METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Emine Bostancı

Office: C-107

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Overview - components in passenger cars

Overview - power conversion devices

Energy storage

- Electrochemical batteries
    - Li-ion battery systems (extra slides)
- Supercapacitor
- Flywheel
- Hydrogen – production, storage and safety
- Hybridization of energy storage

Overview - Components in Passenger Cars

Drivetrain Components:

Energy storage

- Physical (container: tank)
- Mechanical
- Chemical
- Electrical

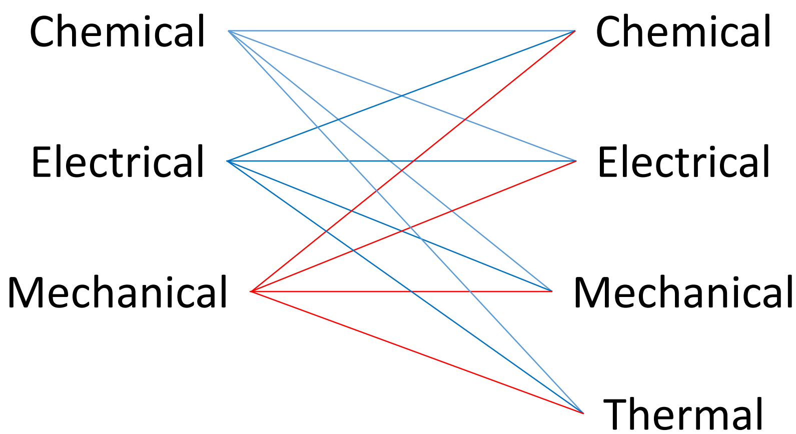
Power conversion

- Chemical to chemical
- Chemical to mechanical
- Chemical to electrical
- Mechanical to chemical
- Mechanical to mechanical
- Mechanical to electrical
- Electrical to chemical
- Electrical to electrical
- Electrical to mechanical

Intermediate and byproducts:
Thermal power
Electromagnetic power

Accessories

Overview - Power Conversion Devices



Driver

Electric generator

Fuel cell

Internal combustion engine

Transmission (gear box)

Inverter

Electrolyzer

Rectifier

Wheels

Hydro motors

Differential

Electric motor

Solar Photovoltaics

Converter

Hydrogen reformers

Supercapacitor

Piezoelectric

Power unit of battery

Power unit of flywheel

Overview - Power Conversion Devices

Chemical to chemical ➔ Hydrogen reformers

Chemical to mechanical ➔ Internal combustion engine, driver

Chemical to electrical ➔ Fuel cell, power unit of battery, driver

Mechanical to chemical ➔ ??

Mechanical to mechanical ➔ Gear box, differential, wheels, shaft

Mechanical to electrical ➔ Electric generator

Electrical to chemical ➔ Electrolyzer

Electrical to electrical ➔Inverter, converter, rectifier

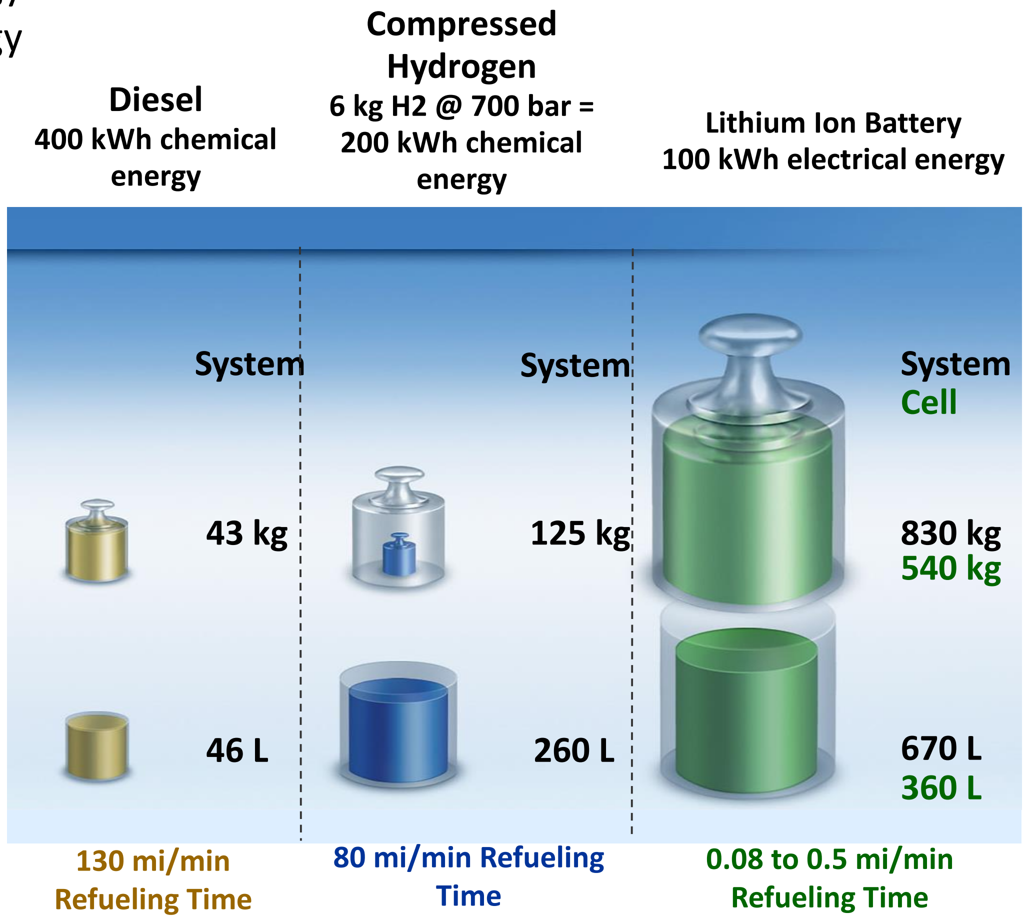
Electrical to mechanical ➔ Electric motor

Energy Storage

"Energy storages" are defined as the devices that store energy, deliver energy outside (discharge), and/or accept energy from outside (charge).

- Fuel tank
- Electrochemical battery
- Supercapacitor
- Li-capacitor
- Flywheel
- Hydrogen storage

Energy source/storage	Nominal Energy Density (Wh/kg)
Gasoline	12,300
Natural gas	9,350
Methanol	6,200
Hydrogen	28,000
Coal (bituminous)	8,200
Lead-acid battery	35
Sodium-sulfur battery	150-300
Flywheel (steel)	12-30

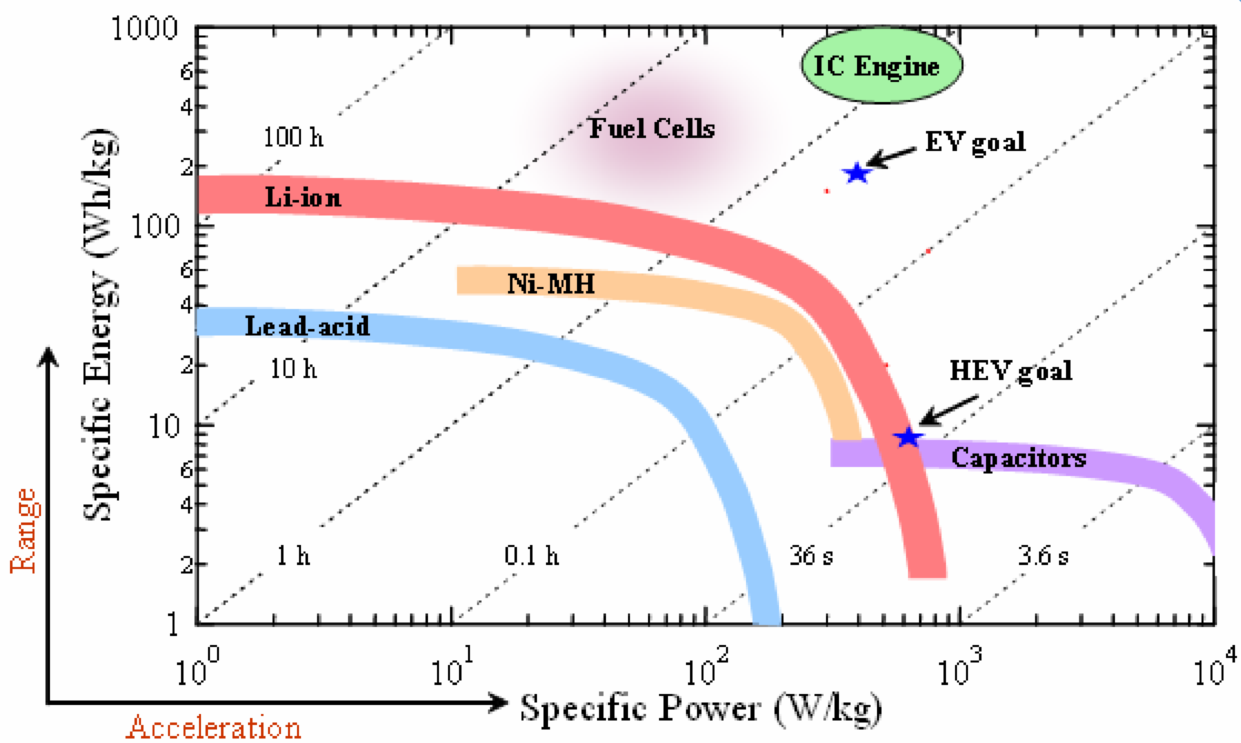


History of Electrochemical Batteries

Year	Inventor	Activity
1600	William Gilbert (UK)	Establishment of electrochemistry study
1745	Ewald Georg von Kleist (NL)	Invention of Leyden jar. Stores static electricity
1791	Luigi Galvani (Italy)	Discovery of "animal electricity"
1800	Alessandro Volta (Italy)	Invention of the voltaic cell (zinc, copper disks)
1802	William Cruickshank (UK)	First electric battery capable of mass production
1820	André-Marie Ampère (France)	Electricity through magnetism
1833	Michael Faraday (UK)	Announcement of Faraday's law
1836	John F. Daniell (UK)	Invention of the Daniell cell
1839	William Robert Grove (UK)	Invention of the fuel cell (H_2/O_2)
1859	**Gaston Planté (France)**	**Invention of the lead acid battery**
1868	Georges Leclanché (France)	Invention of the Leclanché cell (carbon-zinc)
1899	Waldemar Jungner (Sweden)	Invention of the nickel-cadmium battery
1901	Thomas A. Edison (USA)	Invention of the nickel-iron battery
1932	Schlecht & Ackermann (Germany)	Invention of the sintered pole plate
1947	Georg Neumann (Germany)	Successfully sealing the nickel-cadmium battery
1949	Lewis Urry, Eveready Battery	Invention of the alkaline-manganese battery
1970's	Group effort	Development of valve-regulated lead acid battery
1990	**Group effort**	**Commercialization of nickel-metal-hydride batt.**
1991	**Sony (Japan)**	**Commercialization of lithium-ion battery**
1994	Bellcore (USA)	Commercialization of lithium-ion polymer
1995	Group effort	Introduction of pouch cell using Li-polymer
1995	Duracell and Intel	Proposal of industry standard for SMBus
1996	Moli Energy (Canada)	Introduction of Li-ion with manganese cathode
1996	University of Texas (USA)	Identification of Li-phosphate ($LiFePO_4$)
2002	University of Montreal, Quebec Hydro, MIT, others	Improvement of Li-phosphate, nanotechnology, commercialization
2002	Group effort	Various patents filed on nanomaterials for batteries

Energy Storage – Electrochemical Batteries

Batteries are electrochemical devices (storage and conversion) that convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging.



Srinivasan, Venkat and Newman, John. Design and Optimization of a Natural Graphite/Iron Phosphate Lithium-Ion Cell. Journal of the Electrochemical Society 151, No 10(2004). Pp A1530-A1538.

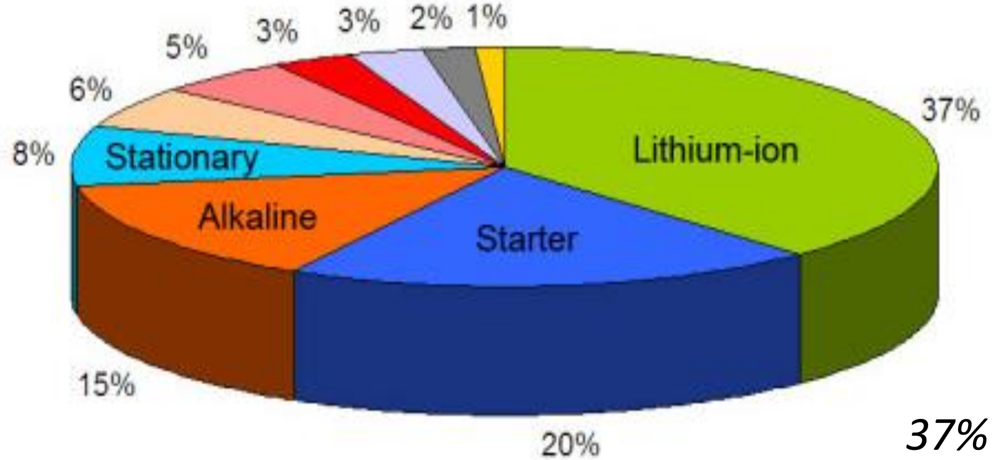
Primary (Single use)

- Alkaline

Secondary (Rechargeable)

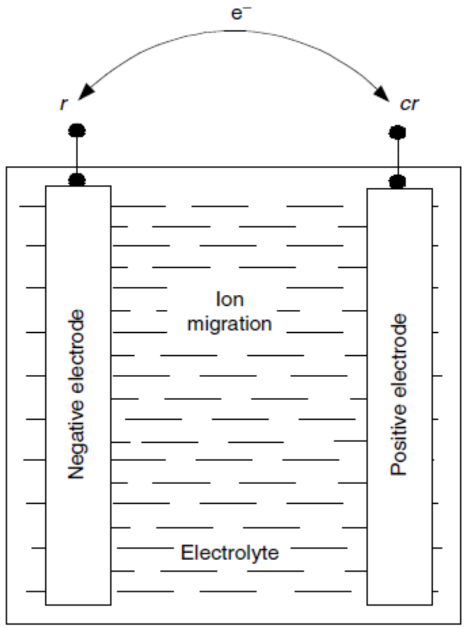
- Lead-acid
- Ni-Cd
- Ni-MH
- Li-ion
- Zinc-Air

Revenue Contributions by Different Battery Chemistries



37% Lithium-ion
20% Lead acid, starter battery
15% Alkaline, primary
8% Lead acid, stationary
6% Zinc-carbon, primary
5% Lead acid, deep-cycle
3% Nickel-metal-hydride
3% Lithium, primary
2% Nickel-cadmium
1% Other

Energy Storage – Electrochemical Batteries



Capacity of a battery: Battery with coulometric capacity (in Ah), which is defined as the number of Ah gained when discharging the battery from a fully charged state until its cut-off voltage.
e.g.: 100 Ah C5 means 20 A discharge for 5 hours

SoC: State-of-charge is defined as the ratio of the remaining capacity to the fully charged capacity, a fully charged battery has an SOC of 100% and a fully discharged battery has 0%.

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

Specific energy: Energy capacity per unit battery weight in Wh/kg (J)

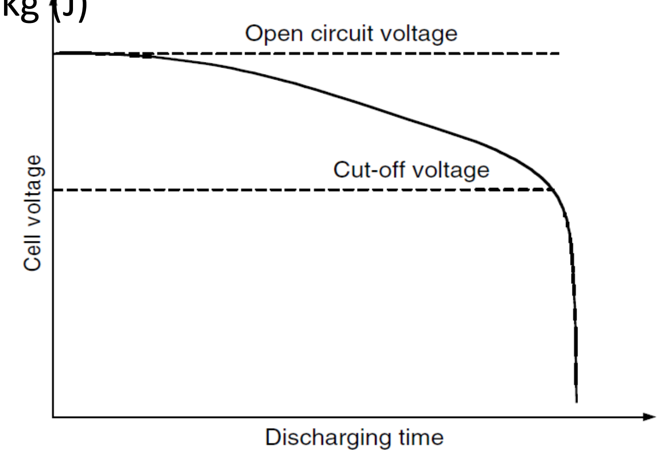
Specific power: Maximum power of per unit battery weight that the battery can produce in a short period

Efficiency: Charging and discharging efficiencies

$$\eta_{discharging} = \frac{V}{V_0} \qquad \eta_{charging} = \frac{V_0}{V}$$

Open circuit voltage

Terminal voltage



Naming Conventions

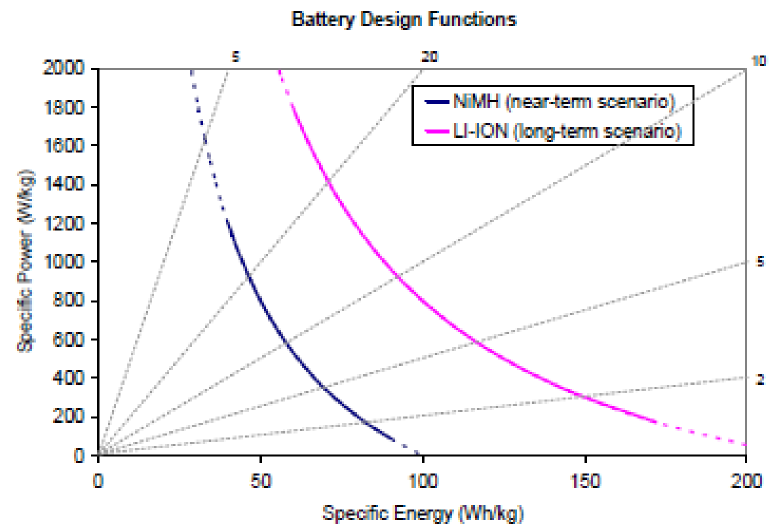
- **Cell**: The most basic element of a battery
- **Block**: Certain number of cells wired in parallel
- **Battery**: Certain number of cells/blocks wired in series
- **Pack or Battery Pack**: Batteries arranged in series and/or parallel configuration
- **Resistance**: When cell manufacturers list resistance in their specs, they refer to AC impedance. However we will be interested in DC series resistance, which actually distributed through the cells.

Energy Storage – Battery Technologies

Status of Battery Systems for Automotive Applications

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 h)	Cost (US$/kWh)
Acidic aqueous solution						
Lead/acid	35–50	150–400	>80	500–1000	0.6	120–150
Alkaline aqueous solution						
Nickel/cadmium	50–60	80–150	75	800	1	250–350
Nickel/iron	50–60	80–150	75	1500–2000	3	200–400
Nickel/zinc	55–75	170–260	65	300	1.6	100–300
Nickel/metal hydride	70–95	200–300	70	750–1200+	6	200–350
Aluminum/air	200–300	160	<50	?	?	?
Iron/air	80–120	90	60	500+	?	50
Zinc/air	100–220	30–80	60	600+	?	90–120
Flow						
Zinc/bromine	70–85	90–110	65–70	500–2000	?	200–250
Vanadium redox	20–30	110	75–85	—	—	400–450
Molten salt						
Sodium/sulfur	150–240	230	80	800+	0[a]	250–450
Sodium/nickel chloride	90–120	130–160	80	1200+	0[a]	230–345
Lithium/iron sulfide (FeS)	100–130	150–250	80	1000+	?	110
Organic/lithium						
Lithium-ion	80–130	200–300	>95	1000+	0.7	200

Values from 2000



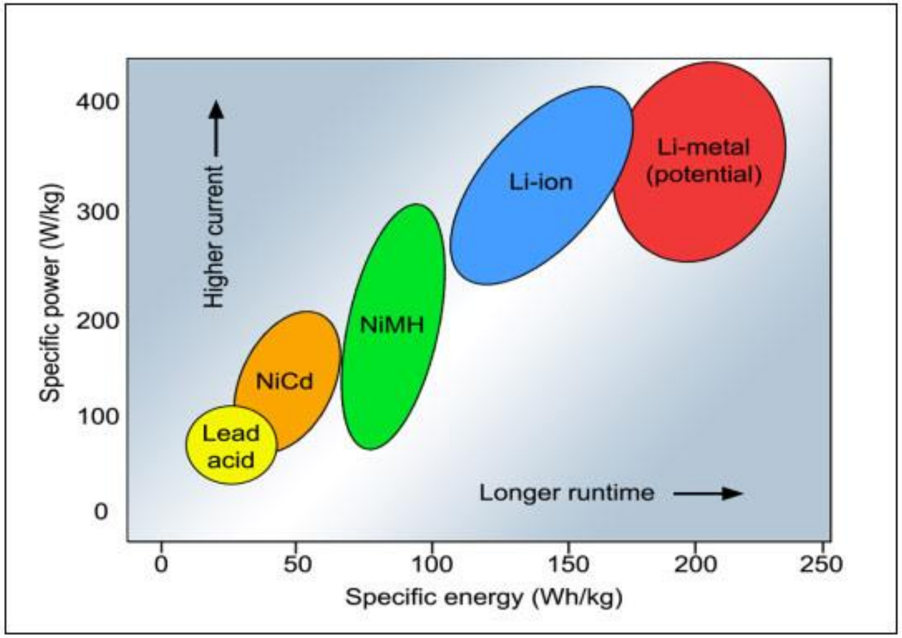
GM EM1
1996 :1,400 kg with Lead-acid batt.
1999: 1,319 kg with NiMH batteries

Toyota Prius
1997: NiMH Batteries

Tesla Model S, Nissan Leaf, Toyota Prius Plug-in, BMW i3:
Present: Li-ion

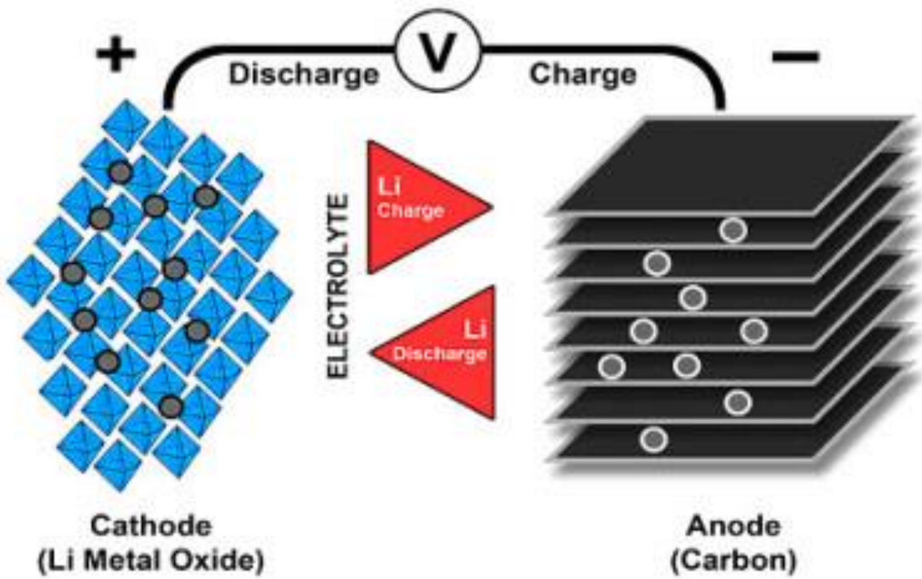
Li-ion Batteries

- Rechargable (secondary) cells
- Highest Energy Density
- Highest Power Density
- Small in size and light in weight
- Fast charge capability
- Long cycle life
- Minimum leakage current



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

Li-ion Batteries



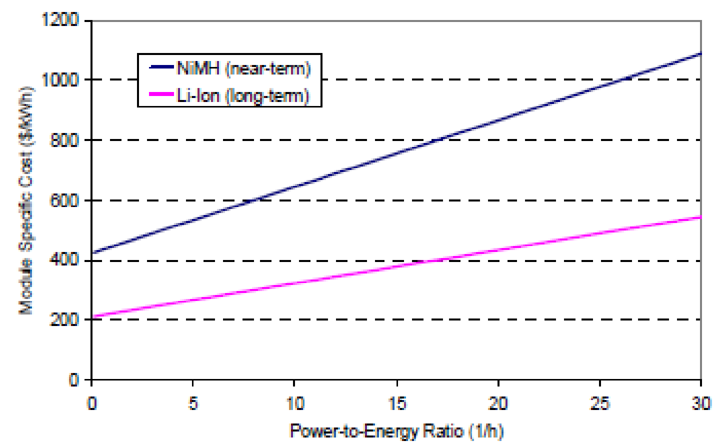
Advantages:

- High energy density
- High efficiency
- Low self discharge

Disadvantages:

- Dangerous since lithium react with water
- Overcharge protection is required
- High cost
- Electrodes expand and contract during charge and discharge, that effects state of health

When the cell charges and discharges, ions shuttle between cathode (positive electrode) and anode (negative electrode). On discharge, the anode undergoes oxidation, or loss of electrons, and the cathode sees a reduction, or a gain of electrons. Charge reverses the movement.



http://batteryuniversity.com/learn/article/understanding_lithium_ion
https://en.wikipedia.org/wiki/Lithium-ion_battery

http://www.nrel.gov/docs/fy07osti/40485.pdf

Li-ion Battery System

Please go to Li-ion Battery System slides!

Supercapacitor

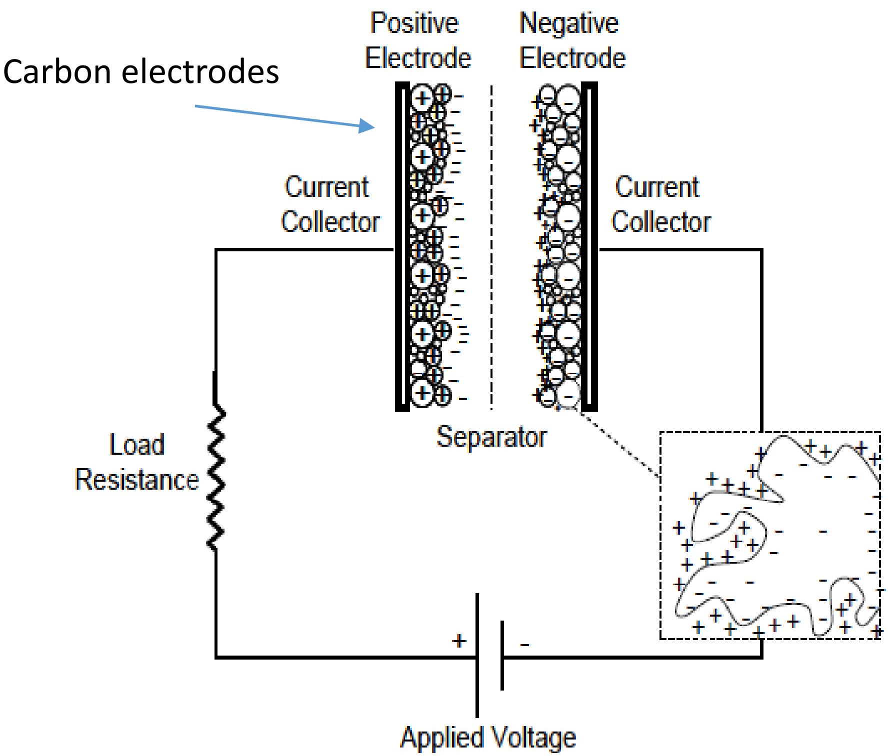
Supercapacitors are governed by the same basic principles as conventional capacitors, but electrodes with much higher surface areas and much thinner dielectrics.

$$C = \frac{Q}{V} = \varepsilon \frac{\mathrm{A}}{\mathrm{d}} \qquad E_C = \frac{1}{2}\mathrm{C}V^2$$

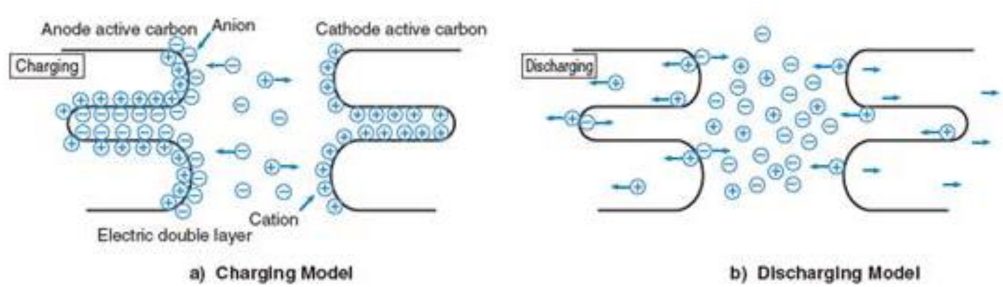
Electron charge transfer between electrode and electrolyte

The supercapacitors have much higher specific power, but much lower specific energy compared to the chemical batteries.

Its specific energy is in the range of a few watt-hours per kilogram, and its specific power can reach up to 3 kW/kg, much higher than any type of battery.



https://www.mitre.org/sites/default/files/pdf/06_0667.pdf



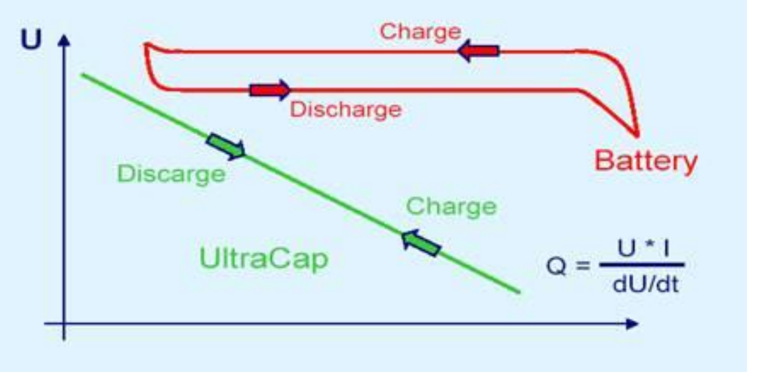
https://www.tecategroup.com/ultracapacitors-supercapacitors/ultracapacitor-FAQ.php

Supercapacitor

<u>Advantages:</u>

- High energy storage as result of using a porous activated carbon electrode to achieve a high surface area.
- Low Equivalent Series Resistance (R_s) compared to batteries, hence providing high power density capability.
- Low Temperature performance capable of delivering energy down to -40°C with minimal effect on efficiency.
- Fast charge/discharge, charging and discharging through the absorption and release of ions and coupled with its low R_s, high current charging and discharging is achievable without any damage to the parts.

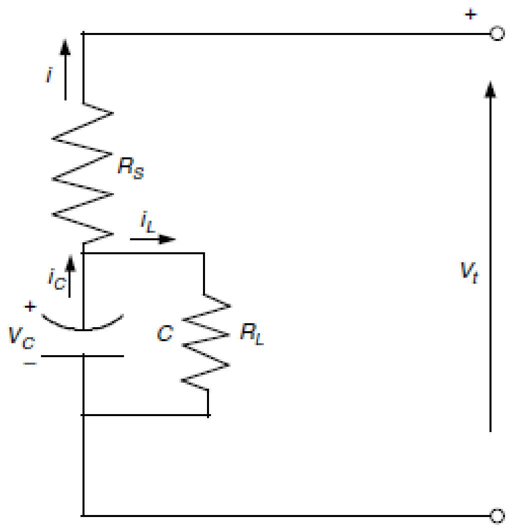
Available Performance	Lead Acid Battery	Ultracapacitor	Conventional Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	< 0.1
Cycle Life	1,000	>500,000	>500,000
Specific Power (W/kg)	<1000	<10,000	<100,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95
Operating Temperature	-20 to 100 C	-40 to 65 C	-20 to 65 C



Supercapacitor

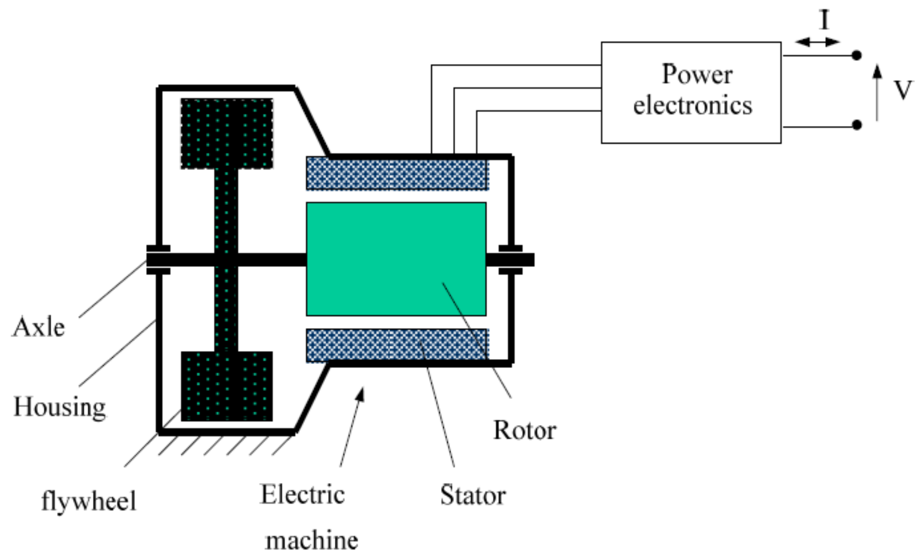
<u>Disadvantages:</u>

- Low per cell voltage, a typical voltage of 2.7 V, so that the cells have to be connected in series.
- Cannot be used in AC and high frequency circuits due to their time constant are not suitable for use in AC or high frequency circuits.



Flywheel as Energy Storage

- All ICE vehicles use flywheels to deliver smooth power from power pulses of the engine
- Electromechanical energy storage device
- Stores kinetic energy in a rapidly spinning wheel-like rotor or disk
- Has potential to store energies comparable to batteries
- Modern flywheels use high-strength composite rotor that rotates in vacuum (to reduce aerodynamic and friction losses)



- Magnetic bearings to reduce bearing losses
- A motor/generator connected to rotor shaft spins the rotor up to speed for charging and to convert kinetic energy to electrical energy during discharging

<u>Drawbacks</u>

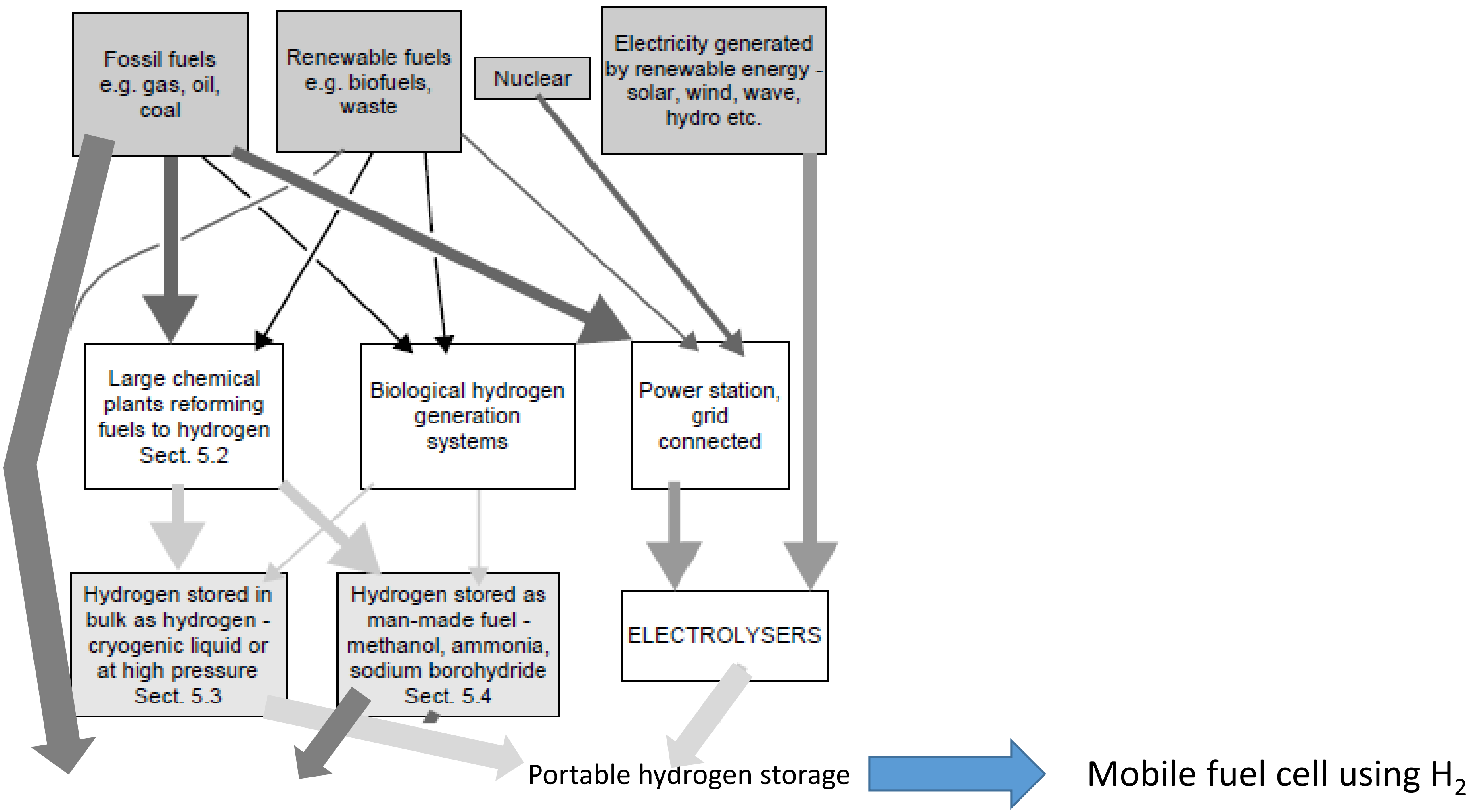
- Very complex, heavy and large for personal vehicles
- Gyroscopic forces reduce the maneuverability of the vehicle
- There are safety concerns incase of a mechanical failure

Rotational speed, rad/sed

$$E = \frac{1}{2} J \omega^2$$

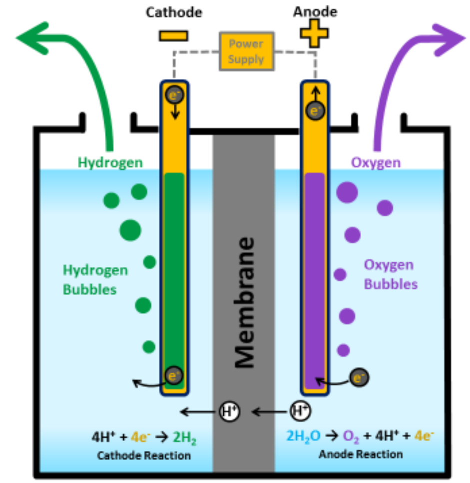
Moment of inertia, kgm^2/s

Hydrogen Production



Hydrogen Production

Electrolysis of water
Applied voltage: -1.9 V
Therotical output voltage = 1.23



Electrolysis: uses a DC current for separation of elements.

$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$

Plasma reforming

<u>Hydrogen is mostly produced from hydrocarbon fuels through reforming</u>

Steam reforming: Steam reforming is a chemical process in which hydrogen is produced through the chemical reaction between hydrocarbon fuels and water steam at high temperature, 250°C.

Methane

$$\begin{array}{lccccccccc} & CH_4 & + & 2H_2O & + & 258\text{ kJ/mol } CH_4 & \rightarrow & 4H_2 & + & CO_2 \\ \Delta H^\circ & -79.4 & & 2\times(-286.2) & & & & 0 & & -393.8 \end{array}$$

Methanol

$$\begin{array}{lccccccccc} & CH_3OH & + & H_2O & + & 131\text{ kJ/mol } CH_3OH & \rightarrow & 3H_2 & + & CO_2 \\ \Delta H^\circ & -238.7 & & -286.2 & & & & 0 & & -393.8 \end{array}$$

Gasoline

$$\begin{array}{lccccccccc} & C_8H_{18} & + & 16H_2O & + & 1652.9\text{ kJ/mol } C_8H_{18} & \rightarrow & 25H_2 & + & 8CO_2 \\ \Delta H^\circ & -224.1 & & 16\times(-286.2) & & & & & & 8\times(-393.8) \end{array}$$

Steam

Carbon capturing is applied.

POX reforming: Fuel is combined with oxygen, 800°C- 1000°C

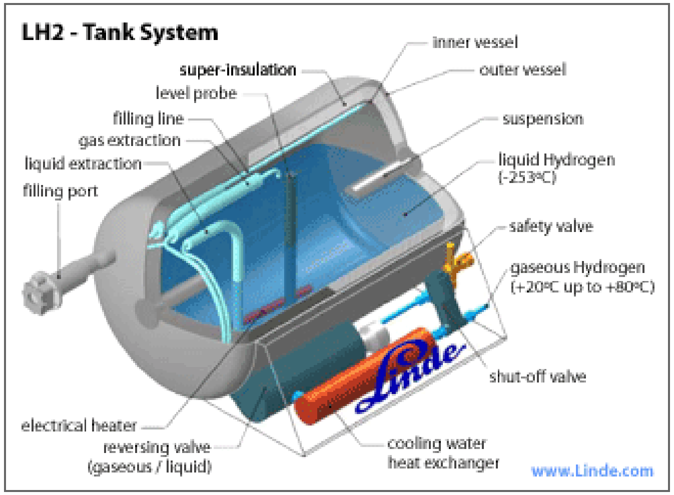
$$\boxed{\begin{array}{l} CH_4 + \tfrac{1}{2}O_2 \longrightarrow CO + 2H_2 \\ C_8H_{18} + 4O_2 \longrightarrow 8CO + 9H_2 \end{array}}$$

Autothermal reforming: Fuel is both combined with oxygen and water steam

[Turning Organic Waste into Hydrogen]

On-Board Hydrogen Storage

Compressed hydrogen: Pure hydrogen can be stored on-board of the vehicle under pressure in a tank. The simplest method.



Liquid hydrogen: Liquefy the gas at cryogenic temperatures (259.2°C). The stored hydrogen is commonly referred to as "LH2". LH2 storage is affected by the same density problems that affect compressed hydrogen. Indeed, the density of liquid hydrogen is very low and 1 l of liquid hydrogen only weighs 71g.

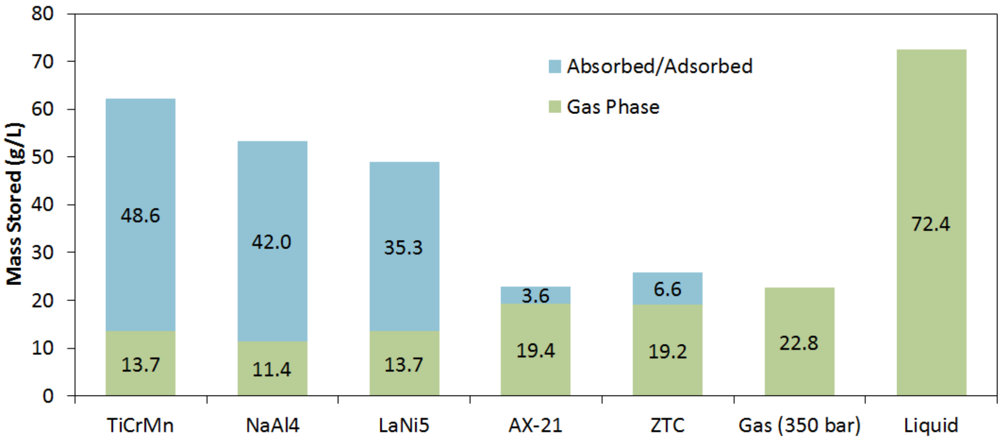
Drawbacks:

- Low temperature as 259.2°C
- Heavily insulated tank to minimize the heat transfer from the ambient air to the cryogenic liquid

Metal hydrides: Some metals combine with hydrogen to form stable compounds that can later be decomposed under particular pressure and temperature conditions. These metals may be iron, titanium, manganese, nickel, lithium, and some alloys of these metals.

$$\text{Heat} + M + H_2 \longleftrightarrow MH_2$$

Metal: Fe, Ti, Mn, Ni



On-Board Hydrogen Storage - Safety

- Hydrogen is a unique gaseous element, possessing the lowest molecular weight of any gas.
- Highest thermal conductivity, velocity of sound, mean molecular velocity, and the lowest viscosity and density of all gases
- High leak rate through small orifices faster than all other gases, 2.8 times faster than methane and 3.3 times faster than air
- Highly volatile and flammable gas, and in certain circumstances hydrogen and air mixtures can detonate (no ignition required)

	Hydrogen	Methane	Propane
Density, kg.m^{-3} at NTP	0.084	0.65	2.01
Ignition limits in air, volume % at NTP	4.0 to 77	4.4 to 16.5	1.7 to 10.9
Ignition temperature, $^{\circ}$C	560	540	487
Min. ignition energy in air, MJ	0.02	0.3	0.26
Max. combustion rate in air, ms^{-1}	3.46	0.43	0.47
Detonation limits in air, volume %	18 to 59	6.3 to 14	1.1 to 1.3
Stoichiometric ratio in air	29.5	9.5	4.0

On-Board Hydrogen Storage - Safety

Which explosion is more dangerous, fuel cell vehicle or gasoline vehicle?

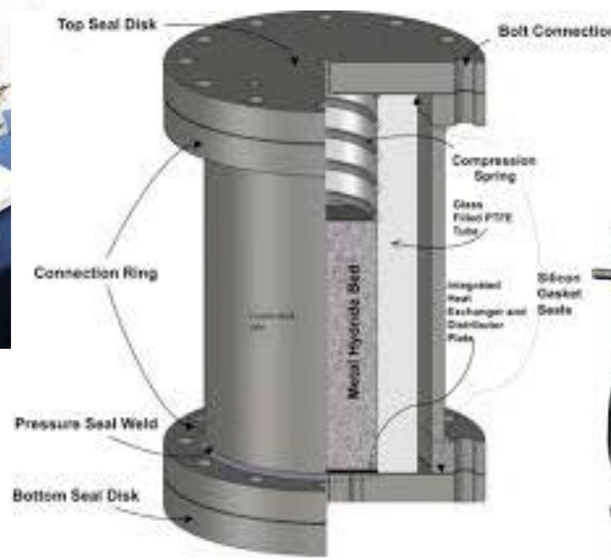
On-Board Hydrogen Storage Comparison

	Compressed hydrogen @200 bar	Compressed hydrogen @300 bar
Mass of empty cylinder	3.0 kg	100 kg
Mass of hydrogen stored	0.036 kg	3.1 kg
Storage efficiency (% mass H_2)	1.2%	3.1%
Specific energy	0.47 $kWh.kg^{-1}$	1.2 $kWh.kg^{-1}$
Volume of tank (approx.)	2.2 l (0.0022 m^3)	220 l (0.22 m^3)
Mass of H_2 per litre	0.016 $kg.L^{-1}$	0.014 $kg.L^{-1}$

	Liquid hydrogen	Metal hydrides
Mass of empty cylinder	51.5 kg	0.26 kg
Mass of hydrogen stored	8.5 kg	0.0017 kg
Storage efficiency (% mass H_2)	14.2%	0.65%
Specific energy	5.57 $kWh.kg^{-1}$	0.26 $kWh.kg^{-1}$
Volume of tank (approx.)	0.2 m^3	0.06 l
Mass of H_2 per litre	0.0425 $kg.L^{-1}$	0.028 $kg.L^{-1}$

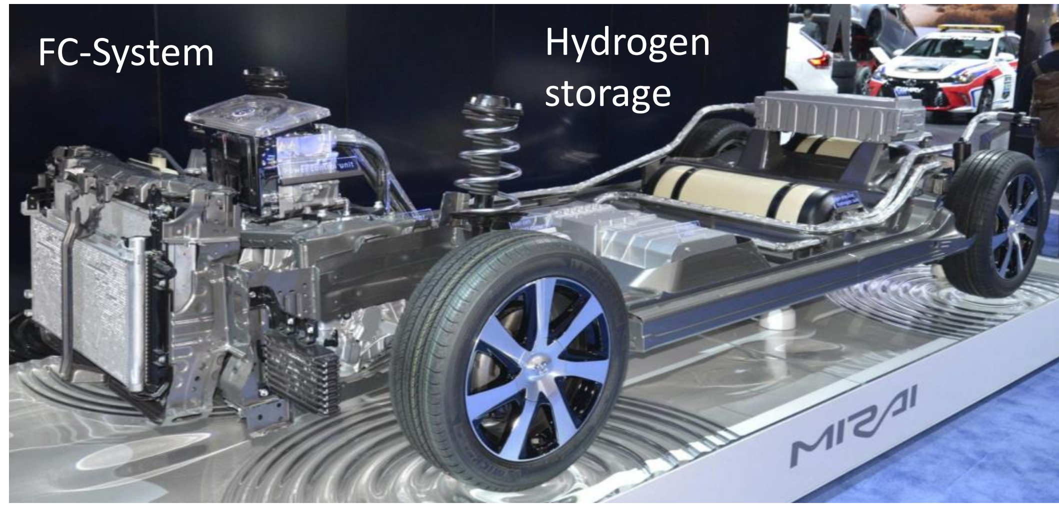
On-Board Hydrogen Storage Comparison

Method	Gravimetric storage efficiency, % mass hydrogen	Volumetric mass (in kg) of hydrogen per litre
Pressurised gas	0.7–3.0	0.015
Reversible metal hydride	0.65	0.028
Cryogenic liquid	14.2	0.040

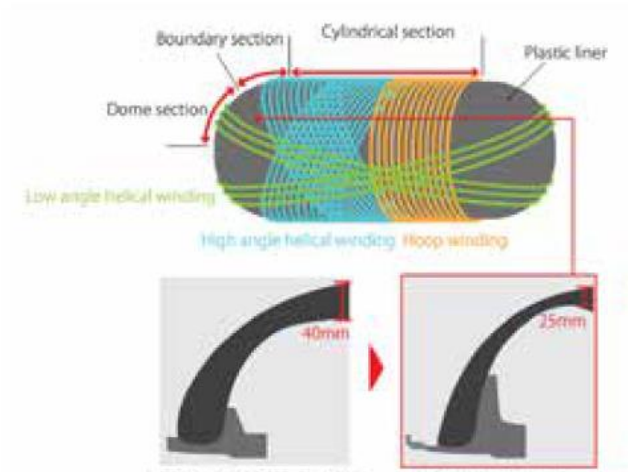


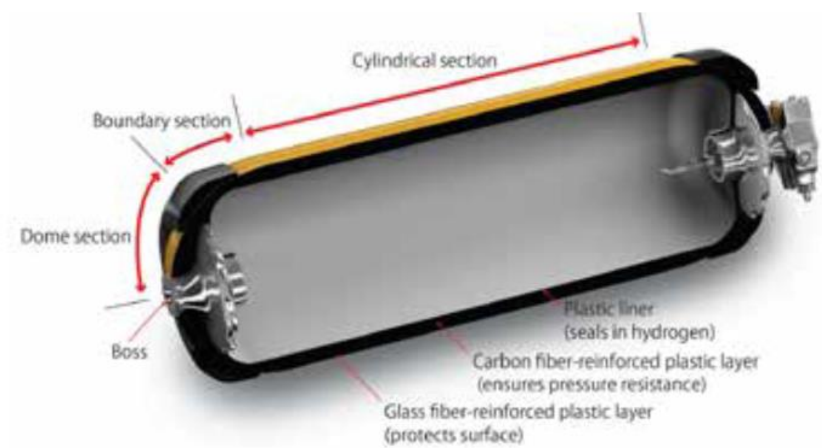
On-Board Hydrogen Storage - Compressed hydrogen

- Carbon fiber enforced plastic
- 700 bar or 350 bar pressure
- 130 kg tank for 6 kg H_2



Structure of Toyota Mirai

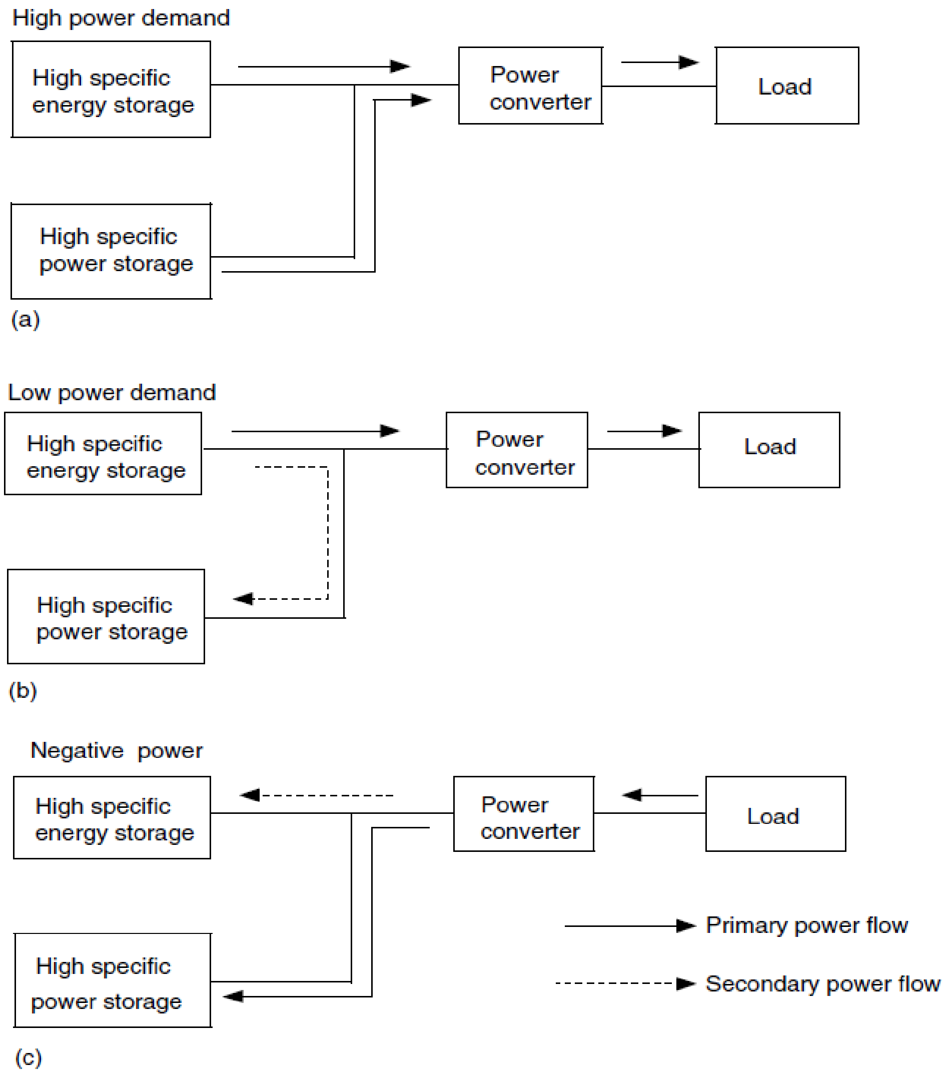




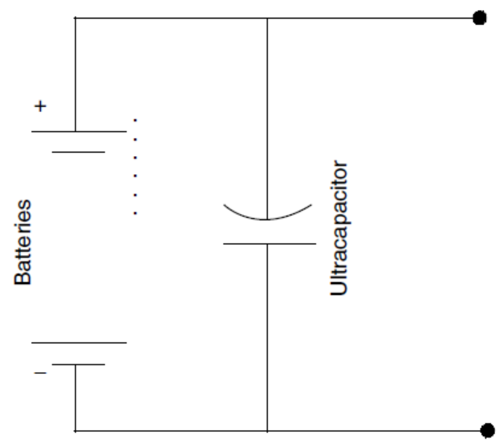
Hybridization of Energy Storage

- Use multiple sources of storage
- <u>Combination of:</u>
  - ➢ High energy density
  - ➢ High power density for power demand and rapid charging capability
- <u>Examples:</u>
  - ➢ Gasoline and battery
  - ➢ Battery and supercapacitor in parallel
  - ➢ Fuel cell stack and battery in parallel

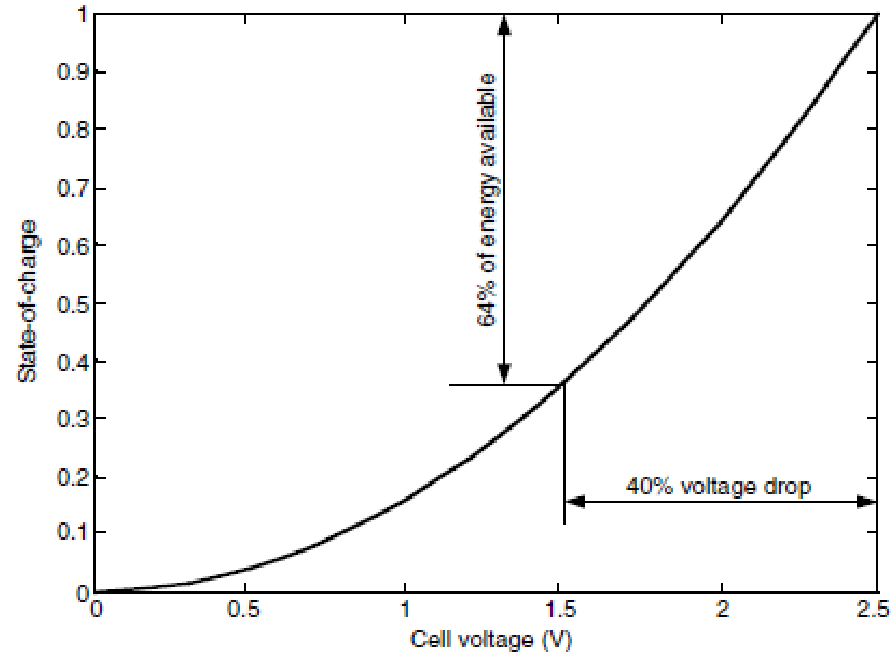
Hybridization of Energy Storage



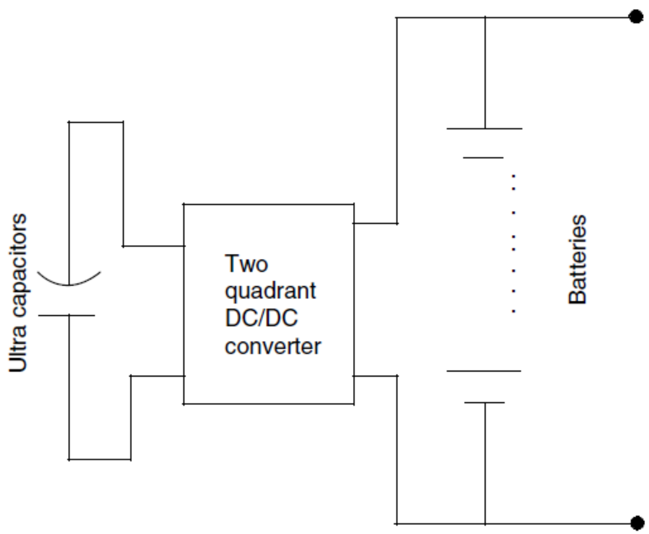
Hybridization of Energy Storage



- Simple but ΔV low: supercapacitor is not fully utilized

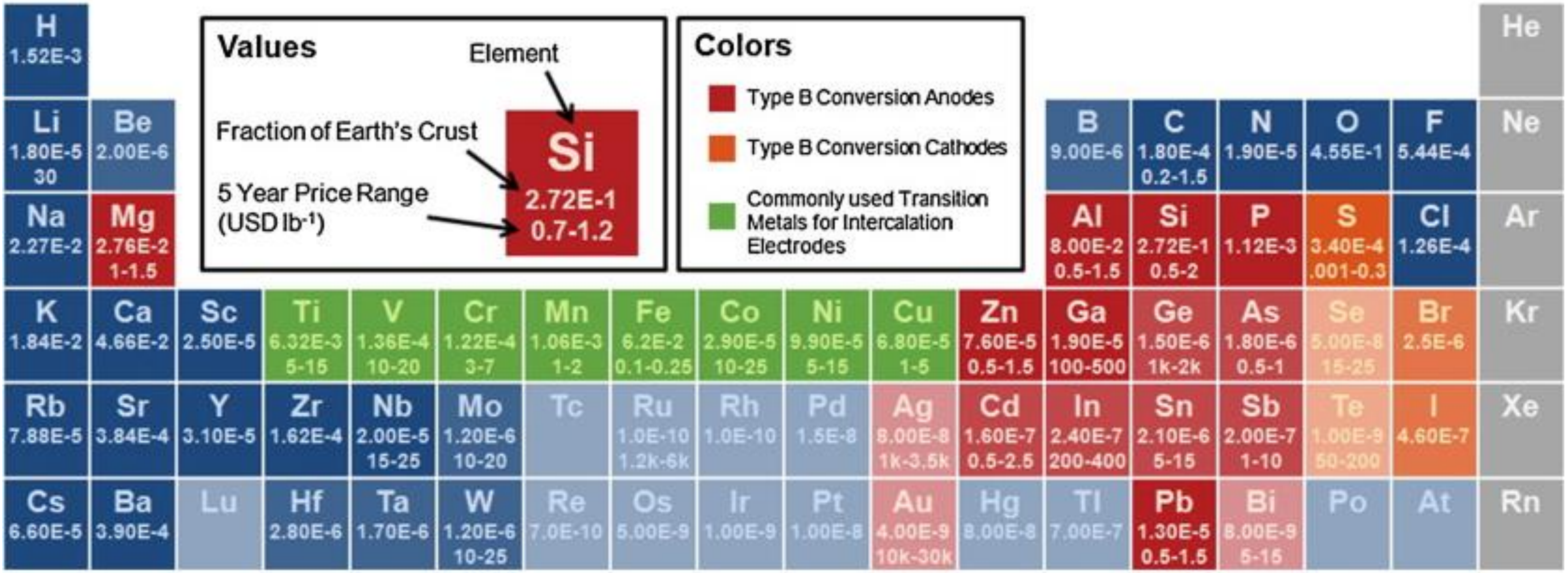


$$E_{utilized} = \frac{1}{2} C(V_1^2 - V_1^2)$$



- One additional power converter but ΔV high: Supercapacitor is fully utilized

Periodic Table



Videos

Advertisement of the week:

Buying a Volkswagen from an old lady...

Textbooks:

Ehsani, M. and Gao, Y. and Emadi, A., “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, 2nd Edition, CRC Press LLC, 2009.

Chau, K. T., “Electric Vehicle Machines and Drives: Design, Analysis and Application” Wiley-IEEE Press, August 2015.