Table of Contents **Page Number**

BATTERY MANAGEMENT SYSTEMS

1. Introduction – Battery:

A battery is an electrochemical device that converts chemical energy into electrical energy. It's made up of one or more electrochemical cells that are connected to external inputs and outputs. Batteries can be charged with an electric current and discharged whenever required. It is a device that produces electricity to provide power for electronic devices, cars, etc. Batteries are divided into primary batteries, which can only be used once, such as dry cell batteries, and secondary batteries, which can be recharged and used many times. Lithium-ion batteries are rechargeable secondary batteries.

Batteries have a positive electrode (cathode) and a negative electrode (anode) made out of metal, between which they are filled with a substance (electrolyte) that conducts electricity carried by ions. The metal electrodes are dissolved by the electrolyte, dividing into ions and electrons. When the electrons move from the anode to the cathode, an electric flow (current) is generated, creating electricity. In secondary cells, electrons are stored at the anode by charging before starting to use the battery, and electricity is produced by the stored electrons moving to the cathode when using the battery.

Different Types of Batteries used in EV vehicles:

The invention of batteries in 1800 marked the beginning of many advancements today. A massive milestone was the invention of the first rechargeable battery in 1859. Today, almost every device from wristwatches to electric vehicles is powered by batteries, the source of direct current. Depending upon the material of cathode and anode, the properties of batteries vary and make them fit for a specific application. Let us dive into the different **t**ypes of EV batteries [1].

1. Lithium-ion (Li-ion) Battery
2. Lead Acid Battery
3. The nickel-cadmium battery
4. The nickel-metal hydride battery [2]

Most of today's EVs use lithium-ion battery packs. It is the same technology used in smartphones and laptop computers and are known for having a high power-to-weight ratio. Very efficient and offering excellent high-temperature performance, they are currently the best option for holding a stable charge and are recyclable[3].

Energy density and Power density:

The two most common concepts associated with batteries are

- Energy density
  - Energy density is measured in watt-hours per kilogram (Wh/kg) and is the amount of energy the battery can store with respect to its mass
- Power density
  - Power density is measured in watts per kilogram (W/kg) and is the amount of power that can be generated by the battery with respect to its mass.

To draw a clearer picture, think of draining a pool. Energy density is similar to the size of the pool, while power density is comparable to draining the pool as quickly as possible [5].

Importance of High Energy Density:

- To better understand lithium-ion batteries, you should understand why a high energy density is a desirable trait in a battery.
- A battery with high energy density has a longer battery run time in relation to the battery size. Alternately, a battery with high energy density can deliver the same amount of energy, but in a smaller footprint compared to a battery with lower energy density. This greatly expands the possibilities for battery applications.
- If the energy density of a battery is too high, it could present a safety issue. When there's more active material packed into a cell, it increases the risk of a thermal event [6].

Comparison of Different Rechargeable Batteries with their Energy Density?

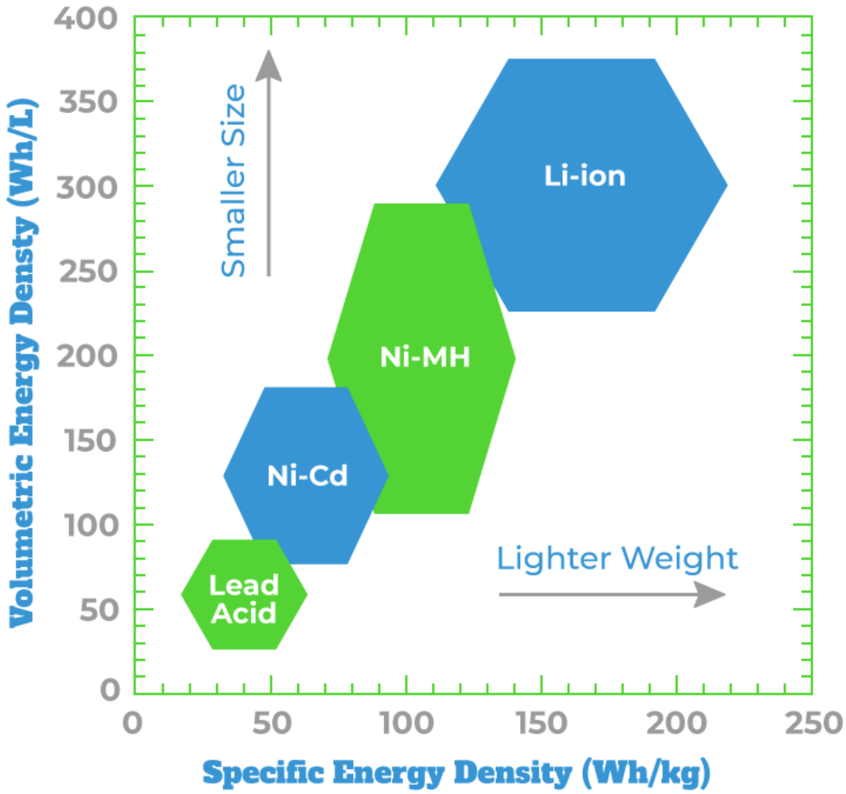
There are several different types of rechargeable batteries with a variety of energy densities reflective of their internal chemistry[6].

(1) Energy density of Lead acid battery ranges between 30-50 Wh/kg

(2) Energy density of Nickel-cadmium battery ranges between 45-80 Wh/kg

(3) Energy density of Nickel-metal hydride battery ranges between 60-120 Wh/kg

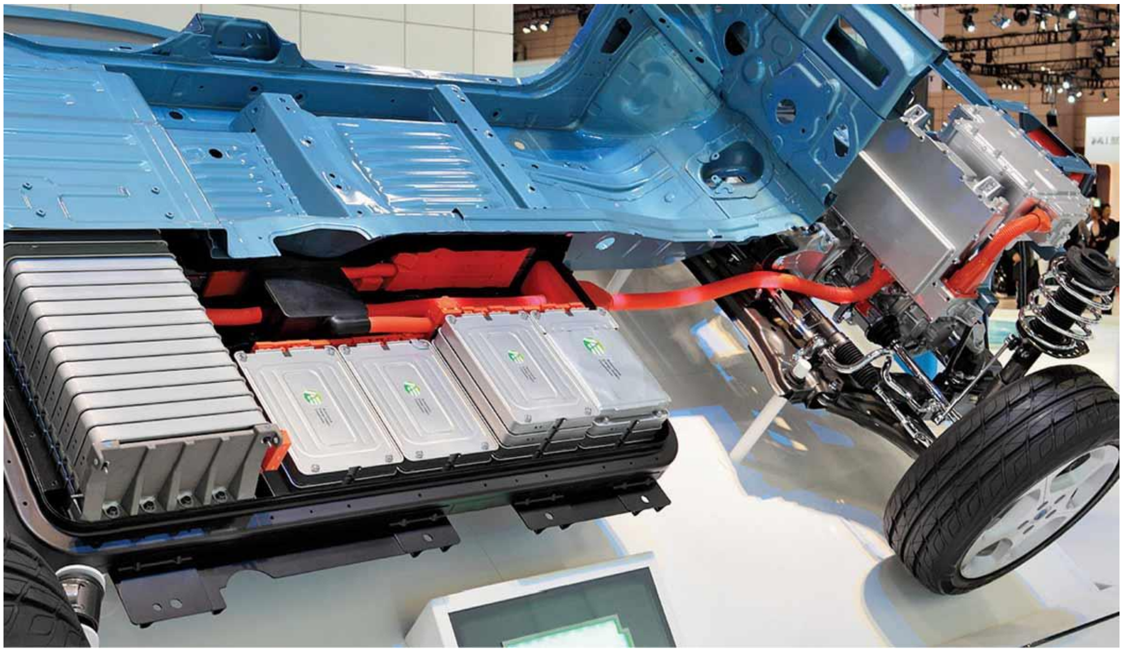
(4) Energy density of Lithium-ion battery ranges between 50-260 Wh/kg ✔



Lithium-ion (Li-ion) Battery:

- Lithium-ion batteries use a metal compound into which lithium is embedded in advance as the cathode. Carbon, which can store that lithium, is used as the anode. This structure generates electricity without dissolving the electrodes in an electrolyte like conventional batteries. In addition to suppressing deterioration of the battery itself and allowing more electricity to be stored, this also enables the battery to be charged and discharged more times. Moreover, since lithium is a very small and light substance, it enables various advantages such as the creation of smaller and lighter batteries [(4).]
- Lithium-ion is a low maintenance battery, an advantage that most other chemistries cannot claim. There is no memory and no scheduled cycling is required to prolong the battery's life.

In addition, the self-discharge is less than half compared to nickel-cadmium, making lithium-ion well suited for modern fuel gauge applications. lithium-ion cells cause little harm when disposed.



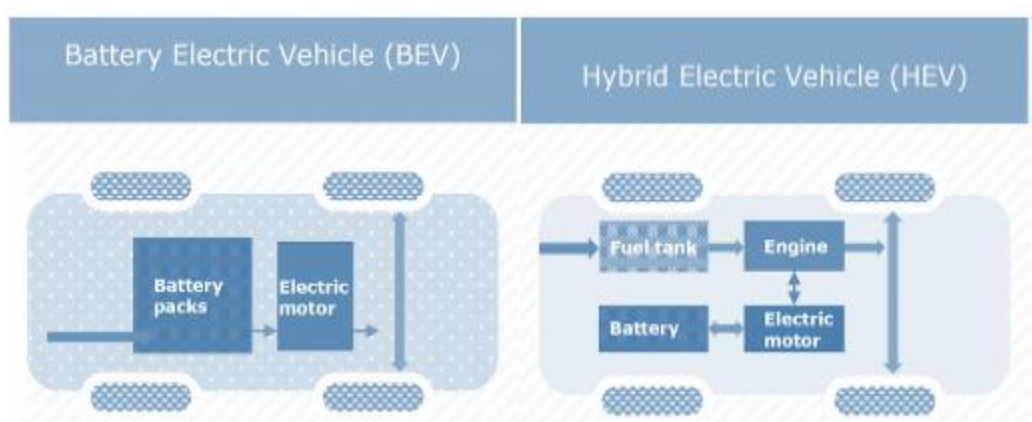
- When it comes to cell housing, there are three different types: cylindrical, prismatic, and pouch-type batteries. You'll find all three in EVs today, and each one has its pros and cons.
- For example, Tesla chooses to use cylindrical batteries because of their reliability and durability. Their battery packs contain hundreds of lithium-ion cells stored under the car's interior carriage. In fact, there are 2,976 lithium-ion battery cells in a Tesla. These lithium-ion battery cells are the highest energy-density battery in the world. Nevertheless, they're cumbersome compared to other types[7].
- Like cylindrical batteries, prismatic batteries feature a solid casing; however, prismatic batteries are generally lighter and can fit well in small spaces due to their rectangular shape.

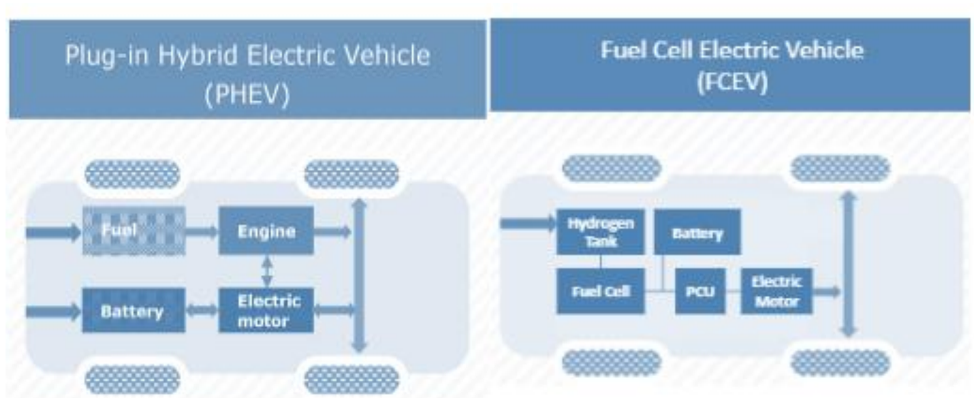
Because of this, Volkswagen has recently made the switch to prismatic batteries. That said, prismatic batteries usually have a shorter life cycle than cylindrical batteries.

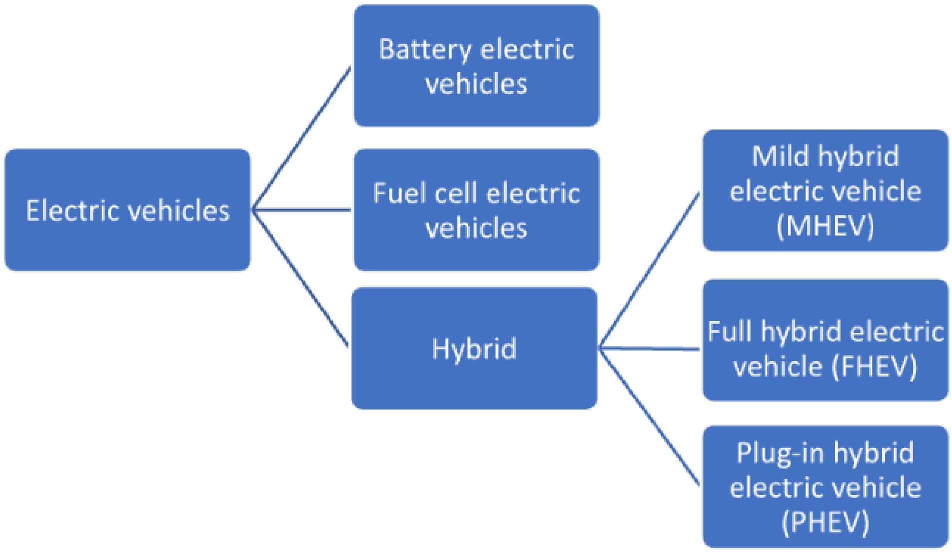
- Pouch-type batteries differ because they're in thin, metal bags, making them more flexible than prismatic and cylindrical batteries. Because of this, they're fantastic for small, oddly shaped spaces, but they can be vulnerable to swelling and pose a potential fire risk. GM and Hyundai both use pouch-type batteries[7].

Types of Electric Vehicles

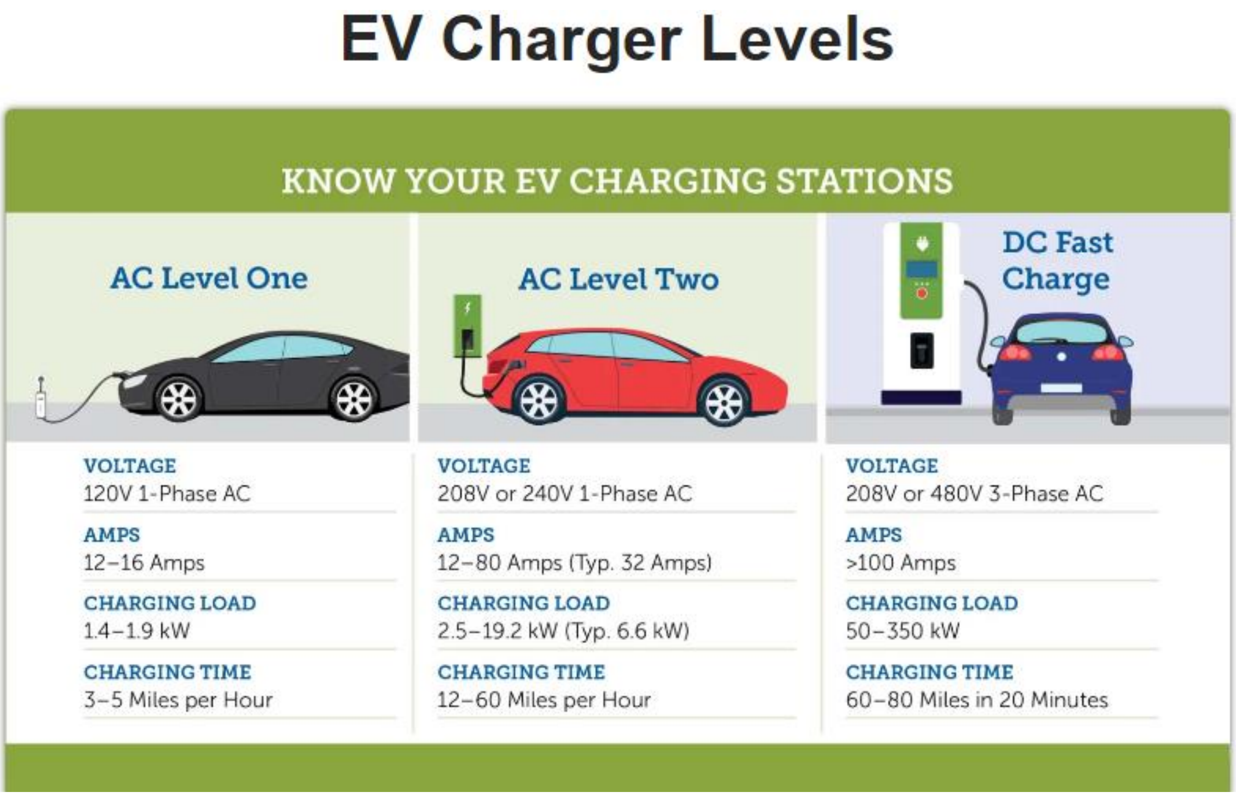
There are four types of electric vehicles available[8]:





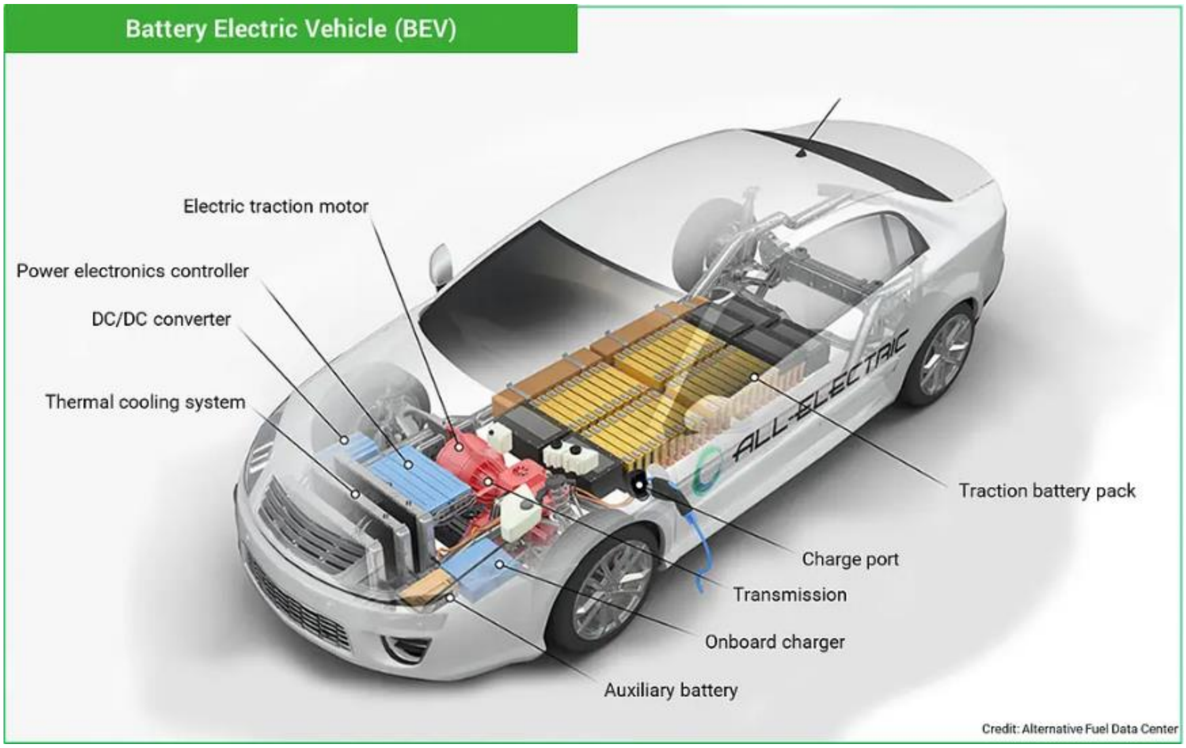


- **Battery Electric Vehicle (BEV):**
    - Fully powered by electricity. These are more efficient compared to hybrid and plug-in hybrids.
    - Also referred to as "All Electric Vehicles" run entirely on electricity only and have no gasoline engine[9].
    - Most of the today's EV have lithium batteries.
    - The battery packs are charged using electricity delivered through an EV charger. There are different types or Levels of EV chargers.
        - Level 1 - Slowest
        - Level 2 – Intermediate
        - Level 3 – Fastest – Most EVs can fast charge via level 3 charger.

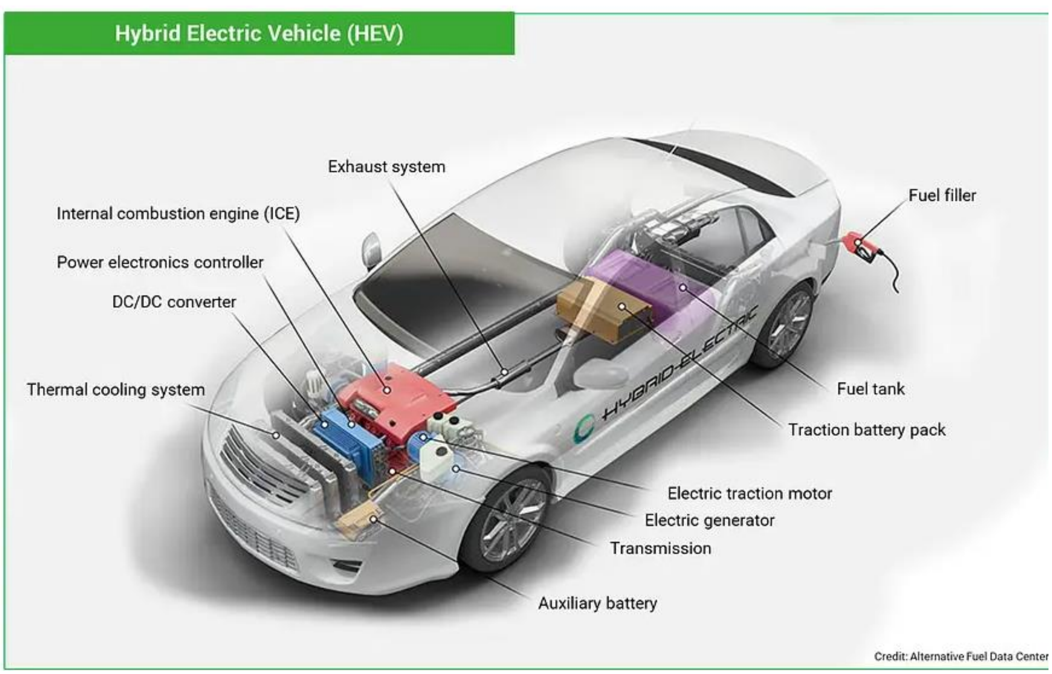


EV charger levels can be divided into regular EV charging and fast EV charging, there are: Level 1, Level 2 and Level 3[(10)].

- Level 3 chargers are the quickest of the bunch. Alternatively known as DC fast-chargers, Level 3 chargers are especially useful during long trips that necessitate charges between destinations, as this sort of charging can add around 100–250 miles of range in 30–45 minutes. Unlike Level 1 and Level 2 charging, Level 3 setups connect to the vehicle by way of a socket with additional pins for handling the higher voltage (typically 400 or 800 volts).

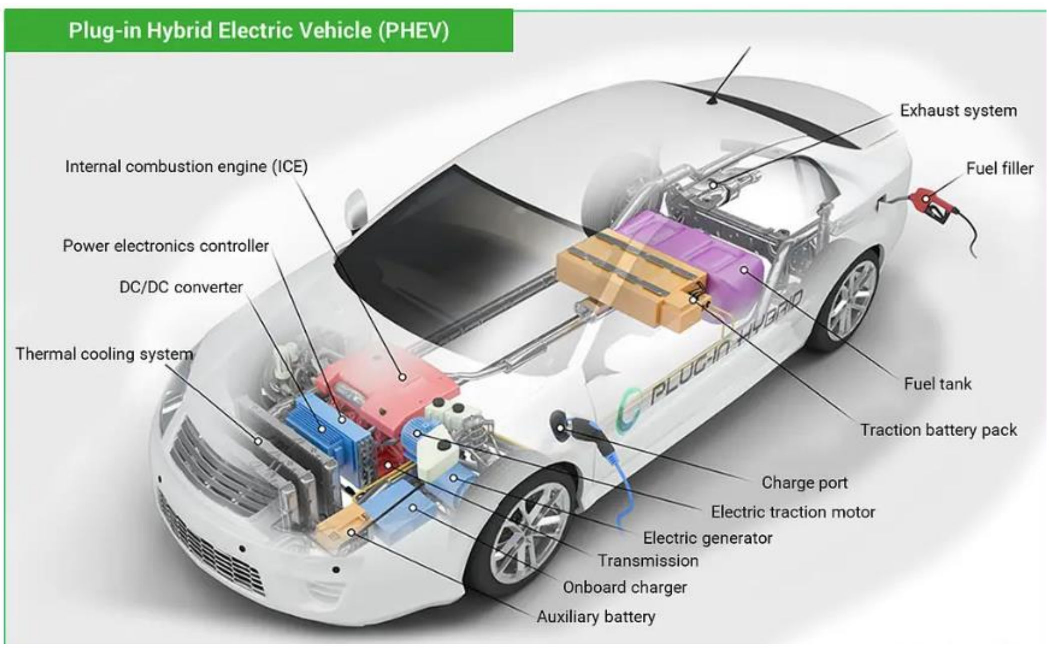


- **Hybrid Electric Vehicle:**
    - **Hybrid Electric Vehicle (HEV):**



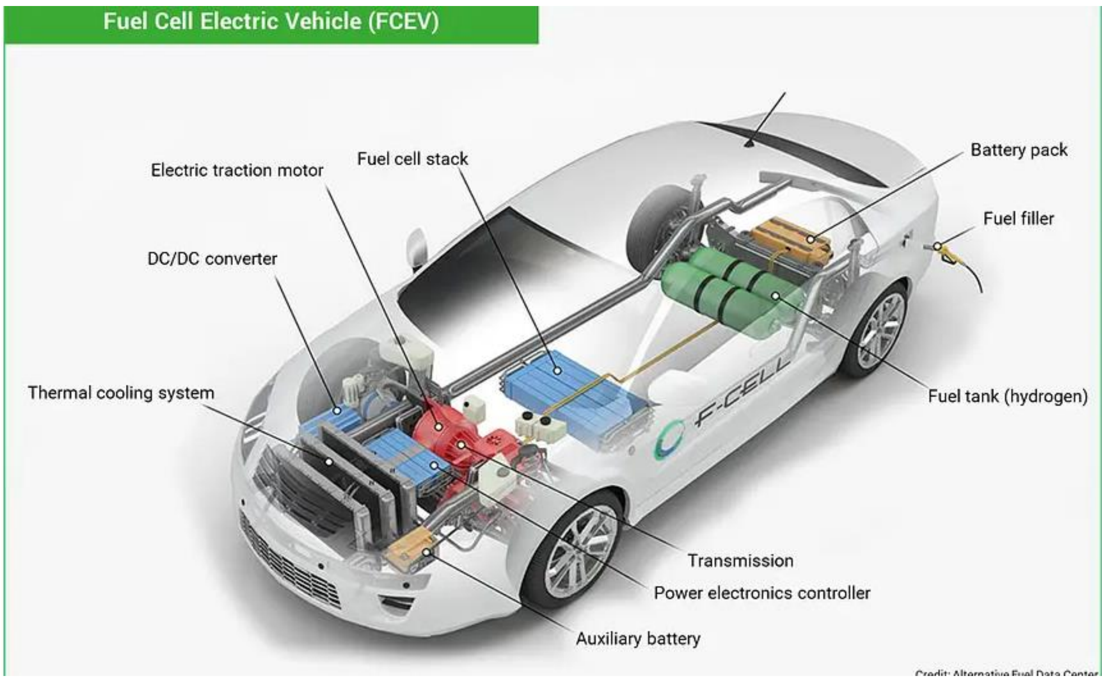
- The vehicle uses both the internal combustion (usually petrol) engine and the battery-powered motor powertrain. The petrol engine is used both to drive and charge when the battery is empty. These vehicles are not as efficient as fully electric or plug-in hybrid vehicles.
- Sometimes referred as self-charging hybrids. Uses both an ICE and an electric motor, which uses electricity stored in a battery pack.
- The battery pack can work as an auxiliary battery for the car, helping to reduce idling when stopped; this results in better fuel economy and lower emissions when compared to a conventional engine car[9].

- **Plug-in Hybrid Electric Vehicle (PHEV):**

- 

    - Uses batteries to power an electric motor and incorporate an ICE that can recharge the batteries to enable longer driving ranges.
    - Uses both an internal combustion engine and a battery charged from an external socket (they have a plug).

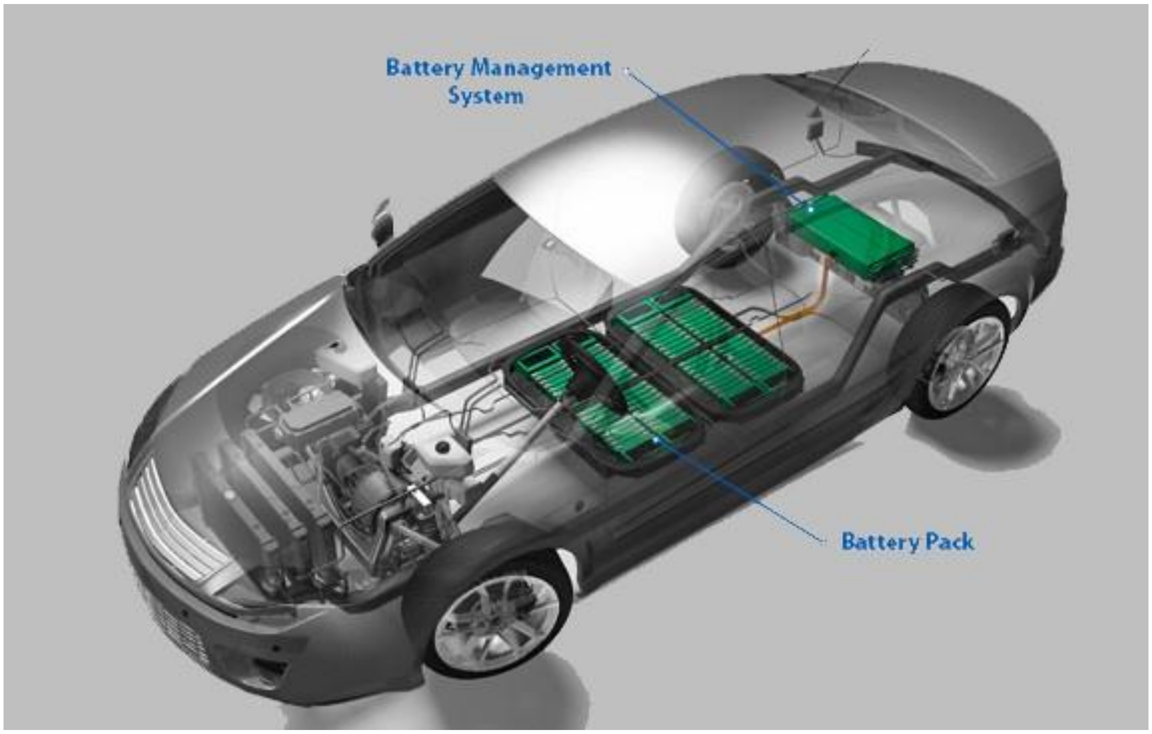
- PHEVs are more efficient than HEVs but less efficient than BEVs.
- This can dramatically reduce fuel use and emissions, especially on short journeys.
- When no electricity is available, a Plugin Hybris can run on fuel alone.

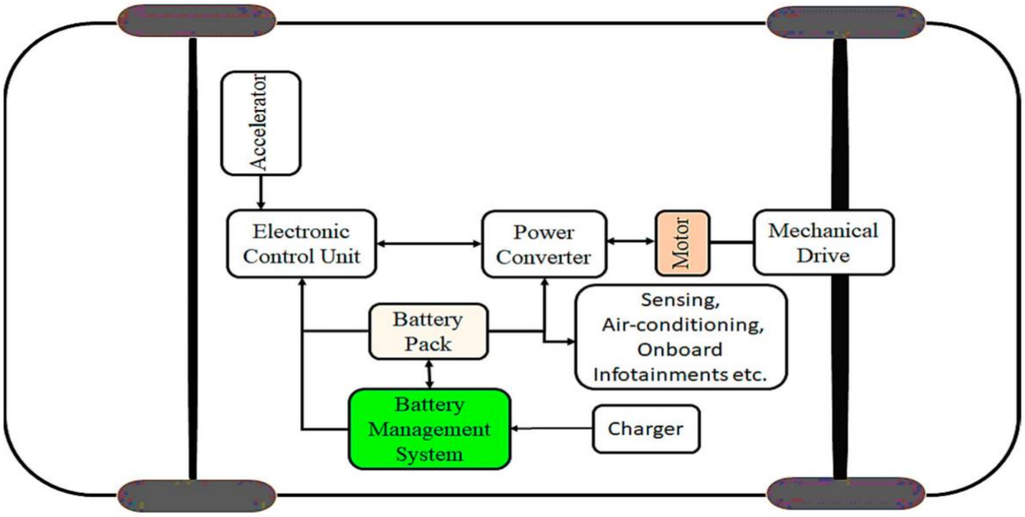


- **Fuel Cell Electric Vehicle (FCEV):**
  - Electric energy is produced from chemical energy. For example, a hydrogen FCEV.
  - Create zero tailpipe emission powered by Hydrogen[9].
  - The energy is stored as hydrogen and then converted into electricity by the fuel cell to propel the vehicle.
  - It has the gas tank used to store pure hydrogen.
  - Production is very limited.

2. BATTERY MANAGEMENT SYSTEM (BMS)

Battery management device in electric vehicles is a mainly designed electronic circuit that ensures the safety and stability of these battery packs.

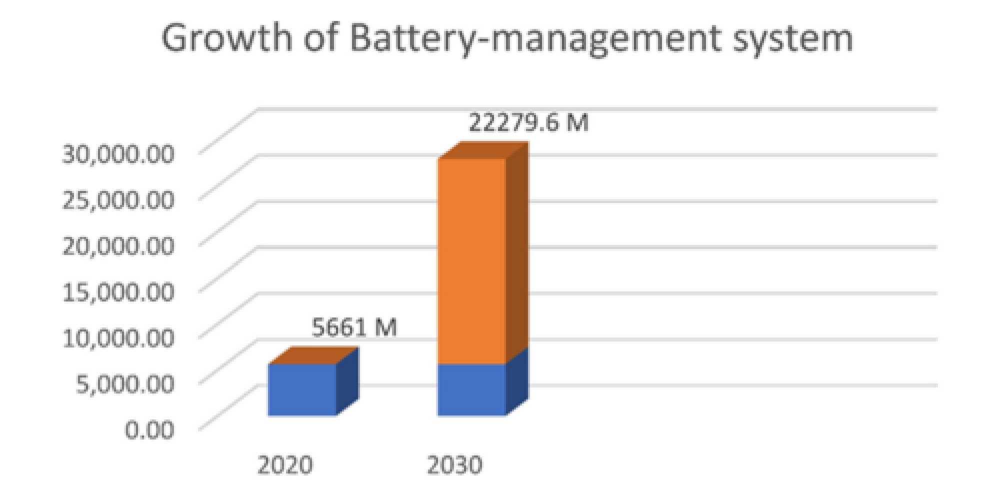




Electric vehicles run on rechargeable battery packs that are made of multiple cell modules arranged in a series and parallel. These battery packs produce several hundred volts of electricity. Various functions inside the car are dependent on them. That is why it becomes a critical component of the vehicle that requires constant monitoring and control[11].

Additionally, it can forecast how much farther the battery will travel before needing to be recharged, let the driver know how much power is left in the battery, and optimize charging to increase battery life[12].

The BMS is responsible for monitoring SOC (State of Charge), SOH (State of Health), SOP (State of Power) and the remaining useful (RUL) of the battery pack as well as for cell balancing, thermal management, and safety. The following graph demonstrates the global market for different applications.



This requires Battery Management System (BMS), an embedded system, which monitors the components closer to the battery cell, as each cell needs to be closely monitored so that there are no voltage fluctuations or imbalance in voltage conditions. The BMS consists of different components that ensure that the battery runs efficiently without chances of possible failures. It safeguards both the user and the battery by ensuring that the cell operates within its safe operating parameters. BMS monitors the State Of Health (SOH) of the battery, collects data, controls environmental factors that affect the cell, and balances them to ensure the same voltage across cells.

It is an embedded system, that has a number of electronic components on a circuit board. This system comprises of purpose built electronics along with purpose built software to enable a specific applications(13).

BMS is responsible for thermal management of the battery and monitors its temperature continuously. If required, BMS can adjust cooling and trigger other safety mechanisms to cease operations and minimize the risks.

Importance of BMS:

- The main function of BMS is to ensure that the battery is protected and any operation out of its safety limit is prevented. It monitors the battery pack's state of charge (SOC) along with the state of health. BMS also manages the battery optimization via cell balancing that improves the life of the battery in the long run. The BMS will also monitor voltage, different temperature parameters, and coolant flow.
- Lithium-ion batteries that possess high charge density, power most electric cars. These battery packs even though are not very big; can be highly unstable. Therefore, these batteries should never be overcharged or be allowed to reach a state of deep discharge at

any point. Thermal Runaway is a condition where the current flowing through the battery on charging or overcharging causes the cell temperature to rise. Conditions like these can harm the lifespan or the capacity of the battery. To ensure this does not happen, we require BMS to monitor its voltage and current.

- This process is very challenging as many cells are put together to form a battery pack in an electric vehicle and every cell needs to be individually monitored for its safety and efficient operation, which requires a specially dedicated system called **the Battery Management System (BMS).**

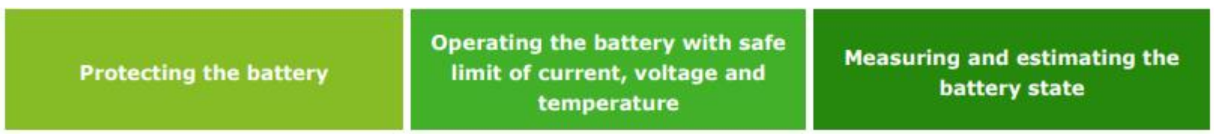
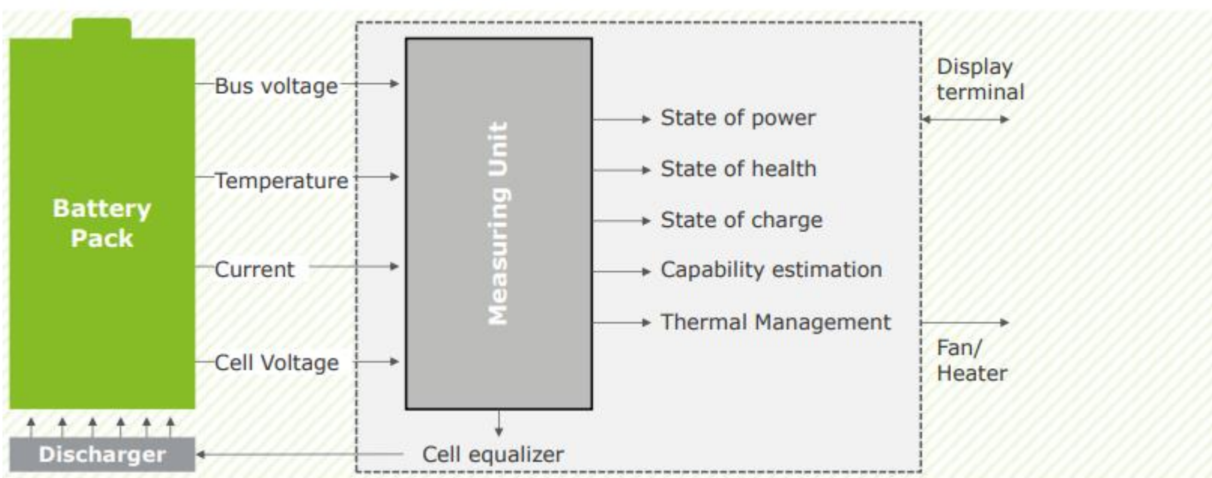
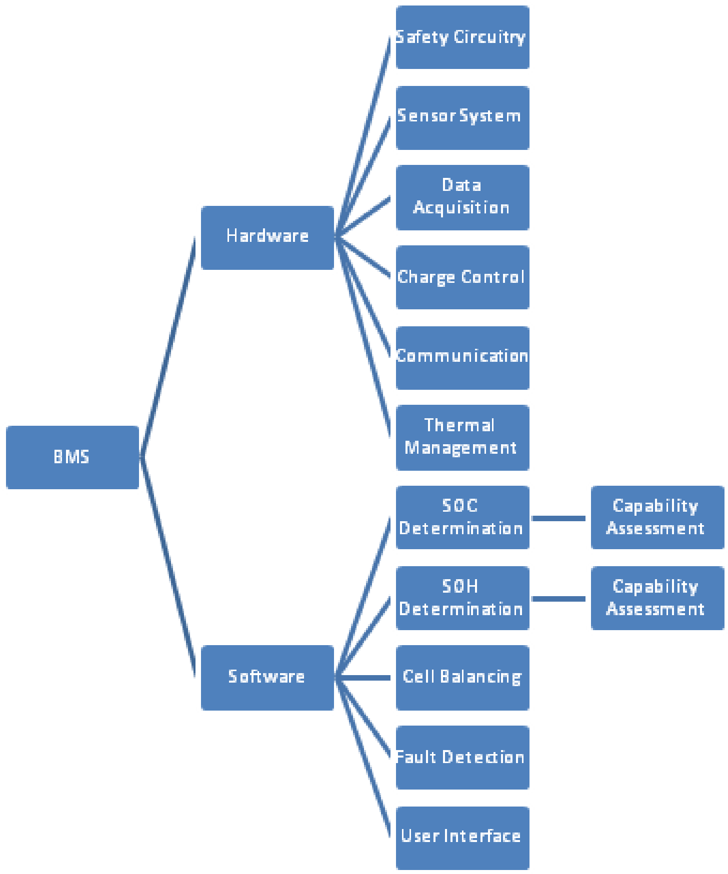


Figure 45 Illustration of a battery management system (BMS)



3. Associated Components:

Concept wise components of Battery Management System[20]



Physical Components of Battery Management System[14]:

1. Battery Pack[14]

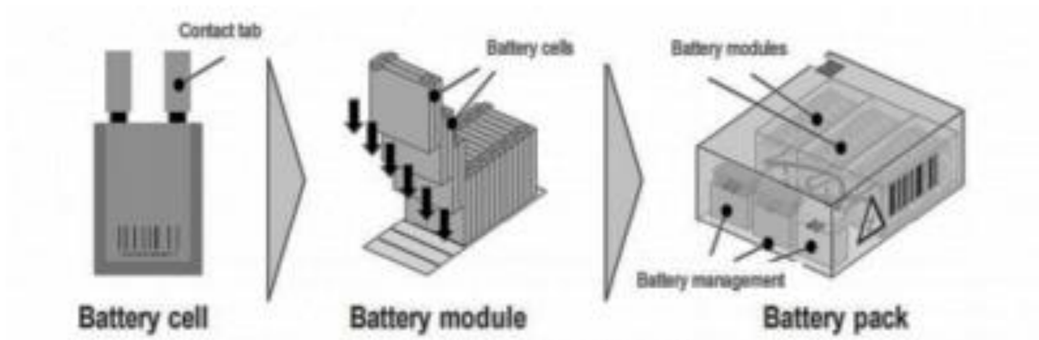


Fig. 1 From battery cells to a battery pack

a. Although the electric car battery is talked about as a single thing, it actually consists of hundreds (and sometimes thousands) of battery cells that are connected in series or in parallel into battery modules. And these modules are then connected into a battery pack, or what everyone simply calls "a battery".

b. Thanks to this arrangement, it is possible to achieve the required capacity and energy, and at the same time it is easier to manufacture, install, but also to inspect and perform maintenance.

2. Micro Controller Unit (MCU)

a. BMS’s central processing unit is the microcontroller. It gathers data from numerous sensors and decides how to control how the battery operates based on that data

3. Sensors

a. Sensors monitor most of the characteristics of the batteries, including voltage, current, temperature, and state of charge. These sensors offer the information required by the microcontroller to make decisions on the operation of the battery.

4. Battery monitoring integrated circuit (BMIC)
5. Cell management controller (CMC)
6. Battery management controller (BMC).
7. Battery cell controller
8. Battery Gateway
9. Cutt off FETs[19]
   a. FET (Field Effect Transistor) driver is accountable for connection and isolation between load and charger of the battery pack. The behavior prediction is done through voltage, current measurements, and real-time detection circuitry.
      i. They can be connected to a battery pack's low or high side.
      ii. NMOS (N-channel metal-oxide semiconductor) FETs activation is needed for enabling high-side connection and requires a charge pump driver. A reference for the solid ground is set using a high-side driver for the rest of the circuitry.

      > An N-channel metal-oxide semiconductor (NMOS) is a microelectronic circuit used for logic and memory chips and in complementary metal-oxide semiconductor (CMOS) design.

      iii. We use a low-side FET driver to reduce costs in integrated solutions since a charge pump is not needed. High voltage devices are not required in such cases.

    iv. The ground connection of the battery pack floats using low-side cut-off FETs. This can affect the IC performance, making it more sensitive to insinuated noise measurement.

10. Monitoring of Temperature

11. Cell voltage Balance[19]

    a. It is crucial to determine the health of the battery pack. That is why cell voltage monitoring is done to ensure that the cells are in a proper running condition for attaining a long battery life.

    b. The operating voltage ranges from **2.5V to 4.2V** in a lithium-ion battery.

    c. The battery life is significantly affected while performing battery operations beyond the voltage range. This reduces the life of a cell, which may even make it unfit for use.

    d. Connecting the battery pack in parallel increases the overall drive current, whereas series connection adds the overall voltage.

12. Communication Interface

    a. BMS can communicate with various other devices, including an automobile's onboard computer, thanks to the communications interface. This interface can deliver important diagnostic data regarding the condition and functionality of the battery.

13. BMS Algorithms [19]

    a. To make quick and effective decisions in real-time based on the information received. For this purpose, a microcontroller for battery management system is needed to collect, organize and assess the information from the sensing circuitry.

b. Renesas' ISL94203 is the most famous example of employing a battery management system algorithm. It is a standalone digital solution embedded in a single chip with programmable capabilities.

c. The memory space and microcontroller for battery management system clock cycles can be cleared using these standalone solutions.

14. Real Time Clock (RTC)

a. Allowing the user to know the battery pack's behavior before any alarming event, the real-time clock acts as a black box system for time-stamping and memory storage. Used in black-box applications for accurate timekeeping

Hardware of Battery Management System[20]:

Hardware

- Safety circuitry has long been used in BMS. However, with more sensors being used in the latest BMS, improvements in current safety circuitry designs can be implemented, such as the addition of **accurate alarms and controls to prevent overcharge, over-discharge and overheating**.
- The sensor system consists of different sensors to monitor and measure battery parameters including cell voltage, battery temperature and battery current. Some researchers have proposed adopting EIS (Electrochemical Impedance Spectroscopy) to monitor internal impedance. However, both space constraints and device costs hinder the feasibility of these measurements outside laboratory environments. Thus, current,

voltage, and temperature should be measured to improve the capability of state tracking in real life applications.

- Data acquisition (DAQ) and data storage are critical parts of the software in the BMS to analyze and build a database for system modeling. Charge control is a subsystem governing the charge-discharge protocol. Batteries are often charged by the constant current/constant voltage method (CC/CV) and will thus need to include a potentiostat and a galvanostat.
- A variable resistor may be necessary to help balance cells or perform internal resistance measurements. Cell balancing control is still a critical design feature with room for improvement in order to equalize the battery pack and estimate the battery status in an efficient way.
- Most subsystems in a BMS are stand-alone modules, and hence, data transfer throughout the BMS is required. Communication through a CAN Bus is a prominent way to transfer data within the BMS. With the development of smart batteries, more data can be collected to communicate with the user and the charger through the microchips incorporated within the battery.
- In addition, wireless and telecommunication techniques are gradually being incorporated into charging systems that facilitate communication between the battery and the charger. A module for thermal management is critical because temperature differences have an impact on cell imbalance, reliability and performance. Thus, it is important to reduce the temperature difference among cells, which must be monitored and operated under proper temperature conditions.

Software:

- The software of the BMS is the center of the whole system because it controls all hardware operations and analyses of sensor data for making decisions and state estimations. Switch control, sample rate monitoring in the sensor system, cell balancing control and even dynamic safety circuit design should be handled by the software of a BMS.
- Determination of SOC and SOH will be integrated into a capability assessment, which also presents the life status of the battery and sets the operating limits according to state-of-the-art algorithms, such as fuzzy logic, neural networks, state-space-based models and so on. The objective of cell balancing is to maximize battery performance without overcharging or over-discharging. *Its nature is to make the SOC levels of cells closer to each other*. The controller will control the charge process based on a comprehensive strategy that depends on the SOC of each cell. Thus, the accurate SOC estimation of each cell is the basic for improving the balancing.
- Most soft faults will be discovered through online data processing. An intelligent data analysis is required in order to provide battery fault warning and indicate out-of-tolerance conditions. Historic data will be recorded and provide the pre-alarm condition before the possible faults. The user interface should display the essential information of the BMS to the users. The remaining range should be indicated on the dashboard according to the SOC of the battery. Additionally, abnormal alarming and replacement suggestions are needed to inform the users in terms of the estimation and prediction of the battery.

Basic Understanding of Functioning of Battery Management System

- The BMIC monitors the individual battery cells and must be able to quickly – in a matter of microseconds – inform the CMC of the situation so that the CMC or BMC is able to react and, if necessary, correct an unfavourable situation. In order to prevent temperature leaks, the BMIC needs to notice immediately the battery cell that is overheating and send this information further on as quickly as possible.
- The BMC must decide how serious the situation is, how to proceed, and the overheated cell must be shut down if necessary. **And all of this must happen in the blink of an eye.**
- The accuracy of the measurement and the ability to respond to adverse conditions depend primarily on the frequency of communication from the BMIC to the CMC and BMC, the more often they communicate, the greater the chance that they will successfully resolve a situation that could be risky.
- However, it is not at all easy to design an effective communication network in an electric car due to electrical noise.
- Of course, before correcting the BMS tries to prevent any unfavorable situation, so apart from the BMIC, CMC and BMC modules it also consists of circuits that balance the energy loads of different cells, in this way all cells work more or less the same and do not tend to cause problems.

4. Functioning of BMS:

Battery Management System performs the following important functions[20]:

(a) Discharging Control

(b) Thermal Management

(c) Charging Control

(d) State-of-Charge Determination

(e) State-of-Health Determination

(f) Sensing electrical isolation- avoiding Electric Shock

(g) Performance Optimization

(h) Cell Balancing

(i) Communications

1. Discharging Control

- The **primary goal of a BMS is to keep the battery from operating out of its safety zone**. The BMS must protect the cell from any eventuality during discharging.

2. Thermal Management[13][22]:

- BMS continuously monitors the temperature and performs the function of thermal management. It measures the parameters like average temperature, coolant intake temperature, coolant output temperature and temperatures of individual cells. This is done to **avoid the over-heating** of the battery. BMS triggers several cooling mechanisms whenever the battery is over-heated.

- For instance, when the BMS senses an increase in temperature, the output power is automatically reduced. Hence, power dissipation is reduced. The cooling medium in thermal management systems can be either air or liquid. Air cooling systems depend on either the convection of surrounding air or the airflow of the fans. But, air cooling systems are considered to be inefficient and additional cooling mechanisms increases the weight of the BMS.
- In the case of liquid cooling systems, the battery is either submerged in the coolant or the coolant can directly flow through the battery without contacting the battery. Liquid cooling systems are considered to be more efficient than air cooling systems. This is because liquid has better thermal conductivity than air.
- Overcharging of lithium-ion-cells can lead to thermal runaway and potentially an explosion. BMS continuously monitors the voltage of the pack as well as individual battery and controls the supply of the current to avoid overcharging. BMS can enforce the limits of maximum charge or discharge current according to temperature.

3. Charging Control

- Batteries are more frequently damaged by inappropriate charging than by any other cause. Therefore, charging control is an essential feature of the BMS. For lithium-ion batteries, a 2-stage charging method called the constant current – constant voltage (CC-CV) charging method is used. During the first charging stage (the constant current stage), the charger produces a constant current that increases the battery voltage. When the battery voltage reaches a constant value, and the battery becomes nearly full, it enters the constant voltage (CV) stage. At this stage, the charger maintains the constant voltage as the battery current decays exponentially until the battery finishes charging.

4. State-of-Charge Determination

- One feature of the BMS is to keep track of the **state of charge (SOC)** of the battery. The SOC could signal the user and control the charging and discharging process. There are three methods of determining SOC:
    - through direct measurement,
    - through coulomb counting and
    - through the combination of the two techniques.
- To measure the SOC directly, one could simply use a voltmeter because the battery voltage decreases more or less linearly during the discharging cycle of the battery.
- In the coulomb-counting method, the current going into or coming out of a battery is integrated to produce the relative value of its charge. This is similar to counting the currency going into and out of a bank account to determine the relative amount in the account.
- In addition, the two methods could be combined. The voltmeter could be used to monitor the battery voltage and calibrate the SOC when the actual charge approaches either end. Meanwhile, the battery current could be integrated to determine the relative charge going into and coming out of the battery.

5. **State-of-Health Determination**

- The state of health (SOH) is a measurement that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery.
- Any parameter such as cell impedance or conductance that changes significantly with age could be used to indicate the SOH of the cell. In practice, the SOH could be estimated from a single measurement of either the cell impedance or the cell conductance.

6. **Sensing electrical isolation- avoiding Electric Shock:**

- The BMS also checks that the vehicle chassis is completely isolated from the high voltage battery pack at all times to prevent the user from getting an Electric Shock.

7. **Performance Optimization:**

- BMS is responsible for 28echarging the performance of the battery pack. Lithium-ion batteries perform best when their State of Charge (SoC) is maintained between the minimum and maximum charge limits defined in the battery profile. Overcharging as well as deep discharging degrades the capacity of the battery, thereby shortening its life.
- At the time of charging, BMS determines how much current can safely go in and communicates the same to the EVSE (Electric Vehicle Supply Equipment or the Charger). During discharge of the battery, BMS would communicate with the motor controller to avoid the cell voltages reaching too low. The vehicles can show a

corresponding alert to the user to charge the battery pack. The BMS also controls the charging of the battery pack by energy generated through regenerative braking.

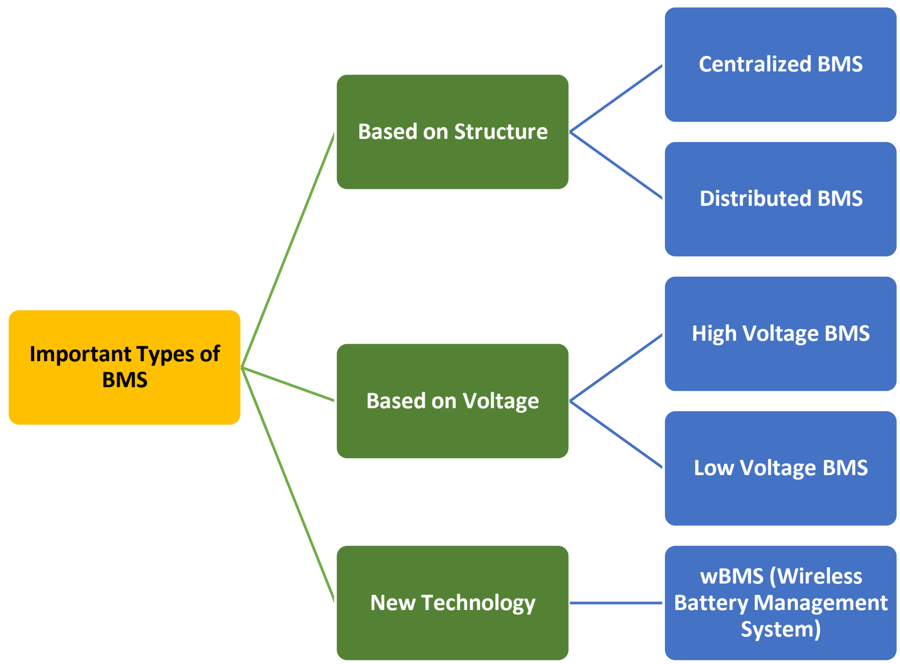
8. Cell Balancing:

- Individual cells in the battery pack can develop differences in capacity with time, which amplify with each charge/discharge cycle. This imbalance limits the amount of energy that can be derived from the battery, and also how much the battery pack can be charged. Cell Balancing is needed to maintain the cells at equal voltage levels and maximise the capacity utilization of the battery pack. Measurement of individual cell voltages by BMS indicates their relative balance and acts as a pointer to how much charge equalization is required. The BMS performs cell balancing by draining excess energy from cells that are more charged than others, through active or passive balancing techniques.

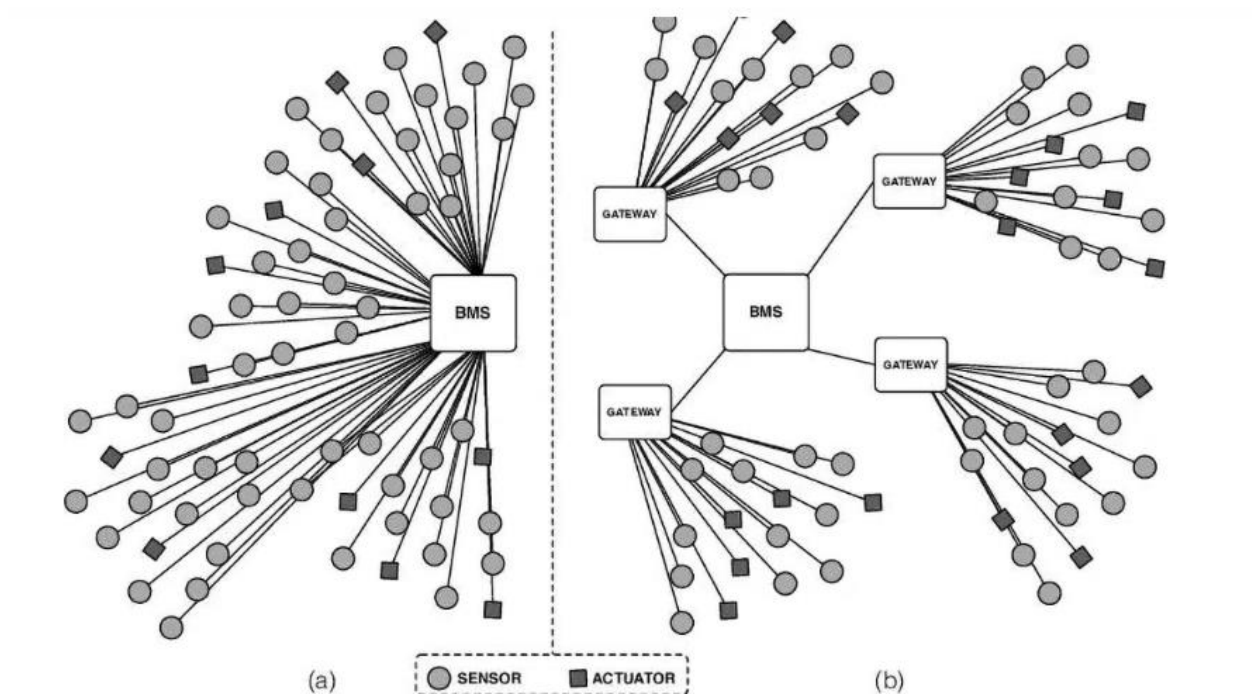
9. Communication

- The BMS is responsible for communicating with other ECUs (Electronic Control Units) in the vehicle. It relays the necessary data about the battery parameters to the motor controller to ensure the smooth running of the vehicle. In case of AC charging, BMS communicates with the onboard charger to monitor and control the charging of the battery pack. For DC charging, a communication link is established directly between the EVSE and the BMS. BMS communicates the required output voltage and current levels to the EVSE, and sends instructions to start and stop the charging process.

5. Types of Battery Management Systems:



i. Based on Structure[15]



a) Centralized Battery Management Systems

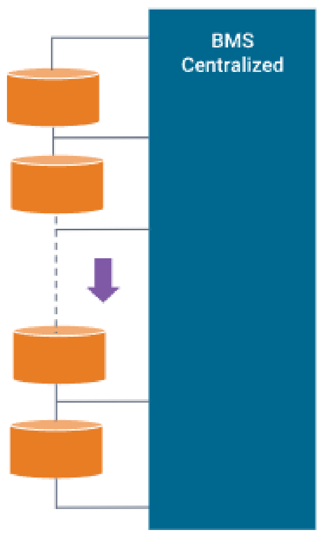
b) Distributed Battery Management Systems

ii. Based on Voltage[16]

b. High Voltage Battery Management Systems

c. Low Voltage Battery Management Systems

Centralized Battery Management Systems[12][17][18]**:**

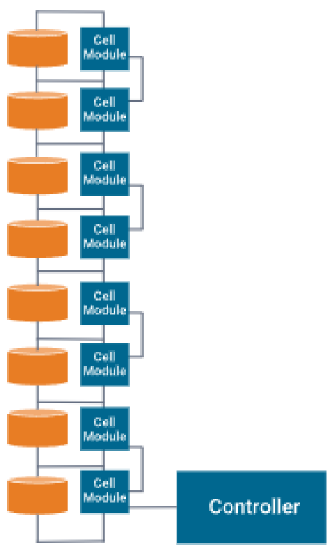


- It has a central BMS in the battery pack assembly.
- All the battery packages are connected to the central BMS directly.
- Advantages:
  - It is more compact, and it tends to be the most economical since there is only one BMS.

    - Its ability to provide a comprehensive view of the battery pack, enabling effective control and management of the entire system
- Disadvantages:
    - Since all the batteries are connected to the BMS directly, the BMS needs a lot of ports to connect with all the battery packages. This translates to lots of wires, cabling, connectors, etc. in large battery packs, which complicates both troubleshooting and maintenance.
- In centralized BMS, there is a single board comprising a centralized controller and a smart circuit for all the operations and internal communication.
- The centralized controller performs the functions of monitoring, maintaining battery voltages, temperature, and cell balancing by means of an instantaneous reference to each cell of the battery.
- The total board is commonly powered from battery output.
- The wire harness collected records related to battery state of health and state of charge are communicated internally and externally by the smart circuit board.
- BMS hardware with a centralized architecture can be divided into high-pressure areas and low-pressure areas. The high-voltage area is responsible for collecting the voltage of the single battery, collecting the total voltage of the system, and monitoring the insulation resistance.
- The low-voltage area includes power supply circuit, CPU circuit, CAN communication circuit, control circuit, etc.

- **With the continuous development of passenger car power battery systems to high capacity, high total voltage, and large volume, BMS with distributed architecture is mainly used in plug-in hybrid and pure electric vehicles.**

Decentralized Battery Management Systems[12][17][18]:



- Considerably different from the other topologies, where the electronic hardware and software are encapsulated in modules that interface to the cells via bundles of attached wiring.
- A distributed BMS incorporates all the electronic hardware on a control board placed directly on the cell or module that is being monitored.
- This alleviates the bulk of the cabling to a few sensor wires and communication wires between adjacent BMS modules.
- Consequently, each BMS is more self-contained, and handles computations and communications as required. However, despite this apparent simplicity, this integrated

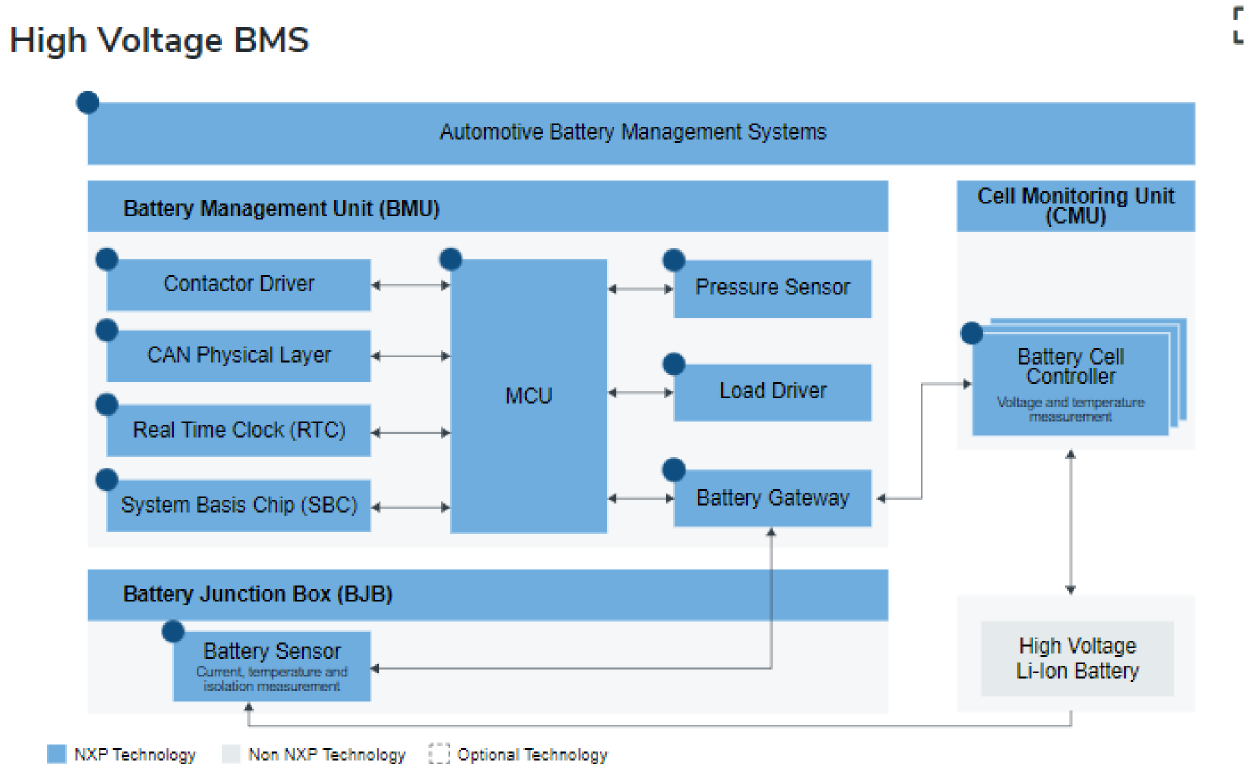
form does make troubleshooting and maintenance potentially problematic, as it resides deep inside a shield module assembly.

- The first is to have extremely high scalability, which can be extended down to a single battery.
- Secondly, the connection reliability is high, basically, there are no excessively long cables, and the batteries and the measurement circuit are closely integrated, which also reduces interference and errors. Security is also high.
- It is also easy to maintain, as only a small unit needs to be replaced if something breaks.
- But there are also some shortcomings:
- The cost is very high. Because each unit has an additional set of equipment, the overall cost is very high.
- The volume is too large. There is a measurement system next to each cell of each battery, which will affect the volume of the entire battery panel.

Comparison between Centralized and Distributed BMS[23]

ASPECT	CENTRALIZED	DISTRIBUTED
Scalability	Limited	High
Flexibility	Limited	High
Fault Tolerance	Low	High
Redundancy	Minimal	High
Communication Complexity	Low	High
Integration Simplicity	High	Moderate
Cost	Low	Moderate

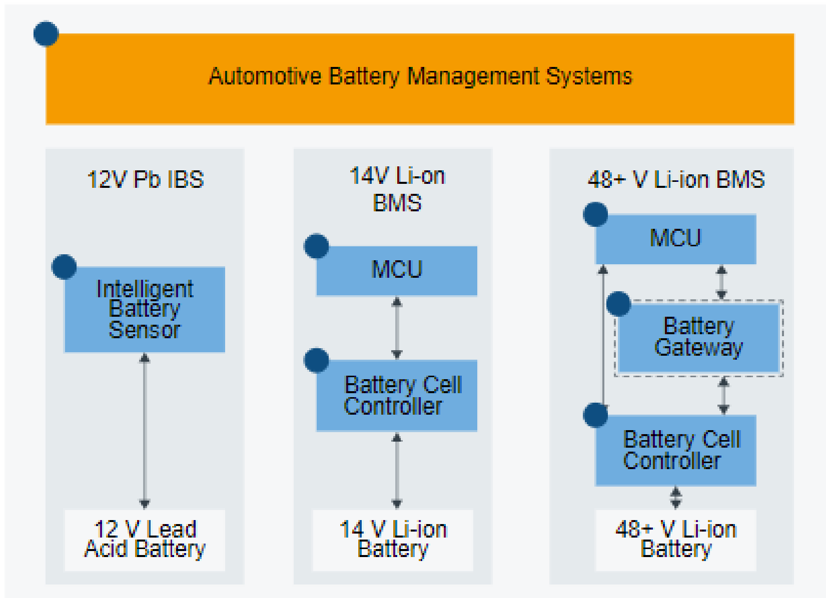
High Voltage Battery Management System:



- High voltage batteries are batteries with many sets of parallel cells in series stacked to produce a battery pack with voltages reaching up to 1000V(21).
- A high voltage battery management system (HVBMS) is a battery management system that is designed to manage high voltage battery packs. High voltage battery packs are typically used in electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and energy storage systems (ESSs).
- HVBMSs are more complex than traditional battery management systems because they need to be able to handle the higher voltages and currents associated with high voltage battery packs. HVBMSs also need to be able to protect the battery pack from a wider range of safety hazards.

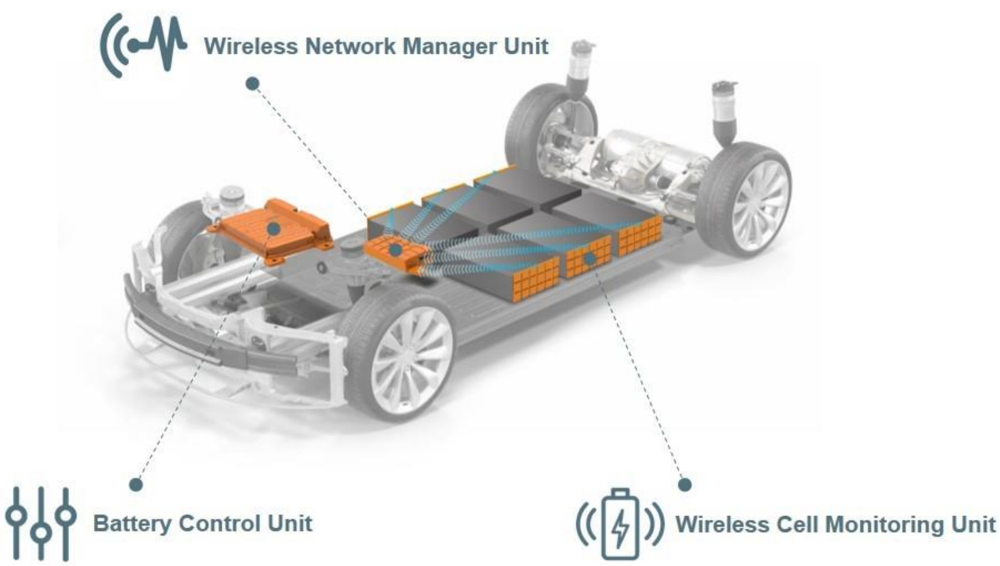
Low Voltage Battery Management System:

Low Voltage BMS



- *Low Voltage BMS*. Low voltage BMS supports 12 to 16 faucets depending on the required module and 8 temperature sensors. The number of cells is added through the cell interface.

6. Wireless Distributed Battery Management System (wBMS)[24]



The electric vehicle (EV) industry's evolution to wireless battery management systems (wBMS) was in many ways inevitable. The benefits of wireless vs. wired BMS is crystal clear to anyone who's grappled with the complexity, BOM cost, space, and labor penalties inherent to wired systems, no matter the application. This technology eliminates the wired physical connections typically needed in other Battery Management System (BMS) architectures, allowing for greater flexibility, increased efficiency, improved reliability and reduced costs, all crucial aspects in electric vehicles[26].

Wireless Battery Management System, in contrast, has shown promise in saving up to 90% of the wiring and up to 15% of the volume in battery packs for next-generation EVs. This is achieved by eliminating the communication wiring harness and connectors, leveraging instead of an intelligent battery module with fully integrated electronics—the only exposed connectors are the +ve and –ve terminals.

But the benefits achievable with wBMS technology can only be realized with massive investments in the design, validation, and manufacturing infrastructure needed to accommodate it.

- The security and safety requirements unique to wireless systems invite a top-to-bottom reassessment at every stage of the battery pack life cycle, from manufacturing to reuse.
- To fully unlock the cost benefits of wBMS, OEMs must first regard battery packs as assets to be effectively managed over time—through the “first life” on board the vehicle, and on to the “second life”—to achieve the highest possible return on investment. Only then will the cost savings of wBMS clearly and fully manifest
- The use of wireless communication throughout the factory floor for wBMS production truly opens the door to touchless, fully robotic EV battery pack manufacturing
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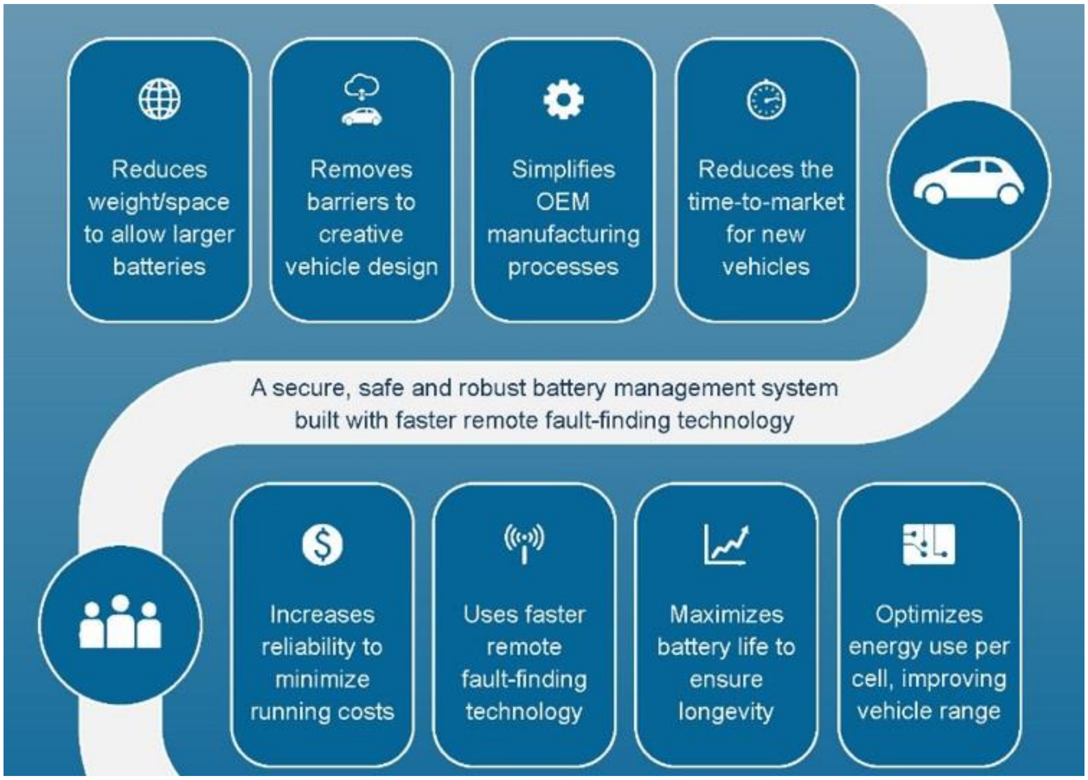
- 

- **Fully robotic manufacturing** - The use of wireless communication throughout the factory floor for wBMS production truly opens the door to touchless, fully robotic EV battery pack manufacturing. In addition to leveraging the benefits of wBMS at the vehicle level, OEMs can further reduce their CAPEX and OPEX by eliminating the need for valuable personnel to spend time manually wiring battery packs to harnesses and/or testing modules and connections.
- **Lowering the Carbon foot print -** But there's much more that can be done to lower the carbon footprint of a battery pack over its usable lifetime while extending the associated revenue potential. This is achieved through a "reduce, repair, and reuse" strategy whereby wBMS can help reduce costly vehicle recalls, streamline repairs, and promote battery re-usage as a preferred alternative to scrapping and recycling.

- **Easy to maintain a Stock of Spare Module -** wBMS makes it considerably easier to maintain a stock of spare modules, and they are a lot easier to swap in/out of battery packs during vehicle service. There's no time loss or frustration associated with tracking and locating inventory or attempting to remove the battery harness (without breaking it) during a service call. Modules are simply scanned in/out as they migrate through the supply chain, and finally from stock shelf to vehicle, with installation ease that traditional wired BMS could never match. This impacts more than just service in the EV development phase. Pack designers no longer need to spend precious time and space to accommodate how the harness will be removed and replaced, resulting in a faster design and more energy-dense packs
- **Early detection of failure -** wBMS features can also enable batteries to measure and report their own performance, increasing early failure detection and helping avoid costly vehicle recalls, while enabling optimized battery pack assembly. The data can be monitored remotely throughout the battery life cycle—from assembly to warehouse and transport, through installation and maintenance.
- **Longevity** - For OEMs interested in maximizing the usable life—and revenue potential—of their battery packs, wBMS makes second-life battery repurposing much more efficient. Minus the harness, battery packs are much easier to repair and reuse to ensure the longest possible lifetime and a more environmentally friendly carbon footprint overall. OEMs can readily resell their used batteries for applications like solar or wind energy storage once they reach a determined state of health.

- **Zero Cobalt[25] -** This new wireless system can support safe and sustainable zero-cobalt battery chemistries, such as lithium iron phosphate (LFP) – which are important factors in sustainability efforts for automakers.
- **More flexibility[26] -** The solution eliminates the need of daisy-chain communication and wiring by using wireless technology to enable the communication between batteries and control unit. Compared to previous wired distributed solutions, the new wBMS developed by the company reduces the wiring harness by 90% and simplifies the battery cell construction and installation. In particular, the wBMS reduces complexity in the assembly and grants more flexibility for battery modules placement.
- **Sensor Fusion – More Accurate Calculation -** The Marelli wBMS can be delivered with a highly sophisticated software application layer that uses advanced algorithms based on a proprietary technique so-called "Sensor Fusion". The algorithms estimate several crucial parameters of each battery cell – including State of Charge, State of Health, State of Power – to ensure a more accurate calculation of the battery overall status, and informs the other components of the powertrain accordingly.

7. Adoption of AI technologies in Battery Management System[27]:

Battery packs are the most expensive components in EVs and the largest factor contributing to the price differential between EVs and conventional ICE-powered vehicles. In the small and midsize car segments, the average EV costs $12,000 more to produce than comparable ICE-powered vehicles. The reason behind this cost is that most original equipment manufacturers over-engineer battery packs by 10–14% in terms of capacity to slow down the battery degradation rate due to SBMS (Smart Battery Management System) limitations. **This**

over-engineering could be mitigated by implementing accurate and robust SOC, SOH, and SOP estimation strategies on board the BMS.

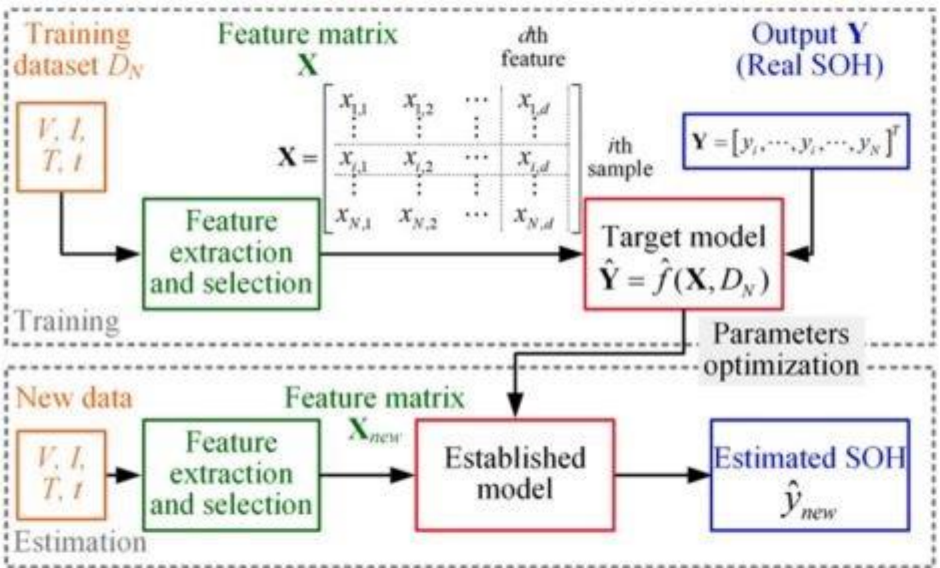
Multiple models can be considered or learned for SOC and SOH estimation. These models are used in combination with an AI-empowered filter. However, a combination of linear and nonlinear filters can be deployed for estimating the states whose time evolutions are governed by linear and nonlinear dynamics, respectively. In this way, **the computational burden can be reduced.**

It is essential to have an accurate estimation of battery voltage, heat generation rate, and state of health under different conditions to maintain the safe and efficient operations of the BMS for EV application.

While AI technology would improve and transform the implementation of LIBs for EV applications, the deployment of AI/ML algorithms into real-world scenarios for predicting and discovering battery materials and estimating the state of the battery system is challenging.

ML techniques can be used to link data, by creating a new dataset construction and/or existing dataset development where a critical correlation in material science is the structure-property relation. A predictive AI/ML approach helps to **extract complicated and nonlinear patterns from training datasets and translate the meta-data into statistical models.** Therefore, fault prognosis as an additional function to the local fault detection function of the BMS would use historical data and machine learning to predict or prevent the occurrence of a fault in the battery system.

The SOH estimation based on ML technologies is shown in following diagram. The overall framework is based on two parts, the offline training process, and the estimation process which could be either offline or online. It is analyzed the impact of entropy as a feature for capacity estimation of the battery by monitoring the variation of voltage, current, and temperature during the aging process. The performance of these sample entropy (SE)-based estimators, revealed that the entropy-based SOH estimation method will be improved once the battery SOC gets to the polarization zone.



The battery SOH estimation structure using ML algorithms [61].

<u>**NXP's AI Development in BMS:**</u>

AI-powered digital twin models (A digital twin is **a virtual model designed to accurately reflect a physical object) in the cloud aim to improve EVs battery range, efficiency, safety, and lifetime and herald multiple new applications.**

NXP® Semiconductors has developed a solution to connect its high-voltage battery management system (HVBMS) through its **S32G GoldBox** vehicle networking reference design to the cloud to leverage an artificial intelligence (AI) powered battery digital twin. By utilizing Electra Vehicles, Inc.'s EVE-Ai™ 360 Adaptive Controls technology , NXP unleashes the **power of digital twin models** in the cloud **to better predict and control the physical** BMS in real time, to improve battery performance, battery **state of health of up to 12%** and enable multiple new applications, such as EV fleet management.

Why should it is important:

As batteries continue to be the costliest element in an electric vehicle (EV), AI-powered digital twin cloud services have a high potential to improve estimations of the battery's state of health (SOH) and state of charge (SOC) for improved efficiency, lifetime and cost. Battery digital twins adapt to ongoing changes in battery health due to operating conditions and provide updated figures back to the BMS for continuously improving control decisions.

Carmakers can use the technology to provide driver insights, such as range and speed recommendations. In addition, adaptive battery control can improve the battery's performance and safely extend its lifespan, reducing warranty costs for the carmaker. Another potential application is EV fleet management, providing fleet operators with invaluable usage insights, such as vehicle charging times and battery predictive diagnostics. Battery care centers can also use this in-depth information to reduce downtimes with rapid diagnostics, and EV charging station operators can effectively optimize their charging service and energy efficiency.

As the EV market grows, so will the supply of second-life batteries. Although they may have reached the end of their ‘automotive life’, these batteries have a significant residual capacity of up to 80%. Tapping into that remaining useful battery life (RUL) in energy storage systems (ESS) for homes has the potential to reduce homeowners’ energy bill.

Digital twin solution:

NXP’s S32K3, NXP’s S32G and EVE-Ai adaptive digital twin

The AI-powered battery digital twin solution with Electra Vehicles, Inc. offers a performance advantage thanks to highly accurate sensors, real-time closed-loop control of the BMS and network connectivity combined with predictive algorithms. The solution comprises three elements. NXP’s S32K3-based HVBMS Reference Design, which offers high precision and accuracy to extend battery life safely. Having precise measurements of the battery’s SOH and SOC leverages the full potential of the battery and thus maximizes driving range with accurate diagnostics.

The second element is NXP’s S32G-based vehicle networking processing solutions. NXP GoldBox offers safe high-performance computing capacity and real-time network performance with secure cloud connectivity for data-driven cloud-based automotive services.

NXP is collaborating with Electra Vehicles, Inc., a leader in AI-based onboard battery controls, data analytics and design, for the third and final element of the digital twin solution, which is to implement its EVE-Ai adaptive digital twin and connect its electrification solutions seamlessly to the cloud.

*“NXP's contribution to the digital twin technology lies in the access to accurate sensor data, real-time closed-loop control of the BMS, high-performance in-vehicle processing and secure connectivity to the cloud for services and over-the-air (OTA) updates. By integrating Electra’s EVE-*Ai *architecture, we address the two main challenges associated with the digital twin approach. These are coping with the abundance of data from our electrification solutions, which requires cleansing and appropriate feature selection, and the variance of use cases, which requires model selection and adaptive training.”*

8. Roles and Skills for Battery management system:

1. Title : BMS Engineer - Field Application[31]

Company: CATL

Role:

- Independently handle basic function tests, differential tests, full function tests and other related tests on PCB level
- Investigate the root causes of failure at system level of BMS, follow up the reliability investigation of electrical components on PCB level and complete the 8D reports
- Concern about customer complaints, optimize the analysis progress according to customer concerns
- Support the workflow of the BMS failure analysis team, collaborate with QA departments, responsible for after-sales products for European customers

Skills:

- Major in Electrical Engineering, Electronic and Information Technology, E-Mobility, Automation Technology, Computer Science or related topics
- Basic knowledge of Battery Management/ Energy Storage Systems
- Familiar with schematic diagram, Faulty Tree Analysis (FTA) / 8D reports
- Familiar with hardware design, process and common failure modes of components, failure mechanisms and corresponding analysis pocesses

- Experience in using CAN devices (CANoe, CANape, CANalyser etc.) is a big advantage
- Experience in project research/development or internship in industry in the field of BMS/ESS
- On-site diagnostic experience with BMS System is a big advantage
- Fluent in German and English, Chinese is an advantage
- Self-motivated, strong ability for self-management, independent and goal-oriented working style

2. **Senior Battery Pack Design Engineer (Battery Swapping)** [32]

Role:

- Hands-On Battery Pack Design: Collaborate with cross-functional teams to design and develop advanced battery packs tailored for battery swapping stations. You will be hands-on in determining pack configuration, cell selection, thermal management, and mechanical integration.
- Safety and Compliance: You will take a hands-on approach to ensure that battery packs meet all safety and regulatory requirements, including AIS-156 certification. Conduct thorough testing, analysis, and validation to ensure compliance with industry standards.
- Performance Optimization: Get hands-on with optimizing battery pack design to enhance energy density, charging/discharging efficiency, and overall performance while minimizing weight and cost.
- Prototyping: Oversee and personally engage in the creation of prototypes for testing and validation purposes. Analyze and interpret data from prototype testing to make informed design improvements.

- Collaboration: Work closely with the R&D team, electrical engineers, and mechanical engineers, lending your hands-on expertise to integrate battery packs seamlessly into electric vehicle systems.

Skills:

- Bachelor's or Master's degree in Electrical or Mechanical Engineering or a related field.
- 1-3 years of hands-on experience in battery pack design for electric vehicles, with a focus on battery swapping technology.
- Strong hands-on knowledge of lithium-ion battery technology, cell chemistry, and manufacturing processes.
- Proficiency in CAD software for hands-on battery pack design.
- Demonstrated hands-on understanding of thermal management, structural integrity, and safety considerations in battery design.
- Strong problem-solving skills and a hands-on approach to working in a collaborative team environment.
- Ability to adapt to evolving industry trends and technologies.
- AIS-156 certification required.

3. Technical expert AUTOSAR BSW development for Battery Management System (BMS) controller for EV[33]

Roles:

- Technical expert - embedded software development, integration, validation & documentation of AUTOSAR Base software (BSW) in Battery Management System (BMS) controller for future electric vehicles.
- Requirements Elicitation, clarification and review.
- Understand the required input / output, parametrizations and derive/propose multiple/alternative/innovative design solutions.
- Documentation of High / Low Level design, Source code and Unit Tests
- Work closely with designers, developers, QA, partners, suppliers and team-members
- Support for execution of function/system testing (PIL/SIL/HIL/Vehicle)
- Participation in all the necessary technical and project forums for Information gathering, clarifications and reporting
- Need based international travel (short term)

Skills:

- Experience with function/software development-cycle from software requirements, configuration & optimization to validation
- Hands-on experience in Complex Device Driver (CDD) Development, Integration, test environment creation for validation
- Hands-on experience in configuring various AUTOSAR BSW stacks & integration with RTE/Application Layer, OS-configuration.
- Knowledge of programming/scripting in Embedded-C, C , Perl/Python, CAPL on Windows Platform

- Familiarity with ECU / Microcontroller architecture, Communication Protocols (Ethernet, FlexRay, CAN, LIN, I2C and SPI)
- Knowledge of ASPICE, FuSa ISO26262, software quality guidelines
- Experience in working with various data acquisition, analyses & debugging tools (Vector DaVinci Configurator, CANoe, CANalyzer, CANape, Lauterbach TRACE32)
- Experience in embedded static-code analysis, test framework creation and testing (unit/MC/DC integration/functional)
- AUTOSAR MCAL driver development for multi-core controllers
- Working knowledge of Agile Methods / tools: Scrum/Kanban, JIRA, Confluence and experience with DevOps-CI/CD/Jenkins, Version & Configuration Management
- Aptitude and willingness to deep-dive into technical topics / ability to offer solution with an innovative approach

4. SW function developer for HV Battery Management System (BMS)

Roles:

- Embedded software – Model Based Development (MBD), integration, validation & documentation of AUTOSAR software in HV Battery Management System (BMS) controller for hybrid & electric vehicles.
- Requirements elicitation, clarification and review.
- Understand the required input / output, parametrizations and derive/propose multiple/alternative/innovative design solutions.
- Documentation of High / Low Level design, Source code and Unit Tests

- Work closely with designers, developers, QA, partners, suppliers and team-members
- Support for execution of function/system testing (PIL/SIL/HIL/Vehicle)
- Participation in all the necessary technical and project forums for Information gathering, clarifications and reporting

Skills:

- MBD, MATLAB modelling - Implementation of software products
- Developing program modules
- Unit Testing – Tessy. SIL
- Embedded C Programming, Algorithms, Data Structures, OS
- Working in agile software development life cycles (SDLC)
- Vector DaVinci Developer, PREEvision
- Configuration Management (Eg : SVN/GIT/CVS/PVCS/Clearcase)
- Testing Tools (Eg : Tessy/Polyspace)
- Measurement Calibration Diagnostic (MCD) (Eg : CANAPE /CANOE/Canalyzer/Candela Studio/INCA)

5. Senior Hardware Engineer (BMS) | Bangalore | 10+ Years

Roles:

- BMS Hardware Design: Lead the design, development, and validation of hardware components for the Battery Management System, including PCBs, sensors, microcontrollers, and communication interfaces.

- System Integration: Collaborate closely with software engineers, mechanical engineers, and other stakeholders to integrate BMS hardware seamlessly into the overall vehicle architecture.
- Performance Optimization: Continuously optimize BMS hardware for efficiency, accuracy, and reliability, considering factors such as power consumption, thermal management, and fault tolerance.
- Safety Compliance: Ensure that all BMS hardware designs meet industry safety standards and regulatory requirements, and contribute to the development of safety documentation.
- Testing and Validation: Plan and execute comprehensive testing and validation procedures to validate BMS hardware functionality, performance, and durability.
- Documentation: Create and maintain detailed hardware design documentation, including schematics, BOMs, and design specifications.
- Collaboration: Work closely with cross-functional teams to provide technical guidance, support, and troubleshooting expertise.
- Innovation: Stay current with the latest advancements in BMS technology and contribute to the company's competitive edge through innovative hardware solutions.

Skills:

- Bachelor's or Master's degree in Electrical Engineering, Computer Engineering, or a related field.
- Minimum of 8+ years of hardware engineering experience in the automotive industry, with a strong focus on Battery Management Systems.
- Proficiency in hardware design tools, including CAD software (e.g., Altium Designer), and experience with PCB layout design.

- Strong knowledge of analog and digital electronics, microcontroller-based systems, and communication protocols (e.g., CAN, SPI, I2C).
- Familiarity with automotive safety standards and compliance (ISO 26262).
- Excellent problem-solving skills and a systematic approach to troubleshooting hardware issues.
- Strong communication skills and the ability to collaborate effectively with multidisciplinary teams.
- Innovative mindset and a passion for pushing the boundaries of hardware engineering in the automotive industry.

9. Global Leaders of Battery Management System [29]:

Contemporary Amperex Technology Co., Ltd. (CATL) is a Chinese manufacturer of lithium-ion batteries for EVs and energy storage systems and battery management systems. According to the company, CATL has been “ranked No. 1 globally in EV battery consumption volume for five consecutive years.

1. **Contemporary Amperex Technology Limited CATL), China**
2. **LG Energy Solution, Korea**
3. **BYD Co, China**
4. **Panasonic, Japan**
5. **SK Innovation, Korea**
6. **Samsung SDI, Korea**
7. **CALB (China Aviation Lithium Battery Co), China**
8. **Gotion Hi Tech, China**
9. **Sunwoda Electronic Co Ltd, China**
10. **Farasis Energ, China**

10. Global Start ups of Battery Management System [30]:

1. **Recurrent** – EV Battery Health Monitoring
2. **Open Energy** – Automatic Battery Swapping
3. **LibCycle** – Safe Battery Transportation
4. **Evyon** – EV Battery Repurposing
5. **Automotive Cells Company (ACC**) – Fast-Charging Automotive Cells
6. **IONETIC** – High-Performance Battery Packs
7. **Nexus Power** – Bio-Organic Battery Materials
8. **ni-cat –** AI-assisted Battery Research & Development
9. **EVolution** – Intelligent Battery Management Systems
10. **Universe Energy –** Robotic EV Battery Disassembly

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