



The Battery A to Z

by BatteryDesign.net

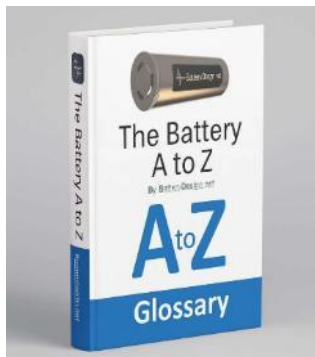
Having worked for a major vehicle OEM for over 30 years and the last 14 years in electrification including battery research and conceptual design it was time to do something different.

In the daytime that is consulting on battery design. In spare time that is building batterydesign.net to be a place to share information, knowledge and ideas.

However, it's not all about me. The site now has lots of people who contribute articles, posters and information. If you would like to write a post on a technical subject then please do drop me a line: nigel@batterydesign.net

Aims of Battery Design

- a central resource for battery designers
- fundamental pages explaining the physics
- posts that give you an overview of the fundamentals
- lists of suppliers and manufacturers of cells, parts and complete packs
- free to use, free to post and free benchmarking data
- references that take you to another level of understanding
 - just written a new paper that changes our thinking? write a short brief and share with us along with a link to the paper and your research group
- posts accepted from individuals, academics, institutions, manufacturers, consultancies and OEM's
- Support BatteryDesign.net by sharing and contributing or [support / sponsor our pages](#)



The latest version of the Battery A to Z is always available at:

Battery A to Z Glossary

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12V Battery - Traditionally the 12V battery has been the electrical energy storage device used in passenger vehicles. The most common chemistry has been **lead acid**, however, as of 2020 we are seeing a move towards **lithium iron phosphate**.

V_{\min}	V_{\max}	Description
6V	16V	For functions that must retain their performance during the engine starting event.
8V	16V	Functions that do not have to retain their performance during engine starting event. The V_{\min} value could be breached if the engine is cold, hence, if possible the function should operate at 6V or not have to retain performance under engine start.
9V	16V	Functions that must retain their performance when the engine is not running.
9.8V	16V	For functions that must retain their performance when the engine is running.

18650 – Cylindrical cell format where the diameter of the cell is 18mm and the height of the cell is 65mm.

21700 – Cylindrical cell format where the diameter of the cell is 21mm and the height of the cell is 70mm.

24V Battery - The 24V battery packs tend to be used in commercial vehicles for starting and vehicle operation. In passenger cars the **12V battery** performs the same functions, 12V nominal as the peak power demands are lower than those in large commercial vehicles.

3rd Electrode or Reference Electrode is added to a battery cell so that the anode and cathode potentials can be referenced against a known point.

3D Electrodes – another way to increase energy density is with 3D electrodes. Increasing the surface area and connection to the active materials can improve a number of features of the cell.

400V Architecture – can mean many things as claims are often made based on the maximum system voltage rather than the nominal battery pack voltage.

46xx Cylindrical Cells - an abbreviation for the new class of 46mm diameter cylindrical cells.

48V Battery - synonymous with the MHEV, but has been adopted for a range of other applications.

4R's Repair, Reman, Repurpose, Recycle - Before moving to the recycling of a battery the following options should be considered:

1. Repair
2. Remanufacture
3. Repurpose



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This approach can reduce cost, impact on the customer and most importantly the impact on the planet. Batteries are not emissions and toxic waste free and so the life cycle analysis (LCA) must be considered from cradle to grave.

800V Architecture - can mean many things as claims are often made based on the maximum system voltage rather than the nominal battery pack voltage.

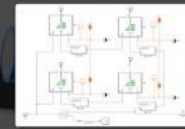
AASB – All Solid State Battery

AB Battery System – a single battery system that combines two different types of battery cells.

A data company that offers software to enhance battery performance throughout its lifetime. Its platform, “The Voltt”, reduces time and costs in developing new electric products for various industries. Utilizing advanced battery testing methods, this platform facilitates cell selection, benchmarking, and system design.

ABOUT:ENERGY

Empowering engineers to build battery systems through simulation



AC = Alternating Current

Accelerated Rate Calorimetry (ARC) - an adiabatic testing method used to analyse the thermal stability, decomposition, and runaway potential of chemicals, explosives, and batteries.

Acetonitrile Electrolyte – with a salt and other additives has high ionic conductivity. This high ionic conductivity allows ease of movement of ions between the anode and cathode. Thus allowing faster charge and discharge. With the right additives the acetonitrile electrolyte can enable a cell to work over a wide temperature range.

ACIR = Alternating Current Internal Resistance is normally the impedance of the cell at 1kHz. **Internal Resistance: DCIR and ACIR**

Acoustic Testing - typically in the ultrasonic frequency range, sends sound waves through the cell and detects internal changes based on wave propagation patterns. Acoustic testing has many advantages, particularly its sensitivity to low-Z components such as electrolyte

Active Balancing – the idea here is to redistribute the energy across the cells. Give energy from the cells with the highest SoC to the cells with the lowest SoC. This is the ideal cell balancing approach.

Active Mode – the BMS is on, communicating and monitoring all sensors.

Aerogel – synthetic porous ultralight foam material derived from a gel, in which the liquid component for the gel has been replaced with a gas. Possible uses in battery packs based on its thermal insulation properties.

Aerospace Battery Systems - have some very unique requirements and hence characteristics. One of the most comprehensive sources of information is NASA.

Ah = Ampere-hour and is the unit of cell capacity.

Aluminium - used in electrical busbars, cell cases, module housings and for pack cases. Hence a number of different grades of aluminium based on the requirements from electrical resistance, thermal conductivity, strength and corrosion resistance.



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Aluminium Air – high energy density and low cost. The aluminium anode and air cathode along with an aqueous electrolyte, generate power through the oxidation of aluminium by oxygen from the air.

Aluminium Ion – the aluminium metal anode can exchange three electrons during the electrochemical process, hence can deliver a theoretically high volumetric and gravimetric capacity.

Anode – the negative or reducing electrode that releases electrons to the external circuit and oxidizes during the electrochemical reaction.

Anode-Cathode – in chemistry, we define Cathode as the electrode where reduction takes place and Anode the electrode where oxidation occurs. Both, during the discharge and recharge electrons move from the Anode to the Cathode. {Anode and Cathode swap places}.

Anode Free – a battery cell where the Anode is formed during the cell formation cycles.

Anode Manufacturing - there are 4 steps in electrode manufacturing:

1. Mixing
2. Coating
3. Drying
4. Calendering

The electrode manufacturing process is the same for all of the cell chemistries and formats in terms of the basic steps.

Anode Overhang - the extra material in a battery cell's anode that extends past the intended boundaries. This is intentional as cathode overhang can result in:

- dendrite growth
- accelerated aging
- potential safety issues

Hence a measure of this is important in any cell assembly system.

Aqueous Battery – battery based on an electrolyte dissolved in water.

Areal Capacity - the amount of electrical charge a battery electrode can store per unit area, essentially measuring the capacity of an electrode based on its surface area.

Aviation Battery Systems – have some very unique requirements compared to other mobile batteries. Weight is a key attribute and hence the gravimetric energy density (Wh/kg) is a key target.

BaaS = Battery as a Service is the name for swappable battery packs. [Designing swappable batteries](#): *Swappable batteries inherit outer design, power output and data exchange protocols of their precursors.*

Balancing – all about the dissipation or movement of energy between cells. The aim being to align them all with respect to state of charge. Aligning the state of charge of all of the cells in a pack will allow the pack to deliver the most energy and power. This becomes more crucial as the pack ages and differences between cells become more significant.

Bank charging – split the pack in two to charge it. Thus an 800V drive pack becomes two 400V packs in parallel for charging.

Battery Capacity - is the current capacity of the battery and is expressed in Ampere-hours, abbreviated Ah.



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- **Chemical Capacity** – full storage capacity of the chemistry when measured from full to empty or empty to full. This is normally defined at a given C-rate and maximum and minimum voltages.
- **Designed Capacity** – the storage capacity allowed to be used by the application. Often called the **Usable SoC Window** for the battery pack. This is a reduced window designed to ensure safety, performance and longevity.
- **Available Capacity** – this is the capacity that can be accessed taking into account the temperature, age, health and use of the cell.

Battery Cell - the smallest building block of a functional battery. The battery can be a single cell or many cells arranged in series and parallel.

Battery Cell Manufacturing Process – the main three sections are: Electrode Manufacturing, Cell Assembly and Cell Finishing.

1. Electrode Manufacturing
 - a. Mixing
 - b. Coating
 - c. Drying
 - d. Calendering
2. Cell Assembly
 - a. Slitting
 - b. Final Drying
 - c. Cutting
 - d. Winding or Stacking
 - e. Terminal Welding
 - f. Canning or Enclosing
3. Cell Finishing
 - a. Filling
 - b. Formation and Sealing
 - c. Ageing
 - d. Final Control Checks

Battery Charging - charging a battery cell or a battery pack involves passing an electric current through the cell in the opposite direction to the current it delivers when being discharged

Battery Chemistry - The fundamental battery chemistry or more correctly the Electrochemistry.

- [Lead Acid](#)
- [Lithium Ion](#)
- [Nickel Metal Hydride](#)
- [Sodium Ion](#)

Battery Chemistry Roadmap – the main chemistries are Lithium and Sodium based, but there are many variations and hence research strands looking to improve energy density, lifetime or cost.

Battery Disconnect Unit – contains the **contactors**, **fuses**, pre-charge circuit and **current sensors**. This unit sits inside/on top of the battery pack and has all of the components for monitoring, activating, and deactivating the high-voltage battery system.

Battery Electric Driveline - the pure battery electric drive is perhaps the simplest. The downside is the energy density of the onboard storage system.



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Battery Energy Storage Systems - abbreviated as BESS are electricity storage systems that primarily enable renewable energy and electricity supply robustness.

Battery Management System – the BMS is the hardware and software control unit of the battery pack. This is a critical component that measures cell voltages, temperatures, and battery pack current. It also detects isolation faults and controls the contactors and the thermal management system. The battery management system protects the operator of the battery-powered system and the battery pack itself against overcharge, over-discharge, overcurrent, cell short circuits and extreme temperatures.

Battery Management System Algorithms - a number of fundamental functions that the Battery Management System needs to control and report with the help of algorithms. These include:

- **State of Charge** (SoC)
- **State of Certified Energy** (SOCE)
- **State of Power** (SoP)
- State of Capacity (SoQ)
- State of Energy (SoE)
- **State of Health** (SoH)
- State of Function (SoF)
- State of Resistance (SoR)
- Contactors Control
- **Cell Balancing**
- Temperature Estimation
- HV Isolation
- Operational Limits Protection
- Diagnostics
- Fallback Modes
- Logging
- **Remaining Useful Life** (RUL)
- Safety Diagnostics

Battery Pack - may have one or more cells, even thousands of battery cells. If it has multiple cells these will be connected together in series and parallel. This group of cells will need electrical busbars as interconnects, a mechanical system to hold all of the cells together, a monitoring and control system and maybe a cooling system to manage heat output from the cells.

In every aspect of the operation of the battery pack it's capability will be limited by the weakest cell. Note that the weakest cell might change depending on the operating conditions.

Hence, careful design of the electrical, thermal and mechanical system in a pack is crucial if you want the performance to equal the sum of the parts. These are the **Battery Basics**.

Battery Pack Sizing - in simple terms this will be based on the energy and power demands of the application. The full set of initial requirements to conceptualise a pack is much longer: **Data Required to Size a Pack**. This page will take you through the steps and gradually build up the complexity of the task.

Battery to Vehicle Mechanical Integration - the mechanical structure of the battery is one thing, but we need to consider battery to vehicle mechanical integration. The total vehicle unladen weight can be around 2000kg and the battery pack can be 500 to 600kg and hence a significant portion of the overall weight.

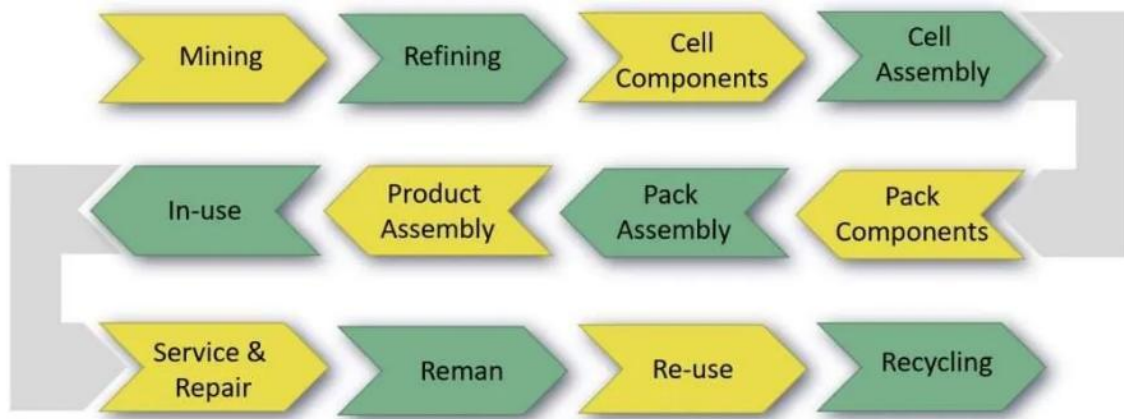


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Battery Value Chain - looks at the whole eco system from mining the raw materials through to recycling.

- Mining
- Refining
- Cell Components
- Cell Assembly
- Pack Components
- Pack Assembly
- Product Assembly
- In-use
- Service and Repair
- Remanufacture
- Re-use
- Recycling



BCCM – Battery Charge Control Module sits between the Battery and the Charger.

BDU – **Battery Disconnect Unit** – contains the **contactors**, **fuses**, pre-charge circuit and **current sensors**. This unit sits inside/on top of the battery pack and has all of the components for monitoring, activating, and deactivating the high-voltage battery system.

Behind the Meter (BTM) – a type of energy storage system installed on the load side of the grid.

BESS – **Battery Energy Storage Systems**

Binder – something that holds the active materials together.

Biomimetics – inspired by nature and can include materials and structures that mimic biological processes.

Bipolar Battery – The bipolar battery essentially moves the series connections inside the cell. This brings a number of advantages and significant challenges.

Black Mass - the intermediate product in battery cell recycling and arrived at after shredding. Black mass contains valuable metals including: cobalt, nickel, manganese and lithium.

Blade Cell – a cell format invented by BYD and optimised for [Cell to Pack](#) designs.



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The BYD Blade cell or perhaps more importantly is the deletion of the module and move to cell to pack. This is basically a prismatic cell, but with a very particular design.

The blade cell has a high aspect ratio and has been designed to maximise the energy that can be put into an LFP battery pack.

BMS – the **Battery Management System** is the control system that manages and reports out the status of the battery.

BMS Testing – as well as establishing the accuracy of SoC and SoH functions it is important to check the handshake with the wider system.

BOL – Beginning of Life.

Boost charging with a CC-CV-CC-CV scheme

Burst Disc – mechanism that can operate under extreme conditions when battery cells are venting or in thermal runaway. Thus allowing the gases to escape the pack safely.

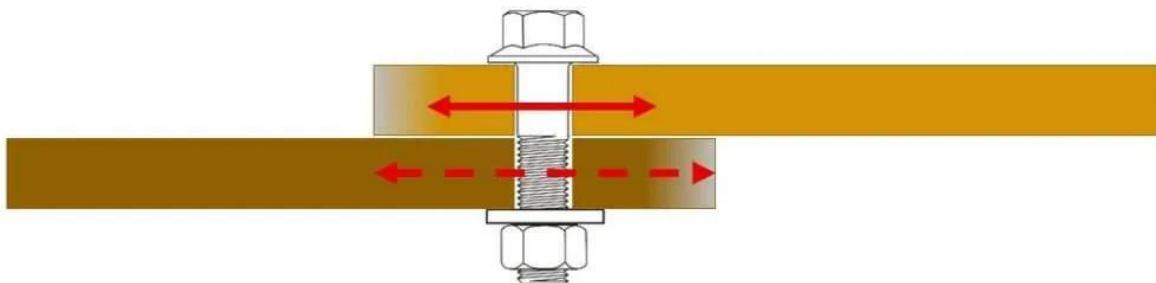
Busbars - are the main electrical connections between cells, modules and connect all of the HV system to the outlet connector. Normally made from copper or aluminium.

Busbar Fasteners – bolted, sprung, welded. With all options it is important to maintain contact pressure, cleanliness and to take account of all of the loads on the joint.

Busbar Joints - a critical aspect around battery pack busbars are the joints. It is important to consider the fundamental requirements of the joint:

- contact resistance
- overlap
- corrosion
- surface treatment
- mixed materials compatibility

Busbar Joint Overlap - the optimal overlap length in a bolted joint should be 5–7 times the busbar thickness.



Busbar to Cell Connectors - physically different for each **cell format**. However, all have the same requirements around low electrical resistance and good mechanical integrity. That mechanical integrity includes the joint with the cell.

Button Cell – otherwise known as a [coin cell](#), used a lot in early stage cell chemistry development.



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C2B – Cell to Body is a step on from C2P and integrates some of the vehicle body parts and functions into the pack and vice versa.

C2C – Cell to Chassis integration that means the battery pack itself is part of the vehicle chassis.

C2P – Cell to Pack is all about reducing cost and increasing the volumetric density of battery packs. This is primarily aimed at road vehicle battery design. This can offer some significant increases in energy density and cost reductions. However, this does remove barriers between cells and hence brings into focus the task of how to stop cell to cell propagation.

Calcium Ion - Calcium ion battery (CIB) chemistry is viewed as greener with a more resource-secure future. Calcium is the fifth most abundant element in the Earth's crust (accounting for approximately 41,500 ppm, compared to lithium's 200 ppm) and benefits from a well-established global supply chain through the limestone and cement industries.

Calendar Ageing – the capacity loss of the battery with time and without cycling.

Calendaring – in the calendaring process the dried anode and cathode are run separately between rollers to compress the active layer. This brings the thickness and porosity to a given dimension.

Calorimetry - a branch of thermodynamics that deals with heat transfer quantification. Heat can be transferred during a variety of processes, such as chemical reactions, phase changes, or dissolution of solutes in a solvent. Calorimetry follows the first law of thermodynamics, which states that energy cannot be created or destroyed, only transferred.

Capacity – battery capacity is expressed in ampere-hours.

Capacity per Gram - the capacity of the anode or cathode material per unit mass.

Carbon Black - an electrically conducting agent that enables the formation of the electrical wiring within an electrode. It has typically been specified by loading, surface area and subsequent powder or electrode resistivity.

Carbon Nanotubes – added to both anodes and cathodes to improve electrical and thermal performance, also add mechanical stability. Can be an enabler for Si anodes.

Case – the enclosure for the pack.

Cathode – the positive electrode, at which electrochemical reduction takes place. As current flows, electrons from the circuit and cations from the electrolytic solution in the device move towards the cathode.

Cathode, Anode and Electrolyte – are the basic building blocks of Cells and Batteries.

Cathode–Electrolyte Interphase - a thin film that forms on the surface of the cathode in electrochemical cells, such as lithium-ion batteries. It is the result of the oxidative decomposition of electrolyte species—including solvents, salts, and additives—which occurs when the cathode operates at high voltages or interacts chemically with the reactive cathode surface. Historically less researched than its anode counterpart, the **solid electrolyte interphase** (SEI), the CEI is increasingly recognized as a critical factor in determining battery cycle life, capacity, and safety, particularly in high-energy-density systems

- **Solid Electrolyte Interphase (SEI)**: forms on the anode, primarily during the first cycle, and is essential for stability.
- **Cathode Electrolyte Interphase (CEI)**: forms on the cathode, is generally thinner, less stable, and more complex than the SEI.

CC – Constant Current



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CC-CV – Constant Current - Constant Voltage

Cell Ageing Tests - a difficult set of tests that require you to think about the analysis procedure and questions they need to solve before you test. Fundamentally we break these tests into Calendar Tests and Cycle Tests.

Cell Assembly - There are 6 steps in the cell assembly process, but there is variations depending on the cell format:

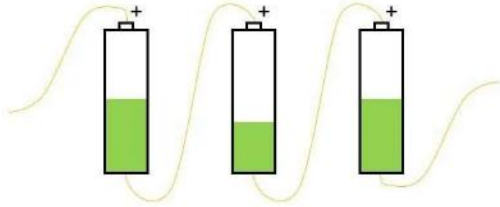
1. Slitting
2. Final drying
3. Cutting
4. Winding or Stacking
5. Terminal welding
6. Canning or Enclosing

Cell Balancing – this is all about the dissipation or movement of energy between cells. The aim being to align them all with respect to state of charge. Aligning the state of charge of all of the cells in a pack will allow the pack to deliver the most energy and power. This becomes more crucial as the pack ages and differences between cells become more significant.

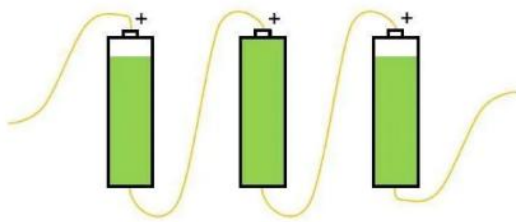


Cell Balancing

A set of **cells connected in series** will all see the same current, whether they are generating it when discharged or accepting it when charged. If all of the cells have the same initial **SoC** and the same capacity then they should charge and discharge equally.



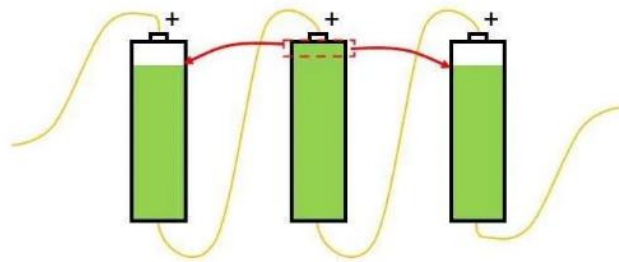
However, if one cell has a slightly lower capacity it will be discharged further in SoC and it will go slightly overvoltage each time it is charged up. Over time this will result in a further reduction in its capacity.



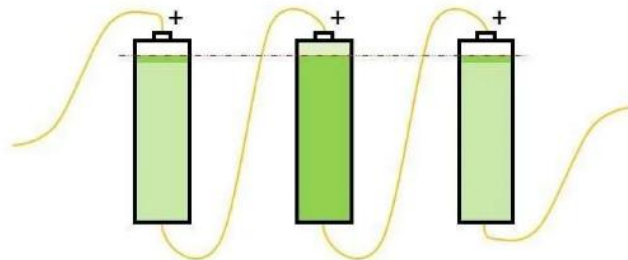
When we then come to recharge this group of cells the centre cell will reach the maximum cell voltage first and the BMS will prevent further charging.

We need to remove charge from this cell so that we can charge the other cells in the string.

If we balance the cells then we can recharge them all to their maximum SoC. This means we need to ideally move charge from the higher SoC cell to the lower SoC cells.



After balancing the centre cell will have a lower SoC, but the 3 cells will all be at the same SoC and so we can now charge them up to the maximum voltage.



The simplest way to balance a cell is to switch on a resistor across a single cell and slightly discharge it.



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Cell Benchmarking -

Cell Canning - the electrodes either as a roll or pack of stacked layers are loaded into the can or pouch. Depending on the cell format will change how this canning or enclosing process is completed.

Cell Cycle Lifetime - when we consider the **lifetime** of a battery cell we normally look at the **cell cycle lifetime** and the **cell calendar lifetime**.

The cell cycle lifetime is the number of charge and discharge cycles that a battery can complete before losing performance. This cycle lifetime is affected by a number of parameters:

- Temperature
- Usable SoC Window
 - upper and lower SoC limits
- Charge Rate
- Discharge Rate
- Temperature Gradient

Cell Defects - there are a number of defects that can occur within a battery cell.

- Open-Circuit Defects
 - tab weld failure
 - tab tear
 - terminal corrosion
 - premature activation of protection device
- Short-Circuit Defects
 - direct short
 - metallic particle contaminants
 - metallic burrs and tears from tabs and foils
 - missing / insufficient separator overhang
 - hole / local weak spot in separator
 - plating-induced short
 - insufficient electrode overhang
 - missing / insufficient coating
 - overloaded electrode coating
 - electrode wrinkle
 - electrode buckle
 - sharp electrode curvature

Cell Design – a look at all elements of what goes into a battery cell and how to optimise the design of everything from the anode porosity through to the tab to case.

Cell Electrode Pressure and Expansion - cell electrode pressure and expansion feels like two conflicting areas that have to be managed to enable performance over lifetime.

Cell External Short Circuit - by cell external short circuit we mean an electrical short circuit, a very low resistance path between the positive and negative terminals of the cell.

Cell Final Assembly and Finishing - there are 4 steps in the final assembly and finishing processes around battery cell manufacture:

1. Filling
2. Formation and Sealing
3. Ageing
4. Final Control Checks



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Cell Joining Techniques - there are many cell joining techniques. When we say joining we mean external electrical cell joints to **busbars**, some of these will be specific to certain cell formats. Firstly though it is good practice to think about the properties and features of these joints:

- electrical
 - low electrical resistance of the joint
 - low resistance maintained over lifetime
- mechanical
 - appropriate pull strength
 - intermetallic and material corrosion resistance
 - vibration durability
 - low mechanical input to cell during joining process
- thermal
 - low thermal resistance
 - low heat input into cell during joining process

Cell Legislation - When designing and prototyping a new battery cell one of the first things we have to confront is shipping the cell to potential customers.

Cell Manufacturing - one part of the battery manufacturing chain, but perhaps one of the most difficult parts. Perhaps worth breaking it into: The Process, Strategy and Capex.

Cell Matching – what level of cell matching do you do prior to assembling a battery pack? Assuming the battery pack will be balanced the first time it is charged and in use.

Cell Manufacturing Equipment - cell manufacturing covers a lot of specialist areas and hence there is a range of equipment suppliers. The **cell manufacturing process** is laid out in 14 steps covering everything from mixing chemicals, dryers, printing and electrical testing. This then breaks down again, requiring equipment and supporting equipment, building infrastructure and software.

Cell Manufacturing Process – there are 3 main sections that we can then break down into 14 steps overall:

1. Electrode Manufacturing
 - a. Mixing
 - b. Coating
 - c. Drying
 - d. Calendering
2. Cell Assembly
 - a. Slitting
 - b. Final Drying
 - c. Cutting
 - d. Winding or Stacking
 - e. Terminal Welding
 - f. Canning or Enclosing
3. Cell Finishing
 - a. Filling
 - b. Formation and Sealing
 - c. Ageing
 - d. Final Control Checks

Cell Mechanics - although a battery cell is an electrical storage system very much in terms of the thermodynamics, there is also a lot of cell mechanics. From the enclosure and it's integrity, through the sealing system to the dynamics of the cell in a harsh environment.

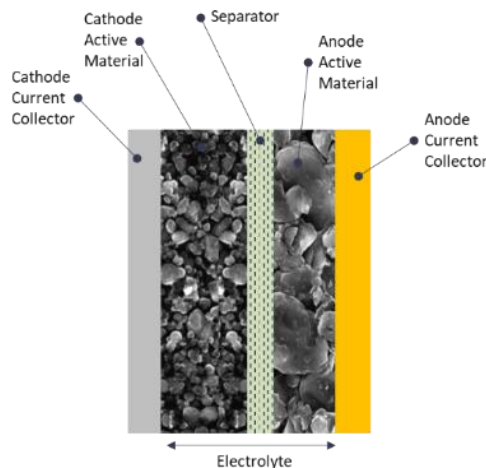


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Cell Roadmap - when looking at a product roadmap there will be a request to understand how the energy storage system will improve throughout the lifetime of the product. Also, you will need to understand if the roadmap contains disruptive elements that might require a redesign of the product.

Cell Stack - the cell stack comprises: anode electrode, anode active material, separator, cathode active material, cathode electrode and of course the electrolyte. The cell stack is the basic unit of the working electrochemistry.



The cell stack comprises:

- anode electrode
- anode active material
- Separator
- cathode active material
- cathode electrode
- Electrolyte

Cell Tab Design - the tab serves as the final current-carrying element in this path. Its current-carrying capacity is therefore a critical factor that affects both electrical efficiency and thermal stability. Any limitation in tab conductance can result in increased ohmic losses, localized heating, and potential degradation of cell lifetime and safety.

Cell Temperature - a critical parameter that you need to know before charging or discharging a cell. A cell is a 3 dimensional structure that is also inhomogeneous and hence you will observe temperature gradients within the cell. The temperature limits, gradients and heat rejection rate will define the overall power capability of the cell. Cell temperature is related to:

- Safety
- Degradation rate
- Instantaneous charge/discharge power

Cell Temperature Sensing - a critical function of any Battery Management System (BMS) this is because the cell temperature needs to be kept within a band to maintain safe operation. This band is narrower still to maintain the lifetime of the cell and hence reduce ageing.

Cell Testing - and the data thereof underpins the fundamental design of a battery pack from the initial sizing through to control system parameterization and final sign-off of the system. These tests come under a few high level

- Diagnostics
- Performance data
 - electrical
 - thermal
 - mechanical
- BMS data
- Ageing performance
- Abuse tests
- Legislative testing



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Cell to Cell Variation - there is going to be Cell to Cell Variation in production and in use. Both of these topics are significant and important to understand as the result can be an under-performing or short-lived battery pack.

Cell Vent - design is a critical aspect of the overall design. Get this right and when things go wrong the cell will vent in a controlled manner. The cell vent is designed to operate at a particular pressure:

- above the normal operating pressure
- below the maximum cell strength limit

Cells – the lowest definable working battery electrochemical element. *Tags:* **Cell, Cells**
Category: **Cells**

Cell Voltage Delta – difference in resting voltage for cells at different points in a series string. A threshold maximum voltage difference will trigger **cell balancing**.

Centralised BMS – long leads are required to connect the central control unit to every cell in the pack.

Charge – the process of electrical energy being converted into chemical energy.

Charge Voltage – voltage that the battery is charged to when charged to full capacity.

Charging Protocols – approaches to charging:

- **Constant Current – Constant Voltage** (CC-CV)
- Constant Power – Constant Voltage (CP-CV)
- Multistage Constant Current – Constant Voltage (MCC-CV)
- Pulse charging
- Boost charging with a CC-CV-CC-CV scheme
- Variable Current Profile (VCP)
- Stepped Constant Current – Constant Voltage (SCC-CV)
- **Non-Linear Voltammetry** (NLV)

Chemistry Analysis - there are a lot of techniques in the area of battery chemistry analysis and here we plan to list and link to further details on those: **Galvanostatic Intermittent Titration Technique**, OCV & Diffusion Coefficient...

Chemistry Mechanics – at a fundamental level the mixture and layers of the active chemistry need to stay in position and intact. Within the cathode and anode mixture binders are used to hold the particles together and to adhere them to the electrode.

During charge and discharge the active layers change in thickness and this can put a significant strain on the active layers.

Choco-SEB - the chocolate swapping electric blocks is an idea from CATL to standardise the swappable battery. Hence important that we look at the format and options that come along from different manufacturers.

CID – Current Interrupt Device, comprises a thin metal diaphragm which is part of the positive terminal. Abnormally high gas pressure inside the cell pushes the diaphragm upwards, breaking the electrical connection, thereby isolating the cell's jellyroll from the external circuit.

Clean Room - a space where the concentration of particles, microbes, and other contaminants is precisely regulated. In the case of batteries there are a number of levels of cleanliness used depending on the material, component and manufacturing stage. Clean rooms are classified according to the number and size of particles permitted per volume of air.



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Clearance – the line-of-sight distance between two conductors through the air.

Cloud Data – data from a **battery management system** can be stored in the cloud. Once there it is possible to run calculations on that pack data and data from other packs to learn more around how it is operating and ageing. This then allows the battery management system to be updated in terms of calibration, limits and even imposing restrictions around its safe use.

CMP – Cell to Module to Pack approach of battery design.

CNT – **Carbon NanoTubes** have high thermal and electrical conductivity, plus high strength making them useful additives to anodes and cathodes.

Coating – the process of applying the active materials to the backing electrodes.

Coating Density - the mass of cathode or anode material applied per unit area.

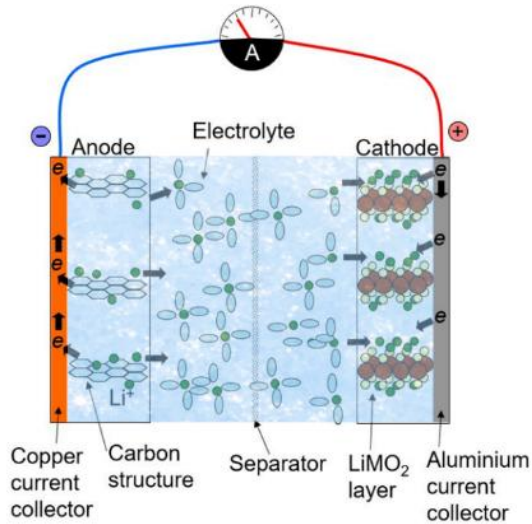
Coin Cell – used a lot in early stage cell chemistry development as it is normally the simplest bilayer.

Cold Temperature Charge / Discharge - at cold temperatures lithium ion cells suffer from a significant decrease in available capacity.



Cold Temperature Charge / Discharge

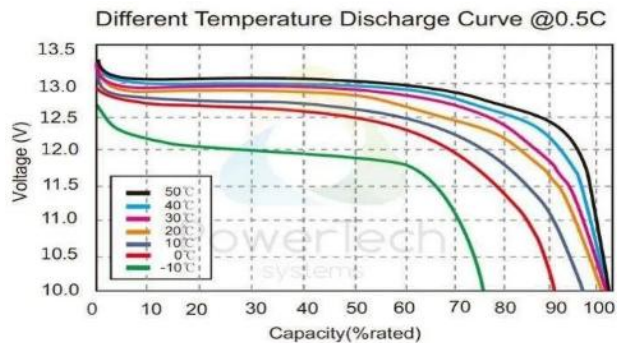
What are the Cold Temperature Charge / Discharge limitations and mechanisms?



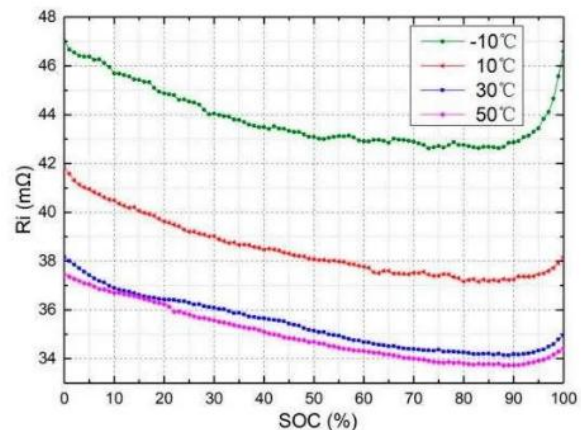
Luo et al describe the reasons for poor performance in cold temperatures as:

1. poor kinetics on both the interphase and the electrodes, which means larger SEI resistance and a reduction in the Li^+ diffusion coefficient in the cathode and anode
2. decreased ionic and electronic conductivity, lower viscosity, and high freezing point of the electrolyte
3. **lithium plating** and Li dendrites on the surface of the anode, which threaten the safety and cycle life of LIBs.

At cold temperatures lithium ion cells suffer from a significant decrease in available capacity.



The DCIR of the cell increases significantly as the temperature decreases. Significantly reducing the available peak and continuous power.



Luo H, Wang Y, Feng YH, Fan XY, Han X, Wang PF. [Lithium-Ion Batteries under Low-Temperature Environment: Challenges and Prospects](#). *Materials* **2022**, 15(22), 8166



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Compression Pads - used to manage the dimensional change of the cell during the breathing process and for the gradual permanent swelling that occurs throughout the battery lifetime. The cell expands during charging and contracts during discharge, this “breathing” is a small change in cell thickness. The permanent swelling can be such that at end of life a cell can be 10% to 20% thicker.

Computed Tomography Scanning of Battery Cells -

Condensation – changes in temperature of the pack components can result in the condensation of water vapour from the air within the pack enclosure. This can result in corrosion, isolation issues and shorts.

Connectors – within a battery pack there will be a large number of connectors. These will be low voltage (LV) power / signal types and high voltage (HV) connectors. These pages will concentrate on the HV from the bolted joint through to the main power connections on the pack.

Constant Current – Constant Voltage (CC-CV) – charging protocol.

Constant Power – Constant Voltage (CP-CV) – charging protocol.

Contactor – a switch that can be operated by the control system. They are essentially a relay.

Control - of the battery pack will be based on the cells, the pack design and the application. From this an envelope will be created where the pack can deliver fully on it's power and energy demands. Outside of this normal operational window the BMS will control the pack in a number of ways.

Cooling Systems – there are a number of **different cooling systems / media** used to extract the heat generated in a battery pack, the main options are:

- Air cooled
- **Passive**
- Active
- Liquid cooled
- Isolated from water-glycol
- **Fully immersed dielectric**
- Phase change
- Active refrigerant cooling
- Passive phase change material (PCM)
- Two phase dielectric fluid

Coolants - typically liquids that allow the transfer of heat between the battery cells and a heat sink. Typically the heat sink is air, but could be water for a boat or a ground heat sink for stationary battery packs. The most commonly used coolants are:

- Air
- Water
- Deionized water
- Water glycol
- Dielectric fluids
 - Single phase
 - Two phase
- Refrigerants

Cooling Plate Design - probably the most common battery cooling system used in electrified vehicles as the system can use water-glycol as the cooling fluid.

- heat transfer coefficient is typically 1000 to 5000 W/m².K



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- cooling fluid temperature increases with heat rejected from a cell, leading to higher delta temperatures on wide spans of the cooling plate
- cools just one surface of the cell, hence creating a delta temperature across the cell
- typically made from thin aluminium for low weight and high thermal conductivity, means they need to be electrically isolated from the cells
- **thermal interface material** required to bridge the gap between coolant plate and cell surface
- power required to cool and flow the fluid needs to be considered in most applications
- coolant liquid can leak from plates, hoses and most likely joints thus risking electrical isolation

Copper - malleable and ductile, excellent thermal and electrical conductivities and good corrosion resistance. Used in current collectors in cells and busbars in packs.

Copper Busbars - initially size at $5A/mm^2$ before doing the detailed electrothermal analysis.

Costs - associated with everything in the battery pack from chemistry, assembly, logistics through to end of life.

Coulomb – unit of electric charge. One coulomb (1C) equals one ampere-second (1As).

Coulomb Counting – SOC Estimation by Coulomb Counting is based on the measurement of the current and integration of that current over time.

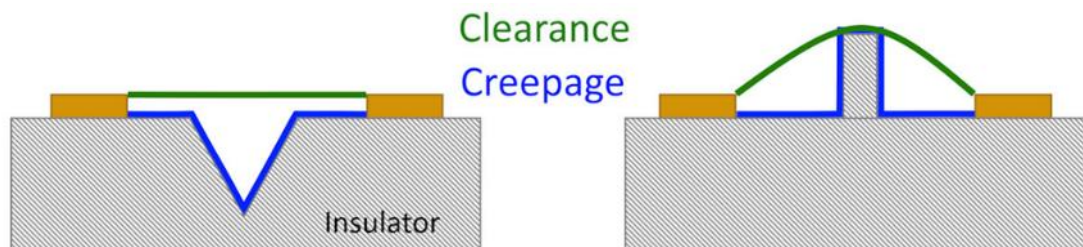
Coulombic Efficiency - also known as Faradaic Efficiency, this is the charge efficiency by which electrons are transferred in a battery. It is the ratio of the total charge extracted from the battery to the total charge input to the battery over a full cycle.

C-rate – a measure of the rate at which a battery is charged or discharged relative to its capacity. It is the charge or discharge current in Amps divided by the cell capacity in Amperehours. An nC-rate is the constant-current charge or discharge rate that a cell can sustain for $1/n$ hours. This current (in A) equates to the cell nominal capacity (i.e. C Ah) multiplied by $n h^{-1}$ i.e. $i=nC$. For example, a fully charged 20Ah cell should be able to deliver 10A for $1/n = C/i = 20/10 = 2$ hrs, or the c-rate is $n=i/C = 0.5h^{-1}$

Creepage – the distance between two conductors on the surfaces of the parts or along the surface of the insulating material.

Creepage and Clearance - high voltage circuits can discharge across a gap, the gap can be through the air or across a surface.

- Creepage: distance between two conductors on the surface.
- Clearance: the distance between two conductors through the air.



Critical Self-Heating Temperature - describes the threshold beyond which thermal runaway becomes almost certain. At T_2 the cell is self-heating so rapidly that the reaction cannot be stopped anymore.



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For NMC/graphite cells this occurs at around 170 – 190 °C, compared to 230 – 260 °C for LFP/graphite.

Crush Testing – important at Cell, Module and Pack level. There are a number of standards, look at these and the variations across them.

CSC – Cell Sensor Circuit that brings voltage sensing, temperature sensing and balancing together for a sub-grouping of cells. This then communicates with the BMS master board in a **Master and Slave BMS**.

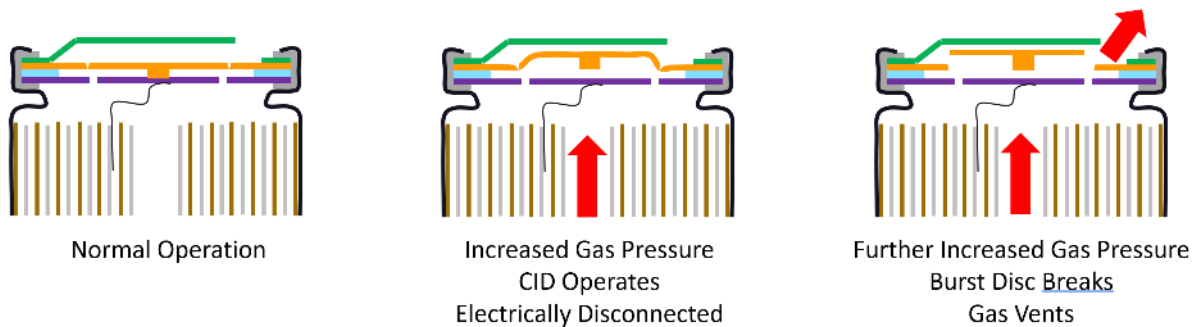
CTB – **Cell to Body** design that further integrates elements of the battery pack into the overall structural design.

CTC – Cell to Chassis integration that means the battery pack itself is part of the vehicle chassis.

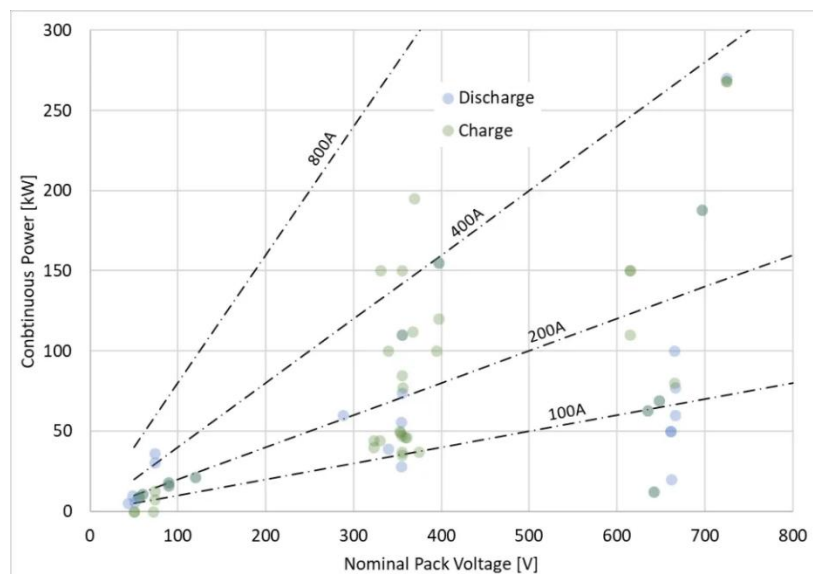
Current Collector - can be found as the metallic backing sheet of the anode and the cathode. These are normally copper or aluminium, depending on the chemistry and on whether it is the anode or the cathode. Typically the current collectors are 5 to 25µm in thickness

Current Derate – a reduced current charge or discharge capability.

Current Interrupt Device (CID) – installed in cells to ensure their safety. The CID disconnects the cell electrically when the pressure inside the cell increases above the design level.



Current Rating – we normally consider the continuous and peak current rating. The **continuous current rating** is really useful in sizing busbars, fuses, contactors and thermal management systems.



The peak rating vs time is another system target we use early on as this is set by the cell capability and for a number of components is limited by the transient thermal capability.



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Current Sensor – can include resistive or magnetic elements based on their structure. We use these elements for sensing the current to be measured.



A specialist supplier of custom built lithium battery packs, COTS battery modules, portable power and energy storage systems for industrial, energy, autonomous and defence applications. Designed for high reliability in the most demanding environments, for sectors as diverse as oil & gas, oceanography and robotics. Custom design and battery pack assembly from a UK based battery pack manufacturer with over 30 years experience.

Cutoff Voltage – specified closed circuit voltage at which a cell discharge is terminated.

Cycle Ageing – the capacity loss in a battery through charge and discharge repeated cycling.

Cycle Life – the number of charge and discharge cycles that a battery can complete before losing performance.

Cylindrical Cell – The layers of the cell are wound in a spiral. Normally these cells have the lower case as the negative terminal and the top centre as the positive terminal.

Cylindrical Cell Sidewall Rupture – a significant issue in most module designs as it nearly always results in thermal propagation to neighbouring cells.

DC – Direct Current

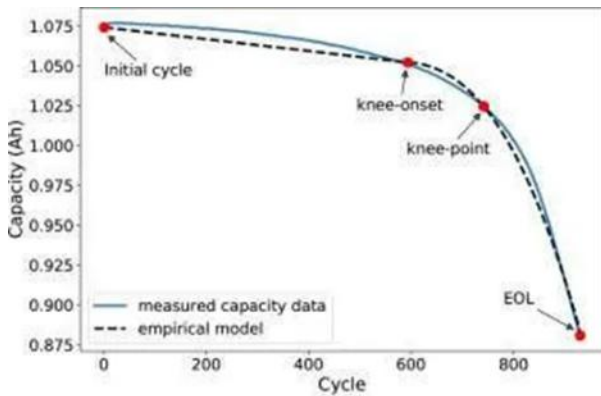
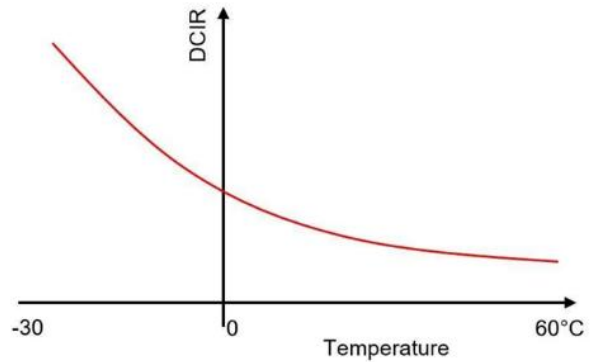
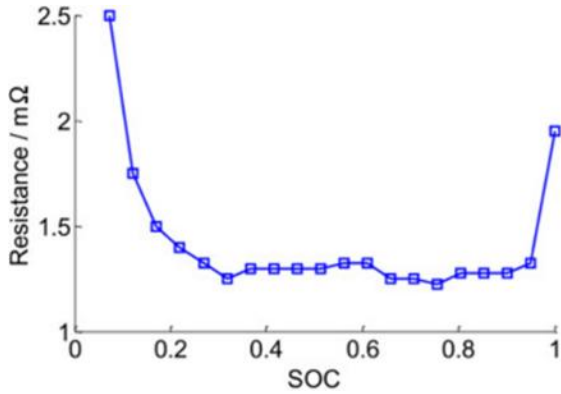
DCIR – Direct Current Internal Resistance is the internal resistance of the cell. This is the resistance in charge and discharge to a direct current demand applied across the terminals.



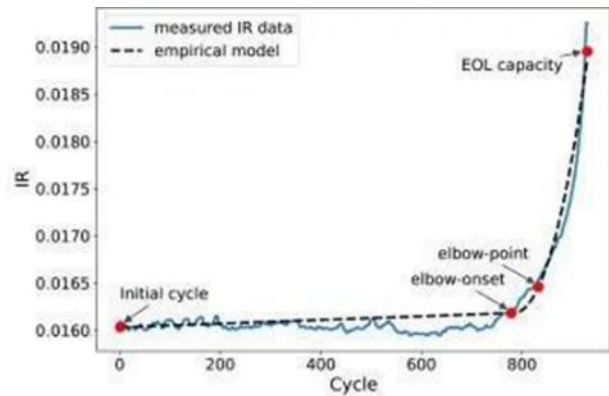
Direct Current Internal Resistance (DCIR)

We often quote a single number for the DC internal resistance of a cell (DCIR). This is normally at 50% SoC and 25°C and for a 10s discharge pulse.

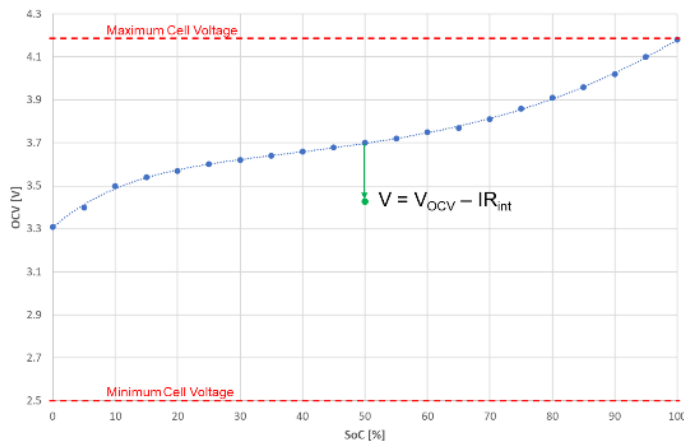
However, the DCIR of a cell changes versus SoC, temperature, pulse time and age of the cell.



(a) capacity



(b) internal resistance



If we have an OCV of 3.7V @ 50% SOC and an internal resistance of 0.025Ω and we draw 10A from the cell the voltage will drop 0.25V This is simply Ohms Law.

$$V = 3.7V - 10A \times 0.025\Omega = 3.45V$$

Hence the voltage of the cell under a 10A load will be 3.45V.

We can also calculate the maximum current we can draw taking the cell down to the minimum voltage:

$$2.5V = 3.7V - I \times 0.025\Omega$$

$$I = (3.7V - 2.5V) / 0.025\Omega = 48A$$



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Defects - Within every component and sub-assembly of a battery pack there can be defects.

- **Cell Defects**
 - Open Circuit
 - Short Circuit
- **Pack Defects**
 - Components
 - Functions

De-Rate – when the charge or discharge current (power) limits communicated to the vehicle are reduced.

Dielectric Immersion Cooling - for a battery pack is perhaps the ultimate method of controlling **cell temperatures**. Dielectric Fluid: an electrically non-conductive liquid that has a very high resistance to electrical breakdown, even at high voltages.

Differential Voltage Analysis - non-invasive electrochemical voltage spectroscopy technique, used in the diagnosis of the internal state and degradation of batteries.

Discharge – the process of chemical energy being converted into electrical energy. The cell has a current demand and hence the state of charge (SOC) is decreasing. Establishing the **maximum cell discharge capability** is difficult without understanding the design in detail. However, you can work towards establishing this limit with a number of measurements and calculations.

DoD – Depth of Discharge is equal to $1 - \text{SoC}$



In the process of building the Benchmarking posts we have developed a number of databases and spreadsheets to make that easier.

Doyle Fuller Newman Battery Model - often abbreviated as the Newman mode, is the starting point for a lot of battery electrochemical models.

The galvanostatic charge and discharge of a lithium anode/solid polymer separator/insertion cathode cell is modelled using concentrated solution theory. The model is general enough to include a wide range of polymeric separator materials, lithium salts, and composite insertion cathodes. Insertion of lithium into the active cathode material is simulated using superposition, thus greatly simplifying the numerical calculations. Variable physical properties are permitted in the model.

Marc Doyle, Thomas F. Fuller and John Newman, Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell, 1993 J. Electrochem. Soc. **140** 1526

Drone Battery Systems - The fundamental parameters are:

- Peak takeoff power
- Flight time
- Range
- Peak power required to safely land
- Reserve energy required for aborted landing
- Accurate SOx parameters
- Lifetime



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Drying - immediately after coating the electrodes are dried. This is done with convective air dryers on a continuous process. The solvents are recovered from this process. Infrared technology is used as a booster on Anode lines.

Dry Electrode – eliminating the solvents in the processing and coating of the electrodes has a number of benefits.

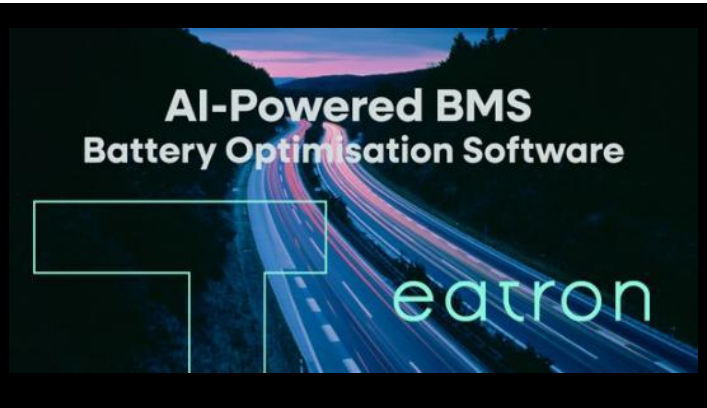
Dry Room – typically aim for a dew point of -30°C or lower, equivalent to less than 1% relative humidity (RH).

Dry Separator – the separator is produced without solvents being used in the process.

Dual-Ion – battery technology that offers a low cost solution for grid based storage. Cations and anions both participate in the intercalation and deintercalation processes using graphite as both cathode and anode material.

DUT – Device Under Test

Offering embedded applications for High and Low Voltage Battery Management that are not only automotive grade, safe and robust but also integrated with AI & cloud layers with analytics, offering OTA updates and continuous software improvements to enable its customers to achieve superior performance and reliability over the lifetime of the vehicles.



E-Bus – buses fully or partially propelled by battery-powered electric motors.

ECM – Equivalent Circuit Model is an electrical circuit designed to represent the dynamic behaviour of a battery cell using electronic components (capacitors, resistors and inductors).

Efficiency – When you charge and then discharge a battery cell you lose energy, the ratio of the amount of discharge to charge energy is the efficiency.

- Coulombic Efficiency
- Voltaic Efficiency
- [Round Trip Efficiency](#)

EIS = [Electrochemical Impedance Spectroscopy](#)

E-LCV – light commercial vehicles, including vans and light-duty trucks, fully or partially propelled by battery-power electric motors.

Electrical - the electrical design of a battery covers a wide array of topics.

Electrical Energy Consumption - electrical energy consumption can be calculated by first looking at the electrical power and then looking at the time over which that power is used.

Power (P) = Voltage (V) × Current (I)

where:

- I is current (Amperes)
- P is power (Watts)



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- V is voltage (Volts)

Then energy used by an electrical appliance, we can use the formula:

$$\text{Energy (E)} = \text{Power (P)} \times \text{Time (t)}$$

where:

- P is power (Watts)
- t is time (seconds)
- E is energy (Joules)

Electric Vehicle - a vehicle with one or more electric motors that provide the propulsion. The electrical supply doesn't have to be a battery as it could be off-vehicle or from a generator.

- **BEV** = Battery Electric Vehicle: has a battery pack that supplies power to an electric drive motor.
- **HEV** = Hybrid Electric Vehicle
- **PHEV** = Plugin Hybrid Electric Vehicle: has an internal combustion engine that is assisted by one or more electric motors that are supplied power from a battery pack that can be recharged from the engine and the grid (plugin).
- **FCEV** = Fuel Cell Electric Vehicle: a fuel cell converts hydrogen to electricity that in turn supplies an electric drive motor. This is buffered by a battery that can deliver transfer power and transient regeneration, thus allowing the fuel cell to operate at a more constant power level.
- **REEV** = Range Extended Electric Vehicle: a battery electric vehicle with an electric generator that can supply power to the electric motor / battery to extend the vehicle's range. Base on the fact that fuel + generator is a higher energy density than batteries.

Electric Vehicle Charging - as the automotive world is moving towards electrification, Electric vehicle charging is the talk of the town. Range anxiety is one of the biggest issues of electric vehicle adoption. Charging or Fast charging electric vehicle is key infrastructure requirement. The process of adding energy to a battery cell or cells in a pack and so moving the **State of Charge** from a low value towards 100%. This simple process is actually far from simple and covers the electrochemical, thermal, electrical, infrastructure, standardisation and all the way through to electricity generation.

Electrification - typically means replacing an engine that burns fossil fuel partly or completely with an electric motor and battery system. This approach can be applied to many different systems from portable generators through to air transport. Designing a battery pack means you need to understand the electrification system and requirements that it will operate in. This is the same whether the battery is for a remote control or a space station. It might just be fewer requirements, but there will be requirements and inputs from the system.

Electrochemical Impedance Spectroscopy (EIS) - offers a non-destructive route to in-situ analysis of the dynamic processes occurring inside a battery by measuring the complex impedance.

Electrode – the electrical part of a cell and consists of a backing metallic sheet with active material printed on the surface.

Electrode Dimensions - the cell **electrodes** are key parts of a battery cell and as such the dimensions of the electrodes are also a key aspect. The electrode dimensions define the area and volume of the active material, hence the overall **capacity** of the cell.

Electrode Manufacturing - there are 4 steps in electrode manufacturing:

1. Mixing



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2. Coating
3. Drying
4. Calendering

The electrode manufacturing process is the same for all of the cell chemistries and formats in terms of the basic steps.

Electrolyte – the medium that allows ionic transport between the electrodes during charging and discharging of a cell.

Electrolyte Additives – used for a number of functions, including:

- improved SEI formation
- reduce irreversible capacity loss and gas generation
- enhance thermal stability of LiPF_6
- protect the cathode material from dissolution and overcharge
- improve the physical properties of the electrolyte

Electrolyte Decomposition - when thinking about electrolyte decomposition we should consider this in stages:

- decomposition of electrolyte in bulk storage
- decomposition of electrolyte prior to cell formation
- in use decomposition / aging
- decomposition of the electrolyte during thermal runaway

Electrolyte Filling - a partial vacuum is created in the cell and a pre-determined quantity of electrolyte is delivered to the cell. The partial vacuum helps the distribution and hence wetting of all layers within the cell. The electrolyte is dispensed based on a defined volume of liquid. A second quality check is the weight of the cell before and immediately after filling.

Enclosure Design - the key elements of a battery pack enclosure design, the high level functions can be grouped into:

- Mechanical
- Electrical
- Thermal
- Chemical
- Safety

End of Line Testing - needs to be applied to materials, components, sub-systems and complete assemblies.

Energy - defined as the capacity of a body for doing work. The SI unit of energy is the joule. 1 joule is the work done by a force of 1 newton moving a distance of 1 metre in the direction of the force. The product of power (watts) and duration (seconds). One watt second = one Joule. All forms of energy fall into two categories, potential and kinetic energy.

Energy Management System (EMS) – overarching management of the system and combination of sensors, components and battery packs. In a vehicle this can be a function that is part of the Vehicle Control System (VCS).

Energy Storage - device or physical media that store some form of energy to perform some useful operation at a later time. There are so many options for storing energy, let's concentrate on electrical energy. Of course this can and often does entail a transfer between electrical and another form:

- **Hydroelectric:** electricity is used to drive electric motors that mechanically drive pumps to move water from a lower to a higher height above ground level. Then when



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the energy is required the water drives the pumps in reverse and the electric motors generate electricity.

- **Compressed Air:** similar to hydroelectricity, but the working medium is air and it is compressed and re-expanded.
- **Batteries:** electrical energy is stored electrochemically. There are many options in terms of **chemistry** for battery energy storage, some better suited to stationary applications – such as **flow batteries**.
- **Supercapacitors:** often used for high power/low energy applications as capacitors are able to deliver very high discharge rates, but energy storage density is lower than batteries.
- **Thermal Storage:** electricity is used to heat a thermal mass. The thermal mass is insulated to reduce heat loss. The thermal mass is then used directly to heat air/water for building heating or to drive steam turbines to turn the energy back into electricity.
- **Hydrogen:** electricity is used to electrolyse water, the resultant hydrogen is compressed or liquidised and stored. A fuel cell can then be used to generate electricity from the hydrogen gas.

EOL – End of Life

Equivalent Circuit Model - a phenomenological model widely used in industry to simulate the voltage response for subsequent Battery Management System control and state estimation. By conducting experiments to measure the battery voltage at various SoCs and temperatures it is possible to develop an ECM that relates the applied current and the voltage.

EREV – **Extended Range Electric Vehicle** is an electric vehicle with the addition of an internal combustion engine generator.

eScooter - development of the eScooter battery is really interesting. This 2 wheel vehicle might just be THE electric vehicle. The eScooter title appears to cover the stand on electrified scooter through to the more powerful sit on electrified Vespa.

ETP or E2P – electrode to pack technology removes the cell casing and instead puts the stack together directly in the pack enclosure.

E-Truck – medium- and heavy-duty trucks fully or partially propelled by battery-powered electric motors.

EU Battery Regulation - new EU Battery Regulation 2023/1542 entered into force on 17 August 2023 and covers the whole lifecycle of batteries from production to reuse and recycling. While the Battery Regulation is already in force, further legal documents will be published in the coming years specifying certain aspects of the implementation (see timeline below). Among the new requirements, for example, is the Battery Passport that goes with every new LMT, industrial (> 2 kWh), and EV battery and contains material pathways, product specifications and lifetime data.

EUCAR Hazard Levels - define the outcome of cell level safety testing. These levels are normally used to describe the outcome of tests such as overcharge as part of the cell specification.



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Description	Description	Classification Level & Effect
0	No effect	No effect. No loss of functionality
1	Passive protection activated	No defect; no leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/ Damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage, mass change < 50%	No venting, fire or flame; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting, mass change ≥ 50%	No fire or flame; no rupture; no explosion. Weight loss ≥50% of electrolyte weight (electrolyte = solvent + salt).
5	Fire or flame	No rupture; no explosion (i.e. no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (i.e. disintegration of the cell).

EV – Electric Vehicle

EVSE – Electric Vehicle Supply Equipment or Charging Station (Can be AC or DC). These are outside the Vehicle either Type 1 or 2 AC in our Home, Office or Public or Type 3 DC Fast Charging Public Stations.

Extended Range Electric Vehicle - an electric vehicle system with an additional energy storage and conversion system. A Fuel Cell could be that alternative, but we tend to describe that as a FCEV and keep the EREV or REEV definition as an internal combustion engine based generator.

Extra-Low Voltage (ELV) - systems are broken down into three categories:

1. Safety Extra Low Voltage (SELV)
2. Protective Extra Low Voltage (PELV)
3. Functional Extra Low Voltage (FELV)

These categories describe circuits operating at voltage levels that are generally considered safe (typically ≤ 50 V AC or ≤ 120 V ripple-free DC) but distinguish between how they are isolated from higher voltage systems (like the mains) and whether they are connected to earth.

Faraday Constant – the electric charge carried by one mole of electrons (or singly-ionized ions).

Fast Charging – charge time is a key metric for a battery pack, especially packs in transport applications. As technology evolves there is a push to reduce charge times.

FC – Fast Charging is all about rapidly charging the cell or battery pack in a very short time. Normally this would not take the cell to fully charged as it is all about getting a usable amount of energy into the battery in the shortest time.

Fire Suppression - there are mechanical, electrical and control strategies in place to prevent a battery pack going into thermal runaway but at some point these are likely to fail and hence the need for fire suppression.

The basic list of extinguishants:

- Water Extinguishants
- Foam Extinguishants
- Powder/Dry Powder Extinguishants
- Carbon Dioxide (CO₂)
- Halon-Based Extinguishants



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Flexible Printed Circuits (FPCs) – the hidden nervous system of high-voltage batteries, yet their reliability is often overlooked.

Flow Battery - in a Flow battery we essentially have two chemical components that pass through a reaction chamber where they are separated by a membrane. A significant benefit is that the charged fluids can be stored in containers, significantly extending the energy storage capacity.

Formation – the process of initially charging and discharging the cell after it has been assembled. So named because this process “forms” the electrochemical system.

Formation Temperature - during formation several processes take place that lead to significant changes in the cell properties. These processes include:

- solid electrolyte interphase (SEI) formation
- cathode electrolyte interphase (CEI) formation
- structural changes in the active material
- copper corrosion
- aluminium dissolution

Based on the Arrhenius equation, temperature affects the reaction kinetic. Thus having a significant impact on the resultant properties.

Formation & Aging - Formation is the process of initially charging and discharging the cell after it has been assembled. After the formation process, the battery goes through a period of aging, which involves repeated cycles at different rates and rest times. The purpose of aging is to stabilize the battery’s electrochemical performance and make its voltage more accurate.

Formats - there are many different formats of battery cells, from button, cylindrical, prismatic and pouch. There are also a number of other formats and lots of sub-formats.



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Formats

Button/Coin Cells - mostly used in primary cells and available in a wide range of sizes for hearing aids, card readers and calculators.

In the chemistry research world coin cells are used for early testing of chemistry as they are small and simple to make in the lab. Therefore, it is possible to make and electrically test a large number of cells prior to moving to a larger format.



Coin Pouch Cell - the active cell elements are circular and normally the same size as the coin cells. However, the case of the cell is a circular pouch.

Cylindrical Cells - the layers of the cell are wound in a spiral. Normally these cells have the lower case as the negative terminal and the top centre as the positive terminal. The cylindrical format limits the packing density to at best hexagonal close pack.



Pouch Cells - they look like an aluminium jiffy bag with +ve and -ve terminals protruding from the edge. They need to be supported mechanically and need a controlled pressure applied to the surface to deliver the power and energy over their lifetime.



Prismatic Cells - as the name suggests these are a prismatic block, normally with the outer case made from aluminium. These cells need a pressure applied to the main faces of the cell in order to maintain their performance over time.



Blade Cells - a derivation of the prismatic cell, but an important step as it enable the LFP EV pack by removing the overhead of the module. First introduced by **BYD**, the blade format has been adopted by a number of manufacturers.





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Fluoride-Ion – seen as a replacement for lithium and possibly the post-lithium technology with “up to 7x the Wh/kg” of current Lithium technology.

Foil - or **Electrode** is the backing metallic sheet (**current collector**) with active material printed on the surface.

Front of the Meter (FTM) – a type of energy storage system installed on the utility or grid side.

Functional Safety - all about reducing the risks around the electrical and control aspects of a battery design. The process needs to work through the following steps:

1. detailed analysis of the intrinsic hazards of lithium-based batteries
2. hazard and risk assessment of the automotive lithium-based battery
3. address the specific risks deriving from the automotive application
4. safety goals to required to keep the battery under control
5. safety requirements for the hardware design

Fuse – device that protects electrical circuits against undesired high currents. We can use passive fuses and pyro fuses in battery design.

Galvanostatic Intermittent Titration Technique (GITT) – measures the transient voltage change and **open circuit voltage (OCV)** change during the charging and discharging processes using only a constant current supply and specified cut-off intervals.

Gas Pressure – the gas inside the cell is a mix of CO, CO₂, H₂, C₂H₂ and other chemicals. This mix is dependent on cell chemistry.

In a 21700 cell the pressure post formation is ~260mbar for an NMC811/Gr+Si cell.

This pressure changes by ~140mbar over charge/discharge and increases by ~1mbar for every ageing cycle.

Gas Sensing – one way of understanding when a cell has failed and a possibility of thermal runaway if there is no intervention.

GB38031 – China EV safety standard from Ministry of Industry and Information Technology (MIIT).

GITT – Galvanostatic Intermittent Titration Technique is a measurement technique used to estimate diffusion coefficients, OCV, over-potentials and resistance. First described by Weppner and R. A. Huggins.

Graphene Aluminium Ion – graphene cathode and aluminium anode, high charge rate battery technology.

Graphite – line allotrope of carbon, made of carbon atoms bound hexagonally in sheets.

- **Hexagonal Layers:** graphite consists of carbon atoms arranged in a hexagonal lattice, forming flat, two-dimensional sheets.
- **Bonding Structure:** within each layer, every carbon atom is strongly covalently bonded to three other carbon atoms.
- **Layered Structure:** these hexagonal sheets are stacked on top of each other.
- **Weak Interlayer Bonding:** the layers are held together by weak van der Waals forces, not strong covalent bonds. Because of this, the layers can easily slide over one another, which makes graphite soft, slippery, and an excellent lubricant.

It is used as a thermal-insulating electrical-conductor, as a nuclear-reactor moderator and as a self-lubricant.



The Battery A to Z

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In lithium ion batteries it is used as the **anode**. In battery cells we see the use of natural and synthetic graphite.

Graphite Anode - the negative or reducing electrode that releases electrons to the external circuit and oxidizes during and electrochemical reaction. In a lithium ion cell the anode is commonly graphite or graphite and silicon. Natural graphite anode has the advantages of lower cost, high capacity and lower energy consumption compared with the corresponding synthetic anode. But synthetic graphite performs much better in electrolyte compatibility, fast-charge turnaround and battery longevity.

Gravimetric Energy Density – **Wh/kg** of a battery pack.

Grid Battery Energy Storage Systems – typically MWh units grouped to provide 10 to 250MWh of storage. Often though these systems are specified in terms of power capability and duration. This definition fits with the language used utility scale systems.

Harness - a low voltage / signal harness is required to connect the voltage measurement points, temperature sensors and other sensors to the measurement channels. This can be done directly with a central control board or a number of lower level measurement boards that are then daisy chained to allow them to communicate with the central processor.

Heat Generation in a cell can be defined quite simple for the case where the cell is operating within it's normal limits. The two largest parts of this are the joule heating (I^2R) and the reversible entropy. At high charge and discharge rates the joule heating term dominates and hence can be a good first estimate of the heating. At lower rates the reversible term can be endothermic and hence can produce strange results if ignored.



Heat Generation in a Cell

Heat generation in a cell can be defined quite simple for the case where the cell is operating within its normal limits. The following expression gives the heat flow [W]:

$$\dot{Q} = I \left(V - V_{oc} - T_{ref} \frac{dV_{oc}}{dT} \right)$$

Where: I = current [A], V_{oc} = open circuit voltage [V], T_{ref} = reference temperature [K], T = cell temperature [K]

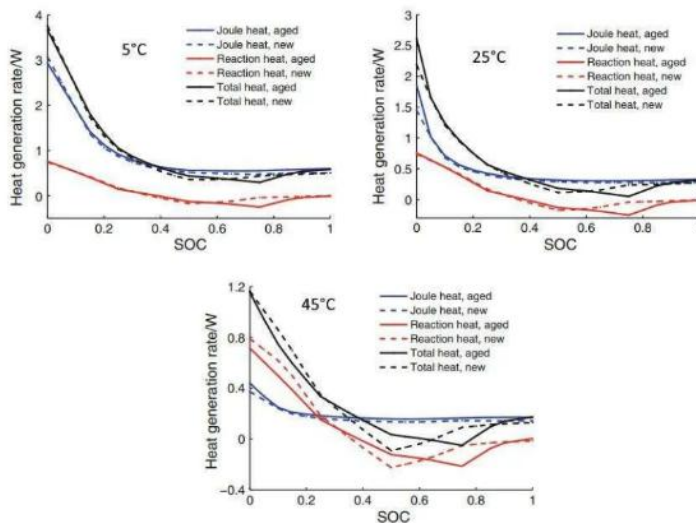
The first part of this equation is the irreversible Joule heating term:

$$I(V - V_{oc})$$

The second part is the reversible entropy term or Reaction heat terms:

$$I T_{ref} \frac{dV_{oc}}{dT}$$

A comparison of these two terms is shown based on the experimental analysis of a power type prismatic LMO-G (lithium manganese oxide/graphite) with nominal capacity 8 Ah. The battery has a maximum discharge current rate of 20C and maximum charge current rate of 10C.



Guangming Liu, Minggao Ouyang, Languang Lu, Jianqiu Li, Xuebing Han, [Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors](#), J Therm Anal Calorim (2014) 116:1001–1010

From these graphs you see that the entropy term can be endothermic under certain conditions. When charging this cell the entropy term becomes very significant, especially at low SoC. Charging the fully discharged cell shows that it will cool down even further until it reaches around 20% SoC.

This shows how important it is to fully characterise the thermal behaviour of a cell in order to properly model and then design a battery pack to optimise charging.



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Heat Pump – extracts heat from a source, such as the battery pack, it then amplifies (increases the working fluid temperature) and transfers the heat to a radiator where it can be cooled by the ambient air.

HES – Hybrid Energy Storage System is where we use a mix of battery cell types to improve the overall capability of the battery pack.

High Concentration Electrolytes - engineered by combining a high concentration of lithium salt with weakly coordinating diluents. This unique chemical composition drives the creation of an anion-rich solvation structure. This tailored environment is highly advantageous because it enables the formation of dense, inorganic **Solid Electrolyte Interphase (SEI)** and **Cathode Electrolyte Interphase (CEI)** protective layers.

High Voltage – in battery design this is anything above 60V.

High Voltage Interlock Loop (HVIL) – a low voltage signal loop that runs in parallel with and part of the HV connections, cables and components. Meaning that if the HV loop is broken the HVIL is also broken. Thus giving the ability to easily detect a disconnect in the HV system.

HiPot Test - applies a high potential to the cell to measure leakage current and/or internal resistance. HiPot testing is used to detect short circuits due to defects and/or insulation failures and is often used in battery **Quality Control (QC)**.

- **Pros:** Nondestructive, rapid (~seconds), and can directly measure the presence of an internal short.
- **Cons:** Not spatially resolved and unable to detect latent defects.

HOMO-LUMO – the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels of the electrolyte.

HPPC – Hybrid Pulse Power Characterisation

Humidity – typically a [dry room](#) with a dew point of -30°C or lower is equivalent to less than 1% relative humidity (RH).

HV – High Voltage battery pack. “High Voltage” means the classification of an electric component or circuit, if its working voltage is $> 60\text{ V}$ and $\leq 1500\text{ V DC}$ or $> 30\text{ V}$ and $\leq 1000\text{ V AC}$ root mean square (rms).

HV Battery Junction Box - brings together the measurement, control and connections of the battery high voltage (HV) system. Therefore, it would normally contain:

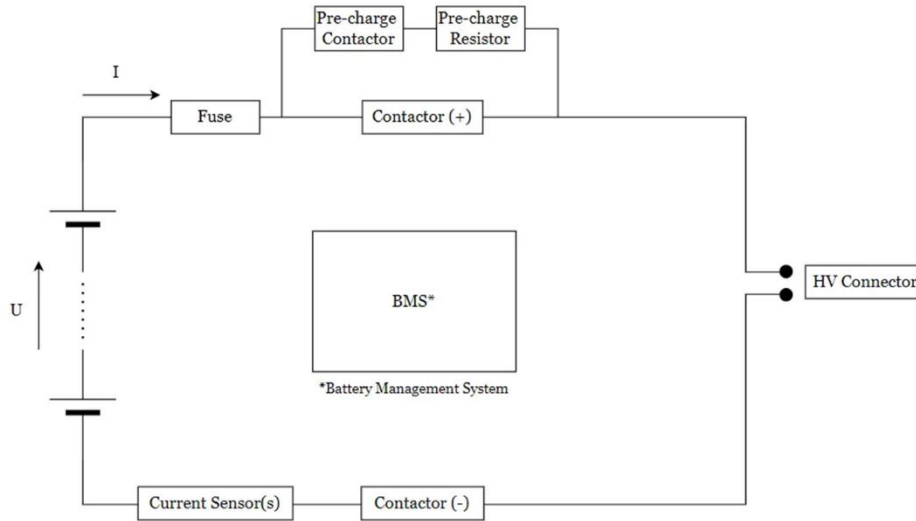
- contactors
- pre-charge resistor and contactors
- fuses
- current sensor
- connectors



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HV Distribution



HVIL – High Voltage Interlock Loop.

Hybrid Battery Pack - one that uses more than one type of battery cell or supercapacitor. The aim being to provide a broader set of capabilities, such as:

- Improved balance between energy and power
- Hot and cold performance
- More accurate state estimation

Hybrid Electric Vehicle (HEV) – Parallel Hybrid or Hybrid Electric Vehicle abbreviated HEV. Called the “Self-Charging Hybrid” by Toyota as the battery pack cannot be independently charged from a plug.

Hybrid Energy Storage Systems (HESS) - consist of two or more energy storage devices that offer different attributes and together can deliver a more capable overall system.

Hybrid System – a system that stores and uses energy in more than one form, eg a vehicle that has a petrol engine and an electric motor that can recover energy to store in a battery and reuse at a later time.

ICA – Incremental Capacity Analysis is an analysis method used to investigate the state of health. It is based on the differentiation of the battery capacity over the battery voltage. Can be used for a full or a partial cycle.

IEC 62619 - specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications, including stationary applications.



Gain new insights into battery material behaviour, in real time, with single particle resolution

Incremental Capacity Analysis (ICA) - is a non-destructive/damaging method used to investigate the [state of health](#). It is based on the differentiation of the battery capacity over the battery voltage. Can be used for a full or a partial cycle. Frequently used alongside [Differential Voltage Analysis](#) (DVA) for estimating [State of Health](#) (SOH). **Note** ICA is the inverse of DVA.



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Industrial Vehicles - cover a wide range from manufacturing pallet movers, through robots, construction vehicles and airport vehicles. These applications can be tough in terms of environment, 24/7 operation and in terms of their unique requirements.

Initial Coulombic Efficiency - the ratio of the first discharge capacity to the first charge capacity in a battery, representing the percentage of charge recovered after the initial cycle.

Instrumenting Cells – if you are going to instrument a cell you need to be able to do this reliably and robustly. The process flow diagram illustrates the experimental stages employed for cell instrumentation and includes: sensor fabrication, cell modification and sensor insertion. The diagram highlights the different verification stages for assessing LIB performance, operation and ageing.

Insulation – use of a poor conducting material to restrict flow of current to almost zero.

Insulation and Isolation – electrically we need to insulate and isolate the battery.

Insulation Resistance – value of resistance between any two points.

Internal Resistance – the DC internal resistance of a battery pack.

Inverter – converts between DC and AC. DC being the battery pack and AC being a motor or grid. These units can be one-direction or bi-directional.

Iron Air Battery - a reversible rust process where the oxygen from the air rusts the iron during discharge and then during charging the iron oxide is converted back into iron and oxygen is released.

Isolation – disconnection and separation of electrical equipment from every source in such a way that the disconnection and separation is secure.

Isolation Resistance – the value of resistance, measured at a specified voltage, between a HV bus and ground. For the complete HV system to ground with the contactors closed should be $>500\Omega/V$ and hence for a battery pack its resistance target must be specified by the HV System designer, typically $>1,500k\Omega$.

Joining Techniques for Pack Enclosures

1. Mechanical / Adhesives
2. Friction Stir Welding
3. GMAW Welding
4. Hybrid Laser Welding
5. Hot Wire Laser
6. Precision Power Laser

Joule - the SI unit of energy is the joule. Defined as: 1 joule is the work done by a force of 1 newton moving a distance of 1 metre in the direction of the force. It may also be defined in electrical terms as: the amount of energy needed to sustain 1 amp for 1 sec in a 1 ohm resistance. Named after James Prescott Joule, one of the first to measure the “rate of exchange” between mechanical energy and heat.

Kalman Filter – an estimator of information of a system from noisy (or uncertain) directly or indirectly related measurements.

Key Cell Metrics - there are a number of key cell metrics that we expect to see on any cell specification sheet:

- Wh/kg = [gravimetric energy density](#)
- Wh/litre
- [Ragone Plot](#): W/kg vs Wh/kg



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- W/kg
- W/litre
- \$/kWh
- Number of cycles at C/3 discharge and C/3 charge down to 80% SoH
- Safety
- Environmental impact assessment
- Normalised Heat Rate [W/Ah]
- Efficiency = discharge energy / charge energy – this is particularly important to grid storage applications

Key Pack Metrics - when designing a battery pack you will always be asked to benchmark it. For this there are a number of key metrics:

- Safety
- Wh/kg – [Pack Gravimetric Energy Density](#)
- Wh/litre – [Pack Volumetric Energy Density](#)
- W/kg
 - [Ragone Plot](#) – Power density vs Energy Density
- W/litre
- \$/kWh
- [Cell to Pack mass ratio](#)
- [Cell to Pack volume ratio](#)
- Durability – % of pack capacity available after 10 years

Knee Point – describes a sudden change in the gradient of a cell cycling curve. Also called:

- rollover failure
- nonlinear aging
- sudden death
- saturation
- second-stage degradation
- two-phase degradation
- capacity plunge
- drop-off

kWh – kilo **Watt hour** is 1000 Watt hours and is a unit of energy equivalent to 1000 Watts of power expended for one hour of time.

Labels – a battery pack needs a nameplate and labels that meet the requirements of the market it is to be sold for use in.

Laser Welding - one of many [welding techniques](#) used in the battery industry. Welding in Multi mode instead of Single mode laser beam, can increase the thermal strain on the Current Collector due to the higher heat input.

LCA – Life Cycle Analysis

Lead Acid - a battery with electrodes of lead oxide and metallic lead that are separated by an electrolyte of sulphuric acid. Energy density 40-60 Wh/kg.

Leak Detection - a key test for systems and components within the battery pack from cells, contactors, cooling system and the enclosure.

Leclanche Cell – a electrolytic cell also known as a dry cell that uses a moist paste rather than a liquid as an electrolyte. Flashlight batteries are dry cells with a zinc cup for an anode, a



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carbon rod for a cathode, and a paste made of powdered carbon, NH_4Cl , ZnCl_2 , and MnO_2 for an electrolyte.

Legislation, Rules and Regulations – there are many different pieces of legislation, rules and regulations around battery design. Especially when we look at that from chemistry to pack and all applications.

LEV – Light Electric Vehicle

LFP – Lithium Iron Phosphate, a **lithium ion** cathode material with graphite used as the anode. This cell chemistry is typically lower energy density than **NMC** or **NCA**, but is also seen as being safer.

Lifetime - For **primary cells** the shelf storage time or calendar ageing discharge rate is the most important factor with respect to lifetime as this will determine how long you can store the cell before using it.

For **secondary cells or rechargeable cells** we are interested in the calendar ageing and the cycle ageing. The calendar ageing will show how the capacity reduces with time, even when the battery cell is not being used. The cycle ageing will show you how many cycles the cell can deliver at a given charge and discharge rate.

As a rule of thumb we would expect to get 1000 complete cycles for an energy cell and 3000 complete cycles for a power cell before the capacity dropped to 80% of the original Ah value when new.



Lifetime

Ageing of a battery manifests itself in two ways:

1. **Capacity fade** – the available energy at a defined discharge rate will decrease.
2. **Increasing internal resistance** – as the internal resistance increases the voltage will drop lower under load. Hence the available power before hitting the minimum voltage will decrease. Also, the I^2R heating of the cell will increase.

Causes of degradation:

- Time
- High Temperature
- High Voltage/SoC
- Current Load
- Low Temperature
- Stoichiometry
- Mechanical Stress
- Low Voltage/SoC

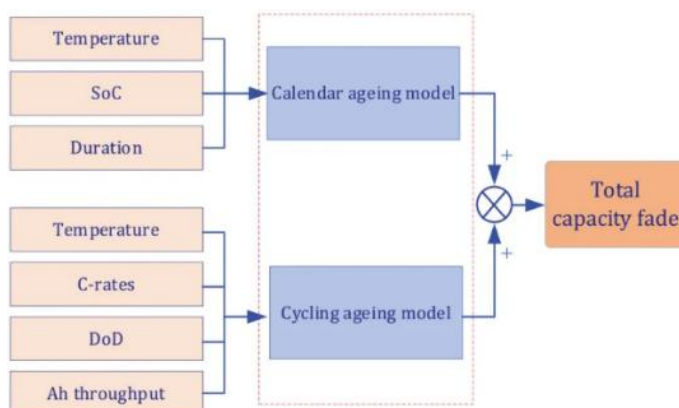
Typically the five principle degradation mechanisms are:

1. SEI growth
2. Electrolyte dry-out
3. Lithium plating
4. Mechanical loss of active material
5. Particle cracking

The standard method used by industry has two fundamental test regimes as inputs:

1. **calendar ageing** – where the cells are held at different fixed temperatures and SoC.
2. **cycle ageing** – where the cells are cycled through a complete charge discharge at different fixed temperatures.

At regular intervals the capacity of the cells are measured. This data is then used as inputs to the ageing predictions, a simple summation of these two parts gives the overall ageing model.



T. M. N. Bui, M. Sheikh, T. Q. Dinh, A. Gupta, D. W. Widanalage and J. Marco, “A Study of Reduced Battery Degradation Through State-of-Charge Pre-Conditioning for Vehicle-to-Grid Operations,” in *IEEE Access*, vol. 9, pp. 155871-155896, 2021



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Life Cycle Analysis - of a battery is quite complex and hence the intention is to cover that in posts. First though we need to breakdown the stages:

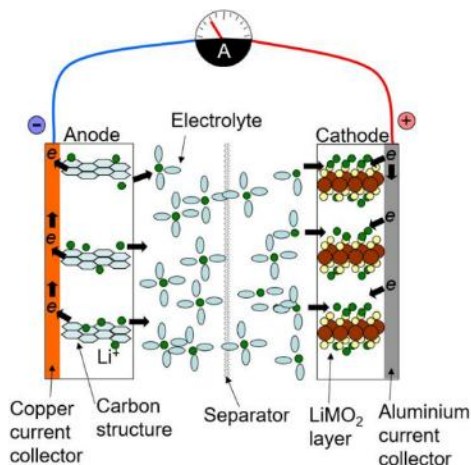
- Mining
- Refining
- Processing
- Assembling
 - **Cell Assembly Process**
- Use
- **4R's**
 - Repair
 - Remanufacture
 - Reuse
 - Recycling
- Landfill

LiPF₆ – Lithium hexafluorophosphate

Lithium - a soft, silvery-white alkali metal. Atomic number of 3 and symbol Li. In the **Lithium Ion** cell the cathode is a lithium transition metal oxide, eg manganese or cobalt or a combination of transitional metals. The anode is a graphite-based material, which can intercalate or release lithium.

Lithium Air - promised as the beyond lithium ion technology with unrivaled energy density.

Lithium Ion Chemistry - in the **Lithium Ion** cell the cathode is a lithium transition metal oxide, eg manganese or cobalt or a combination of transitional metals. The anode is a graphite-based material, which can intercalate or release lithium.



When discharge begins the lithiated carbon releases a Li⁺ ion and a free electron. The Li⁺ ion, which moves towards the electrolyte, replaces another Li⁺ ion from the electrolyte, which moves towards the cathode. At the cathode/electrolyte interface, Li⁺ ions then become intercalated into the cathode and the associated electron is used by the external device.

This process is reversed when we charge the cell.

Lithium Iron Phosphate - abbreviated as LFP is a **lithium ion** cathode material with graphite used as the anode. This cell chemistry is typically lower energy density than **NMC** or **NCA**, but is also seen as being safer.

- **Cathode:** lithium iron phosphate ($LiFePO_4$), which acts as the positive electrode, coated onto an aluminium foil.
- **Anode:** typically composed of carbon (usually graphite) layered on copper foil.
- **Electrolyte:** contains lithium salts in an organic solvent facilitates the movement of lithium ions between these electrodes
- **Separator:** microporous polymer prevents direct contact but allows ion passage.



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LiFePO_4 features an orthorhombic crystal structure of the olivine type. This lattice is built from three distinct units: PO_4 tetrahedra, LiO_6 octahedra, and FeO_6 octahedra. A defining characteristic of this chemistry is the strong phosphorus-oxygen (P-O) covalent bond within the PO_4 tetrahedra. This robust bond tightly “locks” the oxygen atoms into the lattice, making them extremely difficult to detach even under severe thermal stress or overcharge conditions. This structural rigidity prevents the lattice from collapsing or releasing oxygen, giving LFP batteries their exceptional thermodynamic stability and safety profile.

- LiFePO_4
- Voltage range 2.0V to 3.6V
- Capacity ~170mAh/g (theoretical)
- Energy density at cell level: 186Wh/kg and 419Wh/litre (2024)
- Maximum theoretical energy density ~380Wh/kg ~1100 Wh/L

Lithium Metal Battery - differs from the traditional **lithium ion battery** in that it uses Metallic Lithium as the anode. Widely regarded as the next-generation battery system thanks to their intrinsically high energy density, however, these batteries have a trade-off between energy density and cycle life.

Lithium Plating – This is the deposition of metallic lithium on the surface of the graphite anode. This is one of the most significant degradation mechanisms.

Lithium Rich Manganese – high specific capacity because of both cationic and anionic redox activity and are expected to be developed and applied as cathode materials for a new generation of high-energy density lithium-ion batteries.

Lithium Sulfur – perhaps the most mature of the beyond Li-ion’ battery chemistries with a potential energy density of >600Wh/kg.

Lithium Titanium Oxide - shortened to Lithium Titanate and abbreviated as LTO in the battery world. An LTO battery is a modified lithium-ion battery that uses lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) nanocrystals, instead of carbon, on the surface of its anode. This gives an effective area ~30x that of carbon. The options for the cathode material are varied.

LMB – Lithium Metal Battery

LMFP – **Lithium Manganese Iron Phosphate** brings a lot of the advantages of LFP and improves on the energy density.

LMO – Lithium Manganese Oxide

LMR = **Lithium Manganese Rich**

LNMO – Lithium Nickel Manganese Oxide

Localised High Concentration Electrolytes - characterised by a high concentration of lithium salt combined with weakly coordinating diluents. The key advantages and applications of LHCEs include:

- High Anodic Stability and Efficiency
- Enhanced Safety and Flame Retardancy
- Improved Operational Range

Long Duration Energy Storage (LDES) – a storage system that has a discharge duration of longer than 10 hours and can store energy for hours, days, weeks or even between seasons.

Lossless Balancing – this approach switches cells in and out of the circuit during charging. This means we have a lot of switches and that these switches have to be designed to carry the full current.



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Low Voltage – DC system operating below 60V.

LRM – Lithium Rich Manganese has a high specific capacity because of both cationic and anionic redox activity

LTMO – Layered Transition Metal Oxide

LTO = **Lithium Titanium Oxide**

LV – abbreviation of Low Voltage and in automotive world this means below 60V DC.

M3P – **CATL's** trade name for their own developed variation on LFP.

Magnesium-Ion – function is very similar to lithium-ion batteries, comparable energy density to lithium-ion along with potential for improvement as there are double the electrons for every individual magnesium ion.

mAh – milli Ampere-hour is one thousandth of an Ampere-hour (Ah), this is commonly used when stating the capacity of rechargeable batteries used in mobile phones. 1 mAh = 3.6 Coulombs

Manufacturing Process – the three major sections of the cell manufacturing process are: Electrode Manufacturing, Cell Assembly and Cell Finishing.

Maritime Battery Applications - come in many forms and sizes, all have the common theme of the marine environment.

Master and Slave BMS – a slave will monitor and control a sub-set/module of cells and communicate back to the master.

Materials - throughout the battery from a single cell to a complete pack there are many different materials. Hence it is important to look at those in terms of their characteristics and application in battery design.

Mechanical - the mechanical design of the cell to pack to system covers so many elements that we have broken this down into sub-sections and sub-pages.

Mechanical Shock - in a lot of applications batteries will experience a shock load. Hence it is important that both cells, packs and the system is tested against the correct legislation and design requirements.

Memory Effect – phenomenon in which a cell, operated in successive cycles to the same, but less than a full, depth of discharge experiences a depression of its discharge voltage and temporarily loses the rest of its capacity at normal voltage levels.

Metrics – a Pugh Matrix is a good way of making a high level comparison between applications and the key pack metrics.

In the case of mobile consumer products such as a mobile phone the lifetime of the battery is perhaps not as important as it would be in the case of a grid storage system. The mobile phone has a 2 to 3 year life before most are upgraded. A grid storage system needs 20 years of operation.

Microgrid – a local power generation and distribution system integrating distributed energy sources, storage devices, energy conversion equipment, loads, and monitoring and protection devices, etc., which is able to operate on and off grid.

Mica - covers a group of silicate minerals used in a thin sheet form as a thermal barrier in battery pack designs to contain **thermal runaway**.

Mid Nickel – chemistry with a Nickel content of 40% to 60%.



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Mild Hybrid Electric Vehicle (MHEV) – a hybrid electric vehicle where the electric system operates below 60V. This limits the amount of power that the system can deliver, but also significantly reduces the costs.

Mixing - the anode and cathode materials are mixed just prior to being delivered to the coating machine. This mixing process takes time to ensure the homogeneity of the slurry.

- **Cathode:** active material (eg NMC622), polymer binder (e.g. PVdF), solvent (e.g. NMP) and conductive additives (e.g. carbon) are batch mixed.
- **Anode:** active material (eg graphite or graphite + silicon), conductive material (eg carbon black), and polymer binder (eg carboxymethyl cellulose, CMC)

Mobile Battery Applications - there are a lot of mobile battery applications and we can group those under this heading.

Modelling - of any battery pack will cover the electrical-thermal performance attributes of the cells. This mathematical modelling is likely to initially be a simple spreadsheet based model, then over time as the data and requirements mature so will the model.

Materials => Cell Design => Cell Assembly => Cells => Modules => Pack => System => Recycling

Module – a common grouping of cells that can be built as a sub-assembly and be replicated many times to form a total battery pack. Normally this will include:

- Cells in series and parallel
- Electrical interconnects between cells
- Voltage sense harness
- Temperature sensors
- Local control board for sensing
- Mechanical system to hold all of the cells – for pouch and prismatic cells the module will need to apply pressure over the lifetime of the cells to support their operation.
- Heating/cooling interface

Module Design - a group of cells, traditionally a physical unit that can be transported to enable a lower cost service and repair of the battery pack.

Module External Short Circuit - an electrical short circuit, a very low resistance path between the positive and negative terminals of the module. The purpose of this test is to simulate an abuse condition for the module where it is mishandled or misused. The maximum current could be limited by a fuse in the module. Insights as to the behaviour of the cells can be gained from analysis of the individual **cell external short circuit** tests,

Module Testing - testing the **module** or a group of cells is an important step in the development of a battery pack and it's robustness. Fundamentally you are looking to establish:

- Performance
- Electrical
- Mechanical
- Thermal
- Legislative Testing

Motors – by motors we mean electric motors and as part of the overall system it is important to understand the basics. So many terms and types that it can be daunting:

- Brushed DC Motor
- Brushless Motor
- Induction Motor



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- Permanent Magnet DC (PMDC)
- Permanent Magnet Synchronous Motor (PMSM)
- Stepper Motor
- Synchronous Motor

Multistage Constant Current – Constant Voltage (MCC-CV) – charging protocol

Na⁺ – **sodium ion** cell.

Nail Test – originally designed to replicate a cell failure caused by a piece of rogue metal that gets into the cell during production. This metal particle can create an **internal short-circuit** between the anode and cathode resulting in the **thermal runaway** of the cell.

The metal nail causes a short circuit between the active layers and hence rapid electrical heating. This is one of the most severe cell tests and part of a suite of abuse tests. There are a number of methods that can be used to **trigger thermal runaway** of a cell.

Na Ion – Sodium Ion battery cell.

NCMA – Nickel Cobalt Manganese Aluminium cathodes are more stable than NMC.

Negative Electrode – the **anode**.

NEV – new energy vehicles, including EV, hydrogen and other new type of fuel cell vehicles.

NFPA 855 - the primary standard and benchmark for the installation of **Battery Energy Storage Systems** (BESS) in North America, specifically designed to mitigate major risks such as **thermal runaway**, fire, and toxic gas release. It covers the design, installation, commissioning, and maintenance of various **battery chemistries**, including Lithium-Ion, Lead-Acid, and Flow Batteries.

Nickel - pure nickel is malleable and ductile, and is resistant to corrosion in air or water, and hence is used as a protective coating on **busbars** or just at busbar joints.

Pure nickel is manufactured by the Mond process, in which impure nickel is reacted with carbon monoxide (CO) to produce Ni(CO)₄, which is then decomposed at 200°C to yield 99.99% Ni.

Nickel Cadmium – rechargeable battery that uses nickel oxide hydroxide and metallic cadmium as electrodes. Today it is the technology of choice for several highly demanding industrial applications. This is due to: superior resistance to mechanical and electrical stress able to operate at extreme temperatures and a frequently cycling temperature.

Nickel Hydrogen – has the positive electrode of nickel oxide from the nickel-cadmium cell, and a hydrogen negative electrode from the hydrogen-oxygen fuel cell. The energy density is low at ~60Wh/kg, cost high, but cycle life can be ~200,000 and hence find a niche application in space craft.

Nickel Iron – the NiFe battery, nickel(III) oxide-hydroxide positive plates and iron negative plates, with an electrolyte of potassium hydroxide.

Nickel Metal Hydride – battery has a nickel-hydroxide cathode, a metal hydride (a variety of metal alloys are used) anode, and aqueous potassium hydroxide electrolyte. This is a rechargeable battery chemistry that has been superseded by lithium ion, but has seen a lot of use in Toyota hybrids. Energy density 40-110 Wh/kg at cell level.

Nickel Zinc Battery – consists of a Nickel Oxide cathode and a Zinc anode in a small amount of potassium hydroxide electrolyte.

NiMH – Nickel Metal Hydride



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Ni-Rich – lithium-ion cells that have greater than 75% Nickel in the cathode.

NMC – Lithium Nickel Manganese Cobalt Oxides are a family of mixed metal oxides of lithium, nickel, manganese and cobalt. Nickel is known for its high specific energy, but poor stability. Manganese has low specific energy but offers the ability to form spinel structures that allow low internal resistance.

NMP – *N*-Methyl-2-pyrrolidone is an organic solvent used heavily in lithium ion battery fabrication, as a solvent for electrode preparation, because NMP has a unique ability to dissolve polyvinylidene fluoride binder.

Nominal - the Nominal Capacity, Energy and Voltage in battery engineering are important terms to define.

Nominal Capacity - of a cell is the capacity (Ah) measured at a standard temperature and charge / discharge rate. The discharge capacity test is preceded by a standard charge cycle and ends at a given terminal voltage. The charge capacity is preceded by a standard discharge cycle and ends in Constant Voltage (CV) mode when the current drops to that defined by the standard charge cycle.

Nominal Energy - of a cell is the measured charge / discharge electrical energy at a given **c-rate** and temperature. The cycles are specified as the standard charge discharge cycles and hence end at a given terminal voltage during discharge and at a end charge current during the constant voltage charge cycle.

Nominal Voltage – of a cell is specified at a given charge / discharge rate and temperature. It is calculated from the measured Nominal Capacity and Nominal Energy. Nominal Voltage equals Nominal Energy divided by Nominal Capacity.

N-Methyl-2-Pyrrolidone (NMP) – an organic solvent used heavily in lithium ion battery fabrication, as a solvent for electrode preparation, because NMP has a unique ability to dissolve polyvinylidene fluoride binder. Safety:

- It is toxic to the reproductive system of male and female test animals.
 - The reproductive effects of NMP have not been studied in humans.
 - Based on the animal tests, you should treat NMP as a potential human reproductive hazard.
- Overexposure to NMP irritates:
 - eyes
 - skin
 - nose
 - throat
- Can also affect the central nervous system or brain causing symptoms of drunkenness similar to the effects of drinking alcohol.

N/P Ratio - refers to the ratio between the *effective capacity* of the **anode** (negative electrode, N) and the **cathode** (positive electrode, P). In simple terms, it compares how much lithium the anode can store versus how much the cathode can provide.

OBC = On Board Charger rectifies or converts the AC mains current into DC and sends it to the Battery Pack with a handshake to the BMS that defines charge limits and capability at any point in time.

OCV = Open Circuit Voltage is the no load voltage as measured across the terminals of a cell or even across a pack.

Ohm Ampere-hour – a useful metric when looking for a cell with the lowest internal resistance.



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Open Circuit Voltage (OCV) – is the potential difference between the positive and negative terminals when no current flows and the cell is at rest.

Overcharge – charging beyond the maximum cell capacity, a critical safety issue for the large-scale application of lithium-ion batteries.

Pack Defects - When we look at battery pack design we need to think about the physical defects that get included based on poor design / manufacturing / assembly or all of these together. These can be broken down by component, sub-system and by looking at the functions: mechanical, thermal, electrical and control.

Pack Design – it is important to look at the components and the system, plus we look at Mechanical, Electrical, Thermal, Safety and Control.

Pack Enclosure - A battery pack enclosure can be in many forms depending on the application. We can break down the functions of the enclosure into these headings:

- Mechanical
- Electrical
- Thermal
- Safety
- Manufacture
- Transport
- 4R's

Pack Enclosure Materials - a number of different materials and construction techniques have been used:

- Steel
- Aluminium
- Carbon fibre
- Plastic

Pack External Short Circuit - by pack external short circuit we mean an electrical short circuit, a very low resistance path between the positive and negative terminals of the pack.

The purpose of this test is to simulate an abuse condition for the pack where it is mishandled or misused.

The maximum current could be limited by a fuse, contactors or pyro fuse. Legislation should be reviewed for the application to understand the short circuit test, in addition the pack design guidance on ensuring the safe operation of the pack should be adhered to.

Pack Internal Resistance – a key parameter to calculate and then measure is the battery pack internal resistance. This is the DC internal resistance (DCIR) and would be quoted against temperature, state of charge, state of health and charge/discharge time.

Pack Manufacturing - covers all levels from from single cells where tabs, temperature sensor and simple control circuits are added through to assemblies with thousands of cells and complex cooling systems.

Pack Mass - when looking at battery design we need to know the pack mass for a number of reasons, irrespective of the application:

- transportation
- case structural requirements
- vehicle or location structural requirements
- recycling



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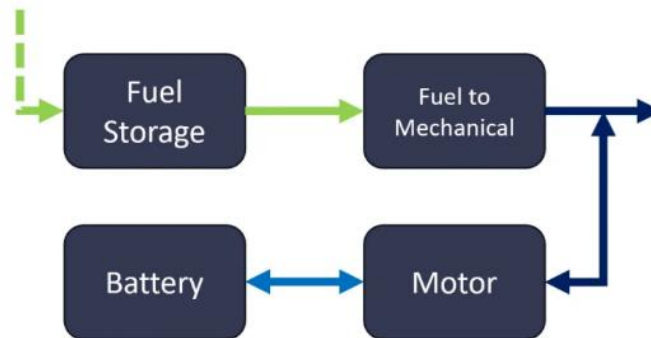
Pack Mechanics - the mechanical design of a battery pack needs to consider every element of the system. You need to look at static stiffness, dynamic stiffness and behaviour of components.

Pack Testing - battery packs are designed to last a decade or more in harsh environments, preferably without the need to be serviced or repaired. Therefore it is important to carry out comprehensive pack testing.

Pack Thermal Runaway - at a pack level we need to consider more than the cells when we look at thermal runaway. However, we need to start with the cell.

Pack to System Mechanics - the mechanical structure of the battery is one thing, but we need to consider pack to system mechanics and the integration.

Parallel Hybrid - here we see that the connection between the two systems is at the mechanical outputs. This means that the fuel to mechanical system has to operate over a wider speed and torque range, but being mechanically connected means the fuel to mechanical output is more efficient overall.



Pros

- recuperation of mechanical energy
- optimisation of the fuel to mechanical system
- single refuelling system

Cons

- complex system calibration

Particle Cracking - when we look at [battery lifetime](#) we see particle cracking as one of the mechanisms of capacity loss. Particle cracking is the mechanical fracture of particles in the cathode or anode materials and caused by stress on those particles. The primary driver is the charge discharge movement of Lithium ions that results in the expansion and contraction of the electrodes.

Particle Size Distribution (PSD) – The PSD of active materials directly impacts their tap density and compactibility—two critical factors that determine how densely an electrode can be packed during calendaring. A higher tap density allows for denser coatings, which is essential when aiming for higher energy density in cells.

Parts List for a Battery Pack just lists the major systems and the parts, including software for the BMS.

Passive Balancing - perhaps the simplest form of cell balancing with a resistor that is switched on and off across the cell. In the example shown with the 3 cells the balancing resistor would be switched on for the centre cell. Discharging this cell and losing the energy to heat in the balance resistor (typically 30Ω to 40Ω).



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Passive Cooling - means the battery cell or pack is not actively cooled, instead it relies on heat conduction, radiation and convection. This heat transfer will apply in both directions, to and from the environment.

Passive cooling should be the starting assumption for all battery pack designs, the drive cycles and user cases could set requirements for a more aggressive thermal management system. However, it is always good to start with the simplest approach.

PAS 63100:2024 - has been written to help installers manage the fire related hazards associated with **Battery Energy Storage Systems** (BESS).

PbA – abbreviation of **lead acid battery**.

PBA – Prussian Blue Analogues

pCAM – **Precursor Cathode Active Material** is a powder-like substance critical to manufacture lithium-ion batteries. It contains materials such as: Nickel, Cobalt, Manganese.

Perforated Current Collectors - using laser-perforated copper foil allows the silicon-carbon composite to form inter-penetrating "stitches" through the current collector, tightly holding the electrode together and preventing delamination caused by expansion forces.

Performance Testing - we do performance testing at Cell, Module, Pack and System level. These tests would normally include:

- Capacity
 - Ah capacity
 - vs temperature
 - vs rate
- Energy
 - Wh capacity
 - vs temperature
 - vs rate
- Power
 - Peak discharge
 - Continuous discharge
 - Charge

Phase Change Material - there are a number of different **battery cooling options**, a close coupled phase change material is not going to cool the battery but absorb thermal energy if the cells get too hot.

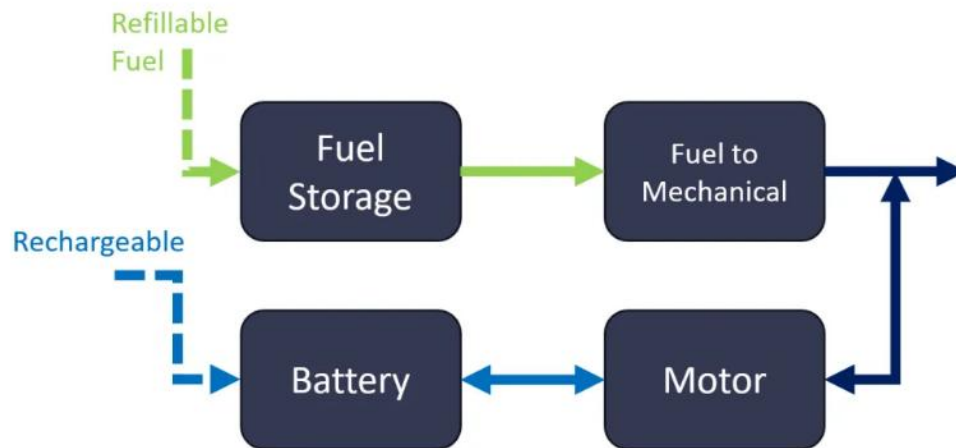
Plastics - a vast array of plastics are used across the battery pack for structure, sealing, isolation and protection.

Plug-in Hybrid Electric Drive - the main addition here is you can charge the battery pack from the grid. To make this worthwhile the battery pack is made larger, extending the electric only range.



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Pros

- recuperation of mechanical energy
- optimisation of the fuel to mechanical system
- longer electric only operation

Cons

- complex system calibration
- two refuelling options

Most notably the battery pack can be recharged from the grid, hence “Plug-In”.

Polyacrylic Acid - used as a **binder** for active materials. Particularly it has been applied to anodes with **Silicon** as it provides a strong flexible adhesive that can accommodate the high expansion.

Polyethylene Terephthalate - used in the battery industry as it has a number of strong properties:

- high structural stability
- electrical insulation
- resistance to cracking
- low water absorption
- 100% recyclable

Polytetrafluoroethylene - used as a **binder**, for both anodes and cathodes due to its high chemical and thermal resistance.

Commonly known as Teflon, a thermoplastic polymer used for non-stick coatings and bearings.

Polyvinylidene Fluoride - used as a **binder** and a coating on **separators**. Widely used, especially for cathodes, known for its good mechanical, chemical, and electrochemical properties.

Positive Electrode – the **cathode**.

Positive Temperature Coefficient (PTC) - device is so named as it increases in resistance as the temperature increases. Hence as a device within a battery cell it protects the cell against over-current or short circuits.

Potassium Ion – potential to be a low cost storage based chemistry, but large large change of ~60% of graphite with the insertion of K ions puts high strain on lattice and so limits cycling.

Pouch Cell – they look like an aluminium jiffy bag with +ve and -ve terminals protruding from the edge. They need to be supported mechanically and need a controlled pressure applied to the surface to deliver the power and energy over their lifetime. **Power vs Energy Cell** – what are the key differences between them.



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Power Electronics - when designing a battery it is important to understand the system and that means the power electronics.

Power Tools - the failures of these packs that have a tough life mechanically and the DIY abuse mode is to use (discharge) and then store them in a discharged state until required again in 6 months time. Hence cell imbalance and over-discharged pack failure modes are common.

Precharge – when closing battery contactors onto a capacitor load there would be a very high current that could cause damage to the contactors or cells, or result in the fuse blowing. Thus a **precharge resistor** and contactor allows that maximum current to be controlled.

Pre-Charge Resistor – when the battery pack contactors are closed onto a motor and inverter there will be an inrush of current into the inverter capacitor. This very high current is at a minimum likely to age the contactors, it could permanently damage the contactors.

Precursor Cathode Active Material (pCAM) – a powder-like substance critical to manufacture lithium-ion batteries. It contains materials such as: Nickel, Cobalt, Manganese.

Prelithiation – introduces extra active lithium ions through various lithium sources. These extra lithium ions contribute to the formation of the solid electrolyte interphase (SEI), hence improving the delivered energy density of the cell.

Pressure Equalisation Vent – when changing altitude the pressure and hence forces on a large battery pack can be significant. This can cause the vent disc to break or put pressure on the sealing system. Thus a gortex vent is often used to allow the pressure inside the pack to equalise with the ambient conditions.

Primary Cell – a cell that can only be discharged once.

Prismatic Cell – as the name suggests these are a prismatic block, normally with the outer case made from aluminium.

Pulse charging – charging current is pulsed, could be from minutes to many kHz

Pyro Fuse – a fuse that can be blown by a signal.

Quality Control – at all stages of battery manufacturing we need to have Quality Control (QC). As battery technology continues to evolve, so too must our strategies for ensuring their safety and reliability. This means testing and analysis to ensure all of the manufacturing processes are in control.

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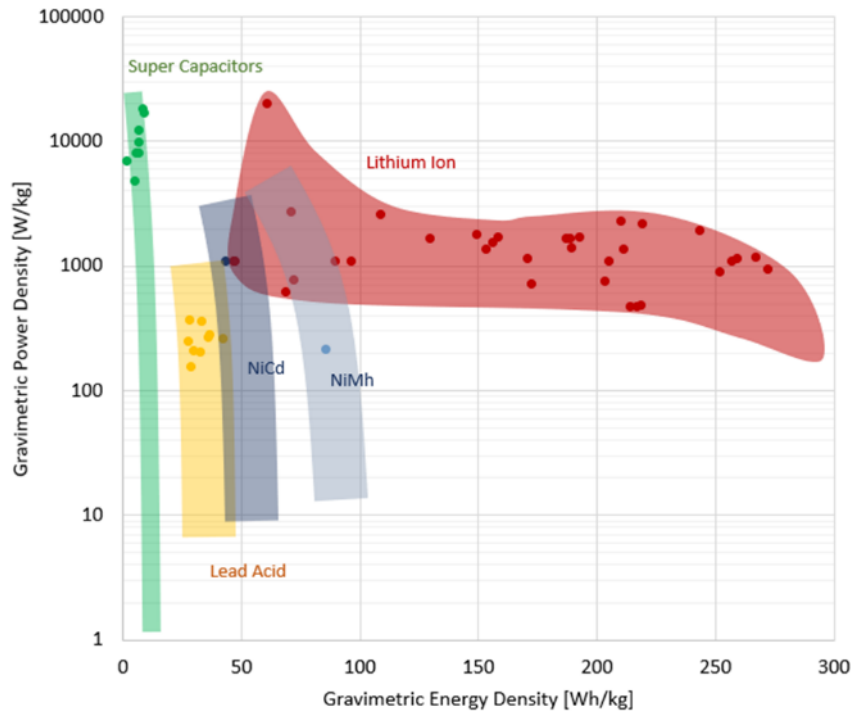


Ragone Plot – a plot of power density vs energy density.

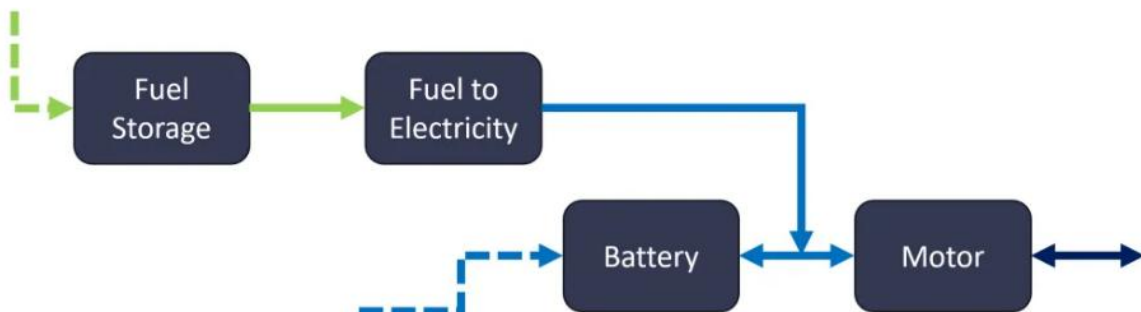


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Range Extended Electric Drive - removing the mechanical link and creating an electrical output from the fuel conversion allows the systems to be optimised more independently. Breaking the mechanical link does though increase the losses and hence there is a trade.



Pros

- recuperation of mechanical energy
- optimisation of the fuel to electrical conversion
- electrical connection more flexible than mechanical

Cons

- two systems to be packaged
- two refuelling options

Rate of Change of Frequency (RoCoF) – electrical grid refers to how quickly the grid's frequency is changing over time, typically measured in Hertz per second (Hz/s).

Recycle – at some point we need to Recycle batteries. This can be approached in many different ways and even could result in going back to the raw materials.

Recycling Processes – there are many and varied depending on many factors. However, in all of these the key aim is to recover high quality materials at the lowest possible cost/impact. We should also note that for a battery pack this is the last step in the 4R's (Repair, Reman,



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Repurpose, Recycle) as we should first of all extract as much economic use from the pack as possible.

REEV – Range Extended Electric Vehicle is an electric vehicle with the addition of an internal combustion engine generator.

Reference Electrode or 3rd Electrode is added to a battery cell so that the anode and cathode potentials can be referenced against a known point.

Refurbish – or **Remanufacture** is a pathway to reuse a battery pack in a new application by actively repairing it and replacing aged cells, modules, or components.

Remaining Useful Life (RUL) – a key function declared by the battery management system. A prediction of how many cycles the pack has before hitting the minimum requirements for operation.

Remanufacture - if the battery pack fails in your car it is costly to replace it with a brand new battery. One alternative is to replace it with a battery that has been remanufactured. This remanufactured pack might have been assembled using good cells/modules from a number of older battery packs. It will have been tested and will often come with some form of warranty.

Repair - battery packs are made from a large number of parts. Often it is not the battery cells that fail and hence a repair or replacement of the failed part is logical.

Repurpose - or Reuse or 2nd Life are all about another use for a battery after it has come to the end of its primary intended use.

Requirements – a list that the battery pack must be engineered to and deliver. This can include the targets, but also needs to include the legal requirements, functional requirements and features.

Resistance – the electrical resistance of a battery pack and even an individual cell can be complex. However, in its simplest form it is Ohm's law: Voltage = Current x Resistance. Hence, the larger the resistance, the larger the voltage drop for a given current demand.

When we look at the components in a battery pack then we need to consider the following when looking to estimate the total resistance:

- Cells
- Cell connections
- Module busbars
- Connections between busbars and components
- Busbars themselves
- Fuses
- Contactors
- Current sensors
- Connectors

RESS – Rechargeable Energy Storage System

Road Vehicle Power Demand - Let's look at the road vehicle power demand for the simple steady state condition. We will look at the tractive effort and power required:

- Aerodynamic forces
- Rolling resistance
- Acceleration
- Gradients
- Hotel loads



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RoCoF – Rate of Change of Frequency in an electrical grid refers to how quickly the grid's frequency is changing over time, typically measured in Hertz per second (Hz/s).

Round Trip Efficiency – the amount of energy delivered divided by the amount of energy input. This sometimes includes the conversion efficiency, eg Rimac quote their stationary storage system: AC round trip efficiency >92%.

RUL – Remaining Useful Life

Runtime Balancing – each cell is connected to an individual low DC-DC power converter, then each converter is connected in series. This then allows the power delivered and received by each cell to be completely controlled based on their capability.

Safety - in the BMS there are a number of limits used to ensure the safe operation of the battery pack, including: voltage limits, temperature limits, current limits and minimum SoH for safe operation.

There are also a number of measurements used for safety diagnostics at cell level, including:

- Moving Average Voltage Deviation (MAVD)
- **Relaxation delta Voltage** (RdV)
- delta State Of Health (dSOH)

Safety Diagnostics –

Sealing - needs to be considered across the components and at a system level. There are so many aspects of the pack where we need to consider sealing:

- cell can/case
- HV contactors
- cooling system
- HV and LV connectors
- pack enclosure

All of these are trying to keep something inside and/or stop dust, gas or liquids entering.

Secondary Cell – a rechargeable battery cell.

Second Life - **Repurpose** or Reuse or 2nd Life are all about another use for a battery after it has come to the end of it's primary intended use.

SEI – is a passivation layer called the Solid Electrolyte Interphase and is formed on electrode surfaces from decomposition products of electrolytes. The SEI allows Li^+ transport and blocks electrons in order to prevent further electrolyte decomposition and ensure continued electrochemical reactions.

Self Discharge of Cells – dependent on the **chemistry**, temperature and age of the cell. These reactions occur in any electrochemical systems and are very difficult to avoid completely. This is because some self discharge reactions involve chemical reactions which will always take place at a rate proportional to temperature. For Lithium Ion cells the self-discharge is typically 2 to 3%/month.

Self-Healing Binders - dynamically cross-linked polymers specifically engineered to adapt to the massive volumetric expansion of silicon anodes. Unlike conventional covalently cross-linked binders, which suffer irreversible damage once their chemical bonds are broken, self-healing binders utilize reversible dynamic bonds that act like “microscopic Velcro”. These bonds typically rely on noncovalent interactions such as hydrogen bonding, ionic interactions, boronate ester bonds, metal-ligand coordination, and π - π stacking.



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Self-Heating Onset Temperature - the temperature at which a cell begins self-heating under adiabatic conditions. It describes the lowest temperature at which a cell will begin to heat up, if it cannot pass any heat to its environment. It is therefore a theoretical, worst-case lower value, as cells in real-world battery packs can readily exchange heat.

NMC/graphite cells begin self-heating at approximately 90 – 110 °C, while for LFP/graphite it occurs around 150 – 170 °C.

Semi-Solid State Battery - use some liquid electrolyte to overcome the interface issues with the true **solid state battery**.

Sensors - the sensors in a battery could be all or a subset of the following:

- Cell voltage
- **Current flow**
- **Cell temperature**
- Humidity
- Fluid level
- Pressure
- **Gas Sensing**
- Pack voltage
- **Isolation Resistance**
- Earth Bonding Impedance
- Coolant temperature(s)
- Coolant flow rate
- Force / deformation
- Dielectric strength of coolant

Some of these might be direct measurements and some might be an estimation. A fusion of sensor data over time is often used to estimate other parameters and hence form virtual sensors.

The minimum for the simplest of battery packs would be temperature and cell voltage. The single battery cell in a mobile phone would have voltage and temperature sensors.

Separator – material that separates the anode and cathode electrically whilst allowing ions to pass through.

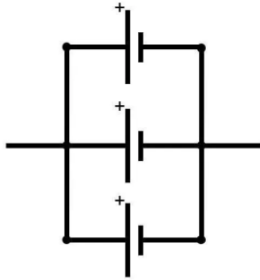
SEI Growth - initial SEI formation is essential to protect the anode from further electrolyte degradation. Continued SEI growth occurs throughout the battery's life, particularly during cycling. Excessive SEI growth leads to Capacity Fade, Increased Resistance and possible Safety Hazards.

Series and Parallel – the stringing of the cells in the battery pack.



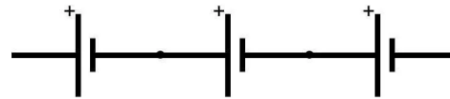
Series and Parallel

When assembling large battery packs it is necessary to connect cells in series and parallel. Actually the normal method is to assemble them in parallel groups and then to assemble these groups in series.

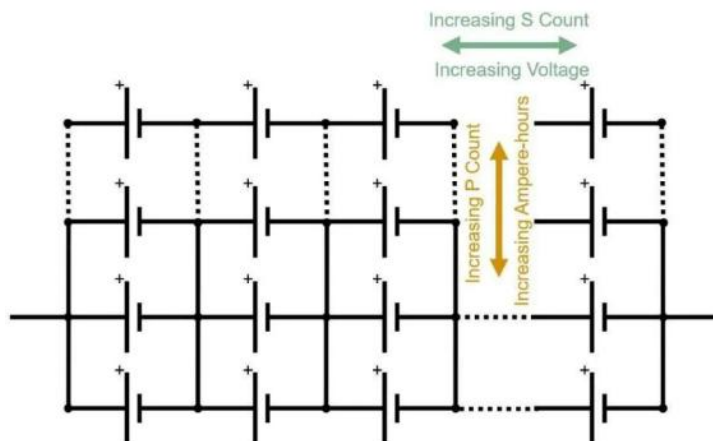


Cells that are in parallel have the positive terminals all connected together and the negative terminals all connected together. The voltage of the group of cells in parallel will be the same as a single cell. The nominal capacity of the group of cells will be P multiplied by the nominal capacity of a single cell.

When connecting cells in series the negative terminal of the first cell is connected to the positive terminal of the second cell. The negative terminal of the second cell is connected to the positive terminal of the third cell. This continues until we reach the total number of cells required in series. The nominal voltage of the final set of cells is the number of cells in series times the nominal voltage of a single cell.



This basic principle of series and parallel can be extended to any numbers you wish to create. The diagram below shows the basic principles.



The nominal capacity of this battery configuration is given by:

$$\text{Nominal Energy in Wh} = S \times V_{\text{nomcell}} \times P \times Ah_{\text{nomcell}}$$



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Series Hybrid - the series hybrid is used in diesel-electric trains as it allows some optimisation of the diesel engine as it doesn't need to operate over the full torque and speed map and removes the requirement for a multi-speed gearbox.



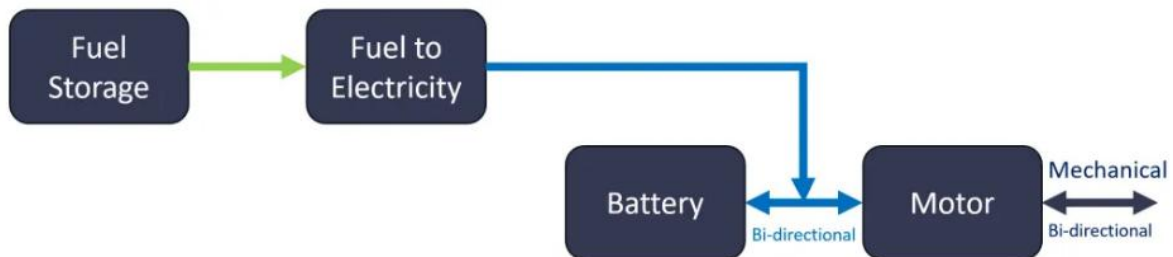
Pros

- no battery
- simple system
- fuel to electricity conversion can be remote
- no multi-speed gearbox and clutch

Cons

- energy losses through conversion
- no regen / recuperation
- electrical power demand mapped to conversion

Series Hybrid with Storage - adding energy storage to this system opens up a number of opportunities. Mechanical energy can be recuperated and stored in the battery. Also, electricity produced by conversion from fuel can also be stored in the battery, allowing the conversion to be optimised.



Pros

- recuperation of mechanical energy
- optimisation of the fuel to electricity conversion
- slower reacting fuel to electricity conversion
- ev only operation possible

Cons

- More complexity
- Higher cost

Shock Test - to represent the sudden deceleration of an object such as when it is dropped and hits the floor or it is involved in a crash. It can also be invoked in normal transport such as when a plane experiences turbulence or a vehicle is driven over a speed bump.

Short Circuit - mean an electrical short circuit, a very low resistance path between the positive and negative sides of the cell or cells. A short circuit can be inside a battery cell or external to a battery cell.

Siemens/Wh – a useful metric when looking for a cell with the lowest internal resistance.



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Silicon Anode – as an additive to graphite anodes it is seen as a drop-in to increase the efficiency and energy storage capacity of lithium-ion batteries. However, the downsides have been increased expansion and hence material degradation reducing cycle life.

Single Crystal Cathode - a cathode material made of micron sized particles that resemble single crystals. The benefits are:

- Safety
- Thermal stability
- Cycling stability
- Particle integrity
- High-voltage stability

Challenges

- Structural stability – can become structurally unstable after being cycled at high voltages
- Capacity fade – after being cycled at high voltages
- Irreversible structure degradation
- Longer ionic transport pathway

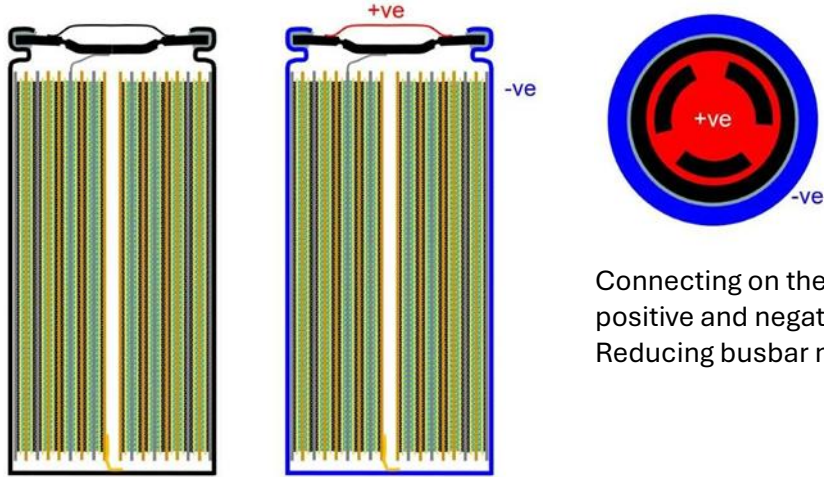


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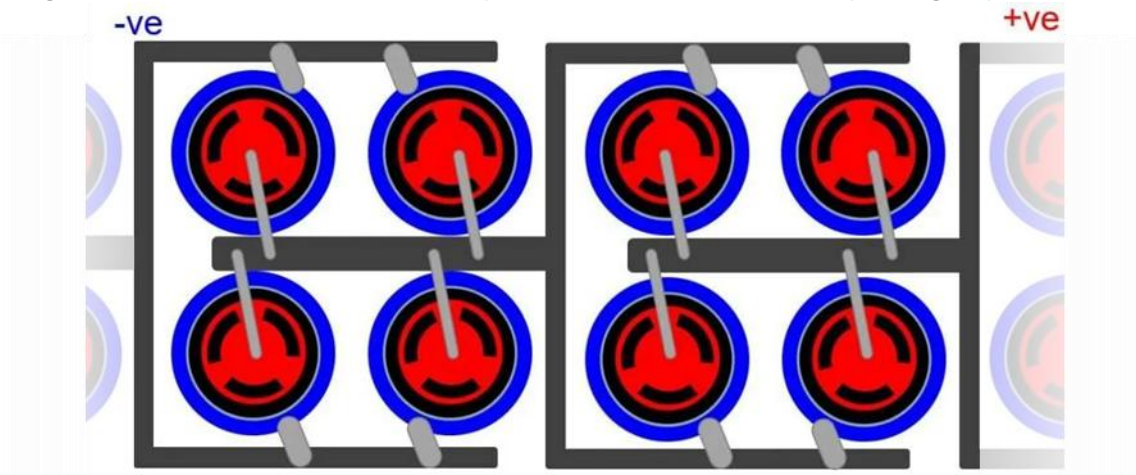
Single Sided Busbars

For cylindrical cells the case is the negative terminal, you don't have to connect at the base.

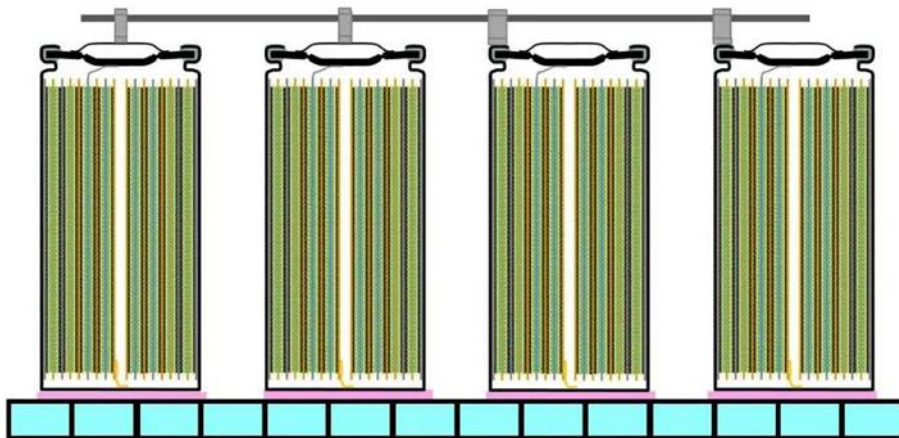


Connecting on the top edge means the positive and negative busbars are on top. Reducing busbar material.

Tuning fork like busbars connect cells in parallel and series in this 2s4p sub-group.



The single sided busbar design allows the cells to be cooled on the side or the base of the can.





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Sleep Mode – the battery pack is isolated, there is no balancing, the BMS will be in a low power mode where it occasionally looks at sensor inputs and listens out for a communications request to wake.

Slitting - electrodes are coated in standard widths up to around 1.5m. Hence, the next step is slitting. This stage runs along the length of the electrodes and cuts them down in width to match one of the final dimensions required for the cell.

SoC – the State of Charge for a battery pack is normally declared to the user based on the usable capacity window. Hence in absolute terms the SoC might be limited to a maximum of 95% at cell level, but to the user this would be shown as 100%.

Sodium - a soft, silvery coloured metal which, like other members of the alkali group of metals, is extremely reactive. As for the other members of the group, it can be prepared by electrolysis of the fused halide or hydroxide. Along with potassium, it is one of the more common alkali metals, there being 28300 ppm in the earth's crust, primarily as the carbonate, chloride or nitrate.

Sodium Ion Cathodes - the cathode materials for sodium-ion batteries (SIBs) are primarily categorized into four distinct classes:

1. layered transition metal oxides
2. polyanionic compounds
3. Prussian blue analogues
4. organic materials

Sodium Ion Layered Transition Metal Oxides - the most mature **sodium ion cathode** technology due to its high theoretical capacity and structural similarity to commercial lithium-ion cathodes. These materials are classified by the sodium coordination environment (Octahedral 'O' or Prismatic 'P') and the number of transition metal layers (e.g., 2 or 3).

Sodium Ion Organic Cathode Materials - emerging as sustainable alternatives free from critical minerals, offering structural tunability and flexibility.

Sodium Ion Polyanionic Compounds - these **sodium ion cathode** materials feature a 3D framework of polyanion units (e.g., PO_4 , P_2O_7) which provides robust structural stability and safety, often at the cost of lower intrinsic electronic conductivity.

Sodium Ion Prussian Blue Analogues - possess an open 3D framework with large channels that allow for “zero-strain” intercalation of sodium ions, suitable for long-cycle life applications.

Sodium Nickel Chloride Battery - also known as the Zebra Battery, consists of a negative liquid sodium electrode and a solid positive electrode containing nickel chloride and nickel.

Sodium-ion battery - operate analogously to lithium-ion batteries, with both chemistries relying on the intercalation of ions between host structures. In addition, sodium based cell construction is almost identical with those of the commercially widespread lithium-ion battery types. However, sodium-ion batteries are characterised by several fundamental differences with lithium-ion, bringing both advantages and disadvantages:

Advantages:

- Environmental abundance: Sodium is over 1000 times more abundant than lithium and more evenly distributed worldwide.
- Safety: Sodium-ion cells can be discharged to 0V for transport, avoiding thermal run-away hazards which have plagued lithium-ion batteries.
- Low cost: Sodium precursors (such as Na_2CO_3) are far cheaper than the equivalent lithium compounds.



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- Four major families of **materials for cathode chemistry** options:
 - **layered transition metal oxides**
 - **polyanionic compounds**
 - **prussian blue analogs**
 - **organic cathode materials**
- Cathode materials can be synthesized from more sustainable transition metals such as Fe, Cu or Mn.

Disadvantages:

- Sodium-ion cells have lower energy densities than lithium-ion. This is due to sodium being significantly heavier and larger than lithium, as well as Na^+/Na having a higher reduction potential than Li^+/Li .
- Sodium-ion technology is not as well established as lithium-ion.

SoH – State of health is the current usable capacity divided by the as new usable capacity of the pack. The user will see a lower than total capacity to increase the life of the battery.

Solid Electrolyte Interphase - formed on electrode surfaces from decomposition products of electrolytes. The SEI allows Li^+ transport and blocks electrons in order to prevent further electrolyte decomposition and ensure continued electrochemical reactions. The solid electrolyte interphase (SEI) is primarily formed in the first battery cycle from the reduction of the electrolyte, and allows Li ion transport while preventing further electrolyte decomposition. The SEI layer formation can be improved with electrolyte additives.

Solid Polymer Electrolyte - such as polyethylene oxide (PEO)-LiTFSI, polycarbonates, and block-copolymer systems, trade some conductivity (10^{-5} - 10^{-3} S cm^{-1} at 60-90 °C) for exceptional processability. Moreover, SPEs can be cast as free-standing films, laminated at low pressure to electrodes, and formulated with ceramic fillers or ionic plasticizers to tune modulus and transport.

Solid State – anode, cathode and electrolyte are solid.

SOP – State of Power is published by the BMS and is an estimation of the maximum power that the battery can accept or/and output at the current point in time.

SOX – abbreviation for all of the “State of ...” functions that the BMS publishes to the system.

Specific Heat Capacity – for the main lithium ion chemistries the following generic heat capacities for a cell are:

- Lithium Nickel Cobalt Aluminium Oxide (NCA) = 830 J/kg.K
- Lithium Nickel Manganese Cobalt (NMC) = 1040 J/kg.K
- Lithium Iron Phosphate (LFP) = 1130 J/kg.K

Split Pack – a pack that splits into two parts, thus allowing the two sections to operate in parallel or in series. Often used with 800V packs to allow 400V charging and 800V drive. Charging the two sections in parallel is known as [Bank Charging](#).

SSB – Solid State Battery

Stacking - for pouch cells the electrodes stacked: anode, separator, cathode, separator, anode, separator etc.

Some prismatic cells have stacked electrodes and some have a flat wound jelly roll.

Challenges:

- Alignment of layers
- Avoid punctures of separator



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- Separator folding
 - lots of countermeasures applied over time like separator envelope welding not all manufacturers countermeasure in this way
- Check humidity
 - an important test that should be done before assembly and before the filling stage, is checking the humidity of the separator

Standard Hydrogen Electrode (SHE) – a reference point for measuring electrode potentials. Defined as a potential of 0V under standard conditions (298 K, 1 atm pressure, 1 M concentration).

State of Certified Energy (SOCE) - means the measured or on-board usable battery energy at a specific point in its lifetime, expressed as a percentage of the certified usable battery energy.

State of Charge (SoC) – abbreviated as SoC and defined as the amount of charge in the cell as a percentage compared to the nominal capacity of the cell in Ah.

State of Health (SOH) – this is the total available charged capacity of the cell as a percentage compared to the nominal capacity in Ah when the cell was new.

State of Power (SOP) – in a lot of battery applications the State of Power (SOP) is a key output from the BMS. This will take into account the **State of Charge**, **State of Health** and other parameters such as temperature.

How much power can the battery pack deliver for the next 10 seconds or 30 seconds?

Stepped Constant Current – Constant Voltage (SCC-CV) – fast charging protocol.

Stepped Fast Charge Limits – the result of a limited test regime applied by the cell supplier to establish the maximum charge current for the cell.

Storage - a key aspect to consider for any battery cell or system with cell(s) installed are the storage conditions. Key parameters to consider are:

- Safety
 - chemical
 - electrical
 - fire
- Ageing

String – a number of batteries/modules connected in series.

Supercapacitor - often used for high power/low energy applications as capacitors are able to deliver very high discharge rates, but energy storage density is lower than batteries.

Swappable Batteries – Unlike fixed batteries that can be redesigned with each new generation of vehicles, swappable batteries inherit outer design, power output and data exchange protocols of their precursors for maximum utilization purposes. It's typical of swap operators to mix modern batteries into their stocks of older ones and offer them at different prices.

System – the wider system and it's requirements are fundamental to the design of a battery pack. This means we need to understand the **power electronics** and how they operate, what they require, their failure modes and any legislative requirements.

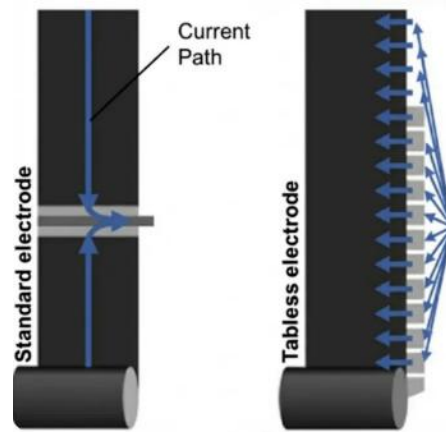
Different applications have different system requirements, duty cycles and use cases.



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Tabless Cell – this design connects the entire edge of the electrode to the terminal. This spreads current flow evenly across the surface, reducing resistance and lowering heat generation during operation. A tabless structure also removes the space and mass taken up by the tabs themselves, enabling higher energy density by allowing more active material to be packed into the cell.



Tap Density - is the powder density and as the name suggests the container is tapped to encourage it to settle. Several parameters influence tap density:

- **Particle size:** Larger particles are generally more spherical, indirectly contributing to a higher tap density.
- **Shape of secondary particles:** Smooth, spherical particles tend to pack more efficiently, resulting in higher tap density.
- **PSD uniformity:** A narrower PSD (smaller D90/D10) improves packing behaviour, again leading to a higher tap density.

Targets – a set of high level numbers that the battery pack needs to meet. Be careful to ensure that these are targets that the pack itself can be test against and are not part of the wider system. eg a battery pack can have a usable kWh target, but should not have a vehicle range target.

Teardown - one way of understanding how a product, system or component works is to do a teardown. Essentially take it apart.

Note: no teardown should be undertaken without the appropriate training, equipment, facilities and safety equipment.

Temperature – a critical parameter that you need to know before charging or discharging a cell. A cell is a 3 dimensional structure that is also inhomogeneous and hence you will observe temperature gradients within the cell. The temperature limits, gradients and heat rejection rate will define the overall power capability of the battery.

Temperature Gradient – the maximum temperature differential in a cell is normally specified as $\sim 2^{\circ}\text{C}$ to minimise the degradation in capacity of the cell. This requirement will drive the cell selection versus application along with the cooling system design.

- High temperature and the SEI layer on the anode grows faster. If the SEI layer grows fast it tends to be more porous and unstable.
- At low temperatures we see slower diffusion and intercalation with the possibility of lithium plating. Lithium plating removes lithium from the active cell, reducing cell capacity. Also, lithium plating can subsequently into lithium dendrites that can cause electrical shorts.

Temperature Limits – these temperatures will change with chemistry and by cell manufacturer, therefore, it is really important to use the limits as advised by the manufacturer. In addition you will need to test the cell to gain the detailed understanding of how the cell behaves in your application versus temperature.

The limits will also be blurred by the design of the battery and control system. One example is the maximum operating temperature for the cell.



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Terminal Welding - The anodes are connected to the negative terminal and the cathodes to the positive terminal. The process and robustness of this joint are important to understand as welding the cell to busbars can damage the internal welds.

Challenges:

- Trimming of tabs and avoiding any burrs or particles being left behind
- Gathering all of the foils and presenting them to the welder
- Aligning gathered electrode foils with tab
- Weld position alignment, whether that is Laser Alignment, spot weld or ultrasonic horn and anvil alignment
 - Wear of electrodes / horn / anvil
 - Consistent energy burst, energy oscillation, changes in materials or even surfaces
- Ensuring no sputter contaminates cell
- Ensuring good consistent electrical connections

Ternary Battery – battery chemistry that integrates a cathode composed of three metallic elements, such as nickel, cobalt and manganese.

Testing - prior to having an actual cell the chemistry will be tested as a half cell against a reference electrode. These tests give directional data for the electrochemists developing the next generation of chemistry.

The battery cells will then mature from A-sample through to D-sample. At each stage these cells will be performance tested, undergo ageing cycle testing, parameterization for modelling and stages of legislative testing.

Thermal - most battery cells operate happily within the temperature range that we are happy to operate in, namely 0°C to 35°C. However, in lots of applications we want them to operate below freezing and up to much higher temperatures.

Depending on the extremes of the environment the battery cell(s) might have to be heated and/or cooled.

Also, the fundamental operation of the battery cell changes with temperature. This means that temperature gradients in cells can have a significant effect on performance and lifetime. You can extend this to cells at different temperatures in the pack.

Thermal Conductivity – If we look at the active layers of a cell the thermal conductivity in the plane of the layers is approximately 10x to 100x that through the planes.

This should not be unexpected as the electrodes are made from sheets of aluminium and copper. Two of the best materials for thermal conductivity.

These values though have a large range:

- 15 to 160 W/mK In-Plane
- 0.2 to 8 W/mK Through-Plane

Thermal Interface Materials – their purpose is to transfer heat between two solid surfaces. In the case of a battery this is normally between the outer surface of the cell case and a cooling plate.

Production tolerances of the cell, cooling plate and the assembly will mean there are gaps between the two surfaces. If a cell runs hotter than another cell then it will age faster or even become unstable if it gets very hot. Therefore it is important to run all of the cells at the same temperature and one element of that is a consistent thermal connection to the cooling system.

TIM materials tend to be grouped based on how they are supplied/applied:



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- Thermal paste
- Thermal adhesive
- Thermal gap filler
- Thermally conductive pad
- Thermal tape

Thermal Management System - or perhaps more correctly the Battery Thermal Management System (BTMS) encompasses the control and temperature regulation of a battery system to ensure optimal performance, reliability, and lifetime. Hence it is everything from the cell to the heat rejection to the environment.

This means we need to consider the cell requirements, other sources of heat flux, the transport medium, heat exchange, sensing, control and use cycles.

Thermal Propagation - we tend to use thermal runaway to describe a single cell and thermal propagation to describe the cell to cell spread.

Most of the propagation mechanisms involve thermal transfer from the cell in thermal runaway to neighbouring cells.

- Conduction cell to cell
- Hot vent gas
- Particle or core projection
- External failure propagation

Thermal Runaway - in general, thermal runaway can be attributed to 3 main types of abuse conditions; mechanical, electrical and thermal. The likelihood of each of these potential risks varies depending on chemistry, design and operating conditions, with the likelihood of failure generally becoming higher with battery aging.

If you heat a battery cell to somewhere above 130°C then exothermic chemical reactions inside the cell will increase the temperature and further reactions will take place. The result is an uncontrolled runaway and increase in temperature. The cell should vent in a controlled manner with fire and molten material. In severe cases the cell may explode. The energy released from one cell failing is likely to heat neighbouring cells that again could be triggered into thermal propagation.

Thermal Testing - the thermal characteristics of a battery cell or pack are as important as the electrical characteristics as they can limit performance and increase ageing.

Third Electrode – electrode used in cells to establish the potential of the anode and cathode independently.

Tin Anode - a promising anode material for **sodium ion** batteries. Theoretical specific capacity = 847 mAh g⁻¹ and volumetric capacity = 6238 mAh cm⁻³.

Total Energy – is the nominal cell voltage multiplied by the nominal cell capacity, both as measured at a given discharge rate.

Triggers of Thermal Runaway – can be one of a number of inputs, primarily:

- electrical abuse
 - short circuit
 - internal particle
 - dendrite growth resulting in a short
 - overcharging the cell
- thermal abuse
 - overheating of the cell with an external heat source



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- heat from another cell
- mechanical abuse
 - crushing of the cell in an impact
 - puncturing of the cell

Thermal Runaway is part of the many aspects of cell and pack design that have to be understood. Thermal runaway is also a huge subject in it's own right.

UL – Underwriters Laboratories

Ultra-High Precision Coulometry - relies on:

1. accurate high precision current measurement
2. precision voltage measurement
3. accurate and stable time base

Having these three core capabilities allows for precise measurements of cell capacity, cycling losses and hence changes in the cell performance over the first few cycles.

UL 1642 - applies to cell and pack. Many of the required tests are similar to what is required in UL 1973 but focused on the cell's performance.

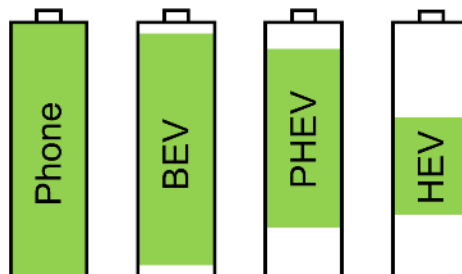
UL 1973 - the safety standard for battery systems used in stationary applications, such as energy storage systems. ESS units listed to UL 9540 standards must meet the requirements in UL 1973. UL 1973 requires a safety analysis, such as a failure modes and effects (FMEA) assessment, and includes functional safety requirements for electronics and software components identified as critical to the battery system's safety.

UN38.3 Transport Test - covers testing of cells, modules, packs and products with installed lithium ion batteries. UN/DOT 38.3 is a self-certify standard. However, because of potential liability issues, it is best to use a third party test laboratory. UN 38.3 is a combination of environment tests, mechanical, thermal and electrical stresses.

UN Regulation 100 – uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train.

Usable Energy – is the energy available within the **usable SoC window** of the cell or pack.

Usable SoC Window – If we want a battery cell to last a lot of cycles, extend the life in a power application or to ensure the available power is consistent then we need to set a usable SoC window that is smaller than 100%.



Vanadium Redox Flow Battery – a **Flow Battery** employs vanadium ions as charge carriers.

Variable Current Profile (VCP)

Vehicle to Grid (V2G) – allows the battery in an electric vehicle to put energy back into the electricity grid.

Vehicle to Vehicle (V2V) – allows the battery pack on one vehicle to be used to charge another electric vehicle.



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Venting - gases can build up in a cell over time or suddenly when the cell fails. At some point, and depending on the cell design, the gas pressure will cause the safety valve in the cell to release or the cell case to fail. A cell venting doesn't necessarily mean it will go into **thermal runaway**, but a thermal runaway will be predated by the cell venting.

Voltaic Efficiency - the ratio of the average discharge voltage to the average charge voltage over a cycle. The charging voltage is always higher than the rated voltage to activate the chemical reaction within the battery and hence losses.

Volumetric Energy Density – Wh/litre of a battery cell or pack.

Watt - the SI unit of power and is equal to 1 joule per second. Named after James Watt, Scottish engineer (1736-1819) and pioneer in steam engine design. It is useful to have some examples, even if some of these are a bit out of the ordinary:

- 2.5×10^{-15} W = minimum discernible signal at the antenna terminal of a good FM radio receiver
- 1.0×10^{-12} W = average power consumption of a human cell
- 2.0×10^{-9} W = power consumption of 8-bit PIC chip in “sleep”
- 1.0×10^{-6} W = approximate consumption of a quartz wristwatch
- 30 W = 9 mph on an electric bicycle or approximate power required to walk
- 220 W = electric bicycle power to maintain 20 mph on the flat
- 3000 W = heat output of a domestic electric kettle
- 75,000 W = Family car peak power (100PS)
 - [Road Vehicle Model](#)
- 1.3×10^6 W = maximum power for a 6 seat eVTOL
- 1.6×10^7 W = rate at which a typical petrol pump transfers chemical energy to a vehicle
 - [Charging at the Speed of a Petrol Pump](#)
- 2.074×10^9 W = peak power generation of Hoover Dam
- 3.9×10^{26} W = Sun energy production

Watt Hour - a unit of energy equivalent to one Watt of power expended for one hour of time.

Weakest Cell - when we connect cells in series the resultant pack is only as strong as the weakest cell in the string.

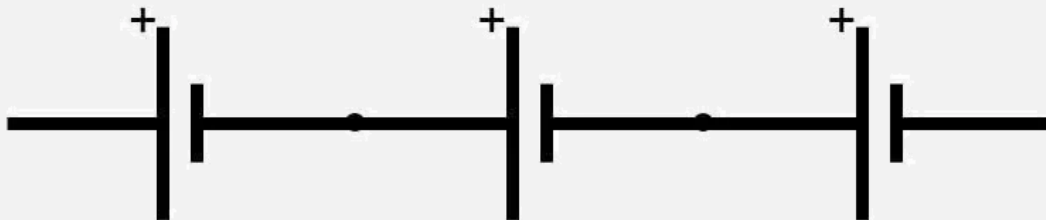


Weakest Cell

When we connect cells in series the resultant pack is only as strong as the weakest cell in the string.

- Discharging, first cell to hit 2.5V stops the discharge of the whole pack.
- Charging, first cell to hit 4.2V stops the charging of the whole pack
- If one cell hits 60°C then pack has to stop charge and discharge

Example: In the simplest string of three cells in series, let us assume they are LFP with a nominal 3.2V and 100Ah. However, in reality the middle cell has a capacity of just 95Ah.



This means that when we discharge the string of cells and we have extracted 95Ah the middle cell will be at the end of discharge and hence we will have to stop. Hence what was a pack with a nominal capacity of $3s \times 3.2V \times 100Ah = 960Wh$ will actually have a capacity of $3s \times 3.2V \times 95Ah = 912Wh$.

We haven't just lost 5% of the energy of one cell, but 5% of the total pack energy.

The impact of this is you need to ensure:

- All cells are made identical
 - same capacity
 - same internal resistance
- All connections between cells are identical
- Cooling and Heating of all cells is identical

There can be a number of reasons why cells age differently and fail [1] and the overall electrical/thermal design of the pack is important [2].

This means we need:

- Quality control in cell manufacturing
- Pack engineering that can design, model and validate all functions of the pack
- [Battery management system](#) (BMS) that can control the pack over its lifetime



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Welding - the process of joining two pieces of metal together by hammering, pressure or fusion. Filler metal may or may not be used. Welding is normally done to form a mechanical joint, however, in the field of batteries this is often an electrical joint. Sometimes tested mechanically to ensure that the joint is good.

There are a number of types of welding:

- Ultrasonic
- [Laser](#)
- Pulsed Arc or micro-TIG
- Stir
- Resistance

Wet Separator – the separator is produced using solvents.

Wettability - refers to the ability of the [electrolyte](#) to spread and penetrate the porous electrode materials, crucial for battery performance and safety. Poor wettability can lead to issues like reduced capacity, increased resistance and safety problems.

Wh – **Watt hour** is a unit of energy equivalent to one Watt of power expended for one hour of time.

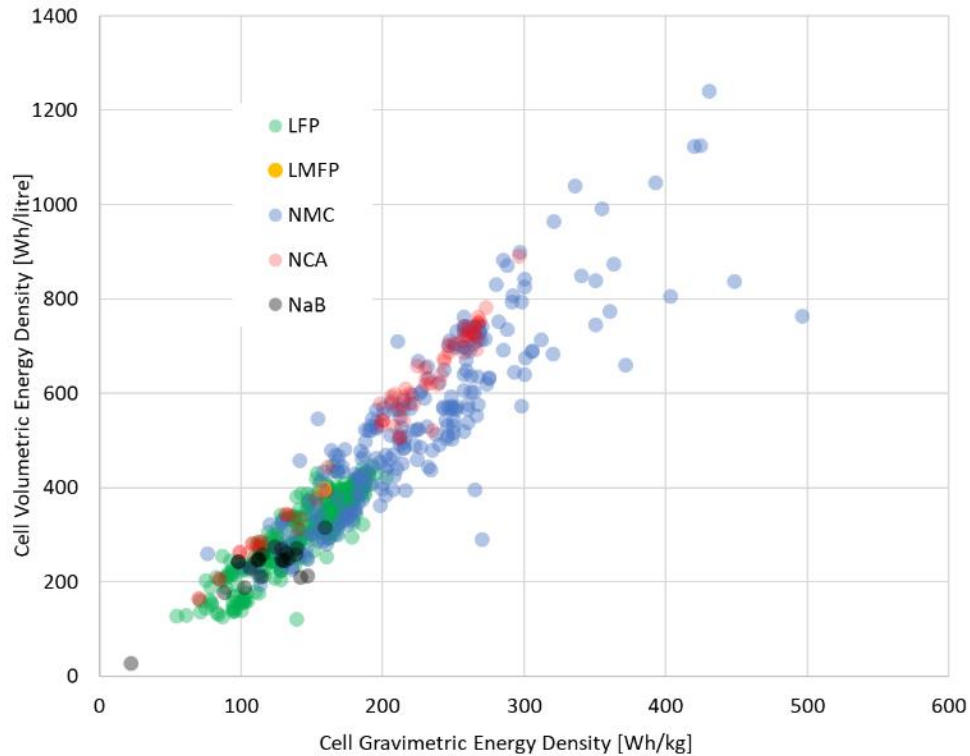
Wh/kg – gravimetric energy density of a battery cell or pack.

Wh/litre – volumetric energy density of a battery cell or pack.

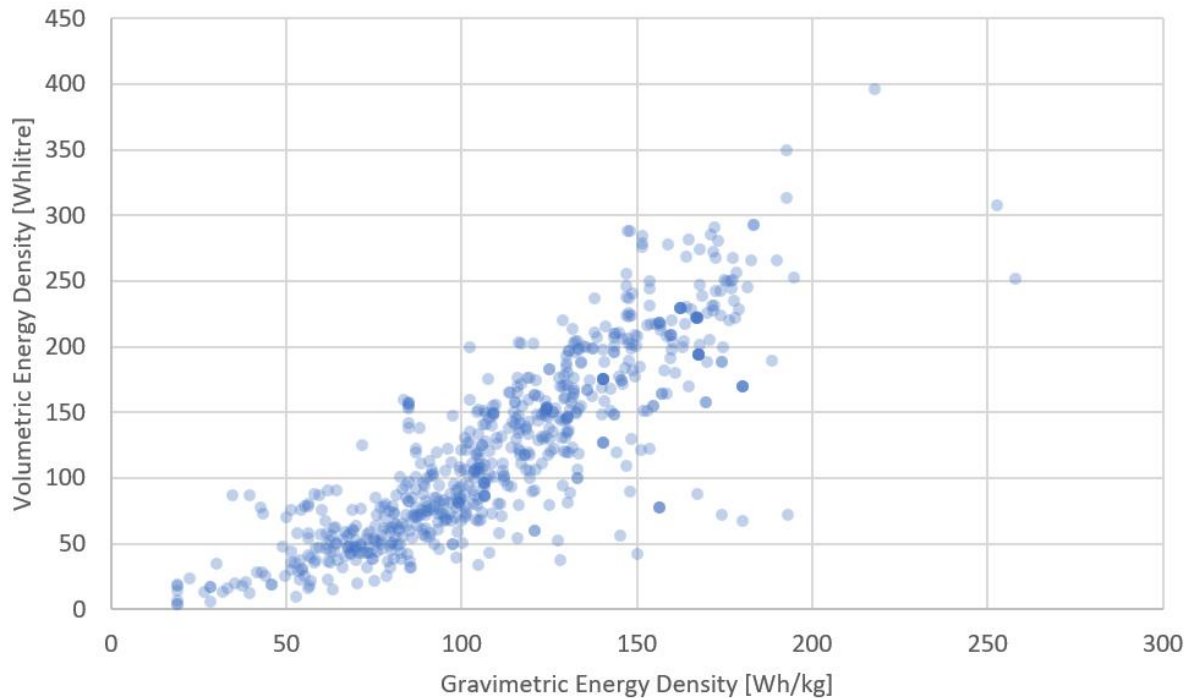


Gravimetric and Volumetric Energy Density

The [cell database](#) has been used to compare different cell chemistries with Volumetric Energy Density [Wh/litre] plotted versus Gravimetric Energy Density [Wh/kg].



At a battery pack level we see that 200Wh/kg and 300Wh/litre are at the top end of the metrics for [packs in the database](#).





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Winding - in a [cylindrical cell](#) the anode, cathode and separator are wound into a spiral. Some prismatic cells have stacked electrodes and some have a flat wound jelly roll.

W/kg – gravimetric power density of a cell or battery pack.

W/litre – volumetric power density of a battery cell or pack.

Wireless BMS – one option for reducing the wiring complexity and weight in a battery pack is to use a wireless connection. Here the modules or cells report voltage and temperature signals back to the central control system in the battery wirelessly.

XRD – X-Ray Diffraction is an analytical technique primarily used for phase identification of a crystalline material and can provide information on unit cell dimensions. This is used to understand the fundamental chemical structure in the anode and cathode materials used in a battery cell.

Zebra Battery – [Sodium-Nickel-Chloride Molten Salt Battery](#)

ZEV – Zero Emission Vehicle

Zinc Air – perhaps the most promising metal-air battery technology. Typically it has a zinc anode, an oxygen permeable cathode, a separator, and a caustic alkaline electrolyte. Promising low cost, high stability and high energy density. [Zinc Bromine](#) – promising flow battery technology.

Zinc Bromide Battery - a [flow battery](#) where two oppositely charged liquids are passed through an ion-exchange membrane to produce electricity.

Zinc Carbon – a primary battery chemistry, commonly used in batteries for radios, toys and household goods.

Z Stack - cell architecture where the electrodes are cut into individual sheets and stacked layer-by-layer. The [separator](#) is a continuous “Z” interlayer. Each anode and cathode sheet typically has its own dedicated **tab** or very short current-collection distance.



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Thanks to

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