METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Prepared by: Arda Esen

Emine Bostancı

Office: C-107

Content

1. Lithium Ion Cells
2. Battery Management System (BMS) Options
3. Battery Management System (BMS) Functions

Lithium Ion Cell Formats

Cylindrical: Size ranges from 14400 to 32650

- 18650 cell 18 is diameter in mm, 65 is length in mm.
- 18650 and 20700 cells are used in Tesla models.
- Capacity ranges from 300 mAh to 6.000 mAh

Prismatic: Various sizes

- Capacity goes up to 150 Ah (Narada)
- Widely used in stationery Energy Storage Systems (ESS)

Example: BMW i3

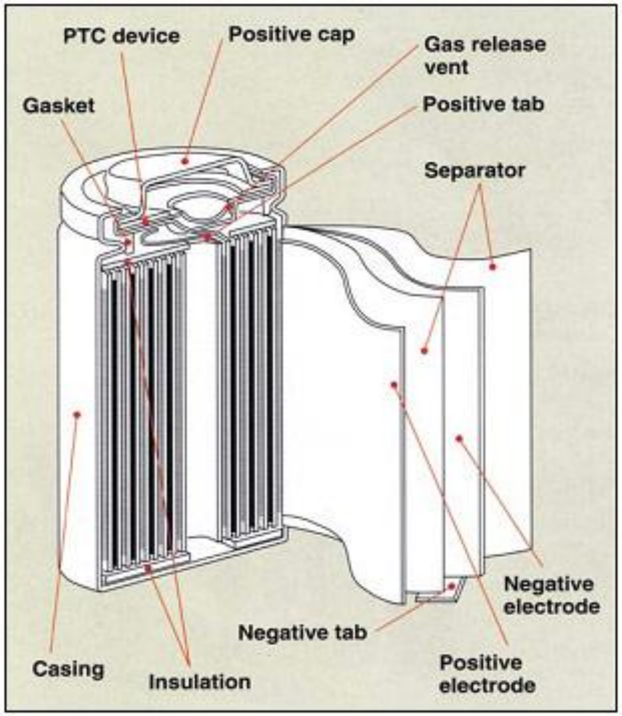
Pouch: Various sizes

- Capacity goes up to 240 Ah (Kokam)
- Mostly in cell phones

Example: Chevy Bolt and Nissan Leaf

Lithium Ion Cell Formats - Cylindrical

Cross section of a lithium-ion cylindrical cell.



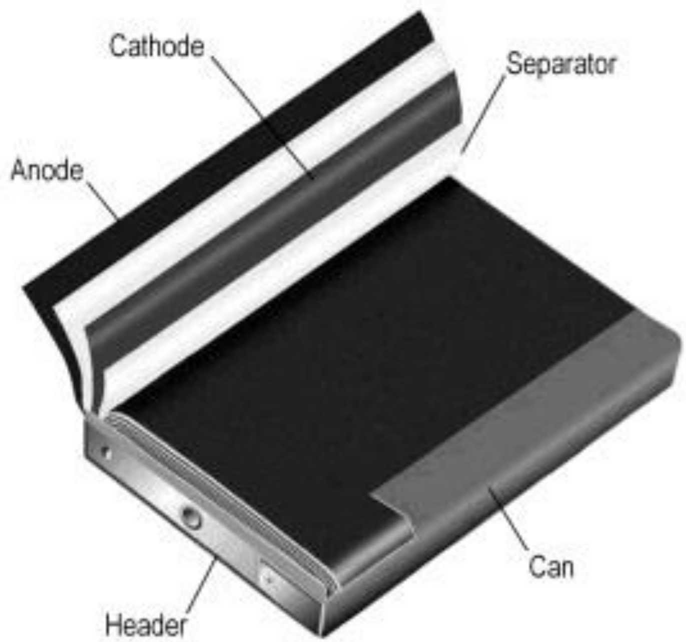
The cylindrical cell design has good cycling ability, offers a long calendar life and is economical, but is heavy and has low packaging density due to space cavities.

Popular 18650 lithium-ion cell

The metallic cylinder measure 18mm in diameter and 65mm the length. The larger 26650 cell measures 26mm in diameter.

Lithium Ion Cell Formats - Prismatic

Cross section of a prismatic cell.



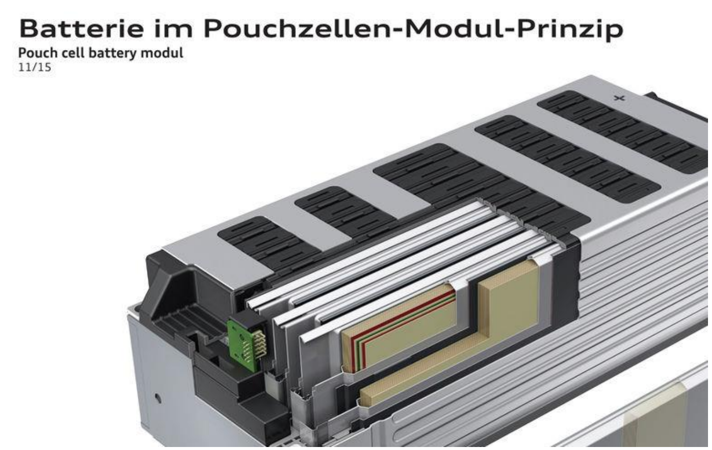
The prismatic cell improves space utilization and allows flexible design but it can be more expensive to manufacture, less efficient in thermal management and have a shorter cycle life than the cylindrical design.

Lithium Ion Cell Formats - Pouch Cell

The pouch cell offers a simple, flexible and lightweight solution to battery design. Some stack pressure is recommended but allowance for swelling must be made. The pouch cells can deliver high load currents but it performs best under light loading conditions and with moderate charging.

Swollen pouch cell

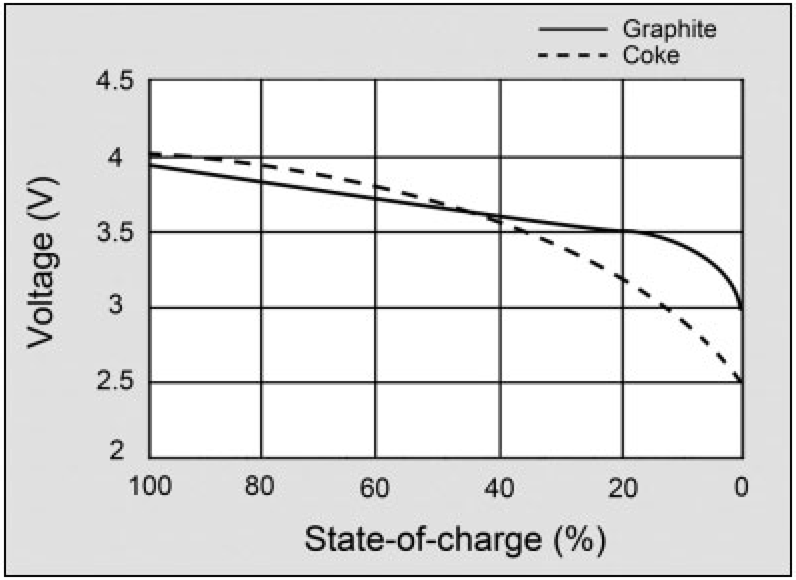
Swelling can occur due to gassing. Improvements are being made with newer designs. Large pouch cells designs experience less swelling



[Nissan battery pack production]

Lithium Ion Cell Chemistries

Li-Ion is the name of the battery type, where lithium ions Li^+ are migrating trough electrolyte (liquid or solid). Li-Ion batteries are named according to their cathode materials. As anode materials, graphite is commonly used.



A battery should have a flat voltage curve in the usable discharge range. The modern graphite anode does this better than the early coke version.

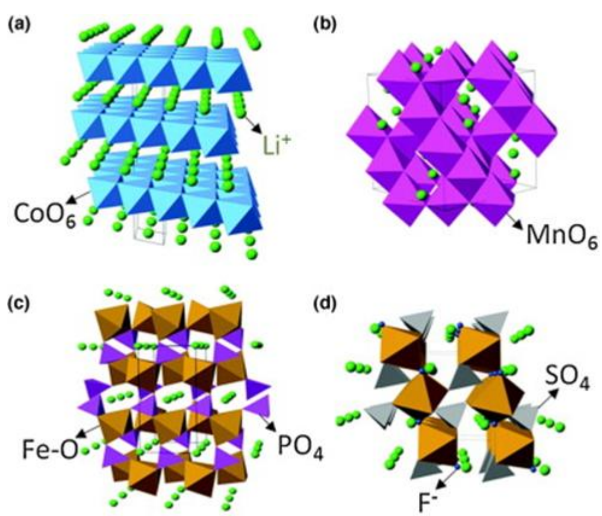
Source: https://batteryuniversity.com/learn/article/lithium_based_batteries

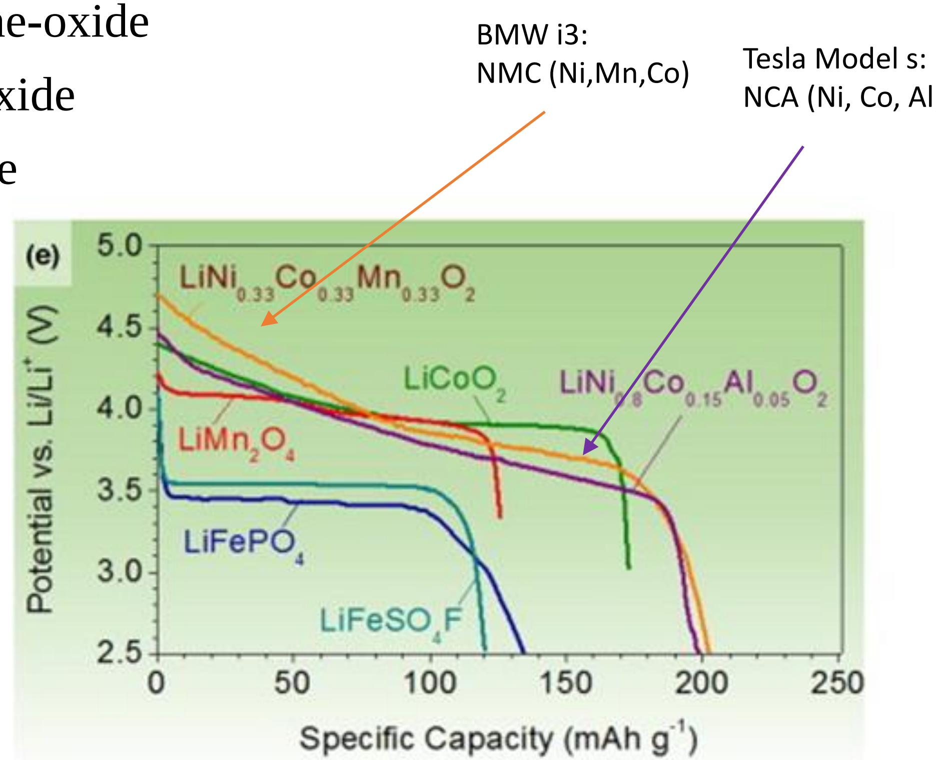
Video suggestion: The Truth About Tesla Model 3 Batteries: Part 1

Lithium Ion Cell Chemistries

Many Lithium Ion chemistries are available. They are usually named according to the composition of the cathode.

- LCO : $LiCoO_2$, Lithium-cobalt-oxide
- NMC : LiMnNiCo, Lithium-manganese-nickel-cobalt
- LFP : $LiFePO_4$, Lithiyum-iron-phosphate
- LMO : $LiMnO_2$, Lithium-mangane-oxide
- LNO : $LiNiO_2$, Lithium-nickel-oxide
- LTO : $Li_4Ti_5O_{12}$, Lithium-titanate

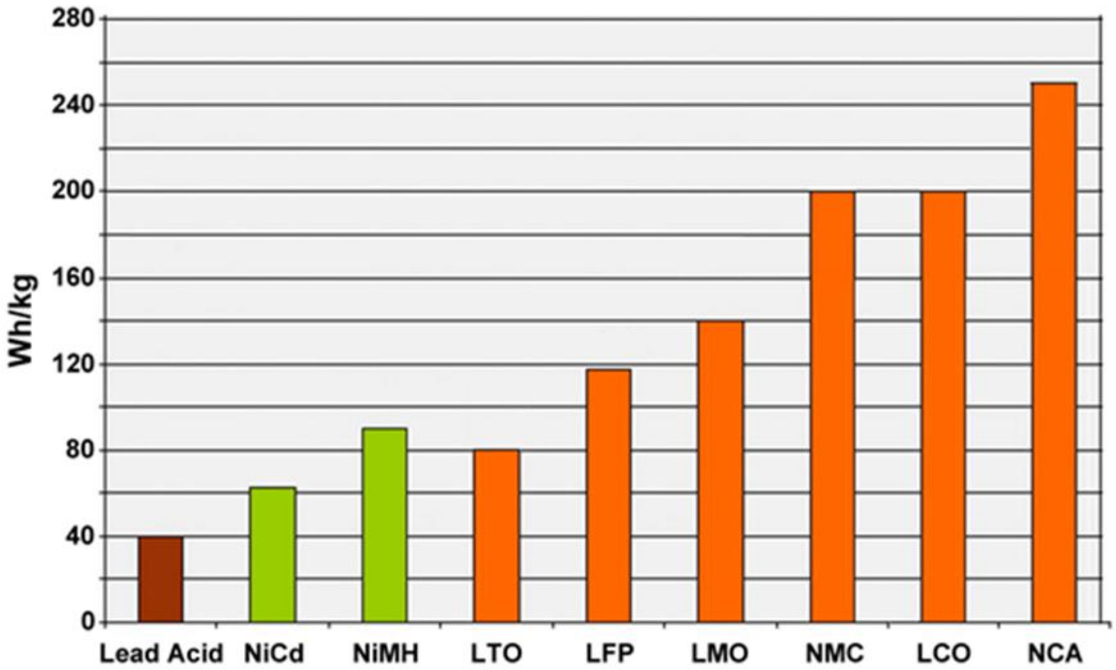




Li-ion Batteries - Different Cathode Materials

Specifications	Li-cobalt	Li-manganese	Li-phosphate	**NMC** (Ni,Mn,Co)
Voltage	3.60V	3.70V	3.30V	3.60/3.70V
Charge limit	4.20V	4.20V	3.60V	4.20V
Cycle life [2]	500	500–1,000	1,000–2,000	1,000–2,000
Operating T.	Average	Average	Good	Good
Specific energy	150–190Wh/kg	100–135Wh/kg	90–120Wh/kg	140Wh/kg
Specific power	1C	10C, 40C pulse	35C continuous	10C
Safety	Average. Requires protection circuit and cell balancing of multi cell pack.		Very good, needs cell balancing and V protection	Good, needs cell balancing and V protection
Thermal runaway	150°C (302°F)	250°C (482°F)	270°C (518°F)	210°C (410°F)
Cost	Raw material high	Material 30% less than cobalt	High	High
In use since	1994	2002	1999	2003
Researchers, manufacturers	Sony, Sanyo, FDK, Saft	NEC, Samsung, Hitachi	UT, QH, MIT A123, Valence	Sony, Sanyo, Nissan Motor
Notes	Very high specific energy, limited power; for cell phones, laptops	High power, average to high specific energy, power tools, medical, **EVs**	High power, average specific energy, higher self-discharge than other Li-ion	Very high specific energy, high power; tools, medical, **EVs**

Lithium Ion Cell Chemistry



NCA enjoys the highest specific energy; however, manganese and phosphate are superior in terms of specific power and thermal stability. Li-titanate has the best life span.

Safety of Lithium Ion Cells

- Li-Ion cells perform magnificently but very unforgiving if operated outside a tight safe operating area (SOA).
- Out of SOA, unrecoverable damage occurs, from reduction of useful life (economical loss) to structural/physical damage, including Thermal Runaway (risk of fire)

Tesla Model S Spontaneously on Fire in Los Angeles

Safe Operating Area

- SOA of Li-Ion cells is determined by cell chemistry and limited by:
  - Voltage
    - High voltage cut-off limit for charge cycle
    - Low-voltage cut-off for discharge cycle
  - Temperature
  - Current
- These limits also vary according to charge and discharge cycle.

Battery Pack Example – BMW i3

Validation summary: Safety (abuse tests)

	Items	Test condition		B sample	
				Criteria	Results
DV	Nail penetration	Nail diameter: 3 mm, speed 40 mm/sec (QC/T condition)		QC/T Pass	5L4ss
	Controlled crush test	15% and 50% of cell height or force of 1000times cell mass	X	QC/T Pass (EUCAR Level 4↓)	5L2
			+Z		5L3
	Thermal stability test	Until 150℃, heat-up rate 5℃/min, Holding 30 min at 150℃			5L4
	Overcharge test	CC/CV mode, 0.5C (94A), 6V, cutoff SOC 200% cell (2P)			10L2 (5 set)
	External short circuit test	Resistance 1 mΩ, Holding 10 min			5L2
	Force discharge	CC discharge, 1C, 2.5 hrs			5L2

https://pushevs.com/2018/04/05/samsung-sdi-94-ah-battery-cell-full-specifications/

Efficiency of Lithium Ion cells

Li-Ion cells have a significant advantage over cells with different chemistries regarding Energy and Charge.

Energy: Due to very low internal resistance, I^2R (wasted heat inside cell) is lower. During power applications, this advantage is easily observed.

Charge: Different than other chemistries, all charge transferred to the cell during charge cycle can be recovered during discharge cycle.

Aging

Li-Ion cells have longer life than other chemistries but still have a limited cycle and calendar life

Calendar life (years): Changes with chemistry. LFP and LTO cells have no calendar life (operated under 4.0V) Others have specific calender lifes.

- LFP : $LiFePO_4$, Lithiyum-iron-phosphate
- LTO : $Li_4Ti_5O_{12}$, Lithium-titanate

Cycle life (numbers): a single charge+discharge period is called one cycle. Each chemistry has its own cycle life.

Capacity of a brand new cell decreases with increasing number of cycles.

Modelling

- A chemist thinks of a cell in terms of its processes, while an EE finds it more useful to view a cell in terms of an electrical circuit, **The Equivalent Model**.
- Simplest model is using a voltage source and a series resistance (internal resistance R_i)
- R_i is not a simple resistance that can be measured with an ohm meter.

$$R_i = \frac{\Delta V}{\Delta I}$$

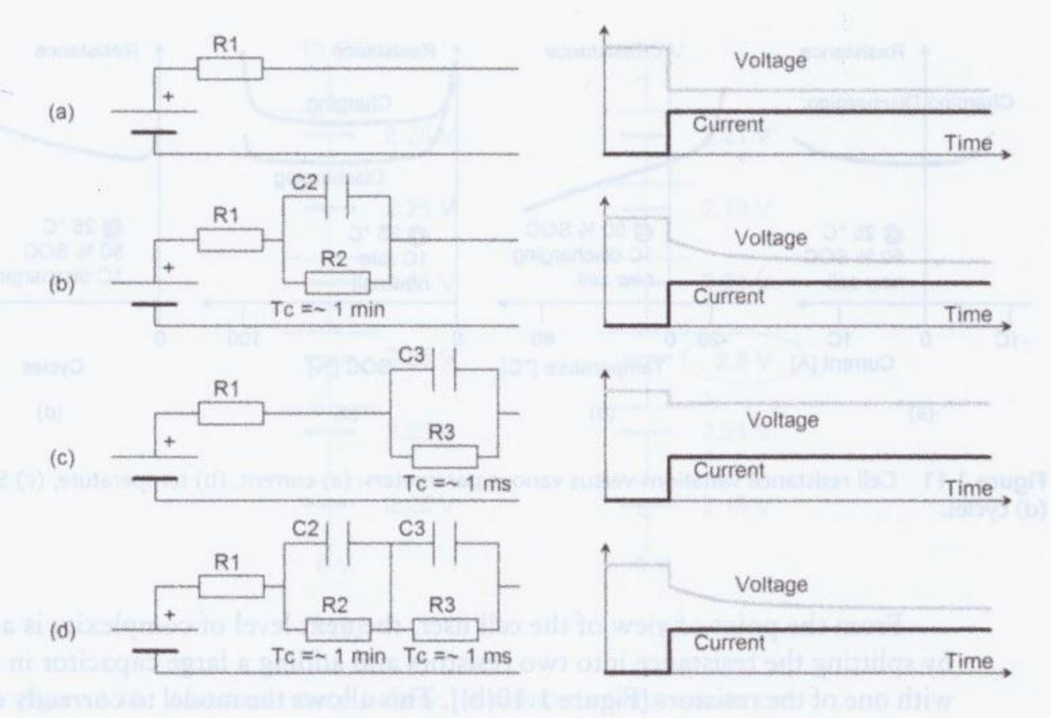


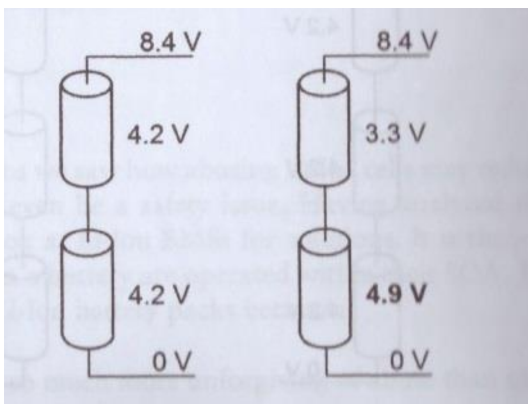
Figure 1.10 Electrical equivalent models of a Li-Ion cell and plots of voltage and current: (a) simple R, (b) with relaxation RC, (c) with AC impedance RC, and (d) with both RC circuits.

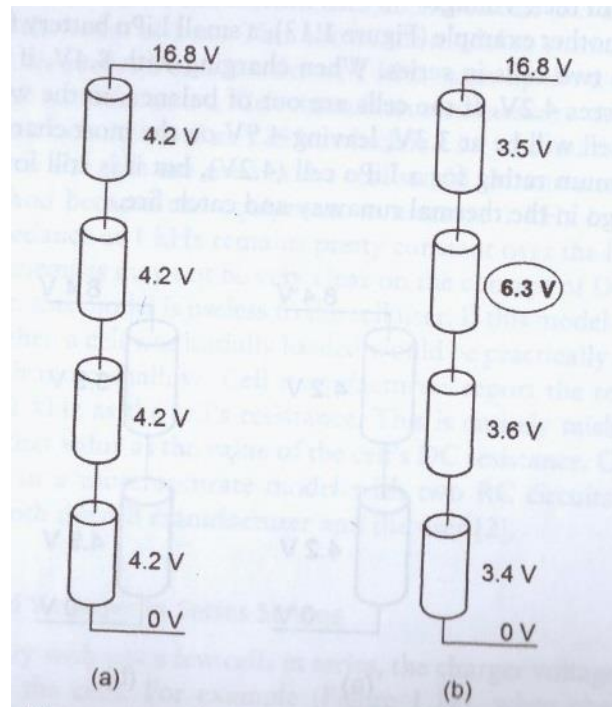
Factors Effecting R_i

- **SoC**: R_i is higher when charge level is less than %10 and higher than %90 (indicative, changes with chemistry)
- **Temperature**: R_i is higher at colder temperatures
- **Current**: R_i increases with higher currents
  - Note: R_i of a cell during charge cycle is higher than it is during discharge cycle
- **Usage**: R_i increases over time as the cell is used (aging)

Unequal Voltages in Series Strings

- In a battery with few cells in series (low voltages), voltage is divided nearly equally among the cells
- In a battery with large number of cells in series (high voltages), the overall pack voltage will not be evenly divided among the cells. This is true for any chemistry.



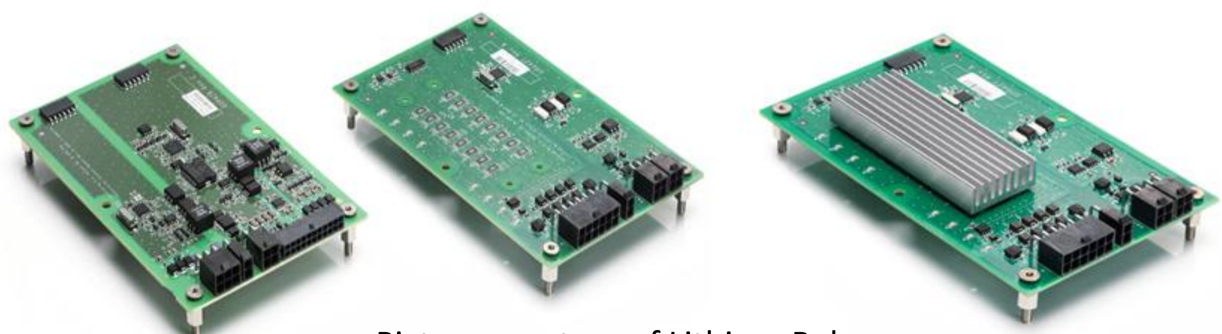


2S and 4S Unequal Voltage Distribution

Li-Ion Battery Managment Systems

A Battery Managment System (BMS) is an application specific PCB. The task of a BMS is to ensure that the cells in a battery are operated or kept within their **SOA**. This is particularly important for large Li-Ion battery packs because:

- Li-Ion cells are much more unforgiving of abuse/misuse than other chemistries
- With many cells in series, large battery packs are more prone to be charged and discharged unevenly due to unbalance among cells.



Picture courtesy of Lithium Balance

4S BMS

We have to use a BMS with a Li-Ion battery pack because we can never find two identical cells in real World!

Li-Ion Battery Managment Systems

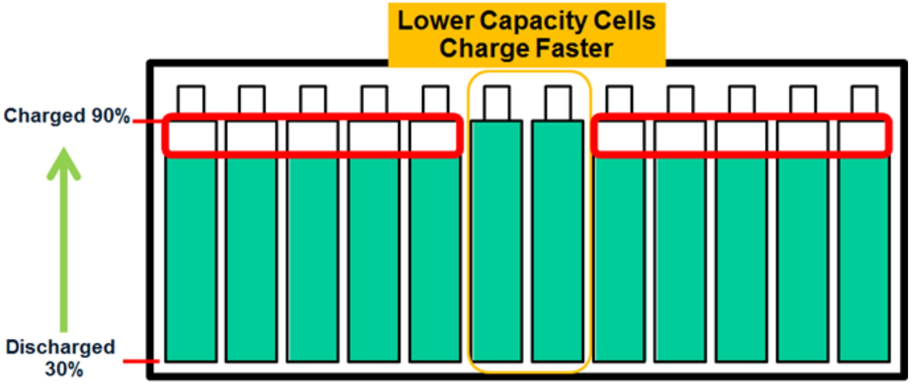
- Used to protect the battery pack in one way or another:
- To monitor the Battery
- To protect the Battery
- To estimate the state of the Battery
- To maximize the Battery's performance
- To report to user or other external devices

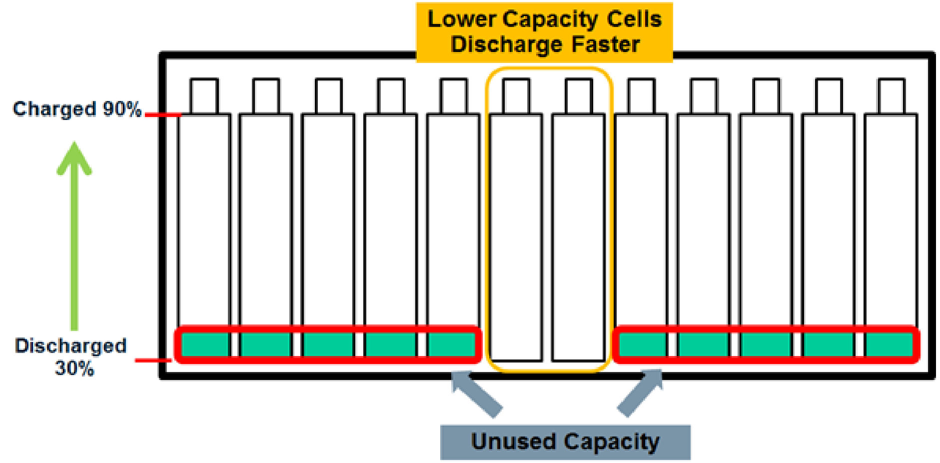
BMS Functions

- Prevent the voltage of any cell from exceeding a limit
- Prevent the temperature of any cell from exceeding a limit
- Prevent the voltage of any cell from dropping below a limit
- Prevent th<e charging current from exceeding a limit
- Prevent the discharging current (load current) from exceeding a limit

Why is a BMS Essential?

- While charging, as soon as any cell reaches its maximum voltage (high voltage cut-off level), charger must be turned off. Otherwise cell with the highest voltage will be damaged and even can catch fire.
- While discharging, as soon as any cell reaches its minimum voltage (low voltage cut-off level), load must be turned off. Otherwise cell with the lowest voltage will be damaged.
- As cycles count, unbalancing among cells make the Battery lose its capacity. A BMS should balance the cells throughout their useful life to preserve the maximum initial capacity.
- To prevent the cells from operating in Thermal Runaway conditions.



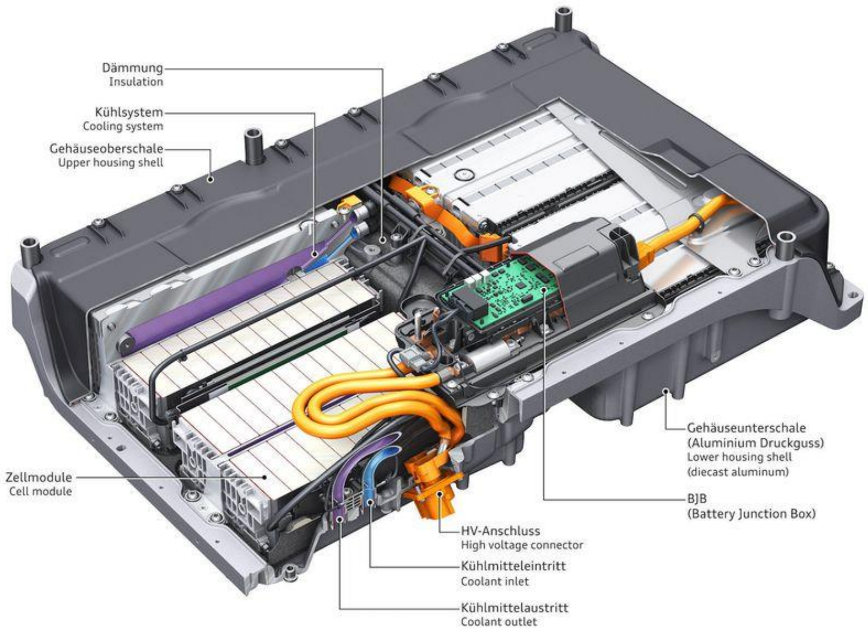


Lithium Ion Batteries

The Battery is formed when the blocks have been assembled in parallel to achieve the required capacity (in Ah) and when enough number of blocks have been connected in series to achieve the required voltage level and when the BMS is connected to the assembly.

The followings are essential for a Lithium Ion Battery:

- SoC
- DoD
- Capacity
- Balance and Balancing
- SoH



SOC: State of Charge

- **The SoC** of a Battery (or a cell) at a given time is the proportion of the available charge at that point versus the total charge available when fully charged. It is experessed as percentage, %0 when fully discharged and %100 when fully charged and anywhere in between.
- The SoC evaluation process is also known as **fuel gauge** in EVs because of its analogy to a gas car’s fuel gauge.
- Every cell has its own SoC and the Battery has its own.

DoD: Depth of Discharge

- The DoD of a Battery (or a cell) is a measure of charge removed from it. It is expressed either in Amp-hours (Ah) (preferably) or as percentage.

Picture courtesy of GoldenCell Batteries

12V 22Ah LFP Battery

Capacity

- The actual **Capacity** of a Battery (or a cell) is equal to its DoD when it is completely discharged.
- Capacity is expressed in Amp-hours.
- The nominal capacity of a cell is specified by the manufacturer.

Balance and Balancing

- Balancing is the term used for the process of bringing the SoC levels of cells in a battery closer to each other, in order to maximize the battery's capacity.
- A balanced battery is the one in which, at fully charged point, all of its cells are at 100% SoC

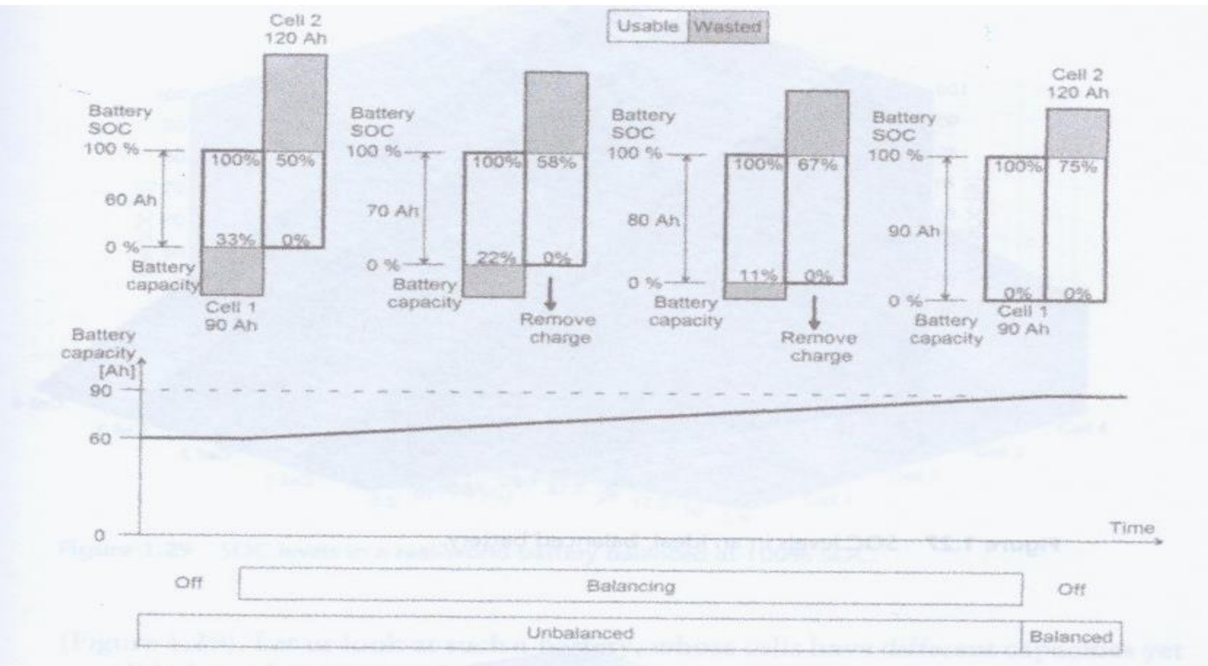


Figure 1.26 The balancing process maximizes battery capacity.

Please note that the balancing process is made between two cells with different capacities.

State of Health

- The **State of Health** of a Battery is an arbitrary figure of merit of its actual condition. It is expressed in percentages.
- The SoH is arbitrary because it is not a measure of a specific physical quality.
- %100 SoH means the Battery's current condition meets its specifications.
- As the Battery is used in time, the SoH decreases. Below %100, the SoH is arbitrary and is defined differently by various manufacturers.
- A BMS may use the following (in different weights) to calculate the SoH of a Battery:
  - Increase in cell resistance
  - Decrease in actual capacity
  - Number of Charge/Discharge cycles
  - Self discharge rate
  - Time
- The SoH level, below which the Battery is considered not to be suitable for the specific need, is also arbitrary.

2. BMS Options

Functionality- What it does?
Technology- How it does it?
Topology- How it is physically arranged?

BMS Functionality

In an increasing order of complexity, BMS types are:

- Constant current/constant voltage (CC/CV) Chargers
- Regulators
- Meters
- Monitors
- Balancers
- Protectors

BMS Functionality - CC/CV Chargers

- CC/CV chargers are standart, regulated power supplies, which are used to charge batteriers.
- First stage: CC mode. Stops when the battery reaches to a preset voltage.
- Second stage: CV mode. Stops when the battery reaches to peak voltage.

Note that there is no feedback loop from cells. Only the battery voltage is controlled, which is the sum of the cell voltages in series string.

CC/CV Charger as a BMS

- Does not prevent overcharging of individual cells
- Does not prevent overdischarging of cells
- Does not balance the pack

Conclusion: CC/CV charger is not sufficient as a BMS. It can not keep the pack in SOA (Safe Operating Area). Can only be used in 1S applications.

BMS Functionality - Regulators

- A regulator is a shunt placed accross a cell to bypass some or all of the charging current when the cell is fully charged. In its simplest form, a regulator is a voltage clamp.
- Application drawback: Charger and regulator have to be matched.
- Unmatched application results: Overcharged cell or damaged regulator because of over current.

Regulator as a BMS

- Does not prevent overcharging of individual cells
- Does not prevent overdischarging of cells

- Conclusion: Regulator can only balance a pack (if the charger and regulator properly matched). It is not sufficient as a BMS. It can not keep the pack in SOA.

BMS Functionality - Meters

Simply monitors parameters but does not actively control charging or discharging. They may meet the needs of a researcher, who may be satisfied with simply knowing the individual cells' voltages and intervene manually if anything is amiss.

- Measures each cell voltage
- Measures pack current and temperature
- Compiles this data to predict SoC
- Reports them in a display and may additionally give a warning

Meter as a BMS

- Does not prevent overcharging of individual cells
- Does not prevent overdischarging of cells
- Does not balance the pack

- Conclusion: Meter is not sufficient as a BMS. It can not keep the pack in SOA.

BMS Functionality - Monitors

Monitors are like Meters in the sense that they meausre each cell’s voltage but **they do close the control loop**. Should anything be amiss, they take correction action by themselves and indirectly control the charger and/or the load current (not able to interrupt current).

Monitor as a BMS

- Does not balance the pack
- Does not include a switch or breaker to stop charge/discharge current
- Conclusion: Monitor is not sufficient as a BMS. It keeps the pack in SOA. But can not support a sustainable efficient operation due to unbalancing in time.

BMS Functionality - Balancers

Like a monitor but with the added ability to maximize the pack's performance by balancing the cells

Balancer as a BMS

- Does not include a switch or device to stop charge/discharge current
- Includes I/O connections to drive switch or breaker.
- **Conclusion:** Balancer is sufficient as a BMS as long as it is wired in the proper way that allows it to control the charging source and the discharging load.
- Balancers are by far the preferred choice by professionals (automakers, stationary battery energy storage system manufacturers, etc) for large Li-Ion packs

BMS Functionality - Protectors

Like a balancer but with the added ability to turn off pack current

Protector as a BMS

- Protector is completely sufficient as a BMS
- Protector can only be used with small batteries and usually found as an integral part of the battery (enclosed in battery housing).
- Can either be contactor based or equipped with FET switches (low current applications)

Technology

There are basically two classes of Technologies used to implement a BMS: analog and digital.

Analog (Simple) BMS

- With quite limited capabilities, they are sufficient to keep the pack in SOA, balance the cells and turn off the current.
- User has no information about individual cell voltages, resistances and capacities, and has limited information about pack current and temperature.
- SoH evaluation can not be made.
- Efficiency of the pack decreases more in time with respect to packs equipped with digital BMSs.

Digital (Sophisticated) BMS

- A digital BMS is fully aware of each cell's voltage (and possibly more, such as its temperature and its conditions). Therefore, it is able to report this data, which is invaluable in allowing an analysis of the state of the pack. This is normally a requirement for a large, professional Li-Ion pack.

➢ All systems require some form of Analog Front End (AFE). The distinction between analog and digital is related to how the cell voltage informations are processed.

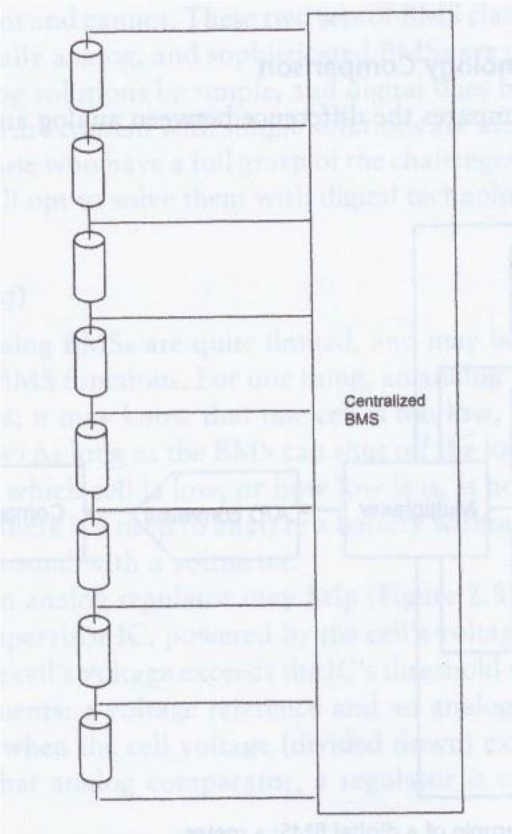
BMS Topologies

- BMSs can be categorized based on how they are installed: seperately and directly on each cell, altogether in a single device, or in some intermadiate form. This is a farmore important characteristic of a BMS that it would first appear, as it affects cost, relibility, ease of installation & maintenance, and measurement accuracy
- Or BMSs can be categorized according to functionality:
  - Centalized
  - Master-Slave
  - Modular
  - Distributed

BMS Topologies - Centralized

Entirely located in a single assembly, from which a bundle of wires (N+1 wires for N cells in series) goes to the cells. Using only one assembly has several advantages:

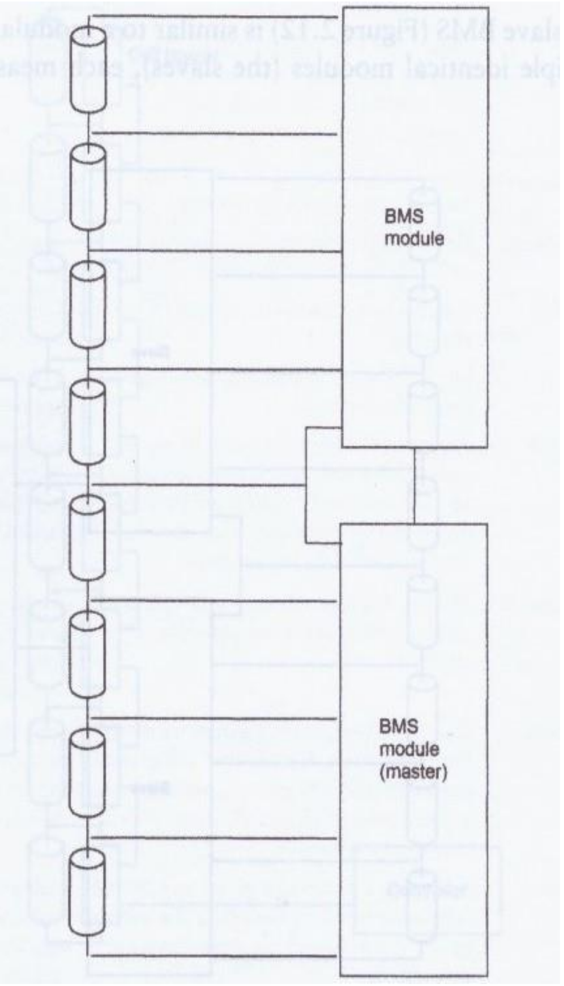
- Compact
- Least expensive approach
- Ease of installation and maintenance
- Suitable for small capacity packs



BMS Topologies - Modular

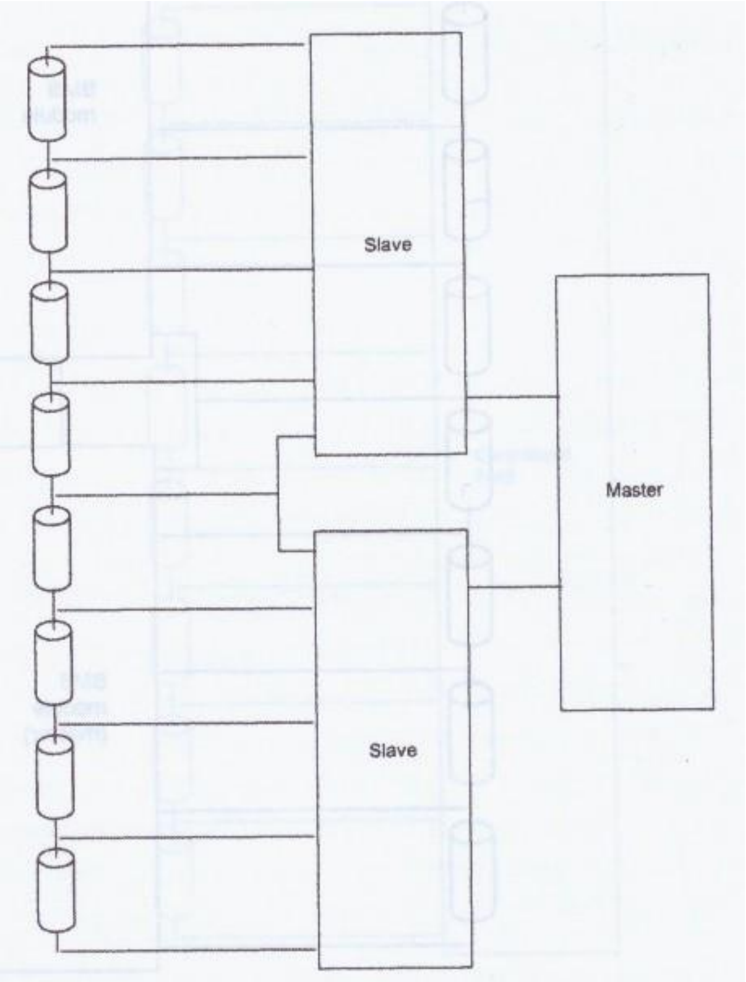
Similar to a centralized one, but the BMS is divided into multiple, **identical** modules, each with its bundle of wires going to one of the batteries in the pack. Typically, one of the modules is appointed as a master, as it is the one that manages the entire pack and communicates with the rest of the system, while the other modules act as slave modules, simple remote measuring devices. A communication link transfers the readings from slave modules to the master module.

- Not expensive
- Ease of installation & maintenance
- Expansion to large packs is straightforward
- Some AFE inputs will remain unused



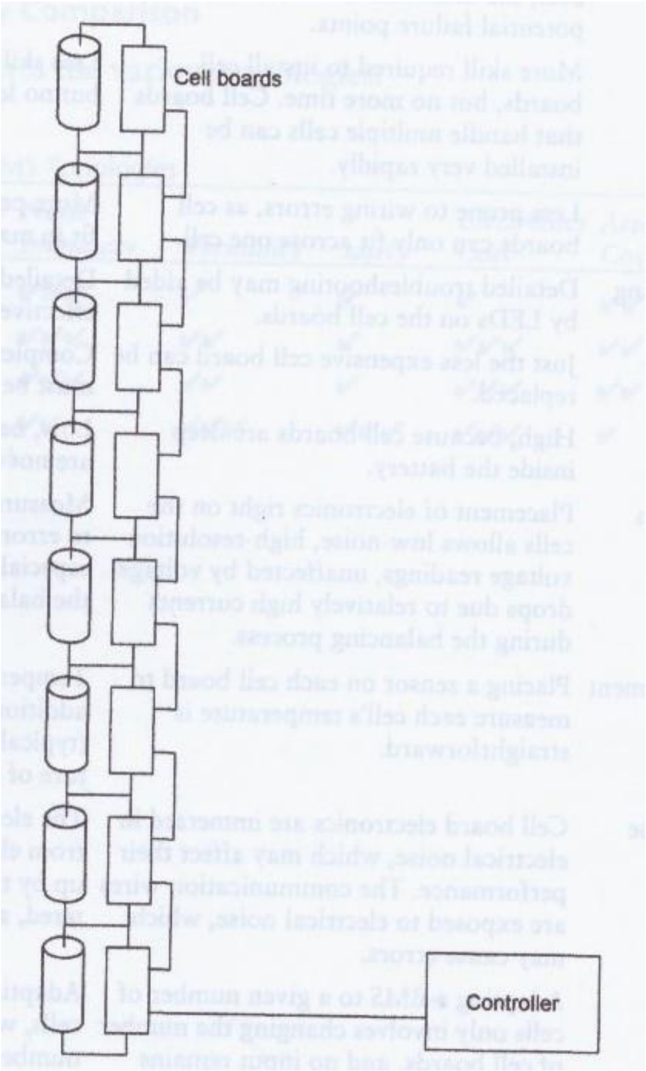
BMS Topologies - Master – Slave

- Similar to Modular BMS but master and slave modules are different.
- Slaves are identical and simple, master is different and complex
- Expensive
- Installation & maintenance gets complicated
- Application specific, all AFE inputs can be used



BMS Topologies - Distributed

- Significantly different from the other topologies (in which the electronics are grouped and housed seperately from the cell).
- In a distributed BMS, the electronics are contained on cell boards that are placed directly on the cell being measured. Cell boards are connected to a controller which handles computation and communication.



3. BMS Functions

A given BMS may implement one or more of these functions

- Measurement
- Management
- Evaluation
- Communication
- Logging and Telemetry

BMS Functions -Measurement

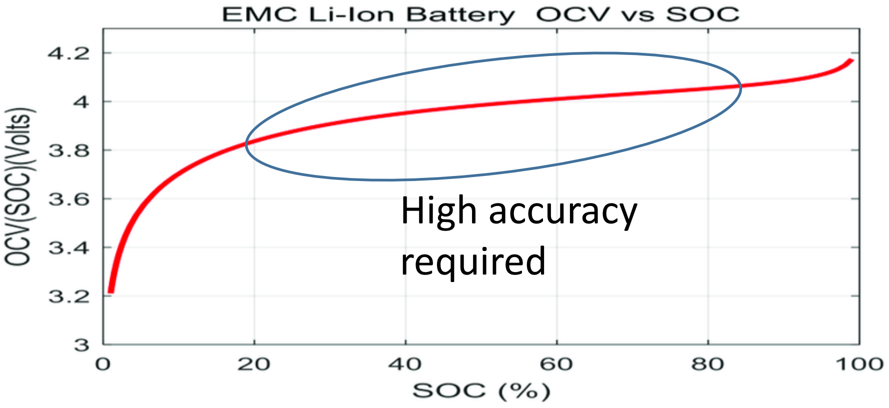
- The first function of a sophisticated, digital BMS is to gather data about a pack

In the order of importance, these are:

- Cell voltages
- Cell temperature or at least Battery temperature
- Pack current

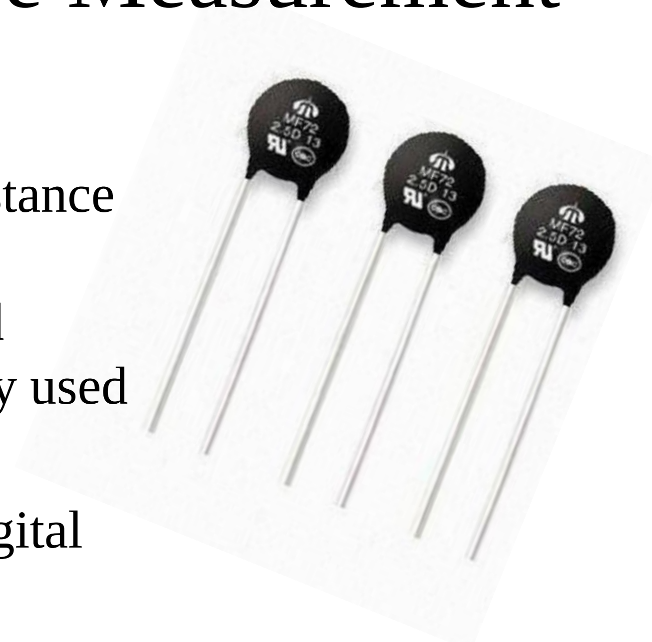
BMS Functions –Voltage Measurement

- **Method:** In distributed BMS applications, cell boards measure the cell voltage directly from the cell, while the others (centralized, modular and master-slave topologies) measure the voltage difference between the two taps on either side of a cell.
- **Rate:** Frequency of the readings. Depends on application (0.1Hz -100 Hz)
- **Accuracy:** Depends on its use and where it corresponds on the OCV versus SoC curve (1mV – 500 mV).



- **Isolation:** Path between the high voltage point and low voltage measurement must be isolated.

BMS Functions - Temperature Measurement



- **NTC thermistors:** Resistors with a negative temperature coefficient, which means that the resistance decreases with increasing temperature. They are primarily used as resistive temperature sensors and current-limiting devices. **NTC** sensors are typically used in a range from −55°C to 200°C.
- **Pack Level**: Some analog BMSs and almost all digital BMSs. Not sufficient for thermal management
- **Battery Level**: Almost all digital BMSs. Still not sufficient for thermal management
- **Cell Level**: Some digital BMSs, especially distributed BMSs. Sufficient for thermal management

BMS Functions - Current Measurement

- **Direct Reading**: in small batteries with small currents in analog BMS applications
- **Indirect Reading**: Reading over a current shunt or a hall effect sensor: digital BMS applications for reading high pack currents with high accuracy (SoC, DoD, SoH evaluation etc).

BMS Functions - Management

A BMS may manage the pack in three ways:

- Protection
- Thermal management
- Balancing

BMS Functions – Management/Protection

Whenever a pack comes to the limits of SOA a good BMS will control the current in 3 ways:

- Interrupt the current by itself (protector)
- Send a request to interrupt the current (balancer)
- Limit the current to a safe or desired level (equipped with a current limiting device) **valet mode** of a BEV is a good example.

Monitored conditions are cell voltages, cell temperatures and pack current

BMS Functions – Management/Thermal

- Li-Ion Cell working temperature range : -20°C – 60°C
- Automotive environment : -50°C – 85°C
- Military applications working conditions : -40°C – 60°C
- Military applications survival conditions are even worse!

A good BMS collects data at cell level and requests external devices to maintain the desired temperature levels for Li-Ion cells by either cooling or heating.

BMS Functions – Management/Balancing

Balancing leaves room for more charge, without overcharging the most charged cell. A BMS can balance a Battery in two ways:

- Passive: Removed energy is wasted in heat
- Active: Energy is transferred between cells.

Balancing algorithms can be based on:

- Instant voltage
- Final voltage
- SoC history

These algorithms operate on different parts of the OCV (Open Circuit Voltage) versus SoC curve.

BMS Functions - Evaluation

From the measured data, BMS calculates or estimates certain parameters that relate to the state of the pack. These are:

- SoC (the only parameter a standard user wants to know)

The rest is referred by researchers/manufacturers to improve the performance of the pack:

- DoD
- Resistance
- Capacity
- SoH

BMS Functions - External Communication

This is the bi-directional communication between the BMS and the external system.

Data carried from the BMS:

- Request to the system to reduce Battery current or stop it.
- Data on the status of the pack and the BMS itself

Data carried to the BMS:

- System configuration commands
- Data from external sensors

Communication Method

Dedicated Wire, which has a specific, dedicated function.

- Analog (continuously variable) signal
- Digital (on/off) control signal

Data Link, a communication link with digital data.

- Wired, serial data port (RS232, CAN Bus, Ethernet)
- Wireless radio link (Wi-Fi, Bluetooth)
- Light link (Fiber optic, infrared link)

BMS Functions - Logging and Telemetry

For low frequency readings a BMS may store records but for high-end applications, data is sent to a nearby logger. Log may include some or all of the following:

- Pack Level: Voltage, current, SoC, SoH, resistance
- Charge and discharge current limits
- Cell Level: Minimum and maximum voltage and temperature
- Warnings
- Errors

The log data can also be transmitted to a remote location which is called Telemetry. Cellular modems are widely used for this application.

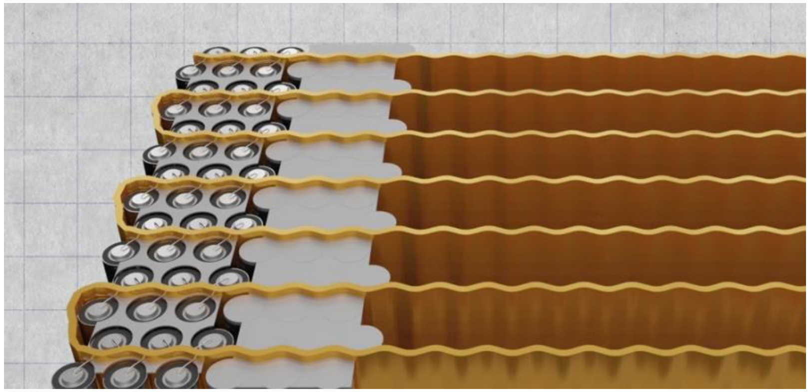
Battery Pack Cooling - Heating

Forced air cooling: Usually not sufficient for high performace aplications

Liquid cooling – Cold plate cooling: The coolant can be used to remove heat from the pack and to also provide heating of the pack for fast charging at low temperatures.

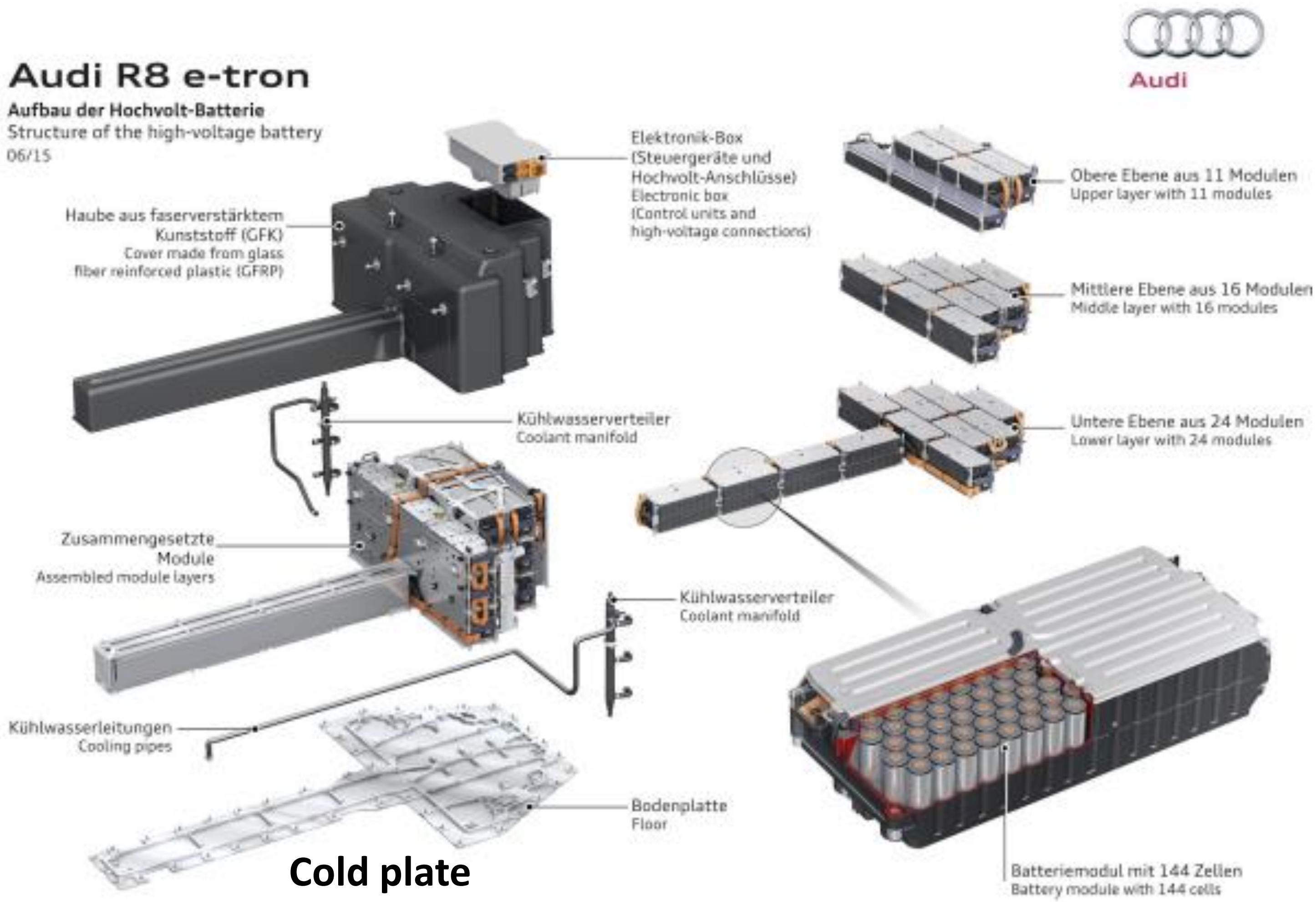
- Both the BMW i3 and the Chevy Bolt use a bottom cooling plate in its battery with the cooling medium being a refrigerant for the BMW and water glycol for the Chevy.
- The Chevy Bolt has side-mounted tabs meaning the cooling base plate is potentially drawing heat from the wrong edge of the cell.
- Tesla uses cooling manifolds as cooling plates. A water and glycol mixture is pumped through manifolds.

Source: https://avidtp.com/what-is-the-best-cooling-system-for-electric-vehicle-battery-packs/

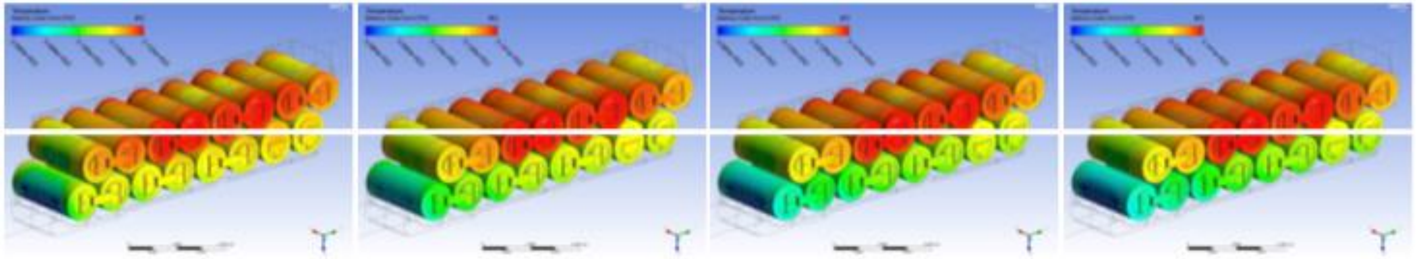


[Chevy Volt battery system animation]

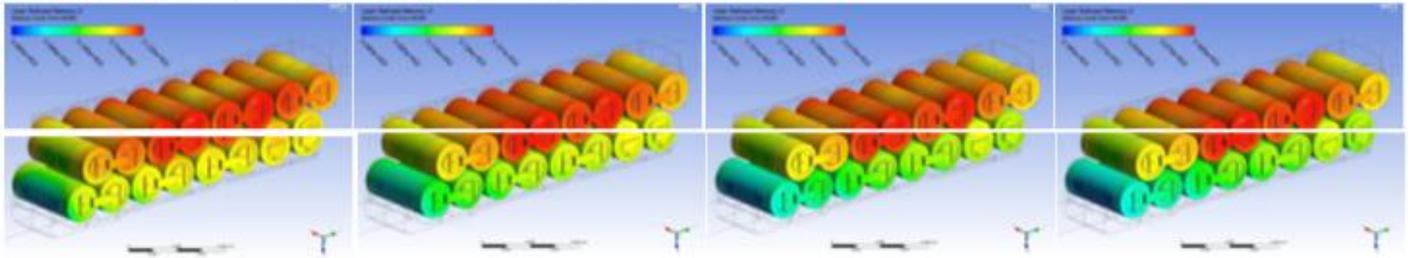
Battery Pack Cooling - Heating



Battery Pack Cooling - Heating



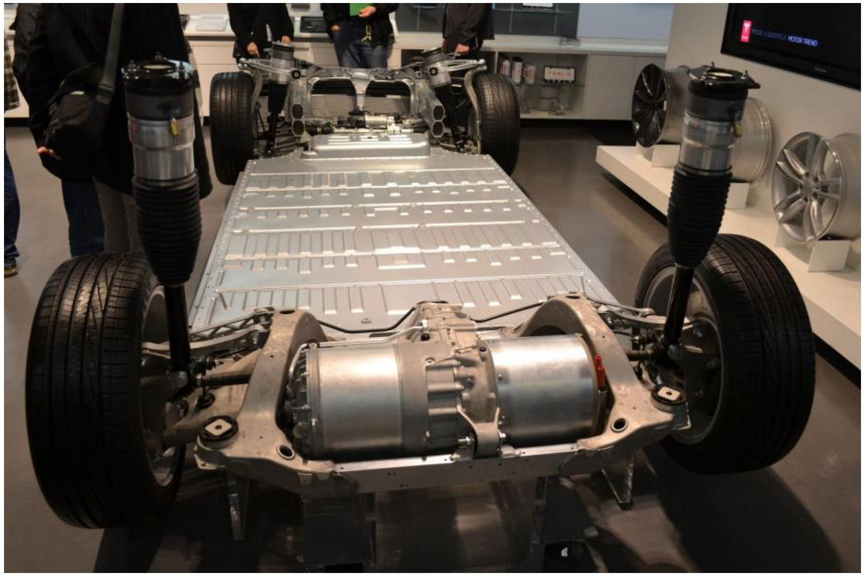
CFD results at 200, 400, 600 and 800 seconds



SVD ROM results at 200, 400, 600 and 800 seconds

Battery Pack Example – Tesla Model S

- The 85 kWh battery pack weighs 1,200 lb (**540 kg**) and contains 7,104 lithium-ion battery cells in 16 modules wired in series (14 in the flat section and two stacked on the front). Each module contains 6 groups of 74 cells wired in parallel; the 6 groups are then wired in series within the module.
- As of June 2012, the battery pack used modified Panasonic cells with nickel-cobalt-aluminum cathodes. Each cell was of the 18650 form factor (i.e., an 18 mm diameter, 65 mm height cylinder), similar to the Panasonic NCR18650B cell that has an energy density of 265 Wh/kg. Analysts estimate battery cost to be around **21–22%** of the car cost.



Source: https://en.wikipedia.org/wiki/Tesla_Model_S

- Lithium-ion batteries operate best at certain temperatures. The Model S motor, controller and battery temperatures are controlled by a liquid cooling/heating circuit. Waste heat from the motor heats the battery in cold conditions, and battery performance is reduced until a suitable battery temperature is reached.

[Tosla EV Car, Battery Pack Tear Down]

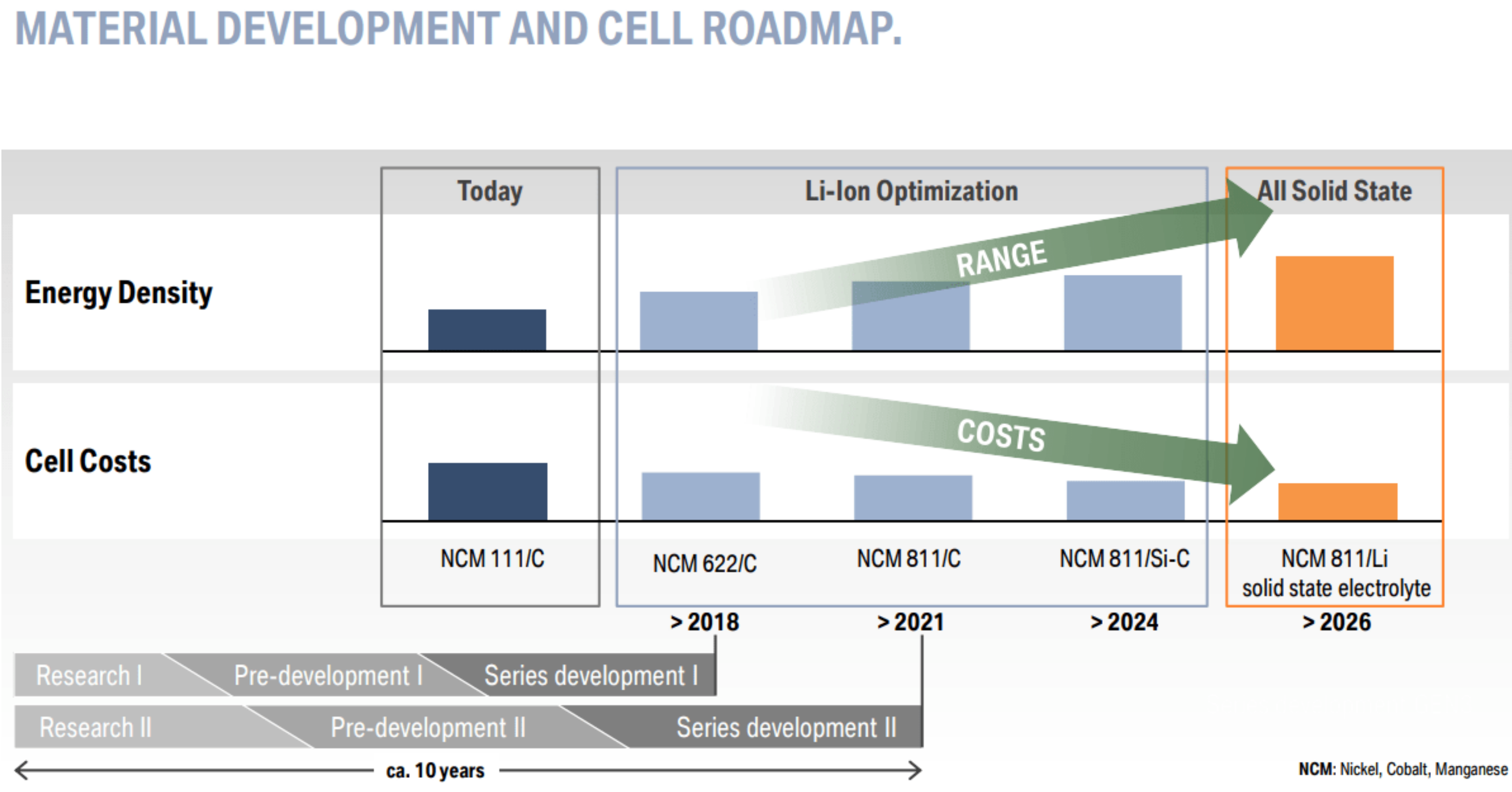
Battery Pack Example – BMW i3

i3 60 Ah: 22 (18.8 usable) kWh lithium-ion battery
i3 94 Ah: 33 (27.2 usable) kWh lithium-ion battery
i3 120 Ah 42.2 kWh lithium-ion battery

- BMW i3 will get its battery upgraded with NCM 622 cells and the capacity will increase from 94 to 120 Ah. With 120 Ah battery cells, the BMW i3 will have a total battery capacity around 42,62 kWh (96 x 120 Ah x 3,7 V).

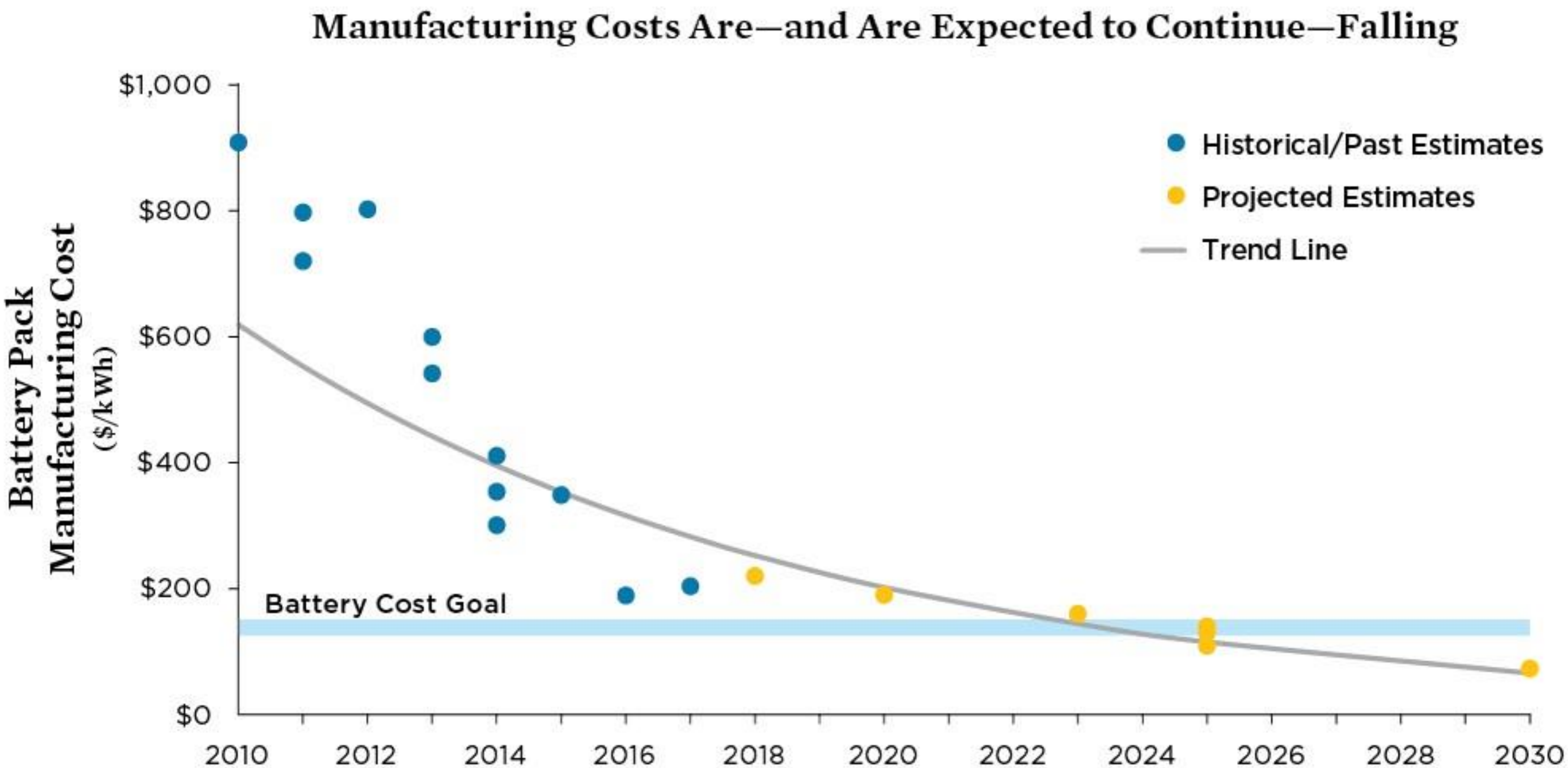
https://pushevs.com/2018/04/05/samsung-sdi-94-ah-battery-cell-full-specifications/

Battery Pack Example – BMW i3



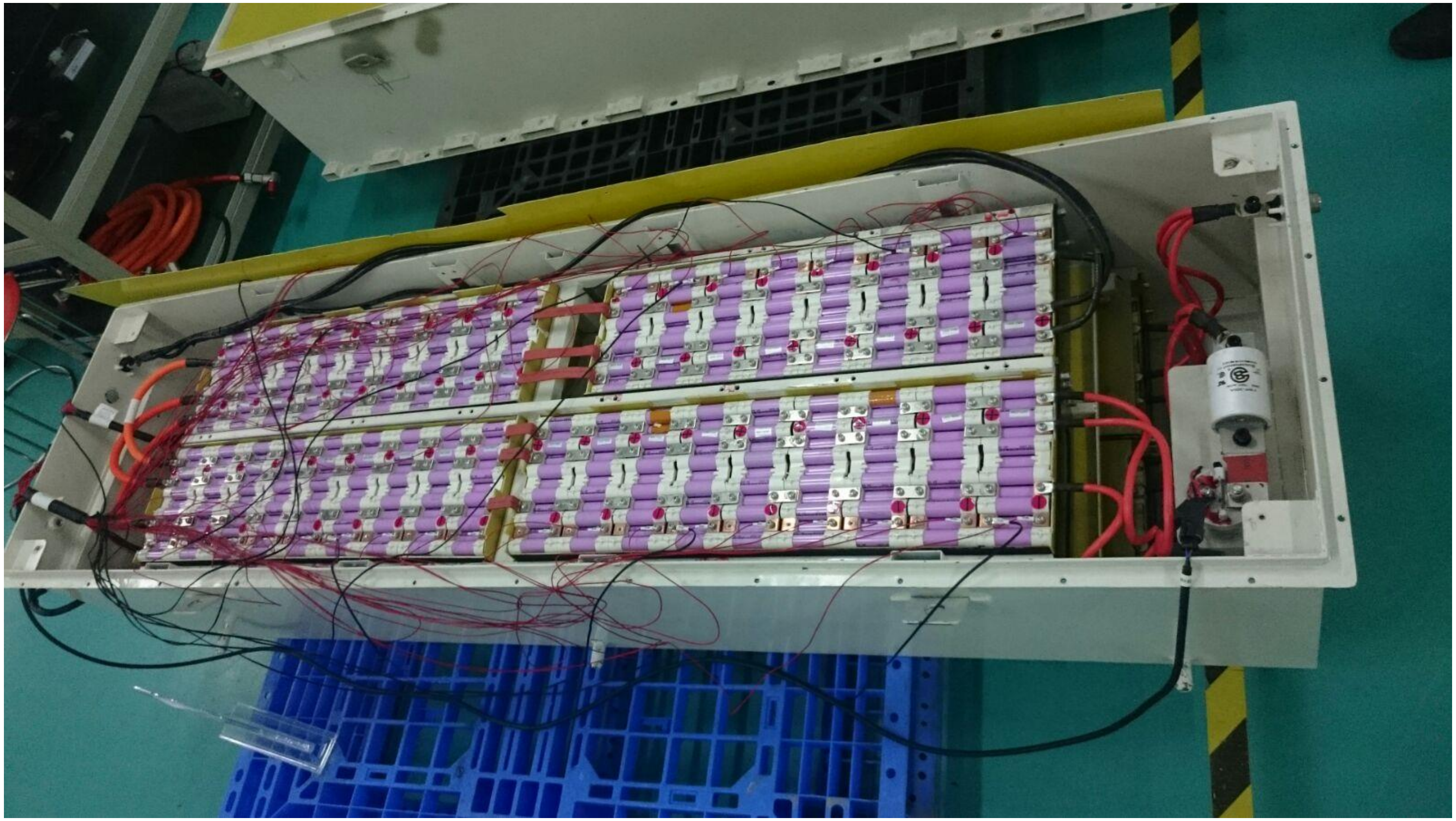
https://pushevs.com/2018/04/05/samsung-sdi-94-ah-battery-cell-full-specifications/

Battery Pack Manufacturing Costs

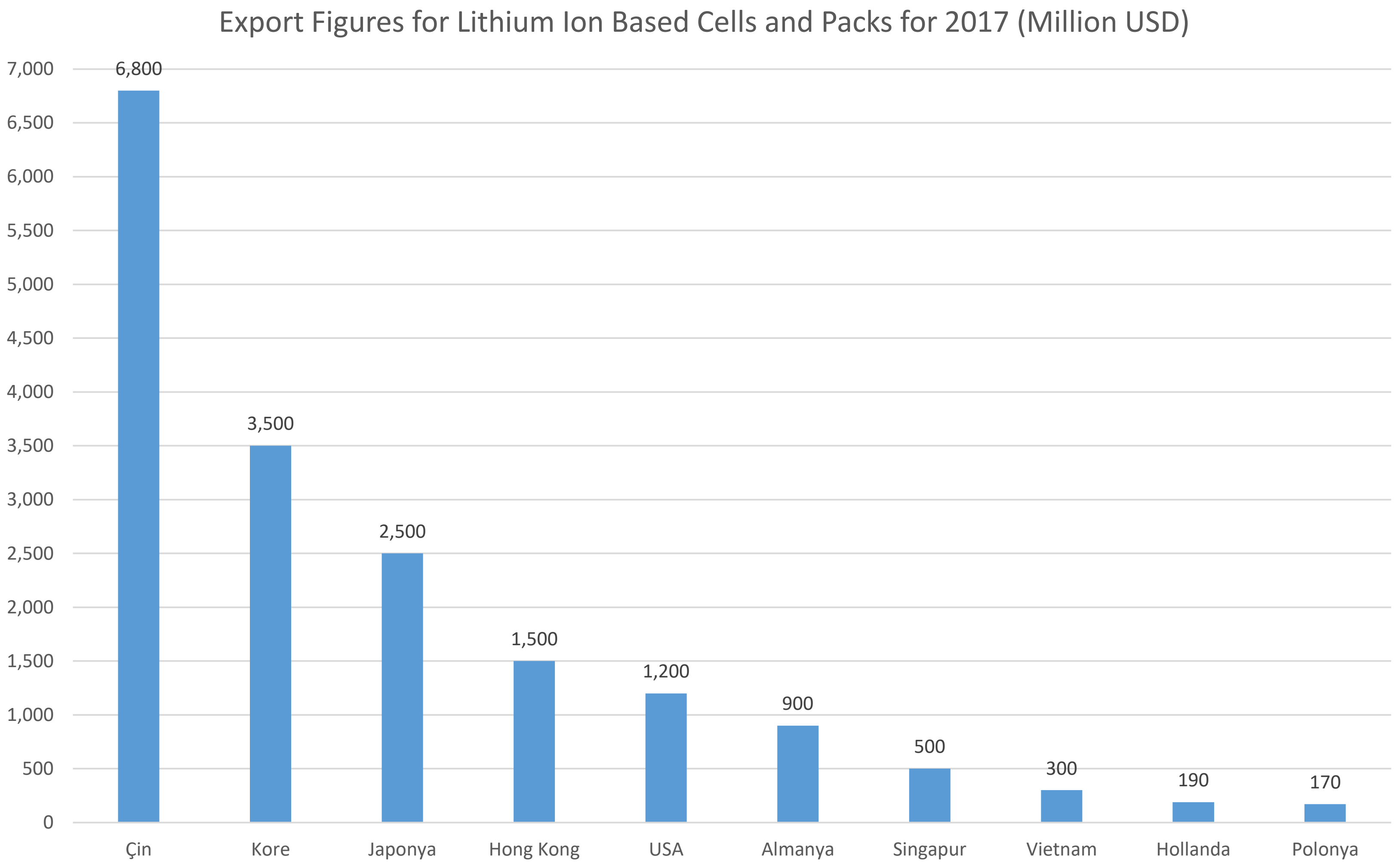


Lithium Ion Battery Pictures (Small)

Lithium Ion Battery Pack Pictures



Lithium Ion Based Cell Export



Links

18650 Lithium Ion Cell Techinal Specs

https://industrial.panasonic.com/ww/products/batteries/secondary-batteries/lithium-ion/cylindrical-type/NCR18650PF

Lithium Ion Cell Overcharging Fire

https://www.youtube.com/watch?v=YuKF8XfCVKQ

Tesla EV Car, Battery Pack Tear Down

https://www.youtube.com/watch?v=NpSrHZnCi-A

Balancing of cells

https://www.youtube.com/watch?v=0KSFitqvap0

The Truth About Tesla Model 3 Batteries: Part 1

The Truth About Tesla Model 3 Batteries: Part 2

Textbooks:

Reading Material:

- Andrea, D., **“**Battery Management Systems for Large Lithium-Ion Battery Packs”, Artech House, 2010.
- Korthauer, R., “Lithium Ion Batteries: Basics and Applications”, 1st Edition, Springer, 2018.
- Weicker, P., “A Systems Approach to Lithium Ion Battery Management”, Artech House, 2014.

Summary of most common lithium-ion based batteries

Chemistry	Lithium Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Manganese	Lithium Iron Phosphate	Lithium Nickel Cobalt Aluminum Oxide	Lithium Titanate
Short form	Li-cobalt	Li-manganese	NMC	Li-phosphate	Li-aluminum	Li-titanate
Abbreviation	$LiCoC_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNiMnCoO_2$ (NMC)	$LiFePo_4$ (LFP)	$LiNiCoAlO_2$ (NCA)	Li_2TiO_3 (LTO)
Nominal voltage	3.60V	3.70V (3.80V)	3.60V (3.70V)	3.20, 3.30V	3.60V	2.40V
Full charge	4.20V	4.20V	4.20V (or higher)	3.65V	4.20V	2.85V
Full discharge	3.00V	3.00V	3.00V	2.50V	3.00V	1.80V
Minimal voltage	2.50V	2.50V	2.50V	2.00V	2.50V	1.50V (est.)
Specific Energy	150–200Wh/kg	100–150Wh/kg	150–220Wh/kg	90–120Wh/kg	200-260Wh/kg	70–80Wh/kg
Charge rate	0.7–1C (3h)	0.7–1C (3h)	0.7–1C (3h)	1C (3h)	1C	1C (5C max)
Discharge rate	1C (1h)	1C, 10C possible	1–2C	1C (25C pule)	1C	10C possible
Cycle life (ideal)	500–1000	300–700	1000–2000	1000–2000	500	3,000–7,000
Thermal runaway	150°C (higher when empty)	250°C (higher when empty)	210°C(higher when empty)	270°C (safe at full charge)	150°C (higher when empty)	One of safest Li-ion batteries
Maintenance	Keep cool; store partially charged; prevent full charge cycles, use moderate charge and discharge currents					
Packaging (typical)	18650, prismatic and pouch cell	prismatic	18650, prismatic and pouch cell	26650, prismatic	18650	prismatic
History	1991 (Sony)	1996	2008	1996	1999	2008
Applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, powertrains	E-bikes, medical devices, EVs, industrial	Stationary with high currents and endurance	Medical, industrial, EV (Tesla)	UPS, EV, solar street lighting
Comments	High energy, limited power. Market share has stabilized.	High power, less capacity; safer than Li-cobalt; often mixed with NMC to improve performance.	High capacity and high power. Market share is increasing. Also NCM, CMN, MNC, MCN	Flat discharge voltage, high power low capacity, very safe; elevated self-discharge.	Highest capacity with moderate power. Similar to Li-cobalt.	Long life, fast charge, wide temperature range and safe. Low capacity, expensive.

Characteristics of commonly used rechargeable batteries

Specifications	Lead Acid	NiCd	NiMH	Li-ion[1]		
				Cobalt	Manganese	Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life[2] (80% DoD)	200–300	1,000[3]	300–500[3]	500–1,000	500–1,000	1,000–2,000
Charge time[4]	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%[5]	30%[5]	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V[6]	1.2V[6]	3.6V[7]	3.7V[7]	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C[8] 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C[9] (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to °F)	–20 to 65°C (–4 to 49°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months[10] (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory[11]		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency[12]	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High[13]		

BMS -Custom Versus Off-the-shelf (COTS)

- Custom: You own, you control, you pay a lot, you wait for some time, you may fail up at the end. Essential for demanding (high voltage/high energy/high power) applications with complex communication capabilities.
- COTS: fast, easy, cheap, only suitable for small packs with voltages 48V and less. Expect low reading accuracy and relatively poor protection performance.