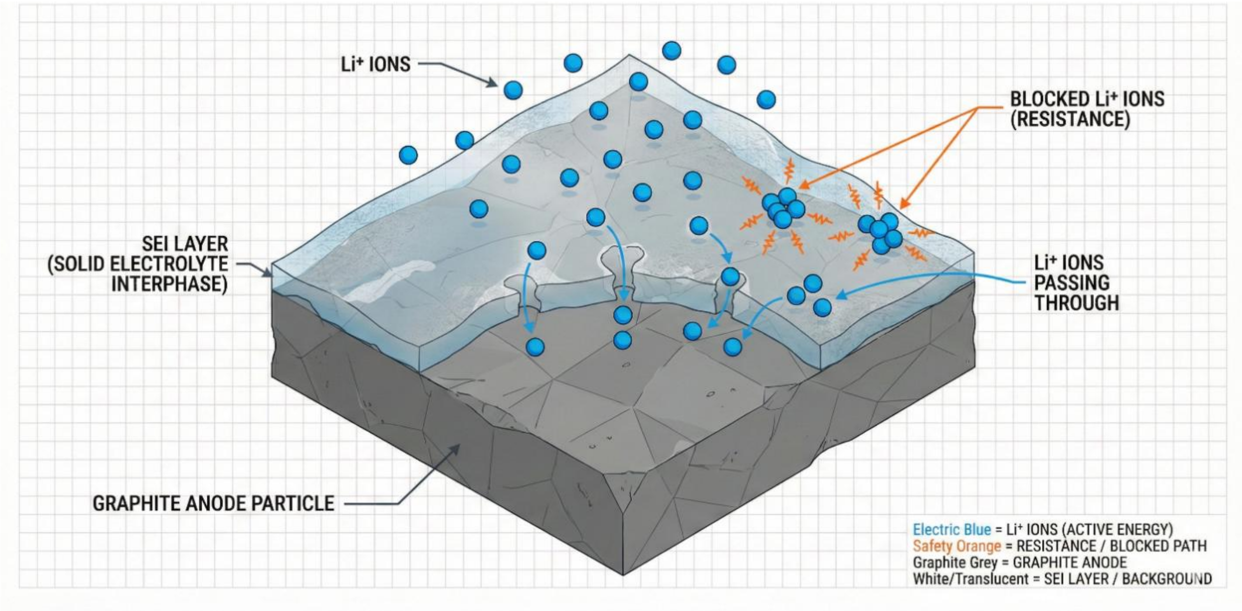
- **Silicon note:** Silicon can bond with a lot more lithium (about 10x the capacity of graphite per weight), but it expands ~300% in volume when fully lithiated, causing huge mechanical strain and potentially particle cracking and rapid capacity fade. In practice, cells may include a few percent silicon in the



graphite to boost capacity ~5-10% while trying to manage the expansion via special binder or nanoparticle design.

- **Safety link:** An overcharged or very fast charged cell can cause *lithium plating* on the anode rather than intercalation. This plated lithium is highly reactive (especially if the cell is then exposed to air or if the dendrites grow and short the cell internally). Also, the anode surface reacts with electrolyte to form the layer.

- **Material trend:** Research continues into alternatives like lithium titanate (LTO) anodes for special cases (LTO has zero plating risk and fast charge ability, but much lower cell voltage and energy density, used in some bus batteries requiring ultra-fast charge and long life).

- **1.2.2 Cathode (Positive electrode during discharge):** The cathode is a lithium metal oxide or polyanion compound that contains lithium ions and host structures that can store lithium. Common cathode materials in EVs:

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- **NMC (Nickel Manganese Cobalt oxide)** – e.g. $Li(Ni_xMn_yCo_z)O_2$. Various formulations like NMC111, NMC532, NMC622, NMC811 (the numbers indicate fraction of Ni:Mn:Co). Higher Ni usually means higher energy but less stability.
- **NCA (Nickel Cobalt Aluminum oxide)** – $LiNiCoAlO_2$, similar to high-Ni NMC but with aluminum for stability. Used in e.g. Panasonic/Tesla cells a lot.
- **LFP (Lithium Iron Phosphate)** – $LiFePO_4$, a phosphate material with no cobalt/nickel.
- **Others**: There's also LMO (Lithium Manganese Oxide, spinel type) often blended into others, and emerging ones like LMFP (adding Manganese to LFP to improve energy).
- **Function:** The cathode is the source of lithium during discharge. When charged, lithium ions are removed from the cathode (oxidizing the transition metal ions) and inserted into the anode. During discharge, lithium goes back into the cathode. The cathode largely determines the battery's nominal voltage (different materials have different potentials) and energy density.
- **Influences:**
  - *Voltage*: e.g. LFP has ~3.3 V nominal per cell, NMC ~3.7 V, NCA ~3.6-3.7 V.
  - *Energy & Power*: High-nickel NMC/NCA have high energy (because Ni helps pack more lithium per volume and higher voltage), but slightly lower stability. LFP has lower voltage and a bit lower capacity, so less energy, but can have high power output and long life.
  - *Thermal stability*: LFP is very stable even at 250 °C (it will not release oxygen until very high temp), meaning it's hard to make it go into thermal runaway – it will basically just stop working rather than burst into flame (unless extreme conditions). NMC or NCA, especially with high nickel, will start releasing oxygen at lower temperatures (around 180–220 °C for NMC) which can feed fire. That's why some consider LFP "safer" in a thermal abuse scenario.

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- *Cost and materials*: LFP uses iron and phosphate (cheap, abundant, non-toxic). NMC/NCA use cobalt and nickel (more expensive, cobalt is conflict mineral). The supply chain concerns drive some automakers to switch standard-range models to LFP (e.g. Tesla now uses LFP in some Model 3).

- **Safety link:** Overcharging a cathode beyond full lithiation can cause it to become highly unstable (e.g. overcharged NMC can release large amounts of oxygen, fueling combustion of electrolyte). That's one reason not to charge past 100%. Additionally, cathode decomposition at high temp contributes to thermal runaway heat release.

- **Environmental note:** Cathodes contain heavy metals (Ni, Co) – proper recycling is important to avoid environmental contamination and to reclaim these valuable materials.

1.2.3 Electrolyte (Ion conductor): The electrolyte in Li-ion batteries is typically a liquid solution of a lithium salt in a mixture of organic solvents:

- **Solvent**: Common solvents include ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC), diethyl carbonate (DEC), ethyl methyl carbonate (EMC), etc. They are organic carbonates which have high dielectric constants to dissolve lithium salts and are stable (enough) against the electrodes' voltage ranges (with caveats).

- **Salt**: Lithium hexafluorophosphate (**$LiPF_6$**) is the ubiquitous salt in most Li-ion electrolytes. It provides Li^+ for conduction. $LiPF_6$ has good conductivity and stability but isn't perfect – it can react and produce PF_5 and HF if moisture is present. New salts like LiFSI (lithium bisfluorosulfonimide) or LiTFSI (lithium bis(trifluoromethanesulfonyl)imide) are being explored for better stability, especially for high-voltage cells.

- **Additives**: Electrolytes often have proprietary additives (a few percent) that dramatically improve performance – for instance, additives that help form a better SEI (like vinylene carbonate, VC), or that protect the cathode (like lithium difluorophosphate, LDP), or shut down micro-current at high temps (like certain phosphates).

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- **Function:** The electrolyte's job is to carry lithium ions between cathode and anode. It must wet the electrodes and separator so Li^+ can move freely. It must *not* conduct electrons – otherwise the cell would self-discharge or short internally (the separator and electrolyte together should only allow ionic current).

- **Properties:** Needs to be stable within the voltage window of the cell: roughly 0V vs Li at anode (actually ~0.1-0.2V in graphite) to ~4.2-4.3V vs Li at cathode. Typical electrolytes are stable up to ~4.2V; above that they start oxidizing significantly at cathode (that's one limit for pushing cells to higher voltage for more energy). They also decompose a bit below ~1V at anode, which is why SEI forms (the decomposition products make the SEI and then further decomposition slows).

- **Safety link:**

  - Electrolyte is **flammable**. Solvents like EMC, DEC have low flash points. If the cell leaks and there's an ignition source, the electrolyte can catch fire (it's like a flammable solvent fire, with additional nasties in it). That's why a battery that vents gas in thermal runaway often ignites – the gas is vaporized solvent.

  - Electrolyte can decompose to produce **toxic gases**. $LiPF_6$ with moisture yields HF (nasty acid gas). Thermal breakdown can also generate CO, CO_2, various organics.

  - **Moisture sensitivity:** The manufacturing of cells requires ultra-dry conditions because even ppm of water reacting with $LiPF_6$ will generate HF which attacks the cell internally (damaging the SEI and consuming lithium). Also moisture can react with the cathode surface (especially if cathode is something like $LiNiO_2$-based, which can form hydroxides).

- **Thermal role:** Electrolyte can boil/expand if overheated (leading to cell swelling/pressure). It can also fuel combustion if cell breaches. Some electrolytes include a "shutdown" additive on separator (a PE layer that melts and closes pores at ~130°C), which halts ion flow like a fuse – ideally stopping current and heating, but it doesn't always prevent runaway if the heat is coming internally.

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In summary, think of the electrolyte as the blood of the battery – carrying ions between electrodes. But it's also the most chemically volatile part: flammable and reactive.

New dev: Solid electrolytes (ceramics or polymers) are being researched to replace liquid electrolyte, which could enhance safety (non-flammable, no leakage) and possibly enable lithium metal anodes. But that's in future "solid-state batteries".

- **1.2.4 Separator (Barrier + Ion Pathway):** The separator is usually a very thin (<30 μm) porous plastic film. Common materials: polypropylene (PP), polyethylene (PE), or a multilayer of both. Some have ceramic coatings to improve heat tolerance.

- **Function:** Keep the anode and cathode physically apart (no direct contact, which would cause an internal short) while allowing Li^+ ions to flow through the pores filled with electrolyte. It's basically a **physical insulator** but **ionic conductor** (indirectly, via electrolyte).

- **Key property:** Must be electrically insulating (very high resistance to electron flow) but have good porosity (~40% pores) for ion flow. Also, it should be thin to minimize distance ions travel (reducing internal resistance) yet strong enough not to tear under manufacturing, and stable in battery chemicals.

- **Safety role:** Many separators are designed to **shut down** at a certain temp. For example, a PE layer may melt around 130°C and its pores collapse, stopping ion flow (so current in cell stops – halting the reaction that's causing heat). This can sometimes abort a thermal runaway if it's from overcurrent/overheat. However, if temperature continues to rise, the separator itself can melt entirely or shrink, potentially causing electrodes to touch – which is very bad (that's an internal short). High-quality separators have features to resist shrinkage at high temp (some use ceramic-filled separators).

- **If separator fails:** If it develops a tear or hole, parts of anode and cathode can contact, causing a dangerous internal short. That will lead to a rapid uncontrolled discharge of that portion of the cell, heating it locally – possibly triggering thermal runaway. This can happen due to manufacturing defect (metal particle pierces it) or due to mechanical abuse (crushing a cell can crumple layers together).

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- **Contaminants:** Even dendrites or lithium plating spikes can penetrate separators. So, keeping the charging gentle enough to avoid plating also helps avoid internal shorts.
- **Handling:** Separators are quite fragile. In prismatic or pouch cells, they are stacked or wound carefully to avoid wrinkles or punctures.

Safety link: The separator is one of the first things to give in a thermal runaway scenario (it melts), after which the anode and cathode can fully short and then you basically dump all remaining energy as heat rapidly. Thus, preventing separator failure (through not overheating in the first place) is crucial.

- **1.2.5 Current Collectors:** These are the foils onto which the electrode materials are coated:
- **Anode current collector = Copper (Cu) foil.** Typically ~6-10 µm thick in a cell. Copper is used because it's stable at anode potential (near 0V vs Li, where aluminum would alloy with lithium and corrode). Copper is heavy though, contributing to weight.
- **Cathode current collector = Aluminum (Al) foil.** Also ~10-20 µm thick. Aluminum is used because at the ~4V cathode potential, it's stable (copper would dissolve at high potential in presence of electrolyte). Al is lighter.
- These foils collect electrons from the electrode coating (which is usually a mix of active particles + binder + conductive carbon) and provide a path to the external terminals (via tabs welded to the foils).
- They must have good electrical conductivity and not react with the electrolyte at the operating potentials.
- **Safety aspect:**
    - If a cell gets extremely over-discharged (drained to 0 and beyond), the copper collector can start dissolving into the electrolyte (because below ~2V, the SEI breaks down and Cu can migrate). Then if you recharge, copper can re-deposit in places creating internal shorts. This is why BMS generally don't allow deep over-discharge either – it's bad for cell health and can cause internal shorting.

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  - In thermal runaway, the metal foils can serve as heat conduits and also as fuel for arcs. Molten copper can form if a large short happens.

- From a design perspective, current collectors are "dead weight" (they don't store energy) but necessary. Reducing their thickness or replacing with lighter material would improve energy density. Some researchers try copper-coated Al or vice versa in sections of the cell, but it's tricky due to electrochemical stability.
- **1.2.6 Binder and Conductive Additive:** Often overlooked, each electrode (anode and cathode) is not pure active material. They are made of:
- Active material (e.g. graphite or NMC powder),
- Conductive carbon (like carbon black, to ensure electrical connectivity since the powders alone might not all touch each other or the foil),
- Binder (a polymer like PVDF – polyvinylidene difluoride – in many cells, or others like styrene-butadiene rubber SBR + CMC for anodes, etc.).
- The binder glues the particles to each other and to the foil. PVDF is common with NMC, etc., because it's chemically stable and sticks well (used with a solvent NMP during coating).
- If binder degrades (e.g. extreme heat or chemical attack), the electrode coating can detach or get pulverized, losing contact. That can create areas of the electrode that become electrochemically "dead" or cause particles to isolate – increasing resistance and causing heating in other spots.
- Non-uniform distribution of conductive additive or binder can cause some regions of the electrode to carry more current than others, leading to local hotspots or faster degradation there.
- **Manufacturing defects** like inadequate binder can lead to **particle delamination** (particles falling off the collector) which means lost capacity and possibly debris floating in the cell (which could short something).

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- So, while binder & additive don't participate in the battery reaction (they are inert ideally), they ensure the reaction can happen uniformly and safely across the electrode.
- New binders (water-based, etc.) are being used to make manufacturing greener (traditional PVDF requires toxic NMP solvent).

Why it matters to safety: If poor adhesion causes some areas to have no active material (it fell off), the cell's effective capacity is reduced unevenly and it might lead to lithium plating on cycles (because lithium has nowhere to go in those areas). Also, conductive carbon adds flammability (it's essentially like fine coal) – though the main flammable part is still electrolyte. But if a cell goes into thermal runaway, the carbon and binder decompose and add to the heat output.

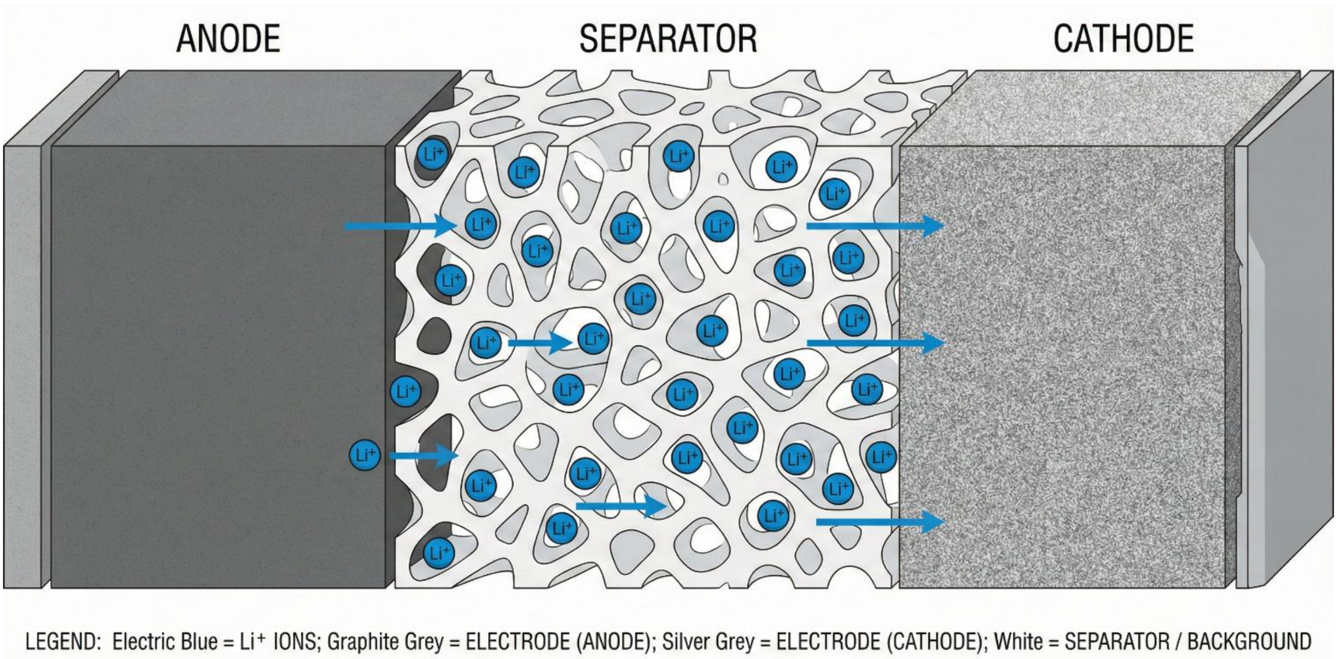

Figure 19 Lithium-ion cell cross-section (schematic)

This illustration shows the layers: a copper current collector coated with graphite (anode, green), a porous separator (middle, grey dashed), an aluminum current collector coated with lithium metal oxide (cathode, purple). During charge, positive

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lithium ions (Li^+) move from the cathode, through the separator and electrolyte, and intercalate into the anode. Electrons (e^-) flow through the external circuit (since they cannot go through the separator) from cathode to anode. During discharge, the process reverses (Li^+ leave the anode back to cathode, and electrons flow through the load from anode to cathode). The electrolyte fills the space in pores (not shown for clarity). The current collectors connect to the cell terminals.

2. Common Battery Chemistries in Automotive (NMC, LFP, NCA)

2.1 Why Different Chemistries Exist: No single battery chemistry is best at everything. EV manufacturers choose a cell chemistry by balancing several factors: - **Energy Density (Wh/kg & Wh/L):** Impacts vehicle range. (High-nickel chemistries like NCA/NMC excel here). - **Power Capability:** How well it delivers/accepts high current (some chemistries handle fast charge/discharge better). - **Safety and Thermal Stability:** Resistance to overheating or ignition (LFP is very robust thermally). - **Cycle Life and Calendar Life:** How many charge/discharge cycles before significant degradation (LFP tends to have long cycle life, thousands of cycles). - **Cost and Resource Availability:** Use of expensive or scarce materials (LFP uses common materials and is cheaper per kWh than cobalt-rich chemistries). - **Operating Temperature Range:** e.g. performance in cold weather (LFP can show more performance drop in cold conditions, requiring good thermal management).

Because of these trade-offs, we see some EV models now using **LFP** for standard-range versions (prioritizing cost, safety, and longevity) and **NMC/NCA** for long-range or high-performance versions (prioritizing energy density and perhaps power). As technology evolves, new blends (like adding manganese or using silicon anodes) try to capture benefits of each.

2.2 Overview of Key Chemistries (Strengths & Challenges):

- **NMC (Nickel Manganese Cobalt Oxide):** This is a family of cathodes (with variants like NMC111, 532, 622, 811 indicating ratios of Ni:Mn:Co).
- *Strengths:* Good all-around performance – high **specific energy** (thus enabling long range) and decent power capability. Continuous improvement has made NMC the workhorse of many EVs. Also, it has a moderate self-heating rate (better thermal stability than pure cobalt oxide).

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- *Challenges:* Contains cobalt and nickel – expensive and supply-chain sensitive. Cobalt in particular raises ethical and cost issues. Safety margin depends on exact formula and how it's managed; higher nickel content improves energy but usually reduces thermal stability (NMC811 is more reactive than NMC111). Also, NMC cells still need robust BMS oversight to prevent overcharge/overheat (like any high-energy chemistry).

- **NCA (Nickel Cobalt Aluminum Oxide):** Chemistry used in e.g. many Tesla Panasonic cells ($LiNiCoAlO_2$). It's similar to NMC high-Ni.

- *Strengths:* **Highest energy density** among common cathodes – great for maximizing range. Also capable of high discharge power. Long cycle life can be achieved if well-managed.

- *Challenges:* NCA is known to require very careful control – **marginal safety** tolerance compared to LFP. It's more prone to thermal runaway if abused (high Ni content). Thus, the vehicle's BMS and thermal system must be top-notch. Cost is influenced by nickel and cobalt pricing. In practice, NCA batteries perform excellently in range and power (used in performance EVs) but need slightly more cautious charging profiles to ensure longevity and safety.

- **LFP (Lithium Iron Phosphate):** Cathode of $LiFePO_4$.

- *Strengths:* **Safety and stability** are the biggest pros – LFP doesn't ignite easily and can tolerate higher temperatures before runaway (it releases minimal oxygen when heated). It also typically achieves very high cycle life – 2000+ cycles with modest degradation is common. No cobalt or nickel – so it's cheaper and environmentally friendly. Also, LFP voltage is lower, but it has a very flat discharge curve (voltage stays steady during much of discharge), which can be useful for state-of-charge estimation and consistent performance. It's a great choice for durability-focused applications.

- *Challenges:* Lower **energy density** – about 90-150 Wh/kg at cell level (where NMC/NCA can be 200+ Wh/kg). This means an LFP pack for the same range will be larger and heavier. In vehicles where space is abundant (or range requirements are moderate), this is acceptable; in long-range premium EVs, it's a drawback. Also, LFP can have reduced performance in cold weather

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(cells exhibit higher internal resistance at low temps, meaning more voltage drop and lower usable energy until warmed). Manufacturers mitigate this with pack heating systems. Finally, self-discharge and balancing can be a bit higher (LFP cells have slight higher self-discharge than NMC), but a good BMS can handle that.

Chemistry	Typical Strengths	Typical Challenges
NMC	High energy (long range); balanced performance; widely used	Contains Co & Ni (costly); thermal stability varies with Ni content (needs careful BMS)
NCA	Very high energy & power; proven in performance EVs	High Ni & Co (cost); somewhat lower inherent safety margin (robust monitoring needed)
LFP	Excellent safety (stable even if fully charged); long cycle life; low cost (no Co/Ni)	Lower energy density (heavier packs); lower cold-temp performance; flat voltage (needs accurate SOC algorithms)

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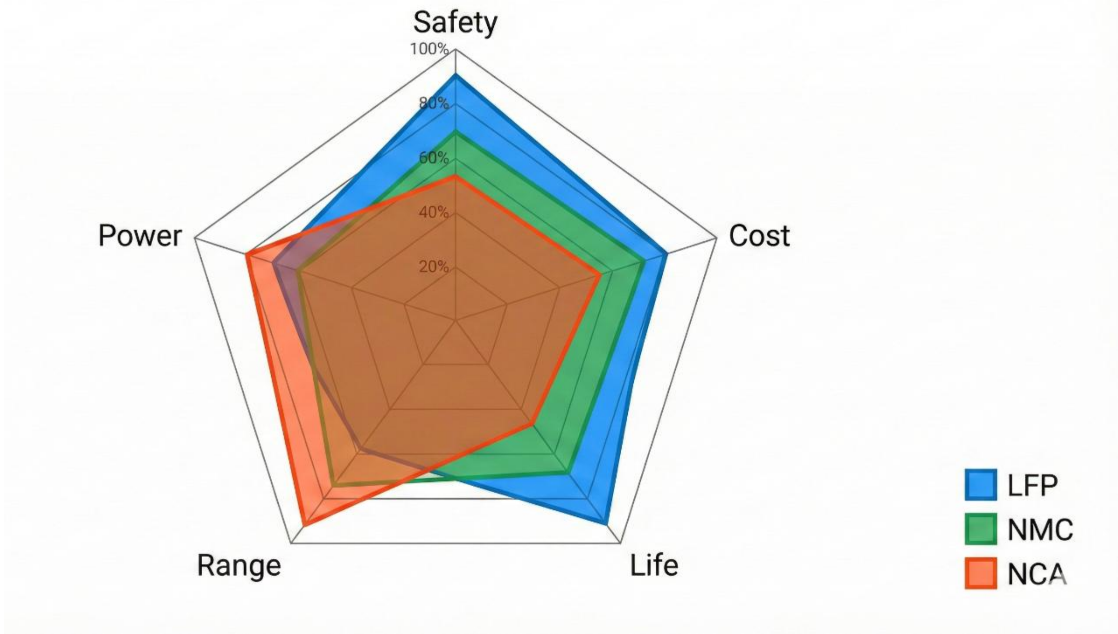

Figure 20 Battery type performance comparison

Automotive practice is that "Safer chemistry" still needs control. Even with a thermally stable chemistry like LFP, you cannot be complacent. If you severely overcharge an LFP cell, it can still fail violently. Or if it's internally damaged, it can short out. The BMS still imposes strict limits for LFP cells just as it would for NMC – the difference is LFP might tolerate abuse a bit better (more of a safety buffer). But **no EV battery is "plug and play" without a BMS**. All chemistries require monitoring. Conversely, higher-risk chemistries like NCA, when managed well, operate very safely in millions of cars. So chemistry influences risk, but does not eliminate it.

3. Chemical Processes During Operation (Charge/Discharge and Ageing)

3.1 What Happens During Charge and Discharge?

A lithium-ion battery is basically a **rocking-chair** battery: lithium ions shuttle between anode and cathode. - During **charging**: an external power source (charger) pushes electrons into the negative electrode (anode) and pulls electrons from the positive electrode (cathode). To maintain charge neutrality, lithium ions leave the cathode's crystal structure and travel through the electrolyte into the anode, where they insert (intercalate) into the graphite layers (or other anode material). So, the anode **gains**

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lithium (becomes lithiated) and the cathode **loses** some lithium (becomes de-lithiated). The battery is now storing chemical energy. - During **discharging**: the reverse happens. The circuit connected to the battery (e.g. motor/inverter) allows electrons to flow out of the anode, doing work (turning the motor) and returning into the cathode. Inside the battery, lithium ions depart the anode (leaving anode graphite structure) and migrate back through the electrolyte into the cathode, reoccupying their sites in the cathode lattice*[53]*. The anode loses lithium (becomes de-lithiated) and the cathode regains lithium (lithiated).

This is a **reversible reaction** (within operating limits). No lithium is supposed to be consumed permanently in the process – it just goes back and forth between electrodes. In a brand new battery, nearly all lithium is cycled between cathode and anode without side reactions.

- **Electrons vs Ions:** Remember, electrons go through the external circuit (that's why you can power a device), while ions go internally through the electrolyte. They meet up at the other electrode to balance charge. The separator ensures electrons can't go straight through internally (which would short-circuit the cell).

No heavy math is needed to understand this – it's essentially **two sponges soaking up and releasing lithium ions**, and by moving those ions, we also force electrons to move through the circuit (producing current for use). Charging pushes ions into the anode (like squeezing them into a sponge) and discharging releases them to the cathode.

3.2 Intercalation vs. Side Reactions – Why Batteries Age: In a perfect battery, the only processes would be intercalation and de-intercalation of Li^+ in the electrodes, which are highly reversible. However, real batteries undergo **side reactions** over time: - **Electrolyte decomposition:** Especially on the first charge, the electrolyte will react with the anode (at ~0.1–0.2 V vs Li) and with any high-energy surfaces. This forms the SEI (more on that in a moment). A little decomposition continues every cycle – consuming electrolyte solvents and salts. - **Lithium consumption:** Whenever a side reaction happens that produces a solid (like SEI growth) or other compounds, it usually ties up some lithium irreversibly. Those lithium atoms become part of a compound in the SEI or other deposits and are no longer free to shuttle between anode and cathode. This means **loss of cyclable lithium**, which translates to

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capacity fade (less lithium available to carry charge). - **Structural wear:** Repeated insertion and removal of Li can cause mechanical strain. The cathode might see micro-cracks form (especially in high-nickel chemistries). The anode particles can expand with lithium insertion and contract on removal; over hundreds of cycles this can cause some loss of contact or surface changes. If particles electrically isolate or lose contact with the current collector, that active material is effectively lost. - **Increase in internal resistance:** Side products like SEI (which is an insulating layer) get thicker, which makes it harder for ions to pass. The contacts between particles might degrade, increasing resistance. Also, corrosion of current collectors or contacts can add resistance. Higher internal resistance means more heat generation (I^2R losses) and voltage drops, so the battery can't deliver or accept high current like it used to (this is **power fade**). - **Possible plating:** If charging conditions are not ideal (e.g. very fast charge at low temperature or when the battery is already quite full), lithium plating can occur on the anode surface – this is a side reaction that really ages a battery quickly. The plated lithium is mostly irreversible (it doesn't go back into the cathode; it's stuck as metal or reacts to form new SEI). It also can grow dendrites that risk internal shorting.

In summary, as a battery ages you see: - **Capacity loss (Ah or kWh):** due to loss of active lithium and sometimes loss of active electrode area. For example, after 1000 cycles maybe the battery is at 80% of original capacity. - **Impedance rise:** the battery's voltage drops more under load and it can't charge as fast without overheating because internal resistance is higher. - **Self-discharge increase:** older cells may lose charge faster when sitting, because the reactions that consume lithium (and produce SEI) continue slowly even at rest, and seals may be less perfect.

These ageing effects are accelerated by things like: - High temperature (heat speeds up chemical reactions – every 10°C rise roughly doubles many reaction rates, so a battery kept at 40°C will age much faster than one at 20°C). - High state of charge (keeping a battery at 100% SOC for long periods strains the cathode lattice and also the high voltage promotes electrolyte oxidation). - Deep cycles (full 0–100% swings) cause more expansion/contraction and more cumulative SEI than shallow cycles (20–80% for example). - High charge/discharge C-rates (more stress, more heat, possibly lithium plating on charges).

Battery management in EVs often mitigates these: e.g. BMS might not charge to full 4.2 V except when needed (some EVs use a slight buffer, charging to 4.15 V by

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default to extend life), and thermal management keeps cells cool. Owners are advised to avoid extreme SoC when possible (e.g. don't leave the car at 100% in hot weather daily). Some modern EVs will automatically limit charge to 80-90% unless you override for a trip.

3.3 The SEI Layer – A Necessary Protector (and Inevitable Aging Factor): The **Solid Electrolyte Interphase (SEI)** is a nano-film that forms on the anode (and to some extent on the cathode, though we often specifically discuss anode SEI). It's called "interphase" because it's at the interface between the solid electrode and liquid electrolyte.

- When you first charge a new cell, the anode potential drops to near 0 V vs Li. This is so low that the electrolyte is not stable – it **reduces** on the anode surface, breaking down into various components (lithium salts, organic fragments) that precipitate out and coat the anode. However, those decomposition products end up forming a passivation layer that **prevents further electrolyte from decomposing** on that surface. In other words, the SEI is a *sacrificial layer* – it's consumed some electrolyte and lithium, but now that it's there, it *protects the anode* by stopping continuous reaction. It's **ionically conductive** (Li^+ can still go through it) but **electronically insulating** (e^- cannot pass, so it stops further electron transfer reactions from electrolyte).

- A good SEI is crucial: it allows lithium-ion batteries to be rechargeable. Without SEI, each charge cycle the electrolyte would keep decomposing until the cell dies quickly. With SEI, the anode is kind of "stabilized."

- **SEI composition:** It's typically made of compounds like Li_2CO_3 (lithium carbonate), LiF (from $LiPF_6$ breakdown), lithium alkyl carbonates, and other organics/inorganics. It has a multilayer structure (an inner dense inorganic-rich layer, and an outer more organic porous layer). Thickness might start at 10-50 nm after formation, and can grow with cycling or time.

- **SEI is good because:** it **prevents continual electrolyte breakdown** and also prevents the anode from exfoliating (graphite layers are protected from co-intercalation of solvents). Without SEI, batteries would have very short life and gas like crazy on first charge. So it's often called a "hidden hero" or "necessary evil."

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- **SEI is bad because:** it **consumes lithium** (every bit of SEI ties up some lithium permanently) and it **impedes ion flow** if it gets too thick. A thicker SEI = higher resistance for Li^+ to get through, which means poorer power performance and more heat. Also, if the SEI cracks (say due to expansion/contraction of anode or mechanical stress), the freshly exposed area will react and form new SEI, consuming more lithium. This often happens under harsh conditions (fast charge at low temp can cause localized plating which then forms SEI).

- Over time and especially at *high temperature or high SOC*, the SEI tends to grow further (not remain static). Elevated temperature gives SEI components mobility and causes continued slow reactions, thickening the SEI. High voltage on the cathode can cause some breakdown products that migrate to anode and influence SEI too.

- In summary, **SEI protects but causes aging**. Battery developers try to formulate electrolytes with additives that produce a more stable SEI initially (one that is flexible, ion-permeable, and doesn't continuously grow). Additives like vinylene carbonate (VC) are actually added to deliberately form a better SEI. It's a big area of research to optimize SEI – because a good SEI can enable longer life and even allow different anode materials (e.g. silicon) to work better by reforming nicely after expansion.

A mental image: SEI is like a **self-healing varnish** on the anode. The first coat is applied (formation cycle) – it uses up a bit of material but then it shields the anode. Each time you scratch it (through volume changes or high temp), a little more varnish forms to re-seal it, making the layer thicker and thicker, which wasn't part of the original plan. Eventually it's a thick coat that impedes performance.

Practical note: This is why fast charging in cold weather is particularly harsh chemically – lithium plating can occur (since diffusion is slow at low temp), and that plated lithium will mostly get consumed into SEI on the next cycle, permanently reducing capacity. Many EVs mitigate this by battery pre-warming and by tapering current at low temps. It's also why simply *aging* (time) can reduce capacity even if you don't use the battery much – SEI slowly grows (this is called calendar fade). Keeping a battery at moderate SOC and temperature slows that SEI growth.

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3.4 Charging Conditions Influence SEI and Aging: As hinted: - **High temperatures** speed up SEI growth and electrolyte oxidation (so avoid storing batteries in hot environments for long periods). - **High voltages** (i.e. 100% SOC) put stress on cathode and promote reactions that can migrate and hurt the anode SEI and also thicken cathode surface films. - **Fast charging** – especially beyond what the chemistry comfortably allows – can cause micro-cracks and lithium plating, both of which lead to more SEI formation. - **Long storage** – SEI can grow even when battery is just sitting (especially if at high SOC or elevated temp). Batteries stored at 100% in heat will lose capacity faster than those stored at 50% in cool conditions.

This explains some manufacturer recommendations: e.g. if you plan to not use a device or vehicle for months, leave it around 50-60% SOC in a cool place. And only charge to 100% when needed for a trip, otherwise 80-90% day-to-day is kinder on the battery.

4. Chemical Risks and Hazards: What Can Go Wrong and Why

While we touched on safety in operational terms, here we focus on the **chemical hazards** inherent to lithium-ion batteries and how they manifest:

4.1 Electrolyte Flammability and Decomposition: The electrolyte is highly flammable. If you expose it to flame or a spark, the solvents will ignite *readily*. Even the vapor of electrolyte is flammable (similar to gasoline vapor). In a battery pack fire, the electrolyte acts like fuel. This is why a venting battery (one that's releasing electrolyte vapor) can suddenly catch fire if ignition occurs – the vapor ignites and then the remaining liquid can burn. The flame can be intense and hard to extinguish until the fuel is consumed or cooled.

- Under abuse conditions (overheating, overcharging, internal short), the electrolyte also **decomposes** chemically:
- At the anode side, if overcharged, the electrolyte will reduce and generate gases (like ethylene, ethane, etc.).
- At the cathode side, if overcharged or overheated, electrolyte oxidizes (especially once cathode is fully lithiated or at high voltages) generating gases like CO_2.

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- Some electrolyte components can form carbon monoxide, methane, hydrogen, and more when things really break down.
- These gases not only build pressure (leading to cell swelling/venting) but are often flammable themselves. For instance, CO and H_2 are flammable. So the gas mix inside a stressed cell is a potential bomb when mixed with air.
- **Bottom line:** the electrolyte is the main source of flammable material in a lithium battery fire. Cathodes also release oxygen in thermal runaway (if oxide cathodes), which makes the fire worse by feeding it. So you effectively have a situation of *fuel + oxidizer self-contained* – which is why once a battery cell ignites, it can sustain combustion until the reactants are exhausted or external cooling quells it.

4.2 Gas Formation, Swelling, and Venting: Gas production inside cells is usually an unwanted sign: - Slight gassing happens even in normal life (a little CO_2 from slow side reactions), and cells have a tiny excess space to accommodate this. But excessive gas indicates abnormal reactions (like significant electrolyte decomposition or water contamination). The gas accumulates and **pouch cells swell** (they balloon up like a pillow). Rigid cells (cylindrical or prismatic) have vent mechanisms to release gas once pressure is high, to avoid rupture. - **Causes of gas:** - **Overcharge:** If you overcharge, the cathode and anode start electrolysis of electrolyte, producing gases (e.g., plating causes solvent reduction to gases; high voltage causes solvent oxidation to gaseous products). - **Overheating:** Heat can drive chemical breakdown of electrolyte into gaseous products. - **Contamination (moisture):** Water reacts with $LiPF_6$ to yield HF and **PF_5**, and further reactions can yield gaseous byproducts. It can also cause hydrogen evolution in some cases. - **Internal short/hotspot:** A localized short may heat up part of electrolyte and cause it to decompose into gas at that spot. - **Effects:** - If gas forms and the cell can't vent immediately, internal pressure builds. Pouch cells show this as swelling (puffiness). In metal can cells, pressure builds until a vent (a designed weak point or vent plug) opens. - Once vented, the cell releases those gases (which may carry vaporized electrolyte as well – often you smell a sweet or solvent smell). - Venting is a safety mechanism – better to vent flammable gas in a controlled way than to let pressure build until the cell bursts violently. However, once vented, those gases can ignite if there's a spark (so venting should be into a safe environment). - Swelling in a battery

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pack is a serious warning – it means internal failure or aging gas buildup. Such a battery should not be charged or used further without inspection/replacement.

4.3 Moisture and Corrosion Risk (The HF issue): As mentioned, $LiPF_6$ salt in electrolyte has a nasty trait: in presence of even trace moisture, it undergoes hydrolysis:

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 \text{ (and further to } PF_5 + HF\text{)}$$

This yields **HF (hydrogen fluoride)** – a very corrosive acid (in gas or liquid form). HF will attack basically any tissue (it's dangerous to humans, causing deep burns that might not be immediately painful but cause damage) and also attacks many materials in the cell: - It can dissolve the aluminum current collector if enough forms (especially at cathode). Actually, one ageing mechanism is slight HF presence slowly corroding the cathode Al foil at edges. - It will certainly react with SEI components, potentially making the SEI less stable. - HF also etches glass and many plastics; in a confined space (battery pack or enclosure), HF release is a hazard to electronics and people.

Where does moisture come from? Usually from manufacturing if not dried properly, or from a leak (e.g. a cell seal defect allowing humid air in), or from deliberate abuse tests (like overcharging can also generate some O_2 that reacts to make moisture). Also, some adhesives or contaminants might bring in water.

Even beyond HF, if a cell casing is breached and electrolyte leaks, that electrolyte itself is corrosive to electronics (and any coatings). If it vents as vapor and condenses on nearby circuits, it can corrode them or cause short circuits (electrolyte is not pure water but it can still create conductive paths especially as it decomposes).

Safety implications: - Packs are typically sealed against external moisture ingress not just to protect the battery from water, but also to protect from HF generation inside. Likewise, cells are made in ultra-dry conditions to avoid starting their life with HF. - If you open a battery module that smells horribly acrid (a whiff of something that stings the nose/throat), suspect HF – that means the cells have seen moisture and are decomposing. Proper PPE (acid-resistant gloves, respirator) is needed in that case. - If electrolyte leaks, do *not* expose it to water thinking you'll wash it away – adding water generates more HF. Neutralize first (with something like sodium bicarbonate solution) then clean, and wear appropriate protection.

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4.4 Thermal Runaway – The Chemistry of a Battery Fire: Thermal runaway is the feared cascade we've described. Chemically, what happens inside a cell as it goes into runaway? - **Trigger**: could be external heat (fire or overheating component), overcharge (excessive energy input), internal short (due to damage or manufacturing flaw). For example, say a short happens internally and begins heating a section of the cell. - Around ~60-120 °C: the **SEI layer breaks down** (it's not stable indefinitely; it starts to decompose at elevated temp). This releases heat (exothermic) and also exposes the anode directly to electrolyte. - The organic electrolyte can then **decompose rapidly**, releasing lots of heat and gases. Also, the polymer separator likely melts around 130 °C (if shutdown hasn't already occurred). If it melts enough, the anode and cathode can touch – causing a massive internal short that rapidly dumps energy as heat. - At ~150-200 °C: the cathode (for NMC/NCA) starts to break down (the metal oxides release oxygen gas). Oxygen plus the already hot flammable gases = combustion. The cell at this point likely bursts open and ignites – venting flames. - Temperature now can exceed **500–800 °C** in the core of the reaction. Each cell failing heats its neighbors. - **Propagation**: If one cell in a module goes into runaway, the heat can transfer to adjacent cells. They then start heating internally and the same processes trigger in them after a short delay (this can be seconds or minutes, or in some designs propagation is slower). In a tight module, it can be a chain reaction consuming cell after cell. Batteries can be designed with firebreaks or heat shields to slow this, but in a severe thermal event many or all cells may eventually get involved. - Once a cell has mostly burned, what's left is often a charred shell – but remaining cells might still reignite if not cooled because internal bits can stay hot and undergo further reactions (hence reports of EV fires "reigniting" hours or days later if not thoroughly cooled – residual heat in large format modules can linger).

Thermal runaway is hard to stop once it begins because the battery itself provides fuel and oxidizer (the cathode gives off oxygen, the electrolyte is fuel). Traditional firefighting (which smothers fire by removing oxygen) is less effective – you really have to **cool it** to stop the reactions. That's why firefighters often just flood EV fires with copious water; water both cools and can slow some processes (and yes, water on a lithium battery doesn't cause explosion – lithium metal is mostly not present; it's different from throwing water on a Class D magnesium fire, for instance). Water may also react and produce some HF though, so firefighters wear SCBA.

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Thermal runaway in a Li-ion cell is a self-fueled chemical fire/explosion. It's rare (virtually always triggered by severe abuse or damage), but when it occurs the focus is on containment and cooling because extinction by oxygen deprivation isn't feasible internally.

Modern battery packs include features to mitigate thermal runaway: - Thermal sensors to give early warning and possibly trigger cooling or disconnects. - Fuses that open to electrically isolate modules and prevent one cell's short from drawing huge current from its neighbors. - Venting direction – packs often channel vented gas out of the enclosure away from passengers. - Fire-resistant materials between cells or modules to provide a bit of insulation time. - But ultimately, if conditions overwhelm these measures, cells can still cascade.

For technicians: if a battery is in thermal runaway, **evacuate and do not inhale fumes**. Let the professionals (hazmat/firefighters) handle it. Ensure others are away – the gases are highly toxic (contain HF, CO, etc. plus smoke). Cool the surrounding if safe (water hose from a distance). Never tightly seal a burning battery in a container (pressure could build and explode) – venting is needed to relieve pressure, while cooling to stop the reaction.

5. Safety Measures Related to Battery Chemistry

After understanding the risks, we emphasize a **layered safety approach**: cell chemistry choices, pack design, BMS controls, and good work practices all contribute to safety.

5.1 Multi-Layered Safety Design: Manufacturers incorporate safety at various levels: - **Intrinsic chemistry safety:** e.g. using additives that prevent overheat (some cells have a shutdown separator, or redox shuttles that kick in at high voltage to limit overcharge). - **Mechanical design:** strong casing, pressure vents, thermal barriers, directed venting paths, etc. Also, making sure there's no burrs or debris inside that could cause shorts (quality control). - **Electronics/BMS:** constant voltage and current limiting, temperature sensing on multiple points, algorithms to detect an internal fault (like sudden drop in capacity or imbalance which could indicate a failing cell) and then take action. - **Containment:** The pack enclosure is usually fire-resistant to some degree (to contain a thermal event long enough for occupants to exit). Some pack enclosures are also designed to direct flames downwards or away from sensitive

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areas. - **Fusing and current interruption:** As noted, fuses or pyrotechnic disconnects will isolate parts of the battery if high current surges (like a crash-induced short) occur, to prevent worst-case heating.

From a service perspective, assume the pack is safe *unless* it's been compromised – e.g., after a crash, inspect for coolant leaks into pack or deformation. Undamaged packs are engineered to be safe under normal usage and foreseeable abuse.

5.2 Safe Handling and Storage (Workshop Level): When dealing with battery modules or cells directly (outside of the vehicle or in a lab): - **Handling basics:** - Avoid dropping or striking cells/modules. Mechanical shock can deform electrodes or separator. - **No metal tools** near battery terminals. Use insulated tools. A dropped wrench can short and cause severe burns or fire. - Work on batteries in a well-ventilated area in case of fume release (especially if opening cells). - **Personal Protective Equipment (PPE):** At least safety glasses and gloves when handling cells. If there's risk of electrolyte exposure, use chemical-resistant gloves (nitrile) and perhaps an apron. For high voltage packs, use insulating gloves and mats as required by electrical safety protocols. - **Storage basics:** - Store cells or modules in a **cool, dry place**. Avoid high heat or direct sun. 15–25 °C is ideal. - Do not store near flammable materials. Although inert when not in use, if a cell vents, you don't want it next to solvents or paper. - For long storage, leave cells at ~30-50% SOC (not full, not empty). - Ensure terminals are not able to short: keep modules in insulating packaging or with terminal covers. Maintain a safe separation distance or insulation between modules in storage. - Follow any local regulations – large quantities of lithium batteries might require a fire-rated storage cabinet or room. - Keep water away from stored cells (prevent both short-circuits and the dreaded $LiPF_6$ + H_2O reaction).

Emergency equipment: Have a Class ABC fire extinguisher accessible where batteries are handled. However, note that small extinguishers will not stop a cell in full thermal runaway – they are more for putting out small peripheral fires or preventing spread. For an actual battery fire, the strategy is usually to cool with large amounts of water (if safe to do so) and let it burn out under controlled conditions.

5.3 Recognizing Warning Signs – Don't Continue if: - **Swelling:** If a module or cell is bulging, it's unsafe. That cell is internally damaged or overaged. Disconnect it and do not use or charge it. In an assembled pack, swelling usually means severe failure of at least one cell. - **Hissing sound:** Active venting of gas indicates a cell is in critical condition (pressure relief). If you hear this, stop all operations, evacuate the area around the battery, and allow it to vent in a well-ventilated space. Be prepared for possible ignition. - **Smell:** A sweet, solvent-like or pungent acrid odor means electrolyte is leaking/vaporizing. Do not ignore smells – it could precede a thermal event. Use PPE if you must approach to disconnect. - **Temperature anomaly:** If a battery or module is heating up significantly without an apparent cause (not being charged/discharged at the moment), that could indicate an internal short. An IR thermometer or thermal camera can help spot a hot cell in a module. If one cell is much hotter than others, it's likely in trouble. - **Smoke or discoloration:** Any smoke means a fire has started. Even if it's just a whiff, treat it as emergency – disconnect power, use extinguisher if small, call fire services if large, etc. - **BMS alerts:** In a vehicle, if the car's BMS gives warnings ("Battery fault", "Service battery", or you see sudden unexplained range loss, or imbalance), don't charge the car. Get it serviced. The BMS is detecting something outside normal range, which could include safety risks.

In any of these cases, **do not continue normal operation or charging**. Follow emergency handling: 1. **Stop** charging or discharging. De-energize the system if possible. 2. **Isolate** the battery – move it to a safe area away from people or combustibles if you can do so safely (if not, evacuate the area). 3. **Inform** – call emergency services if there's active venting, fire, or imminent risk. If in a lab/plant, pull the fire alarm or follow protocol. 4. **Follow procedure** – use fire suppression if trained, ventilate the area (open windows/turn on fume hood). Do not inhale fumes – they are toxic.

It's worth noting that lithium-ion battery incidents often give some early signs (e.g. a slight swelling or hiss before fire). If caught in that early window and mitigated (power cut off, cooled down if possible), a full thermal runaway might be averted. Time is critical once symptoms appear.

5.4 First Response Logic (Educational Outline, Not a Full ER Manual): If you suspect a battery is going into thermal runaway or has been severely damaged: - **Stop and stay clear.** Human safety first – batteries can be replaced, lives not. Do not try to save property at risk to yourself if a battery is burning. - If it's a vehicle, **park it outdoors** away from structures if possible, so if it ignites the damage is limited. - **Isolate and secure the area.** Keep people back (at least 50 feet or more for a large pack fire, as explosions are possible). Fumes travel with the wind, so keep others upwind. - **Call emergency services** and inform them it's a lithium battery fire (so they bring lots of

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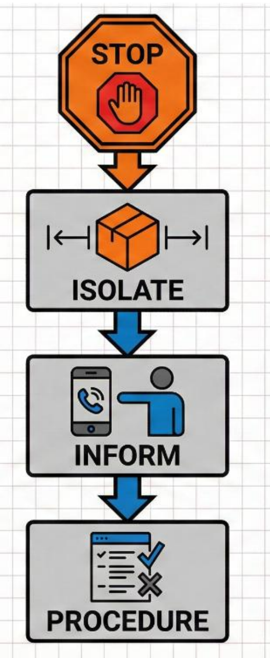
water and perhaps special equipment). - If a small battery (like a lab cell) is smoking but not in flames, you might cautiously drop it into a bucket of sand or saltwater (water can cool it, though it generates HF – only do this in a well-ventilated or outdoor area, wearing PPE). Sand can smother flames externally but won't stop internal reaction; it mostly contains the mess. - **After fire**: remain cautious. Cells can reignite. Firefighters often douse packs for a long time. For small cells, leave them in an isolated area for hours to cool. Do not immediately enclose them in a sealed container (gas could build).

This is why workshops have clear protocols – as discussed, the figure below concept: *Stop, Isolate, Inform, Follow-up.*

5.5 Safety Data Sheets (SDS) and Hazard Labels (CLP/GHS): Any technician dealing with battery chemicals (like electrolyte, or even solvents and adhesives used in battery assembly or repair) should be familiar with reading SDSs and hazard labels:



- **Safety Data Sheets (SDS):** These are documents (required by law for hazardous substances) that provide detailed information on a chemical's dangers and handling. For example, if you have a bottle of electrolyte or a leak from a cell, the SDS will tell you the hazards (flammable, toxic, etc.), first aid measures if exposed, firefighting measures, and how to clean spills and dispose of material. Key sections to quickly check in an SDS: - *Section 2: Hazards Identification* – see hazard classes and pictograms (e.g. "Highly flammable", "Toxic if inhaled", etc.). - *Section 4: First Aid Measures* – what to do for eye contact, skin contact, inhalation, ingestion. - *Section 5: Firefighting Measures* – what type of extinguisher, any special instructions (e.g. "fire may produce HF gas, wear SCBA"). - *Section 7: Handling and Storage* – e.g. "keep container tightly closed and in dry place". - *Section 8: Exposure/PPE* – recommended personal protection (glove material, respirator type if needed). - *Section 10: Stability/Reactivity* – highlights things like "reacts with water, avoid humidity". - *Section 14: Transport info* – classification for shipping (e.g. "Class 9 hazardous material" for lithium batteries). - SDS for a lithium-ion cell or battery will often list: Hazard: "Battery contains flammable electrolyte. If breached, can cause

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burns. Harmful by inhalation." etc., and advise on first aid (flush eyes/skin with water if contact, etc.) and firefighting (use lots of water, wear breathing apparatus).

- **Hazard Labels (GHS/CLP Pictograms):** These are the diamond-shaped symbols on chemical containers. Common ones relevant to batteries: - **Flame icon** 🔥 – flammable (electrolyte, solvents, even the plastic casing of cells). - **Corrosive icon**

(acid spilling on hand) – indicates it can burn skin/metal (strong acids like HF, or alkalis). You might see this on electrolyte bottles due to the HF possibility. - **Health hazard icon** (exclamation mark) – irritant/harmful. Many battery chemicals have this for skin/eye irritant or sensitiser hazards. - **Gas cylinder icon** – for compressed gases (not directly on a cell, but e.g. if shipping pressurised modules).

- **Skull and crossbones** ☠️ – acute toxicity. (Not usually on cells, but if a chemical inside is highly toxic on contact, it could be.)

- **Environment tree/dead fish** – environmentally hazardous (some heavy metal compounds). - There's also a specific *lithium battery handling label* used in transport (illustration of a battery with flames) to warn of the risk of fire if damaged – used on packages of batteries.

- **Signal words:** on labels, "Danger" is more severe than "Warning".

- **Hazard statements:** short codes like "H225 Highly flammable liquid and vapor" or "H302 Harmful if swallowed".

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- **Precautionary statements:** like "P280 Wear protective gloves/protection" or "P370+P378 In case of fire: Use water in large quantities to extinguish".

Reading these at a glance tells you a lot. For example, a chemical labeled with a flame and exclamation mark and "Danger" might have hazard "Highly flammable, causes serious eye irritation". So, you know to keep it away from ignition sources and avoid splashes to eyes (wear goggles).

In the context of EV batteries: - If you ever open a module and plan to handle exposed electrodes or electrolyte, *get the SDS* for the electrolyte or any additives. It will remind you that HF can be present and to use e.g. neoprene gloves, and have calcium gluconate gel on hand for HF exposure (specific first aid for HF). - If you see a label on a battery shipping crate with a flame symbol, treat that package carefully – it's flammable (don't store near heat, etc.). - Battery manufacturers often provide an "SDS" for the battery as a whole. It will say something like: contains lithium hexafluorophosphate and organic solvents (~20% by weight), nickel-cobalt compounds (~30%), graphitic carbon (~15%), etc. Hazards: flammable, do not heat, do not short, produce toxic vapours if breached. First aid: if electrolyte contacts skin, wash with plenty of water. If inhaled, get fresh air, etc. This is useful for emergency personnel too.

5.5.1 Quick Checklist (Workshop SDS use): Whenever dealing with a new chemical (be it a cleaning solvent for battery terminals, or thermal interface material, or

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electrolyte): - Check **Section 2** of SDS: see what pictograms are there and read hazard statements. E.g. "Causes skin burns" means you need serious gloves. - Check **PPE recommendations (Sect. 8)** – it might specify e.g. use nitrile gloves of certain thickness, and fume hood if above certain amount. - If an exposure occurs, have the SDS handy when seeking medical help – bring it with the person or show the doctor, as it has specific treatments (especially for things like HF, where calcium gluconate gel should be applied quickly). - For battery spills: manufacturers often give recommended neutralizers (e.g. baking soda for acid or HF neutralization). SDS Section 6 (Accidental release measures) will say how to clean up a spill safely.

5.5.2 Hazard Label Elements – What to Look For: If you pick up a chemical bottle in the battery lab, do a **"LIFT"**: - **Label** – Read the signal word (Danger/Warning) and the main hazard pictogram. Danger + flame + skull? Extremely flammable and toxic – handle accordingly. - **Instructions** – Precautionary statements like "Use only outdoors or in well-ventilated area" or "Wear respiratory protection" – follow them. - **First Aid** – Sometimes on the label a short line: "IF ON SKIN: rinse immediately with water for 15 minutes" etc. Know these for quick action. - **Transport/Storage icons** – e.g. a temperature limit or "keep dry" icon might be present on battery packs.

For lithium batteries being shipped, labels will indicate if they're tested (UN 38.3) and might have class 9 miscellaneous dangerous goods label. That's more for awareness in logistics.

Automotive Practice – Example: Reading a Cell's SDS: Suppose you have a pouch cell and you suspect a leak. You find the SDS from the manufacturer. Section 2 has: GHS Pictograms: *Flame, Corrosion, Health Hazard*. Signal word: *Danger*. Hazard Statements: "H228: Flammable solid. H314: Causes severe skin burns and eye damage. H373: May cause damage to organs through prolonged or repeated exposure." – This tells you the cell's contents are flammable and very corrosive to skin/eyes (likely due to $LiPF_6$ -> HF risk), and chronic toxicity (maybe cobalt compounds). Precautions: "Keep away from heat, sparks, open flames. Do not breathe vapors. Wear protective gloves/protective clothing/eye protection." First aid: "In case of contact with electrolyte, immediately flush skin or eyes with plenty of water. Remove contaminated clothing." – With this info, you treat any leak with utmost caution: full PPE, ensure ventilation, have calcium gluconate for HF, and no ignition sources nearby. You also now know not to touch it

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barehanded (skin burns) and not to inhale (organ damage over time). This level of detail from the SDS can prevent serious injury.

5.5.3 A Note on Regulatory Compliance: In the EU, new regulations (like the **EU Battery Regulation 2023/1542** and existing CLP/REACH laws) require proper labeling and even a "battery passport" for large batteries in the future. Always ensure any battery shipments follow transport regs (UN 38.3 testing, proper labeling). As an instructor or technician, instill the idea that **safety and compliance go hand-in-hand** – understanding the science (chemistry) behind the rules makes one appreciate why they must be followed.

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Module 4 Recap – Key Points:

- **Battery components:** An EV cell consists of anode (usually graphite), cathode (like NMC, NCA, or LFP), electrolyte ($LiPF_6$ in organic solvent), separator, current collectors (Cu, Al), and binders/additives. Each has a role and a failure mode (e.g. separator damage = short, electrolyte = flammable, etc.).
- **Operation:** During charge, lithium ions move from cathode to anode and are stored; during discharge they move back. Electrons always go in the external circuit in opposite direction to ions. The processes are mostly reversible, but side reactions slowly occur.
- **Common chemistries:**
- *NMC:* Very common in EVs, good balance of properties, but uses cobalt and needs careful thermal management.
- *NCA:* High energy (used for long-range/high performance), but slightly lower stability margin – still safe if managed.
- *LFP:* Extremely safe and long-lasting, but lower energy density – gaining popularity for standard models and buses.
- **Ageing mechanisms:** Batteries degrade due to SEI growth, lithium plating, micro-cracks, electrolyte breakdown, etc. Heat, high SOC, and high stress accelerate these. That results in capacity loss and resistance increase over time.
- **SEI layer:** A double-edged sword – it enables rechargeable chemistry (protects the anode), but its growth consumes lithium and raises resistance. Keeping the battery cool and not over-volting helps slow SEI growth.
- **Chemical hazards:**
- Electrolyte is flammable and can cause fire if released.
- Abuse can generate toxic gases (HF, CO, etc.).

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- Thermal runaway is a complex self-fueled failure – rare but dangerous. Packs are designed to mitigate it, and proper use of BMS and cooling keeps batteries in safe limits.

Safe practice:

- Always handle cells with respect – avoid physical or electrical abuse.
- Use PPE when opening cells or dealing with leaks (assume corrosive/toxic vapors present).
- Store batteries properly (cool, ~30-50% charge for long term, isolated from combustibles).
- Be vigilant for warning signs like swelling or venting – and know how to respond (isolate and get help).
- **SDS/Label literacy:** Know how to quickly find hazard info for the materials you work with. It might literally save your skin (from chemical burns) or your lungs. For example, recognizing that "$LiPF_6$ + H_2O ⇒ HF" tells you why a dry environment is critical inside cells and why vent gas is so hazardous.
- **Regulations:** Shipping and disposing of batteries must follow laws (they are classified hazardous material in transport). End-of-life batteries should be recycled through proper channels, not tossed in general trash – they pose fire risks in waste facilities and contain valuable materials to reclaim.

Armed with this deeper understanding of battery chemistry and safety, vocational instructors and students can confidently handle battery technology in practical settings – maximizing learning and innovation while keeping risks at bay. Always keep the respect for the "chemical beast" that is an EV battery: it stores immense energy, but with knowledge and caution, it can be handled as safely as any other automotive component.

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Self-Check Questions (Module 4):

1. List the main components inside a lithium-ion battery cell and briefly state the purpose of each (anode, cathode, electrolyte, separator, current collectors, binder).
2. In a charged lithium-ion cell, where are most of the lithium ions? And where do the electrons flow during discharge?
3. Compare **NMC vs. LFP** chemistry: give at least two differences in terms of performance or safety.
4. What is the **SEI layer** and why is it formed? Why is it beneficial, and why can it also be detrimental over time?
5. Name two or three factors that accelerate battery ageing.
6. Why is moisture exposure bad for Li-ion batteries? What harmful substance can form, and what are its effects?
7. If a battery cell starts swelling, what does that indicate chemically? What should you do?
8. Describe what **thermal runaway** means in a battery. What are some triggers for it, and why is it hard to stop once started?
9. You open a device and smell a strong, sweet/solvent odour from the battery – what might that mean, and what precautions should you take?
10. When handling a liquid electrolyte or a leaky cell, what PPE is recommended and why?
11. You see a hazard label with a flame symbol and an exclamation mark on a bottle of battery solvent. What general hazards do these indicate, and what precautions would you take before opening that bottle?
12. Explain in your own words why even a "safer" battery chemistry (like LFP) still requires a BMS and careful usage.

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(Refer to the text and sources for answers. Emphasise understanding of concepts over memorisation.)

Resources:

Battery University | Lithium-ion Safety Concerns *http://www.batteryuniversity.com/article/lithium-ion-safety-concerns/*

AC vs DC EV Charging – What are the Differences? – Ampcontrol *https://www.ampcontrol.io/post/ac-or-dc-charging-stations-which-is-best-for-electric-fleet-vehicles*

Constant Current – Constant Voltage Charging - Battery Design

https://www.batterydesign.net/constant-current-constant-voltage-charging/

What Is a Battery Management System (BMS)? - MATLAB & Simulink

https://uk.mathworks.com/discovery/battery-management-system.html

Lithium plating: Purdue researchers tackle the toughest problem ...

https://engineering.purdue.edu/ME/News/2022/lithium-plating-purdue-researchers-tackle-the-toughest-problem-with-lithiumion-batteries

Thermal Runaway in Lithium-Ion Batteries: Causes, Risks, and Preventio

https://envodrive.com/en-us/blogs/articles/thermal-runaway-in-lithium-ion-batteries-causes-risks-and-prevention?srsltid=AfmBOopVHzinCaniU2Ghd0ELu8fuQf-FR0Aof7fww2XU2BvQ___Ty3iE

Chemical transformation of H2O to HF in 1 M LiPF6 Concentrations ...

https://www.researchgate.net/figure/Chemical-transformation-of-H2O-to-HF-in-1M-LiPF6-Concentrations-of-water-blue-and-HF_fig9_324434751

Battery University | BU-401: How do Battery Chargers Work?

http://www.batteryuniversity.com/article/bu-401-how-do-battery-chargers-work/

Battery University | BU-205: Types of Lithium-ion

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http://www.batteryuniversity.com/article/bu-205-types-of-lithium-ion/

Hydrolysis of LiPF6-Containing Electrolyte at High Voltage *https://www.academia.edu/65909180/Hydrolysis_of_LiPF6_Containing_Electrolyte_at_High_Voltage*

The Batteries that Power EVs | Wolfspeed *https://www.wolfspeed.com/knowledge-center/article/the-batteries-that-power-evs/*

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Module 5 – Quality in cell production

Aim of the Module	The aim of this module is to provide a comprehensive overview of the role of quality throughout the entire cell production process, from raw material inspection and monitoring of manufacturing parameters to the testing and qualification of finished cells. Participants will become familiar with the critical stages of production, the quality requirements associated with each technological step, and the methods and tools applied in quality control. The module highlights the importance of quality assurance in relation to performance, lifespan, safety and cost-effectiveness. It also introduces relevant international standards, auditing requirements and transport regulations for lithium batteries. Particular emphasis is placed on common manufacturing defects, their causes and consequences, as well as the strong relationship between quality management and operational safety in the battery industry.
Target	The module is intended for VET educators and professionals involved in battery technology, cell production or quality assurance-related training and professional activities.

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Pre-requisites	• Basic knowledge of battery structure and operating principles • Understanding of the main stages of cell manufacturing • Fundamental electrical and safety knowledge
EQF Level	EQF 4–5
Methodology	The module is delivered through a combination of theoretical and practice-oriented approaches. Participants first gain an understanding of quality requirements and the critical stages of cell production, followed by the practical application of this knowledge through case studies and defect analysis. The learning process includes the analysis of process flow charts, manufacturing examples and measurement results in order to support systems-level thinking. Particular emphasis is placed on quality control methods and tools, as well as on identifying root causes of manufacturing defects.
Evaluation	Evaluation focuses on assessing the acquired knowledge and the ability to apply quality-related aspects in cell production. Participants may complete self-check questions and online tests, and demonstrate their ability to identify critical stages of the manufacturing process and common defects.

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	Assessment also includes the interpretation of quality control methods, analysis of measurement results, and recognition of relevant standards and safety requirements in cell production.

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Contents	The role of quality in battery cell production
	Stages and critical parameters of the manufacturing process
	Quality requirements for finished cells
	Quality standards and auditing requirements
	International regulations for the safe transport of lithium batteries
	Quality control tools and measurement methods
	Common defects and their causes in cell production
Module title	Quality in cell production
Workload	4 teaching hours, 15 studying hours

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LEARNING OUTCOMES		
Learners who successfully complete the training will gain the following knowledge, skills and competencies.		
Knowledge	**Skills**	**Autonomy**
Know the main steps of battery cell production.	Identify key control points in the production process.	Take responsibility for the quality of their own work.
Understand why quality control is important in cell manufacturing.	Perform basic inspections and measurements.	Cooperate with production and quality staff.
Be aware of common production defects.	Interpret simple test results.	Follow quality and safety rules.
Know how finished cells are tested and checked.	Report and document deviations.	Show commitment to defect prevention.
Understand the importance of documentation and traceability.	Comply with procedures in a controlled production environment.	Work in accordance with safety and sustainability principles.

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I. Chapter
The role of quality in battery production

Lesson Objective

To provide a detailed description of the role quality plays in the battery production chain, how it influences the properties of the final product, and how it contributes to sustainability and market competitiveness.

Requirements

- ✓ *The student should recognize the importance of quality in battery production*
- ✓ *Know how to understand the practical implementation of quality assurance*
- ✓ *See the strategic benefits*

(The impact of quality on the economy, society and environment)

- ✓ *Be aware of new challenges and trends*

Concepts

Quality assurance, anode, cathode, electrolyte tightness, separator, cycle testing.

Introduction

Electric vehicles play an important role in the global economy, especially with the proliferation of renewable energy systems and portable electronics. The demands placed on batteries are constantly increasing: longer life, higher energy density, faster charging times and, above all, higher safety. In this environment, **quality** is not just an abstract requirement, but a key factor for competitiveness and sustainability.

The importance of quality in battery manufacturing

Batteries are exposed to extreme physical and chemical stress during operation. Even the smallest manufacturing default can lead to serious consequences: performance degradation, overheating or even fire. Therefore, quality does not only mean the flawlessness of the product, but also:

1. Quality

- reliability,
- economy (lower scrap and fewer recalls),
- longer lifespan, which is also of paramount importance from an environmental perspective,
- safety and consumer satisfaction.

Battery production is a strictly regulated, step-by-step technological process, where quality
assurance is present at different levels.

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Practical implementation of quality assurance

❖ Raw material inspection

A prerequisite for a high-quality battery is high-quality raw materials. The most important components are :

- **Anode** : usually graphite, the purity and grain size of which significantly affect ion flow.
- **Cathode** : lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) or other alloys .
- **Electrolyte** : the liquid or gel that carries lithium ions. Its purity is a key issue.
- **Separator** : a polymer membrane that separates the anode from the cathode and allows only ions to pass through.

❖ Production process control

During battery production, the following critical phases are particularly strictly controlled
(Graph 1):

- **Electrode manufacturing** : cathode/anode layers are applied to a substrate, then dried and pressed.
- **Cell assembly** : electrolyte addition, separator insertion, closing. Even the smallest mistake can be a source of danger.
- **Formation** : During the first charging cycle, the so-called SEI layer is formed, which stabilizes the anode surface. This is where the first performance test takes place.
- The entire process is automated, in a clean room (clean room) takes place, where temperature, humidity and air quality are constantly monitored.

❖ Quality control methods

The inspection methods used during production include:

- **Test measurements** (impedance, voltage, internal resistance)

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- **X-ray examinations** (inspection of internal structure)
- **Leak test** (electrolyte tightness)
- **Cycle testing** (lifetime simulation)
- **Thermal and mechanical tests** (for extreme conditions)

Manufacturing companies often apply IATF 16949, ISO 9001 and ISO 14001 standards, as well as Six Sigma and Lean methods to minimize errors.

❖ **Traceability and data analysis**

Each cell and battery module is assigned a unique identifier, enabling traceability throughout the entire production and life cycle. Data collected through Industry 4.0 solutions helps drive continuous improvement and quickly identify the cause of errors.

2. Battery manufacturing flow chart

The impact of quality on the economy, society and environment

Cost-effectiveness

At first glance, quality assurance may seem like an additional cost, but in fact it pays off in the long run. A recall of a defective battery batch or service costs can cause significant losses. In addition, good quality increases brand trust.

Consumer safety and satisfaction

For end users, safety, reliability and lifespan are the most important issues. For example, electric car owners often consider the condition of the battery when buying a used vehicle.

Sustainability and recycling

A quality battery lasts longer, produces less waste, and is more likely to be suitable for secondary use. Recyclability is facilitated by a well-documented manufacturing process, standardized components, and easy disassembly.

Challenges and trends

The rapid development of battery production also means new challenges:

- Introduction of new technologies (such as solid-state batteries),
- Growing demand and production volume,
- An increasingly complex supply chain,
- digitalization and artificial intelligence.

These trends require continuous adaptation and innovation in the field of quality inspection. The quality of batteries is a key factor in the success of modern technological and energy systems. The appropriate use of materials, a precise manufacturing process, modern testing methods and comprehensive quality management systems all contribute to ensuring that batteries provide reliable, safe and sustainable solutions in the long term. Market competition and the tightening regulatory environment fosters the importance of quality – not only for manufacturers, but also for consumers and society in general.

Self-check questions

1. **Why is quality considered a strategic factor in battery production?**
2. **List at least three possible consequences if the quality is not adequate during production!**
3. **How does the purity of raw materials affect battery performance and lifespan?**
4. **What is the environmental aim of “clean space” room during the cell production?**
5. **What role do inline measuring systems and AI-based image processing play in quality assurance?**
6. **Is traceability important in battery manufacturing?**
7. **Name at least two types of tests performed on finished batteries and explain their purpose.**
8. **How does quality assurance contribute to sustainability?**
9. **What challenges does the introduction of solid-state batteries pose for quality assurance?**
10. **How can high quality reduce manufacturer warranty costs?**

Online test

1. Why is the clean room environment particularly important in battery cell manufacturing?

A) Because materials quickly become contaminated with air

B) Because dust and moisture prevent machines from operating

C) Because contaminants can reduce the lifespan and safety of cells

D) Because this is the only way to charge batteries quickly

2. Which statement is true about low-quality batteries?

A) They usually have a longer lifespan

B) They are easier to recycle

C) They reduce energy efficiency and can be a source of danger

D) They are capable of higher performance than high-quality ones

3. What is the purpose of cycle testing during battery manufacturing?

A) Determining the weight

B) Reducing the production time

C) Optimizing energy consumption

D) Checking the charge-discharge reliability

4. Why is the role of quality assurance important for sustainability?

A) it makes batteries cheaper to buy

B) Because it increases production speed

C) Because it reduces environmental impact through less waste and a longer lifespan

D) Because quality control is mandatory under EU regulations

5. What is the purpose of traceability in battery manufacturing?

A) Only important for marketing purposes

B) Easier to retrieve defective products and optimize the process

C) Sorting batteries by color

D) Measuring the weight of products

6. What factors contribute to improving quality?

A) Automatic and AI-based inspection

B) Faster delivery

C) Smaller battery size

D) Manual inspection only

7. What is the strategic advantage of quality?

A) Only reduction in production time

B) Stronger customer confidence and premium position

C) Products will be heavier

D) No strategic advantage

8. Which of the following is NOT a final test?

A) Extreme temperature test

B) Mechanical impact test

C) Paint color check

D) Cyclic life test

9. Which new technology poses a challenge in quality assurance?

A) Solid-state batteries

B) Mechanical watches

C) Traditional lead-acid batteries

D) Steam engines

Solutions: 1.C, 2.C, 3.D, 4.C, 5.B, 6. A , 7.B, 8.C, 9.A.

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Tarascon , J.-M., & Armand, M. (2001). Issues and challenges facing rechargeable lithium batteries . Nature , 414(6861), 359–367. https://doi.org/10.1038/35104644

Nagaura , T. , & Tozawa , K. (1990). Lithium ion rechargeable battery . Progress in Batteries & Battery Materials , 9, 209–217.

Goodenough , JB, & Kim, Y. (2010). Challenges for rechargeable batteries . Journal of Power Sources , 195(9), 3737–3749. https://doi.org/10.1016/j.jpowsour.2009.11.048

Blomgren , GE (2017). The development and future of lithium -ion batteries . Journal of The Electrochemical Society, 164(1), A5019–A5025. https://doi.org/10.1149/2.0251701jes

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II. Chapter
Steps and important parameters of the production process

The purpose of the lesson:

Introduction to the three main parts of the manufacturing process (electrode manufacturing – cell assembly – molding) and their most important manufacturing parameters

The purpose of the lesson:

To provide a detailed picture of how electrode production is done, what steps it takes, and what the most important parameters are.

Requirements:

- ✓ *Understand the steps of electrode preparation, cell assembly, and shaping.*
- ✓ *Understand the minor steps and their parameters.*

Concepts:

Manufacturing process steps, electrode manufacturing – cell assembly – molding

Battery cell formats, cylindrical, pouch, prismatic,

Electrode manufacturing *steps,* Mixing, Coating and Drying, Pressing, Slitting

Cell assembly steps

Vacuum drying (Vacuum drying), Notching , Stacking , Tab welding , Packaging , Pouch forming), Insertion and pouch welding (Insertion and pouch sealing), Electrolyte filling (Electrolyte filling), Formation , Rolling , Degassing , Folding

Formatting steps

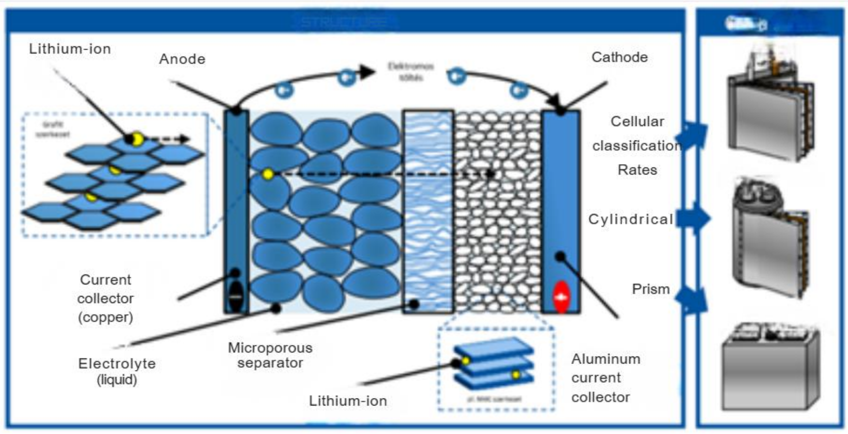
Rolling , Degassing , Folding

slurry , reel , jelly roll

Parts of the manufacturing process

The manufacturing process can be divided into three main parts: Electrode manufacturing, Cell assembly, Formation

Out of the three manufacturing processes, electrode manufacturing and shaping are quite similar between the different battery cell formats (cylindrical, pouch, prismatic), but the electrode assembly process is completely different for each type.



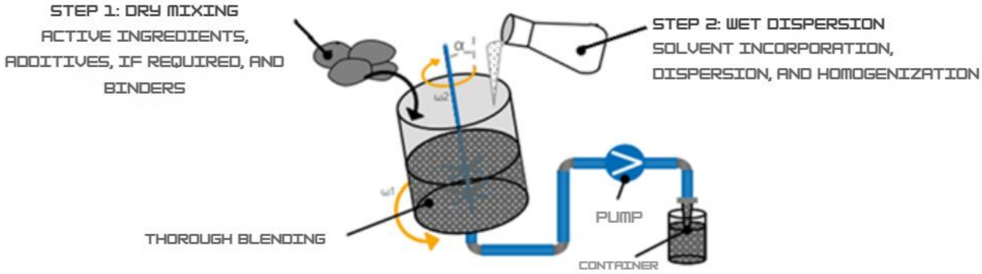
3. Illustration of cell structure

Electrode production

The electrode manufacturing process consists of several steps:

Mixing

During mixing, the active ingredients are mixed in rotating, robust containers with various solvents and dispersants, which are pumped into a storage tank. At the end of the production process, a so-called **slurry** is made from the ingredients.

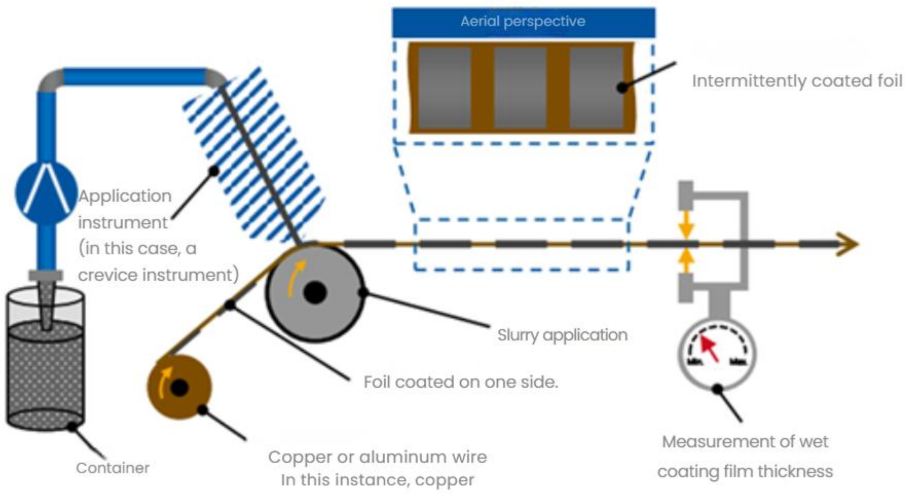


4. Mixing process

The mixing parameters are the axis angle marked a in the picture, which can be **between 0-10^0** , the mixing time (**30 minutes–5 hours**), the mixing temperature (**20-40^{0}C**). After the mixing process, the slurry is transferred to the coating process through the pipelines.

Coating and Drying

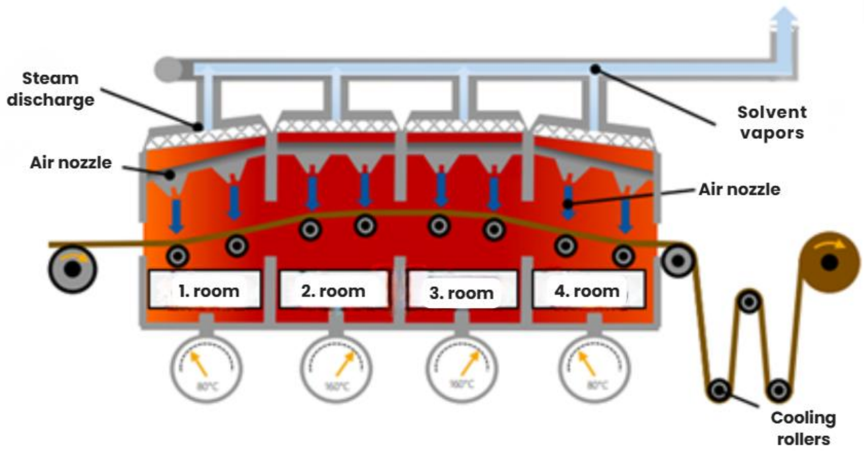
The anode and cathode processes are also **completely separated in** the coating process . In the case of the anode, the slurry coating is applied to copper foil, and in the case of the cathode, to aluminum foil. The application device can be a slot tool, a cutting knife or an anilox roller.



5. Coating process

After coating, the active material is dried on the surface of the film in the next process.

During drying, the solvent is extracted from the material by heat. The film is transported in and out of the ovens using a roller system.

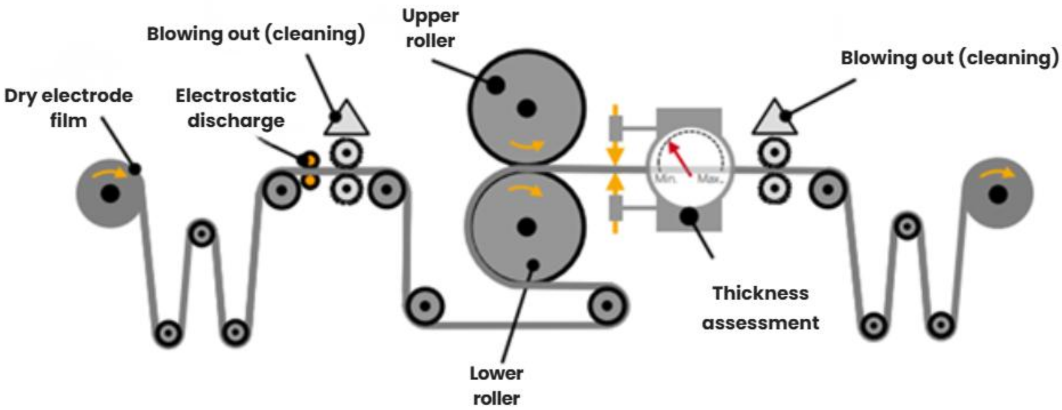


6. *Drying process*

To ensure proper drying and to prevent cracking of the coating surface, **the roll passes through chambers with different temperatures before being pressed** .

Pressing

During pressing with the slurry coated aluminum or copper foil is pressed on both sides by a pair of rotating rollers. Before the pressing process begins, the foil **is statically fired and cleaned** using brushes or air blowing.

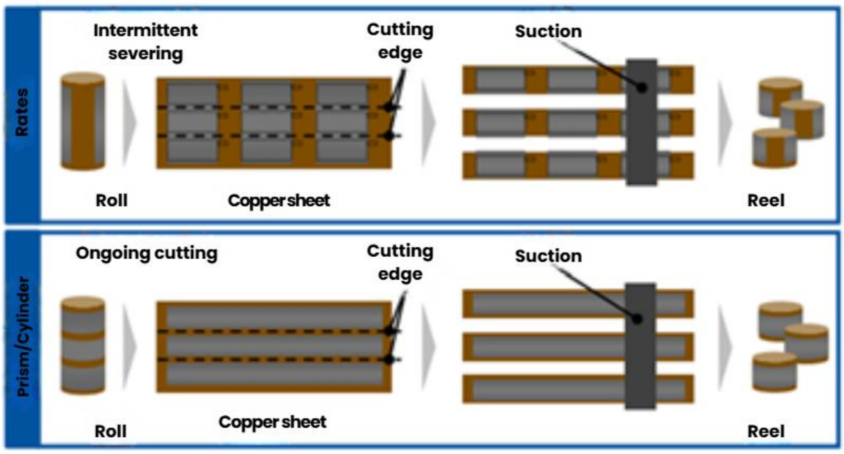


7. Pressing

The main or key parameters of the process are maintaining **constant pressing pressure** (up to approx. 2500 N/mm) , **speed** (60-100 m/min), **preheated rollers** (50°C - 250°C) and surface **accuracy** .

Slitting

The wound rolls are usually transported manually to the cutting station. The essence of cutting is that the rolls are cut lengthwise **into reels** . The width of the cut and the reels is determined by the width of the electrode sheet.



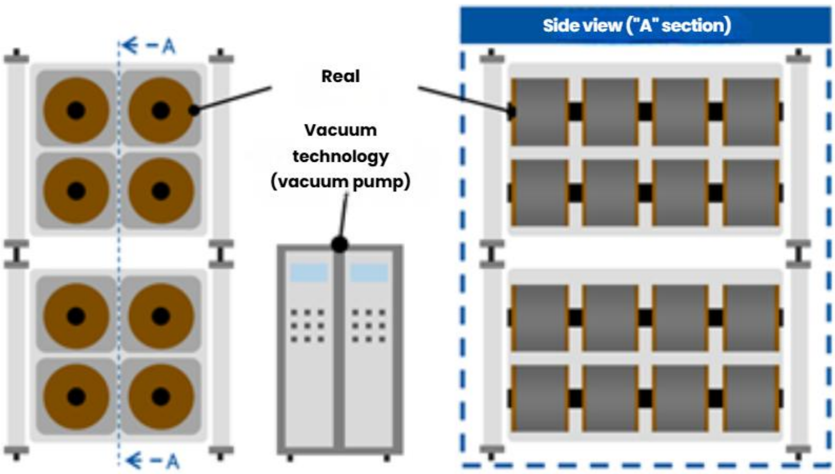
8. Slitting

Cell assembly

Cell assembly lasts from vacuum drying of the electrode coils to the packaging process and can be separated into a total of 5 processes.

Vacuum drying (Vacuum drying)

The wound reels are placed on a special conveyor and then stored in a vacuum oven. The essence of the process is to remove any remaining moisture and solvents from the reels.

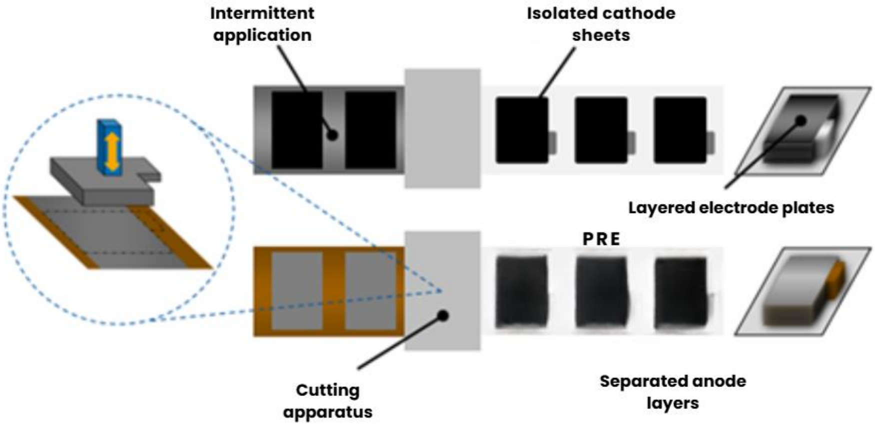


9. Vacuum drying process

The main parameters of the process are: **pressure (0.007 mbar – 1000 mbar), drying time (12-30 hours), drying temperature (60^{0}C - 150^{0}C).**

Notching

The reels arrive in coils for the notching process, during which the cathode and anode foils are unwound and the reels are then cut to the desired size.

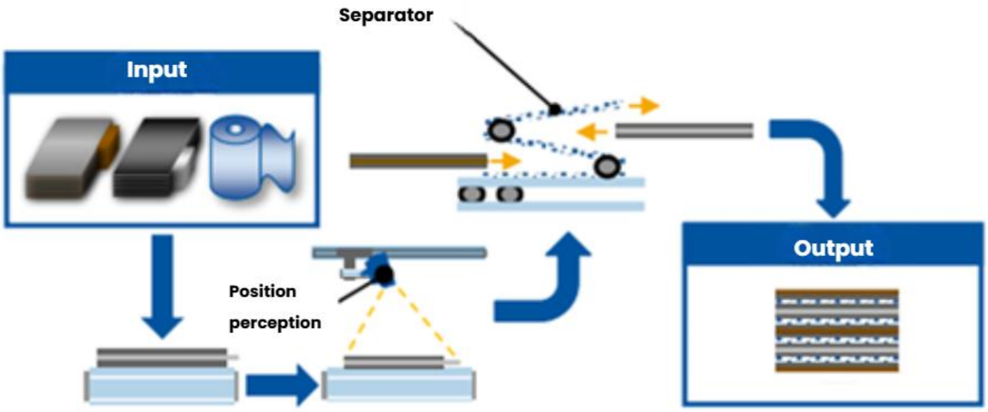


10. Cutting process

The main parameters of the process are the **cutting speed** (approx **. 0.2 seconds per electrode plate**) and the cutting tolerance, which is approx. **200 µm for** both **the length and width of the cut electrode plate** .

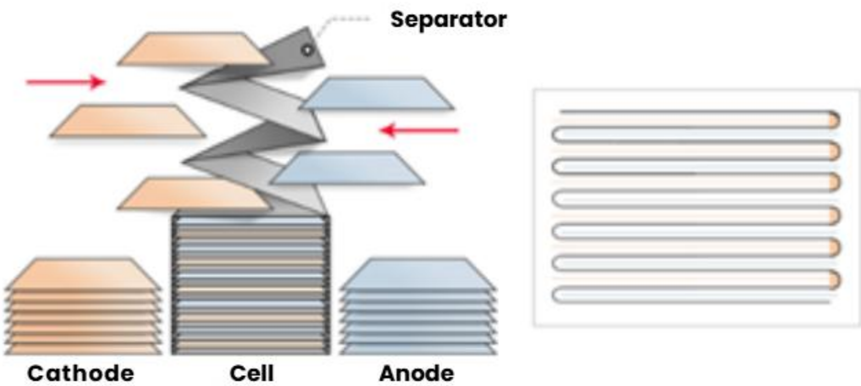
Stacking

In the stacking process, the previously separate anode and cathode production are combined, as they are stacked on top of each other to form the core of the battery cell, the so-called jelly roll.



11. Stacking process

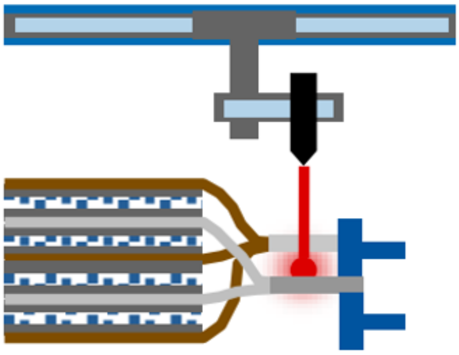
Stacking is one of the most complex and fastest processes in battery cell manufacturing. Stacking machines are loaded with magazines consisting of electrode sheets previously cut in the notching process (anode and cathode magazines), as well as the separator coil. The most common variation of the process is Z-folding.



12. SK Innovation Z-folding technique

Tab welding

During the cutting process, the tool cuts an uncoated piece of foil from the reel together with the coated electrode sheet : these are the tabs of the electrode sheet, which are welded together during the welding process. This allows the anode and cathode electrode sheets to be electrically connected to each other later.



13. Ear welding

Packaging

The importance of the packaging process is placing the cell body in a bag, filling it with electrolyte and sealing the bag.

Deep drawing (Pouch) forming

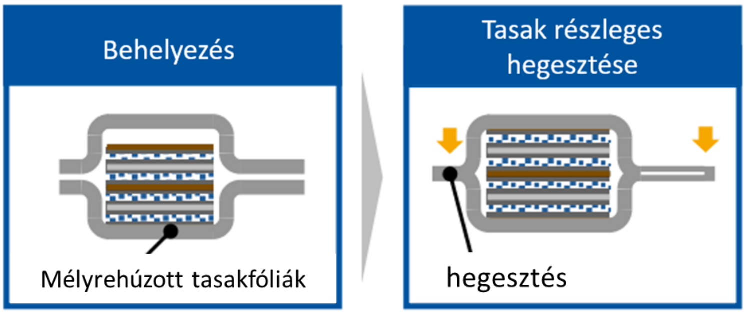
The first step in the packaging process is the deep-drawing of the bag, which arrives at the packaging station rolled up.

14. Deep drawing of a bag and the finished workpiece

The main and critical **parameters of deep drawing are the drawing depth and the pressure** . These factors must be within narrow limits (e.g. too much depth, pressure will reduce the strength of the bag).

Insertion and pouch sealing)

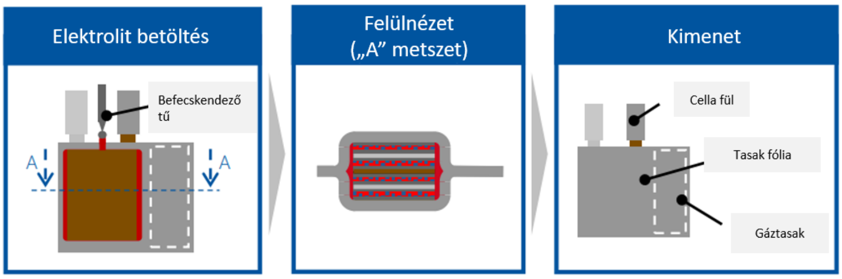
The cell body is then inserted into the deep-drawn pouch. There are two options for deep-drawing the pouch: during plastic forming, the cavity in the pouch is formed on both sides of the cell body, or only on one side.



15. Inserting the cell body into the bag and sealing it (two-part method)

Electrolyte filling

The electrolyte is then filled into the cell body. The injection location varies by product and type; in the figure below, for a unidirectional tab cell, the electrolyte is injected between the two tabs.



16. Electrolyte filling

The main parameters of the process are: **the geometry of the injection needle, the injection pressure (approx. 0.01 mbar) and the constant, continuous filling to ensure a homogeneous distribution of the electrolyte.**

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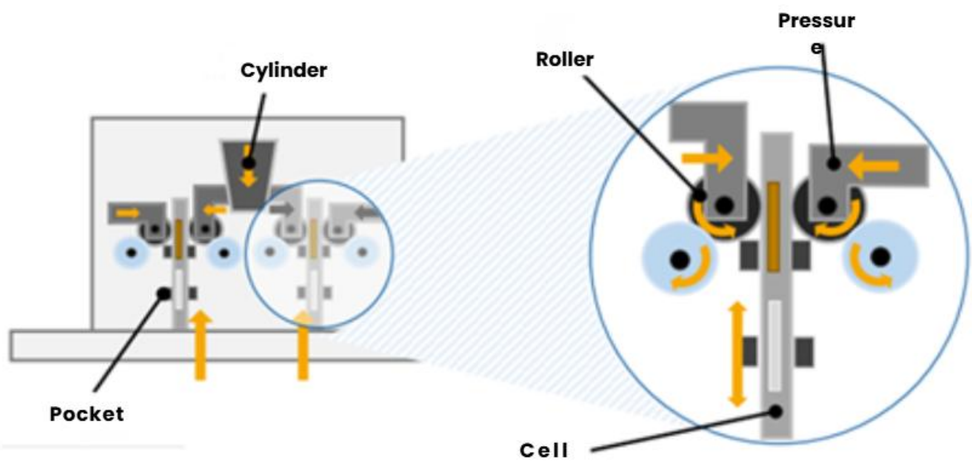
Formation

The third major process in battery cell manufacturing is cell molding. The semi-finished product from cell assembly is transformed into a finished product that can be delivered to the customer by the end of the molding process.

Rolling

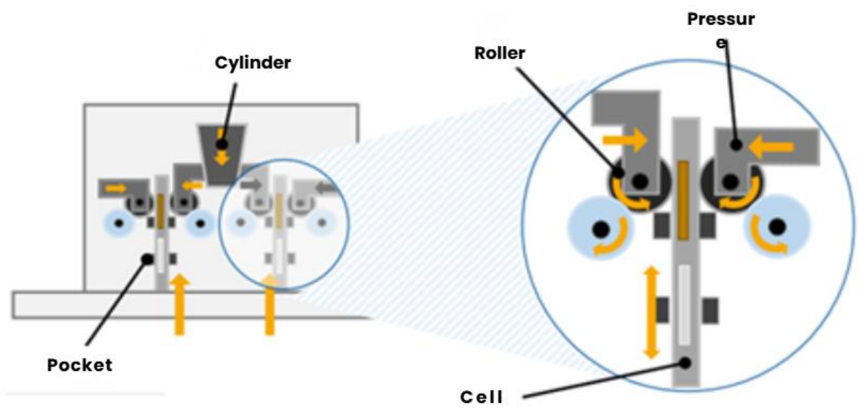
Sent from assembly after cell aging , it is transferred to the rolling station, with the aim of evenly distributing the electrolyte injected in advance (on the packaging) in the cell body using two rollers. The cell is placed in a pocket using a **gripper** , **and then two rollers controlled by two servomotors on both sides** roll the cell with a given pressure for a given cycle .



17. Rolling

Degassing

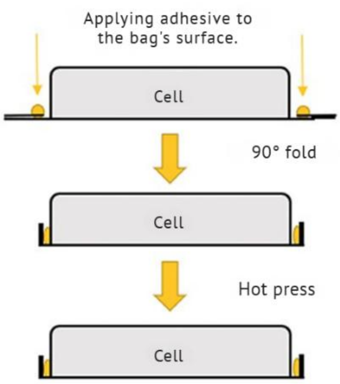
The pre-filling process takes place between rolling and degassing. A large amount of gas is released due to chemical reactions. During degassing, the cell is placed in a special vacuum chamber, in which a piercing knife pierces the gas bag, and two working cylinders on both sides of the cell compress the cell under vacuum with a given pressure. In this way, the released gas is sucked out, and the cell is welded under vacuum at the bottom of the gas bag and at the top of the cell body, using the method used in the packaging process.



18. Degassing

Folding

The final process that changes the mechanical dimensions of the cell is folding . In order to increase the previously mentioned insulation resistance , the side of the cell that was welded and then cut during degassing (in the case of models made with two-part bags, the bottom side as well) **is bent twice by the machine, once by 180⁰ and then by 90⁰** . Folding is achieved by a roller with a special profile that bends the welded part by 180⁰ , and then a press that glues/welds the **150-200⁰C** , molten **PP layers together** .



19. Steps for folding cell edges using adhesive

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Your checking questions

1. What are the main steps in the manufacturing process?
2. What battery cell formats do you know?
3. What are the steps in electrode production?
4. List the steps in cell assembly
5. List the steps of formatting.
6. What is slurry ?
7. What is a reel ?

Online test

1. **Which is not one of the main steps in the manufacturing process?**

   electrode production

   cell assembly

   formatting

   drive

2. **Which is a battery cell format?**

   cylindrical

   square

   pragmatic

   topozootic

3. **Which one does not belong to among the steps of electrode production?**

   Mixing

   Coating and Drying

   Vacuum drying

   Slitting

4. **What are the characteristic parameters of vacuum drying?**

   pressure (0.007–1000 mbar), drying time (12–30 hours), temperature (60–150^{0}C) pressure (0.07–1000 mbar), drying time (10–30 hours), temperature (70–150^{0}C)

pressure (0.7–1000 mbar), drying time (14–30 hours), temperature (80–150^{0}C)

pressure (7–1000 mbar), drying time (16–30 hours), temperature (90–150^{0}C)

5. **Which one is not one of the steps of formatting?**

    Rolling

    Slitting

    Degassing

    Folding

6. **What is the cutting tolerance ?**

    the length of the cut electrode sheet is approx. 200 μm and the width is approx. 100 μm

    The length and width of the cut electrode sheet are both approximately 200 μm.

    the length of the cut electrode sheet is approx. 100 μm and the width is approx. 200 μm

    The length and width of the cut electrode sheet are both approximately 100 μm.

7. **What is a reel ?**

    The wound rolls are cut lengthwise and are called reels .

    The wound rolls are cut in the shorter direction, these are called reels .

    The wound reels are cut lengthwise, which becomes the rolls.

    The wound reels are cut in the shorter direction, which will become the rolls.

Solutions: 1.D, 2. A , 3.C, 4.A, 5.B, 6.B, 7.A

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III. Chapter
Quality requirements for finished cells

The purpose of the lesson:

The student should learn about the quality requirements and testing methods for cells and battery packs, before and during their series production.

Requirements:

on prototypes before mass production of cells and batteries .

Know the tests performed during series production.

Concepts:

Aging

Drop voltage

Insulation resistance

BMS (Battery Management System) Battery Management System

SOC (State of charge) charge level

Parameter test

OCV (Open circuit voltage) no-load terminal voltage

Charging current

Capacity

Introduction

In the automotive industry, the cells called Li -ion do not refer to a single cell type, but have a collective name for several cell types.

These types all have to meet different electrical properties. These properties are included in the data sheet. (find electrical and other characteristics from data sheets)

Testing procedures

Aging : This process is used as the final step in cell manufacturing . This testing process checks whether a short circuit has occurred within the cell during manufacturing. The finished cells are half charged and left alone for 3 weeks, after which terminal voltage measurements are taken at intervals . The cell is considered to be compliant if the terminal voltage does not decrease by more than 5 mV over a period of one week. If the cell passes this test, it is given a unique identifier indicating the terminal voltage value after aging.

Drop Voltage measurement: This also allows a maximum voltage drop of 5mV/week, and is measured before the battery pack is assembled and compared to the value measured after aging.

is measured between the terminals and the packaging before installation in the battery pack . The minimum permissible value is 10 MΩ.

Post-assembly measurements.

Insulation resistance measurement : Insulation resistance is also measured after the battery is assembled, but this is done between the poles and the battery casing . Its lower limit is 10 MΩ.

BMS current consumption measurement: The BMS (Battery Management System) controls the battery and its various parameters . For example, temperature, charge, fan, current output, charge intake. Current is consumed in its operating modes. There are sleep modes, normal and active cooling modes. In the active cooling mode, current is measured at 50% and 100% cooling fan speed.

Measuring the voltage of each cell.

SOC – state of charge measurement. SOC stands for state of charge.

Leakage test: In this test, the casing is tested to ensure that the liquid chemicals in the battery cannot escape or evaporate.

Measurements before series production

Before a new battery type is mass-produced, the prototype must undergo many tests. These tests not only examine electrical parameters, but also the results of mechanical, simulated weather and environmental impacts.

These tests are performed in the operating modes listed in the table. These operating modes are standardized.

Operating modes	48V connector	Vehicle connector	BMS	Relay	Cooling fan	Load
1A	disconnected	disconnected	deactivated	open	deactivated	no
1B	connected	connected	deactivated	open	deactivated	no
2A	connected	connected	activated	open	variable	no
2B	connected	connected	activated	closed	variable	low
2C	connected	connected	activated	closed	variable	high

Parameter test: This test measures the electrical parameters. Battery open circuit voltage (OCV: open circuit voltage) cell open circuit voltage (OCV), breakdown strength, insulation resistance, internal resistance (DCIR) direct current internal. The battery passes the test if it meets the specifications .

High and low temperature storage: This test is performed when the battery meets specifications and there is no physical damage, which is checked visually. The test duration is 2x24 hours, during which the temperature changes every 12 hours between -30°C and 70°C.

Thermal shock test: This test simulates rapid temperature fluctuations . It is used to detect defects related to temperature changes, such as defects, tears, cracks that occur during faulty soldering, gluing, welding or sealing. The test is carried out according to DIN EN 60068-2-14. The temperature range is -30°C to 70°C. The storage time is 15 - 15 minutes after the battery under test has been heated up and then cooled down. This cycle must be performed 100 times. The test is passed if the device under test is working and the parameters meet its specifications after the test .

20. Thermal shock test

Stepped heat load test: In this test, the temperature is reduced in small 5°C steps to -30°C, then increased to +70°C and finally cooled back to room temperature. After the battery under test has reached the desired temperature, a parameter test is performed on it at each step. The test is successful if it meets the specifications at each temperature step .

Mechanical stress acceleration test: This test simulates the situation where the bottom of the car touches or gets stuck or a collision occurs. It checks that no cracks or tears occur on the battery in such cases. The test is carried out in accordance with DIN EN 60068-2-27 and in a position similar to the installed position . The test parameters are maximum acceleration of 500m/s ^{2} for a duration of 6ms, sinusoidal waveform, and stress in X, Y, Z directions, 10 times per direction. The test is successful if the device under test meets the continuously running parameter tests. Enough time must be allowed between periods for the tested piece to return to a vibration-free state.

Vibration test: This simulates the vibration resulting from normal operation. Its purpose is to induce defects resulting from material fatigue. The test is carried out with sinusoidal and broadband vibrations as specified in the DIN EN 60068-2-6 and DIN EN 60068-2-64 standards. The test duration is 8 hours in each direction, a total of 24 hours. It is carried out with a load current of less than 10 A , at room temperature, -30°C and 70°C, in a position similar to the installation position . The tested piece must continuously comply with the parameter test. Finally, the condition of the tested piece must be confirmed by visual inspection.

21. ***Vibration test***

Salt spray test: This test simulates coastal regions and winter road salting. The wet salty environment can cause short circuits, leakage currents and other faults. The test is designed to detect these. The test is carried out according to the IEC 60068-2-11 Ka standard. The test runs for 55 minutes in "2A" mode, which means that the BMS (battery management system) is connected to the 48 V system and the cooling is also on, but no specific load is connected to the battery. Then 5 minutes in "2C" mode, which means that a high load current is delivered compared to the previous state. One cycle consists of 8 hours of spraying and 4 hours of rest. The salt concentration is 5% and the test is carried out over 2 cycles. The test is successful if the tested piece meets the parameter test before, after and during.

*22. **Salt spray test***

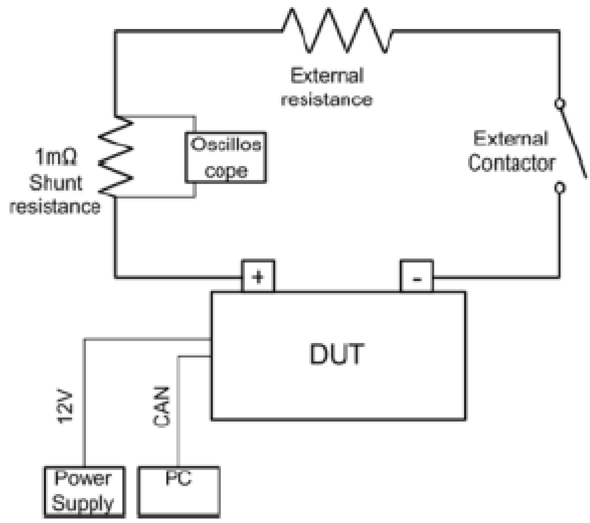
Water resistance test: The purpose of the test is to simulate rain and other wet weather conditions according to ISO 20653. The test is carried out for 1-1 minutes in modes "2A" and "2C" at a temperature of 23±5°C, a humidity of 25-75 %, a water flow rate of 0.6 l/min and a water pressure of 400kPa. The tested device passes the test if it meets the protection specified in the standard and passes the continuous parameter test. Finally, the condition of the devices must be confirmed by visual inspection.

23. ***Water resistance test***

Hot and cold test: The test simulates the effects of cyclically changing humid temperatures. Here we examine how well the battery is protected in hot and cold weather. The test is carried out in accordance with DIN EN 60068-2-64. During the test, our battery operates in "2A" mode, which is the operating mode of a car battery parked on the street. The test duration is 240 hours, which includes 10 cycles, and cooling only occurs in the first 5 cycles. During the test, the parameter test is continuously running , it must meet the requirements each time.

Burning test: The test examines the effects of an accident to see if the battery can withstand a fire without exploding. In this case, the device is exposed to a fuel flame. The test is based on ISO 12405-1. The battery is tested in storage mode with a half-charge. The test is recorded on video and the temperature data is saved continuously for 24 hours after the test. The test has 3 steps: 60s preheating, 60s direct flame and 60s indirect stress. The device passes the test if no explosion-like phenomena occur for 24 hours after the stress.

Short-circuit protection test: The test examines the operation of the overcurrent protection. The test is performed based on the block diagram below and ISO 12405-1.



24. Block diagram

The test is performed in the "2A" mode, i.e. in a car, but not delivering electrical power, at room temperature with a 100% charge level, with loads of 5mΩ, 20mΩ, 60mΩ. During the test, the battery must be working and the overcurrent protection must be activated.

Overcharge protection test: In this case, the overcharge must be interrupted and we check whether it occurs. The test is carried out according to ISO 12405-1, in “2C” mode, fully charged and with a charging current of 1C. The charging current of 1C means that if a battery is 10 Ah, it is charged with 10 A. The measurement is carried out at room temperature and the cell voltage, battery voltage, charging current and the temperature data are read from the BMS.

Self-check questions

1. What is the purpose of aging, and under what conditions does the cell pass this test?
2. Increase cell life; voltage drop should not exceed 50 mV in a week .
3. Detection of manufacturing defects, such as internal short circuits; voltage drop should not exceed 5 mV in one week.
4. the cell capacity ; voltage drop should not exceed 10 mV in a week.
5. Fully charge the cell; voltage drop should not exceed 1 mV within a week.

Online test

1. What is the minimum allowable insulation resistance value before and after battery assembly?

1 MΩ

5 MΩ

10 MΩ

50 MΩ

2. In what temperature range is the thermal shock test performed and how many cycles does the test consist of?

-10 °C to +50 °C, 50 cycles

-30 °C to +70 °C, 100 cycles

-20 °C to +60 °C, 75 cycles

-40 °C to +80 °C, 10 cycles

3. What is the purpose of the salt spray test and which standard specifies the test procedure?

Checking the electrical insulation of a battery; DIN EN 60068-2-27.

Testing for the effects of corrosive environments; IEC 60068-2-11.

Testing the effects of mechanical vibrations; ISO 20653.

Testing the effects of temperature fluctuations; DIN EN 60068-2-14.

4. **What does 1C charging current mean and in which test is this current value used?**

   the battery's nominal capacity , overcharge protection test.

   Maximum allowable current, short circuit protection test.

   The charge intake limit, parameter test.

   Internal resistance measurement current, vibration test.

Solutions: 1 b; 2 c; 3 b; 4 b; 5 a

Online test

https://forms.gle/az14TR4MnrnjNwsu6

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DIN EN 60068-2-27

DIN EN 60068-2-6

DIN EN 60068-2-64

IEC 60068-2-11 Ka

ISO 20653

ISO 12405-1

IV. Chapter
Quality standards and auditing requirements in cell manufacturing

Lesson Objective

The aim of the lesson is to learn about the dangers of lithium batteries, the safety risks of manufacturing, testing and shipping, and the basic requirements to be followed during the procedures.

Requirements

Risks associated with lithium-ion and lithium-polymer batteries

Test types according to the UN Manual of Tests and Criteria

Additional international safety tests

SAE J 2929: Battery System Safety Standard for Lithium-Based Rechargeable Cells in Electric and Hybrid Vehicle Powertrains.

SAE J 2464: Safety and load testing of rechargeable energy storage systems for electric and hybrid electric vehicles.

UL 1642: Lithium batteries.

UL 2580: Batteries for use in electric vehicles.

Concepts

Rechargeable battery:

An energy storage device that is rechargeable and reusable. The most common rechargeable batteries include lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and lithium-ion (Li -ion) batteries.

Cell

A single encapsulated electrochemical unit consisting of a positive and a negative electrode, providing a voltage difference between these terminals

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Lithium Cells and Batteries Test Procedures

UN Test and Criteria Manual

This manual is considered to be one of the most important shipping safety testing standards. All manufacturers that ship lithium batteries must adhere to it.

Lithium batteries fall under UN Category 9 because they are subject to thermal and electrical instability when exposed to uncontrolled environmental conditions or improper handling during transportation.

Risks associated with lithium batteries

- electrolyte leakage,
- heat production,
- gas formation,
- the fire and the explosion,
- electrical hazards (short circuit, high voltage)
- mechanical hazards (vibration, air pressure, impact and deformation).

Specific test procedures for lithium cells and batteries are summarized in chart 1. In general, the test process depends on whether a given device is a cell or a battery.

- All cell types must pass tests T.1–T.6 and T.8.
- All non-rechargeable battery types, including those made from previously tested cells, must meet tests T.1 to T.5.
- All rechargeable battery types, including those made from previously tested cells, must pass tests T.1 to T.5 and T.7.
- Single-cell, rechargeable batteries that have overcharge protection must also pass the T.7 test.
- Cells supplied as part of a battery and not supplied separately are only required to pass tests T.6 and T.8.

- Cells supplied separately must pass tests T.1 to T.6 and T.8.

T.1 – Altitude simulation: Cell/battery storage at 11.6 kPa pressure for at least 6 hours at room temperature (20±5°C)

T.2 – Temperature cycling: Rapid temperature change between high (75±2°C) and low (-40±2°C) storage temperatures, with a minimum of 6 hours of storage at each temperature.

T.3 – Vibration test: Sine wave, logarithmic vibrations from 7 Hz (1 gn peak) to 200 Hz (8 gn peak), 12 cycles in three mutually perpendicular positions

T.4 – Shock test: Half-sine shock with 150 gn peak load, 6 ms duration; 3 shocks in positive and negative directions along each axis. Total of 18 shocks

T.5 – External short circuit: Short circuit with an external resistance of 0.1 Ω at 55 ± 2°C for 1 hour

T.6 – Impact test: A 15.8 mm diameter rod is placed in the center of the sample cell and a 9.1 kg weight is dropped onto it from a height of 61 ± 2.5 cm

T.7 – Overcharge test: 24 hours of overcharging with twice the recommended charging current and minimum test voltage.

T.8 – Forced discharge: The cell is forced to discharge using a 12 V DC power source at the maximum discharge current specified by the manufacturer.

Additional international safety tests for lithium batteries

The International Electrotechnical Commission (IEC) standards are widely used as a reference for different countries and regions to develop their own battery testing standards.

IEC 62281: Standard for the safety of primary and secondary lithium cells and batteries during transportation.

The Institute of Electrical and Electronics Engineers (IEEE) has developed safety standards for lithium batteries.

IEEE 1625: Rechargeable batteries for multi-cell mobile computing devices.

IEEE 1725: Rechargeable batteries for mobile phones.

The Society of Automotive Engineers (SAE):

Standards for electric vehicle (EV) batteries.

SAE J 2929: Battery system safety standard for lithium-based rechargeable cells in the powertrain of electric and hybrid vehicles.

SAE J 2464: Safety and load testing of rechargeable energy storage systems for electric and hybrid electric vehicles.

The Underwriters Laboratories (UL):

Safety standards for batteries that include more stringent testing than usual. In addition, UL also offers battery safety certification for shipping batteries between different countries.

UL 1642: Lithium batteries.

UL 2580: Batteries used in electric vehicles.

UL 2271: Batteries for light electric vehicles.

Self-check questions

1. What are the risks of Lithium batteries?
2. What is T.2?
3. Which one is Forced Discharge?
4. List international safety tests!
5. What does UL stand for?

Online test

1. **Choose which is NOT a danger associated with lithium batteries?**
    a. electrolyte leakage,
    b. heat production,
    c. gas formation,
    d. poisoning
    e. the fire and the explosion,
    f. electrical hazards (short circuit, high voltage)
    g. mechanical hazards (vibration, air pressure, impact and deformation).
    h. acidic or alkaline chemistry
2. **What does the UN Test and Criteria Manual regulate?**
    a. A safety testing standard that all manufacturers that supply lithium batteries must adhere to.
    b. A testing standard that all manufacturers must adhere to
    c. A safety testing standard that all manufacturers that produce lithium batteries must adhere to.
3. **What tests are NOT included in the specific testing procedures for lithium cells and batteries?**
    a. Altitude simulation
    b. Density measurement

   c. Temperature cycle
   d. Vibration test
   e. Impact test
   f. External short circuit
   g. Crash test
   h. Overcharge test
   i. Forced discharge

4. **What did IEEE develop?**
   a. safety standards for lithium batteries.
   b. Safety and load testing of rechargeable energy storage systems for electric and hybrid electric vehicles.
   c. Electrical systems of self-balancing scooters
5. **What standards does SAE include?**
   a. Standards for electric vehicle (EV) batteries.
   b. safety standard for lithium-based rechargeable cells and safety and load testing of rechargeable energy storage systems.

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V. Chapter
International regulations for the safe transport of lithium batteries.

Lesson Objective

Understanding and applying international regulations for the safe packaging and transportation of lithium cells/batteries .

Requirements

- ✓ *Know the UN Model Regulations on the transport of lithium cells/batteries.*
- ✓ *for the safe transport of Lithium cells/batteries by air.*
- ✓ *for the Safe Surface Transport of Lithium Cells/Batteries (Road/Rail/Sea).*

Concepts

UN Model Regulatory System, International Civil Aviation Organization (ICAO), International Air Transport Association (IATA), International Maritime Organization (IMO), European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), Regulations concerning International Carriage by Rail (RID).

Introduction

The UN Model Regulations serve as global guidelines for all aspects of the transport of dangerous goods. These regulations are developed with the involvement of various organizations responsible for ensuring the safe and reliable international transport of goods.

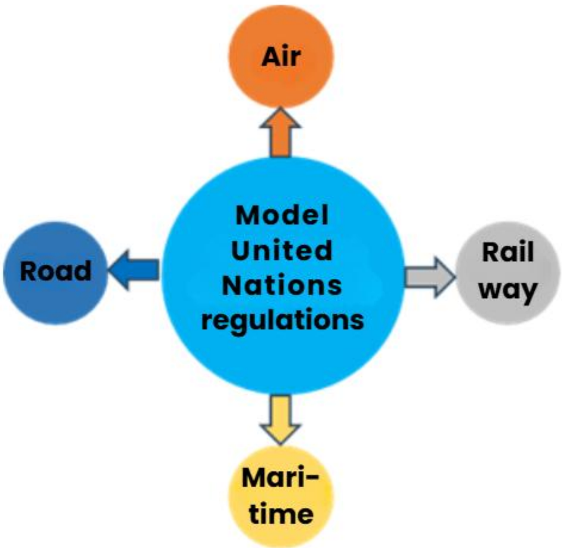
Several international regulatory authorities oversee the transportation of lithium batteries by various modes (air, sea, road and rail):

- United Nations (UN): Provides model regulations that form the basis for international and national regulations.
- International Civil Aviation Organization (ICAO): Develops rules for air transport.
- International Air Transport Association (IATA): Applies ICAO rules, supplemented with additional requirements.
- International Maritime Organization (IMO): Regulates the transport of dangerous goods used in maritime transport.
- European Agreement concerning the International Transportation of Dangerous Goods by Road (ADR): Contains the rules for European road transport.
- Regulations concerning International Carriage by Rail (RID): Regulates European rail transport.

These organizations set detailed standards for packaging, labeling, documentation, and handling of lithium batteries for safe transportation.

UN Model Regulations

The UN Model Regulations were developed by the ECOSOC Committee of Experts on the Transport of Dangerous Goods in the interests of safety, uniformity and environmental protection. The 19th edition is published by the UNECE Secretariat, providing a uniform basis for air, road, rail and maritime transport. (Figure 1)



25. the UN Model Regulations based on multiple modes of transport

Lithium batteries are identified by four-digit UN numbers. The main categories are :

- **UN 3090** – Lithium metal batteries
- **UN 3091** – Lithium metal batteries packed in or with equipment
- **UN 3480** – Lithium-ion batteries
- **UN 3481** – Lithium-ion batteries packed in or with equipment

Lithium batteries are classified as hazard class 9. Main risks: flammable gas formation, internal short circuit (dendrite formation), thermal runaway, oxidation of organic solvents. An additional risk for lithium-ion batteries is the instability of the SEI layer at high temperatures. All batteries must have ventilation, short circuit and reverse current protection, and a safe design .

International regulations for air transport

Air transport is regulated by two organizations:

- **ICAO** – Technical Instructions (TI)
- **IATA** – Dangerous Goods Regulations (DGR), based on ICAO TI

Only lithium batteries that meet UN testing and safety requirements may be transported. Prototypes or small series may be transported by cargo aircraft with regulatory approval. Waste and defective batteries are prohibited from being transported by air, except with approval.

Main specifications:

- max . 30% charge level
- prohibited from being transported on passenger aircraft
- a package/shipment, to be stored separately
- All shipments must be accompanied by a special label and shipping documentation.

Special labels: a) Lithium battery management label (" Lithium Battery Handling "), b) Cargo aircraft only label (" Cargo Aircraft Only "), c) Class 9 hazard warning label

26. Air transport

Delivery conditions.

For lithium metal cells/batteries:

Packing instructions:	PI968-Section IA
Watt-hour value (E):	Wcel > 1 g or Wbat > 2 g:
Maximum net quantity per package:	CAO: 35 kg, PAX: not allowed
Quantity of cells or batteries in the package:	no limit
Wrapping:	I. Lithium metal cells and batteries must be placed in an inner packaging that completely encloses the cell or battery; the cells and batteries must be protected against short circuits (applies only to batteries or batteries packed with the device). II. The device must be secured within the outer packaging and packaged in a way that prevents accidental activation. III. UN approved packaging required: Packing Group II (PG II).
Labeling:	
Shipping documentation:	Shipper's declaration for dangerous goods: UN 3090 LITHIUM METAL BATTERIES, 9, II

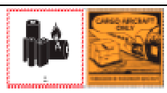
For lithium-ion cells/batteries:

Packaging instructions	UN 3480-PI965			
	PI965-Section II			PI965-Section IB
Li -ion cells/batteries Watt-hour rating (E)	This $_{goal}$ ≤ 2,7 Wh	$E_{cel} > 2.7$ Wh and $E_{bat} \leq 20$ Wh	$E_{cel} > 2.7$ Wh and $E_{bat} \leq 100$ Wh	This $_{goal}$ ≤ 20 Wh E ≤ 100 Wh
Quantity of cells or batteries in the package	no limit	$N_{goal} \leq 8$	$N_{bat} \leq 8$	$N_{bat} > 2$ or $N_{cells} > 8$
Maximum net quantity per package	CAO: 2.5 kg PAX: not allowed	CAO: N/ A PAX: not allowed	CAO: N/ A PAX: not allowed	CAO: 10 kg PAX: not allowed

Packaging: I. Lithium -ion cells and batteries must be placed in an inner packaging that completely encloses the cell or battery; the cells and batteries must be protected against short circuits (applies only to batteries or batteries packaged with the device).

II. The device must be secured within the outer packaging and packaged in a way that prevents accidental activation.

III. UN approved packaging required: Packing Group II (PG II).

Labeling		
Shipping documentation	General warning	"Shipper's declaration for dangerous goods"

The rules aim to minimise heat and fire risks, particularly in aerial environments.

International regulations for surface transport (road/rail/sea)

The UNECE ITC oversees the main conventions:

- **ADR** – Road transport of dangerous goods

- **RID** – rail transport
- **IMDG Code** – maritime transport

In all cases, UN testing, ventilation, short-circuit protection and manufacturing regulations apply.

Packaging instructions

General requirements (ADR 4.1.1 and 4.1.3)

Permitted packaging types:

- Barrels: 1A2, 1B2, 1N2, 1H2, 1D, 1G
- Boxes: 4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G, 4H1, 4H2
- Cans: 3A2, 3B2, 3H2

P903 – Intact cells/batteries

- Protection against displacement and damage within the packaging
- Compliance with general ADR provisions

P908 – Damaged/defective cells/batteries

- Separate inner packaging + leak-proof outer packaging
- Non-flammable, non-conductive, heat-resistant inner material
- Ventilation, vibration and shock protection
- Adding inert absorbent material
- Over 30 kg only 1 pc/package allowed

P909 – For disposal/ recycling

- Metal packaging with non-conductive lining
- Small cells/batteries (≤20 Wh or ≤100 Wh) max . 30 kg/package
- Equipment in strong outer packaging

Shipping conditions: Standalone Lithium cells/batteries

Packaging instructions	ADR/RID/IMDG Special Provisions (SP)188
Lithium content (W) or nominal watt-hour value (E)	Li -metal cells/batteries $W_{cel} \leq 1$ g; $W_{bat} \leq 2$ g Li -ion cells/batteries $E_{cel} \leq 20$ Wh; $E_{bat} \leq 100$ Wh
Quantity of cells or batteries in the package	No limit
Weight limit	The gross weight of the package is 30 kg.
Marking or labeling	I. The shipment contains "lithium metal" or "lithium-ion" batteries; II. The delivery is made according to SP188; III. The package must be handled with care, there is a risk of flammability if damaged; IV. If the package is damaged, special procedures must be followed, including inspection and repackaging . A. For more information, call *** (phone number).
Sea freight container marking	No requirement
Shipping documentation	General warning statement. (the document must contain the same information as the marking content above)
Note: Ecel represents watt -hours per cell ; Ebat represents watt -hours per battery ; Note 2: Wcel represents lithium weight per cell ; Wbat represents lithium weight per battery .	

The number and diversity of regulations make transportation complex and costly. There is a need to standardize and test the requirements. Finally, there is a need to regulate the infrastructure requirements for storing battery shipments at shipping terminals.

Self-check questions

1. What is the main purpose of the UN Model Regulations for the transport of lithium batteries?
2. List the four UN numbers that represent the main categories of lithium batteries.
3. What are the main risks involved in transporting lithium batteries?
4. What is the difference between the role of ICAO and IATA in regulating air transport?
5. Why are the charge levels of lithium-ion batteries limited for air transport?
6. What special labels should be used when transporting lithium batteries by air?
7. What is the difference between ADR, RID and IMDG Code regulations?
8. What special packaging requirements apply to the transport of damaged batteries?
9. What does SP188 mean in surface transport?
10. What problems do the differences between different regulations cause in international transport?

Online test

1. Which organization prepares the UN Model Regulations?

A) ICAO

B) ECOSOC Committee of Experts on Dangerous Goods C) IMOD) IATA

2. Which UN number applies to lithium-ion batteries, whether in or packaged with equipment?

A) UN 3480

B) UN 3481C) UN 3090D) UN 3091

3. Which hazard class do lithium batteries belong to?

A) 3

B) 7 C) 9 D) 5

4. Which organization regulates maritime transport?

A) IMO

B) ICAO

C) IATA

D) ADR

5. What is the maximum charge level allowed for lithium-ion batteries when transported by air?

A) 50%

B) 80% C) 30% D) 100%

6. Which label is NOT mandatory for air transport?

A) " Lithium" Battery Handling "

B) " Cargo Aircraft Only "

C) Class 9 hazard symbol D) " Fragile – Handle with care "

7. Which regulations apply to European rail transport?

A) ADR

B) RIDC) IMDG Code

D) ICAO TI

8. What is the main purpose of packing instruction P908?

A) Safe transportation of damaged batteries

B) Air transportation of new batteries C) Sea transport documentation D) Labeling requirements

9. Which condition is true for SP188?

A) Applies to air transport only

B) Specifies packaging type and weight limits for small batteries

C) Applies to recycled batteries only D) Does not include watt-hour limits

10. What is the main goal of unifying various international rules?

A) Increase delivery time

B) Reduce costs and complexity

C) Reduce battery size

D) Increase charging speed

Correct answers: 1.B, 2.B, 3.C, 4. A , 5.C, 6.D, 7.B, 8.A, 9.B, 10.B.

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VI. Chapter
Testing tools and aids in quality control

The purpose of the lesson:

The student should become familiar with the tools used to test cells and batteries.

Requirements:

Know the different instruments that can be used.

Know which instrument can be used for which measurement.

Know the operating principle of the instruments.

Concepts:

Internal resistance

Voltage measurement

Current measurement

Resistance measurement

Induction

Hall effect

Norton theorem

Thévenin's theorem

DCIR (Direct Current Internal Resistance) DC internal resistance

Multimeter

The multimeter is one of the most versatile and most used tools in electronic measurement technology. The instrument can basically measure DC and AC voltage, DC and AC current, resistance, and also has an open circuit and diode tester . In addition to these, the other measurement functions that a specific type can do are just extra.

Voltage measurement : When measuring voltage, the multimeter is connected in parallel to the terminals of the device to be measured. This means that if we want to measure the voltage of a battery, we connect the measuring tips to the terminals of the battery, if there is a load connected to it, if there is not.

Current measurement : We do not use a multimeter to measure current with batteries because not only HV batteries, but also batteries found in regular gasoline cars can emit more current than a field multimeter can handle. In other low-current electronic applications, we can measure current by breaking the circuit and connecting the instrument in series with it.

Resistance measurement : Resistance is measured within the specified measurement limits by applying voltage from its own element to the measuring tips and measuring the current that starts due to this voltage, "calculating" the resistance value of the component. This is why it is FORBIDDEN to measure resistance in a circuit under voltage or on a component carrying current, because not only can the measuring instrument be damaged, but it can also be life-threatening. During the measurement, we connect the measuring tips to the two terminals of the component that is free of voltage and measure resistance in this way. It is important that we get the most accurate result when the component is not in the circuit and we touch a maximum of one measuring tip.

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27. mΩ meter

This instrument is used to measure the resistance of wires and connections. It is worth using in places where we are interested in the resistance of electrical, galvanic connections, since a 10-100mΩ increase in resistance results in heating and voltage drop at high currents of 100-1000 A. We cannot measure these resistance values with a multimeter because its internal resistance is around 10-20MΩ and such a small resistance value will be measured as 0Ω .

Insulation resistance meter

The multimeter is also not very useful when measuring insulation resistance, because the maximum measurable resistance is 20MΩ, which is much less than the resistance of insulating materials, the voltage emitted for measurement is also low and a high resistance causes unmeasurable current to flow. The insulation resistance meter is much larger, capable of measuring with a maximum test voltage of 1000 V and a maximum measurable resistance of 4 GΩ.

Clamp meter

A clamp meter is a measuring instrument that can measure current without breaking the circuit. We can usually measure between 1 and 2000 A. It is excellent for measuring the load current of a HV battery. This instrument can determine it by measuring the magnetic fields of the conductor through which the current flows. A traditional clamp meter cannot be used to measure direct current because it works on the principle of induction . Direct current can only be measured with a clamp meter that uses the Hall effect. The Hall effect is when a magnetic field deflects charges in a material and therefore a voltage difference is created between two points of a conductive or semiconductor material.

28. clamp meter

Internal resistance test

Internal resistance cannot be measured directly with a multimeter. If we measure the terminals of a battery with a multimeter in resistance measurement mode , we will find that it is damaged and we have not measured anything. The internal resistance of a battery can either be measured with a special instrument or indirectly determined based on the measured data.

When applying the indirect method, we can use Norton or Thévenin's theorem.

For using Norton's theorem, we will need a current measuring device and two high-power shunt resistors of different small resistances. This can also be a copper wire of appropriate thickness and length. We measure the currents flowing through the shunt resistors. We substitute the measured currents and resistance values into the following formula.

$$R_b = \frac{I_2 \cdot R_2 - I_1 \cdot R_1}{I_1 - I_2}$$

In the formula, R_1 is the value of the first resistor, R_2 is the value of the second resistor, I_1 is the current flowing through resistor R_1, and I_2 is the current flowing through resistor R_2. R_b is the desired internal resistance of the battery.

Using Thévenin's theorem , we have a much easier task, although usually the internal resistance of batteries is small and that of voltage meters is large. The internal resistance of batteries is below 1Ω, that of voltage meters is 10MΩ or the equivalent, so we are technically able to measure the open circuit voltage and the voltage across the load resistor with sufficient accuracy.

To measure, we need a voltage meter and a load resistor that can be compared with the expected internal resistance value. In this case, we measure the terminal voltage without load, and then with load. Using the results obtained, we can calculate the internal resistance.

$$R_b = R_t \cdot \frac{U_0 - U_t}{Ut}$$

Where U_0 is the no-load voltage (without load), U_t is the voltage across the load, R_t is the load resistance and R_b is the desired internal resistance.

DCIR measurement (Direct Current Internal Resistance means direct current internal resistance measurement. This measurement method uses the method using the mentioned Thévenin theorem, but it performs measurements automatically, so it can be considered a direct measurement. If we connect the instrument to the battery under test, it will tell us its internal resistance.

29. DCIR measurement

The measurements are made by changing loads and changing the measured current and voltage to determine the internal resistance of the device under test based on Ohm's law.

$$R = \frac{\Delta U}{\Delta I}$$

The definition of Capacity

We can measure the battery capacity indirectly during a discharge or charge cycle. If we discharge the battery from a fully charged state to the lowest allowed terminal voltage during discharge, the product of the discharge current and the elapsed time will be the capacity of the battery or a cell.

$$C = I \cdot t$$

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Self-check questions

1. List multimeters!
2. What are pliers for?
3. What is Thevenin's theorem?
4. What does DCIR stand for?
5. How do we determine capacity ?

Online test

1. **Why should you not use a multimeter in resistance measurement mode to measure internal resistance at the terminals of a battery?**
    a. Because the multimeter would measure too small voltage, it would not be possible to get an accurate result.
    b. During the measurement, the voltage is switched to the device being measured. During the measurement, there is another voltage source that can drive a dangerous current through the instrument.
    c. Because the battery automatically turns off the meter due to short circuit protection.
    d. Because the multimeter would be in the current measuring mode, and thus a short circuit would definitely occur.
2. **What can a mΩ meter be used effectively to test?**
    a. Testing circuit connections
    b. Investigation of the path of large currents
    c. For measuring insulation resistance
    d. For measuring 0.5 watt resistors
3. **What can an insulation resistance meter be used effectively to test?**
    a. Testing circuit connections
    b. Investigation of the path of large currents

   c. For measuring insulation resistance
   d. For measuring 0.5 watt resistors

4. **What physical phenomenon does a clamp meter use which can also measure direct current?**
   a. Ohm's law
   b. Lorentz force
   c. Hall effect
   d. Planck constant
5. **What property of the battery is measured during DCIR measurement?**
   a. Open circuit terminal voltage
   b. Internal resistance
   c. Short circuit current
   d. Load resistance value

Solutions: 1 b ;2 ab; 3 c; 4 c; 5 b

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VII. Chapter
Common errors and their causes in cell production

Description of problems arising during the manufacturing process
(electrode manufacturing – cell assembly – molding)
and exploring their causes

The purpose of the lesson:

To demonstrate the consequences of a faulty assembly process and what those consequences may be .

Requirements:

- ☑ *Understand the steps of electrode preparation, cell assembly, and format shaping.*
- ☑ *know what typical errors occur at different stages of cell production.*
- ☑ *know what consequences indicate typical mistakes.*

Concepts:

material defects ,

coating defects ,

assembly errors,

electrolyte charging errors,

sealing and welding defects,

formatting errors.

Expectations and difficulties

The manufacturing process of lithium-ion batteries has undergone significant development in recent years. The process has been developed in laboratory and pilot conditions with the help of thorough research, which minimize production costs and improve the quality of the cells. However, it is still a great challenge to implement the development in raw materials, manufacturing processes and cell design from laboratory conditions to production, as it involves a complex task consisting of many steps. This requires a thorough knowledge of the process, their components and their interactions with each other.

For successful electric vehicles that minimize CO2 and NOx emissions, battery performance and their cost are key features. Key lithium-ion cell design criteria include high energy and power density, high cyclic stability, high safety and low cost. Maximum energy density and fast chargeability are essential factors in electrode design, but other important considerations include life span of battery(>8 years), temperature range and safety. In comparison, the main considerations for non-electric vehicle batteries, such as industrial stationary batteries, are very high cyclic stability and in some cases high energy density. Furthermore , batteries manufactured for such industrial applications must be flexible in terms of scalability, while lithium-ion batteries have a fixed composition and layout, optimized to minimize space and weight. Due to different requirements, battery modules and packs for electric vehicles and non-electric vehicles differ in both design and configuration.

The development phase of a new battery begins with cell chemistry experiments in the laboratory, where electrodes and small half- or single-layer cells are fabricated using simplified, discontinuous, laboratory equipment. The main goal is to investigate the properties of the raw materials and compositions. Such test cells and their associated electrodes have unoptimized internal structures and often low areal capacities (Ahm^{-2}), making them less suitable for large-scale, application-oriented research, which often faces challenges such as the effect of electrode mass loading on cell and pack performance, fast charging, or discharge performance. Such research is performed on small single- or multi-layer cells. The electrodes of these experimental cells undergo coating and pressing, and are then stacked in a semi-automatic mode. With the help of such tests, the effect of the material and electrode composition on cell performance can be determined. However, the effects of cell composition, production equipment or production parameters on cell performance and production costs are more appropriate to be carried out under conditions similar to real production. This means that the cells used for such tests should be manufactured on at least semi-automatic, but preferably fully automatic, experimental equipment, and these cells should be multilayered, with electrode coatings on both sides.

Ideally , the geometric parameters of the cells (surface area and thickness) match those required for the application to be optimized , providing the basis for the transition to industrial-scale production. Such a transition requires multidisciplinary research and development by engineers, chemists, and physicists.

There are many aspects to consider and a thorough understanding of the components is necessary for efficient production. The raw material, composition and production parameters all affect the physical properties (electrode microstructure, moisture content, etc.) and geometric qualities (electrode stacking accuracy) of the components.

These aspects must be taken into account at all levels, from the electrode, through the cell to the entire battery pack, in order to optimize the electrochemical properties of the final product. Furthermore, systems thinking and understanding, and knowledge of the effects of processes on each other, enable faster and more waste-free production, better quality, and reduced overall costs.

automotive Li -ion battery manufacturing processes

Since 1990, high-performance production processes for small lithium-ion batteries (typical for consumer electronics) have been in place, which have now established the know-how needed to manufacture larger cells (> 20 Ah) for electric vehicles. However, the challenge of producing more cost-effective and higher-quality batteries remains.

In many applications, cells are connected in series or parallel to form a module, which is then equipped with various sockets and voltage, current and temperature control electronics. The modules are then connected in parallel using busbars to achieve the desired voltage pack. The final battery pack also requires a cooling system and casing, as well as a battery monitoring system. Figure 1 illustrates the sequential processes during battery manufacturing.

Common mistakes in cell manufacturing

The production of lithium-ion cells is a highly precise and tightly controlled process. Even microscopic impurities or small geometric deviations can have a significant impact on the safety, capacity and lifespan of the final product. Defects can occur at any stage of production: from raw material preparation, through electrode production and assembly, to final shaping and testing.

Main error categories

Material defects

These defects arise from quality problems with raw materials or improper handling conditions.

Errors :

- *Active material impurities* : Inclusion of metal particles (iron, copper, aluminum) in the electrode material → risk of internal short circuit.
- *Presence of moisture* : Lithium compounds react with water , causing gas formation and loss of capacity.
- *Grain size distribution defects* : Uneven charge release, increased internal resistance.
- *Contamination* : The presence of foreign matter on the surface of the electrodes can reduce performance and increase self-discharge.
- *Poor quality electrolyte* : The composition and quality of the electrolyte solution affects the performance and lifespan of the battery.

Consequences:

- capacity reduction,
- short circuit,
- significant shortening of lifespan-

Coating defects (during electrode production)

The uniformity of the electrode coating is crucial.

Errors:

- *Inconsistent coating thickness* : The coating on the electrodes is not of uniform thickness, which can lead to capacity loss and uneven performance.
- *Excessive coating thickness* : High internal resistance, slower charging.
- *Holes or lack of coating* : Decrease in active surface area → lower energy density.
- *Poor electrode adhesion* : The active material does not adhere properly to the electrode surface, which can lead to reduced battery life.

Reasons:

- Poorly calibrated coating equipment ,
- incorrect setting of paste viscosity,
- uneven drying process.

Assembly errors

The assembly of electrodes, separators and current collectors is a critical point.

Errors:

- *Wrinkle or crease in the separator* → local short circuit.
- *Poor fit : The* active surfaces of the anode and cathode do not overlap properly.
- *Separator damage* : Mechanical tear, puncture.
- *Uneven or damaged membrane* : Defects in the membrane can cause a short circuit in the cell.
- *Poor porosity* : Lack of proper porosity in the membrane affects ion flow and capacitance .

Reasons:

- inaccurate positioning system,
- too fast production speed,
- cutting without managing material stresses.

Electrolyte charging errors

The exact amount of liquid electrolyte is vital.

Errors:

- Too little electrolyte: Poor ion conduction, reduced capacity .
- Too much electrolyte: Pressure increase, risk of leakage.
- Air bubbles: Local conduction problems .

Reasons:

- inaccurate dispenser,

- improper vacuuming ,
- short suction time.

Sealing and welding defects

Sealing the cell housing is crucial for safety and longevity.

Errors:

- *Incomplete sealing* → moisture penetration.
- *Overheated welding points* → material damage.
- *Bad welding position* → weakening of electrical contact.
- *Poor assembly* : Poor assembly of the cell can cause mechanical problems and short circuits.
- *Sealing defects* : Defects in seals can lead to electrolyte leakage and cell failure.

Reasons:

- calibration errors of welding machines,
- operator errors,
- material quality fluctuation.

Formatting errors (first charge cycle)

stable SEI layer forms on the anode surface.

Errors:

- Incorrect charging profile → unstable SEI → rapid capacity loss.
- Too high current: Heat generation, gas formation.
- Too low temperature: incomplete formation of SEI layer.

Other errors

Self-discharge: The cell may discharge involuntarily due to internal faults.

Temperature fluctuations: Extreme temperatures negatively affect battery performance.

- to ensure battery reliability and safety . Quality control procedures such as electrode coating thickness checks, leak tests, and cycle tests help identify defects and prevent future problems.

Impact of defects on cell performance and safety

Error type	Impact on performance	Security risk
Material defect	Decreasing capacity , shorter cycle life	High (internal) short circuit)
Coating defect	Uneven performance , low energy density	Medium
Assembly fault	Short circuit , local warming	High
Electrolyte fault	Slow charge / discharge , capacity loss	Medium
Sealing fault	Moisture caused cell degradation	Medium-high
Formatting fault	Fast aging , unstable operation	Medium

Self-check questions

1. What material defects do you know?
2. List the causes of coating defects!
3. What assembly errors can occur?
4. What causes electrolyte charging errors?
5. What are the consequences of sealing and welding errors?
6. What kind of layer is formed during molding?

Online test

1. **What could be the reason: gas formation and capacity loss?**
   A. material defects
   B. coating defects
   C. assembly errors
   D. electrolyte refill errors
2. **What could be the reason: local management problems?**
   A. material defects
   B. coating defects
   C. assembly errors
   D. electrolyte refill errors
3. **What could be the reason: mechanical tear, puncture?**
   A. material defects
   B. coating defects
   C. assembly errors
   D. electrolyte refill errors
4. **What could be the reason: overheated welding points?**
   A. material defects
   B. sealing and welding defects

C. formatting errors

D. coating defects

5. What could be the reason: internal short circuit?

A. material defects

B. coating defects

C. assembly errors

D. formatting errors

6. What could be the reason: Too high current: heat generation, gas formation?

A. assembly errors

B. electrolyte refill errors

C. sealing and welding defects

D. formatting errors

Solutions: 1. A , 2.D, 3.C, 4.B, 5.A, 6.D,

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VIII. List of figures