1MG11: ENERGY AND POWER STORAGES

Pierre Duysinx

Research Center in Sustainable Automotive Technologies of University of Liege

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References

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Outline

- Introduction
- Energy sources characteristics
- Electrochemical batteries
- Ultra capacitors
- Flywheels
- Comparison

Characteristics of Energy Sources

Energy source characteristics

- Energy and coulometric capacity
- Cut-off voltage and usable capacity
- Discharging/charging current
- State-of-charge
- Energy density
- Power density
- Cycle life
- Energy efficiency and coulometric efficiency
- Cost

Energy and coulometric capacities

- Energy capacity EC [J] or [Wh]

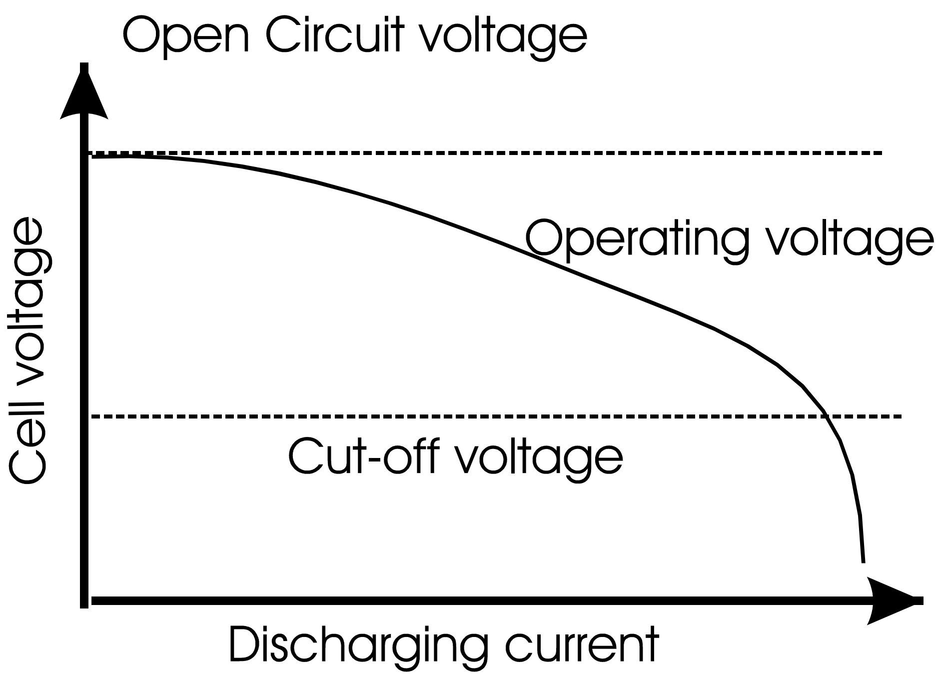
$$\mathrm{EC}(T) = \int_0^T v(\tau)\, i(\tau)\, d\tau$$

  - v(t) and i(t) instantaneous voltage and current
- Coulometric capacity [Ah]

$$\mathrm{CC}(T) = Q(T) = \int_0^T i(\tau)\, d\tau$$

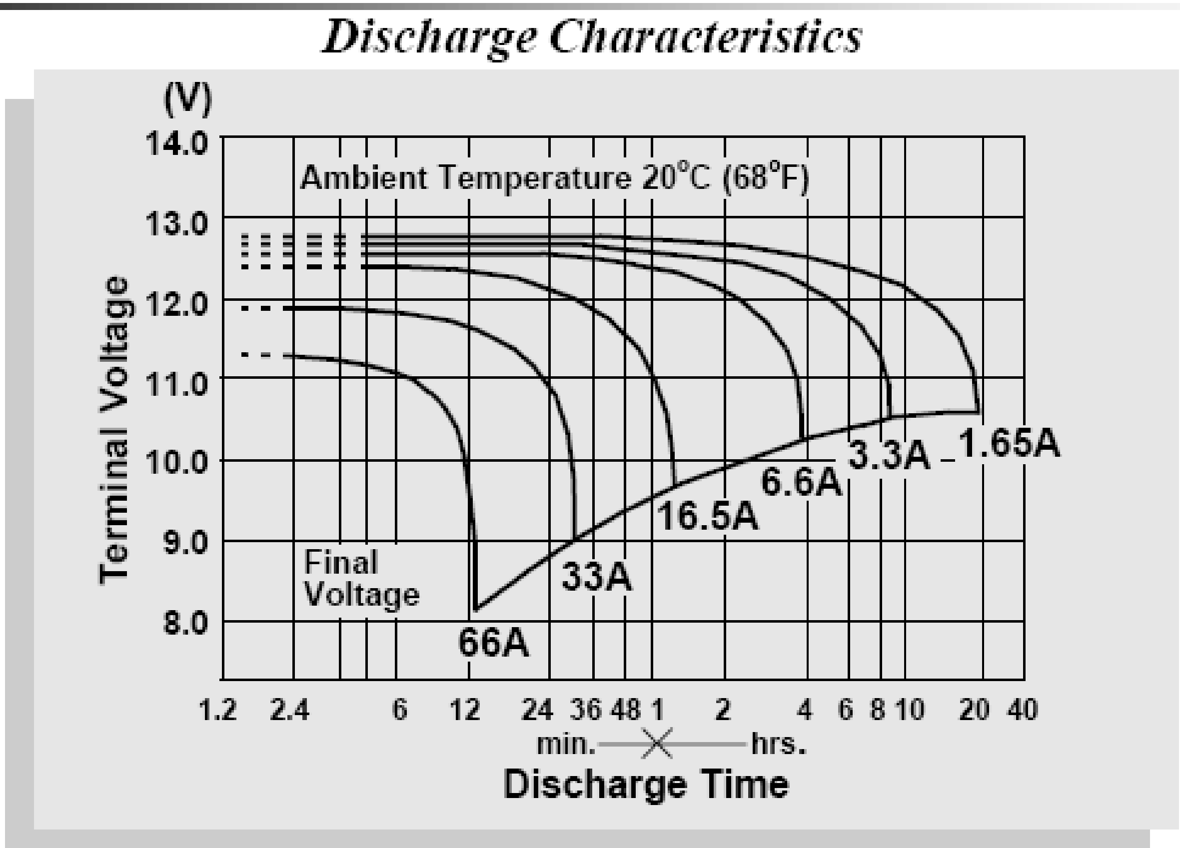
- Mission of EV energy sources: supply electrical energy for propulsion
- For EV, energy capacity is more important and useful than coulometric capacity
- However the coulometric capacity (or capacity) is widely employed to describe the capacity of batteries

Cut-off voltage and usable capacity



- Energy capacity does not represent well the energy content of electrochemical sources
- Batteries can not be discharged down to zero voltage unless being permanently damaged
- Cut-off voltage: knee of discharging curve at which the battery is considered as fully discharged, so called 100% depth of discharge (DoD)
- Usable energy capacity and usable coulometric capacity before cut-off

Cut-off voltage and usable capacity



Discharge curves for Powersonic VRLA batteries

Discharging/charging current

- The battery capacity is determined with constant current discharge-charge tests
  - In a typical constant current test, the battery is initially fully charged and the voltage equals the open-circuit voltage V_{0c}.
  - A constant discharge current is applied. After a certain time t_f, called the discharge time, the voltage drops below the cut-off voltage and the battery is empty.

- For batteries, energy capacity and coulometric capacity vary with
  - Their discharging current,
  - The operating temperature,
  - And the ageing.

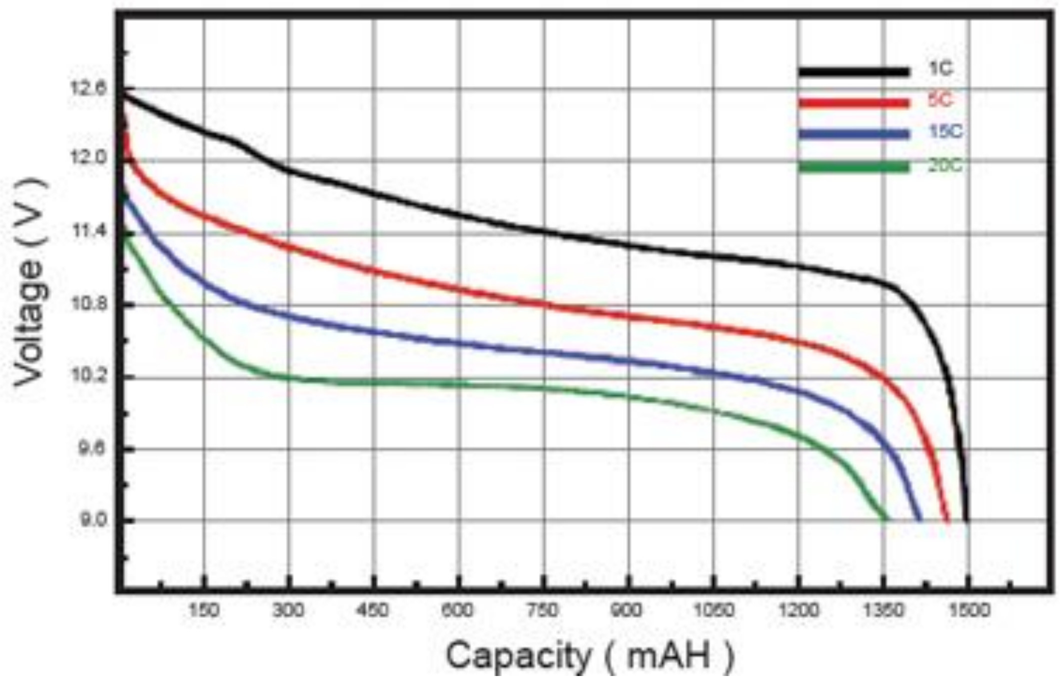
Discharging/charging current

Rate of Discharge :

Rate Discharge Characteristics

Charge:
1A.4.2V(CC-CV).
50mA cut-off. at23±2℃

Discharge:
at each rate.CC.
3.0V cut- off. at23±2℃



Discharge curves for LiPo Ultimate PX-01 batteries

Discharging/charging current

- The C-rate current is defined as the current I_0 that discharges the battery in one hour and which has the same value as the battery capacity Q_0=CC expressed in [Ah].

- Discharge currents are given using a unit-less value called C-rate

$$I = k\, C_n$$

- The C rate is often written as C/k where k is the number of hours needed to discharge the battery with a C-rated current,
  - c=1/k current is a current k times lower than the rated current I_0.
  - Example: C/5 rate for a 5 Ah battery means that kC_n = 1/5*5=1A

Discharging/charging current

- CC (and also the EC) decreases with the increasing C rate

- The discharge time is a function of the discharge current. The phenomenon is often described using the empirical Peukert equation :

$$t_f = \mathrm{K}\, I_2^{-n}$$

'n' is the Peukert exponent which varies between 1 and 1.5 (e.g. in VRLA n~1.35)

$$Q(I) = I^n\, t_f = I_2\, K\, I_2^{-n} = K\, I_2^{1-n}$$

Discharging/charging current

- Peukert equation also expresses the dependency of the battery capacity on the discharge current. If the capacity is Q_2^* for a current I_2^*, the capacity for a discharge current I_2 is

$$\frac{Q_0}{Q_0^*} = \left(\frac{I_2}{I_2^*}\right)^{1-n}$$

- Other more sophisticated models of current dependency can be found in literature:
  - Neural Network-based models
  - Modified Peukert equation for low currents (Kc a constant)

$$\frac{Q_0}{Q_0^*} = \frac{K_c}{1 + (K_c - 1)\left(\frac{I_2}{I_2^*}\right)^{1-n}}$$

State-of-charge

- The residual coulometric capacity is termed as the State-of-Charge (SOC)
- SOC defined as the percentage ratio of the residual coulometric capacity to the usable coulometric capacity

$$q(t) = \mathrm{SOC} = \frac{Q(t)}{Q_0(t)}$$

- SOC is affected by
  - discharging current,
  - operating temperature,
  - and ageing

State-of-charge and energy capacity

- Variation of the state of charge in a time interval dt with discharging current i is approximated using the discharge current by charge balance

$$\frac{d\,\mathrm{SOC}}{dt} = \frac{i}{Q_0(i,t)}$$

where Q(i) is the amp-hour capacity of the battery at current rate i

- Thus the state of charge SOC writes:

$$\mathrm{SOC} = \mathrm{SOC}_0 - \int_0^t \frac{i(t)}{Q_0(i,t)}\,dt$$

State-of-charge and energy capacity

- In case of charge, the state of charge must take into account the fact that a fraction of current I_2 is not transformed into charge due to irreversible & parasitic reactions.

- It is often modeled using the charging or coulometric efficiency

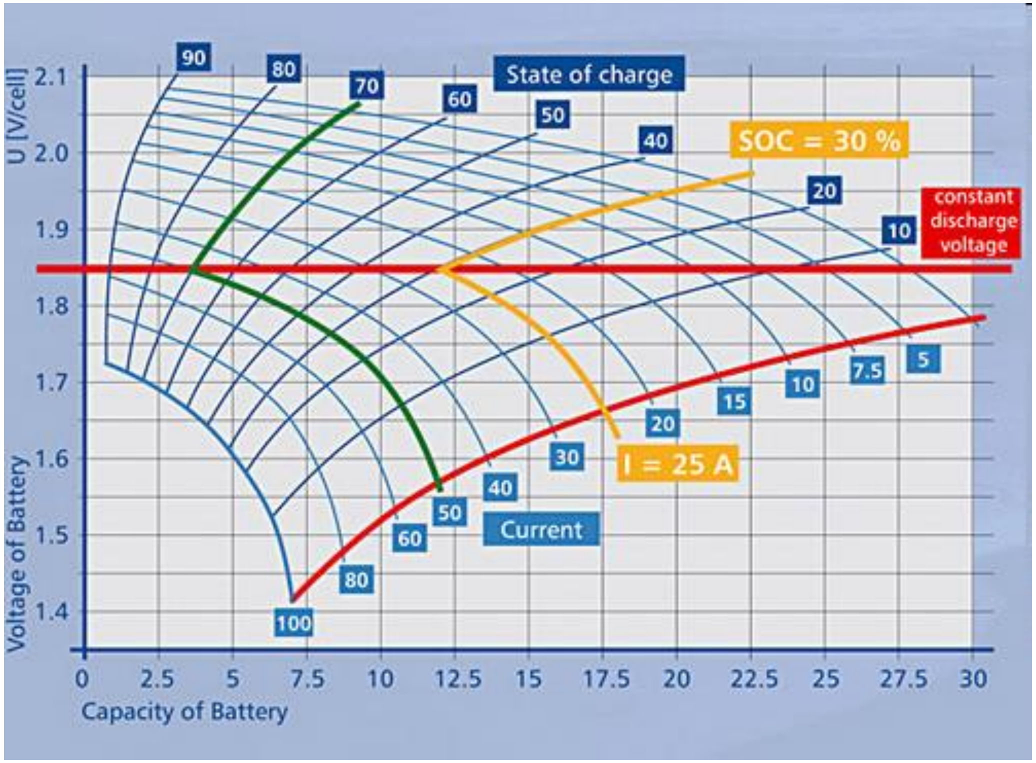
$$\dot{Q} = -\eta_c \, I_2(t)$$

- The coulometric counting method is simple but requires frequent recalibration points.

State-of-charge and energy capacity

- The energy capacity can also be related to the current

$$\mathrm{EC} = \int_0^t v(i, \mathrm{SOC})\, i(t)\, dt$$



Energy density

- Energy densities = usable energy density per unit mass or volume of energy storage
  - Gravimetric energy density or specific energy: [Wh/kg]
  - Volumetric energy density [Wh/l]

- Gravimetric energy density
  - The more important because of weight penalty on consumption and driving range
  - Key parameter to assess suitability to EV

Power density

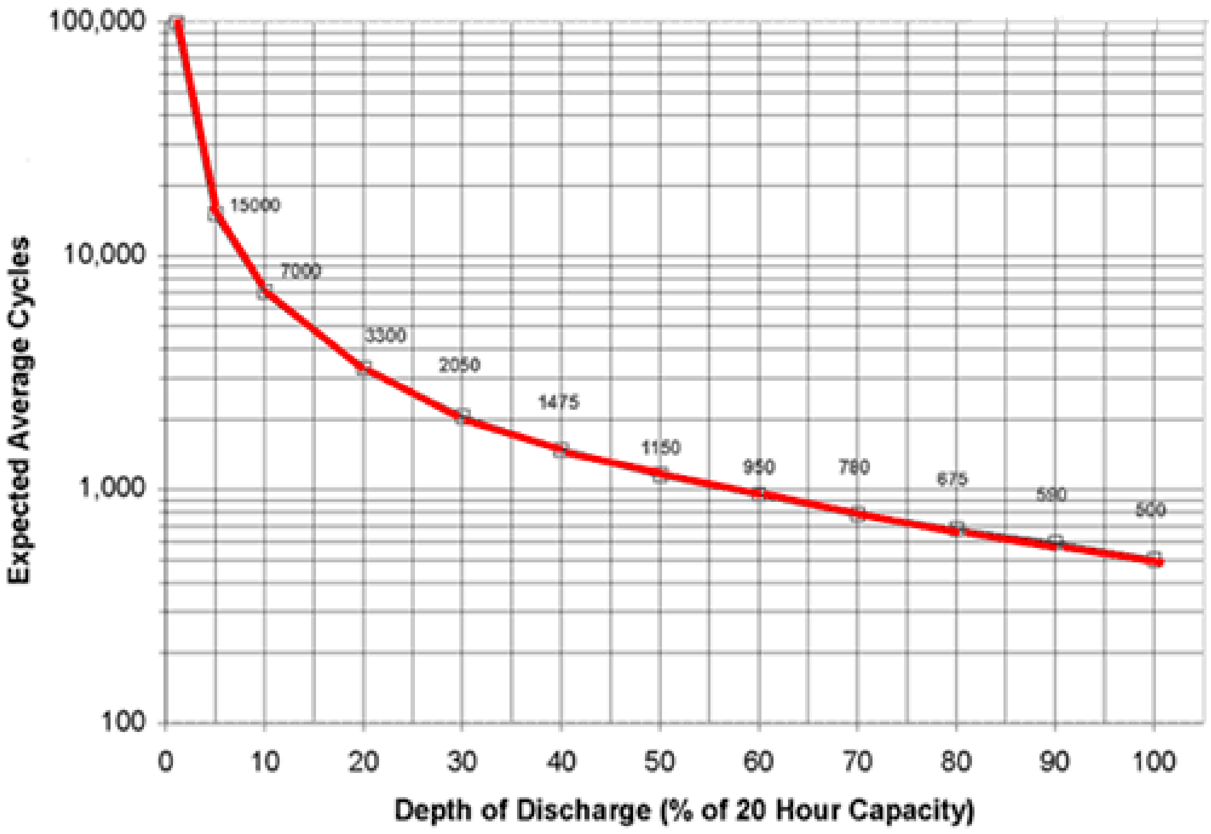
- Power density = deliverable rate of energy per unit of mass or volume
  - Specific power [W/kg]
  - Power density [W/l]
- Specific power is important for EV applications because of acceleration and hill climbing capability
- For batteries, specific power varies with the level of DoD
- Specific power is quoted with the percentage of DoD

Cycle life

- Cycle life: number of deep-discharge cycles before failure
- Key parameter to describe the life of EV sources based on the principle of EV storage
- Cycle life is greatly affected by the DoD characteristics and its is quoted with the percentage of DoD.
  - Example: 400 cycles at 100% DoD or 1000 cycles at 50% DoD
- For energy generation, the life of energy storage systems is defined by the service life in hours or kilohours

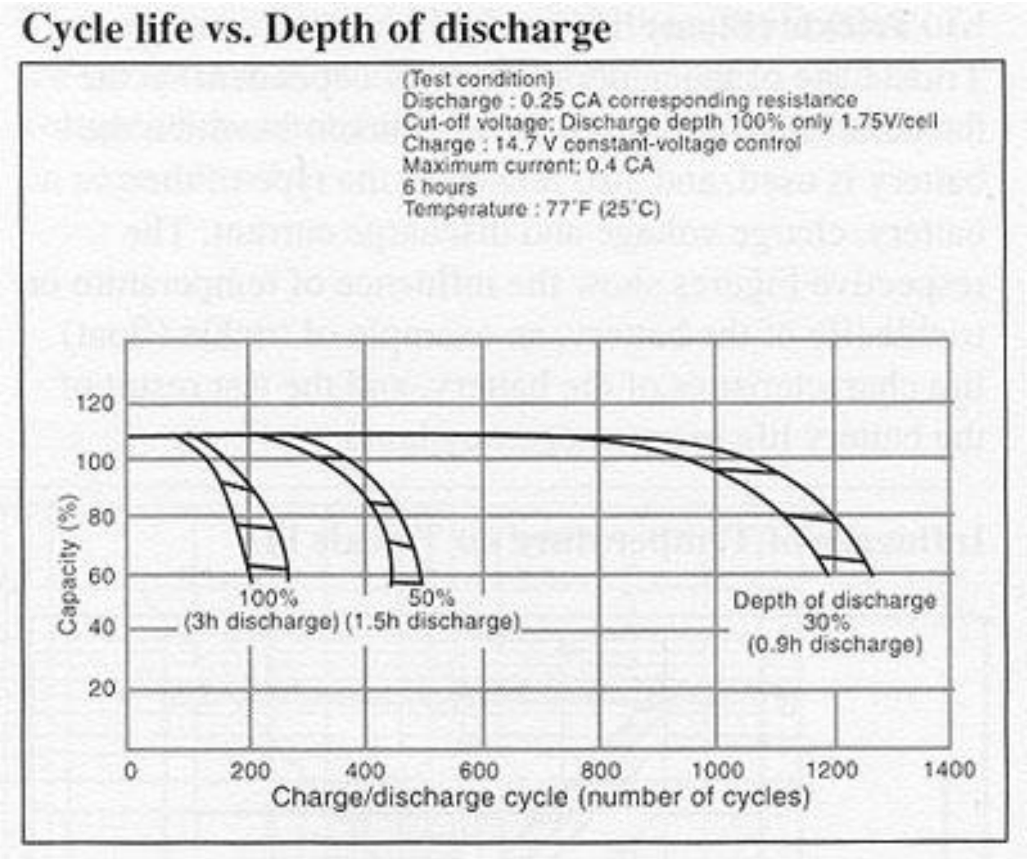
Cycle life

- Influence of DoD on Life time for Lead Acid batteries



Cycle life

- Influence of DoD on Life time for Lead Acid batteries



Energy efficiency

- Energy efficiency is defined as the output energy over the input energy
- For energy storage source, the energy efficiency is simply the ratio of the output electrical energy during discharging over the input electrical energy during charging.
  - Typically for batteries in the range of 60-90%

- Charge efficiency is defined as the ratio of discharged coulometric charge Ah to the charged coulometric capacity Ah.
  - Typically for batteries in the range of 65-90%

- For EV, energy efficiency is more important than charge efficiency

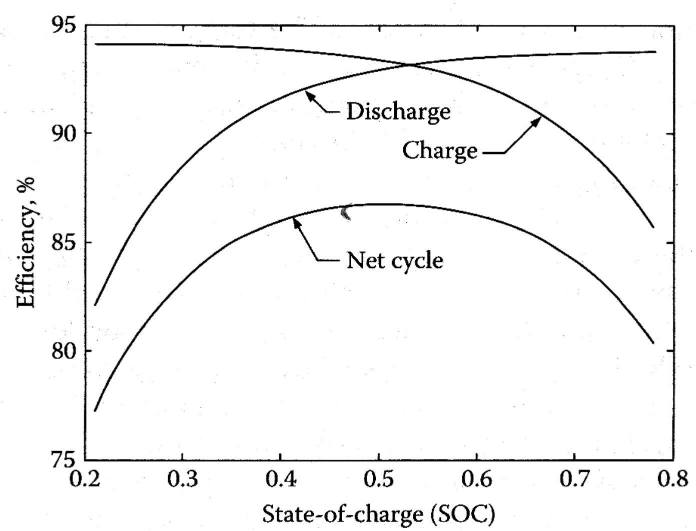
Energy efficiency

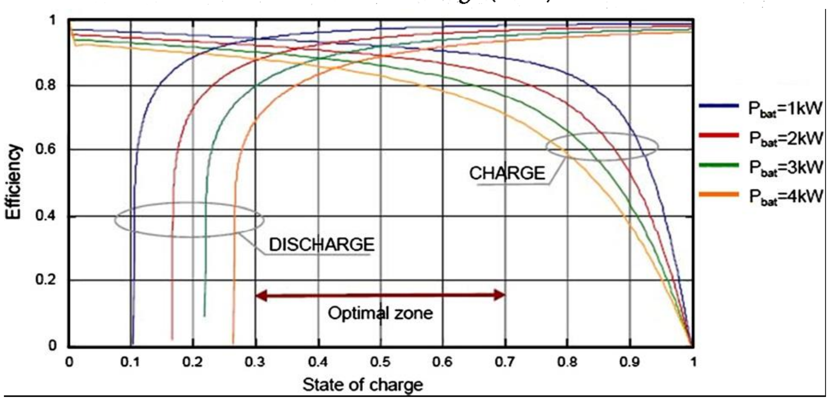
- The energy or power losses of batteries during charging discharging appear in the form of voltage losses. Thus the efficiency of the battery during charging / discharging can be defined at any operating point as the ratio of the cell voltage V to the thermodynamic voltage V_0.

- During discharging: $$\eta_d = \frac{V}{V_0}$$

- During charging $$\eta_c = \frac{V_0}{V}$$

Energy efficiency





- The terminal voltage is a function of the current, the stored energy and the SOC. The terminal voltage is lower in discharging and higher in charging than the electrical potential produced by chemical reactions.
- The battery has a high discharging efficiency with a high SOC and a high charging efficiency with a low SOC.
- Thus net cycle efficiency is maximum around the middle range of SOC

Cost

- Cost includes initial (manufacturing) cost + operational (maintenance) cost
  - Manufacturing cost is the most important one
- Cost is a sensitive parameter for EV sources because it is a penalty with respect to other energy sources
- Cost in €/kWh or $/kWh
- Presently cost in the range of 120 to 1200 €/kWh
- Cost is decreasing and tends to the level of 100 €/kWh in 2024.

Cost

In 2010

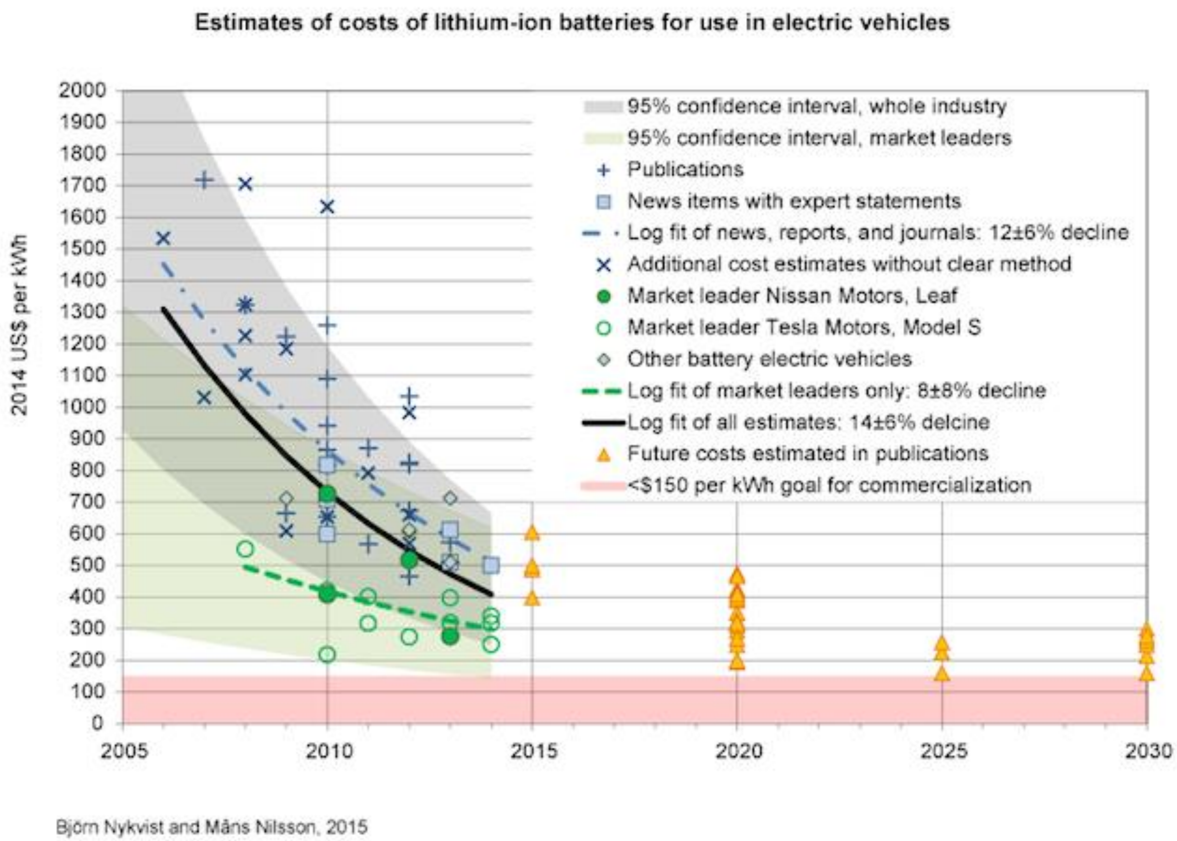
Table 6: Energy Storage System Capacity Capital Costs[14] [15] [16] [17] [18] [19] [20] [21] [22]

Technology	Current Cost ($/kWh)	10-yr Projected Cost ($/kWh)
Flooded Lead-acid Batteries	$150	$150
VRLA Batteries	$200	$200
NiCd Batteries	$600	$600
Ni-MH Batteries	$800	$350
Li-ion Batteries	$1,333	$780
Na/S Batteries	$450	$350
Zebra Na/NiCl Batteries	$800 [1]	$150
Vanadium Redox Batteries	20 kWh=$1,800/kWh; 100 kWh =$600/kWh	25 kWh=$1,200/kWh 100 kWh=$500/kWh
Zn/Br Batteries	$500	$250/kWh plus $300/kW [2]
Lead-carbon Asymmetric Capacitors (hybrid)	$500	<$250
Low-speed Flywheels (steel)	$380	$300
High-speed Flywheels (composite)	$1,000	$800
Electrochemical Capacitors [3]	$356/kW	$250/kW

[1] €600/kWh
[2] The battery system includes an integrated PCS; the PCS price will vary with the rated system output.
[3] Electrochemical capacitors are power devices used only for short-duration applications. Consequently, their associated costs are shown in $/kW rather than $/kWh.

- Source: http://www.altenergystocks.com/archives/2010/03/

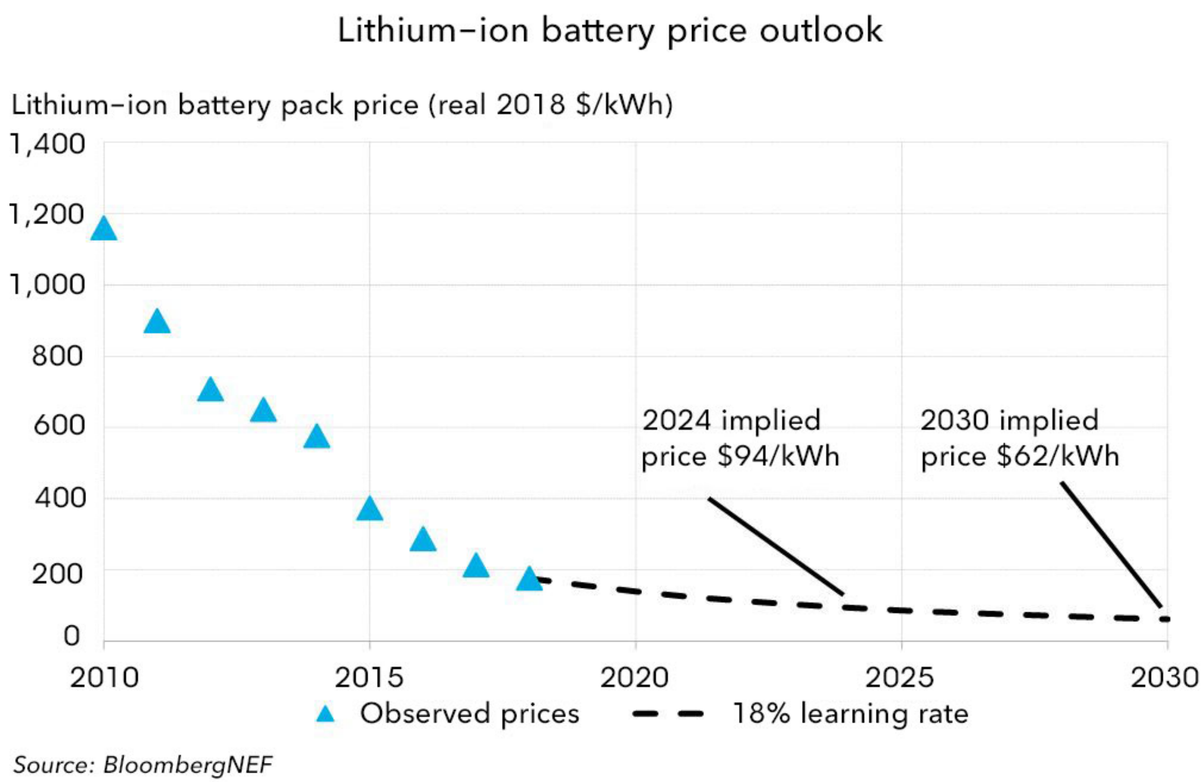
Cost



- Source: **EV Battery Costs Already 'Probably' Cheaper Than 2020 Projections** *https://cleantechnica.com/2015/03/26/ev-battery-costs-already-probably-cheaper-than-2020-projections/*

Cost

- The cost of EV battery cells dropped dramatically in recent years. Total battery **pack price / kWh** is expected to **drop below $100 in next 5 years**



Cost

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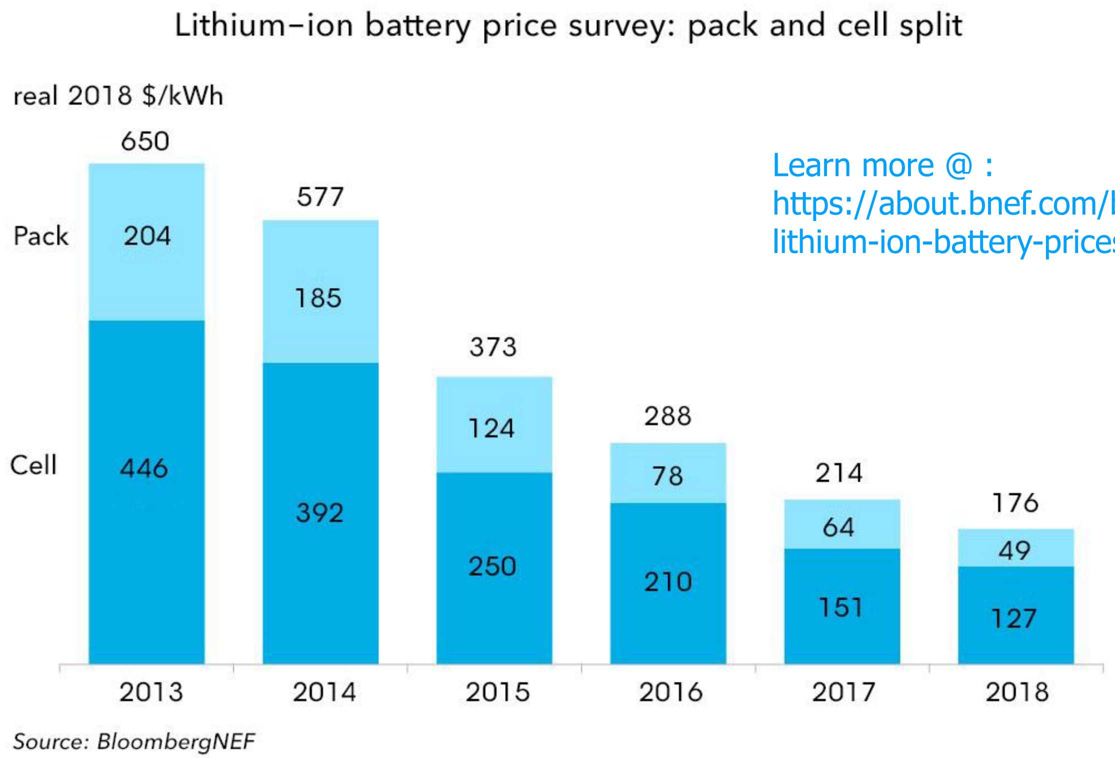


Learn more @ :
https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

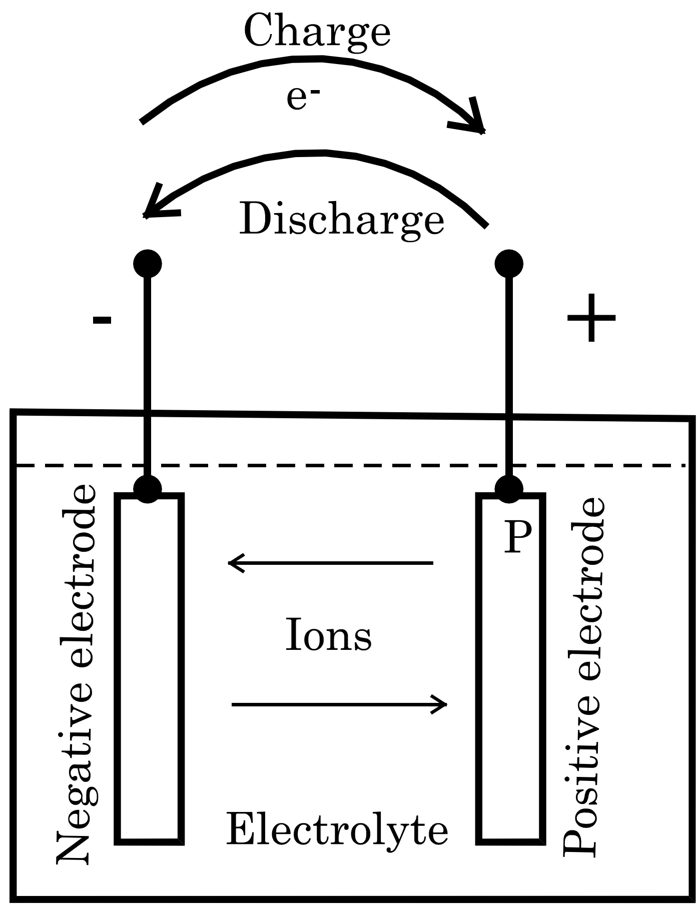
Ideal batteries for EV

- High specific energy → great range and low energy consumption
- High specific power → high performance
- Long life to enable comparable vehicle life
- High efficiency and cost effectiveness to achieve economical operation and maintenance free

Electrochemical batteries

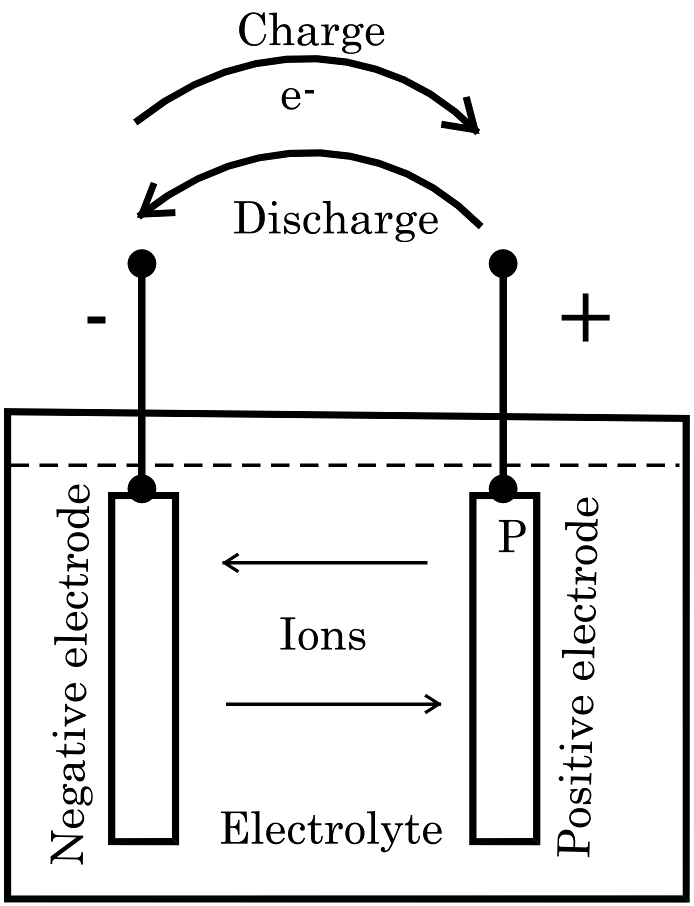
Batteries: principles

- Basic element of each battery is the electrochemical cell
- Cells are connected in series or in parallel to form a battery pack
- Basic principle of batteries
  - Positive and negative electrodes are immersed in an electrolyte
  - Electrochemical Redox reactions happen in both electrodes



Batteries: principles

- During discharge, negative electrodes performs oxidation reaction and electrons are supplied to the positive electrode via the external circuit. Positive electrode performs reduction reaction that absorbs electrons
- During charge, the process is reversed and electrons are injected in negative electrode to perform reduction on negative electrode and oxidation in positive electrodes



Lead-acid batteries

- Invented in 1860, lead acid batteries are successful product for more than one century
- Low price and mature technology even if new designs are still continued to be developed to meet higher performance criteria.

- Battery principle:
  - Negative electrode: metallic lead
  - Positive electrode: lead dioxide
  - Electrolyte: Sulfuric acid
  - Electrochemical reaction:

$$\mathrm{Pb} + \mathrm{PbO_2} + 2\mathrm{H_2SO_4} \leftrightharpoons 2\mathrm{PbSO_4} + 2\mathrm{H_2O}$$

Lead-Acid batteries: electrochemical reactions

- Discharging:
  - Anode (negative electrode): porous lead

$$\mathrm{Pb} + \mathrm{SO}_4^{2-} \rightarrow \mathrm{PbSO}_4 + 2\mathrm{e}^-$$

  - Cathode (positive electrode): porous lead oxide

$$\mathrm{PbO}_2 + 4\mathrm{H}^+ + \mathrm{SO}_4^{2-} + 2\mathrm{e}^- \rightarrow \mathrm{PbSO}_4 + 2\mathrm{H}_2\mathrm{O}$$

Lead-Acid batteries: electrochemical reactions

- Charging
  - Anode (negative electrode)

$$\mathrm{PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}}$$

  - Cathode (positive electrode)

$$\mathrm{PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-}$$

- Overall

$$\mathrm{Pb + PbO_2 + 2H_2SO_4 \leftrightharpoons 2PbSO_4 + 2H_2O}$$

Lead-Acid batteries: Thermodynamic voltage

- Thermodynamic voltage of the battery cell is related to energy released and the number of electrons transferred in the reaction
- The energy released is given by the change of Gibbs free energy ΔG usually expressed per mole quantity

$$\Delta G = \sum_{\text{Products}} G_i - \sum_{\text{Reactants}} G_j$$

In which G_i and G_j are the free energy of products i and reactant species j.

Lead-Acid batteries: Thermodynamic voltage

- In reversible conditions, all the ΔG is converted in electric energy

$$\Delta G = -n\,\mathcal{F} V_{rev}$$

$\mathcal{F}$=96495 F, the Faraday constant, the number of coulombs per mole and V_{rev} the reversible voltage

- At standard conditions T=25°C, p=1 atm

$$V^0_{rev} = -\frac{\Delta G^0}{n\,\mathcal{F}}$$

Lead-Acid batteries: Thermodynamic voltage

- The change of free energy and thus cell voltage are function of the activities of the solution species

- The Nernst relationship gives the dependence of ΔG on the reactant activities

$$V_{rev} = V_{rev}^0 - \frac{RT}{n\mathcal{F}} \ln \left[\frac{\prod \text{Activities of Products}}{\prod \text{Activities of Reactants}} \right]$$

- R universal constant R=8,314 J/mol.K and T absolute temperature

Lead-Acid batteries: Specific energy

- Specific energy is defined as the energy capacity per unity battery weight (Wh/kg)
- The theoretical specific energy is the maximum energy that can be generated by unit total mass of reactants

$$E_{spec}^{th} = -\frac{\Delta G}{3,6\ \sum_i M_i} = \frac{n\,\mathcal{F}\,V_{rev}}{3,6\ \sum_i M_i}\ [\mathrm{Wh/kg}]$$

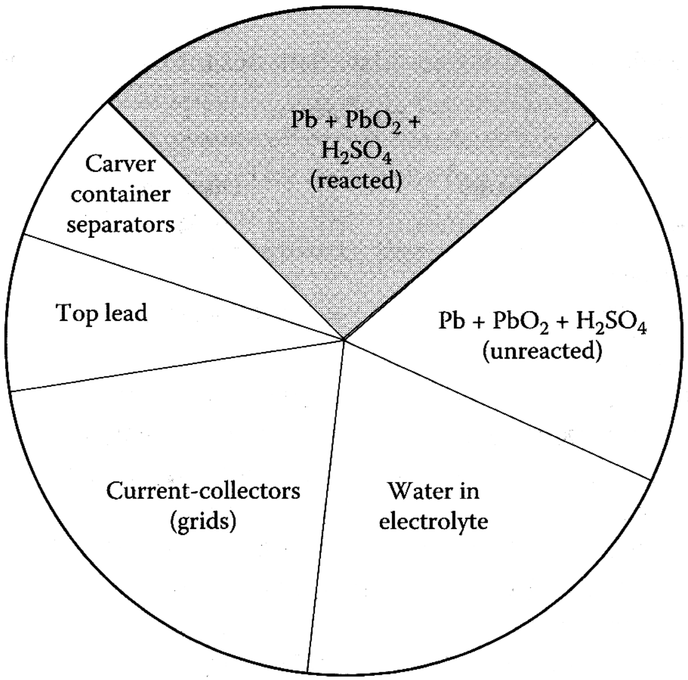
- For lead-acid batteries: V_r=2,03 and ΣM_i=642g

$$E_{spec}^{th} = 170\ [\mathrm{Wh/kg}]$$

- Actual specific energy (with container, etc.):

$$E_{spec}^{real} = 45\ [\mathrm{Wh/kg}]$$

Lead-Acid batteries: Specific energy



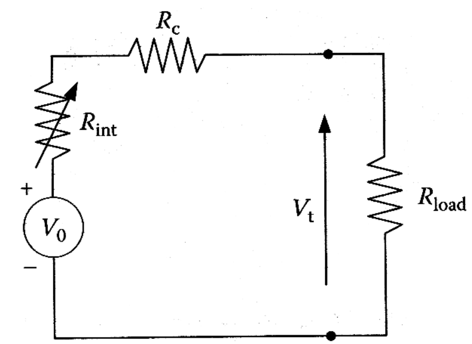
Weight distribution of the component of a Lead Acid battery with a specific energy of 45 Wh/kg and C5/5 rate. From Eshani, Gao, Emadi (2010). Fig 12.5

Maximizing specific energy

- Best specific energy is obtained with the lightest elements:
  - H, Li, Na… for negative electrode reactants
  - Halogens, O, S… for positive reactants
  - Exclude elements, which are not abundant
- Optimized electrode design for effective utilization of the contained active materials
- Electrolytes of high conductivity compatible with materials in both electrolytes
  - Oxygen and Sulfur are often used as oxides or sulfides.
  - Aqueous electrolytes are advantageous at room temperature but forbid the use of alkali-group metals
  - → other metals with a reasonable electro negativity: Zn, Al, Fe and which are rather abundant while not too expensive

Maximizing specific power

- Specific power is defined as the maximum power per unit battery weight that can be delivered
- Specific power is important for battery weight especially in high-power demand applications such as HEV
- The specific power depends mostly on the battery internal resistance



$$P_{peak} = \frac{V_0^2}{4\left(R_c + R_{int}\right)}$$

- R_{int} represents the voltage drop which is associated with the battery current

Maximizing specific power

- The R_{int} represents the voltage drop which is associated with the battery current
- R_{int} depends on two components:
  - Reaction activity

$$\Delta V_A = a + n \log I$$

  - Electrolyte concentration

$$\Delta V_C = -\frac{R\,T}{n\mathcal{F}} \ln\left(1 - \frac{I}{I_L}\right)$$

I_L = limit current

Lead-Acid batteries: Specific power

- The voltage drop
  - Increases with increasing discharge current
  - Decreases with the stored energy

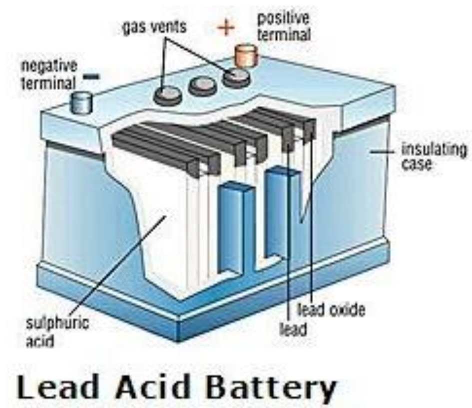
- Specific energy is high in advanced batteries, but still it needs to be improved
- Specific energy of 300 Wh/kg is still an optimistic target
- Some new developments with SAFT
  - HEV batteries with 85 Wh/kg and 1350 W/kg
  - EV batteries with 150 Wh/kg and 420 W/Kg

Energy sources categories

- Rechargeable electrochemical batteries
  - Lead Acid (Valve Regulated Lead Acid=VRLA)
  - Nickel based: Ni-Iron, Ni-Cd, Ni-Zn, Ni-MH
  - Metal/air: Zn/air, Al/air, Fe/air
  - Molten salt: Sodium-β: Na/S, Na/$NiCl_2$, FeS_2
  - Ambient temperature lithium: Li-polymer, Li-ions

- Supercapacitors
- Ultrahigh speed flywheels
- Fuel cells

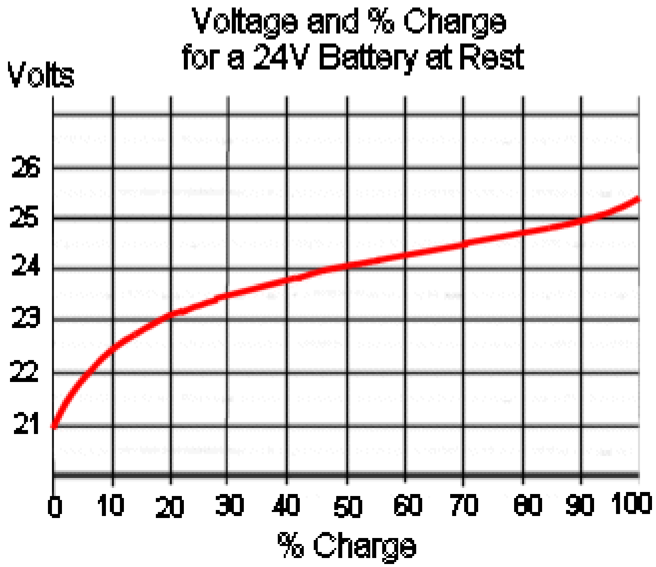
Lead-acid batteries



- Voltages:
  - Nominal cell voltage: 2,03 V (highest one of all aqueous electrolytes batteries)
  - Cut-off voltage: 1,75 V
  - Voltage depends on sulfuric acid concentration, so that voltage varies with SOC
  - Gassing voltage (decomposition electrolysis of water at 2.4 V)
- Energy/ power density
  - Specific energy density: 35 Wh/kg
  - Energy density 70 Wh/l
  - Specific power density: 200 W/kg
- Energy efficiency: >80%
- Self discharge rate: <1% per 48 hours
- Cycle life: 500-1000 cycles
- Cost: 120-150 $/kWh

Lead-acid batteries

- Drawbacks of Lead-Acid batteries:
  - Use of lead and acid (recyclable, but polluting)
  - Weak energy density
  - Weak charge-discharge yield (50%)
  - Voltage depends on sulfuric acid concentration, so that voltage strongly varies with SOC

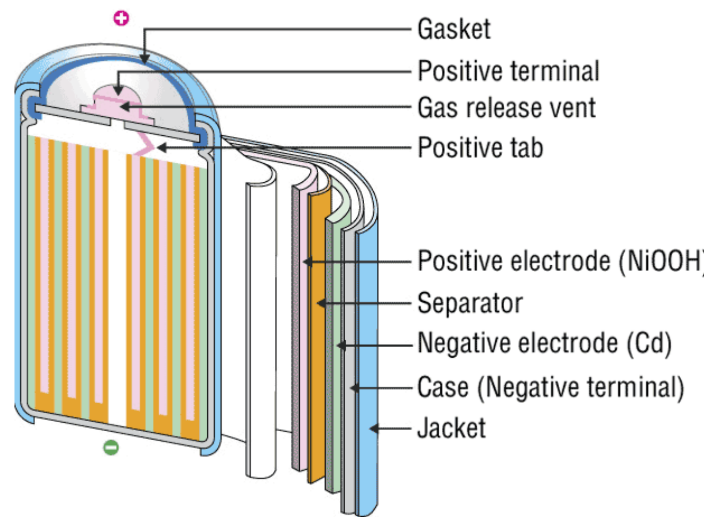


Nickel-based batteries

- Family of different kinds of electrochemical batteries using nickel oxyhydroxide (-OOH)
  - Ni-Fe invented by Edison
  - Ni-Cd is known from 1930ies
  - Ni-MH is used in modern HEV vehicles (1990ies)
  - Ni-Zn is still under development
- Use Nickel oxy hydroxide (NiOOH) as the active material for the positive electrode

Ni-Cd batteries

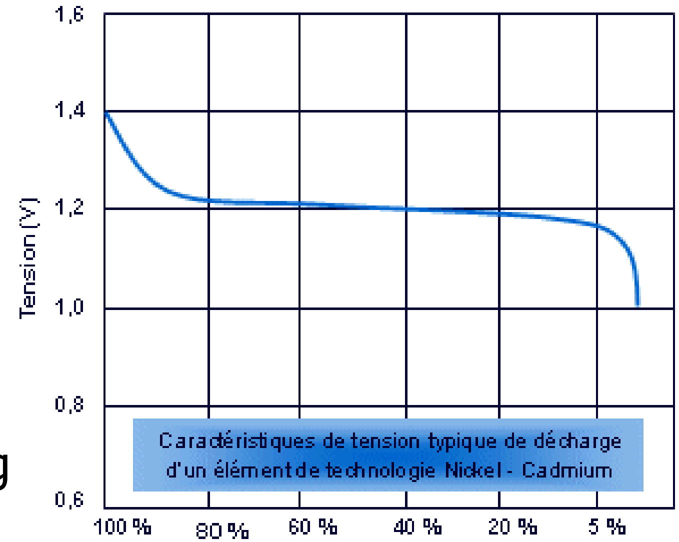
- Developed in the 1930ies, it is used in heavy industry for 80 years
- Battery principle:
  - Negative electrode: metallic cadmium Cd
  - Positive electrode: nickel oxyhydroxide NiOOH
  - Electrolyte: KOH
  - Electrochemical reaction:



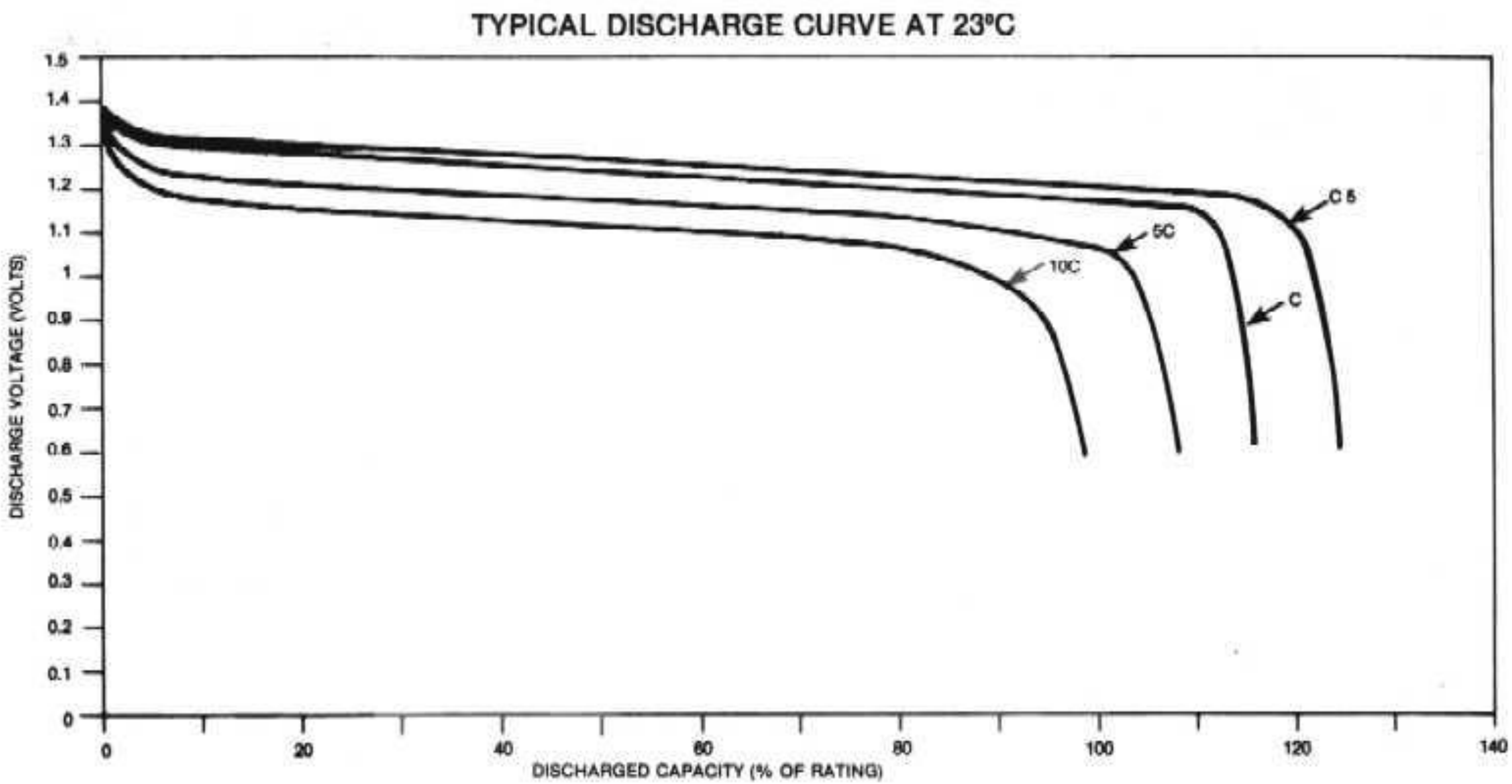
$$\mathrm{Cd} + 2\mathrm{NiOOH} + 2\,\mathrm{H_2O} \leftrightharpoons 2\,\mathrm{Cd(OH)_2} + 2\,\mathrm{Ni(OH)_2}$$

Ni-Cd batteries

- Voltages:
  - Nominal cell voltage: 1,2 V
  - Cut-off voltage: 1,00 V
- Energy/ power density
  - Specific energy density: 56 Wh/kg
  - Energy density 110 Wh/l
  - Specific power density: 80-150 W/kg
- Energy efficiency: 75%
- Self discharge rate: 1% per 48 hours
- Cycle life: ~800 cycles
- Cost: 250-350 $/kWh



Ni-Cd batteries



Discharge curves of Ni-Cd

Ni-Cd batteries

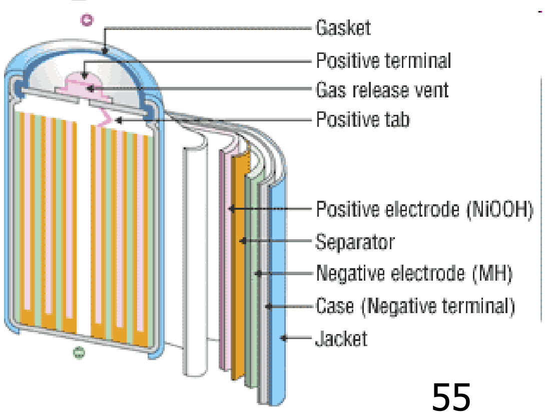
- Advantages:
  - Medium specific energy
  - Medium cycle life
  - Flat curve
  - Good performance in low temperatures
  - Easiness of charge
- Disadvantages
  - Cd environmentally not friendly and carcinogenicity
  - Memory effect sensitivity
  - Self discharge

Ni-MH batteries

- Developed and marketed in the 1990ies, it is a standard battery used in many modern HEV
- Similar principle to Ni-Cd but it uses hydrogen absorbed in a metal hydride for the active material in negative electrode

- Battery principle:
  - Negative electrode: hydrogen absorbed in metal hydride: MH
  - Positive electrode: nickel oxyhydroxide $Ni(OH)_2$
  - Electrolyte: KOH
  - Electrochemical reaction:

$$\mathrm{MH} + \mathrm{NiOOH} \leftrightharpoons \mathrm{M} + 2\,\mathrm{Ni(OH)_2}$$



Ni-MH batteries

- Key compound is MH, the metal alloy that is able to absorb / desorb hydrogen with a high efficiency with a high number of cycles.
  - AB_5 rare-earth such us Lanthanum with Ni
  - AB_2: Ti or Zr alloys with Ni
- Voltages:
  - Nominal cell voltage: 1,2 V
- Energy/ power density
  - Specific energy density: 70 - 95 Wh/kg
  - Energy density 150 Wh/l
  - Specific power density: 200 – 300 W/kg
- Energy efficiency: 75% (70→90) Cycle life: 750-1200 cycles
- Self discharge: 6% per 48 hours Cost: 200-350 $/kWh

Ni-MH batteries

- A porous metal absorbs et exudes the hydrogen atoms

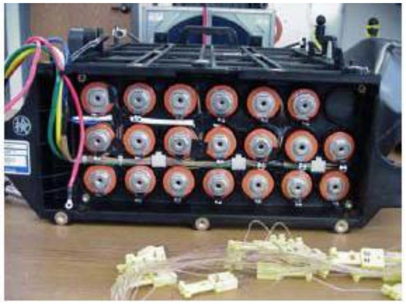
Charge

$$MH_2 \rightleftarrows M + 2H$$

$$2\ H + 2\ OH^- \longrightarrow 2\ H_2O + 2\ e^-$$

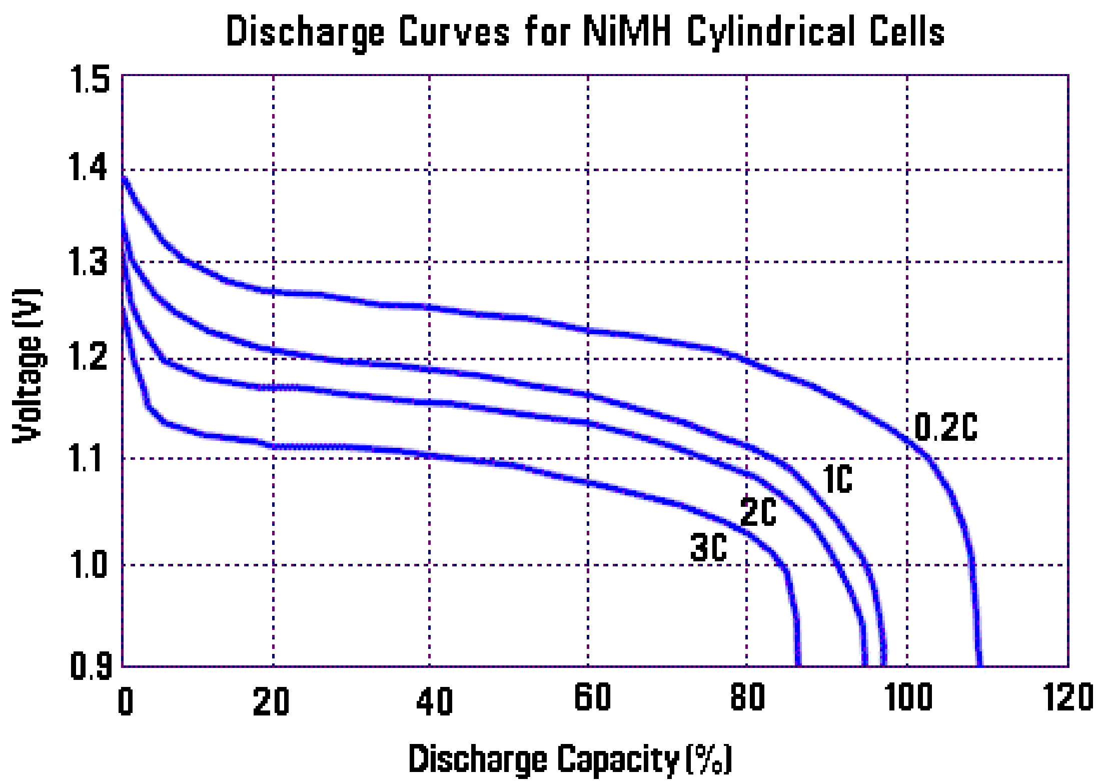
$$K^+ + OH^- + H_2O \longrightarrow KOH + H_2O$$

$$2\ NiO(OH) + 2\ H_2O + 2e^- \rightleftarrows 2Ni(OH)_2 + 2OH^-$$



Discharge

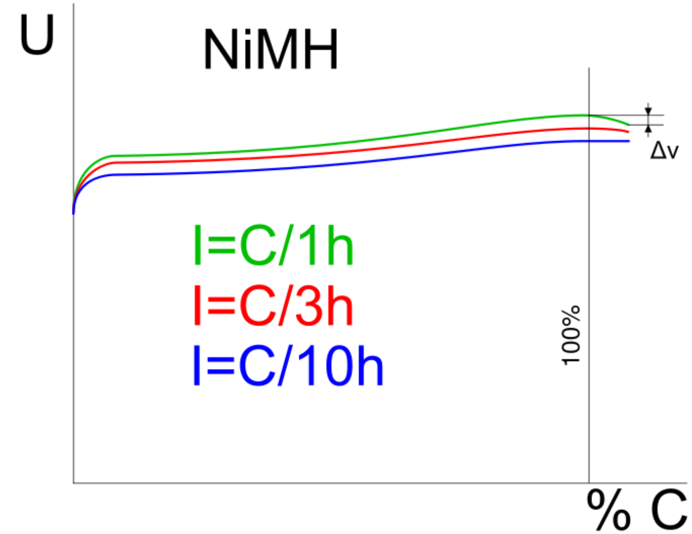
Ni-MH batteries



Discharge curves of Ni-MH

Ni-MH batteries

- Advantages:
  - High specific energy
  - High specific power
  - Flat discharge curve
  - Fast charge
  - Low sensitivity to memory effect
- Disadvantages
  - Do not withstand overcharging
  - Detection of end of charge
  - Little longer life cycle than Ni-Cd



Nickel-Zinc batteries

- Reaction:

$$2\,\mathrm{Ni(OH)_2(s)} \;+\; \mathrm{Zn(OH)_2(s)} \leftrightharpoons 2\,\mathrm{Ni(OH)_3(s)} \;+\; \mathrm{Zn(s)}$$

- ΔV = 1.65 V per element
- Energy density: ~100 Wh/kg
- Self-discharge: 1% /day
- Number of charge-discharge cycles: 400~1000 cycles
- No heavy metals (Hg, Pb, Cd)
- No metal hydrides difficult to recycle
- Zn degradation (growth of dendrites)
- High self-discharge

Lithium-based batteries

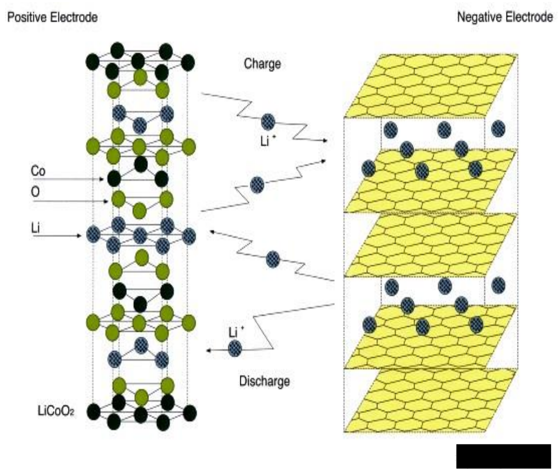
- Lithium is the lightest metallic element which allows for interesting electrochemical properties:
  - High thermodynamic voltage
  - High energy and power density

- Two major technologies of electrochemical batteries using lithium
  - Lithium-polymer
  - Lithium-ions

Li-ions batteries

- First developed in the 1990ies, it has experienced an unprecedented raise and it is now considered as one of the most promising rechargeable battery of the future
- Although still at development stage, it has already gained acceptance in HEV and EV.

Li-ions battery principle



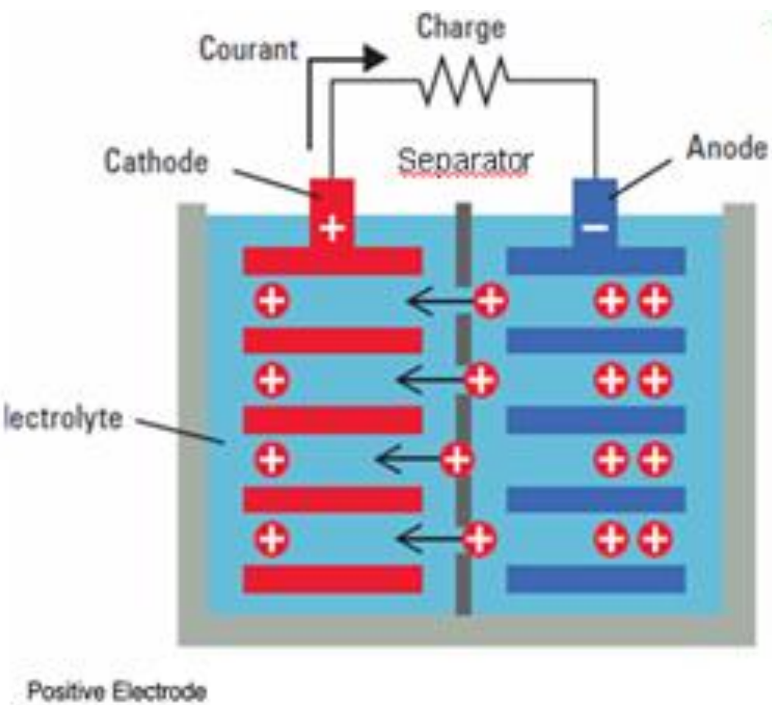
- Negative electrode: lithiated carbon intercalated Li_xC
- Positive electrode: lithiated transition metal intercalation oxide $Li_{1-x}M_yO_z$ (ex $LiCoO_2$)
- Electrolyte: liquid organic solution or a solid polymer

$$\mathrm{Li_xC + Li_{1-x}M_yO_z \leftrightharpoons C + LiM_yO_z}$$

- Electrochemical reaction: <u>for instance </u>with cobalt oxides

$$\mathrm{Li_{(x+y)}C_6 + Li_{(1-x-y)}CoO_2 \leftrightharpoons Li_yC_6 + Li_{(1-y)}CoO_2}$$

Li-ions batteries

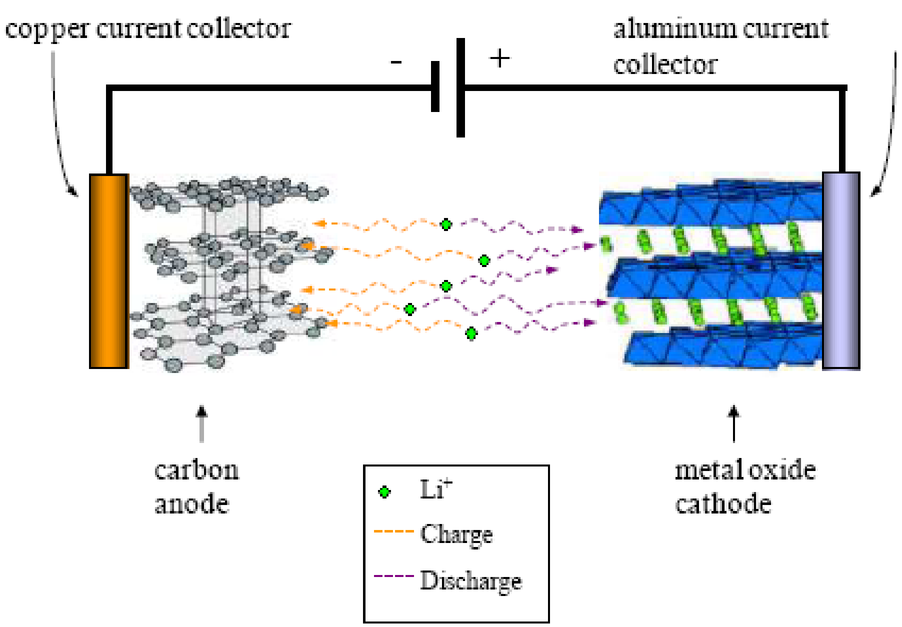


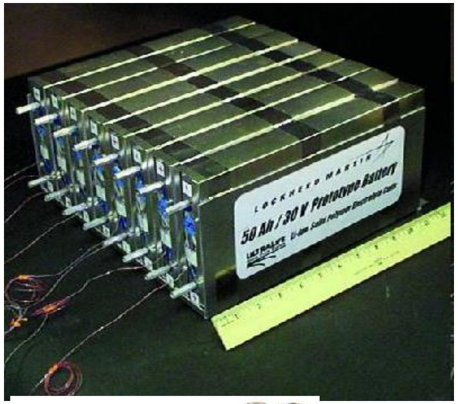
- Reversible exchange of charges (Li+ ions) between two intercalation compounds
- <u>Discharge:</u> Li ions are released from negative electrodes, migrate via the electrolyte and are caught up by the positive electrode.
- Possible positive electrode materials are $Li_{1-x}CoO_2$, $Li_{1-x}NiO_2$, and $Li_{1-x}Mn_2O_4$ that are stable in air, high voltage, reversibility for lithium intercalation reaction.

Li-ions batteries

- Exchange of lithum ions by intercalation between a carbon electrode (anode) and a cathode made of a metal oxyde

$$\mathrm{Li}_{(x+y)}\mathrm{C}_6 + \mathrm{Li}_{(1-x-y)}\mathrm{CoO}_2 \leftrightharpoons \mathrm{Li}_y\mathrm{C}_6 + \mathrm{Li}_{(1-y)}\mathrm{CoO}_2$$

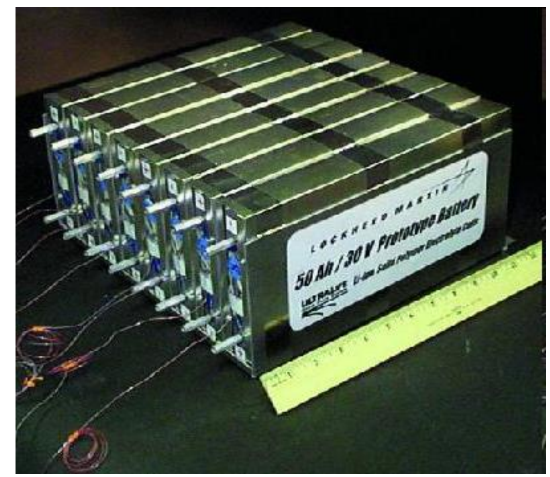




Li-ions batteries

For Li_xC / $Li_{1-x}NiO_2$ battery (C/$LiNiO_2$ or nickel based li-ion battery)

- Voltages:
  - Nominal cell voltage: 4 V
- Energy/ power density
  - Specific energy density: 100-180 Wh/kg
  - Energy density 200 Wh/l
  - Specific power density: 200-300 W/kg
- Energy efficiency: →95%
- Cycle life: > 1000 cycles
- Self discharge rate: 0,7% per 48 hours
- Cost: <200 $/kWh and decreasing
- Higher performance for Li_xC / $Li_{1-x}CoO_2$ but also higher cost due to Cobalt



Li-ions batteries

- Advantages:
  - High specific energy and high specific power
  - No memory effect
  - Low self discharge
  - No major pollutants
- Disadvantages
  - Do not withstand overcharging,
  - May present dangerous behavior when misusage
  - Short circuit due to metallic Lithium dendritic growth

Li-ions batteries

- Characteristics of Li ions batteries

Cathode materials	$LiCoO_2$	$LiMn_2O_4$	$Li(NiCoMn)O_2$	$LiFePO_4$
Reversible capacity (mAh/g)	140	100	150	145
Working voltage plateau (V)	3.7	3.8	3.6	3.2
Charge termination voltage (V)	4.25	4.35	4.3	4.2
Overcharge tolerance (V)	0.1	0.1	0.2	0.7
R.T. Cycle life (cycles)	400	300	400	1000
55℃ Cycle life (cycles)	300	100	300	800
Heat Flow by DSC (kJ/g)	650	150	600	10
Overcharge without PCB	4.9/3C Explosion	8V/3C Firing	8V/3C Firing	25V/3C Pass
Battery energy density (Wh/kg)	180	100	170	130

Li-ions batteries

Cathode

Material	Average voltage	Specific capacity	Specific energy
$LiCoO_2$	3.7 V	140 mAh/g	0.518 kW.h/kg
$LiMn_2O_4$	4.0 V	100 mAh/g	0.400 kW·h/kg
$LiNiO_2$	? V	? mAh/g	? kW·h/kg
$LiFePO_4$	3.3 V	150 mAh/g	0.495 kW·h/kg
Li_2FePO_4F	3.6 V	115 mAh/g	0.414 kW·h/kg

Anode

Material	Average voltage	Specific capacity	Specific energy
Graphite (LiC_6)	0.1-0.2 V	372 mAh/g	0.0372-0.0744 kW.h/kg
Carbone (LiC_6)	? V	? mAh/g	? kW.h/kg
Titanate ($Li_4Ti_5O_{12}$)	1-2 V	160 mAh/g	0.16-0.32 kW·h/kg
Silicium ($Li_{22}Si_6$)	? V	? mAh/g	? kW·h/kg
Si ($Li_{4.4}Si$)	0.5-1 V	4212 mAh/g	2.106-4.212 kW·h/kg
Ge ($Li_{4.4}Ge$)	0.7-1.2 V	1624 mAh/g	1.137-1.949 kW·h/kg

Li-ions batteries : comparison table

Table 1: Characteristics of lithium-ion batteries using various chemistries

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah/gm Anode/cathode	Energy density Wh/kg	Cycle life (deep)	Thermal stability	
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable	Leaf - V2
Graphite/ Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable	Leaf - V1
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable	Tesla Model S
Graphite/ iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	stable	A123
Lithium titanate/ Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable	Altairnano

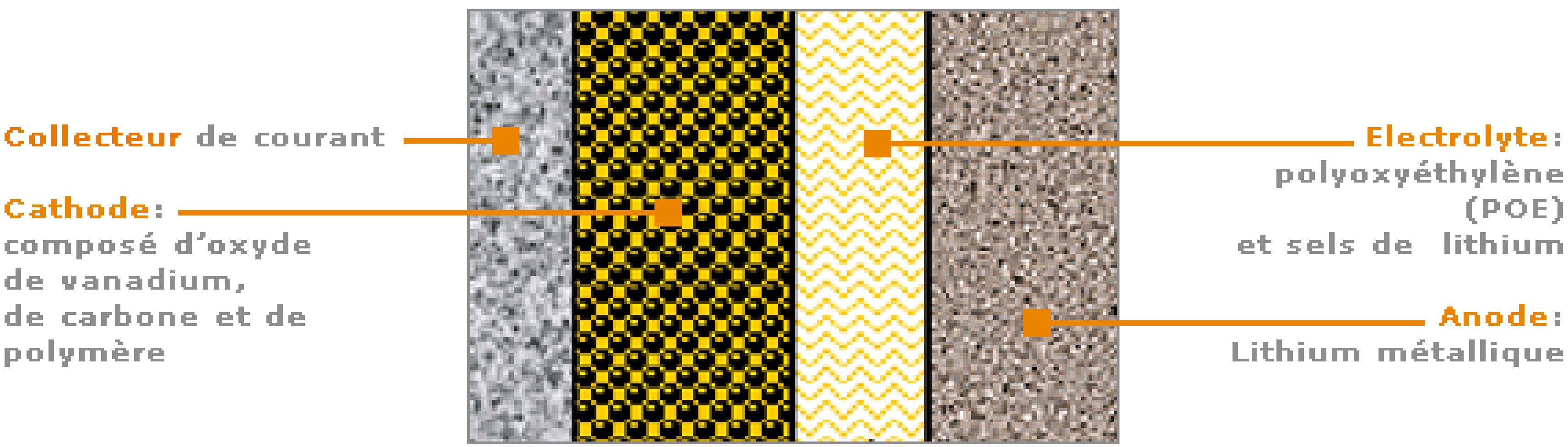
Li-polymer batteries

- Li-ions battery principle:
  - Negative electrode: lithium metal
  - Positive electrode: transition metal intercalation oxide M_yO_z
  - Electrolyte: thin solid polymer electrolyte (SPE)
  - Electrochemical reaction:

$$\mathrm{x\,Li} + \mathrm{M_yO_z} \leftrightharpoons \mathrm{Li_xM_yO_z}$$

- The layered structure of transition metal oxide M_yO_z allows lithium ions to be inserted and removed for charge and discharge
- Discharge: Li ions that are formed at the negative electrodes migrate through the SPE and are inserted into the crystal structure at the positive electrode.

Li-polymer batteries



Li-polymer batteries

- Thin solid polymer electrolyte: improved safety and flexibility
- Capability of fabrication in various shapes and sizes and safe designs
- Possible positive electrode material are Vanadium oxides: V_6O_{13}

Battery Li/SPE/V_6O_{13}

- Voltages:
  - Nominal cell voltage: 3 V
- Specific energy density: 155 Wh/kg
- Specific power density: 315 W/kg
- Energy efficiency: 85%
- Self discharge: 0,5% per month

Li-polymer batteries

- Advantages:
  - High specific energy and high specific power
  - No memory effect
  - Low self discharge
  - No major pollutants
  - Various shapes and sizes
- Disadvantages
  - Lower energy density than Li-ions
  - More expensive than Li-ions
  - Specific energy density: 155 Wh/kg
  - Charging must be carefully conducted to avoid inflammation

Lithium batteries: comparaison

	Pb	Ni-Cd	Ni-MH	Li-ion
Energy density [Wh/kg]	30	30-50	70-80	160-200
Cycles [-]	500-1200	2000	500-1000	1200
Charge time [min]	300-600	180-300	180-300	90-120
Self-discharge max. [%/month]	50	10-20	20	5-10
Ch./disch. Yield [%]	50	70-90	66	99.9
Lifetime [years]	4-5	2-3	1-2	2-3

EV and HEV Applications

Battery Pack of Toyota Prius II

EV and HEV Applications

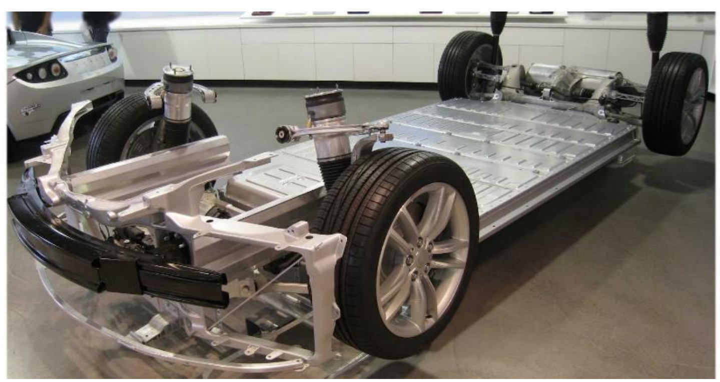
Honda Insight

Ni-MH Battery Pack of Honda Insight

EV and HEV Applications

Tesla Model S

Li ion Battery Pack of Tesla



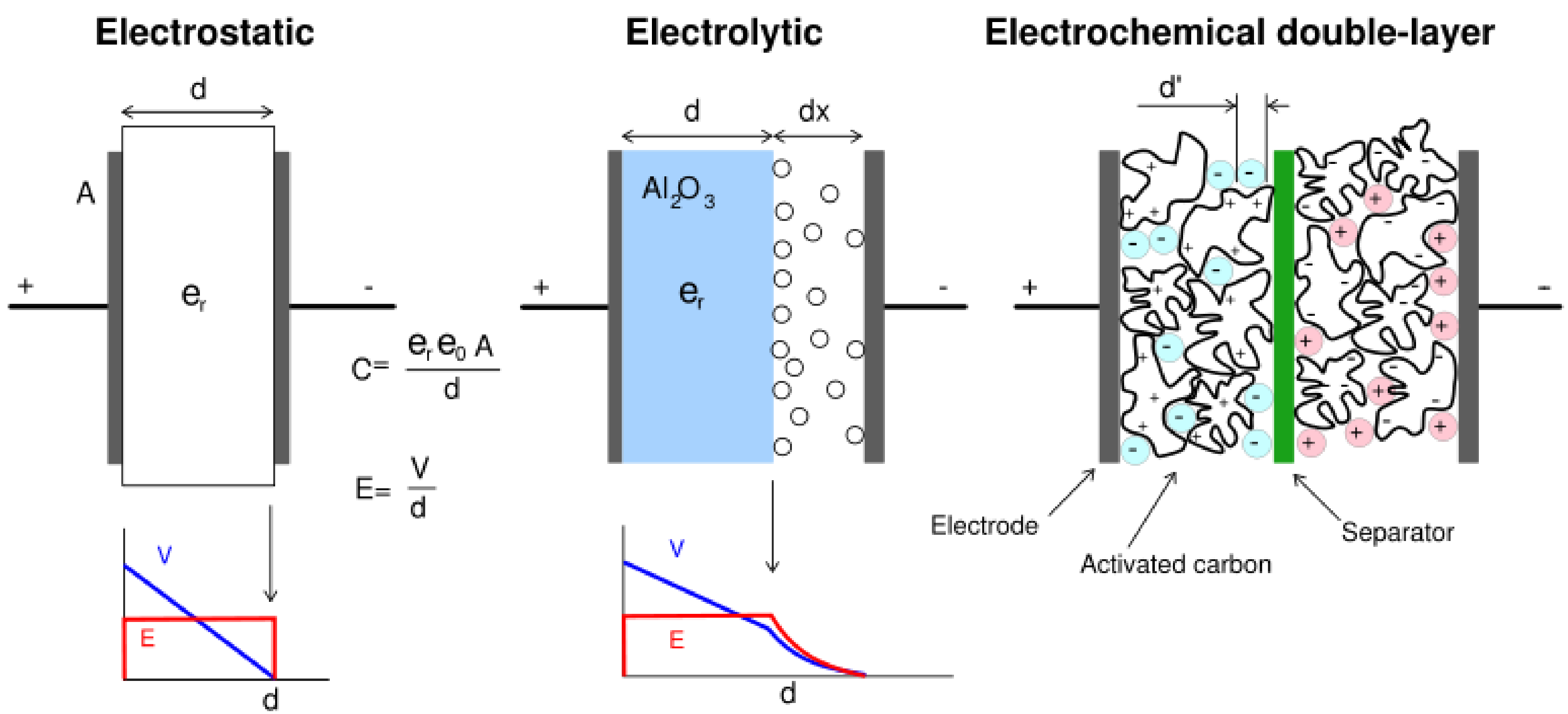
Supercapacitors

Capacitors and Supercapacitors

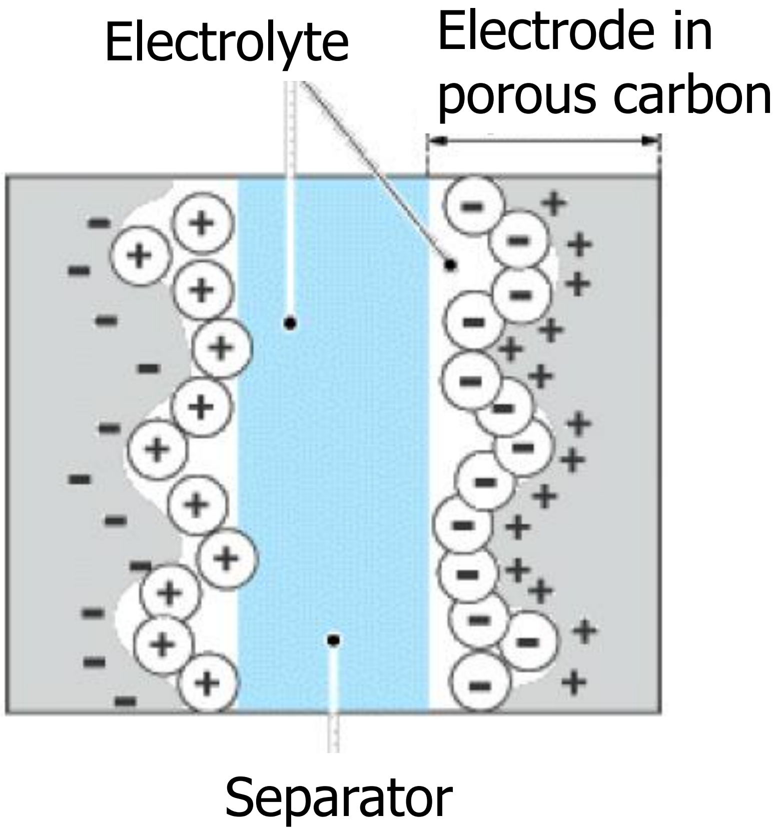
- Capacitors = simple devices capable of storing electrical energy
- Capacitors
  - = electrostatic capacitors
  - Essential components in electronics
  - Capacitance ~ pF to μF
- Electrolytic Double Layer Capacitors (EDLC) or ultra / supercapacitors
  - Capacitance ~ F – kF
  - Working principle: double electrolytic layer by Helmotz

Capacitors and Supercapacitors

- One must distinguish the electrostatic capacitors from supercapacitors that use the Helmotz double layer principle

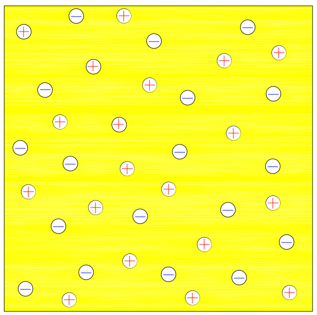


Supercapacitors: principle

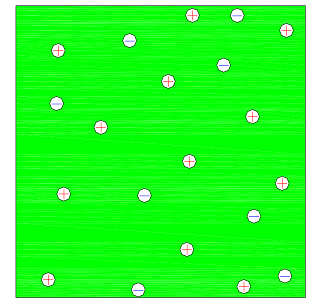


- Supercapacitors are based on the double layer technology
- When carbon electrodes are immersed in aqueous electrolyte, the ions will accumulate at the porous interface of the electrode.
- The ions and the current carriers make capacitors with a gap of a few nanometers

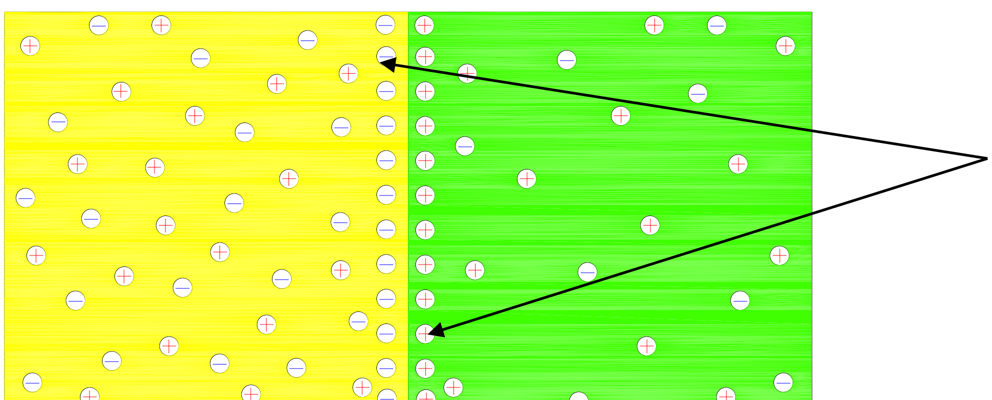
Supercapacitors: Double layer principle



EQUILIBRIUM CONDITION OF MATERIALS
WITH DIFFERENT ELECTRIC CONDUCTIVITY

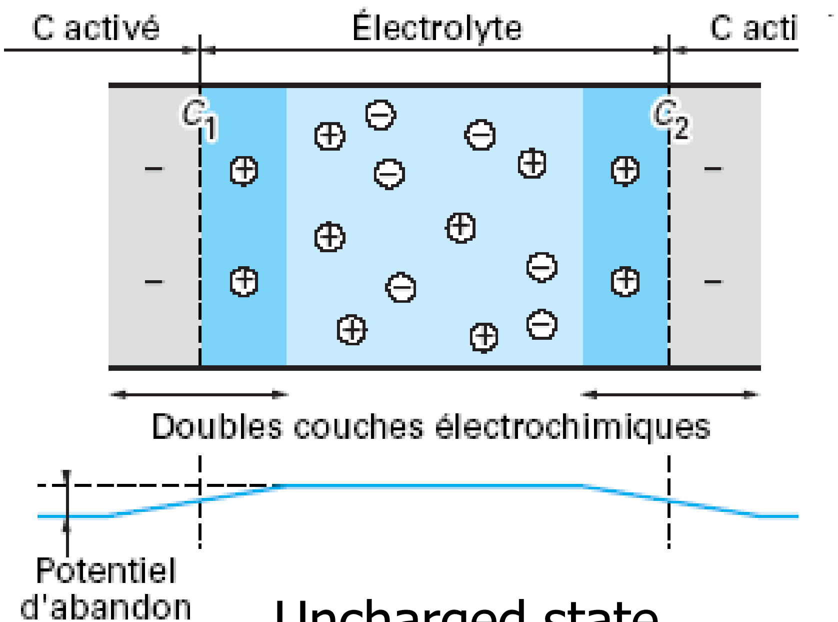


EQUILIBRIUM CONDITION OF A SYSTEM COMPRISING OF TWO DIFFERENT MATERIALS

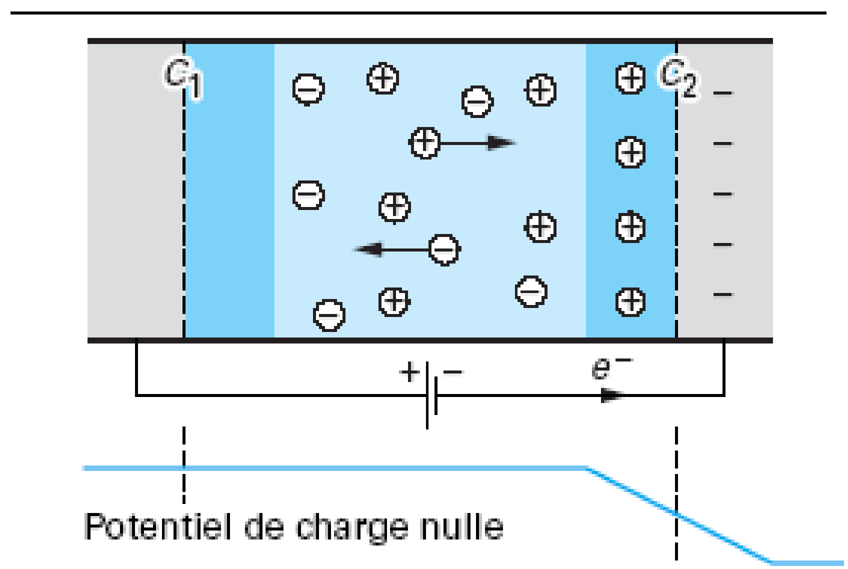


DOUBLE ELECTRIC LAYER

Supercapacitors: principle

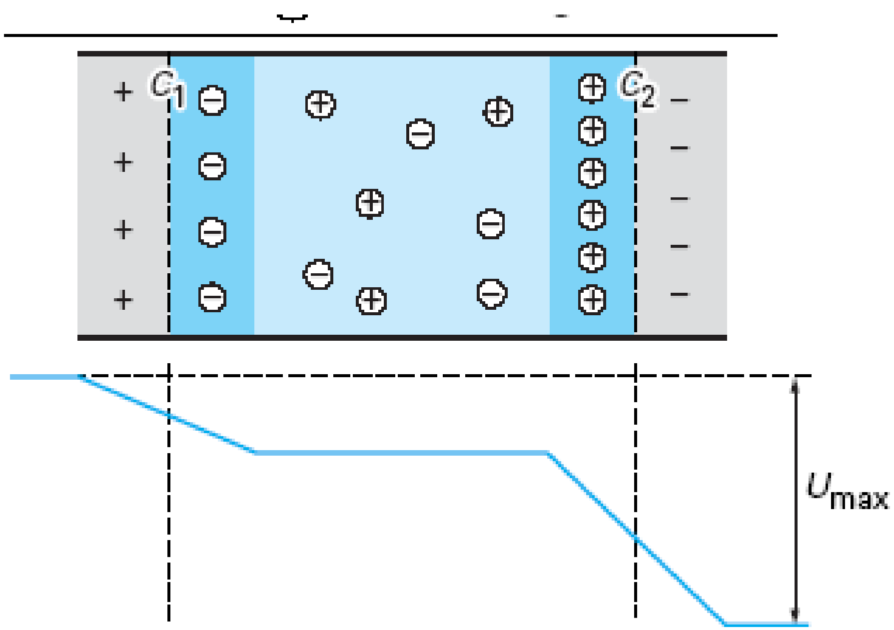


Uncharged state

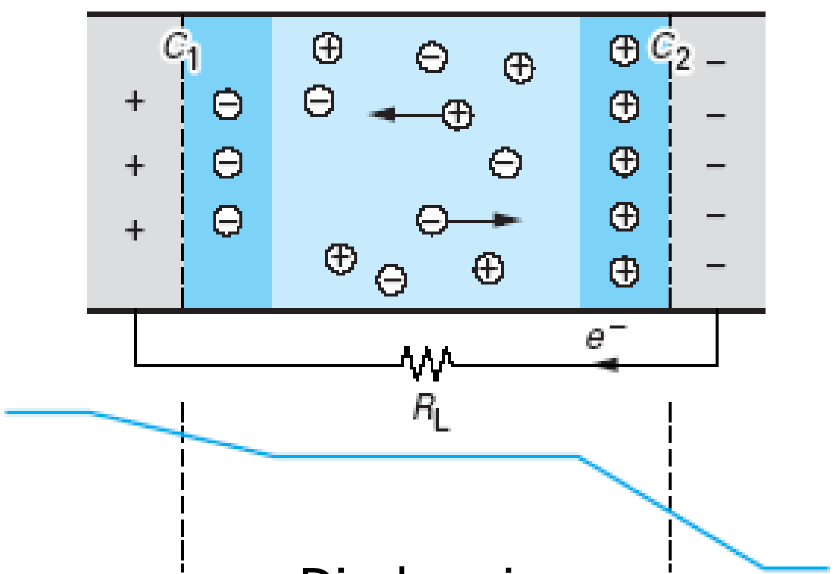


Charging

Supercapacitors: principle



Charged state



Discharging

Supercapacitors

- An electric double layer occurs at the boundary of the electrode and the electrolyte.
- The electric double layer works as an insulator when voltage stays below the decomposition voltage of water.
- Charge carriers are accumulated at the electrodes and one measures a capacitance

$$E = \frac{1}{2} C V^2$$

- Because of the double layer, one has two capacitances in series

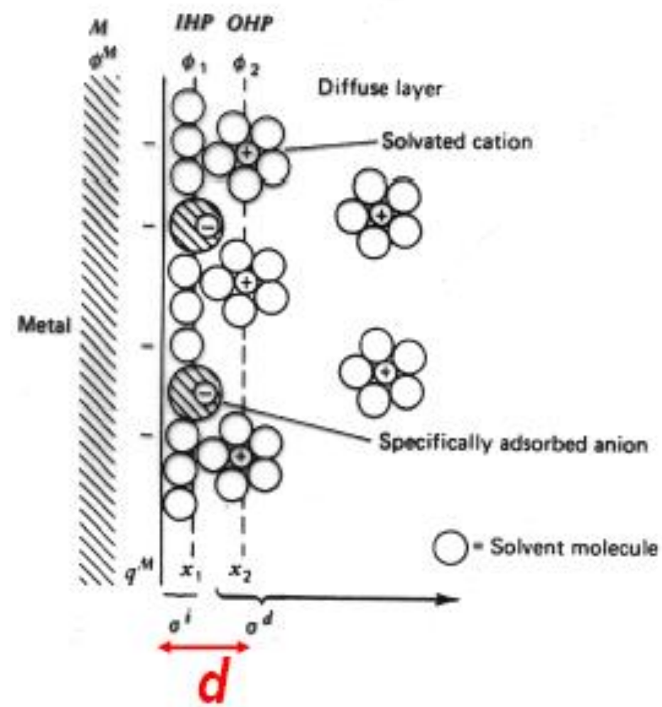
$$\frac{1}{C_{eq}} = \frac{1}{C_{anode}} + \frac{1}{C_{cathode}}$$

Electric double layer capacitor principles

- Capacitance

$$C_e = \frac{\varepsilon \, S}{d}$$

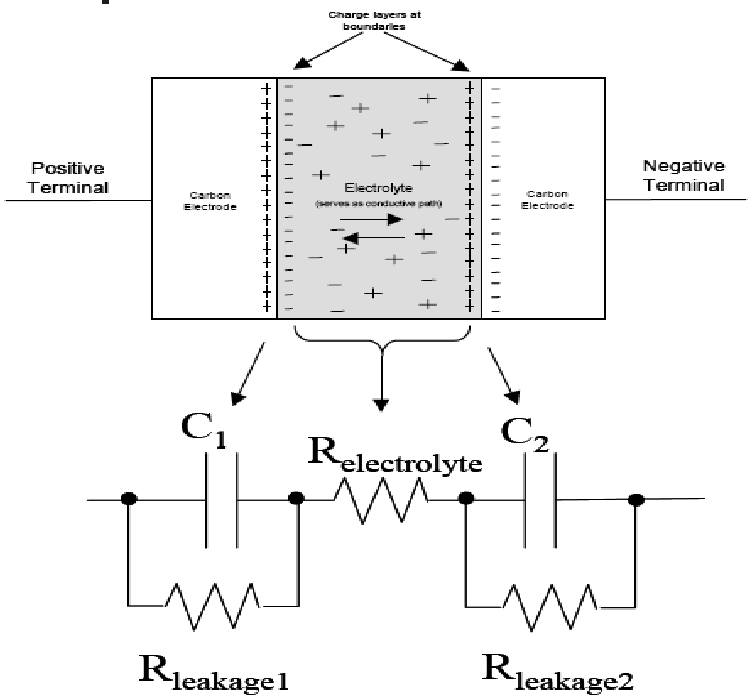
- Distance d of the layer ~1 nm
  - C ~ 0,1 F/m²
- Increase S: surface area of the electrode / electrolyte specific surface
  - For activated carbon, S depends on the micropores amount (<2nm)
  - S~1000 m²/g ➔ 100 F/g

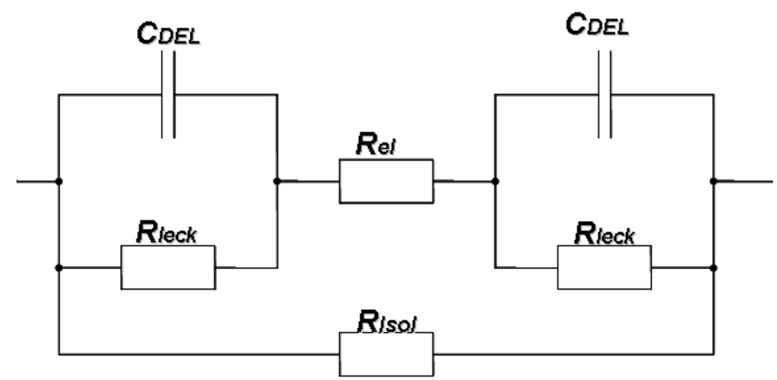


Supercapacitors

- Capacitors with double layers are limited to 0,9 volts per cell for aqueous electrolyte and about 2.3 to 2.3 V with non aqueous electrolyte
- Because the double layer is very thin (a couple of nanometers), capacity per area is high: 2,5 to 5 $\mu F/cm^2$
- With material with a high active area (1000 m^2/g) like activated carbon one gets a capacity about 50 F/g
  - $1000\ m^2/g \times 5\mu\ F/cm^2 \times 10000\ cm^2/m^2 = 50\ F/g$
- Assuming the same amount of electrolyte as carbon, one gets a capacity of 25 F/g
- However, the energy density is rather low: <10 Wh/kg (remind VRLA ~ 40 Wh/kg)

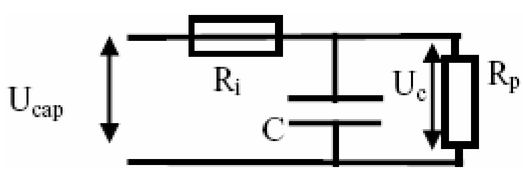
Supercapacitors: modeling





CDEL – Capacity of Double Electrical Layer
Rleak – Leakage Resistance
Rel – Electrolyte Resistance
Risol – Isolation Resistance

Ultracapacitors for Use in Power Quality and Distributed Resource Applications, P. P. Barker



Mierlo et al., Journal of Power Sources 128 (2004) 76–89

Supercapacitors: power electronics and load balancing

- Load balancing between the elementary supercaps is not required but it is recommended
- It has 2 purposes:
  - Keep the output voltage constant as the capacitor discharges (a simple boost converter can be used)

LINZEN *et al.*: ANALYSIS AND EVALUATION OF CHARGE-BALANCING CIRCUITS

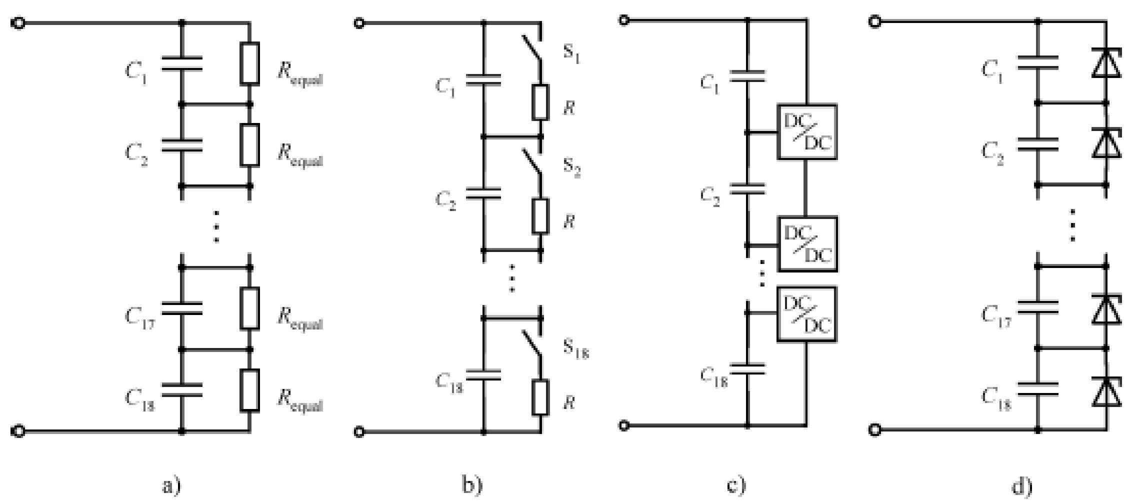
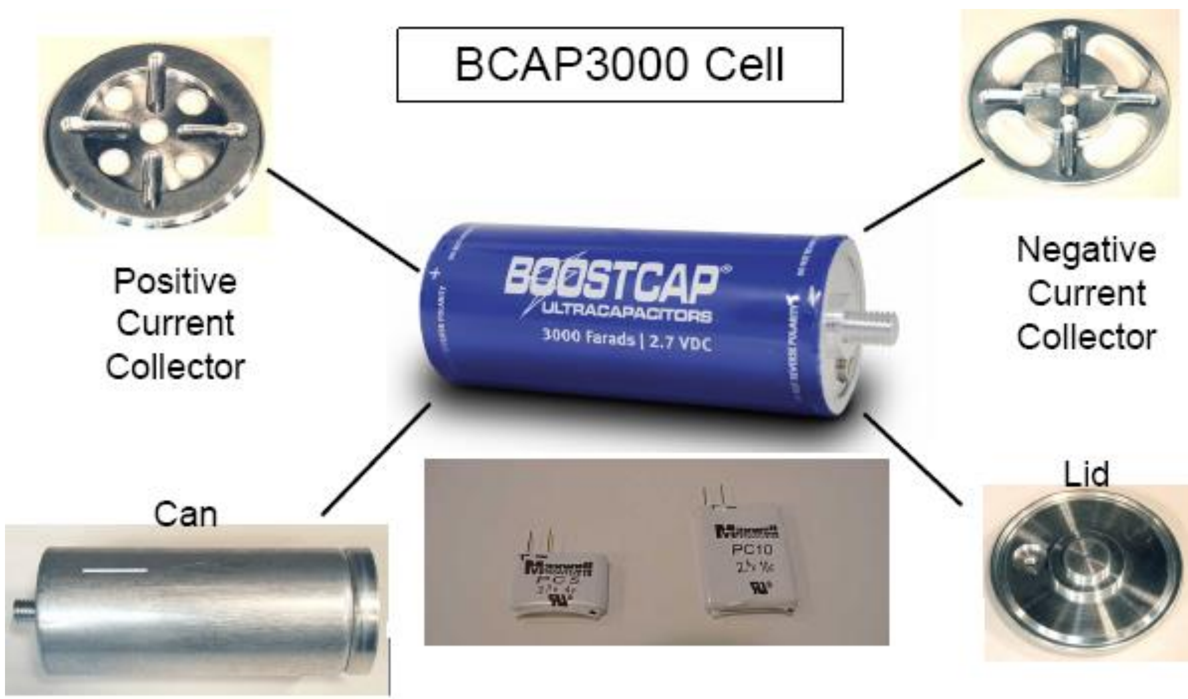


Fig. 2. Cell equalization circuits. (a) Resistor. (b) Switched resistor. (c) DC/DC converter. (d) Zener diodes.

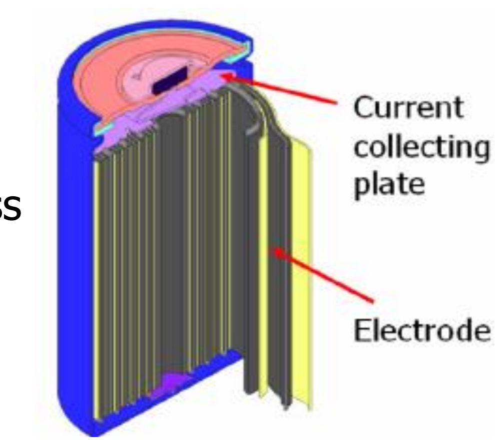
Supercapacitor technologies

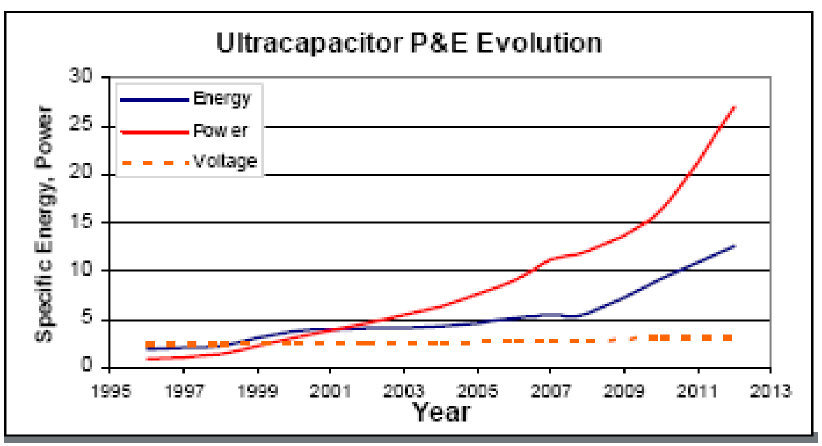
- The basic construction:
  - Jelly roll having end cap current collectors welded to scored electrode foils
  - Lid to can rolled seals and pressure fuse for 15bar.
  - Insulating sleeve with manufacturer trademark, ratings and polarity marks.



Supercapacitor technologies

- Ultra-capacitor performance improvements
  - Increase current collector foil thickness
  - Higher conductivity electrolyte
  - Increase electrode reactive area
  - Researching new materials
  - New chemistries





- Ultra-capacitor energy improvements
  - Higher voltage from better Carbons, and Electrolytes
  - Possibly ions with higher valence

Supercapacitor technologies

- Some typical Maxwell's ultracapacitor packages:

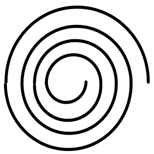
C =	650	1200	1500	2000	2600	3000	F
ESRac =	0.6	0.44	0.35	0.26	0.21	0.20	mΩ
ESRdc =	0.8	0.58	0.47	0.35	0.31	0.30	mΩ
τ =	0.52	0.696	0.705	0.700	0.806	0.900	s
I_{rms} =	105	110	115	125	130	150+	A_{rms}

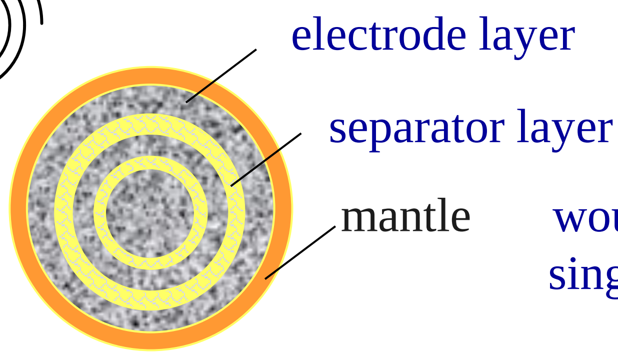
Source: www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf

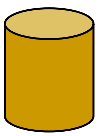
- At 2.7 V, a BCAP2000 capacitor can store more than 7000 J in the volume of a soda can.
- In comparison a 1.5 mF, 500 V electrolytic capacitor can store less than 200 J in the same volume.

Supercapacitor technologies

Traditional - wounded cells

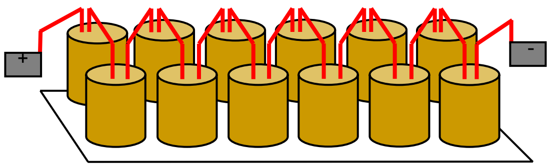






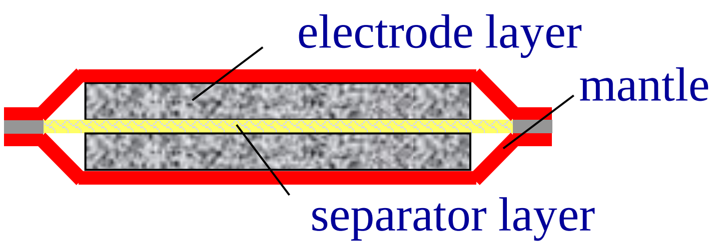
wound supercapacitor
single cell (schematic)

BALANCING SYSTEM



No balancing system required

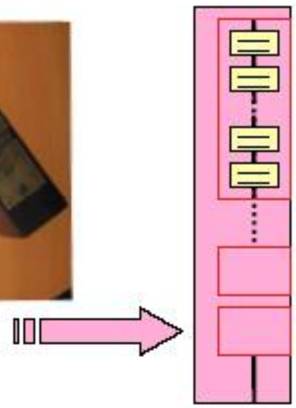
stacked cells



Comparison of SuperCaps technologies

Required Characteristics	**Aqueous Multi-stacked**	**Organic – Acetonitrile Winding assembly (foil)**	**Organic – PC Winding technology**
Based Cell Voltage	1,25V	+3V _3V	
Usual Cell Voltage	**1V**	**2,7V…2,8V**	**2,5V**
Assembly Voltage	0,7V	2,3 to 2,5V	2,1 to 2,3V
Max. Temperature	+100°C	+82°C	+80°C ?
Usual Max. positive	**+60, 80°C possible**	**+65°C**	**+65°C ?**
Usual Max. negative	-40°C	-35°C	<-25°C ?
Assembly	**Internally Stacked cells by design: N cells / 1 case**	Separated cell 1 cell / 1 case	Separated cell 1 cell / 1 case
Advantages	- Low rate of change serial resistance from -40° to +80°C - Integration cells in one case - Ready for high voltage, No external balancing necessary, - Very low chemical risk due to the electrolyte - Low cost material, - Easy recycling	- Highest cell voltage to highest energy density, - Wiring technology very compatible to mass production (automotive),	- High cell voltage to highest energy density, - Low chemical risk with the electrolyte, - Wiring technology very compatible to mass production,
Disadvantages	- Low cell voltage, - Mass production process (automotive) need to be demonstrated.	- Risk due electro-chemical composition of the electrolyte, - High voltage assembly require cells assembly in module	- Higher serial resistance at low temperature, - High voltage assembly require cells assembly in module.

SuperCaps: manufacturing technology



Winding techno. monocell organic electrolyte (ACN, PC)

(2,3-2,7V) 2600F…5000F…

Cell balancing required

Cells Assembly per module 10 to 20 cells

Electrical cells connexion required

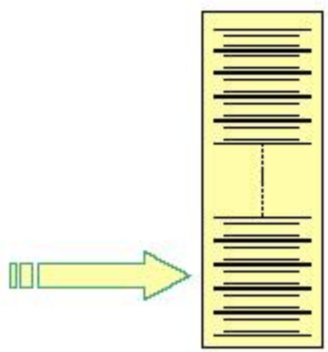
(20 to 50$\mu\Omega$ or more…)

Module Assembly per bloc (400-600V)

Electrolyte limit the maximal temperature

Manufacturers: Maxwell(USA), Batscap (F), Nescap (K), Panasonic (Jp),…

Railway demonstrators by Siemens, Bombardier



Stacked techno. Aqueous electrolyte

Integrated electrical connexion,

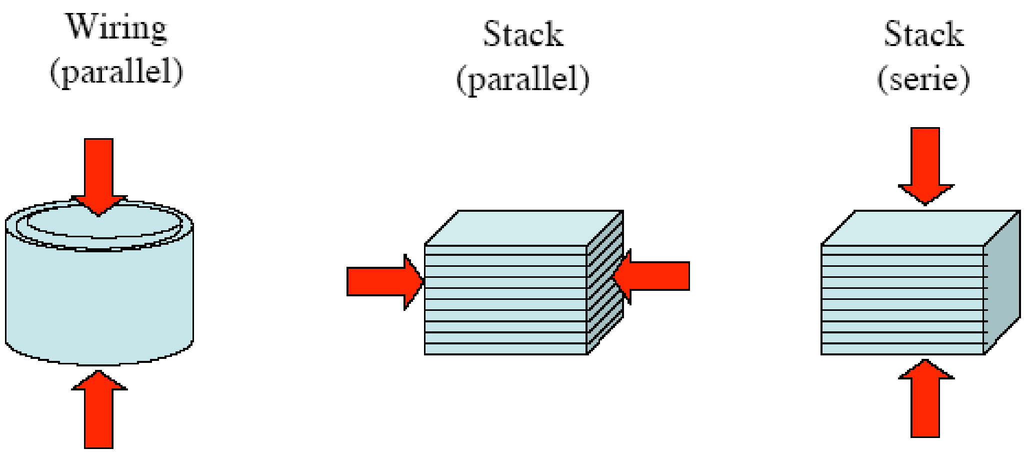
No voltage balancing,

(0,7V)14V…400V…1000V

260F…1F…?

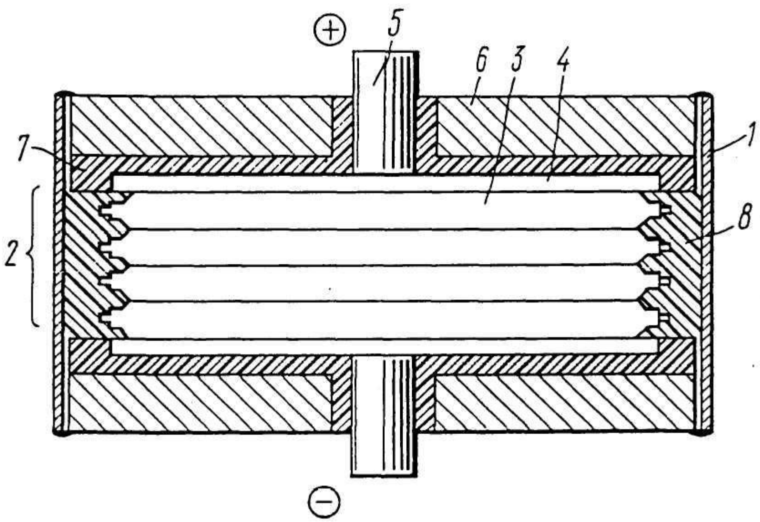
Manufacturers: ECON(Ru), ESMA (Ru),…

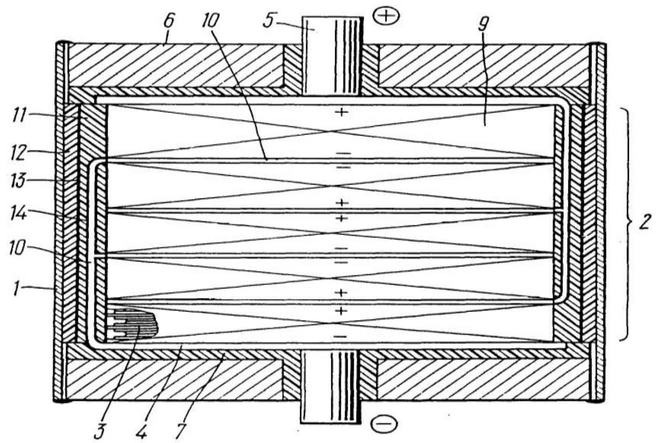
SuperCaps: manufacturing technology

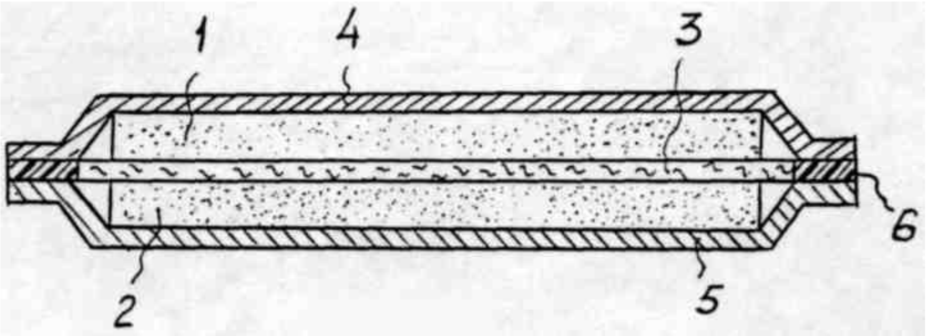


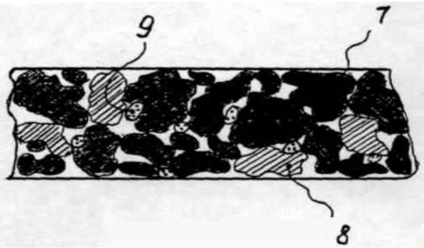
- Working environment:
- - Modular assembly and connection
- - Thermal exchange,
- - Electrical insulation
- - Failure mode

Supercapacitors: stacked constructions









Structure of Newcond GmbH supercaps

SuperCaps Manufacturers

Fabricant	Tecno. electrolyte	Techno. coil	<1000F	2000F 3000F	5000F	9000F 10000F	Production
Maxwell (USA)	ACN 2,8V	winding	Xc	Xc			Mass production
Batscap (Fr)	ACN (PC)	winding	Xc	Xc	Xc	Xc	Starting in 2008
NessCap (Ko)	ACN (PC)	winding	Xp	Xp	Xp		Production
LS (Ko)	ACN 2,8V (PC)	Winding Stack-p	Xc Xp	Xp			Production
Panasonic (Jp)	PC	Winding	Xc	Xc			Production
Nippon.Ch (Jp)	PC	Winding	Xc	Xc			Engineering ?
Nichicon (Jp)	PC	Winding	Xc	Xc			Engineering ?
Meidencha (Jp)	PC	? (Stack-s)		?	?		Special design?

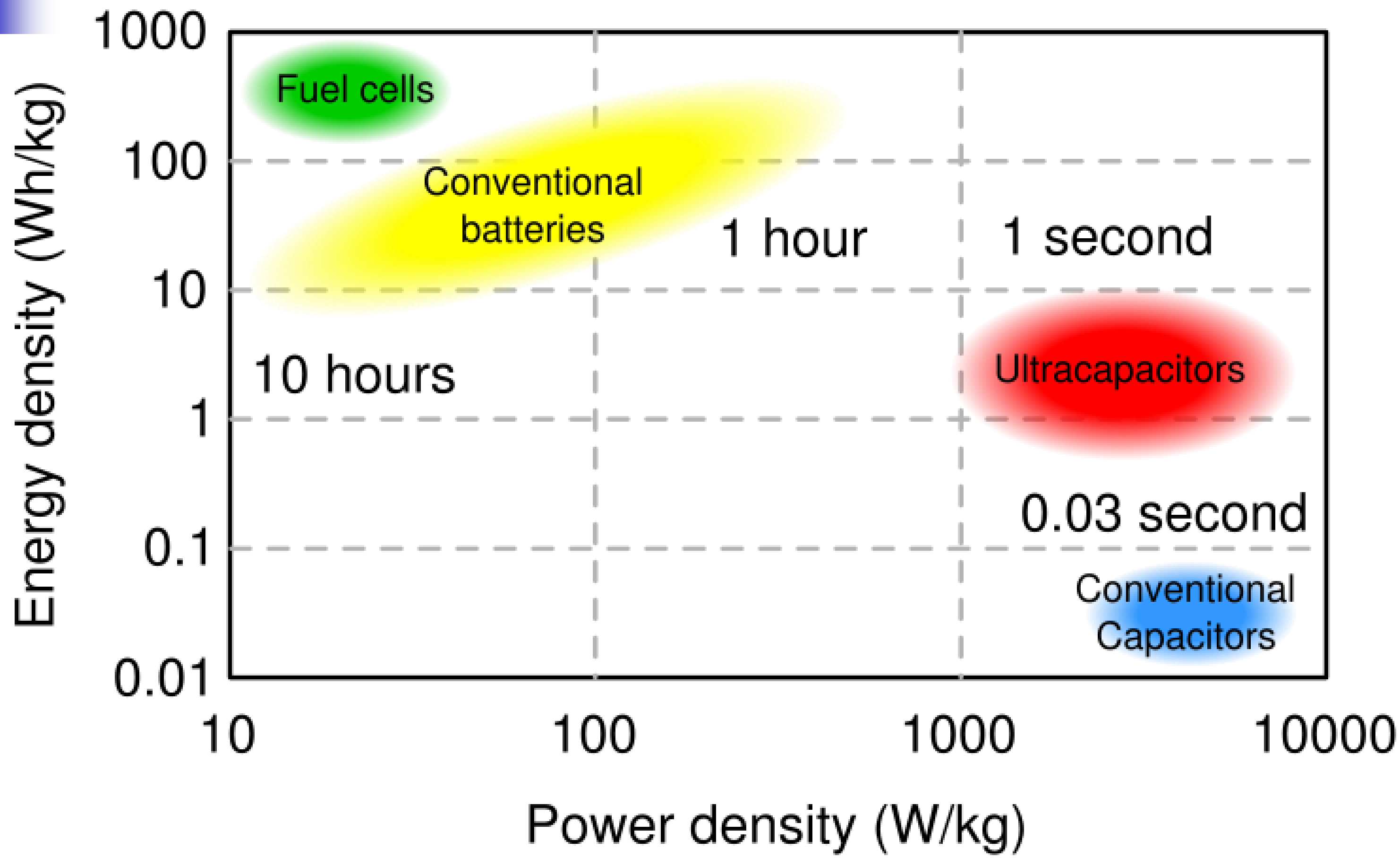
SuperCaps Manufacturers

Fabricant	Tecno. electrolyte	Techno . coil	100F <1000F	2000F 3000F	5000F	9000F 10000F	Production
Honda (Jp)	PC	Winding	Xc	Xc			Engineering ? Honda market ?
WIMA (Germany)	ACN or PC	winding	Xc				Production
ECON (Russia)	AQ	Stack-s Hi.Volt	Xc				Production
ESMA (Russia)	AQ	Stack-s Hi.Volt	Xc				Production
AVX-Bestcap (USA)	AQ	Stack-s	Xc				Mass production
APowerCap (USA-Ukrain-Russia)	AQ	winding	Xp				Production
EEStor (USA)	Barium titanate + Al-oxyde + glass	Stack-s	Xc				E.density:x50 Expected ?
to complete…							

Super capacitors and batteries

- Supercapacitors are distinguished from other classes of storing electrical energy devices such batteries
  - Absorb / release energy much faster: 100-1000 times: (Power density ~ 10 kW/kg)
  - Lower energy density (Energy density < 10 Wh/kg)
  - Higher charge / discharge current : 1000 A
  - Longer lifetime: > 100.000 charge discharge
  - Better recycling performances

Super capacitors and batteries

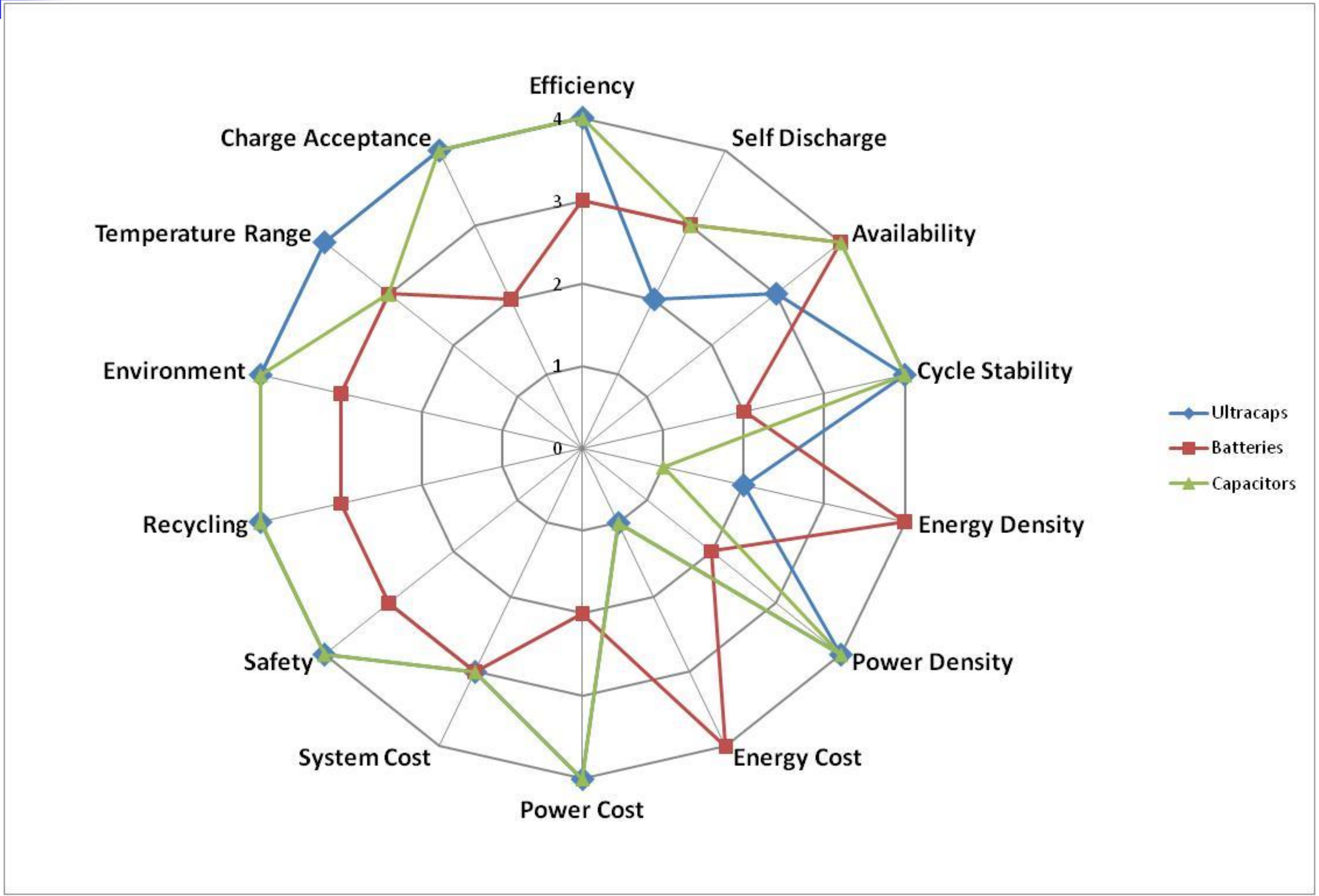


Super capacitors and batteries

	Battery	Supercapacitor	Capacitor
Energy Density (Wh/kg)	**10 to 100**	**1 to 10**	**0,1**
Specific Power (W/kg)	**< 1000**	**< 7000**	**< 100.000**
Charge Time	**1 to 5 hrs**	**0,3 to 30 s***	**10^{-3} to 10^{-6} s**
Life (cycles)	**1.000**	**> 500.000**	**> 500.000**

C.J. Farahmandi, Advanced Capacitor World Summit, San Diego,CA, July 2008 * 10^{-3} to 30 s

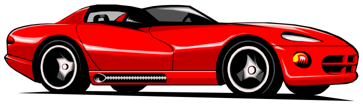
Super capacitors and batteries



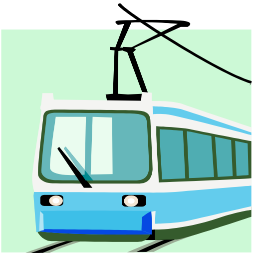
Envisioned applications

- Whenever a high power is requested for a short time (electric and hybrid vehicles, tramways, diesel engine starting, cranes, wind turbines, computers, lasers,…)
- Capacitors are generally combined with another energy source to increase power, to improve economic efficiency and to preserve ecological demand
- Capacitors can be used as buffer for later charging of a battery

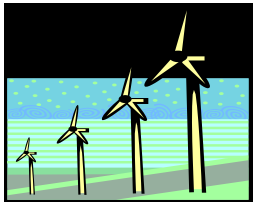
Envisioned applications



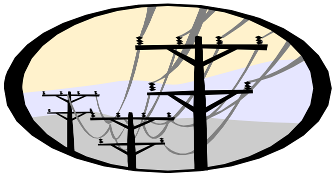
- Major component to low carbon economy: Enhancing energy efficiency
  - Mobile applications:
    - Hybrid propulsion systems
    - Automobile, railway



  - Stationary applications:
    - Clean Electrical Power
    - Smart grids including renewable energy sources



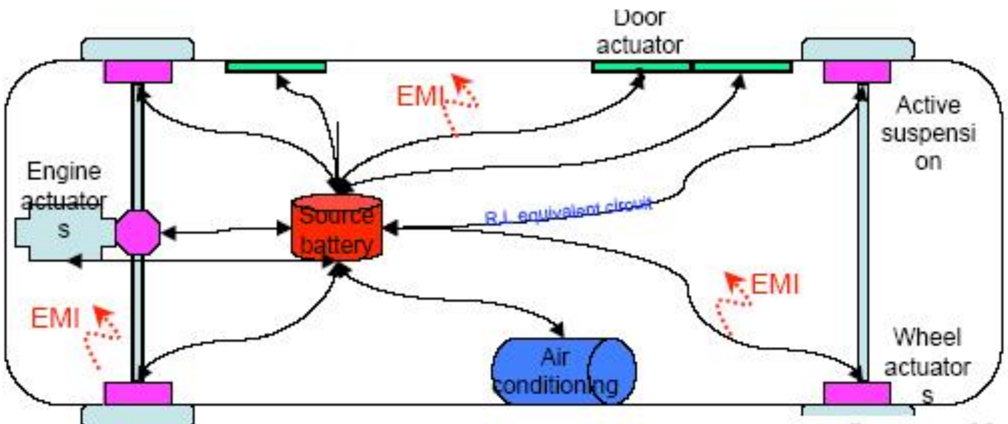
  - New applications
    - Mechatronic applications: All electric systems
    - Medical applications
    - Defense applications
    - Safety applications:
      - Emergency systems



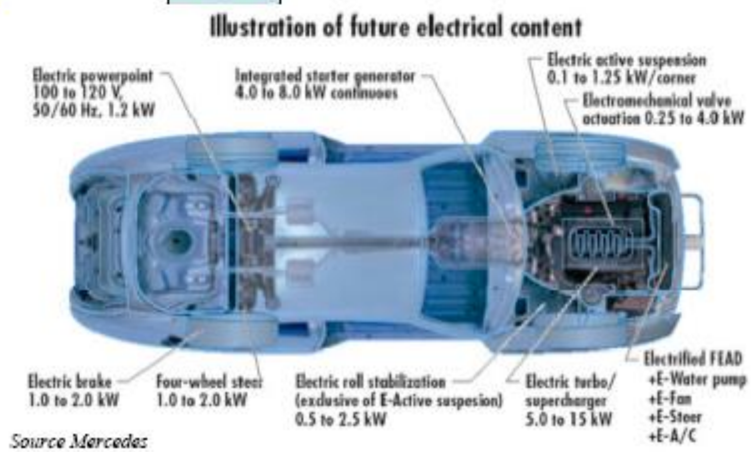
Transport applications

- Stop & Start of engines → 2020
  - Fast start devices of large Diesel engines
  - Start & stop of automobile engines
- Braking Energy recovery → 2020-2030
  - KERS systems
- Peak power source for acceleration → 2020-2030
  - Mild hybrid
- Sub-station stabilization → 2020-2030
  - Reduction of peak power stress
- Short range autonomy of railway vehicles → 2020-2030
  - Tramway and trolley in historical cities

Mechatronic applications



Electrical Actuators need Power & Energy distributed around the vehicle



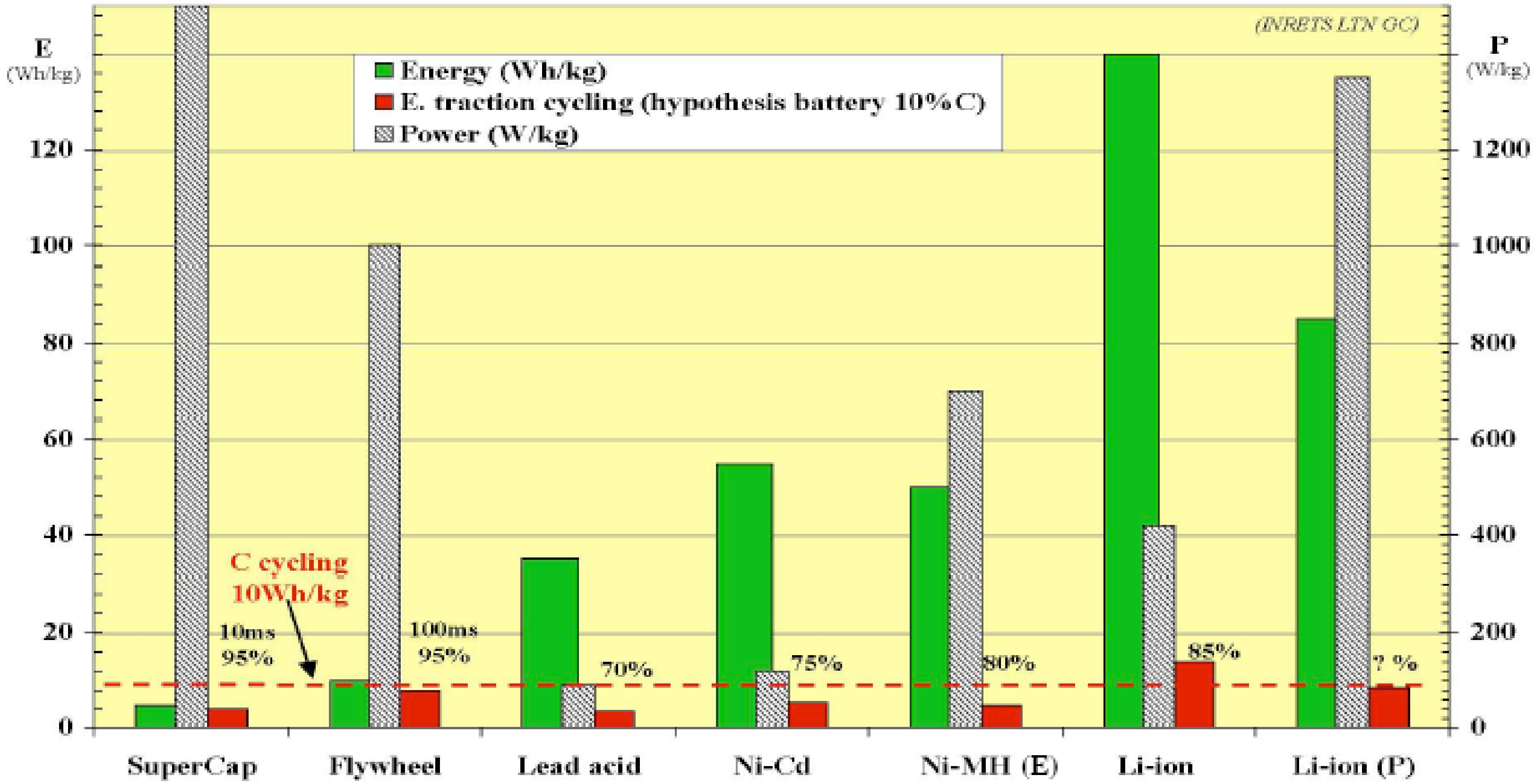
Criteria for power application in transport

- **Intrinsic performance:**
  - High cell voltage, energy density, max temperature 60°C (…80°C…)
  - New generation aqueous and stacked supercapacitors have to be pushed for high voltage and mechatronic
  - Applications
    - lowest ratio Rs / C (reduced losses)
      - *today: 200-300µΩ for 2600F-2,7V - 25°C (DC method) 100-200µΩ for 5000F-2,7V*
      - *tomorrow: < 100µΩ for 9000F-2,7V*
  - Power cycling reliability on vehicle mission profiles

Criteria for power application in transport

- **Assembly performances :**
  - lower total serial resistance (reduce contact resistance), stacked technology
  - simplification of cells balancing
- **Safety :** identified failure modes (gas leakage, …sealing box, neutralization gas) : opening case due to over pressure, or internal electrical disconnection
- **Systems interface :** high voltage DC bus level … high voltage assembly …chopper link
- **Maintenance strategy :** predictive solution, replacing cell strategy

Super capacitors and batteries



Supercapacitors: ECON

Type	Voltage (V)	Current (A)	Capacity (F)	Int. resist (Ohm)	Diameter (mm)	High (mm)	Weight (Kg)	Energy (Kj)	Power (KW)	Specific Energy (Wh/Kg)	Specific Energy (Kj/Kg)	Specific Power (KW/Kg)
9/14	14,0	670	95,00	0,0060	230	95	10	9,31	8,17	0,26	0,93	0,82
12/14	14,0	1350	130,00	0,0045	230	130	15	12,74	10,89	0,24	0,88	0,75
40/28	28,0	4000	104,00	0,0055	230	300	26	40,77	35,64	0,44	1,57	1,37
60/28	28,0	4000	160,00	0,0035	230	380	37	62,72	56,00	0,47	1,70	1,51
90/200	200,0	1100	4,50	0,2000	230	550	36	90,00	50,00	0,70	2,50	1,39
60/260	260,0	1000	1,75	0,3000	230	630	50	59,15	56,33	0,33	1,18	1,13
20/300	300,0	1000	0,44	0,3000	230	200	24	19,80	75,00	0,23	0,83	3,13
40/300	300,0	1000	0,90	0,3750	230	490	40	40,50	60,00	0,28	1,01	1,50
90/300	300,0	1000	2,00	0,3000	230	570	38	90,00	75,00	0,66	2,37	1,97
18/350	350,0	1000	0,30	0,4000	230	310	29	18,38	76,56	0,18	0,63	2,64
40/400	400,0	1000	0,50	0,4000	230	380	32	40,00	100,00	0,35	1,25	3,13
64/400	400,0	1000	0,80	0,4000	230	660	50	64,00	100,00	0,36	1,28	2,00
36/700	700,0	1000	0,15	0,7000	230	420	36	36,75	175,00	0,28	1,02	4,86

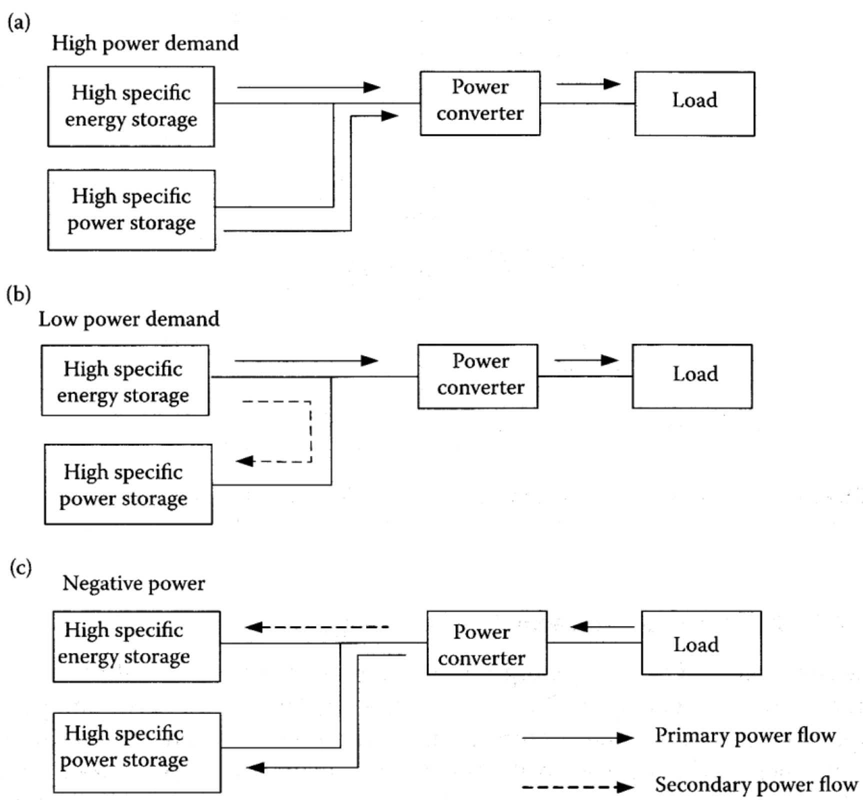
Hybridization of Energy Sources

Hybrid energy storage systems

- The hybridization of energy storages involves combining two or more energy storages together to take advantages of each one can bring while disadvantages of each can be compensated by the other ones.
- Example: hybridization of a chemical battery with a supercapacitor can overcome:
  - Low specific power of batteries
  - Low specific energy of supercapacitors
- The systems aims at exhibiting simultaneously the best properties of each of the two technologies i.e. high energy density and high-power density.
- In this way the whole system is much smaller in weight than if any one of them was considered alone in the sizing.

Hybrid energy storage systems

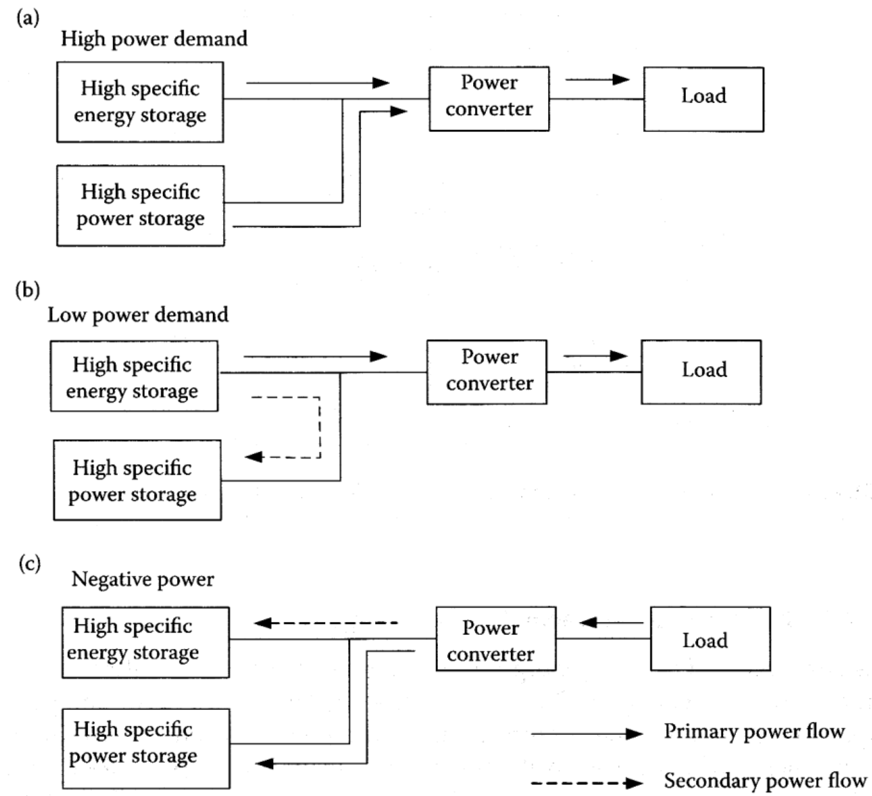
- Basic concept of operations of hybrid energy storage systems
- (a) hybrid powering: in high power demand operations: acceleration, hill climbing. Both energy components deliver their power to the load.



Ehsani et al. Fig 13.18

Hybrid energy storage systems

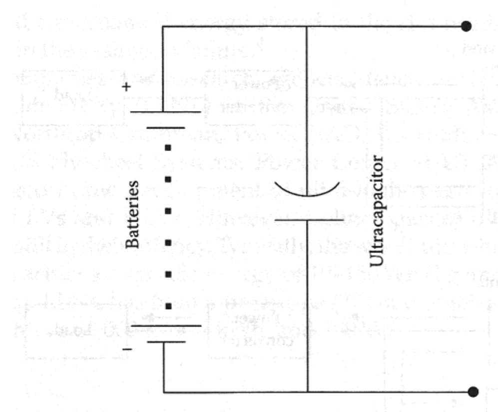
- (b) power split: during low power demand operation such as constant speed, the high specific energy components deliver the power to wheels and charges the high-power component to recover charge loss during acceleration.
- (c) hybrid charging: in regenerative braking, the peak power is absorbed by the high specific power component (Scap). Only a limited part is taken by the high-density component i.e. the battery.



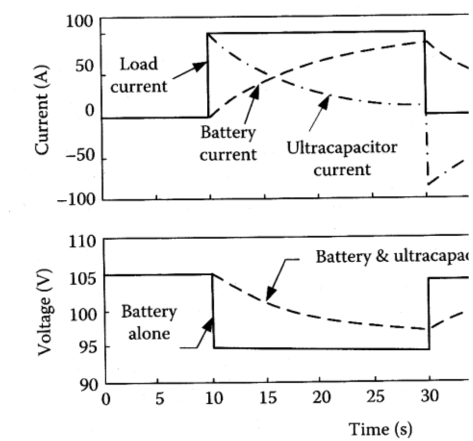
Ehsani et al. Fig 13.18

Hybrid energy storage systems

- There are several viable hybridization schemes for EVs and HEVs: battery + battery hybrids or battery + Supercapacitors
- The simplest way to combine batteries and supercapacitors is to connect them in parallel.
- In this configuration, the supercapacitor acts as a current filter which can significantly level the peak current of the batteries and reduce the voltage drop.



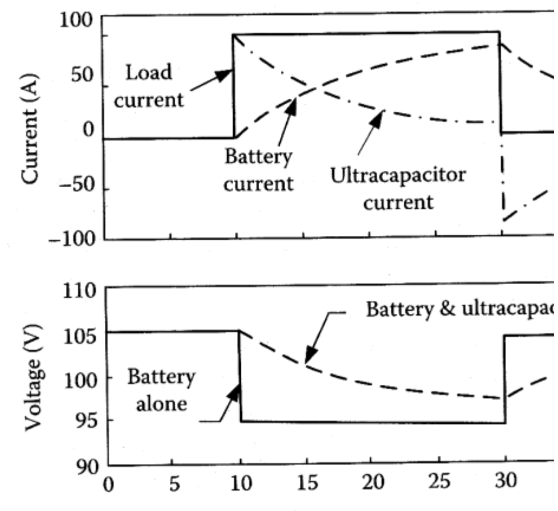
Ehsani et al. Fig 13.19

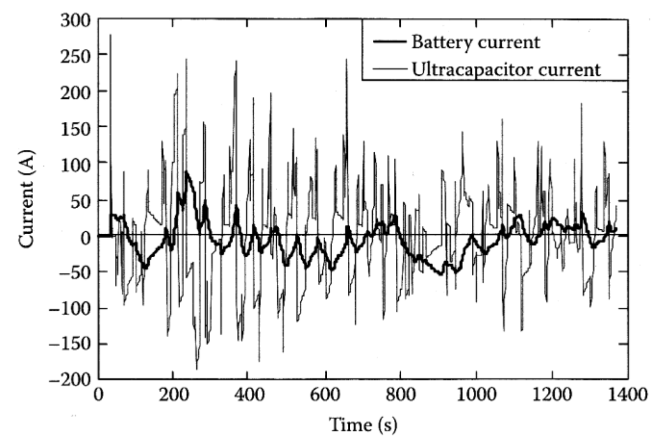


Ehsani et al. Fig 13.20

Hybrid energy storage systems

- In configuration in which the supercapacitor and the batteries are connected in parallel, the supercapacitor acts as a current filter which can significantly level the peak current of the batteries and reduce the voltage drop.
- The major drawback of the parallel connection is that the power flow cannot be actively controlled and the ultracapacitor energy cannot be fully used.

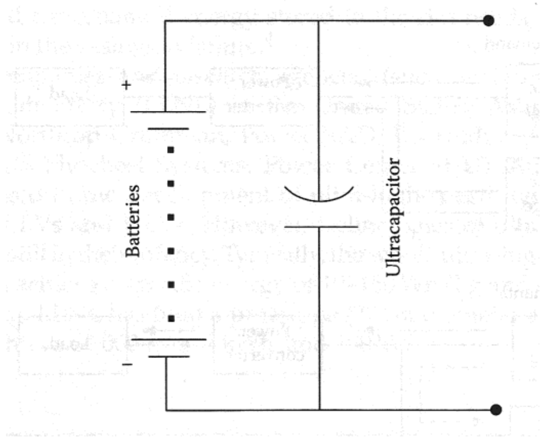




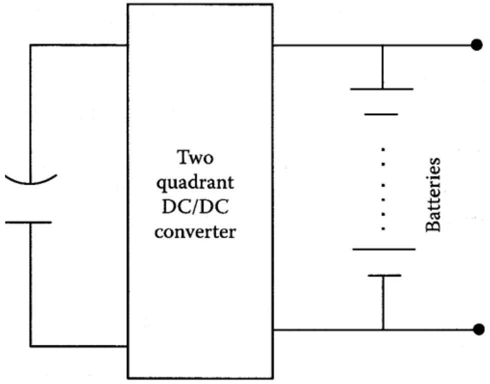
Ehsani et al. Fig 13.20 & 21

Hybrid energy storage systems

- A more complex and smarter way to combine batteries and supercapacitors is to connect them via a two-quadrant DC/DC converter.
- The design allows batteries and ultracapacitors to have different voltages.
- The power flow can be actively controlled, and the energy of the supercapacitor can be fully used.
- In the future supercaps can be substituted by ultra-high-speed flywheels in the hybrid system.



Ehsani et al. Fig 13.19



Ehsani et al. Fig 13.22

Hybrid energy storage systems

TABLE 12.5

Major Parameters of CHPS Battery Alternative at Standard Testing[8]

CHPS Battery Alternative	Specific Energy (Wh/kg)	Specific Power (W/kg)	Energy/Power (h)
Lead–acid	28	75	0.373
NiCd	50	120	0.417
Ni–MH	64	140	0.457
Li–I (CHPS)[a]	100	1000[b]	0.1

[a] Combat Hybrid Power System sponsored by TACOM.
[b] Power capabilities depend on pulse length and temperature.

TABLE 12.6

Characteristic Data of a 42-V Ultracapacitor[7]

Rated capacitance (DCC[a], 25°C)	(F)	145
Capacitance tolerance	(%)	±20
Rated voltage	(V)	42
Surge voltage	(V)	50
Max. series resis., ESR (DCC, 25°C)	(mΩ)	10
Specific power density (42 V)	(W/kg)	2900
Max. current	(A)	600
Max. stored energy	(J)	128,000
Specific energy density (42 V)	(Wh/kg)	2.3
Max. leakage current (12 h, 25°C)	(mA)	30
Weight	(kg)	15
Volume	(l)	22
Operating temperature	(°C)	−35 to +65
Storage temperature	(°C)	−35 to +65
Lifetime (25°C)	(year)	10, C < 20% of initial value, ESR < 200% of initial value
Cyclability (25°C, $I = 20$ A)		500,000, C < 20% of initial value ESR < 200% of initial value

[a] DCC: discharging at constant current.

Hybrid energy storage systems

ABLE 12.7

haracteristic Data of a 42-V Ultracapacitor[7]

	Lead/Acid	Ni/Cd	Ni/MH	Li–I	Ultracap
pecific power (W/kg)	75	120	140	1000	2500
pecific energy (Wh/kg)	30	50	64	100	2
tal weight (kg)	667	417	357	50	1750

ABLE 12.8

Characteristic Data of a 42-V Ultracapacitor[7]

	Lead/Acid	Ni/Cd	Ni/MH	Li–I
pecific power (W/kg)	378.5	581.4	703	1222
pecific energy (Wh/kg)	26.5	40.7	49.2	85.5
attery weight (kg)	116	69	54	35
Jltracap weight (kg)	16.5	16.7	16.9	6.05
otal weight (kg)	132	86	71	41

- The illustrative example shows the sizing energy / power storage for VRAL, Ni/Cd, NiMH or Ucap alone.
- Optimized hybrid energy storage system definitely exhibits a much smaller mass while satisfying both energy and power specifications.

Flywheels

Flywheels

- Principle: Storing energy as kinetic energy in high speed rotating disk

- Idea developed 25 years ago in Oerlikon Engineering company, Switzerland for a hybrid electric bus
  - Weight = 1500 kg and rotation speed 3000 rpm

- Traditional design is a heavy steel rotor of hundreds of kg spinning at ~1.000 rpm.

- Advanced modern flywheels: composite lightweight flywheels (tens of kg) rotating at ~10.000 rpm

Flywheels

- A rotating flywheel stores the energy in the kinematic form

$$E_k = \frac{1}{2} J_f \omega_f^2$$

J_f= moment of inertia and ω_f= rotation speed

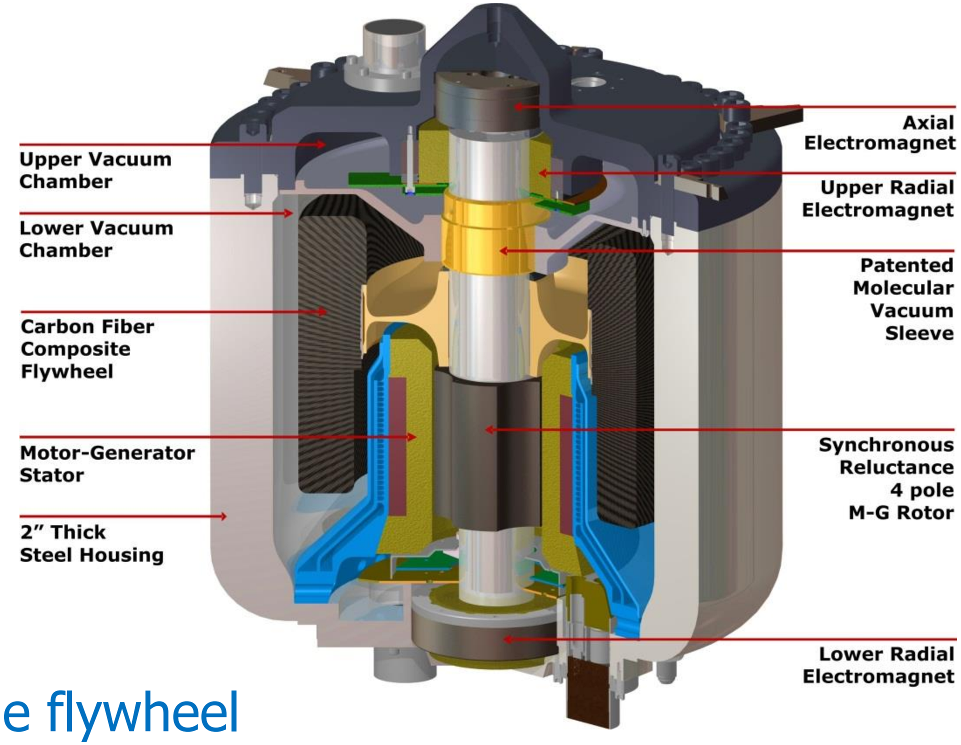
- The formula indicates that enhancing the rotation velocity is the key to increasing the energy storage. One can achieve nowadays rotation speed of 60,000 rpm
- First generation of flywheel energy storage systems used a large steel flywheel rotating on mechanical bearings.
- Modern systems use carbon-fiber composite rotors that have a higher tensile strength than steel and are an order of magnitude lighter.

Flywheels

- With this current technology it is difficult to couple directly the flywheel to the propelling system of the car.
- One would need a continuous variable transmission with a wide gear ratio variation range.
- The common approach consists in coupling an electric machine to the flywheel directly or via a transmission: One makes a 'mechanical battery'
- The electric machine operates as the energy input / output port converting the mechanical energy into electrical energy and vice-versa

Flywheels

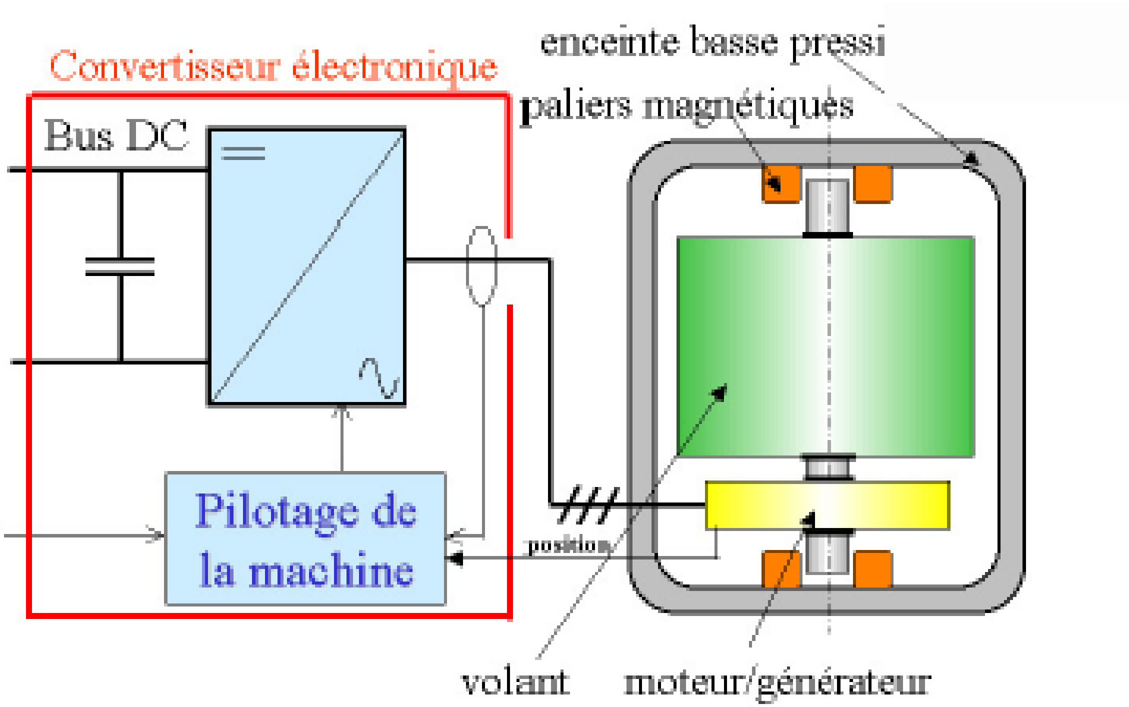
- A typical system consists of a rotor suspended by bearings inside a vacuum chamber to reduce friction and connected to a combination electric motor/electric generator.



Pentadyne flywheel

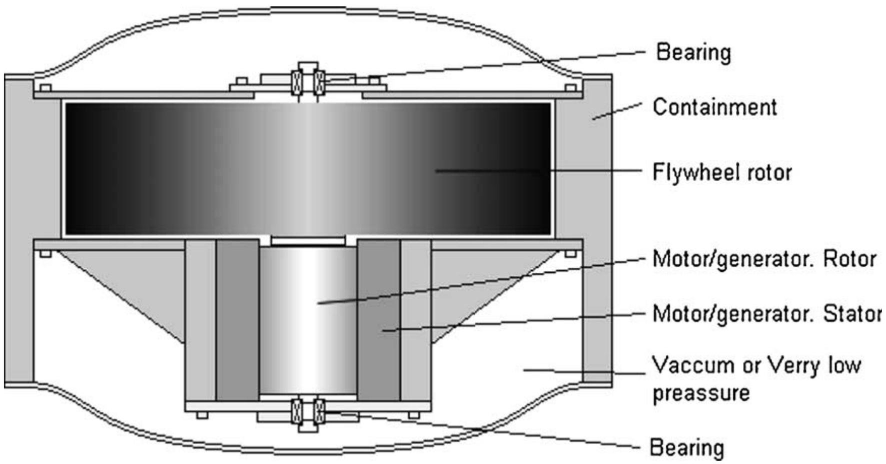
Flywheels

- In order to reduce the friction (hence, losses) the disc is usually in a vacuum chamber and uses magnetic bearings.

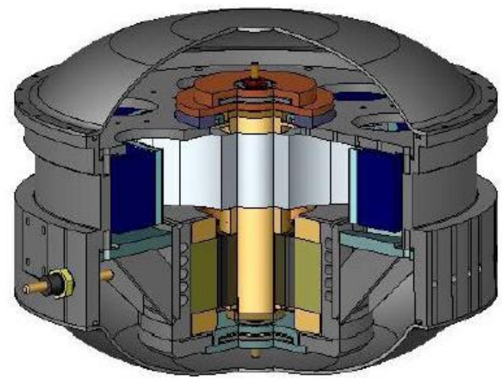


Bernard et al., Flywheel Energy Storage Systems In Hybrid And Distributed Electricity Generation

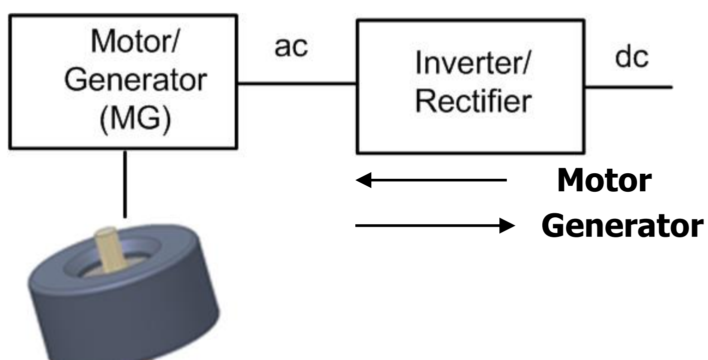
Flywheels



B. Bolund et al. / Renewable and Sustainable Energy Reviews 11 (2007) 235–258

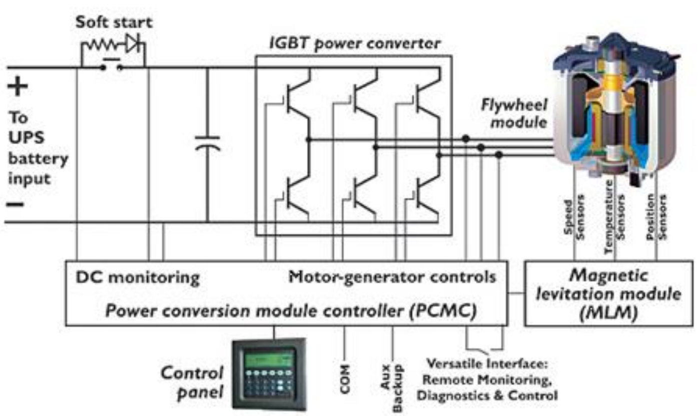


Flywheels Energy Systems



Flywheels

http://www.vyconenergy.com



http://www.pentadyne.com

Flywheels

- Kinetic energy: $E = \frac{1}{2} J \, \omega^2 \qquad J = \int_\Omega r^2 \, dm$
- where J is the moment of inertia and ω is the angular velocity of a rotating disc. $J = m \, R^2 \qquad m = \pi \, R^2 \, a \, \rho$
- For a cylinder the moment of inertia is $J = \pi \, R^4 \, a \, \rho$
- So the energy is increased if ω increases or if J increases.
- Inertia can be increased by locating as much mass on the outside of the disc as possible.
- But as the speed increases and as more mass is located outside of the disc, mechanical limitations become more important.

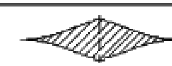
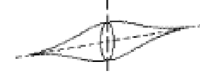
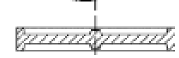
Flywheels

- Disc shape and material: the maximum energy density *e* per unit mass and the maximum tensile stress are related by:

$$e = K\,\frac{\sigma_{max}}{\rho}$$

- Typically, tensile stress has 2 components: radial stress and hoop stress.

Table 1
Shape-factor K for different planar stress geometries

Fly wheel geometry	Cross section	Shape factor K
Disc		1.000
Modified constant stress disc		0.931
Conical disc		0.806
Flat unpierced disc		0.606
Thin firm		0.500
Shaped bar		0.500
Rim with web		0.400
Single bar		0.333
Flat pierced bar		0.305

Flywheels

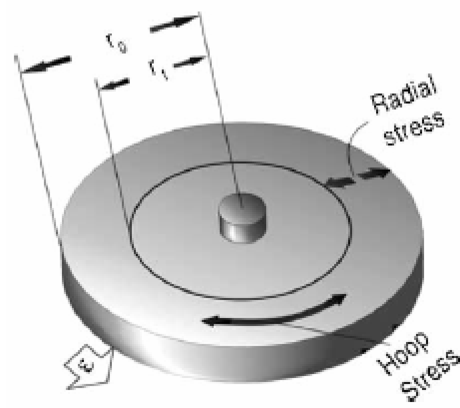
- Disc shape and material: the maximum energy density *e* per unit mass and the maximum tensile stress are related by:

$$e = K\sigma_{max}/\rho$$

- Material can be selected to present the high resistance stress

Table 2
Data for different rotor materials

Material	Density (kg/m^3)	Tensile strength (MPa)	Max energy density (for 1 kg)	Cost ($/kg)
Monolithic material 4340 Steel	7700	1520	0.19 MJ/kg = 0.05 kWh/kg	1
Composites				
E-glass	2000	100	0.05 MJ/kg = 0.014 kWh/kg	11.0
S2-glass	1920	1470	0.76 MJ/kg = 0.21 kWh/kg	24.6
Carbon T1000	1520	1950	1.28 MJ/kg = 0.35 kWh/kg	101.8
Carbon AS4C	1510	1650	1.1 MJ/kg = 0.30 kWh/kg	31.3



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Flywheels

- Since

$$e_m = K\sigma_{max}/\rho \tag{1}$$

- and

$$E_k = \frac{1}{2}J\omega^2 \tag{2}$$

- and

$$J = m\,R^2 \tag{3}$$

- then, from (2) and (3)

$$e_m = E/m = \frac{1}{2}R^2\omega^2 = \frac{1}{2}V^2 \tag{4}$$

- So, replacing (1) in (4) it yields

$$V_{max} = \sqrt{\frac{2K\sigma_{max}}{\rho}}$$

Flywheels

- However, high speed is not the only mechanical constraint
- If instead of holding output voltage constant, output power is held constant, then the torque needs to increase (because P = Tω) as the speed decreases. Hence, there is also a minimum speed at which no more power can be extracted
- The useful energy (E_u) proportional to the difference between the disk energy at its maximum and minimum allowed speed is compared with the maximum allowed energy (Emax) then

$$V_r = \frac{V_{max}}{V_{min}} \qquad \frac{E_u}{E_{max}} = \frac{V_r^2 - 1}{V_r^2}$$

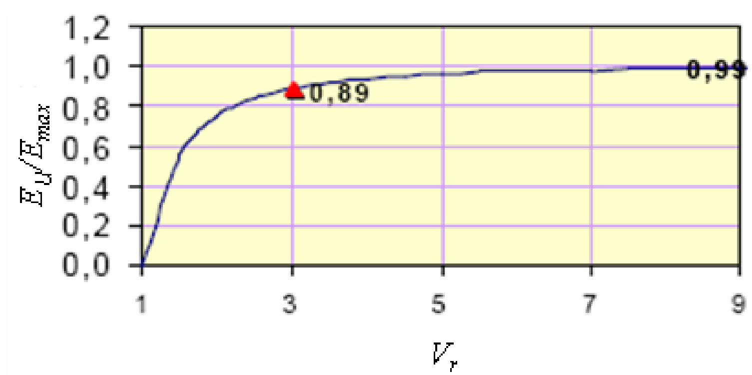

Fig. 4: Evolution in useful energy vs. V_r

Flywheels

- Motor / generators are typically permanent magnet machines. There are 2 types: axial flux and radial flux.
- AFPM can usually provide higher power and are easier to cool.

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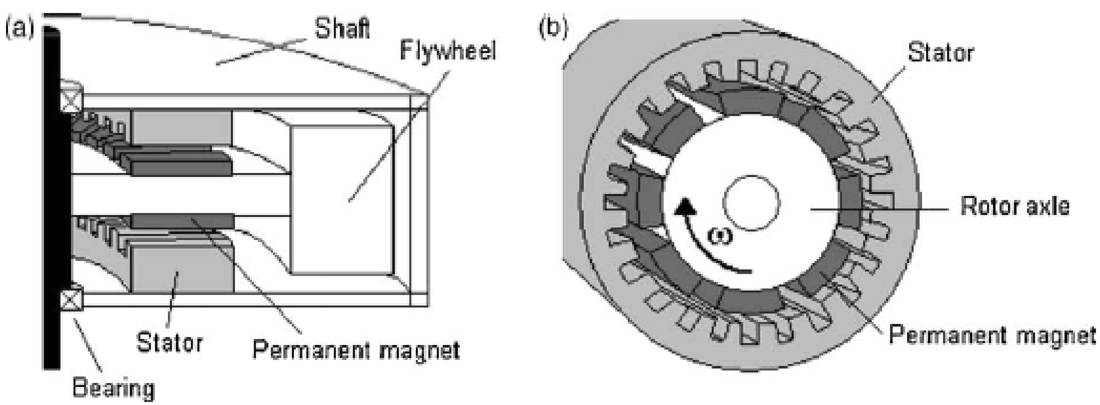
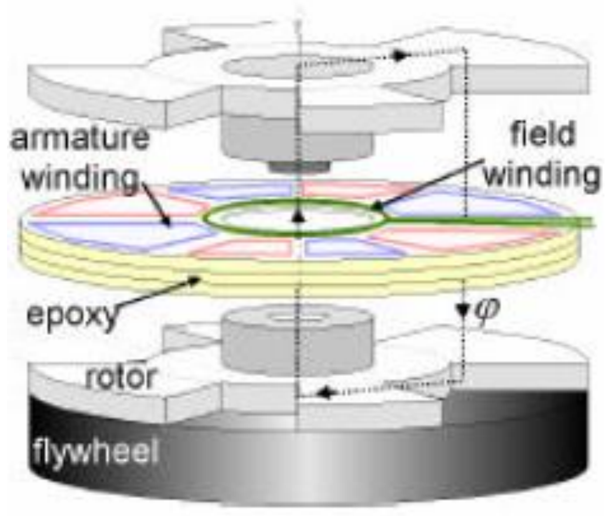


Fig. 3. (a) show an AFPM machine arrangement and (b) show an RFPM machine arrangement.

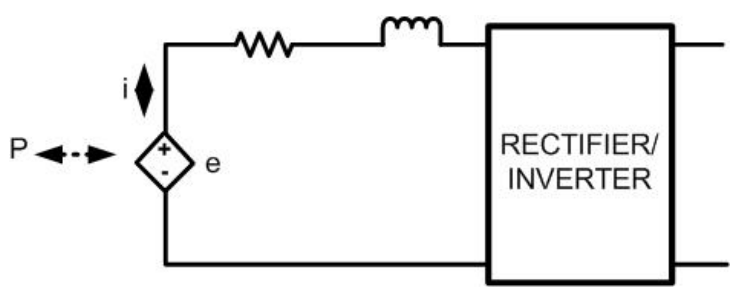


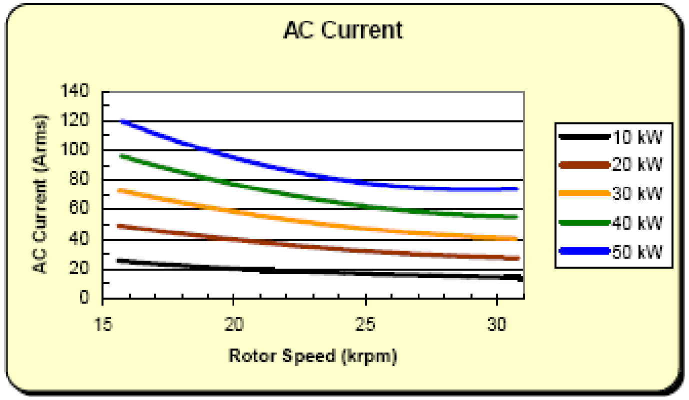
Overview of the homopolar axial synchronous motor/generator

Source: Bernard et al., Flywheel Energy Storage Systems In Hybrid And Distributed Electricity Generation

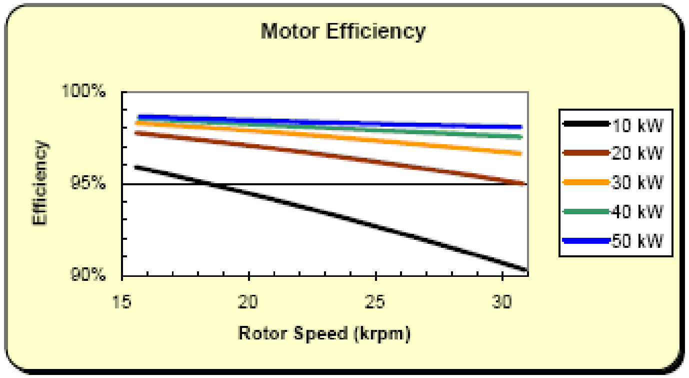
Flywheels

- Simplified dynamic model





- Its typical output



Comparison of energy storage systems for electric and hybrid vehicles

Energy and peak power storages

- Different types of batteries:
  - Lead-Acid: developed since 1900 with a high industrial maturity
  - Ni-Cd : developed from 1930ies, with an industrial maturity
  - Na Ni Cl (Zebra): since 1980ies small series
  - NiMH: since 1990ies, industrial production
  - Li-Ions: still under industrial development

- Peak power sources:
  - Double layer super capacitors
  - High speed flywheels

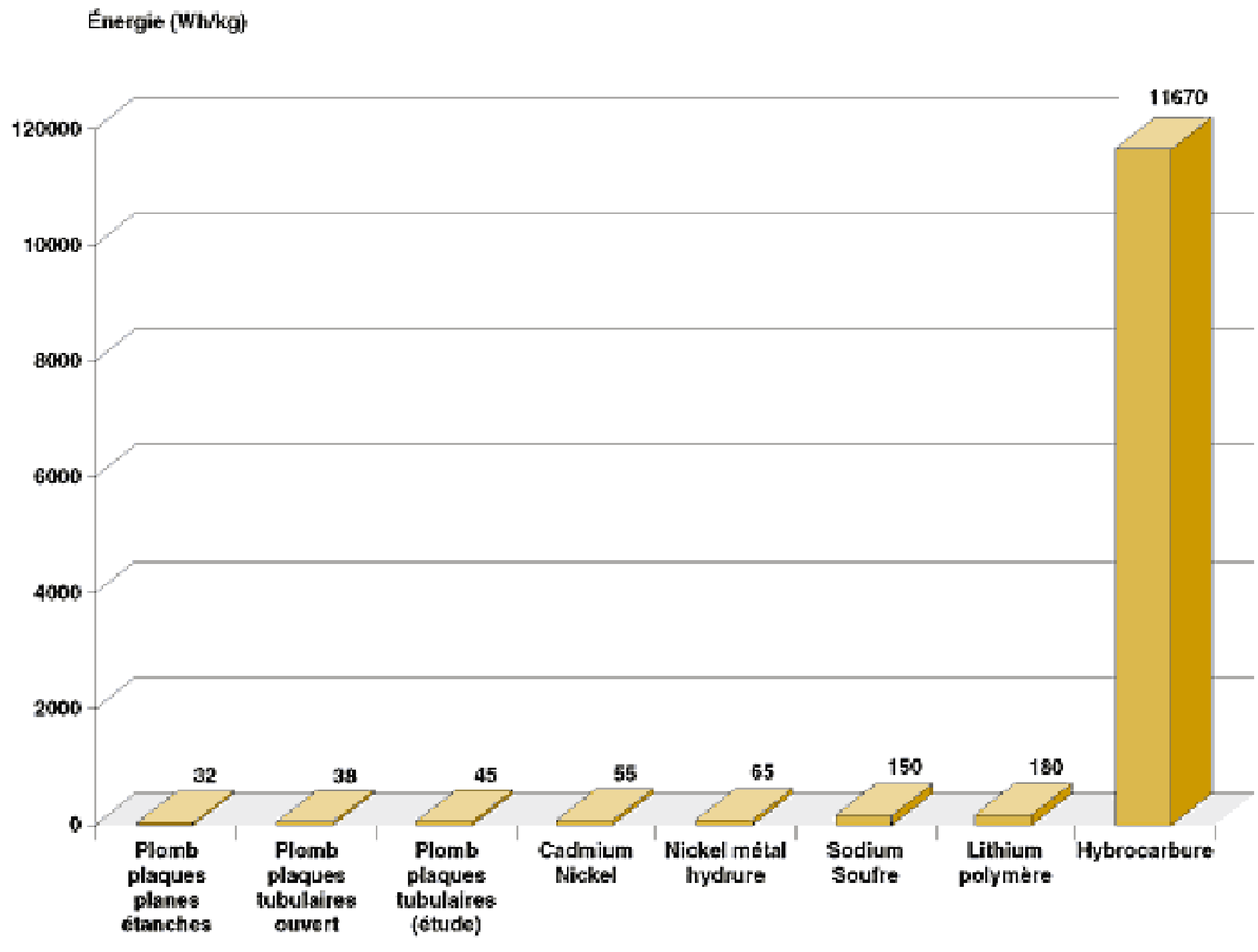
Energy and peak power storages

- Performance criteria for selection (decreasing importance):
  - Specific energy (W.h/kg)
  - Specific power (W/kg)
  - Number of charge cycles
  - Life time
  - Specific cost
  - Charge discharge efficiency
  - Voltage
  - Volume
  - Recycling

Traction batteries

Batteries	Lead acid	Ni-Cd	Ni-MH	Zebra	Li-Ions
Specific energy [W.h/kg]	35-50	50-60	70-95	74	80-130
Specific power [W/kg]	150-400	80-150	200-300	148	200-300
Charge discharge efficiency [%]	>80%	75	70	85	90-95
Life time [cycles]	500-1000	800	750-1200	1200	1000+
Cost [$/kW.h]	120-150	250-350	200-350		200

Problem of batteries w.r.t. fuels

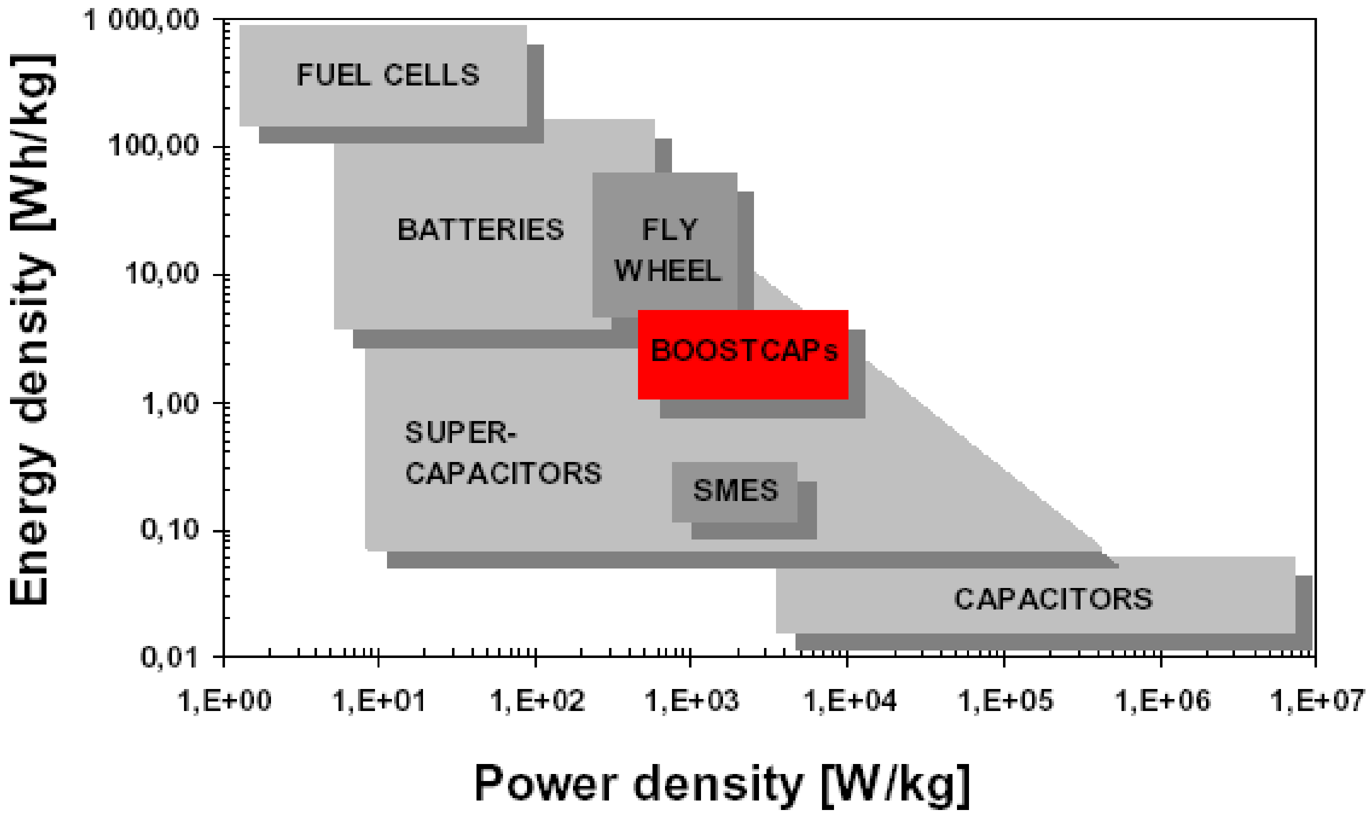


Problem of batteries w.r.t. fuels

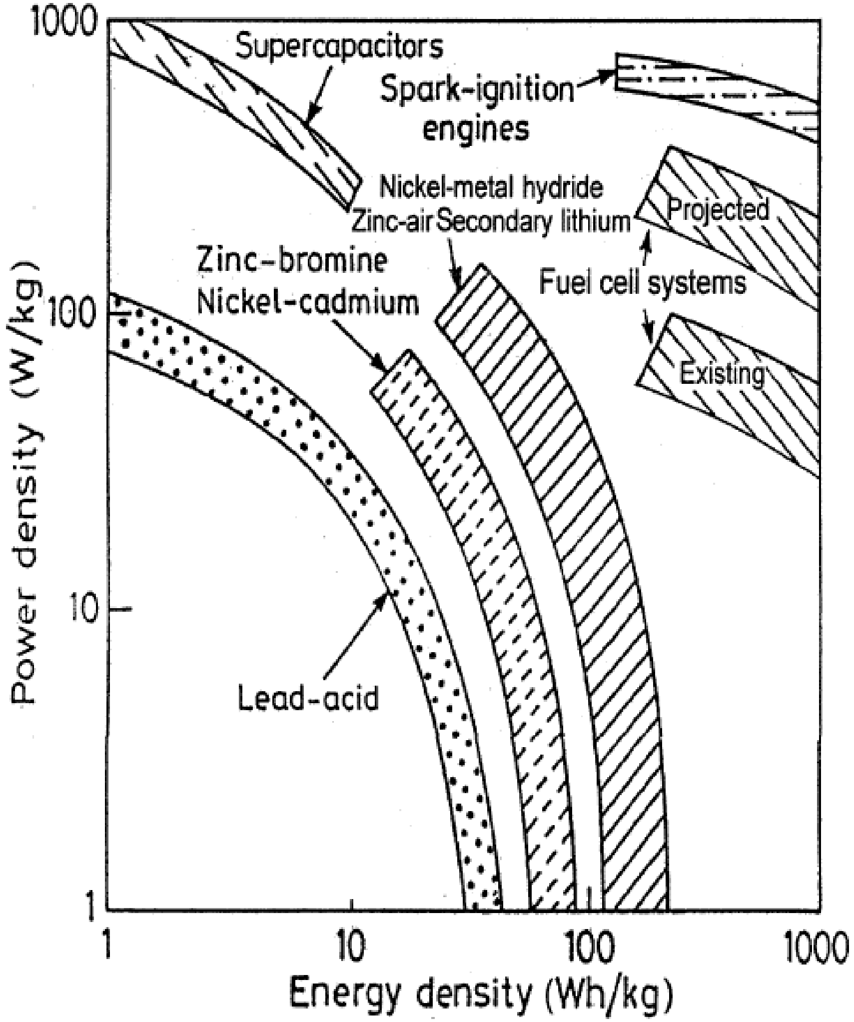
Fuel	Gasoline	Diesel	Li-Ions
Specific energy / PCI [W.h/kg]	11.833	11.667	105
Mean conversion efficiency in vehicle [%]	12	18	80
Specific energy at wheel [W.h/kg]	1420	2100	84

Facteur 200!

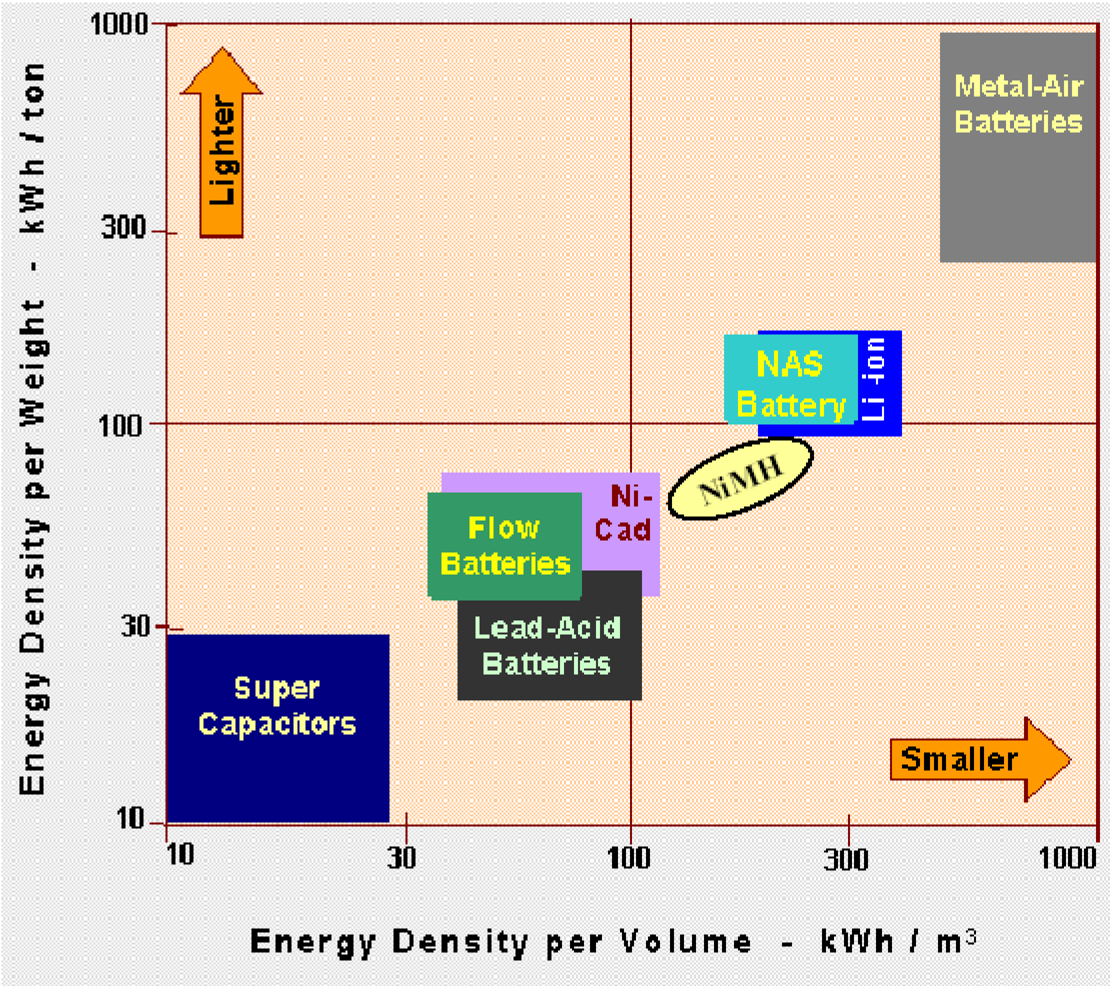
Energy density vs power density



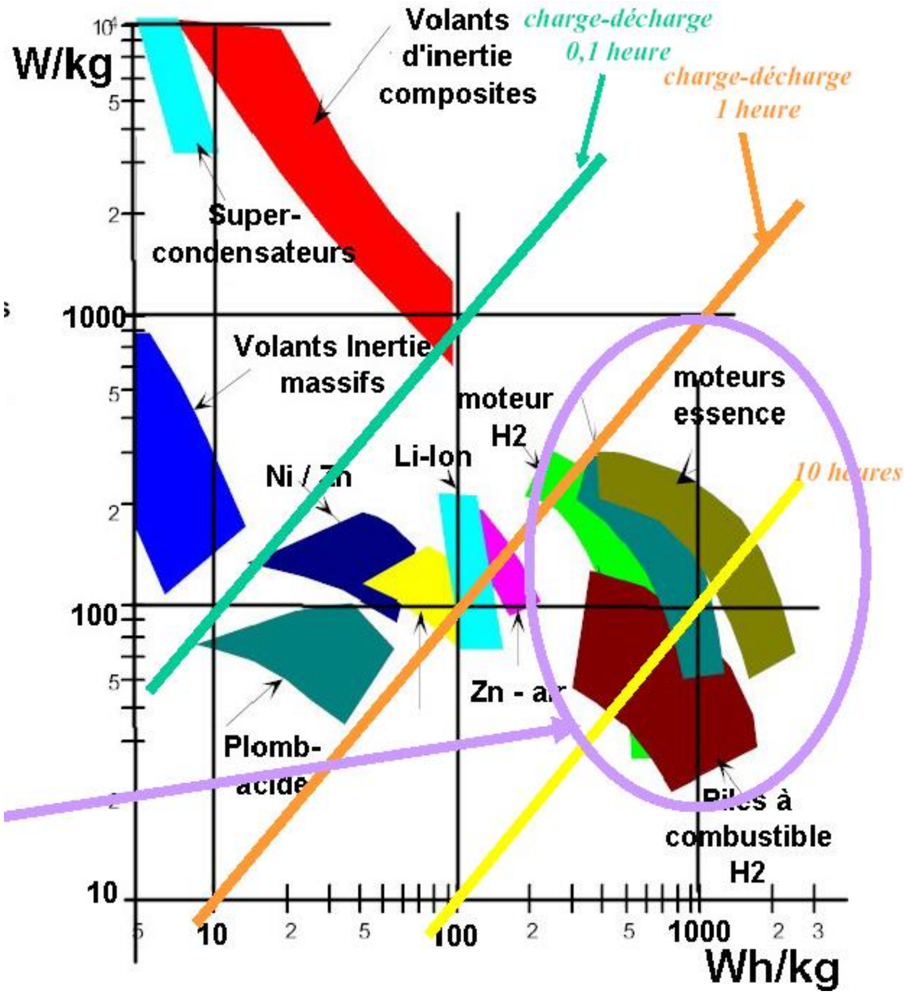
Energy density vs power density



Energy per volume / per weight

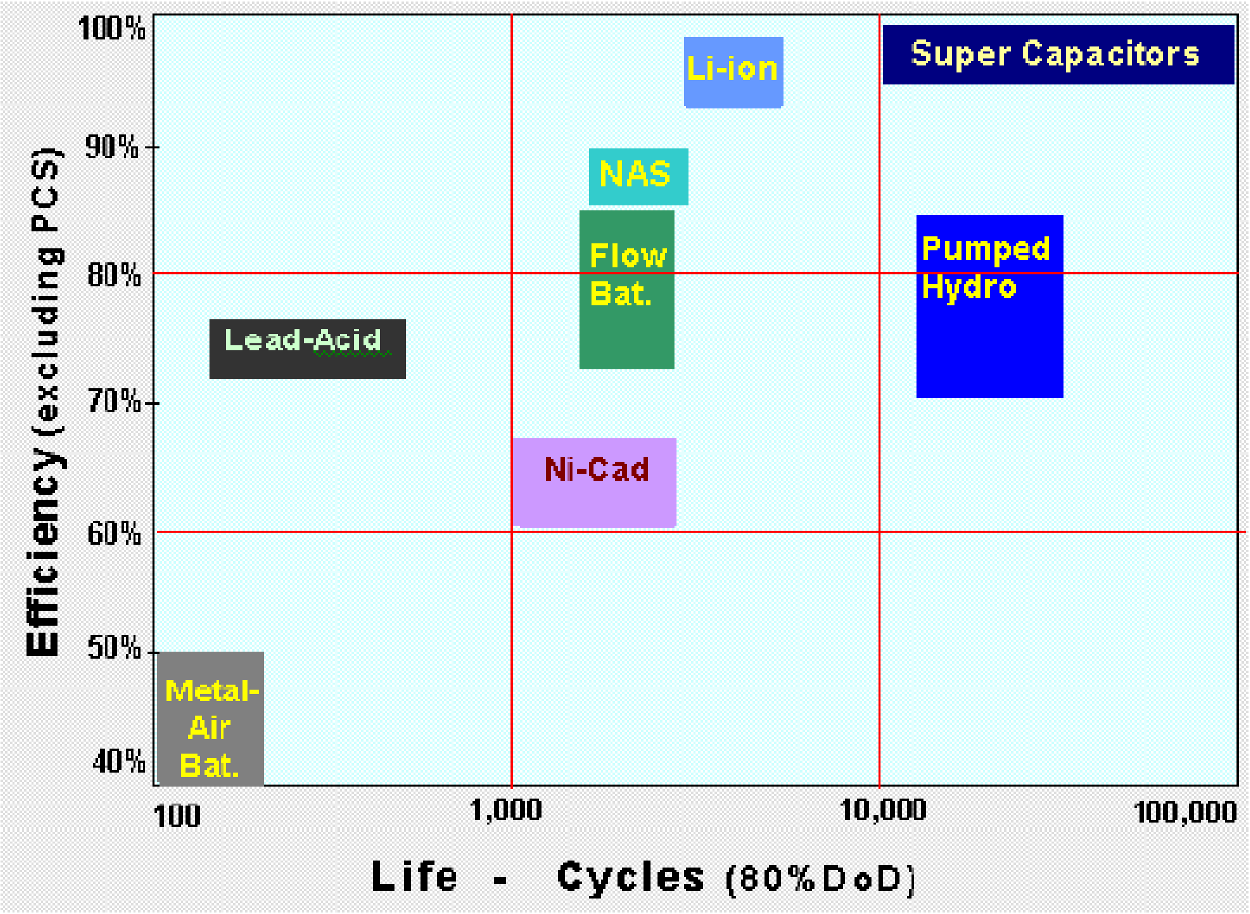


Discharge characteristic time



$$\tau = \frac{E}{P}$$

Efficiency vs life cycles



Investment cost