The Hong Kong Polytechnic University
香港理工大學

Overview

Electric Energy Storage and New Energy Sources for Electric Vehicles (EE546)

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The Hong Kong Polytechnic University

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- **Teaching and learning are mutually motivating**
- Please feel free to give your suggestions on our teaching and learning

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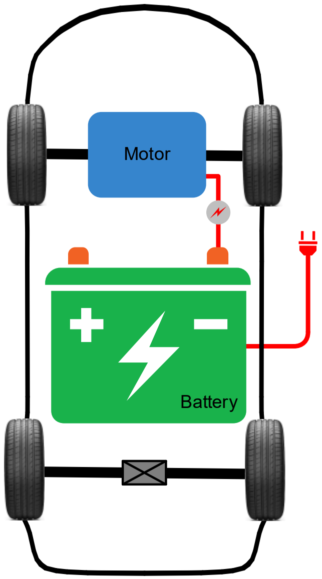
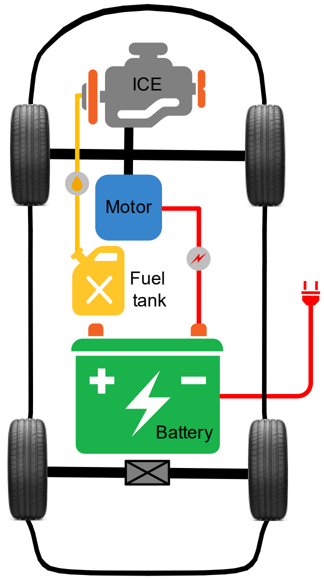
Classification of Electric Vehicles (EVs)

Battery electric vehicles (BEVs)



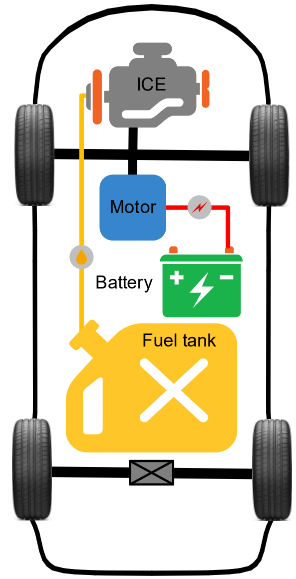
- Driven by motor
- Powered by battery only
- Large battery capacity

Plug-in hybrid electric vehicles (PHEVs)



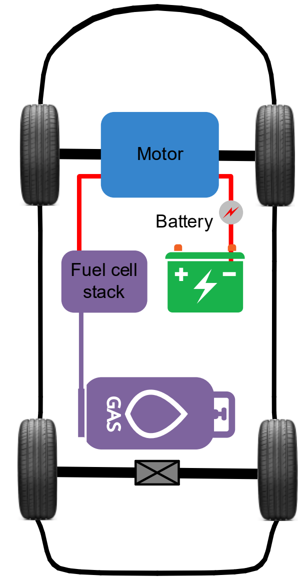
- Driven by both motor and ICE
- Powered by gasoline and battery
- Medium battery capacity

Hybrid electric vehicles (HEVs)



- Driven by both ICE and motor
- Powered by gasoline and battery
- Small battery capacity

Fuel cell electric vehicles (FCEVs)

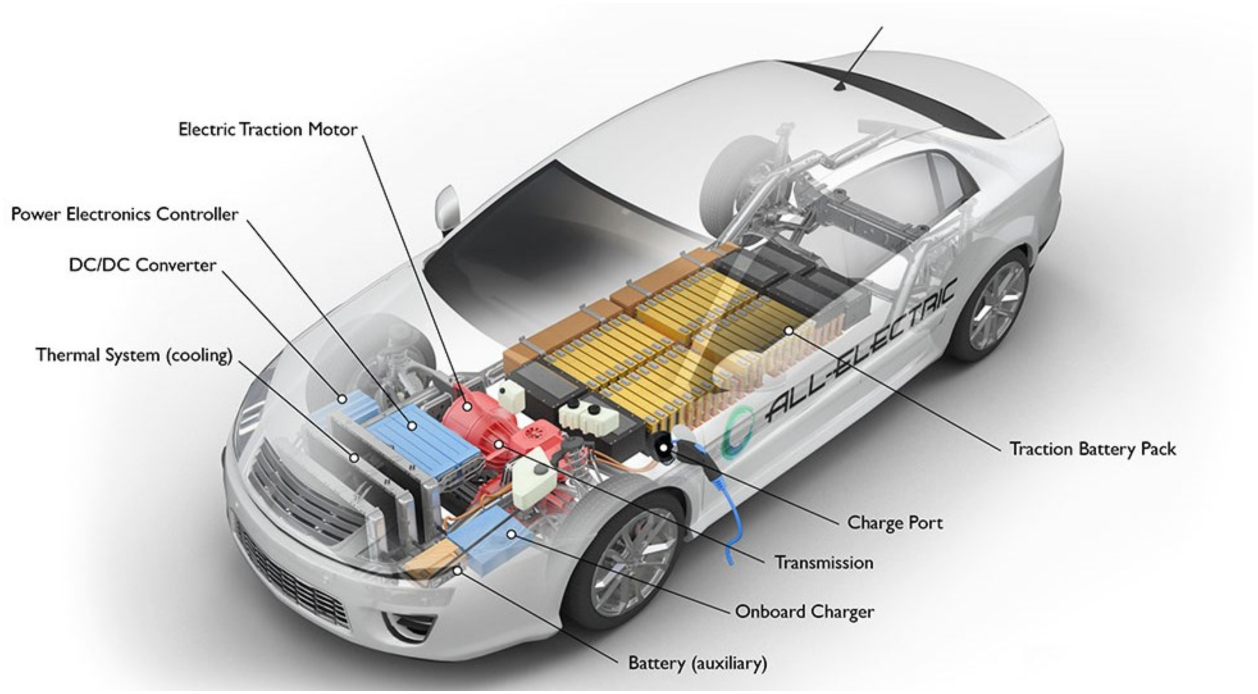


- Driven by motor
- Powered by hydrogen fuel and battery
- Small battery capacity

ICE, Internal combustion engine

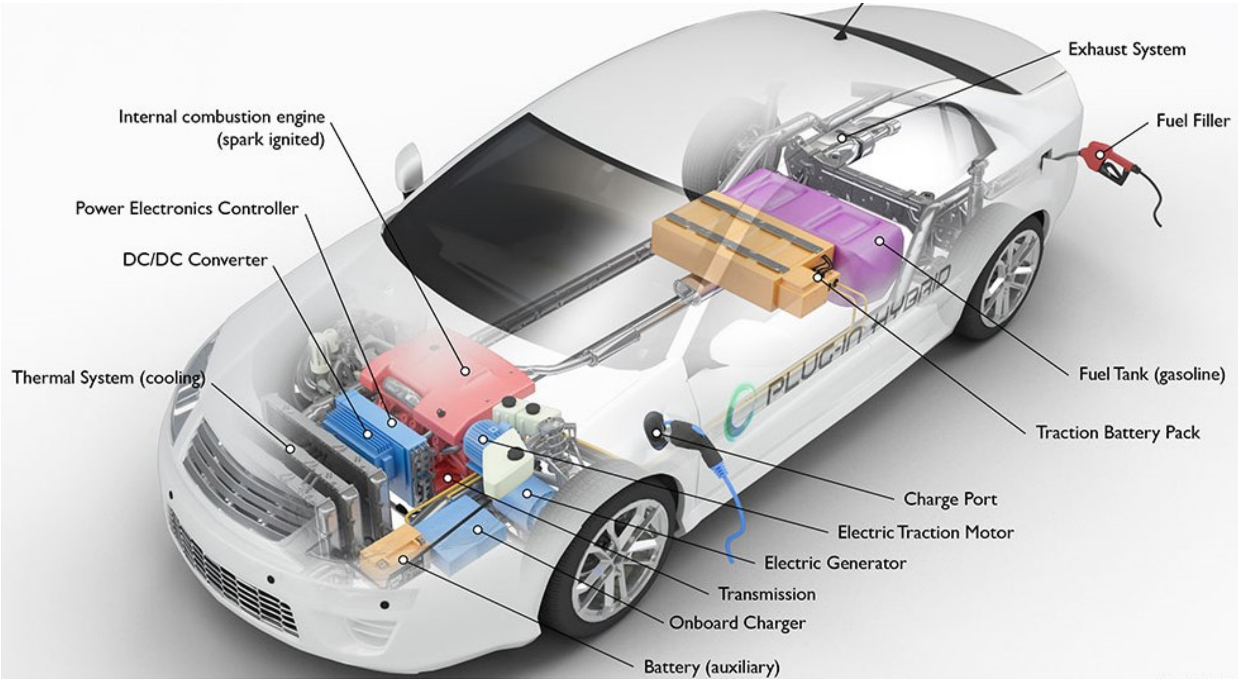
1. Battery EVs

Battery electric vehicles (BEVs), also referred to as all-electric vehicles, have an electric motor instead of an internal combustion engine. The EV uses a large traction battery pack to power the electric motor. Because it runs on electricity, the EV emits no exhaust from a tailpipe and does not contain the typical liquid fuel components, such as a fuel pump, fuel line or fuel tank.



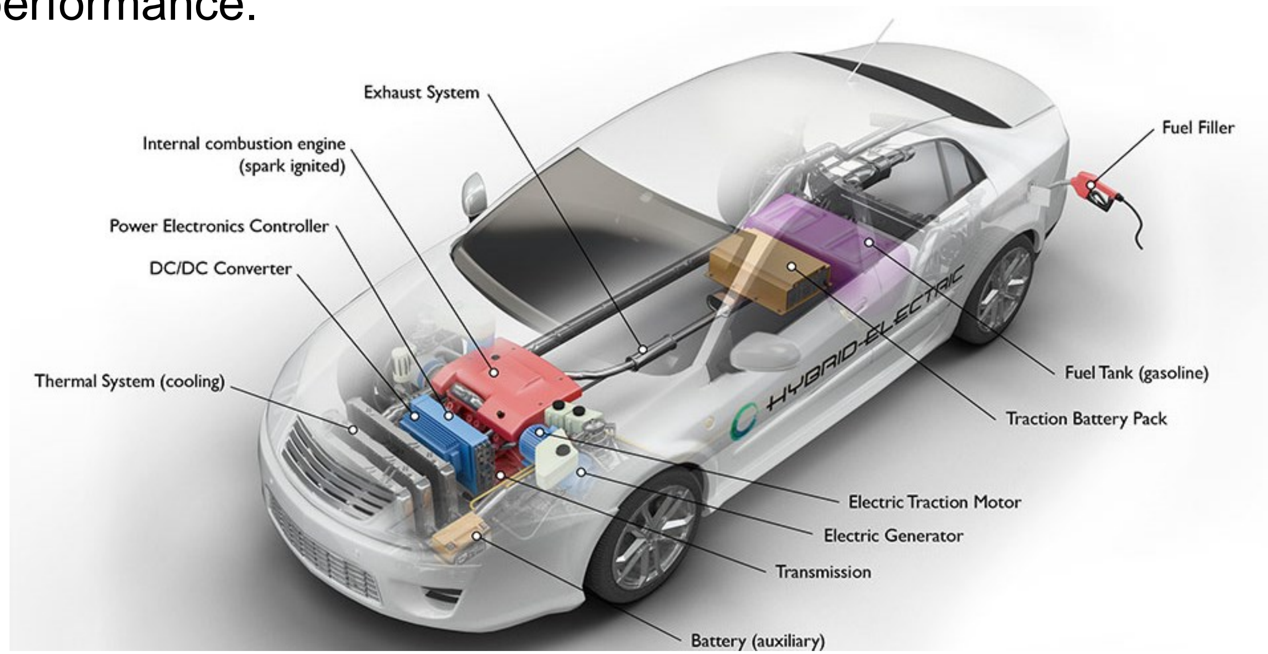
2. Plug-In Hybrid EVs

Plug-in hybrid electric vehicles (PHEVs) use batteries to power an electric motor and another fuel, such as gasoline, to power an internal combustion engine (**ICE**). The PHEV batteries can be charged using a wall outlet or charging equipment, by the ICE, or through regenerative braking. The vehicle typically runs on electric power until the battery is nearly depleted, and then the car automatically switches over to use the ICE.



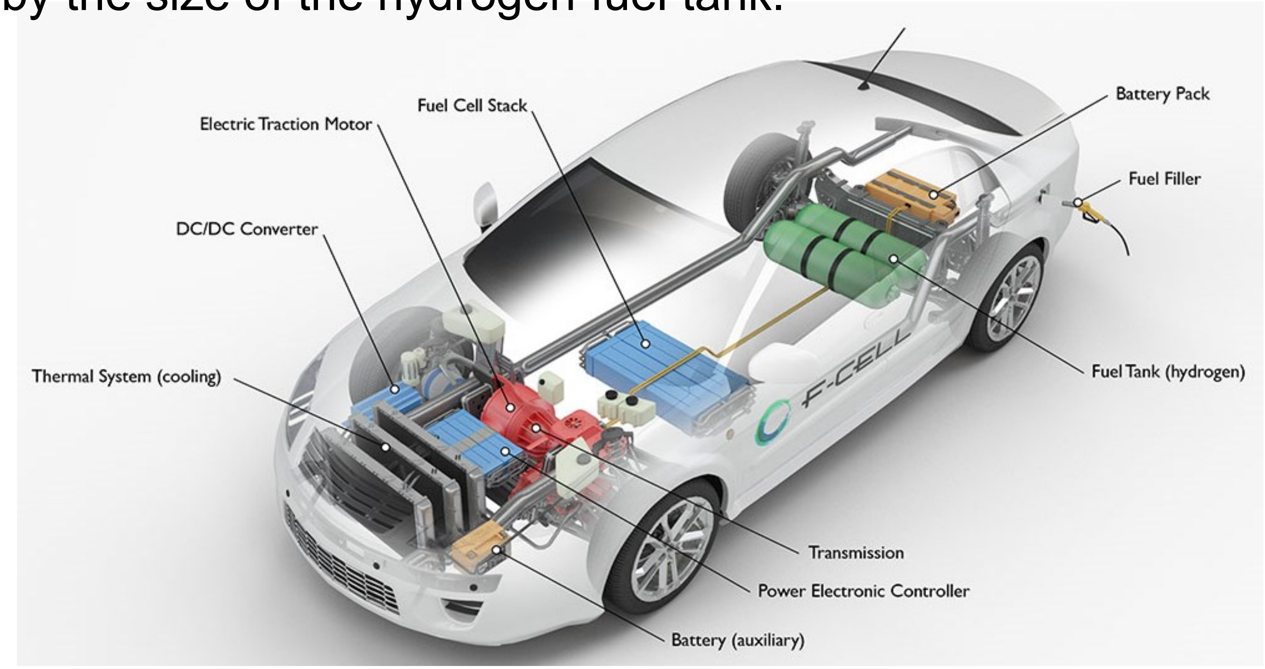
3. Hybrid Electric Vehicles

Hybrid electric vehicles (HEVs) are powered by an internal combustion engine and one or more electric motors, which uses energy stored in batteries. A HEV cannot be plugged in to charge the battery. Instead, the battery is charged through regenerative braking and by the internal combustion engine. The extra power provided by the electric motor can potentially allow for a smaller engine. The battery can also power auxiliary loads and reduce engine idling when stopped. Together, these features result in better fuel economy without sacrificing performance.



4. Fuel Cell EVs

Like all-electric vehicles, fuel cell electric vehicles (FCEVs) use electricity to power an electric motor. In contrast to other EVs, FCEVs produce electricity using a fuel cell powered by **hydrogen**, rather than drawing electricity from only a battery. Most FCEVs today use the battery for recapturing braking energy, providing extra power during short acceleration events, and smoothing out the power delivered from the fuel cell with the option to idle or turn off the fuel cell during low power needs. The amount of energy stored onboard is determined by the size of the hydrogen fuel tank.



Classification of EV Energy Sources

Batteries

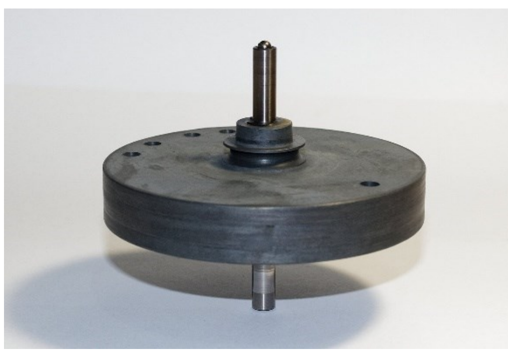
based on electrochemical means to store electrical energy

REF: https://commons.wikimedia.org/wiki/File:Comparison_of_18650_and_21700_batteries_01.jpg

Ultracapacitors

based on electrostatic means to store electrical energy

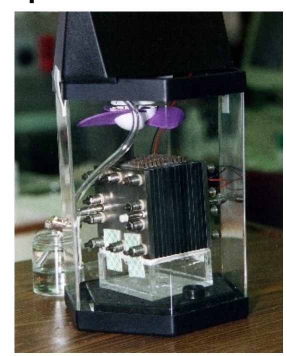
REF: https://studentlesson.com/definition-applications-diagram-working-specifications-characteristics-construction-properties-types-ultracapacitors/



Ultrahigh-speed flywheels

based on electromechanical means to store electrical energy

REF: https://commons.wikimedia.org/wiki/File:Yauza_209-1_(disassembly)_-_capstan-flywheel,_upright_01.jpg



Fuel cells

based on electrochemical means to generate electrical energy

REF: https://commons.wikimedia.org/wiki/File:Fuel_cell_NASA_p48600ac.jpg

In the foreseeable future, batteries are the major energy source for EVs. Major types of batteries that have been developed for EVs are:

- Valve-regulated lead acid (VRLA)
- Nickel-cadmium (Ni-Cd) Memory effect
- Nickel-metal hydride (Ni-MH)
- Zinc/air (Zn/air)
- Sodium/sulfur (Na/S)
- Lithium-ion (Li-ion)
- Sodium-ion (Na-ion) CATL
- Solid-state battery

Performance Comparison

	Specific energy (Wh/kg)	Specific power (W/kg)	Cycle life (Cycles)	Cost (USD/kWh)
VRLA	30-45	200-300	400-600	150
Ni-Cd	40-60	150-350	600-1200	300
Ni-MH	60-120	150-400	600-1200	200-350
Zn/air	230	105	NA	90-120
Na/S	100	200	800	250-450
Li-ion	90-160	250-450	1200-2000	600-1000

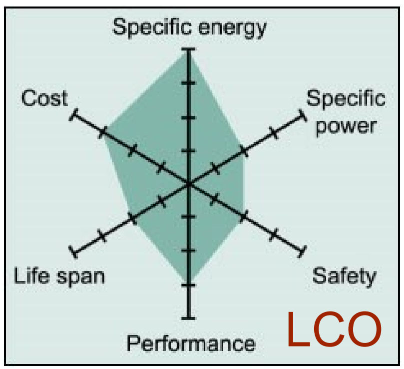
Contemporary Amperex Technology Co., Limited (CATL)

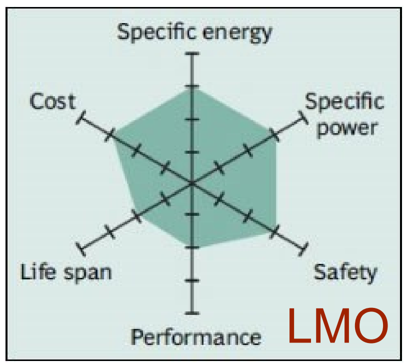
Lesson 2: Batteries

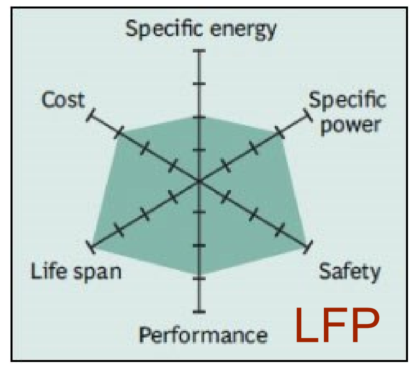
Current research on battery technology is being focused on the development of various Li-ion batteries:

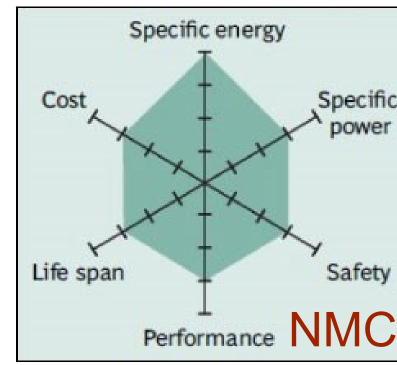
- Lithium cobalt oxide (LCO)
- Lithium manganese oxide (LMO)
- Lithium iron phosphate (LFP)
- Lithium nickel manganese cobalt oxide (NMC)
- Lithium nickel cobalt aluminum oxide (NCA)
- Lithium titanate (LTO)

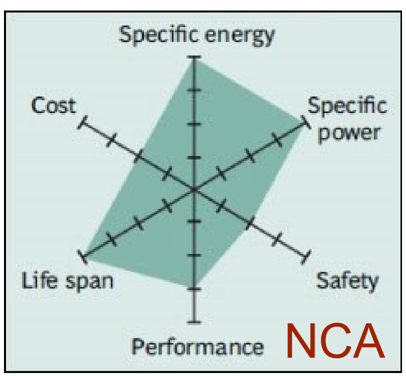
Comparison of emerging Li-ion batteries

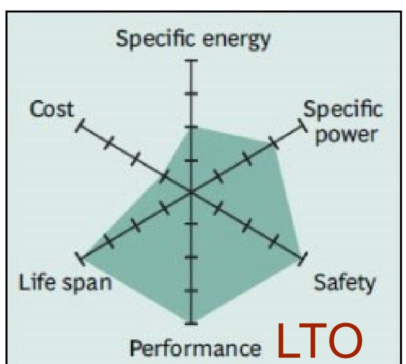












Note

- Cost: Cost-effectiveness
- Life span: Cycle life
- Performance: Low-temperature performance
- Safety: Safety operation

REF: http://batteryuniversity.com/learn/article/explaining_lithium_ion_chemistries

Lesson 3: Ultracapacitors

The ultracapacitor technology is promising for EVs since it offers exceptionally high specific power and practically unlimited cycle life. Nevertheless, it needs significant improvement before practically applicable as the sole energy source for EVs:

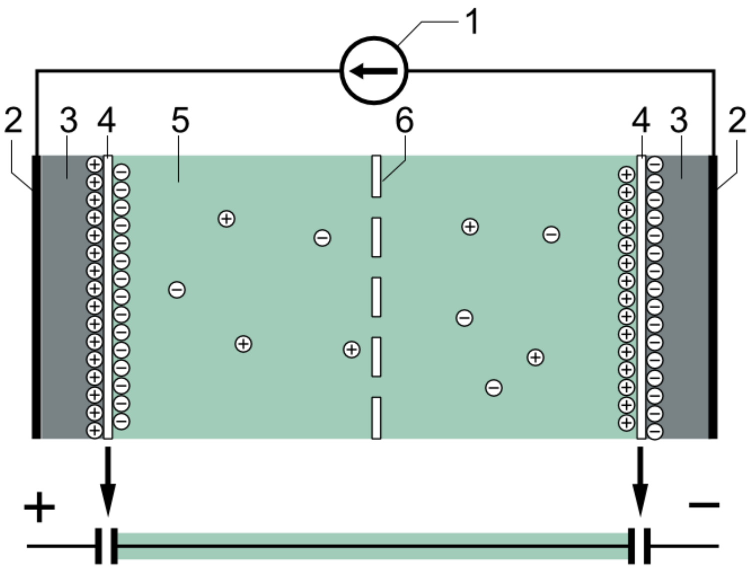
- Its specific energy (5-6 kW/kg) needs to be greatly increased.
- Its initial cost (2,400-6,000 USD/kWh) has to be greatly reduced.

- 48V capacitor module
- High power supply performance
- Low internal resistance

REF: http://www.tongman-sh.com/proshow_01.html

Current research on ultracapacitor technology is being focused on the improvement of its specific energy, such as the use of graphene and carbon nanotubes to increase the usable surface area and hence the energy storage capacity.

Basic design



1. power source
2. collector
3. polarized electrode
4. Helmholtz double layer
5. electrolyte having positive and negative ions
6. separator

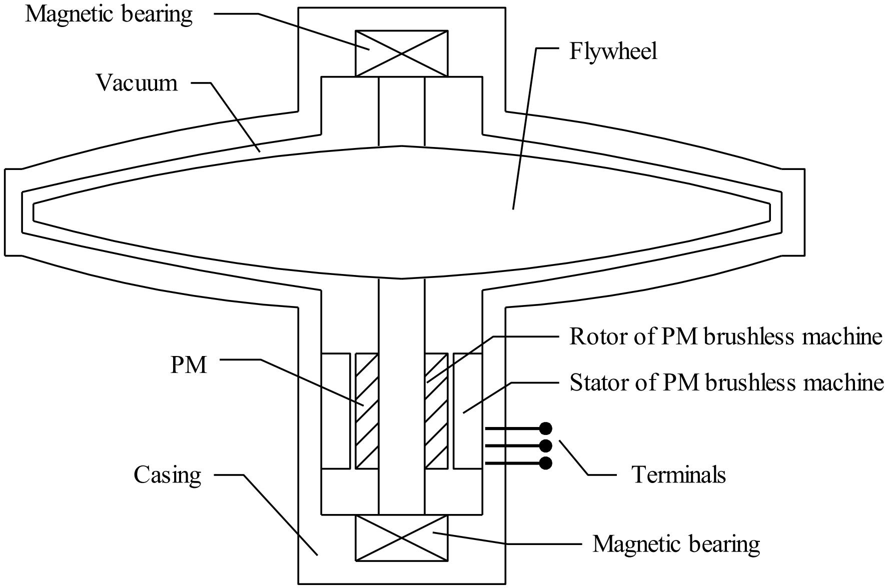
- Electrochemical capacitors (supercapacitors) consist of two electrodes separated by an ion-permeable membrane (separator), and an electrolyte ionically connecting both electrodes. When the electrodes are polarized by an applied voltage, ions in the electrolyte form electric double layers of opposite polarity to the electrode's polarity.

REF: https://commons.wikimedia.org/wiki/File:Electric_double-layer_capacitor_(2_models)_-1_NT.PNG

Lesson 4: Ultrahigh-Speed Flywheels

The ultrahigh-speed flywheel technology exhibits potentiality for EVs. By providing vacuum environment to remove the air friction and magnetic bearings to eliminate the bearing loss, the flywheel can spin up to 60,000 rpm so as to achieve high specific energy and high round-trip efficiency.

97% mechanical efficiency, and
85% round trip efficiency



REF: http://www.cbea.com/www/zy/20150922/4874312.html

Lesson 4: Ultrahigh-Speed Flywheels

- It suffers from the problem of safety concern. When the tensile strength of a flywheel is exceeded or the flywheel is accidentally damaged, the flywheel shatters and instantaneously releases all of its stored energy – so-called flywheel explosion which is as dangerous as a bomb.

- Current research on ultrahigh-speed flywheel technology is focused on improving its **safety precaution** such as the use of composite materials which can disintegrate into tiny powder rather than large chunks, or extending its application to energy storage for EV charging stations where the whole flywheel is embedded in the ground.

- For application to charging station, the ultrahigh-speed flywheel can be used as a **stationary energy storage system** (25-kWh capacity and 130-kW capability) to provide rapid recharging for EVs. Thus, it offers the ability to release high power for rapid recharging while minimizing the corresponding peak power demand on power system.

The leading types of fuel cells include:

- Direct methanol fuel cell (DMFC)
- Alkaline fuel cell (AFC)
- Proton exchange membrane fuel cell (PEMFC)
- Phosphate acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

Performance Comparison

	Power level (MW)	Power density (W/cm2)	Operating temp. (°C)	System efficiency (%)
DMFC	<0.001	0.04-0.23	90-120	10-20
AFC	<0.1	0.2-0.3	60-100	62
PEMFC	<0.5	0.35-0.6	50-120	30-50
PAFC	<10	0.2-0.25	150-200	40
MCFC	<100	0.1-0.2	600-650	47
SOFC	<100	0.24-0.3	500-1100	55-60

Lesson 5: Fuel Cells

- The proton exchange membrane fuel cell (PEMFC) is a natural choice for the fuel-cell vehicle (FEV) because of its **solid electrolyte nature**, **low-temperature operation**, **quick start-up**, proper power level, high power density and good system efficiency.

- To enable the FEV offering affordable price, the fuel-cell initial cost (about 4,800 USD/kW) has to be dramatically reduced.

- Current research on fuel cell technology is being focused on the **reduction of platinum usage** for the PEMFC which requires such noble metal as the electrocatalyst, and the **reduction of operating temperature** for the solid oxide fuel cell (SOFC) which does not desire noble metal as the electrocatalyst.

Storing hydrogen

There are three practical ways to store hydrogen in the FEV:

- compressed hydrogen gas (CHG)
- liquid hydrogen (LH)
- metal hydride (MH)

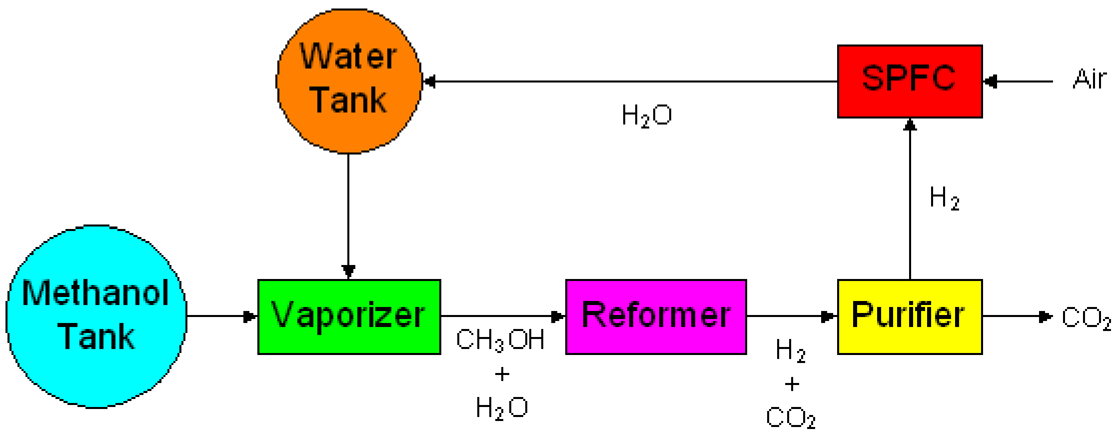
Performance Comparison

	Specific energy (Wh/kg)	Energy density (Wh/L)
CHG [a]	33600	600
LH [b]	33600	2400
Magnesium MH	2400	2100
Vanadium MH	700	4500
Methanol	5700	4500
Petrol	12400	9100

[a] At ambient temperature and 20 MPa
[b] At cryogenic temperature and 0.1 MPa

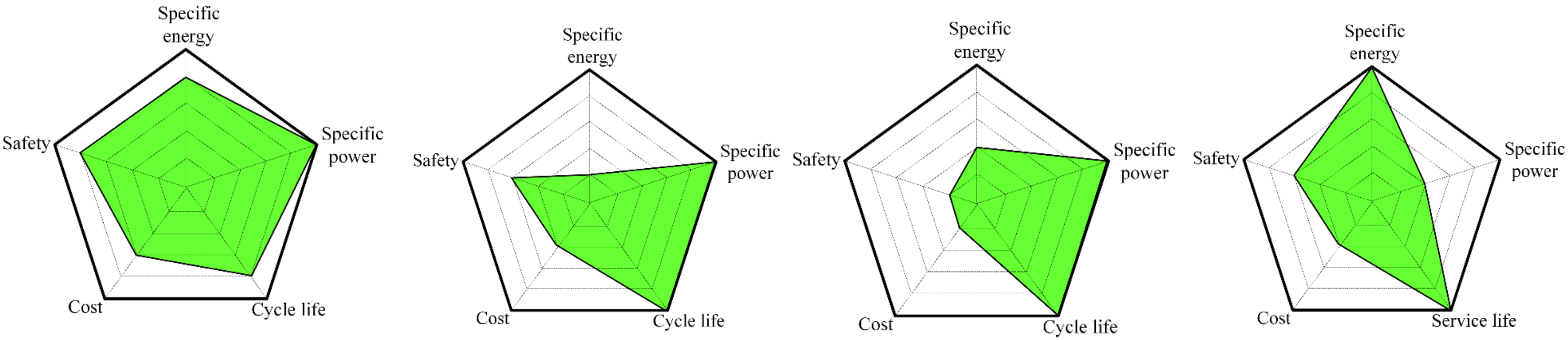
- Hydrogen gas can be real-time produced from a tank of liquid fuel such as methanol by using an on-board reformer. It takes the definite advantage of liquid fuel which does not require complicated and energy-consumed storage methods for hydrogen. Also, it can fully utilize the existing refueling infrastructure for conventional vehicles.

- The use of methanol as the fuel has the drawback of CO_2 emission. Although this technology seems to be contradictory to the pursuit of zero-emission vehicles, it is still environmentally friendly as it does not generate harmful emissions such as CO, NOx and HC.



Solid polymer fuel cell (SPFC)

Performance Comparison of Energy Sources

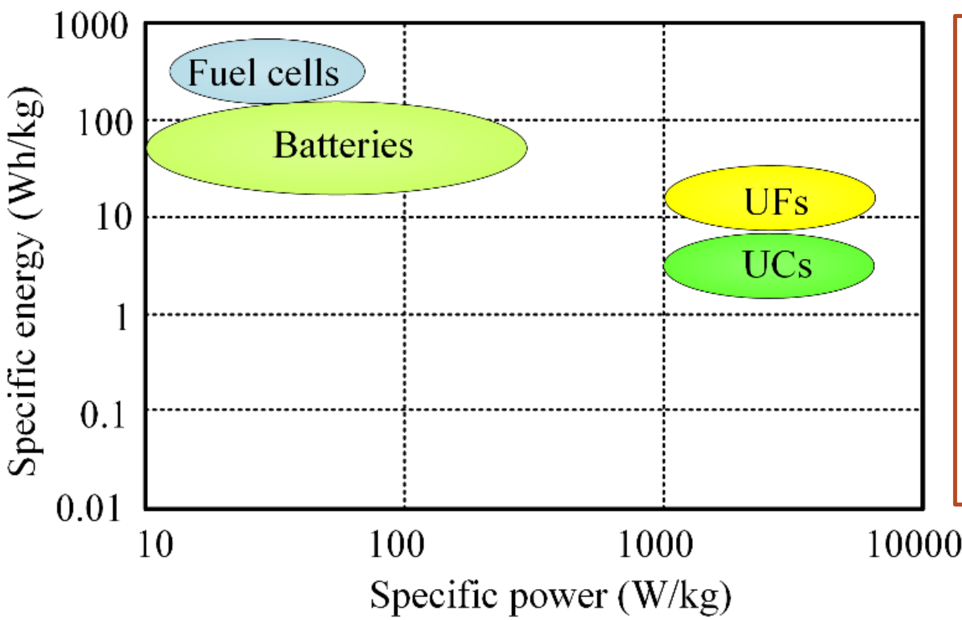


Li-ion battery **Ultracap** **Ultrafly** **PEMFC**

- It compares their performances in terms of the specific energy, specific power, cycle life (equivalent to service life for fuel cells), cost and safety.
- It can be observed that the Li-ion battery is still most preferable, holistically.

Proton exchange membrane fuel cell (PEMFC)

Performance Comparison of Energy Sources



A Ragone chart indicates that none of them can simultaneously offer high specific energy and high specific power. For the battery electric vehicles (BEVs), the specific energy governs the driving range per charge while the specific power determines the acceleration rate.

- In general, a compromise between the specific energy and specific power is necessary, but with more preference on the specific energy.
- If allowable in terms of cost, space and complexity, a hybridization of two energy sources (one with high specific energy and another with high specific power) is preferred.

Lesson 7: Case Study

The course topic is to be confirmed with our students, possibly simulation model of wireless charging system for EVs or introduction of EV model.

Xiaomi SU7 Max – First Xiaomi electric vehicle in overseas

Xiaomi

Donation for collaboration

PolyU

EV models are to be confirmed.

Battery parameters

- Capacity:101 kWh
- Type: Ternary lithium
- CTB integrated technology

Vehicle performance

- Acceleration time of 100 km/h: 2.78 s
- Maximum speed: 265 km/h
- CLTC range: 500 km
- Fast Charging Time (10%-80%): 19 min
- 15 min charging and replenishment : 510 km

REF: https://www.xiaomiev.com/car-config

CTB, Cell-to-body CLTC, China light-duty vehicle test cycle

Lesson 7: Case Study

Hydrogen Bus

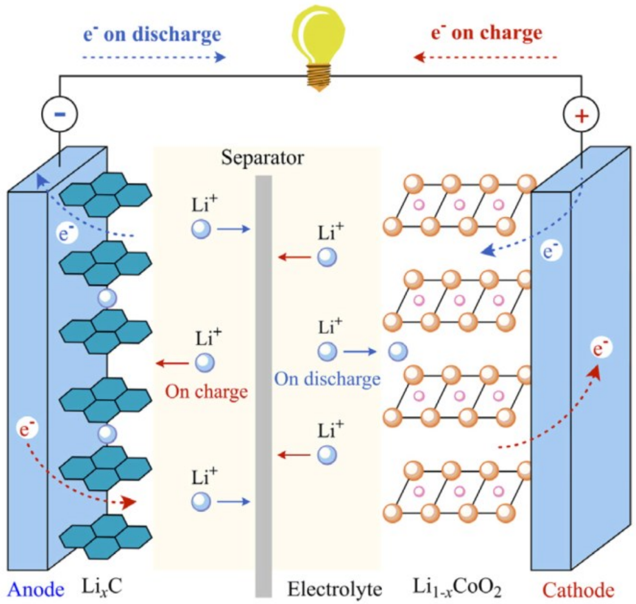
FCHV Information

- 90 kW PEFC Fuel cell stack: twice
- Motor: AC synchronous 80 kW twice
- Hydrogen tank: Compressed hydrogen gas 35 MPa / 150 liter, five (version 2002) or seven (version 2005)
- Passenger capacity: 63 (included 22 seats)

REF: https://en.wikipedia.org/wiki/Toyota_FCHV#FCHV-BUS

FCHV, Fuel cell hybrid vehicle

PEFC, Polymer electrolyte fuel cell



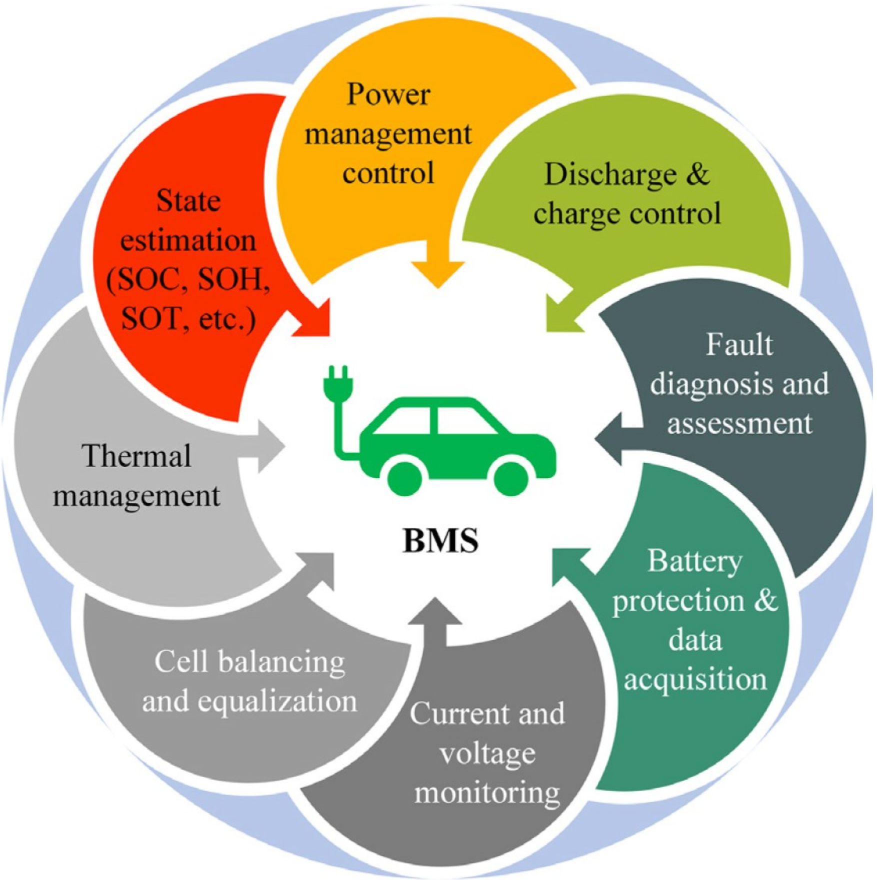
A **lithium-ion (Li-ion battery)** is a type of rechargeable battery that uses the reversible intercalation of Li^+ ions into electronically conducting solids to store energy. In comparison with other commercial rechargeable batteries, Li-ion batteries are characterized by higher specific energy, higher energy density, higher energy efficiency, longer cycle life, and longer calendar life.

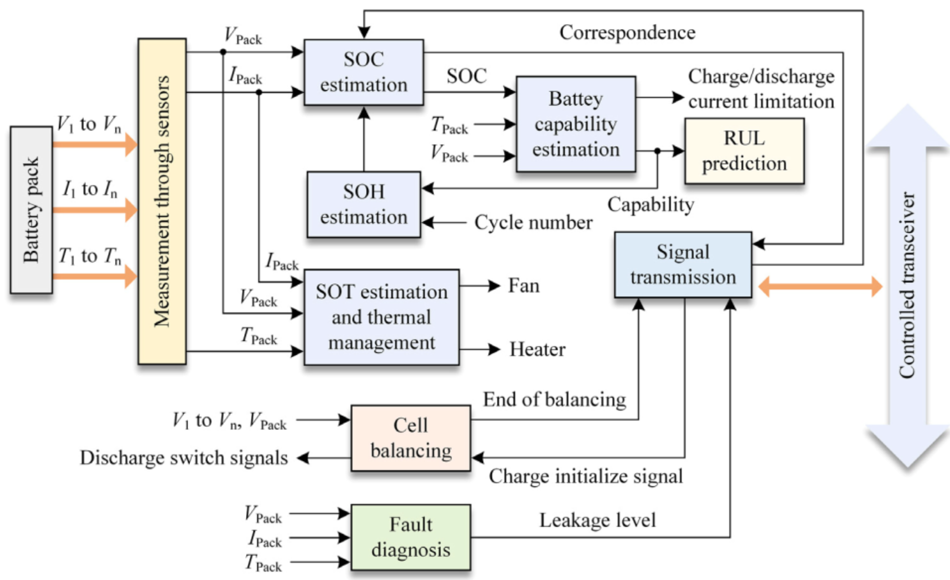
During cell discharge, the negative electrode is the anode, and the positive electrode is the cathode.

- Electrons flow from the anode to the cathode through the external circuit. An oxidation half-reaction at the anode produces positively charged lithium ions and negatively charged electrons.
- The oxidation half-reaction may also produce uncharged material that remains at the anode. Lithium ions move through the electrolyte; electrons move through the external circuit toward the cathode where they recombine with the cathode material in a reduction half-reaction.

REF: W. Liu, T. Placke, and K.T. Chau, "Overview of batteries and battery management for electric vehicles," Energy Reports, vol. 8, pp. 4058–4084, Nov. 2022.

Battery Management System (BMS)





Functional block diagram of battery management system for electric vehicles

REF: W. Liu, T. Placke, and K.T. Chau, "Overview of batteries and battery management for electric vehicles," Energy Reports, vol. 8, pp. 4058–4084, Nov. 2022.

Battery Management System (BMS)

Functions

Monitor: A BMS may monitor the state of the battery as represented by various items, such as:

- **Voltage**: total voltage, voltages of individual cells, or voltage of periodic taps
- **Temperature**: average temperature, coolant intake temperature, coolant output temperature, or temperatures of individual cells
- **Coolant flow**: for liquid cooled batteries
- **Current**: current in or out of the battery
- **Health** of individual cells
- **State of balance** of cells

Electric vehicle systems: energy recovery

Computation

Communication

Protection

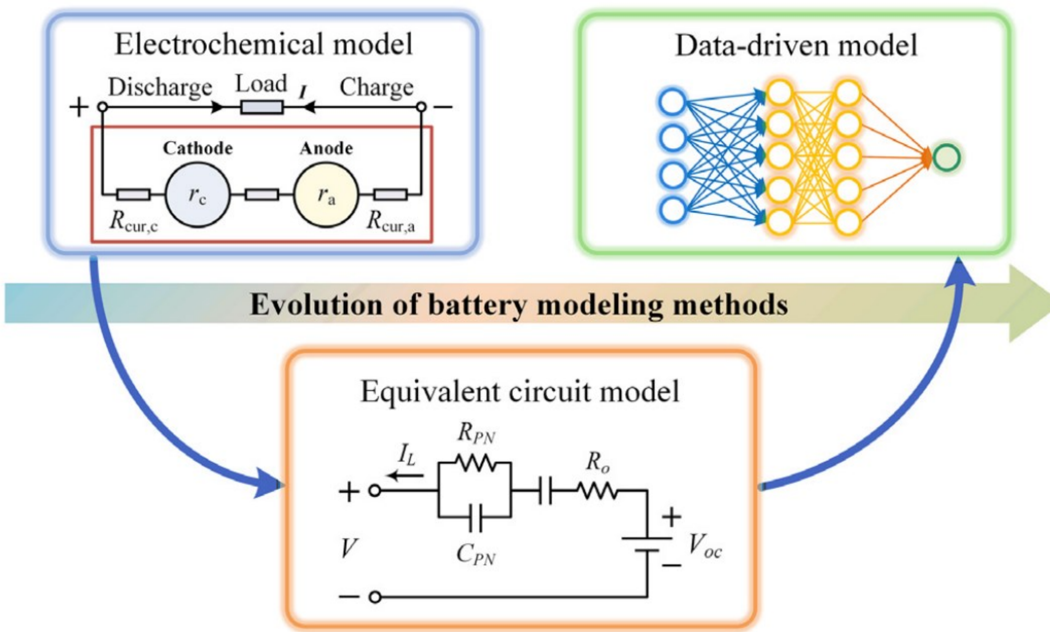
Battery connection to load circuit

Balancing

REF: https://en.wikipedia.org/wiki/Battery_management_system

Battery modeling turns into one of the most significant prerequisites for BMSs, concluding the main significances of battery modeling. To represent the EV batteries, three modeling methods, including:

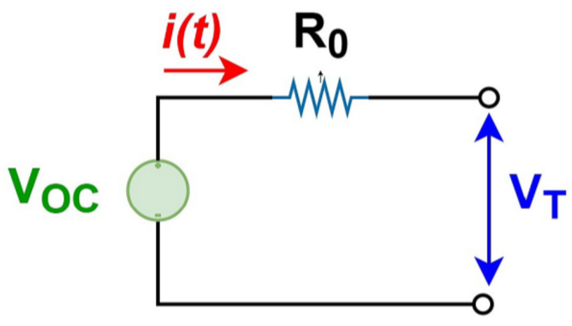
Electrochemical Model	Equivalent Circuit Model	Data-Driven Model
(a) Single-particle model	(a) Integral-order model	(a) Neural network
(b) pseudo-two-dimensional model	(b) Fractional-order model	(b) Machine learning



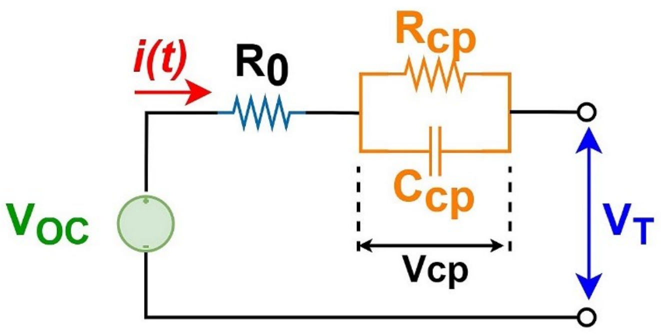
Evolutions map of battery modeling methods

REF: W. Liu, T. Placke, and K.T. Chau, "Overview of batteries and battery management for electric vehicles," Energy Reports, vol. 8, pp. 4058–4084, Nov. 2022.

Common Integer-Order Equivalent Circuit Models



The Rint model



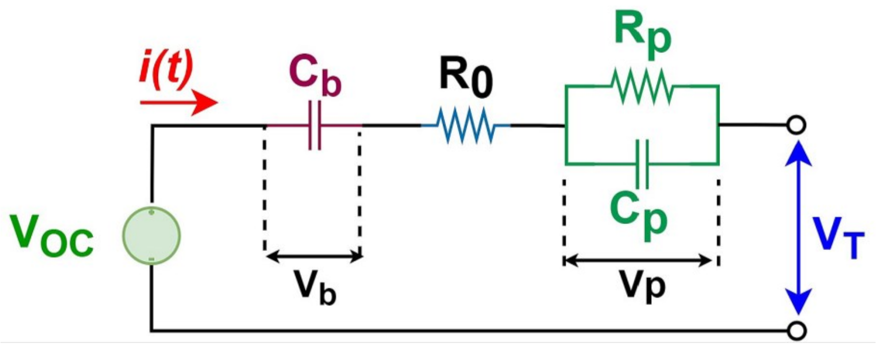
The Thevenin model

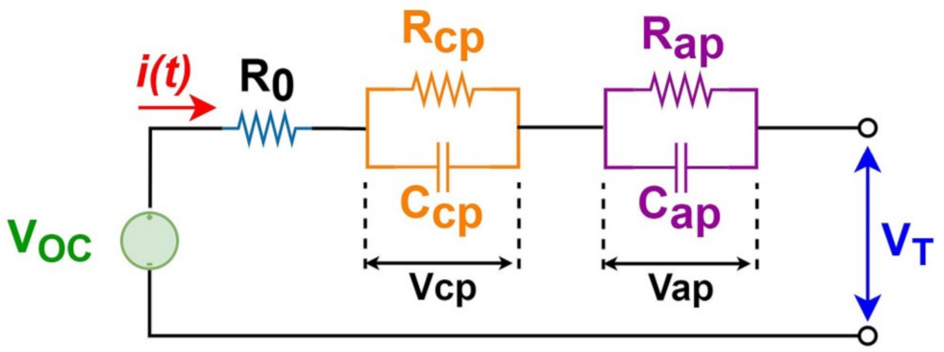
The Rint model: It uses an ideal voltage source V_{OC} and the battery DC internal resistance R_0 in series to describe the dynamic characteristics of the power battery. Also, R_0 and V_{OC} are functions of state of charge (SoC) and temperature.

The Thevenin model: It is based on the Rint model, adding a parallel RC network to simulate the polarization effect of the battery. This model has a relatively simple structure and high simulation accuracy.

REF: Zhou W, Zheng Y, Pan Z, Lu Q. Review on the Battery Model and SOC Estimation Method. Processes. 2021; 9(9):1685. https://doi.org/10.3390/pr9091685

Common integer-order equivalent circuit models





The PNGV model | **Dual Polarization (DP) model**

The PNGV model: On the basis of the Thevenin model, a capacitor C_b can be connected in series to form a PNGV model. This capacitor is used to describe the change in battery open circuit voltage caused by the current integration during the battery's long-term charging and discharging process.

The Dual Polarization (DP) model: In addition to the ohmic and concentration polarizations used by the Thevenin model, the DP model implements activation polarization. The phenomenon of activation polarization occurs at the electrode surface.

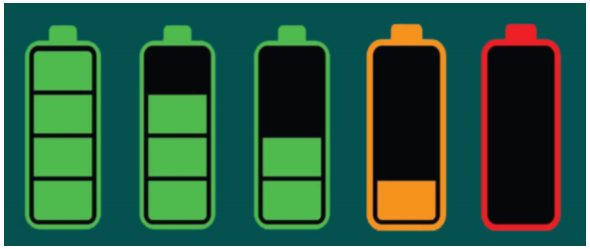
Partnership for a new generation of vehicle (PNGV)

REF: Tekin M, Karamangil M İ. Comparative analysis of equivalent circuit battery models for electric vehicle battery management systems. Journal of Energy Storage, 2024, 86: 111327.

Lesson 10: Battery State of Charge

Definition

- **State of Charge (SoC)**: Current charge level of a battery (0% = empty, 100% = full).



REF: https://www.takomabattery.com/how-to-check-state-of-charge-of-lithium-battery/

Importance in EVs

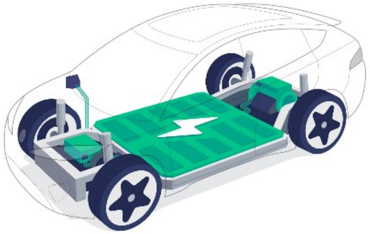
Driving Range
SoC affects how far an EV can travel on a single charge.

Battery Health
Proper SoC management prolongs battery lifespan.

Safety
Prevent overcharging and deep discharging.

REF: https://autos.yahoo.com/ev-range-everything-know-132000750.html

REF: https://commons.wikimedia.org/wiki/File:Antu_battery-charging-080.svg



REF: https://www.evpedia.co.in/ev-blog/stay-charged-and-safe-your-ev-battery-safety-checklist

Measurement Methods

Voltage Method

Measure open-circuit voltage.

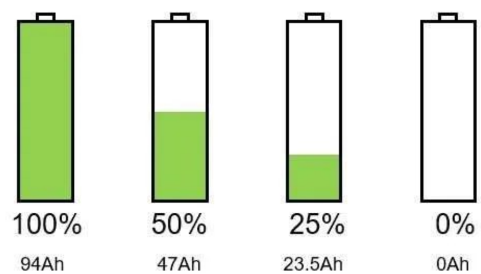
Voltage	State of Charge
12.6+	100%
12.5	90%
12.42	80%
12.32	70%
12.20	60%
12.06	50%
11.9	40%
11.75	30%
11.58	20%
11.31	10%
10.5	0%

REF: https://www.rvtechlibrary.com/battery/bat_volts.php

Coulomb Counting

Tracks charging /discharging currents.

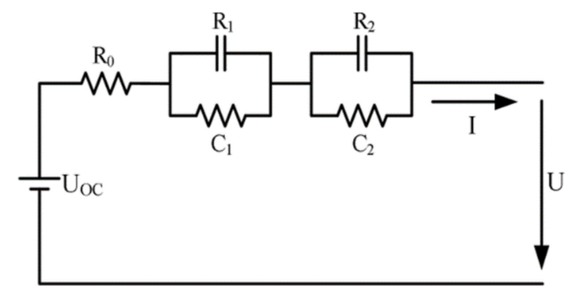
$$SoC(t) = SoC(t-1) + \frac{I(t)}{Q_n}\Delta t$$



REF: https://www.batterydesign.net/soc-estimation-by-coulomb-counting/

Impedance Method

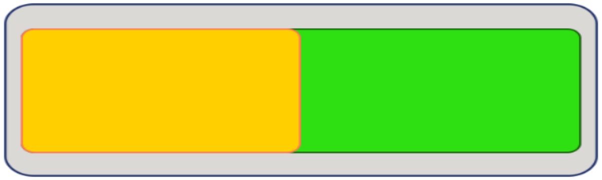
Analyse internal impedance changes.



REF: https://www.researchgate.net/figure/The-battery-equivalent-circuit_fig1_343796730

Definition

- **State of Health (SoH)**: A measure of a battery's overall condition compared to its ideal or original state (100% = new condition).



50% SoH

REF: https://www.biologic.net/topics/battery-states-state-of-charge-soc-state-of-health-soh/

Importance in EVs

Performance Indicator

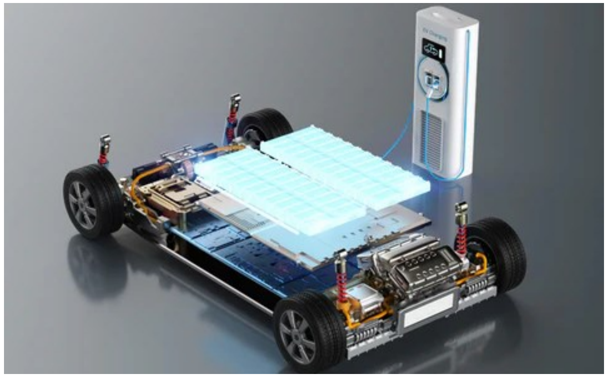
SoH reflects the battery's ability to hold and deliver charge, impacting driving range and efficiency.

Lifespan Assessment

SoH helps predict the remaining useful life of the battery, informing replacement decisions.

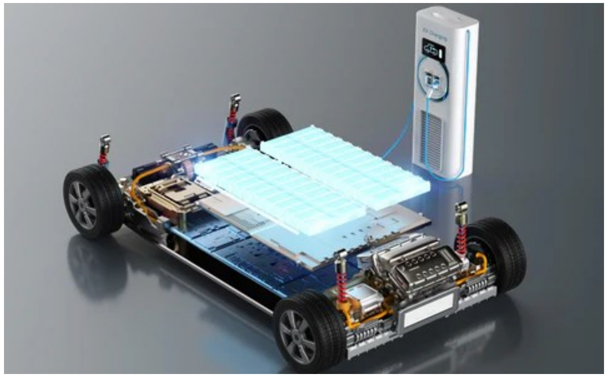
Safety Considerations

Monitoring SoH can pre-vent unexpected failures and enhance vehicle safety.



REF: https://ev-lectron.com/blogs/blog/ev-battery-charging-best-practices

REF: https://www.carandbike.com/news/how-to-maintain-health-of-evs-battery-2951541



REF: https://ev-lectron.com/blogs/blog/ev-battery-charging-best-practices

Measurement Methods

Capacity Measurement

Compare the current capacity of the battery to its original rated capacity to assess degradation.

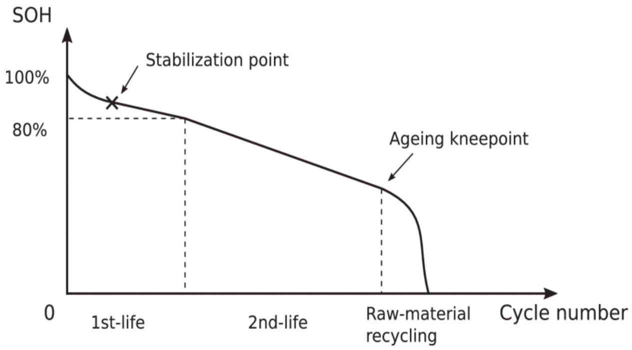
Cycle Life Analysis

Evaluate the number of charge/discharge cycles to determine the impact of usage on battery health.

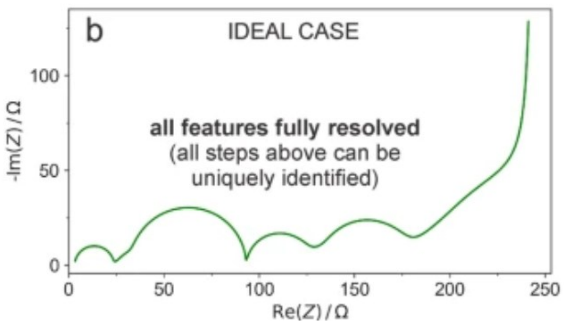
Electrochemical Impedance Spectroscopy (EIS)

Analyse the battery’s impedance at various frequencies to gain insights into its health.

REF: https://www.youtube.com/watch?v=pGsglGnybdM



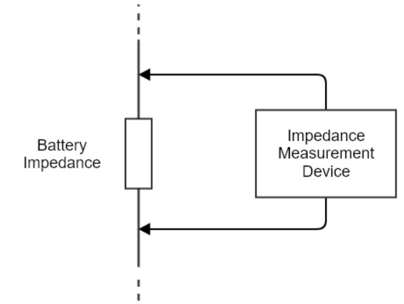
REF: M. Tran, J. Sihvo and T. Roinila, “Internal Impedance in Determining Usability of Used Lithium-Ion Batteries in Second-Life Applications,” in *IEEE Transactions on Industry Applications*, vol. 59, no. 5, pp. 6513-6521, Sept. 2023, DOI: 10.1109/TIA.2023.3280466.



REF: M. Gaberšček, “Understanding Li-based battery materials via electrochemical impedance spectroscopy,” in *Nature Communications*, vol. 12, no. 1, Nov. 2021, DOI: 10.1038/s41467-021-26894-5.

Definition

- **Battery Impedance**: The impedance that a battery presents to the flow of alternating current (AC).
- **Electrochemical Impedance Spectroscopy (EIS)**: A technique that measures the impedance of a battery by applying a small AC signal



REF: https://info.powershield.com/blog/battery-internal-ohmic-measurements-part-2

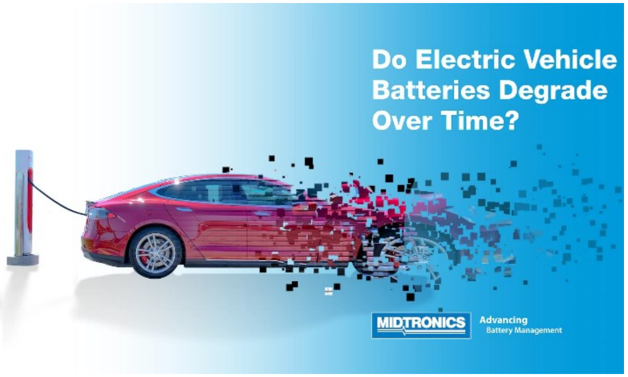
Importance in EVs

Performance Assessment
EIS provides detailed insights into battery health, efficiency, and state of charge.

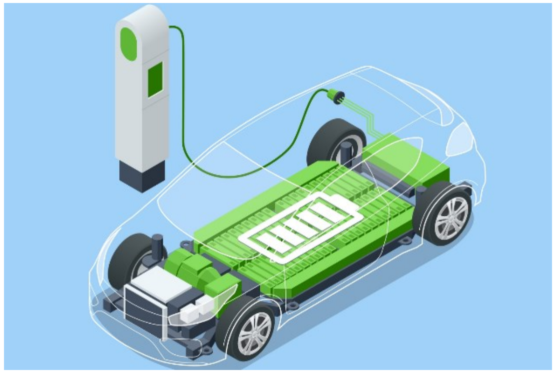
Degradation Monitoring
Changes in impedance can indicate aging, capacity loss, and potential failure modes.

Safety Considerations
Monitoring SoH can prevent unexpected failures and enhance vehicle safety.

REF: https://www.greenwaveev.com/the-facts-on-ev-battery-health-and-longevity/



REF: https://www.midtronics.com/blog/do-electric-car-ev-batteries-degrade-over-time/



REF: https://ev-lectron.com/blogs/blog/ev-battery-charging-best-practices

Applications in EVs

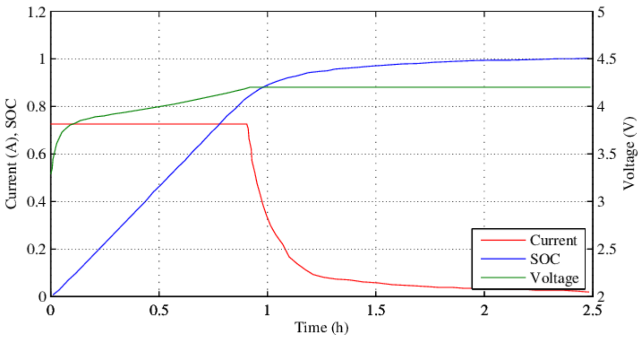
Battery Diagnostics
Analyze the batteries' impedance to assess health and detect issues.

REF: https://ennovi.com/technical-literature/understanding-the-ev-battery-issues-regarding-resale-recycling-and-reuse/

SoH Estimation
Evaluate the batteries' internal resistance and capacity over time.

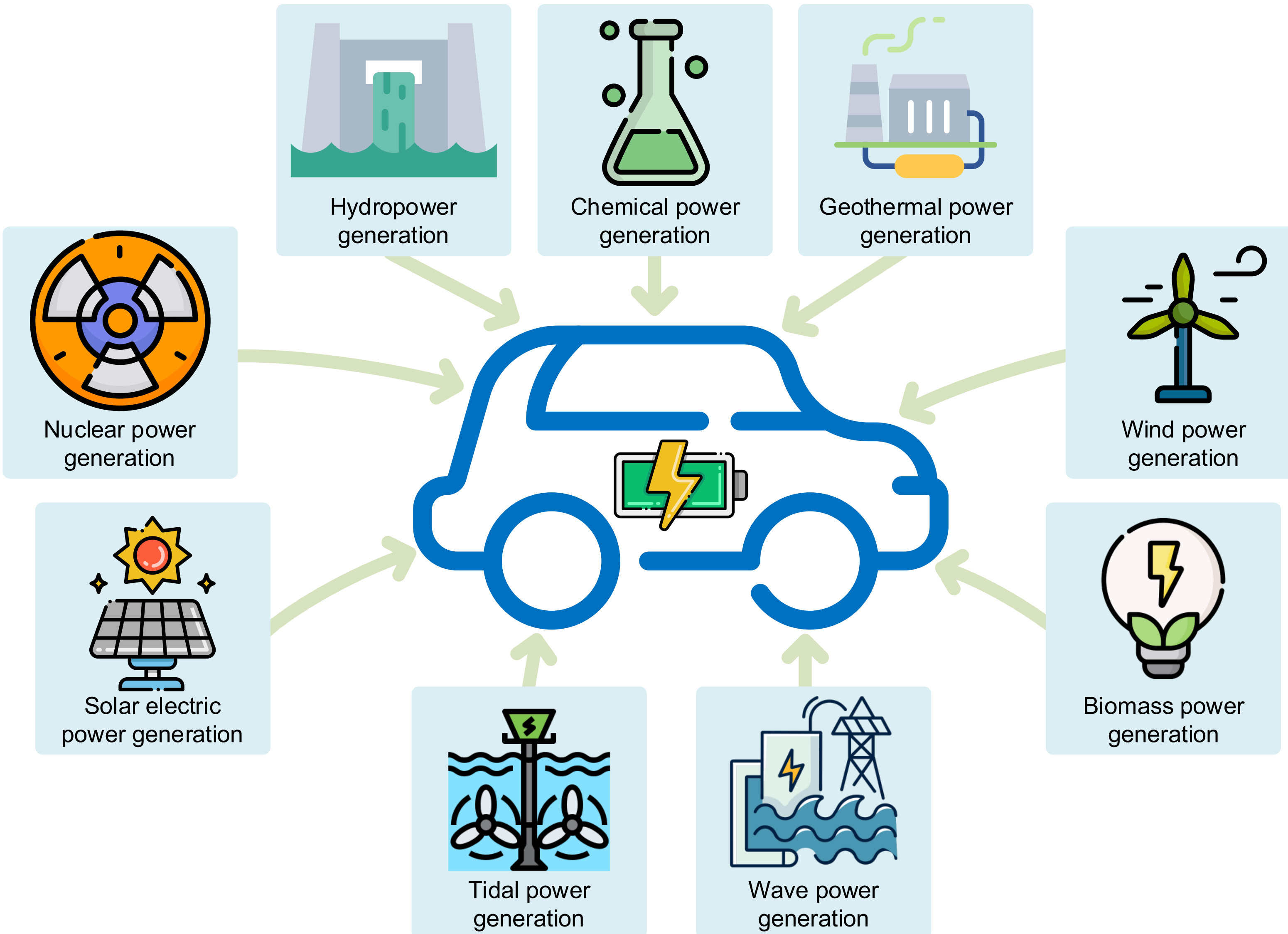
REF: https://www.dekra.com/en/battery-test-for-electric-cars/

Optimization of Charging Strategies
Provide data on battery impedance, helping to determine the best charging strategy.



REF: A. Sassone, D. Shin, A. Bocca, A. Macii, E. Macii, and M. Poncino, "Modeling of the charging behavior of li-ion batteries based on manufacturer's data," *Proceedings of the 24th Edition of the Great Lakes Symposium on VLSI*, Houston, USA, May 2014.

New Energy for Vehicles



Images from Flaticon.com

New Energy for Vehicles

- ***Solar power:*** Solar power, also known as solar electricity, is the conversion of energy from sunlight into electricity, either directly using photovoltaics (PV) or indirectly using concentrated solar power.
- ***Hydropower:*** Hydropower, also known as water power, is the use of falling or fast-running water to produce electricity or to power machines.
- ***Nuclear power:*** Nuclear power is the use of nuclear reactions to produce electricity. Nuclear power can be obtained from nuclear fission, nuclear decay and nuclear fusion reactions.
- ***Tidal power:*** Tidal power or tidal energy is harnessed by converting energy from tides into useful forms of power, mainly electricity using various methods.
- ***Wave power:*** Wave power is the capture of energy of wind waves to do useful work – for example, electricity generation, water desalination, or pumping water. A machine that exploits wave power is a wave energy converter (WEC) or generator.
- ***Biomass power:*** Types of biomass commonly used for bioenergy include wood, food crops such as corn, energy crops and waste from forests, yards, or farms
- ……..

Summary and Review

- **Electric Energy Storage and New Energy Sources for Electric Vehicles**
  - **Energy Sources for Electric Vehicles (Lecturer: Dr. Lucian Wei LIU)**
    - Classification of Electric Vehicle Energy Sources
    - Batteries
    - Supercapacitors
    - Ultrahigh-Speed Flywheels
    - Fuel Cells
    - Hybridisation of Energy Sources
    - Case Study
  - **Battery Management System (Lecturer: Dr. Jinpeng TIAN)**
    - Lithium-Ion Batteries and Battery Management Systems
    - Battery Models
    - Battery State of Charge
    - Battery State of Health
    - Battery Impedance and Electrochemical Impedance Spectroscopy
    - New Energy for Vehicles (Summary and Revision)