BATPOWER
Preparation of the VET sector on battery energy transition

BatPower: Preparation of the VET sector on battery energy transition

2024-1-SK01-KA220-VET-000256192

WP3/A3.3

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Module 1– Introduction

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 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 is a 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,

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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 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 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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

(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 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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

plugging it in to a power source (the electrical grid via a charger) rather than filling up at a gas station.

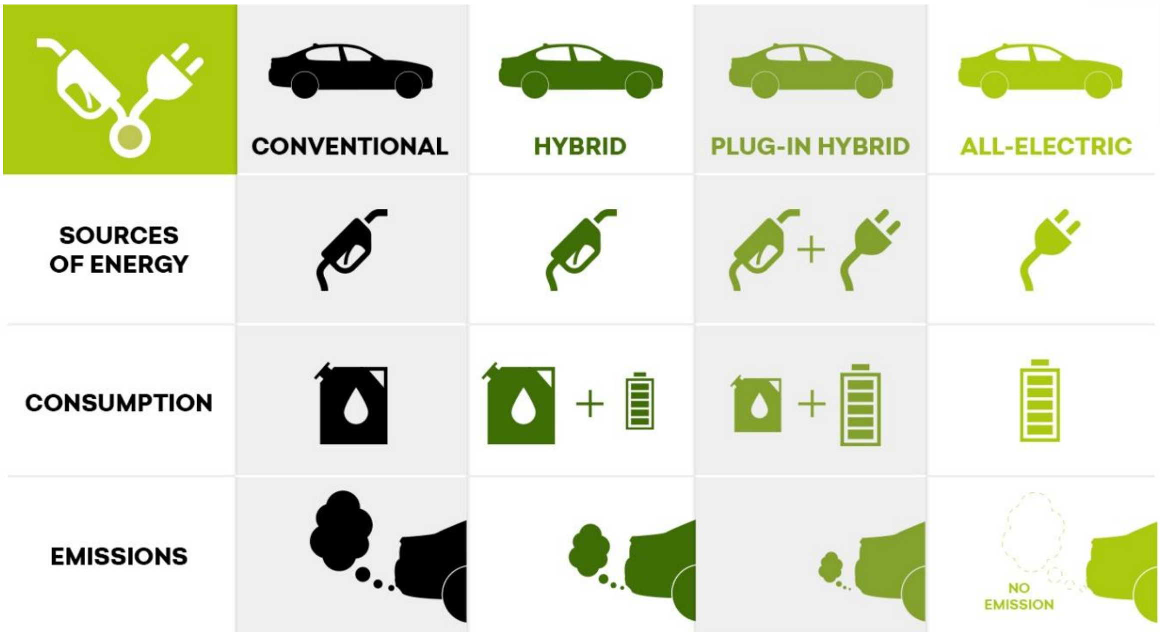


Figure 1 Types of vechicles

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.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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:

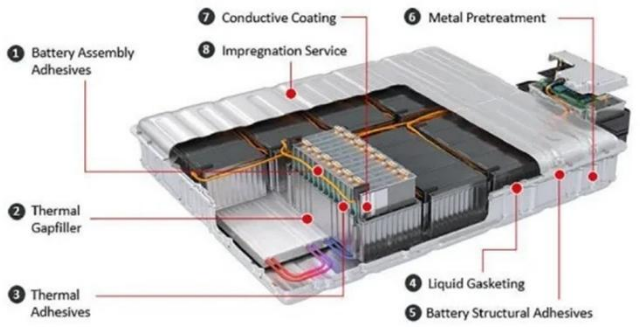


Figure 2 Lithium-Ion Battery Pack

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 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.

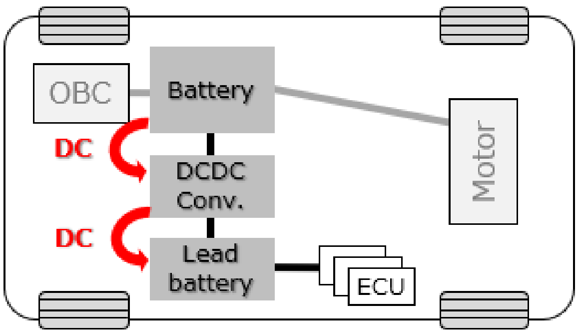


Figure 3 DC/DC converter work in EV

Electric Traction Motor 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,

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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) 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 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.


Figure 4 EV Motor Controller

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.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.


Figure 5 EV inventer

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 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.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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.

Figure 6 EV Charging station

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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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.

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

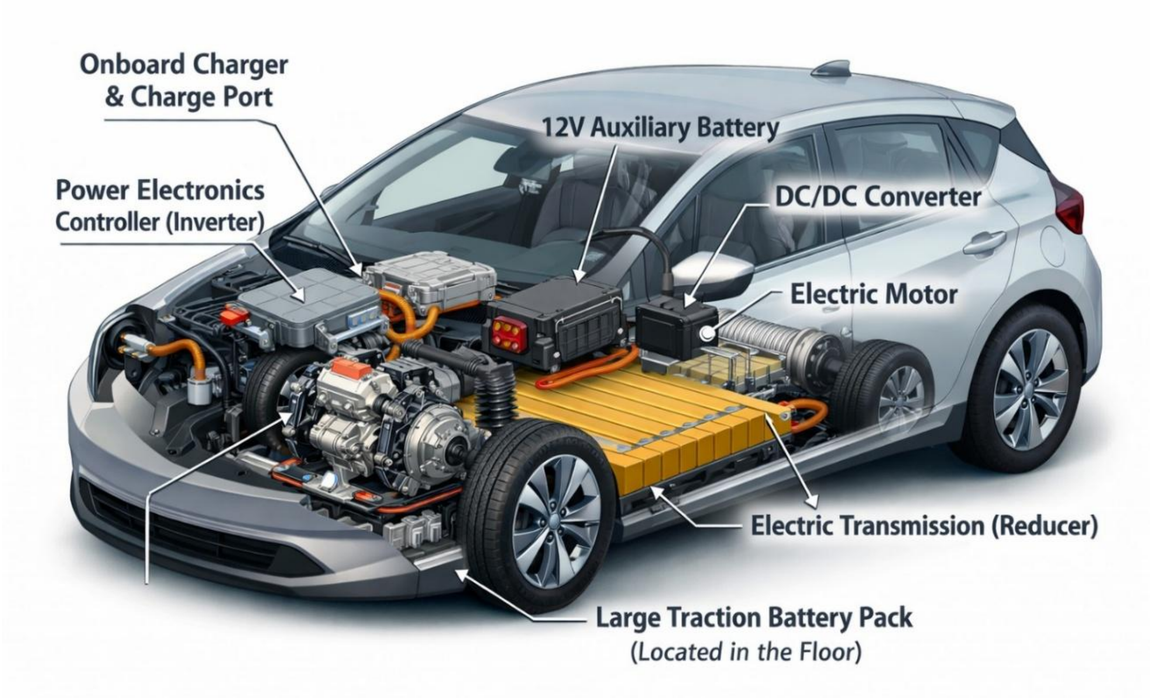


Figure 7 Diagram of a battery electric car

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,

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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).

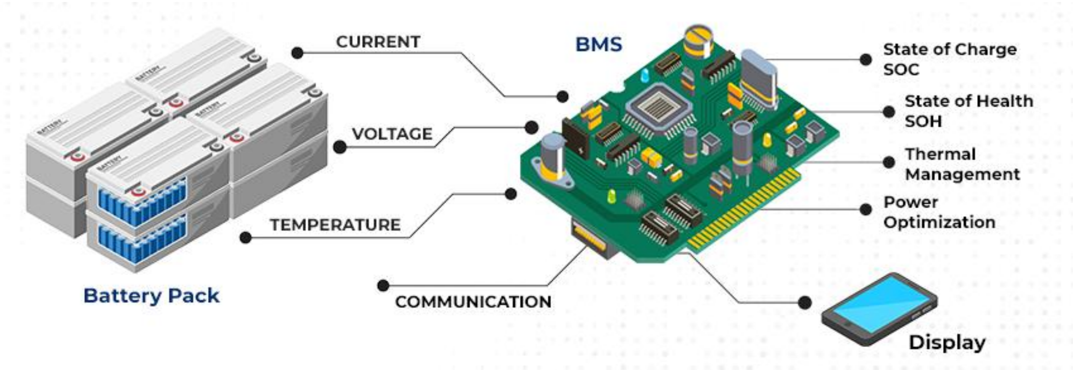


Figure 8 BMS

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 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.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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 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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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 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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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 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

Figure 9 Location of the battery in the EV

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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.

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 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.

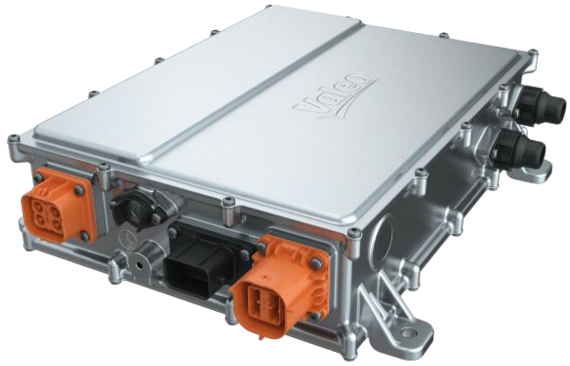


Figure 10 EV Onboard Charger

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

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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 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.

Co-funded by the European Union

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.

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.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

BATPOWER
Preparation of the VET sector on battery energy transition

Module 2 – Battery Components

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Module 3 – Battery Charging and Recharging

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).

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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

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.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

1. Introduction to Battery Charging

1.1 Charging as a controlled electrochemical process

Charging a lithium-ion battery is a controlled electrochemical process in which electrical energy from the grid is converted into chemical energy stored within the active materials of the battery cells. In electric vehicles, this process must be precisely regulated because lithium-ion cells operate within narrow electrical and thermal limits.

Unlike refuelling a combustion vehicle, energy cannot be delivered to a battery at an arbitrary rate. Charging is limited by three main factors: voltage limits of the cells, allowable current levels, and temperature constraints. Exceeding these limits can accelerate ageing, reduce performance, or create safety risks.

Each lithium-ion cell has a defined maximum charge voltage (for many chemistries around 4.2 V per cell). Charging above this value leads to unwanted side reactions such as electrolyte oxidation, structural degradation of the cathode material, gas generation, and potentially lithium plating. At the same time, high charging currents increase internal heating due to electrical resistance. If heat is not effectively dissipated, temperature rises and may compromise safety.

For these reasons, charging in electric vehicles is always supervised by a Battery Management System (BMS). The BMS continuously measures cell voltages, pack current, and temperature to ensure that charging remains within the safe operating area of the battery.

An electric vehicle battery pack consists of numerous lithium-ion cells connected in series and parallel configurations. Cells are assembled into modules, and modules are integrated into the complete battery pack. This modular structure allows the pack to achieve high voltage (typically 300–800 V) and high energy capacity.

In addition to cells, the pack includes:

Battery Management System (BMS)
- High-voltage contactors and fuses
- Current and voltage sensors

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

- Thermal management system (liquid cooling or air cooling)
- Mechanical housing with crash protection

During charging, the BMS supervises all cells to prevent any individual cell from exceeding its voltage limit. If one cell approaches its maximum voltage earlier than others, the BMS reduces charging current or activates cell balancing mechanisms.

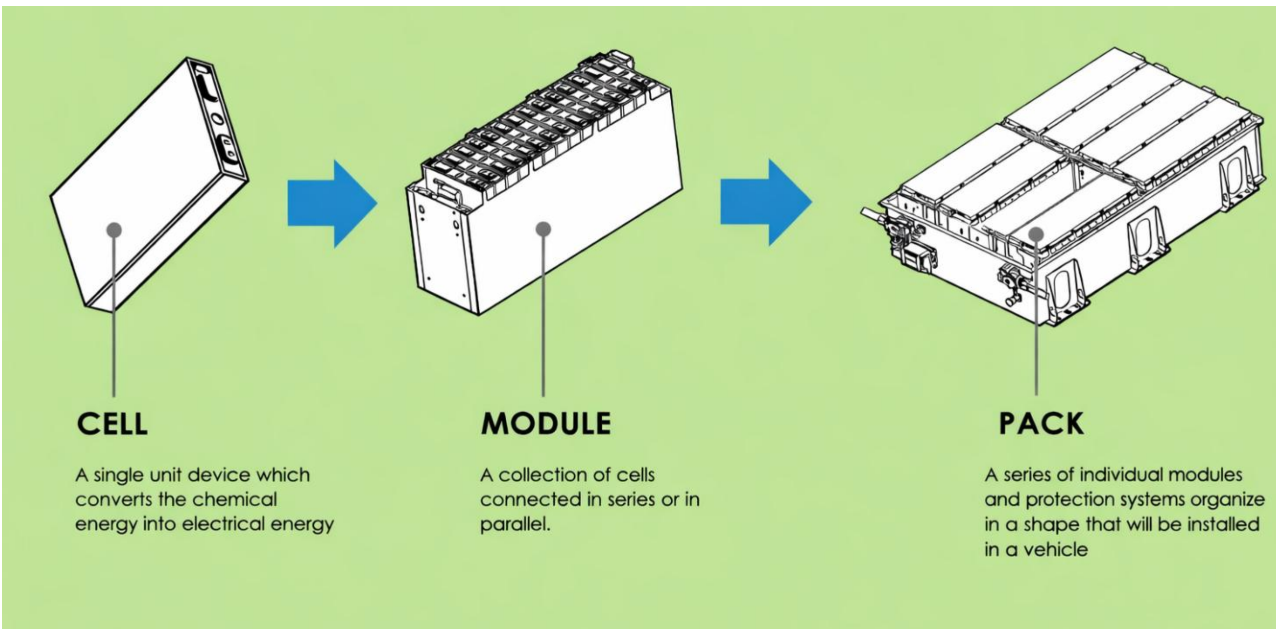


Figure 11 Schematic of an EV battery pack, composed of cells grouped into modules, with a BMS monitoring the cells and controlling contactors

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.*

1.2 Fundamental concepts: capacity, energy and power

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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.

- **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.

Energy (Wh or kWh) represents the total work the battery can deliver. It is calculated as:

Energy = Voltage × Capacity

In electric vehicles, battery size is expressed in kilowatt-hours (kWh) because energy determines vehicle range.

Power (W or kW) describes the rate at which energy is transferred. Charging stations are rated in kilowatts because they define how quickly energy can be delivered to the battery.

The relationship between these quantities is:

Energy = Power × Time

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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*.

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).

1.3 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 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).

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

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.

1.4. AC and DC charging architectures

Electric vehicles can be charged using alternating current (AC) or direct current (DC). The difference lies in where the conversion from AC to DC takes place.

In AC charging, electricity from the grid enters the vehicle as alternating current. The vehicle's On-Board Charger (OBC) converts AC into direct current suitable for the battery. Typical AC charging power ranges from 3 kW to 22 kW. This method is commonly used for home or workplace charging where longer charging times are acceptable.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

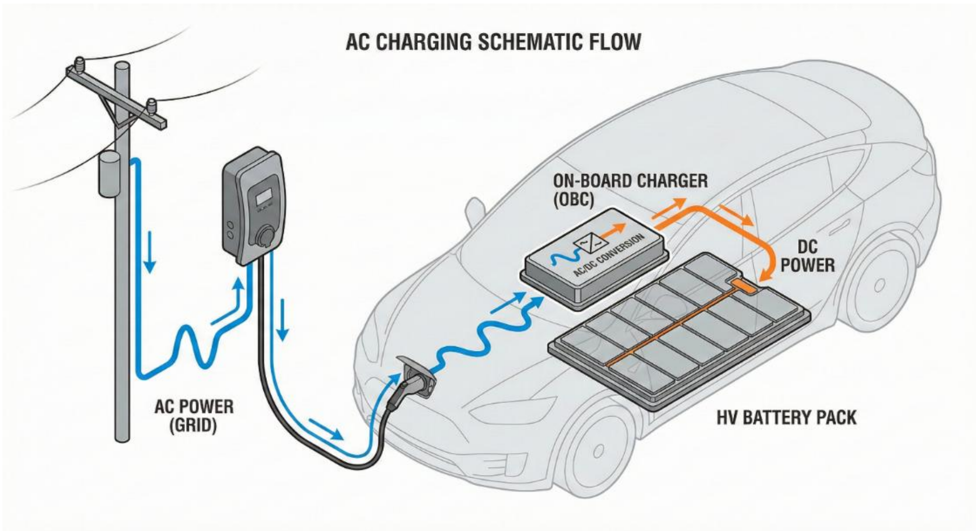


Figure 12 AC Charging Schematic – Grid → AC EVSE (with safety communication) → Vehicle OBC (AC-DC converter) → Battery pack

In DC fast charging, the AC to DC conversion occurs in the charging station. The station supplies regulated direct current directly to the battery pack, bypassing the onboard charger. DC charging allows significantly higher power levels, typically between 50 kW and 350 kW.

Although DC charging reduces charging time, it generates higher thermal loads and increases electrochemical stress on the cells. Therefore, advanced thermal management and precise BMS control are essential.

1.5. The constant current / constant voltage (cc/cv) profile

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

BATPOWER
Preparation of the VET sector on battery energy transition

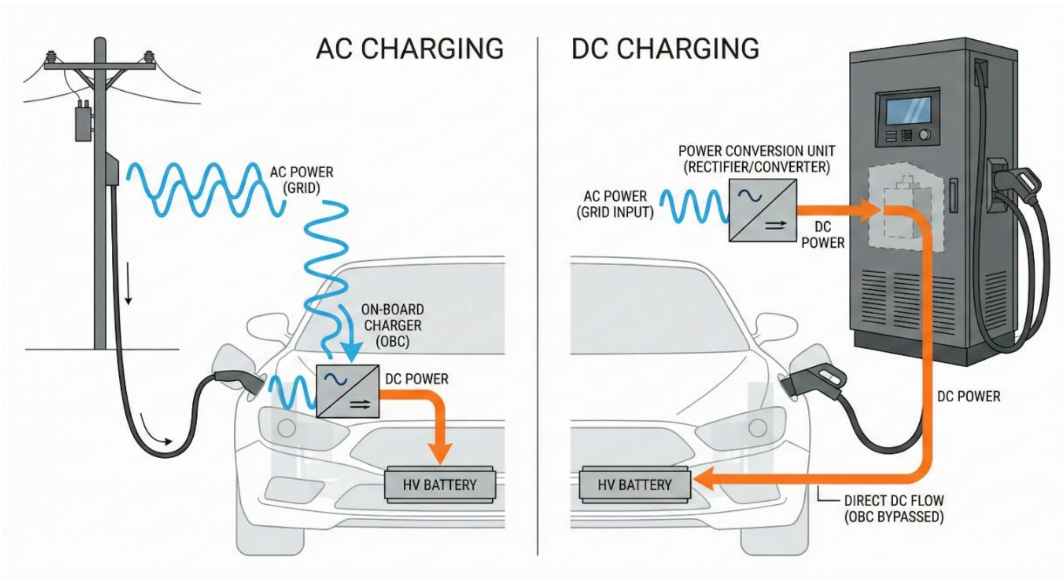


Figure 13 DC Fast Charging Schematic – Grid → High-power DC station → Battery pack.

Lithium-ion batteries are charged using a two-stage method known as Constant Current / Constant Voltage (CC/CV).

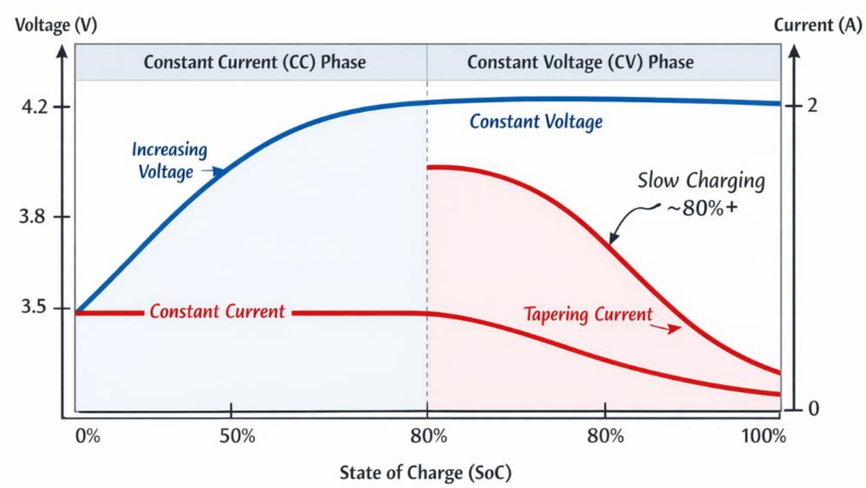


Figure 14 CC/CV charging curve

During the Constant Current phase, the charger supplies a fixed current. The cell voltage gradually increases as lithium ions move into the anode structure. This phase delivers most of the charging energy and determines the overall charging speed.

When the cell voltage reaches its maximum limit, the process transitions to the Constant Voltage phase. The charger maintains the maximum voltage, while the current gradually decreases. This prevents overcharging and allows the battery to reach full capacity safely. Because current decreases significantly during

Co-funded by the European Union

the CV phase, charging above approximately 80% state of charge becomes progressively slower.

1.6. Key parameters during charging

Voltage represents the upper safety boundary for charging. Exceeding the maximum cell voltage accelerates chemical degradation and increases the risk of thermal instability.

Charging current determines the rate of energy transfer. However, internal heat generation follows the relationship:

$$\textbf{Heat} \approx I^2R$$

This means that doubling the current increases heat production fourfold. High current charging therefore, requires effective cooling and precise regulation.

Lithium-ion cells operate optimally within a moderate temperature range (approximately 20–40 °C). At low temperatures, lithium diffusion slows, increasing the risk of lithium plating. At high temperatures, chemical side reactions accelerate and battery ageing increases.

Modern EVs incorporate active thermal management systems to maintain battery temperature within the optimal range during charging.

1.7. State of charge (soc) and state of health (soh)

State of Charge (SOC) represents the percentage of usable battery capacity remaining. It is estimated by the BMS using current integration (coulomb counting), voltage models and temperature compensation.

State of Health (SOH) describes how the battery’s capacity and resistance compare to its original condition. As batteries age, internal resistance increases and capacity decreases. This affects charging behaviour: older batteries may heat more quickly and experience earlier current tapering.

1.8. Role of the battery management system

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

The Battery Management System ensures safe and efficient charging by performing three essential functions: measurement, estimation and control.

It continuously measures:

- Individual cell voltages
- Pack current
- Cell and module temperatures
- Electrical isolation

Based on these measurements, it calculates SOC and SOH and determines allowable charging limits. If any parameter approaches a safety threshold, the BMS reduces charging current or terminates charging.

Cell balancing is an important BMS function near full charge. Slight variations in cell capacity cause unequal voltages. The BMS equalizes these differences, typically through passive balancing, ensuring uniform cell stress and maximizing pack lifespan.

1.9 Safety considerations

Charging high-voltage batteries involves electrical, thermal and chemical risks.

Electrical hazards include electric shock and arc formation. These are mitigated by insulated connectors, locking mechanisms, interlock circuits and residual current devices (RCD).

Thermal runaway is a rare but serious failure mode in

Figure 15 Thermal runaway chain

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

which heat generation triggers self-accelerating chemical reactions. It may result from severe overcharging, internal short circuits or mechanical damage.

Figure 16 Safety poster

Warning signs during charging include abnormal swelling, unusual odours, excessive heating, smoke or audible venting. Charging must be stopped immediately if such symptoms appear.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

CASE STUDY: LOW-TEMPERATURE FAST CHARGING

A vehicle arrives at a 150 kW DC fast charger at −5 °C with a battery SOC of 15%. Initially, the charging power is limited to 40 kW.

The BMS restricts charging current because low temperature reduces lithium diffusion and increases the risk of plating. As the thermal management system warms the battery, allowable charging current increases and power rises accordingly.

This example demonstrates the interaction between electrochemical limits, thermal management and BMS control.

REVIEW QUESTIONS

1) Why is maximum cell voltage strictly limited during charging?
2) Explain why heat generation increases with the square of current.
3) Describe the transition between CC and CV phases.
4) Why does fast charging require active thermal management?
5) How does battery ageing influence charging behaviour?

SELF-ASSESSMENT TASKS

1) In your own words, explain why lithium plating is dangerous.
2) Calculate the approximate time required to add 30 kWh using a 60 kW charger (assume constant power).
3) Identify three safety mechanisms that prevent electric shock during charging.
4) Explain why charging above 80% SOC becomes slower.
5) Discuss the role of the BMS in maintaining long-term battery durability.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Module 4 – Battery Chemistry

1. Why "battery chemistry" matters in real life

When we talk about battery chemistry, we mean the specific materials used inside the cell—especially the cathode, anode and electrolyte. These materials strongly influence how the battery behaves in real life. Chemistry affects charging speed, operating temperature range, energy density (how far the vehicle can drive for a given battery weight), ageing speed, cost and safety behaviour during abuse or damage.

For example, some chemistries have high energy density, which supports long driving range, but they can be more reactive at high temperature. Other chemistries are more thermally stable and last longer, but they store less energy per kilogram, so a battery pack may be heavier for the same range. This is why EV manufacturers choose chemistry based on the vehicle's purpose: city cars may prioritise cost and durability, while long-range or performance models prioritise energy density and power.

A key point for technicians is that chemistry does not remove risk. Even a "safer" chemistry still needs monitoring, controlled charging and good handling. The difference is mainly the size of the safety buffer and how the battery behaves when something goes wrong.

2. Basic chemical structure of a lithium-ion cell

A lithium-ion cell is a layered electrochemical system. Its main parts are the anode, cathode, electrolyte, separator and current collectors. There are also smaller but important components such as binder and conductive additives. Each component has a function and also a typical failure risk.

2.1 Anode

In most EV batteries, the anode active material is graphite (carbon). Graphite has a layered structure that can host lithium ions by intercalation, which means lithium ions

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

slide into spaces between graphene layers. During charging, lithium ions move into the graphite and are stored there. During discharging, lithium ions leave the anode and move back to the cathode.

Graphite is used because it combines reasonable capacity and good cycle stability. Using metallic lithium would increase energy, but metallic lithium tends to form dendrites during charging, which can cause internal short circuits. Because of this risk, classic lithium metal anodes are not used in mainstream EV lithium-ion cells.

Some modern cells include a small amount of silicon mixed with graphite. Silicon can store much more lithium than graphite, but it expands strongly (up to about 300% in extreme conditions), creating mechanical stress, cracking and faster degradation. In practice, small silicon content can improve energy slightly, but it requires advanced design and materials.

Safety link: if charging is too fast or too cold, lithium ions may not intercalate into graphite quickly enough. Instead, metallic lithium can deposit on the anode surface (lithium plating). Plated lithium is highly reactive and can contribute to internal shorts and accelerated ageing.

2.2 Cathode

The cathode is typically a lithium metal oxide or phosphate. It stores lithium when the battery is discharged and releases lithium during charging. The cathode material largely determines the cell's voltage and strongly influences energy density and thermal behaviour.

In EV applications, common cathodes include:

- NMC: lithium nickel manganese cobalt oxide (various ratios, e.g., NMC622, NMC811)
- NCA: lithium nickel cobalt aluminium oxide
- LFP: lithium iron phosphate ($LiFePO_4$)

Cathodes differ in voltage, stability and cost. High-nickel cathodes often provide higher energy density, but they can become more reactive at high temperature and

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

may release oxygen during thermal runaway, feeding combustion. LFP is more thermally stable and releases little oxygen, which is one reason it is considered safer in severe thermal abuse. However, it has lower energy density and lower cell voltage than many NMC/NCA cells.

Safety link: overcharging a cathode can push it into unstable states, increasing gas generation and, in some chemistries, oxygen release at elevated temperature, which accelerates thermal runaway.

2.3 Electrolyte

The electrolyte is the medium that transports lithium ions between anode and cathode. In most lithium-ion cells, it is a liquid mixture of organic carbonate solvents with a lithium salt dissolved in it. A common salt is $LiPF_6$ (lithium hexafluorophosphate). The electrolyte must conduct ions, but not electrons. If electrons could move through the electrolyte, the cell would internally self-discharge or short.

The electrolyte is the most chemically sensitive component. Organic carbonate solvents are flammable. Under abuse (overcharge, overheating, internal short), the electrolyte decomposes and can form flammable and toxic gases. This is why a battery that vents gas can ignite: the vented mixture often contains vaporised solvent plus flammable gases such as hydrogen or carbon monoxide.

Moisture sensitivity: $LiPF_6$ reacts with water and can produce HF (hydrogen fluoride), a highly corrosive and dangerous acid. Even small moisture contamination can damage the cell internally and increase hazards during leakage.

2.4 Separator

The separator is a thin porous polymer film (often PP/PE). It physically separates anode and cathode so they do not touch. Its pores allow electrolyte to fill the separator and allow lithium ions to pass.

Many separators are designed with a “shutdown” effect: at a certain temperature the pores collapse, stopping ion flow and reducing current. This can help prevent runaway in some overheat cases. However, if temperature continues rising, the separator can shrink or melt fully, allowing electrode contact and creating a severe internal short.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Safety link: separator failure is a critical step in many thermal runaway pathways because direct shorting causes rapid heat generation.

2.5 Current collectors

Current collectors are metal foils that carry electrons to and from the electrodes: copper for the anode and aluminium for the cathode. They must remain stable at their respective electrode potentials.

A safety-related issue occurs during severe over-discharge: copper can dissolve and later redeposit as metallic particles, increasing internal short risk during recharging. This is one reason battery systems must avoid deep over-discharge and must be protected by BMS limits.

2.6 Binder and conductive additives

Electrodes are not just active material. They are mixtures of active particles, binder (polymer "glue"), and conductive carbon. The binder holds particles to each other and to the current collector. Conductive carbon ensures electrons can move through the electrode structure.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Poor binder quality or degradation can cause particle detachment, uneven current distribution and local hotspots. Conductive carbon is also combustible in thermal runaway, although electrolyte is usually the dominant fuel.

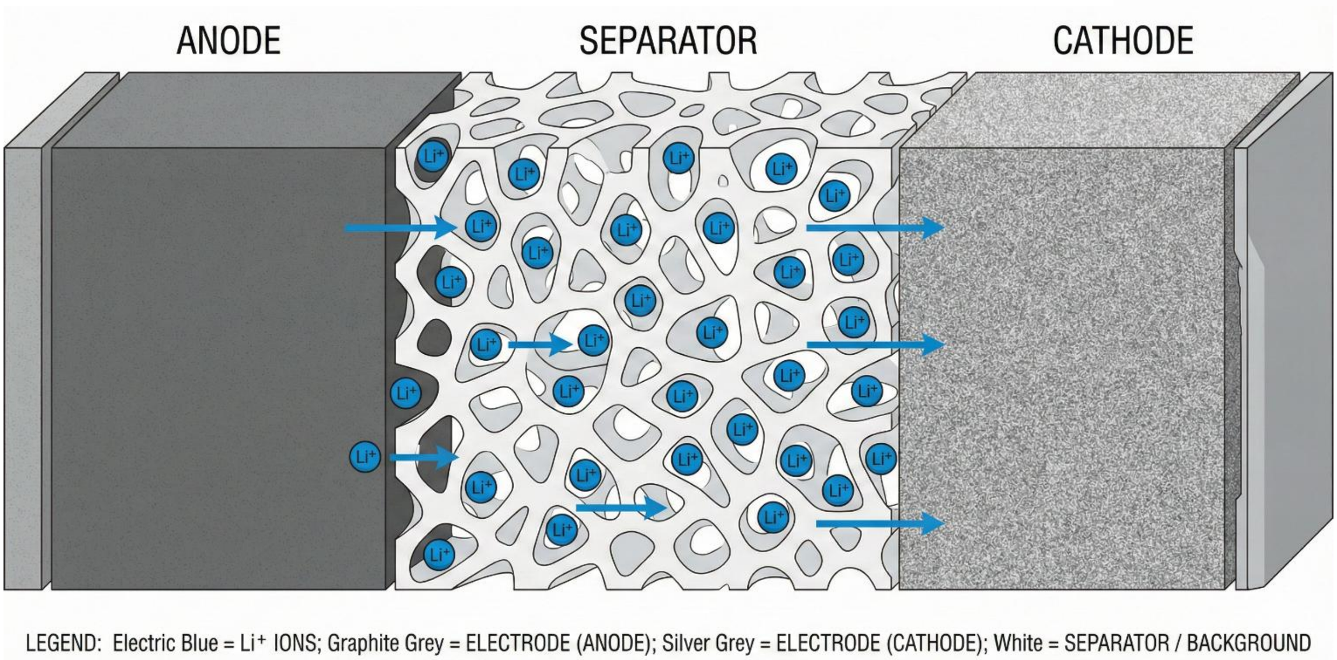


Figure 17 Lithium-ion cell cross-section (schematic). Caption: Layer structure of a lithium-ion cell with anode (graphite on copper), separator, and cathode (metal oxide/phosphate on aluminium). During charge, Li^+ moves from cathode to anode through electrolyte; electrons flow through the external circuit. During discharge, both flows reverse.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

3. How charge and discharge work: ions vs electrons

A lithium-ion battery works like a “rocking-chair” system: lithium ions shuttle between two host materials. The key is that ions move inside the cell through the electrolyte and separator, while electrons move outside the cell through the external circuit.

During charging, an external power source pushes electrons into the anode and pulls electrons from the cathode. To keep electrical neutrality, lithium ions leave the cathode and move through the electrolyte into the anode, where they intercalate. The battery stores energy because lithium is now in a higher-energy configuration (chemical potential difference between electrodes).

During discharging, the circuit (motor/inverter) allows electrons to flow from anode to cathode, doing useful work. Inside the cell, lithium ions move from anode back to cathode. If the separator did not block electrons internally, electrons would take the shortest path and the cell would short-circuit.

This basic mechanism is reversible within safe limits. Ageing begins because real cells also have side reactions.

4. Side reactions and ageing

In a perfect battery, only intercalation and de-intercalation would occur. In real batteries, the electrolyte reacts slowly with electrode surfaces. These side reactions consume active lithium and change interfaces. Over time, batteries lose capacity and their internal resistance increases. Higher resistance means more heating at the same current (I^2R losses) and reduced fast-charge capability.

Ageing accelerates with:

- high temperature (reaction rates increase strongly with temperature)
- high state of charge for long periods (high voltage increases cathode/electrolyte stress)

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

- very fast charging, especially at low temperature (plating risk)
- deep cycling (large expansion/contraction and cumulative stress)

For EV users and service technicians, this explains many manufacturer recommendations: moderate temperature is better, frequent 100% storage is not ideal, and fast charging is best used when necessary rather than constantly.

5. The sei layer: a necessary protector (and an ageing driver)

The Solid Electrolyte Interphase (SEI) is a thin layer that forms mainly on the anode surface, especially during the first charging cycles. It forms because at low anode potentials, the electrolyte is not fully stable and decomposes. The decomposition products create a passivation film.

A good SEI is essential. It is electrically insulating (stops electrons) but allows lithium ions to pass. This prevents continuous electrolyte decomposition and makes lithium-ion cells rechargeable.

However, SEI growth consumes lithium and increases resistance. Over time, the SEI can thicken, especially at higher temperature or after mechanical stress (for example, if the anode expands and contracts and the SEI cracks). When the SEI cracks, fresh surface reacts again, forming new SEI and consuming more lithium.

For technicians, the SEI explains why harsh charging conditions—especially fast charging in cold weather—cause rapid degradation. Cold conditions slow lithium diffusion. If current is too high, lithium plating becomes more likely, and plated lithium often turns into additional SEI later, permanently reducing capacity.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

6. Common automotive chemistries: nmc, nca and lfp

No cathode chemistry is best at everything. EV design is a trade-off among energy density, safety behaviour, cost, and lifespan.

NMC (Nickel Manganese Cobalt Oxide) is widely used. It offers a balanced mix of energy density and power capability. Higher nickel versions typically increase energy density but can reduce thermal stability, meaning careful management and robust thermal control are required. NMC uses cobalt and nickel, which increase cost and raise supply concerns.

NCA (Nickel Cobalt Aluminium Oxide) can reach very high energy density and strong power performance. It has been used in long-range and performance EVs. Because it is high in nickel, it can be more reactive under severe abuse. This does not mean it is unsafe in normal operation—well-designed packs with good BMS and cooling can operate safely at scale—but its inherent safety buffer may be smaller than LFP in extreme thermal abuse.

LFP (Lithium Iron Phosphate) is known for thermal stability and long cycle life. It uses abundant materials (iron and phosphate) and avoids cobalt and nickel, which reduces cost. Its energy density is lower, so packs may be heavier for the same range. LFP can also show reduced performance in cold weather due to higher internal resistance at low temperatures, so good thermal management is still important. LFP's stable chemistry does not remove the need for BMS—overcharge, damage and internal shorts can still cause dangerous failures.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

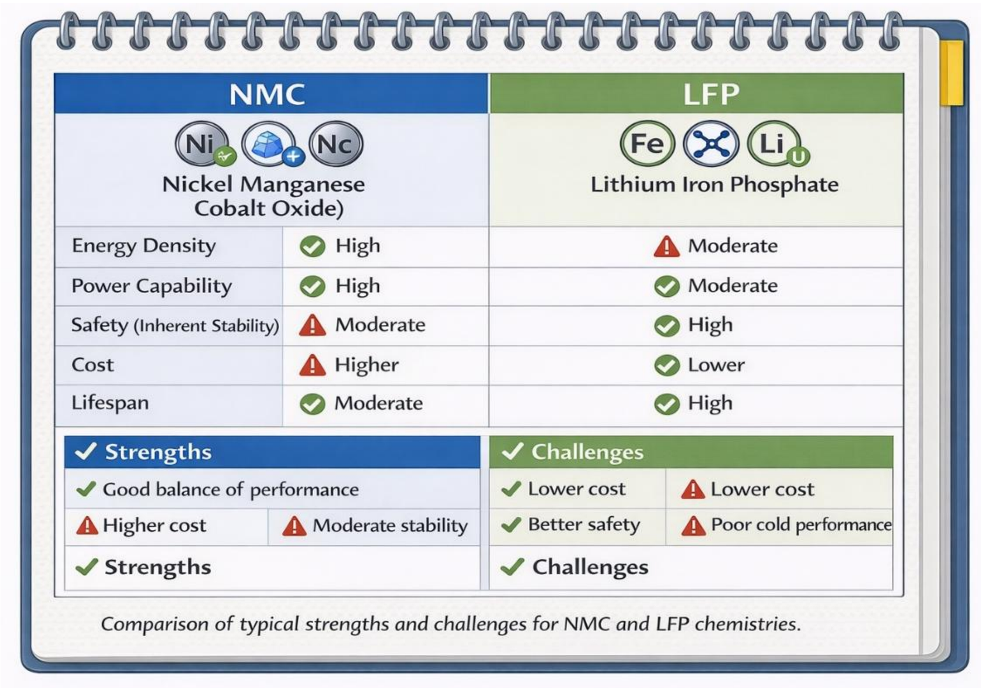


Figure 18 Battery type performance comparison

7. Chemical hazards: what can go wrong and why

Most lithium-ion electrolytes are flammable organic solvents. If a cell leaks and an ignition source is present, the electrolyte can burn. During thermal runaway, electrolyte vapour and decomposition gases can ignite rapidly, producing intense flames.

Electrolyte decomposition also produces toxic by-products. Carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and various organic vapours may be released. In addition, $LiPF_6$ can contribute to HF formation, especially if moisture is involved.

Gas generation, swelling and venting. Gas generation is a common sign of abnormal reactions. It can be triggered by overcharge, overheating, internal short, or contamination. In pouch cells, gas accumulation causes visible swelling. Cylindrical and prismatic cells have vent mechanisms to release pressure. Venting reduces explosion risk but creates a new hazard: flammable and toxic gas is released into the environment, and ignition becomes possible.

Swelling is therefore a serious warning sign. A swollen cell should not be charged or used further without controlled inspection and proper disposal procedures.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Moisture is dangerous for lithium-ion cells because $LiPF_6$ can react with water to produce HF. HF is corrosive and toxic. It can damage cell components and presents a serious hazard if electrolyte leaks or vapours are inhaled.

In practice, technicians must treat suspected electrolyte leakage as a chemical hazard, not only a fire risk. Water should not be used for "washing away" electrolyte in a workshop situation because it can increase HF formation. Proper neutralisation and PPE are essential.

Thermal runaway is a self-accelerating process where heat triggers exothermic reactions, which generate more heat. Typical steps include: breakdown of SEI, rapid electrolyte decomposition, separator failure (leading to internal short), and cathode decomposition. In some chemistries, cathode breakdown can release oxygen at high temperature, feeding combustion.

Once thermal runaway begins, stopping it is difficult because the cell contains both fuel (electrolyte and organics) and, in some cases, oxygen release from cathode materials. The most effective intervention is cooling and preventing propagation to neighbouring cells.

8. Safety practices for workshops, transport and storage

Safe handling is based on prevention: avoid mechanical damage, avoid short circuits, avoid overheating, and follow chemical safety rules.

Workshop handling principles include using insulated tools, avoiding metal objects near terminals, and ensuring a clear work area. If a battery is opened or leakage is suspected, ventilation becomes critical. Appropriate PPE depends on the task, but at minimum includes eye protection and gloves. For high-voltage work, electrical insulating gloves and procedures are required according to local safety regulations.

Storage principles include keeping batteries cool and dry, away from ignition sources and flammable materials. For long-term storage, moderate SOC (around 30–50%) is generally recommended because high SOC increases voltage stress and low SOC

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

increases deep-discharge risks. Terminals should be protected against accidental shorting with covers or insulating packaging.

Emergency awareness is equally important. Warning signs include swelling, hissing, strong solvent-like smell, overheating at rest, smoke or visible venting. If such signs appear, stop all operations, isolate the battery if safe, and follow local emergency procedures.

A Safety Data Sheet is the main document describing hazards and safe handling of chemicals. For battery materials, SDS information helps identify flammability, corrosivity, toxicity and recommended PPE.

Figure 19 Hazard symbols

For fast practical use, key SDS sections are:

- Hazards identification (main hazards and pictograms)
- First aid measures (what to do after skin/eye contact or inhalation)
- Firefighting measures (special hazards such as toxic gases)
- Handling and storage (humidity, temperature, ignition sources)
- Exposure controls/PPE (gloves, goggles, respirators, ventilation)

Hazard pictograms (CLP/GHS) provide quick visual warning. For battery-related chemicals, common symbols include flame (flammable), corrosion (corrosive acids), and exclamation mark/health hazard (harmful vapours or irritation). The signal word "Danger" indicates a higher hazard level than "Warning".

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Figure 20 Check every Safety Data Sheet individually for each product

For technicians, SDS and hazard labels are not bureaucracy. They provide real operational guidance and can prevent severe injury, especially when dealing with electrolyte leakage or unknown fumes.

CASE STUDY

Case: Swelling Module in a Workshop

A technician receives an EV battery module removed from a vehicle after a minor collision. The module shows slight swelling on one side. There is no visible smoke, but a weak sweet/solvent smell is noticed when the module is placed on the bench.

Tasks:

1. Explain two chemical reasons why swelling can occur in lithium-ion cells.
2. Identify the immediate hazards associated with the smell.
3. Decide the correct next actions in the workshop (stop/continue, isolate/inspect, PPE, ventilation).
4. Explain why charging this module would be unsafe.
5. List which information you would look for in an SDS if leakage is suspected.

Expected scientific reasoning: swelling indicates gas formation from electrolyte decomposition or contamination; smell indicates vapours from organic solvents and possibly decomposition products; charging could accelerate reactions, increase temperature and trigger venting or runaway; SDS provides hazard class, PPE, first aid and spill response guidance.

KNOWLEDGE CHECK – QUIZ

1. Which component mainly determines cell voltage?
   a) Separator
   b) Cathode
   c) Binder
   d) Current collector

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

2. What is the separator's primary function?
   a) Conduct electrons
   b) Store lithium ions
   c) Prevent anode–cathode contact while allowing ion flow
   d) Increase energy density

3. The electrolyte is dangerous mainly because it is:
   a) Non-conductive
   b) Flammable and can form toxic gases
   c) A metal
   d) A ceramic

4. SEI is best described as:
   a) A metal foil
   b) A protective ion-conductive, electron-insulating layer on the anode
   c) A gas created at high SOC
   d) A type of cathode chemistry

5. Why is moisture harmful in many Li-ion cells with $LiPF_6$ electrolyte?
   a) It improves conductivity
   b) It produces oxygen
   c) It can lead to HF formation
   d) It stabilises the cathode

6. Which statement is most accurate?
   a) LFP chemistry needs no BMS because it is safe
   b) High-nickel chemistries are always unsafe
   c) All chemistries need monitoring; chemistry mainly changes the safety buffer
   d) Thermal runaway can be stopped by blocking external oxygen only

Answer key for teachers (keep separate if needed): 1b, 2c, 3b, 4b, 5c, 6c

SELF-ASSESSMENT TASKS

1. Component-function map
   Write one paragraph explaining the function of each: anode, cathode, electrolyte, separator, current collectors. Then add one safety risk linked to each component.

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

2. Charge/discharge explanation
   In 6–8 sentences, explain what moves during charging and discharging. Clearly separate the path of Li^+ ions and electrons.

3. Chemistry comparison
   Choose two chemistries (e.g., NMC vs LFP). Compare them in terms of: energy density, thermal stability, cost/materials, and typical use in vehicles.

4. SEI reflection
   Explain why SEI is both necessary and harmful over time. Describe two conditions that accelerate SEI growth.

5. Hazard scenario decision
   You detect swelling and solvent smell in a module. Write a step-by-step safety response plan for the first 10 minutes (what to do, what not to do, PPE, isolation, ventilation, reporting).

6. SDS practice
   If you had access to the SDS, which sections would you check first and why? Provide at least four sections and explain your reason briefly.

GLOSSARY

Anode – negative electrode during discharge; typically graphite in EV cells; hosts lithium during charge.
Cathode – positive electrode during discharge; lithium metal oxide or phosphate; sets voltage and energy behaviour.
Electrolyte – liquid ion conductor (often organic solvents + $LiPF_6$); flammable and chemically sensitive.
Separator – porous polymer membrane preventing electrode contact while allowing ions to pass.
Current collectors – metal foils carrying electrons (Cu for anode, Al for cathode).
Intercalation – insertion of lithium ions into layered electrode materials.
SEI – Solid Electrolyte Interphase; protective layer on anode; enables rechargeability but increases resistance as it grows.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

NMC/NCA/LFP – common cathode chemistries used in EVs with different trade-offs.
Lithium plating – metallic lithium deposition on anode; increases ageing and short-circuit risk.
Thermal runaway – self-accelerating heating due to exothermic reactions leading to fire/explosion risk.
SDS – Safety Data Sheet; hazard and handling document for chemicals.
CLP/GHS pictograms – standard hazard symbols used for chemical labeling.

Co-funded by the European Union
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EACEA. Neither the European Union nor the granting authority can be held responsible for them.

Module 5 – Quality in cell production

1. The role of quality in battery production

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.

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)
- **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?**

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.

References

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

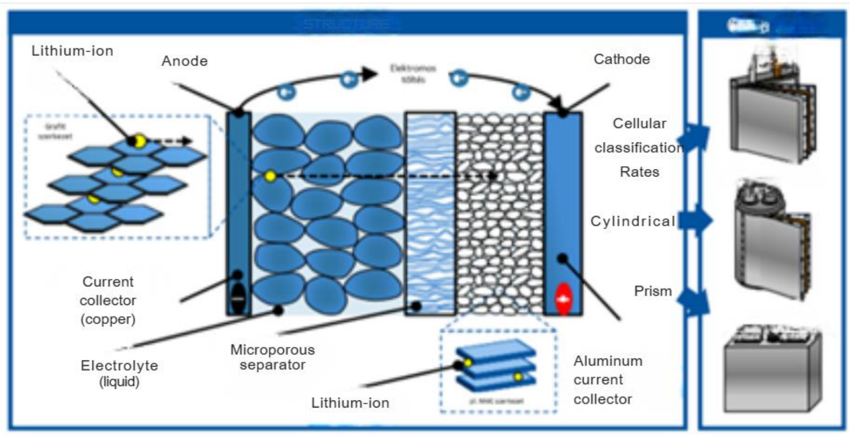
Blomgren , GE (2017). The development and future of lithium -ion batteries . Journal of The Electrochemical Society, 164(1), A5019–A5025. *https://doi.org/10.1149/2.0251701jes*

2. Steps and important parameters of the production process

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.



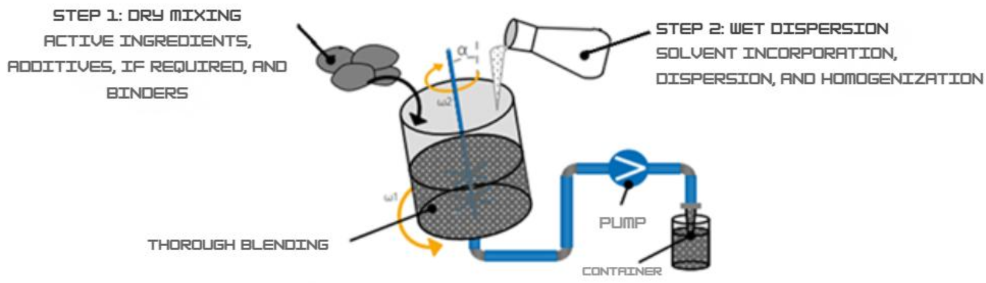
3. Illustration of cell structure

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.

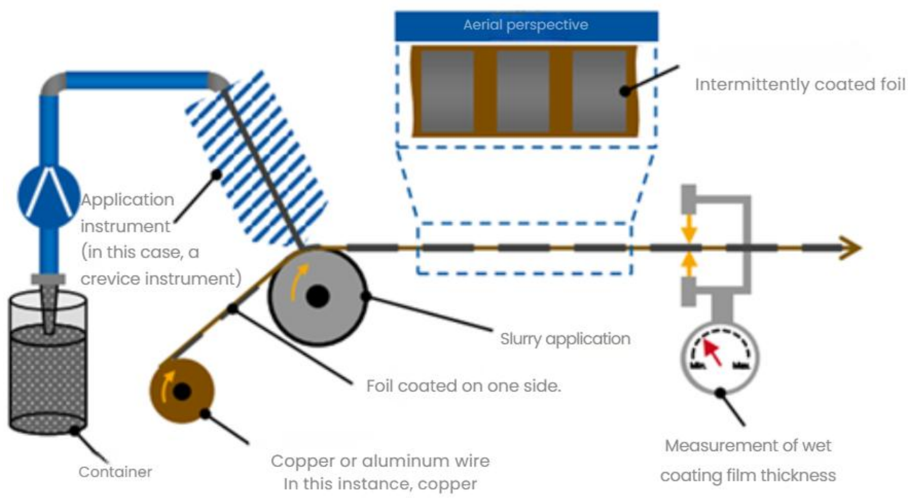


4. Mixing process

The mixing parameters are the axis angle marked a in the picture, which can be **between 0-10⁰** , the mixing time (**30 minutes–5 hours**), the mixing temperature (**20-40⁰C**). After the mixing process, the slurry is transferred to the coating process through the pipelines.

Coating and Drying

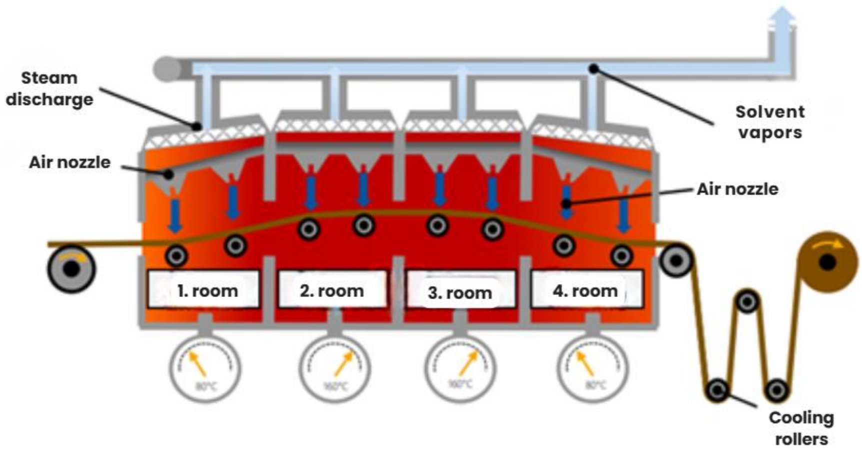
The anode and cathode processes are also **completely separated in** the coating process . In the case of the anode, the slurry coating is applied to copper foil, and in the case of the cathode, to aluminum foil. The application device can be a slot tool, a cutting knife or an anilox roller.



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.

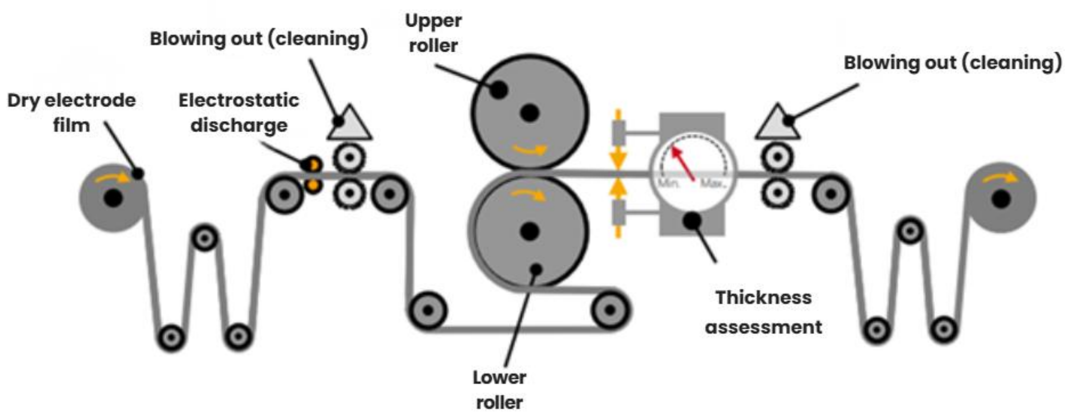


6. Drying process

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.

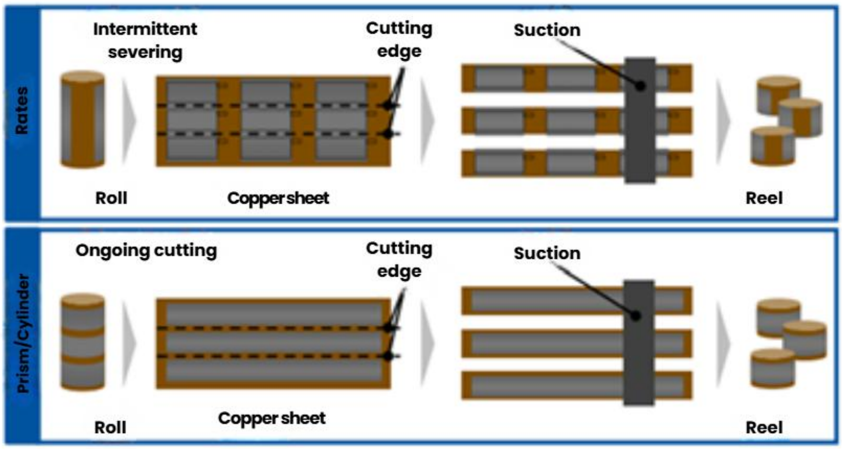


7. Pressing

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.



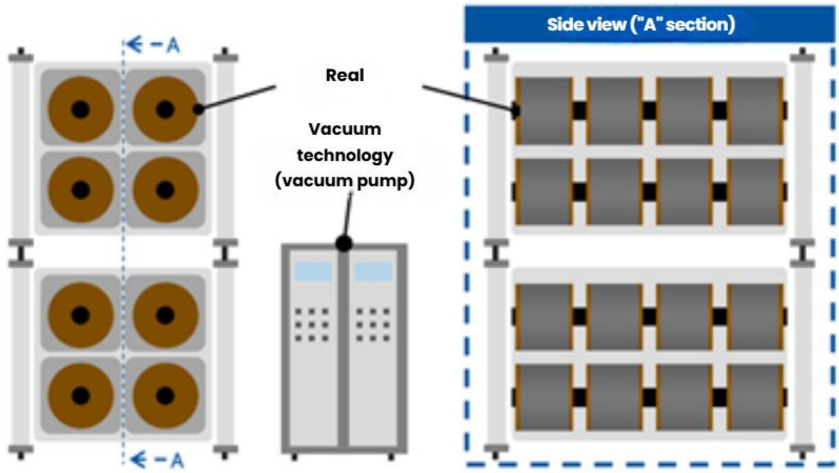
8. Slitting

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.

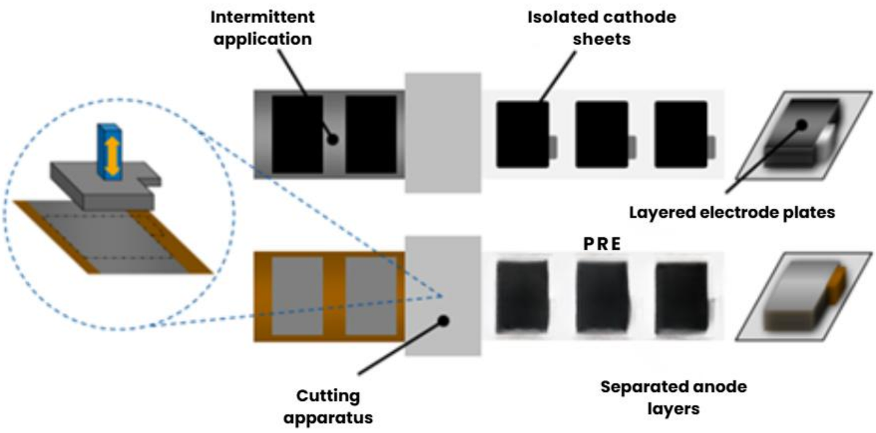


9. Vacuum drying process

The main parameters of the process are: **pressure (0.007 mbar – 1000 mbar), drying time (12-30 hours), drying temperature (60⁰C - 150⁰C).**

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.

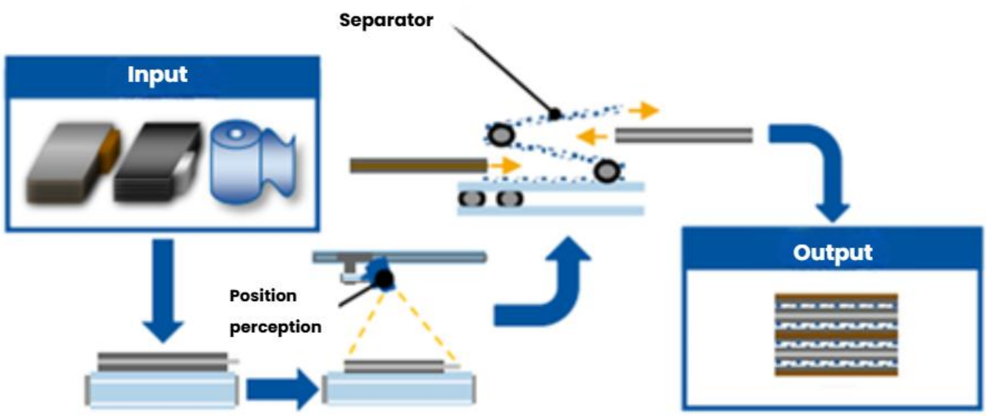


10. Cutting process

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** .

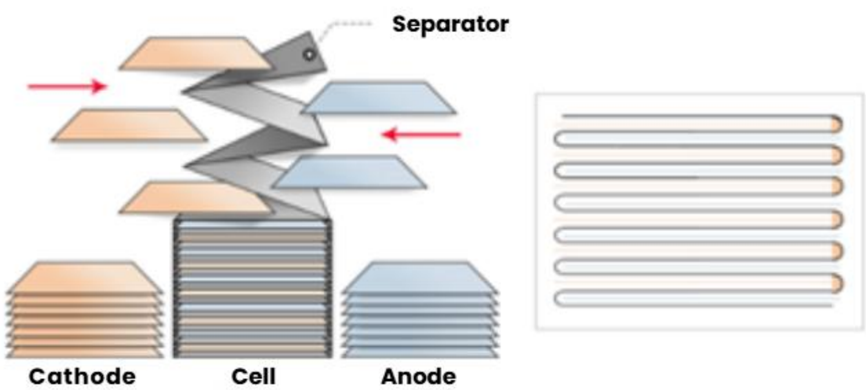
Stacking

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

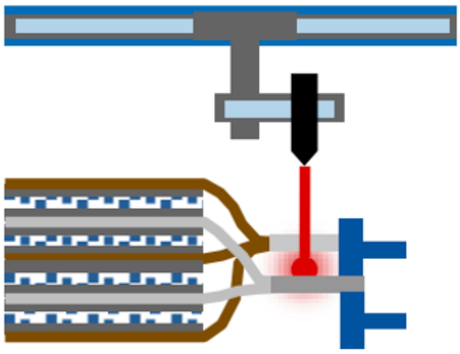
Stacking is one of the most complex and fastest processes in battery cell manufacturing. Stacking machines are loaded with magazines consisting of electrode sheets previously cut in the notching process (anode and cathode magazines), as well as the separator coil. The most common variation of the process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

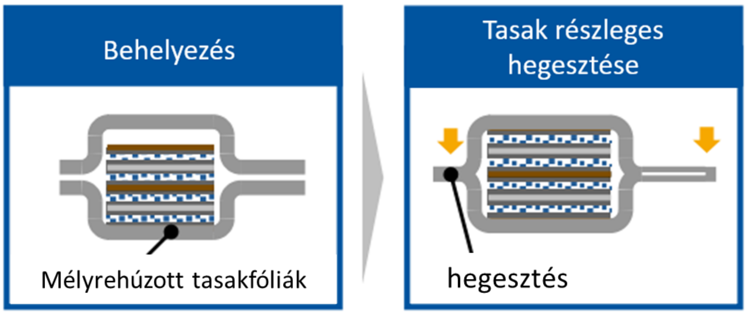
The first step in the packaging process is the deep-drawing of the bag, which arrives at the packaging station rolled up.

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)

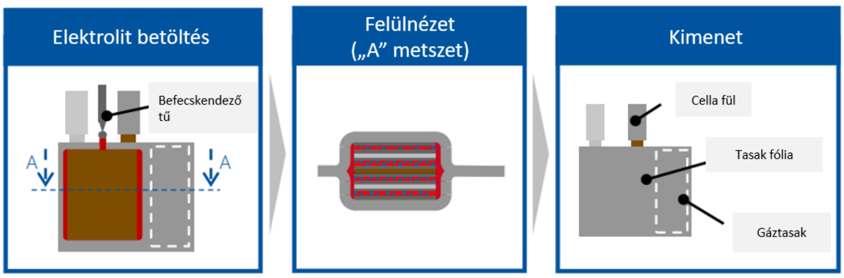
The cell body is then inserted into the deep-drawn pouch. There are two options for deep-drawing the pouch: during plastic forming, the cavity in the pouch is formed on both sides of the cell body, or only on one side.



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

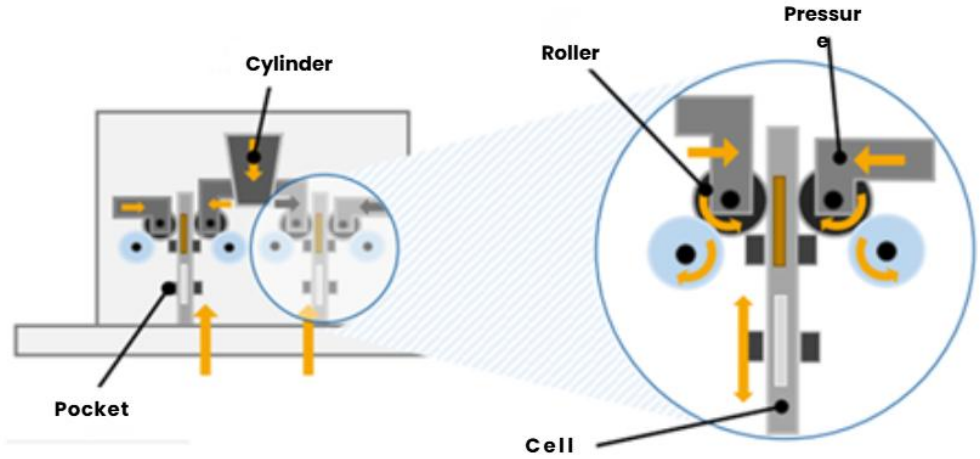
The main parameters of the process are: **the geometry of the injection needle, the injection pressure (approx. 0.01 mbar) and the constant, continuous filling to ensure a homogeneous distribution of the electrolyte.**

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

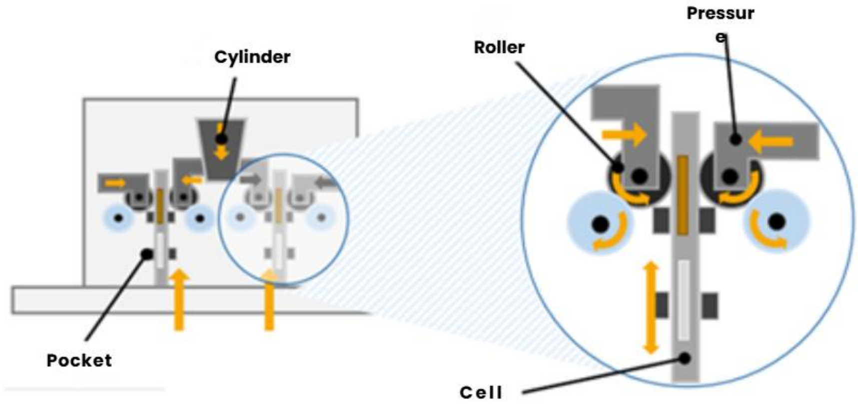
Sent from assembly after cell aging , it is transferred to the rolling station, with the aim of evenly distributing the electrolyte injected in advance (on the packaging) in the cell body using two rollers. The cell is placed in a pocket using a **gripper** , **and then two rollers controlled by two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



17. Rolling

Degassing

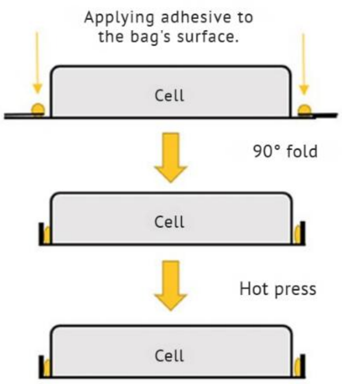
The pre-filling process takes place between rolling and degassing. A large amount of gas is released due to chemical reactions. During degassing, the cell is placed in a special vacuum chamber, in which a piercing knife pierces the gas bag, and two working cylinders on both sides of the cell compress 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 180^0 and then by 90^0** . Folding is achieved by a roller with a special profile that bends the welded part by 180^0 , and then a press that glues/welds the **150-200^{0}C** , molten **PP layers together** .



19. Steps for folding cell edges using adhesive

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

References

1. https://www.raylase.de/en/applications/Battery-Production-electric-mobility/battery-foil-production.html
2. *https://ceyrekmuhendis.com/li-ion-piller-nasil-uretilir-elektrot-uretimi/*
3. *https://www.batterymaking.com/product/lithium-cylindrical-cell-production-line-cylindrical-cell-manufacturing-plant_p945.html*
4. *https://intercalationstation.substack.com/p/dry-batts*
5. *https://www.batterymaking.com/product/lithium-cylindrical-cell-production-line-cylindrical-cell-manufacturing-plant_p945.html*
6. *https://www.batterymaking.com/product/lithium-cylindrical-cell-production-line-cylindrical-cell-manufacturing-plant_p945.html*
7. *https://www.batterymaking.com/product/lithium-cylindrical-cell-production-line-cylindrical-cell-manufacturing-plant_p945.html*
8. *https://villanytanya.hu/cikkek/akkumulator-gyartas/*
9. *https://villanytanya.hu/cikkek/akkumulator-gyartas/*
10. *https://medium.com/@dominic.tsoi/lithium-ion-battery-manufacturing-front-to-end-6015704cc2d6*
11. *https://villanytanya.hu/cikkek/akkumulator-gyartas/*
12. https://www.irjmets.com/uploadedfiles/paper//issue_3_march_2024/50930/final/fin_irjmets1711046694.pdf
13. *https://villanytanya.hu/cikkek/akkumulator-gyartas/*
14. https://www.irjmets.com/uploadedfiles/paper//issue_3_march_2024/50930/final/fin_irjmets1711046694.pdf
15. https://www.irjmets.com/uploadedfiles/paper//issue_3_march_2024/50930/final/fin_irjmets1711046694.pdf

16. https://www.irjmets.com/uploadedfiles/paper//issue_3_march_2024/50930/final/fin_irjmets1711046694.pdf

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
2 B	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 $500 m/s^2$ 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.

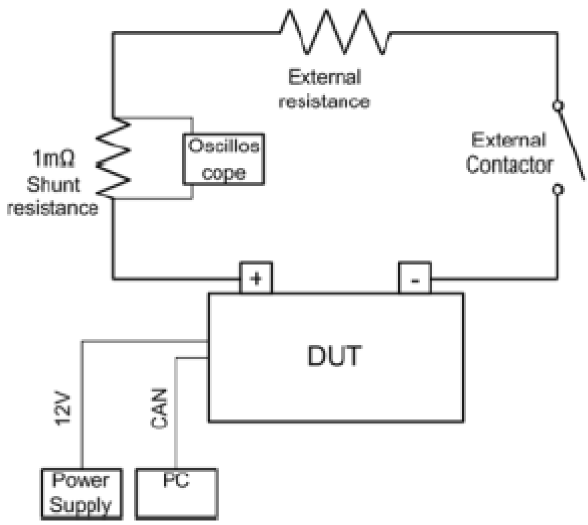
*23. **Water resistance test***

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.

BATPOWER
Preparation of the VET sector on battery energy transition

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

Bibliography

DIN EN 60068-2-14

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

Quality standards and auditing requirements in cell manufacturing

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.

Bibliography

Safety Requirements for Lithium Transportation Batteries

https://www.mdpi.com/journal/energies

United Nations . (2023). UN Manual of Tests and Criteria , Rev. 7 (including amendment 1). United Nations Publications .

https://unece.org/transport/dangerous-goods/manual-tests-and-criteria

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

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.

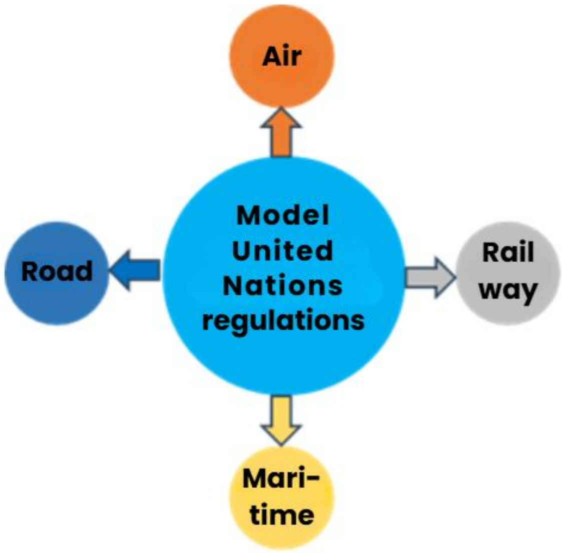
Several international regulatory authorities oversee the transportation of lithium batteries by various modes (air, sea, road and rail):

- 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

(a) (b) (c)

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:

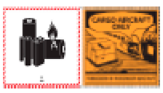
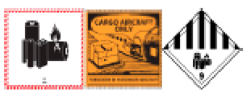
Packaging instructions	UN 3480-PI965	
	PI965-Section II	PI965-Section IB

Li -ion cells/batteries Watt-hour rating (E)	This $_{goal} \leq 2,7$ Wh	$E_{cel} > 2.7$ Wh and $E_{bat} \leq 20$ Wh	$E_{cel} > 2.7$ Wh and $E_{bat} \leq 100$ Wh	This $_{goal} \leq 20$ 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.

BATPOWER
Preparation of the VET sector on battery energy transition

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.

Bibliography

1.Safety Requirements for Lithium Transportation Batteries

https://www.mdpi.com/journal/energies

2. United Nations . (2023). UN Manual of Tests and Criteria , Rev. 7 (including amendment 1). United Nations Publications . *https://unece.org/transport/dangerous-goods/manual-tests-and-criteria*

3.ADR (2023). European Agreement concerning the International Carriage of Dangerous Goods by Road . UNECE. *https://unece.org/about-adr*

4.IATA (2024). Dangerous Goods Regulations , 65th Edition. International Air Transport Association . *https://www.iata.org/en/publications/dgr/*

II. 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

BATPOWER
Preparation of the VET sector on battery energy transition

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.

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.

$$C = I \cdot t$$

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

https://forms.gle/qztFE3NFFCBSBY33A

Bibliography

István Gergely – Electrical Engineering General Press Publishing House, 2009

https://www.electronicdesign.com/technologies/test-measurement/article/21128843/keysight-technologies-measuring-dcir-of-lithium-ion-cells

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html

III. 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,

Bibliography

1. *https://mozees.no/wp-content/uploads/2019/10/Jensen_Unlocking-large-scale-battery-cell-supply-in-Europe.pdf*