MECA0527: ENERGY AND POWER STORAGES Part II: Power storages

Pierre Duysinx

Research Center in Sustainable Automotive Technologies of University of Liege

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Outline

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

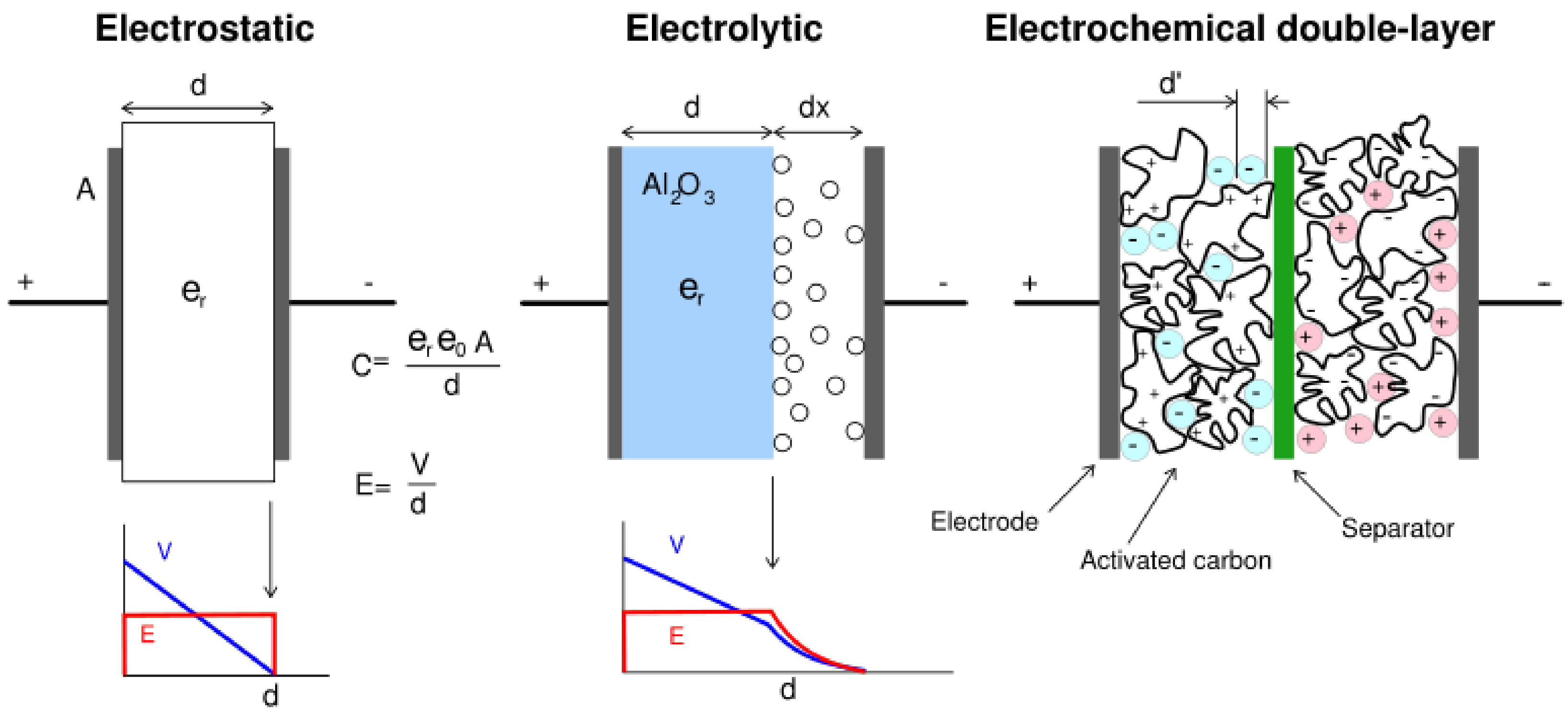
Supercapacitors

Capacitors and Supercapacitors

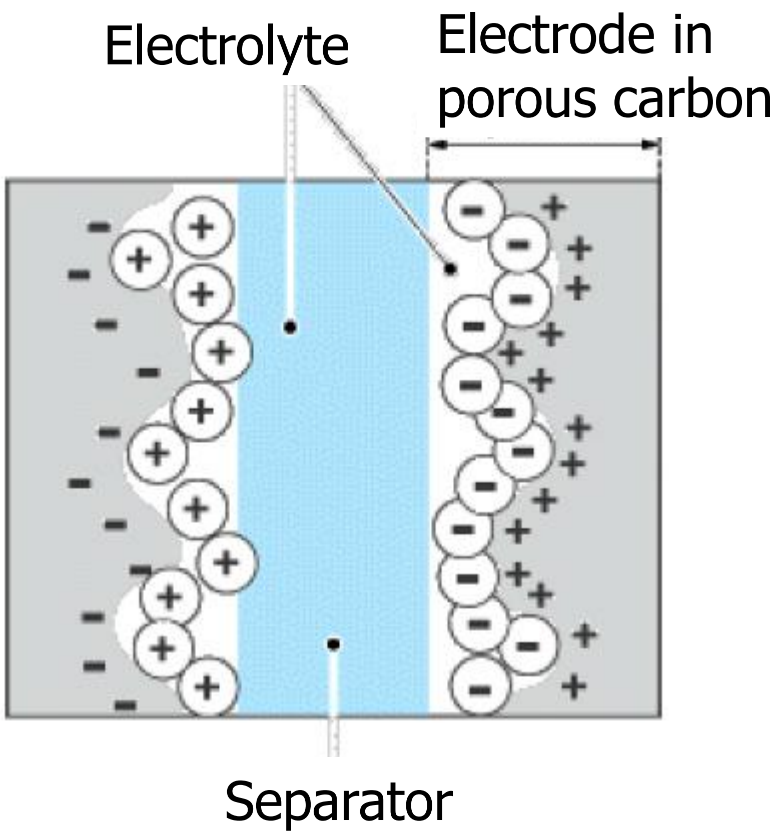
- Capacitors = simple devices capable of storing electrical energy
- Capacitors
  - = electrostatic capacitors
  - Essential components in electronics
  - Capacitance ~ pF to µF
- Electrolytic Double Layer Capacitors (EDLC) or ultra / supercapacitors
  - Capacitance ~ F – kF
  - Working principle: double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

Capacitors and Supercapacitors

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

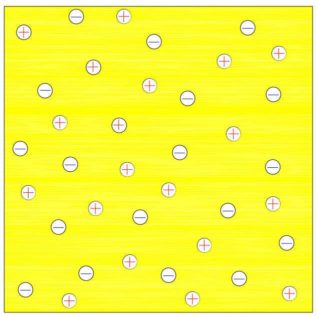


Supercapacitors: principle

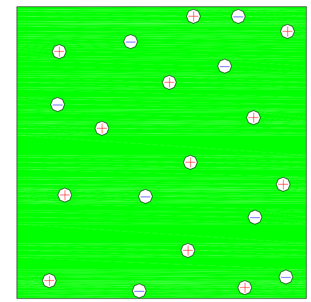


- Supercapacitors are based on the double layer technology
- When carbon electrodes are immersed in aqueous electrolyte, the ions will accumulate at the porous interface of the electrode.
- The ions and the current carriers make capacitors with a gap of a few nanometers

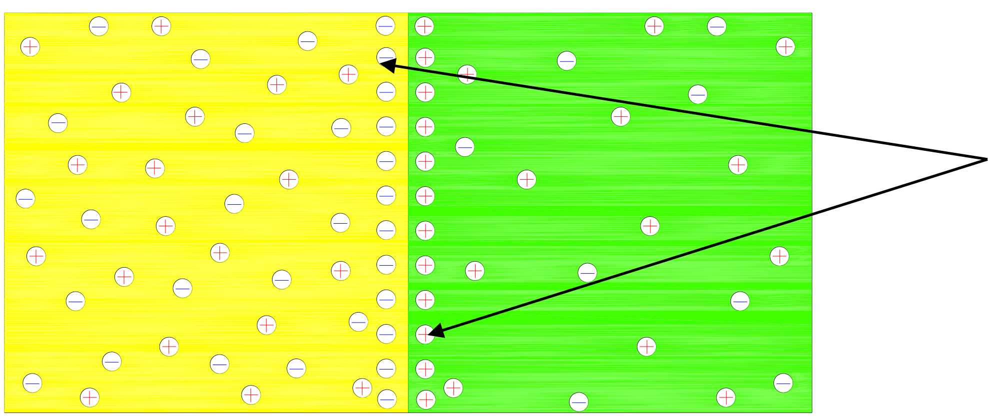
Supercapacitors: Double layer principle



EQUILIBRIUM CONDITION OF MATERIALS
WITH DIFFERENT ELECTRIC CONDUCTIVITY

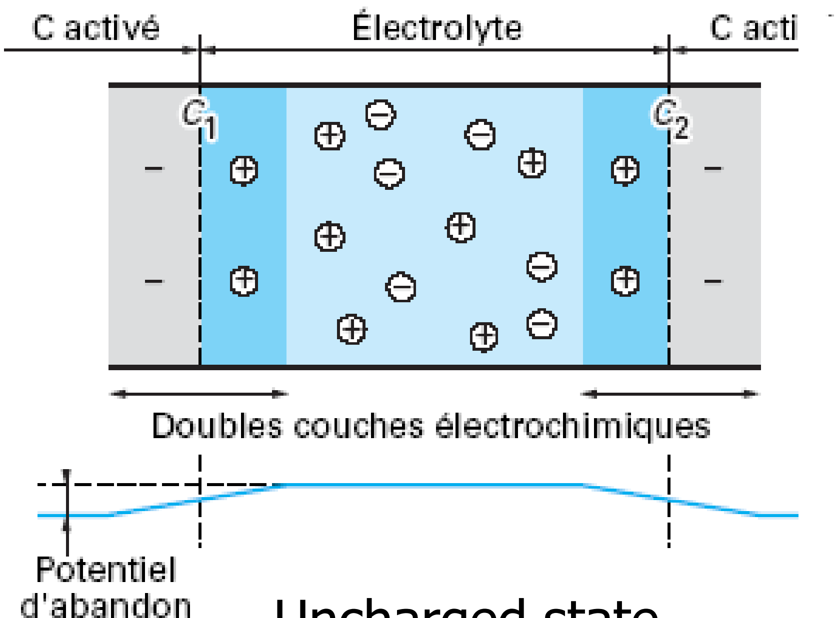


EQUILIBRIUM CONDITION OF A SYSTEM COMPRISING OF TWO DIFFERENT MATERIALS

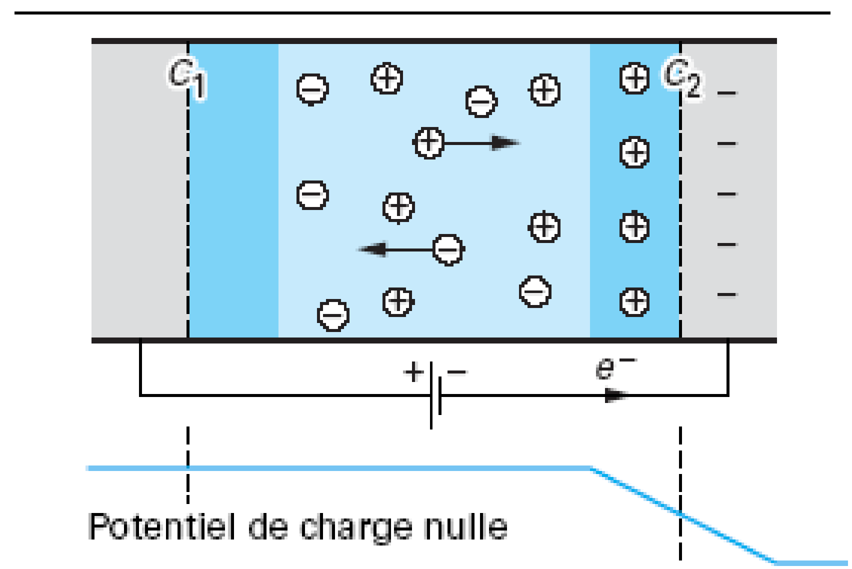


DOUBLE ELECTRIC LAYER

Supercapacitors: principle

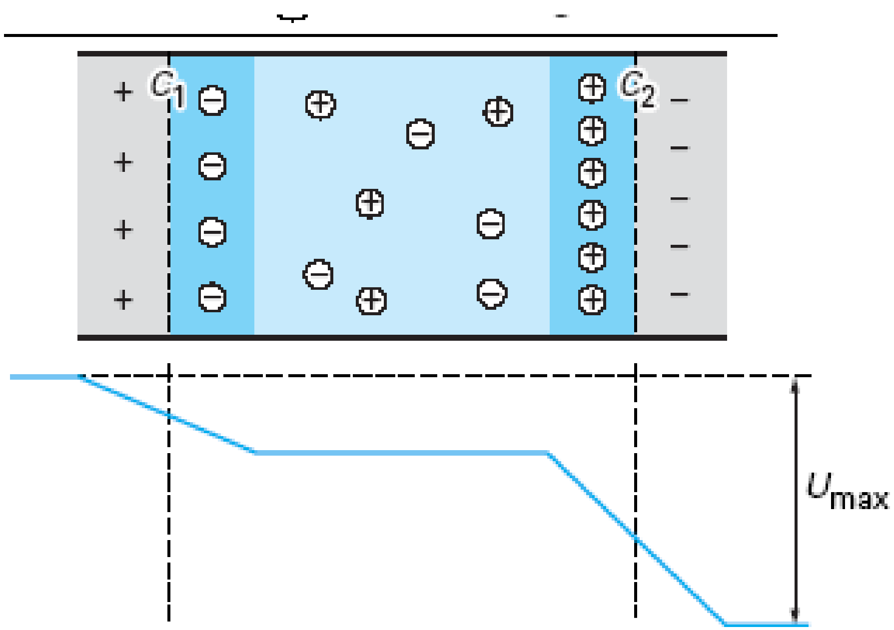


Uncharged state

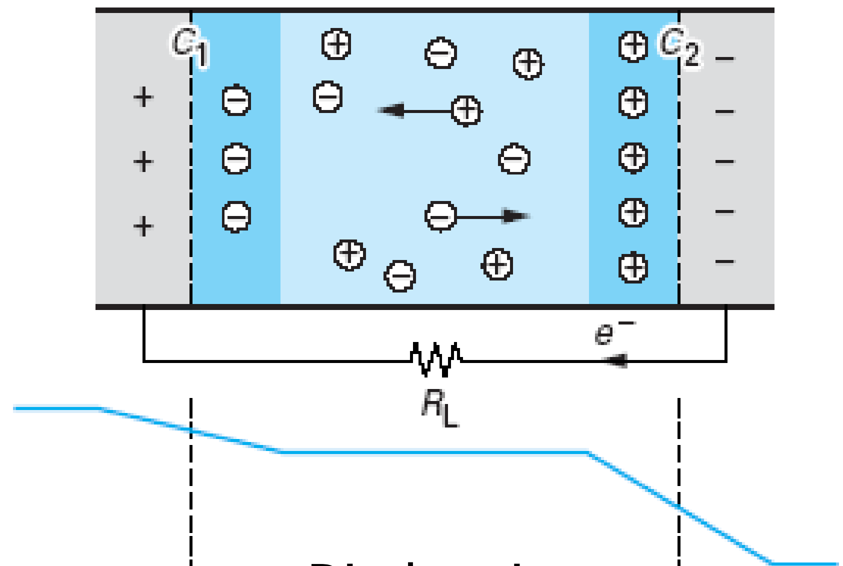


Charging

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 ~10 nm

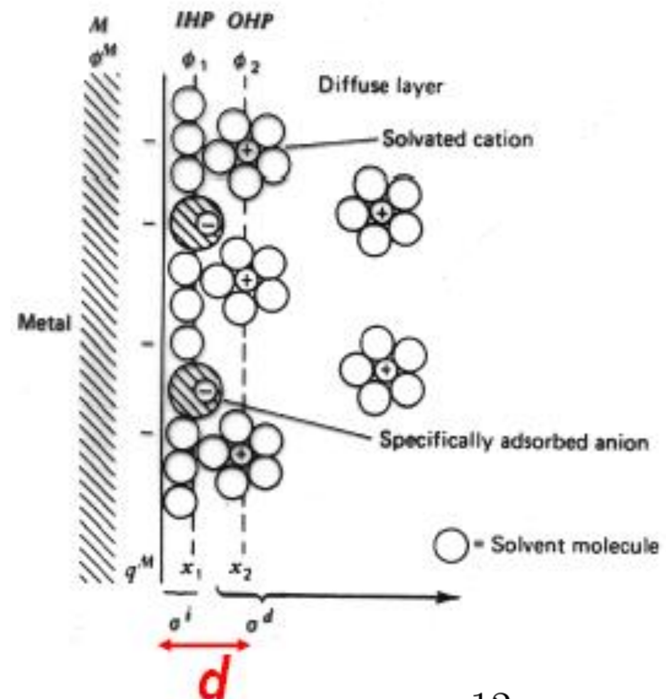
$$\frac{C}{S} \sim \frac{0.694\, 10^{-9}}{10 \cdot 10^{-9}} = 0.069 \sim 0.05\ F/m^2$$

- Surface area S of the electrode /electrolyte specific surface for activated carbon, S (depends on the micropores amount <2nm)

$$S \sim 1000\ m^2/g$$

- Capacitance

$$C \sim 0.069\ F/m^2\ 1000\ m^2/g = 69.47\ F/g \sim 50\ F/g$$



$$\epsilon_0 = 8.85\ 10^{-12}$$

$$\epsilon_r(H_2O) = 78.5$$

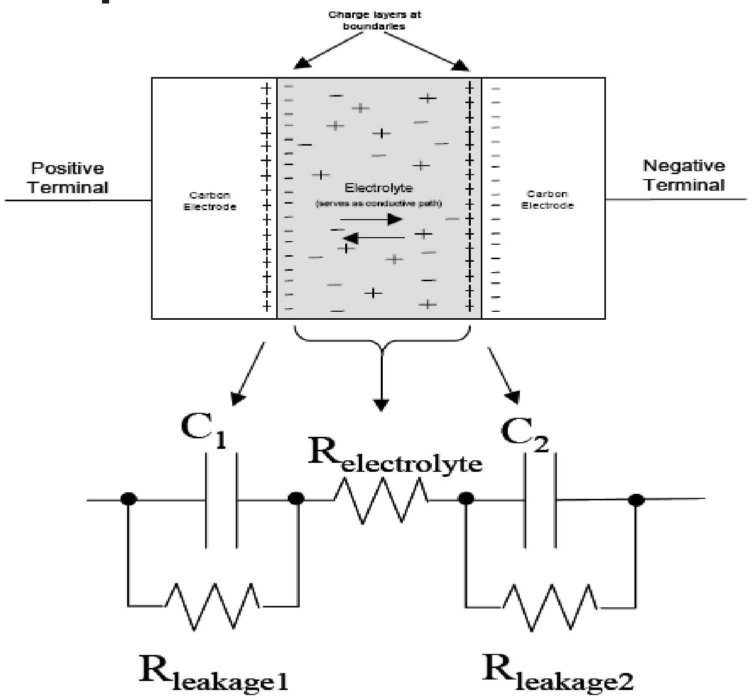
$$\epsilon = \epsilon_0\, \epsilon_r \simeq 0.694\ 10^{-9}$$

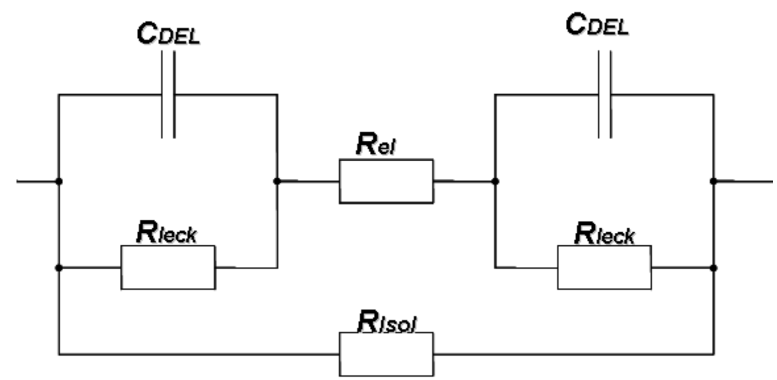
Supercapacitors

- Capacitors with double layers are limited to 0,9 volts per cell for aqueous electrolyte and about 2.3 V with non aqueous electrolyte (ACN)
- Because the double layer is very thin (a couple of nanometers), capacity per area is high: 2,5 to 5 μF/cm²
- With material with a high active area (1000 m²/g) like activated carbon one gets a capacity about 50 F/g
  - 1000 m²/g x 5μ F/cm² x 10000 cm²/m² = 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)

$$E = \frac{1}{2} C\,V^2 = \frac{25}{2}(0.9)^2 = 10.12\ J/g = 2.81\ Wh/kg$$

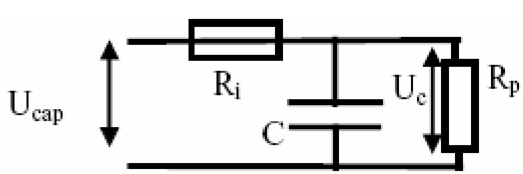
Supercapacitors: modeling





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)
  - Equalize cell voltages (circuit examples are shown next)

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

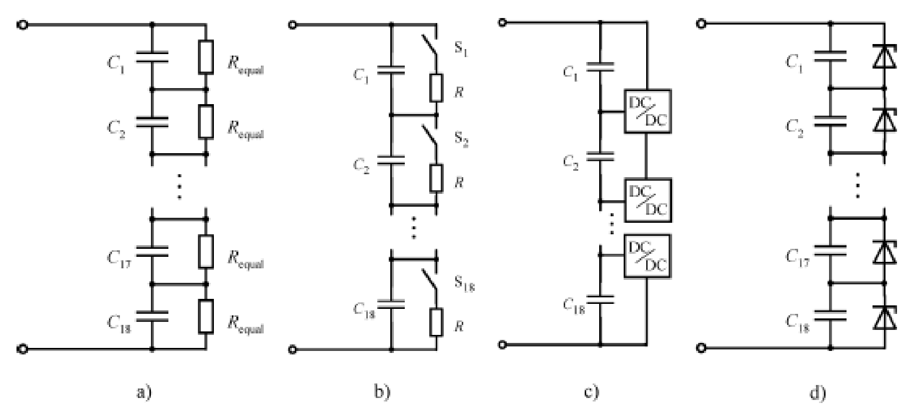
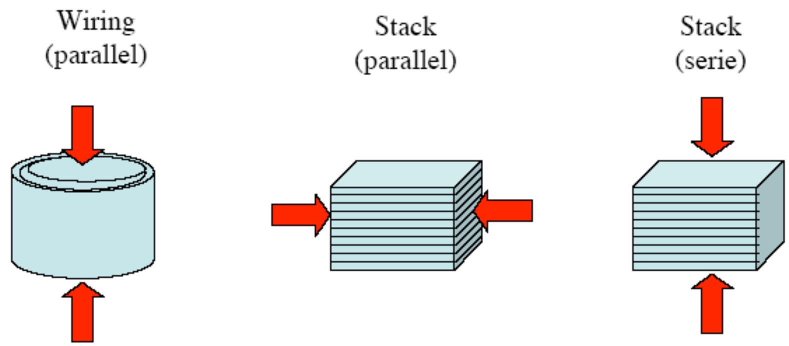


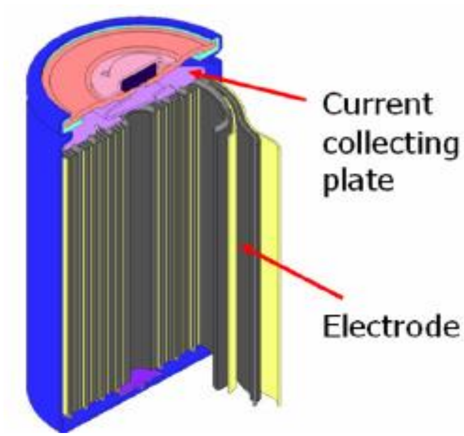
Fig. 2. Cell equalization circuits. (a) Resistor. (b) Switched resistor. (c) DC/DC converter. (d) Zener diodes.

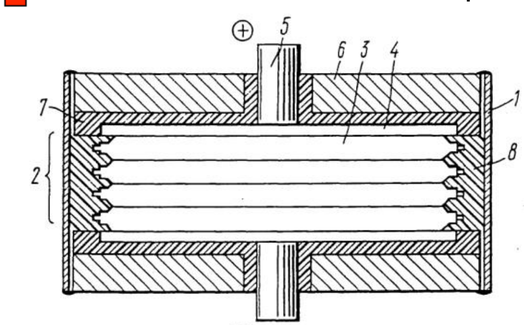
SuperCaps: manufacturing technology

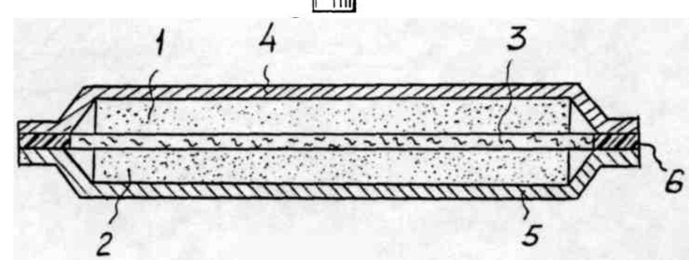
- Wounding vs stacked technologies



Stacked techonologies:
Ex. Newcond GmbH supercaps



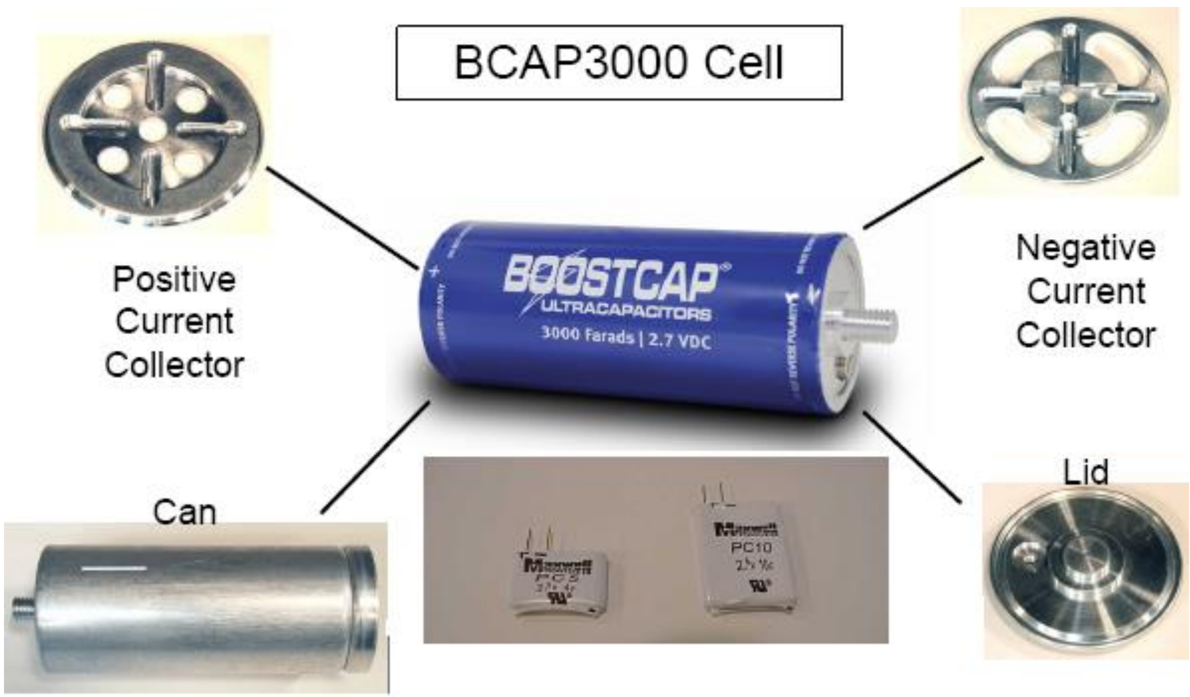




Wounded technolgies

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

- Some typical Maxwell’s ultracapacitor packages:

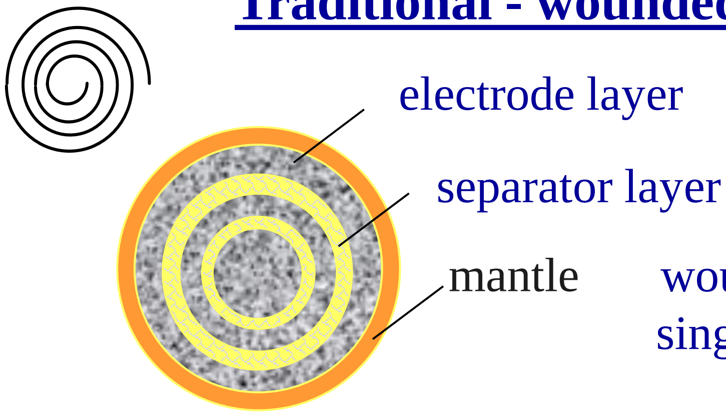
C =	650	1200	1500	2000	2600	3000	F
ESRac =	0.6	0.44	0.35	0.26	0.21	0.20	mΩ
ESRdc =	0.8	0.58	0.47	0.35	0.31	0.30	mΩ
τ =	0.52	0.696	0.705	0.700	0.806	0.900	s
I_{rms} =	105	110	115	125	130	150+	A_{rms}

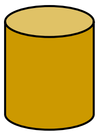
Source: www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf

- 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

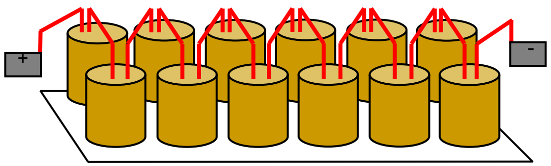
Traditional - wounded cells



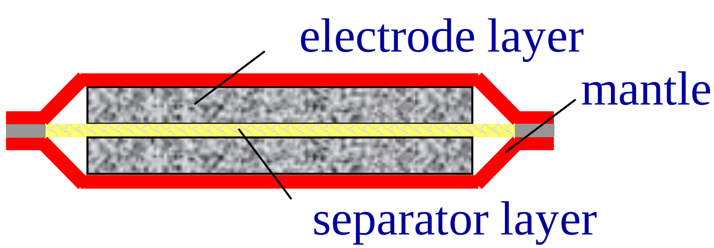


wound supercapacitor single cell (schematic)

BALANCING SYSTEM



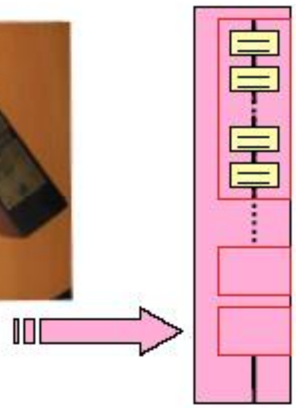
stacked cells



No balancing system required

Ref. D. Sojref, European Meeting on Supercapacitors, Berlin, December 2005

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

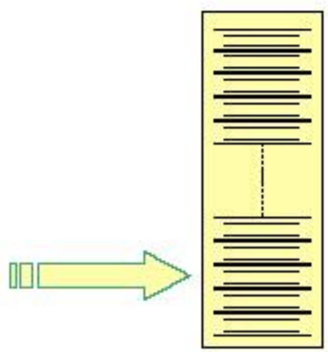
(20 to 50$\mu\Omega$ or more…)

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),…

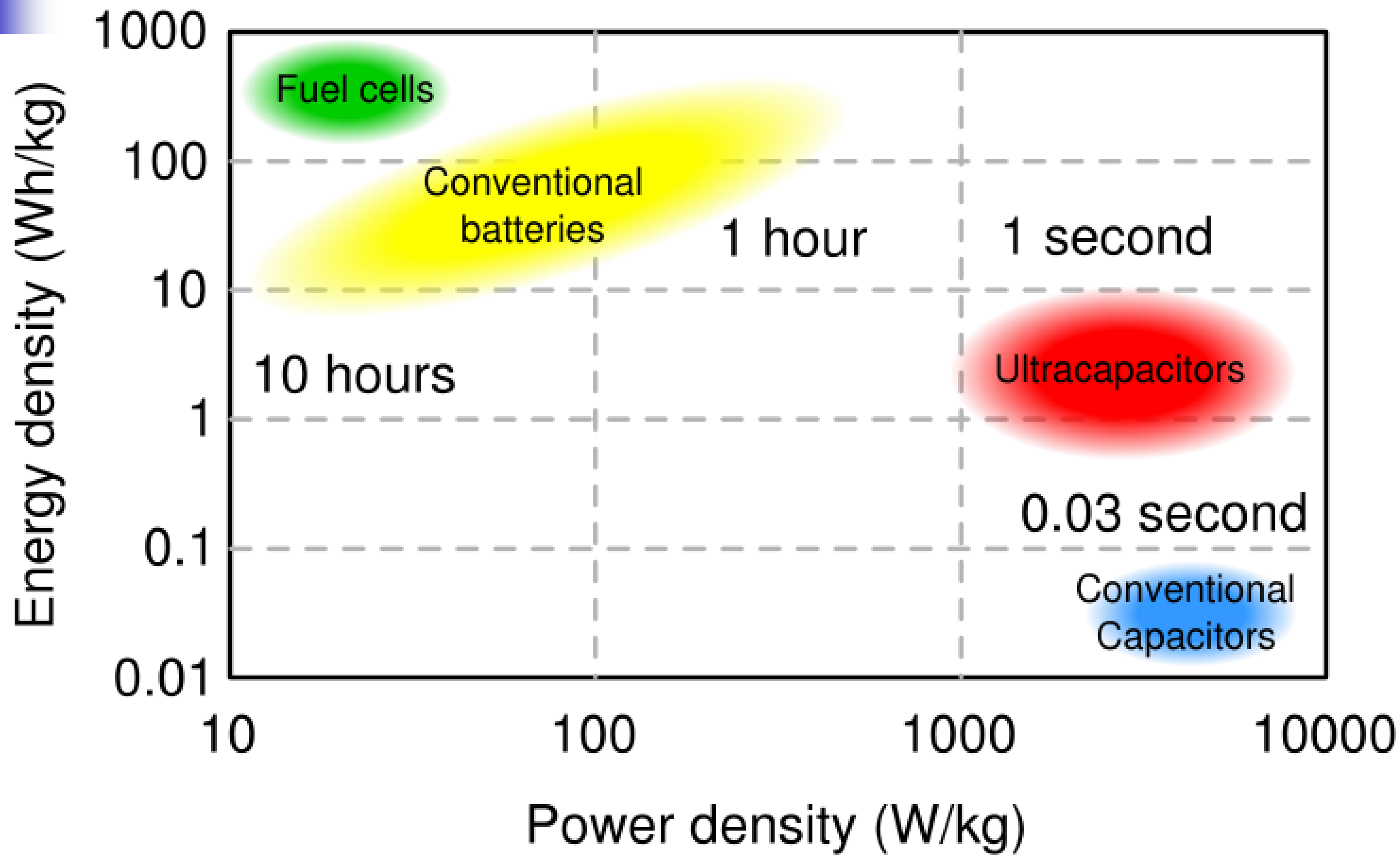
Comparison of SuperCaps technologies

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.

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

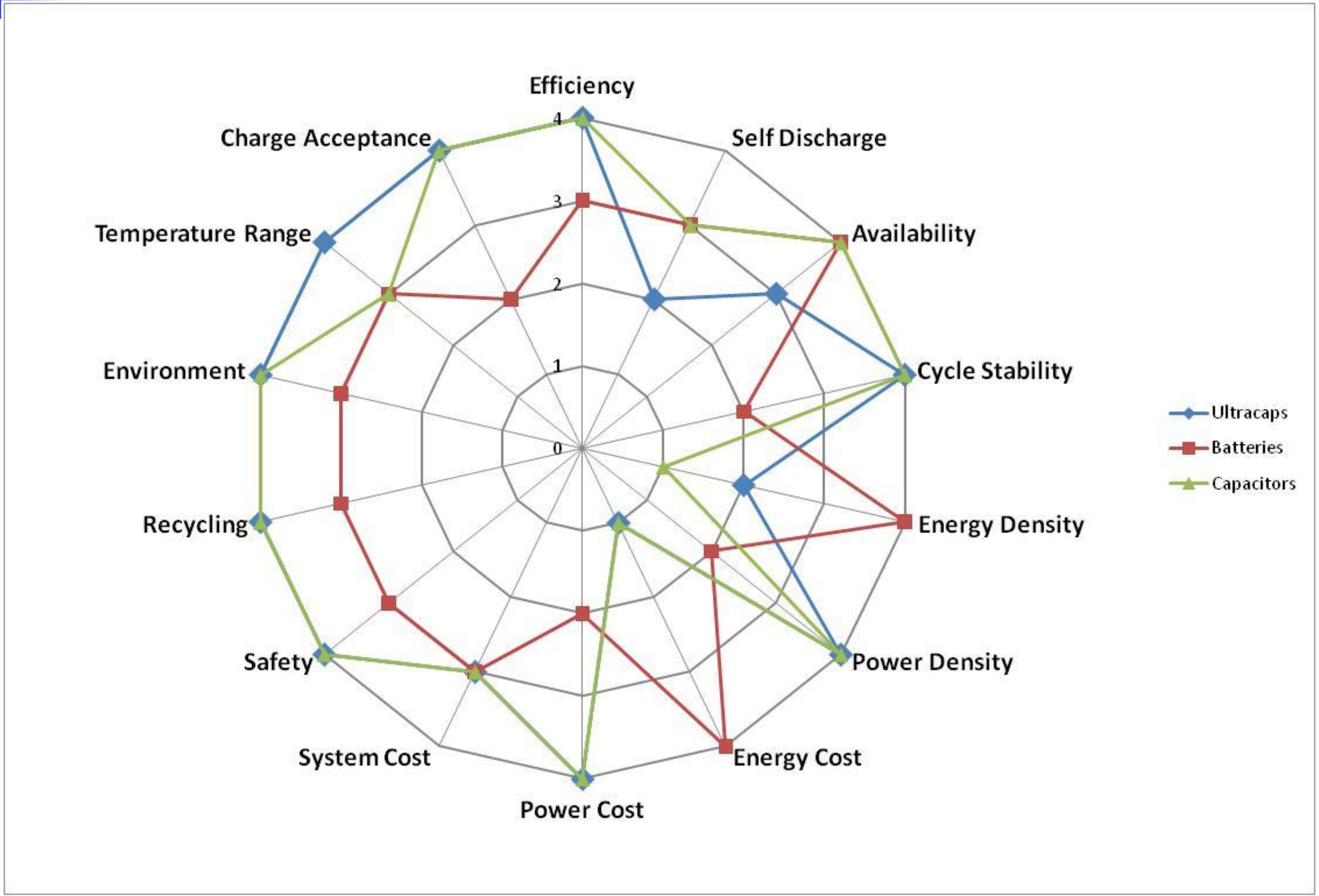


Super capacitors and batteries

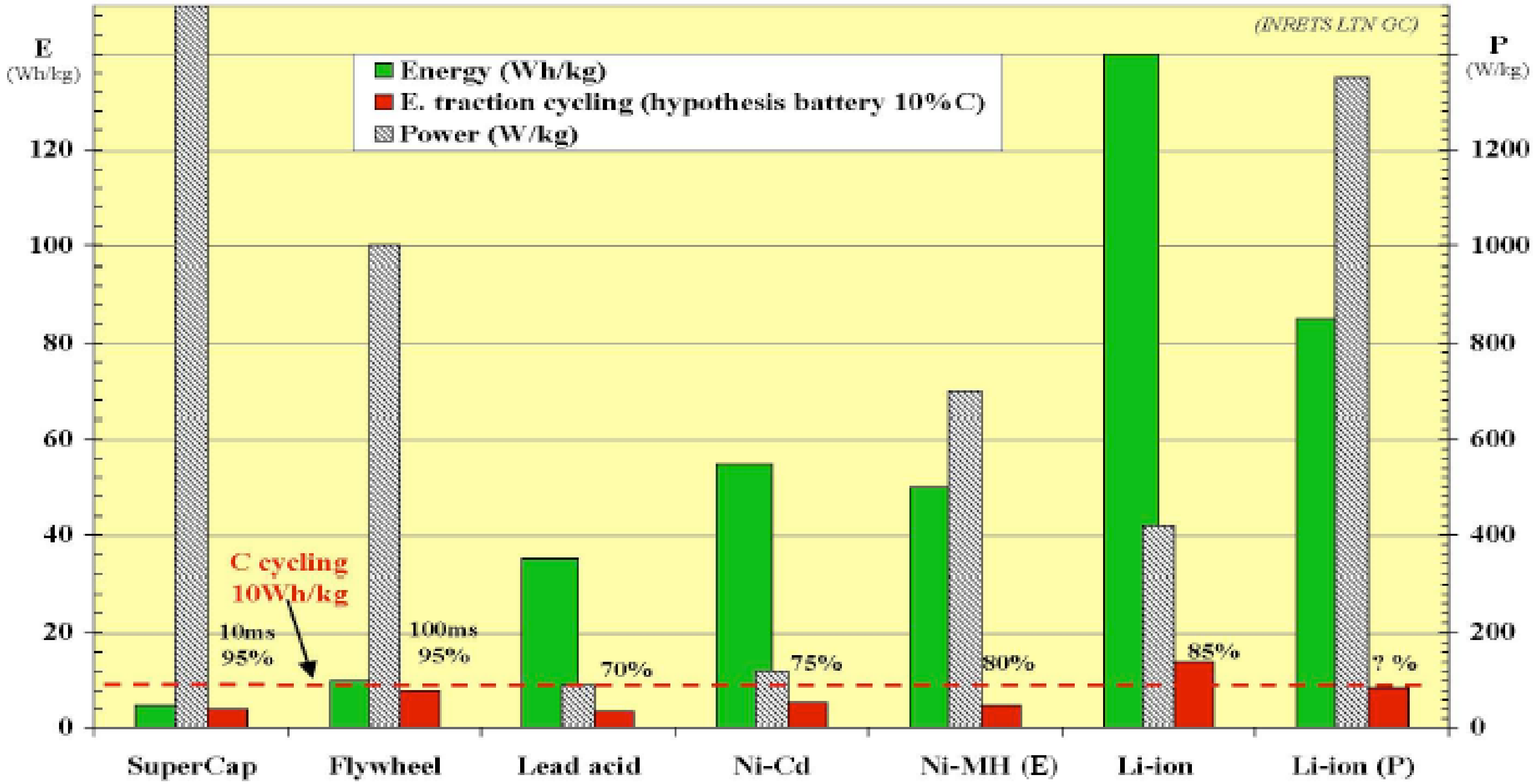
	Battery	Supercapacitor	Capacitor
Energy Density (Wh/kg)	**10 to 100**	**1 to 10**	**0,1**
Specific Power (W/kg)	**< 1000**	**< 7000**	**< 100.000**
Charge Time	**1 to 5 hrs**	**0,3 to 30 s***	**10^{-3} to 10^{-6} s**
Life (cycles)	**1.000**	**> 500.000**	**> 500.000**

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

Super capacitors and batteries



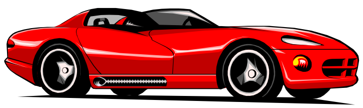
Super capacitors and batteries



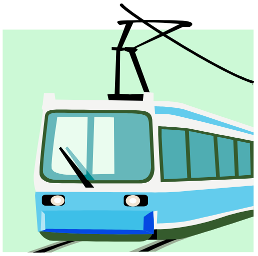
Supercapcitors possible applications

- 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 ➔ hybrid energy storage systems
- Capacitors can be used as buffer for later charging of a battery

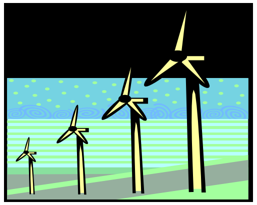
Supercapcitors possible applications



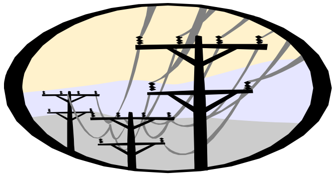
- Major component to low carbon economy: Enhancing energy efficiency
  - Mobile applications:
    - Hybrid propulsion systems
    - Automobile, railway



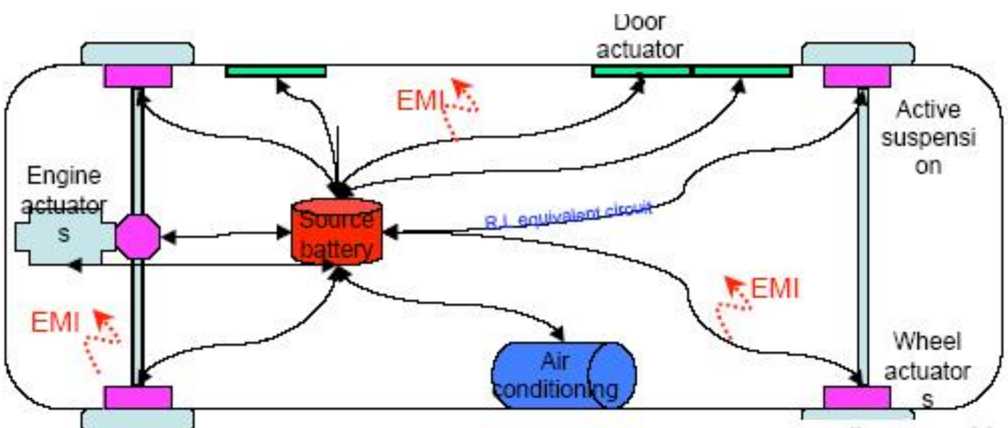
  - Stationary applications:
    - Clean Electrical Power
    - Smart grids including renewable energy sources



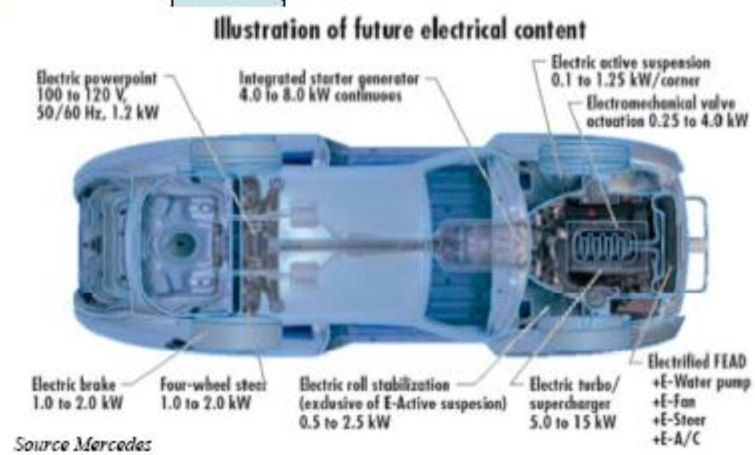
  - New applications
    - Mechatronic applications: All electric systems
    - Medical applications
    - Defense applications
    - Safety applications:
      - Emergency systems



Mechatronic applications



Electrical Actuators need Power & Energy distributed around the vehicle



Transport applications

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

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

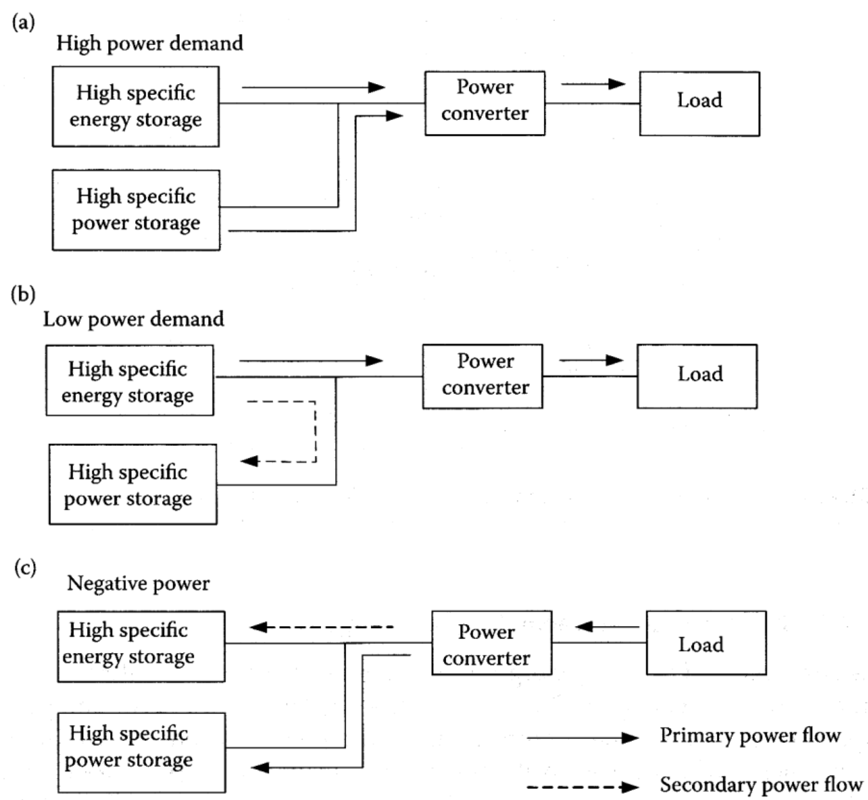
Hybridization of Energy Sources

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

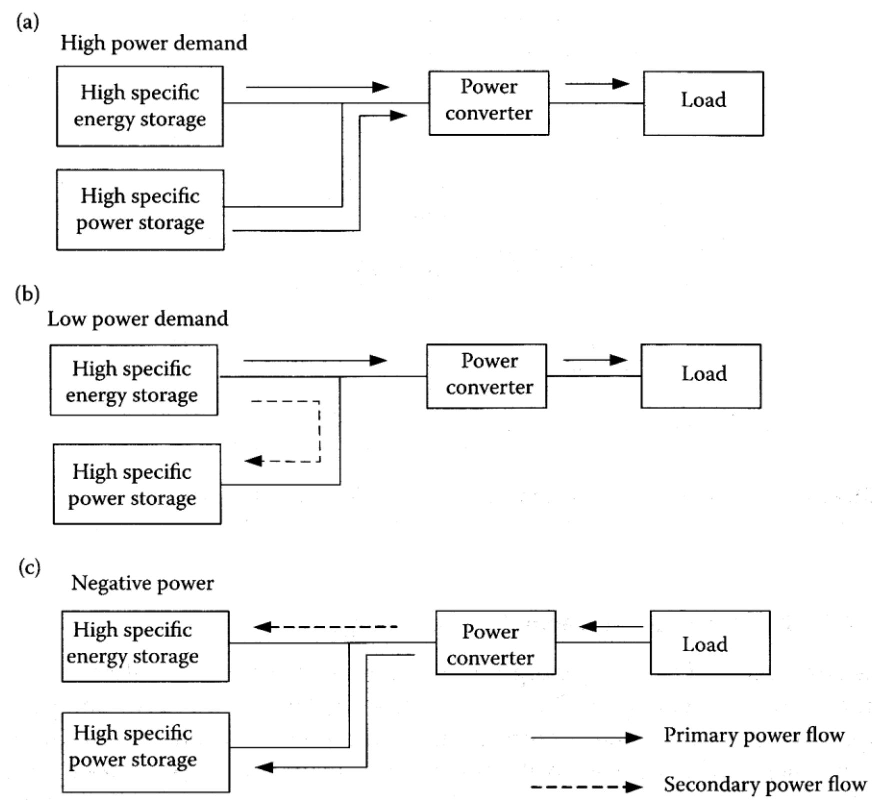
- Basic concept of operations of hybrid energy storage systems
- (a) hybrid powering: in high power demand operations: acceleration, hill climbing. Both energy components deliver their power to the load.



Ehsani et al. Fig 13.18

Hybrid energy storage systems

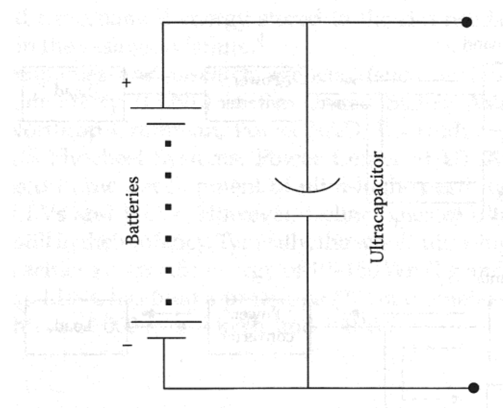
- (b) power split: during low power demand operation such as constant speed, the high specific energy components deliver the power to wheels and charges the high-power component to recover charge loss during acceleration.
- (c) hybrid charging: in regenerative braking, the peak power is absorbed by the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



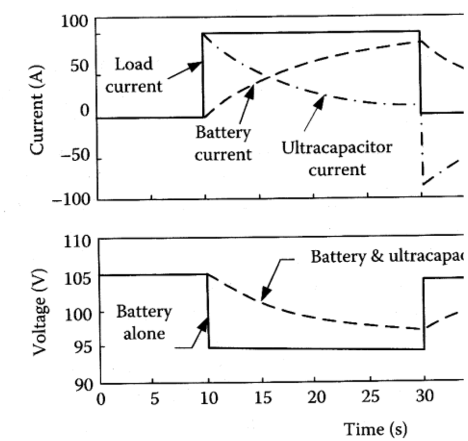
Ehsani et al. Fig 13.18

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.



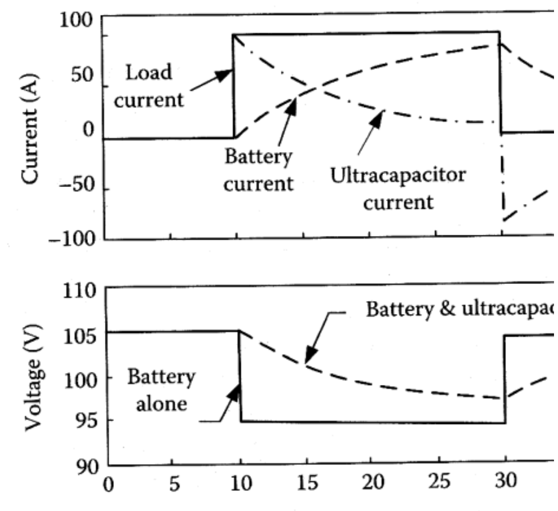
Ehsani et al. Fig 13.19

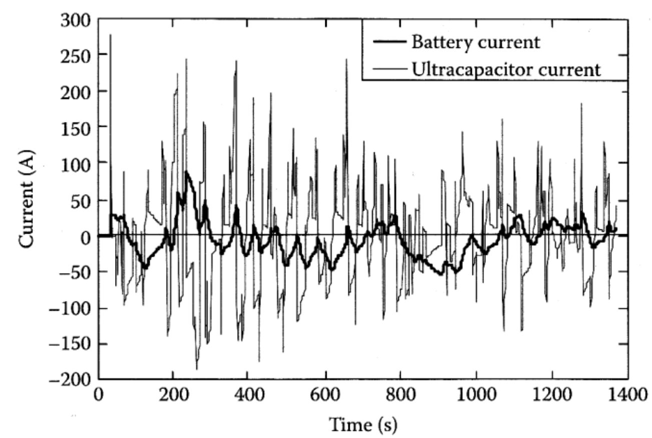


Ehsani et al. Fig 13.20

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.

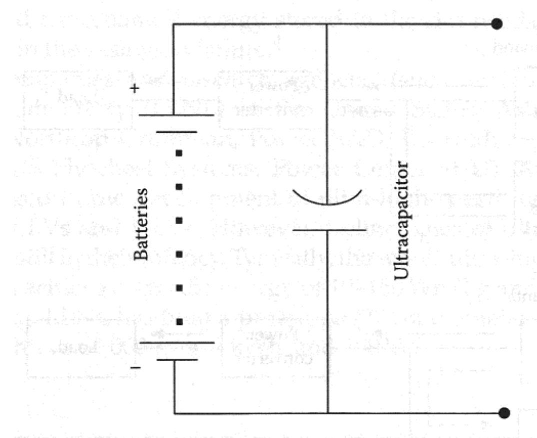




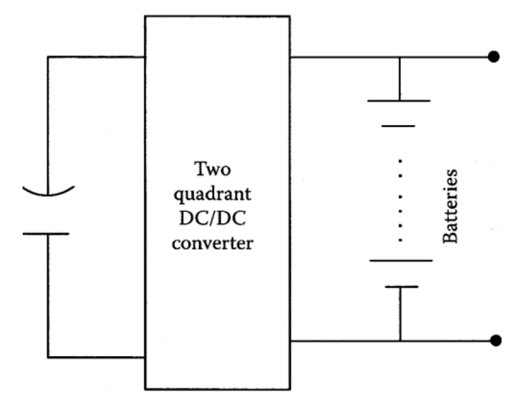
Ehsani et al. Fig 13.20 & 21

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: Sizing

- The best design of a hybrid energy storage including a battery and an ultra capacitor is such that the overall energy and power capacities just meet the energy and power requirements of the vehicle without margin.
- Energy and power requirement of the vehicle characterized by the energy / power ratio

$$R_{e/p} = \frac{E_r}{P_r}$$

  - with E_r and P_r the energy and power requirements.
- E_r and P_r depend on the design of the vehicle drivetrain and control strategies
- When this ratio is defined, the respective size of the battery and ultracapacitors can be determined.

Hybrid energy storage systems: Sizing

- We can determine the weight of the batteries W_b and of the Supercapacitor W_c,

$$R_{e/p} = \frac{E_r}{P_r} = \frac{W_b\,E_b + W_c\,E_c}{W_b\,P_b + W_c\,P_c}$$

- if we know
  - The specific energy densities of the battery E_b and of the supercapacitor E_c,
  - The specific power densities of the battery P_b and of the supercapacitor P_c.

- Assume that $W_c = kW_b$

Hybrid energy storage systems: Sizing

- If $W_c = kW_b$ then it comes

$$k = \frac{E_b - R_{ep}\,P_b}{R_{ep}P_c - E_c}$$

- Thus the specific energy of the hybrid energy storage is

$$E_{spe}^{Hyb} = \frac{W_b E_b + W_c E_c}{W_b + W_c} = \frac{E_b + kE_c}{1+k}$$

- And the specific power of the hybrid energy storage

$$P_{spe}^{Hyb} = \frac{W_b P_b + W_c P_c}{W_b + W_c} = \frac{P_b + kP_c}{1+k}$$

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.

- The illustrative example shows the sizing energy / power storage for VRLA, Ni/Cd, NiMH or Ucap alone.

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
ecific power (W/kg)	75	120	140	1000	2500
ecific energy (Wh/kg)	30	50	64	100	2
tal weight (kg)	667	417	357	50	1750

- Design of energy / power storage system of a combat vehicle.

$$P = 50kW$$
$$R_{ep} = 0.07\ wh/w$$
$$E = 3.5\ kWh$$

- The illustrative example shows the sizing energy/power storage for VRLA, Ni/Cd, NiMH or Ucap alone.
- Li ion battery

$$E_b = 100Wh/kg \quad \Rightarrow \quad W = 3500/100 = 35\ kg$$
$$P_b = 1000W/kg \quad \Rightarrow \quad W = 50000/1000 = 50\ kg$$

- Ucap

$$E_c = 2\,Wh/kg \quad \Rightarrow \quad W = 3500/2 = 1750\ kg$$
$$P_c = 2500W/kg \quad \Rightarrow \quad W = 50000/2500 = 20\ kg$$

Hybrid energy storage systems

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
Iltracap weight (kg)	16.5	16.7	16.9	6.05
otal weight (kg)	132	86	71	41

- Design of energy / power storage system of a combat vehicle.

$$P = 50kW$$
$$R_{ep} = 0.07\ wh/w$$
$$E = 3.5\ kWh$$

- We design a hybrid energy storage assembled from Li ions batteries and Supercapacitors

$$E_b = 100Wh/kg$$
$$P_b = 1000W/kg$$

$$E_c = 2\ Wh/kg$$
$$P_c = 2500W/kg$$

$$k = \frac{E_b - R_{ep}\,P_b}{R_{ep}P_c - E_c} = \frac{100\ -\ 0,07 \cdot 1000}{0,07 \cdot 2500 - 2} = 0,1734$$

$$E_{spe}^{Hyb} = \frac{E_b + kE_c}{1+k} = 454,6798\ Wh/kg$$

$$P_{spe}^{Hyb} = \frac{P_b + kP_c}{1+k} = 1221,6749\ W/kg$$

Hybrid energy storage systems

ABLE 12.7

haracteristic Data of a 42-V Ultracapacitor[7]

	Lead/Acid	Ni/Cd	Ni/MH	Li–I	Ultracap
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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

- Hybrid storage mass

$$W = \frac{E_r}{E_{spec}^{Hyb}} = \frac{P_r}{P_{spec}^{Hyb}} = 40.9274\,kg$$

- Battery mass

$$W_b = \frac{W}{1+k} = \frac{40.9274}{1.1734} = 34,8790\,kg$$

- Ucap mass

$$W_c = k\,W_b = 0.1734 \cdot 34,8790$$
$$= 6.0483\,kg$$

- 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

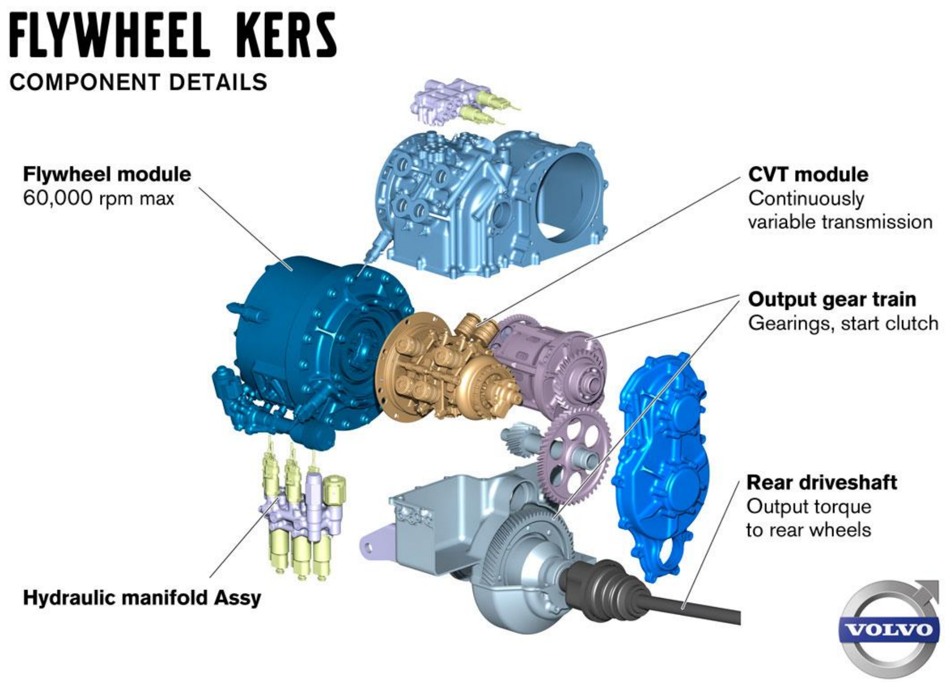
$$E_k = \frac{1}{2} J_f \omega_f^2$$

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 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 connect directly the flywheel to the car propulsion system.
- One would need a continuous variable transmission with a large gear ratio and wide variation range.



Flywheels

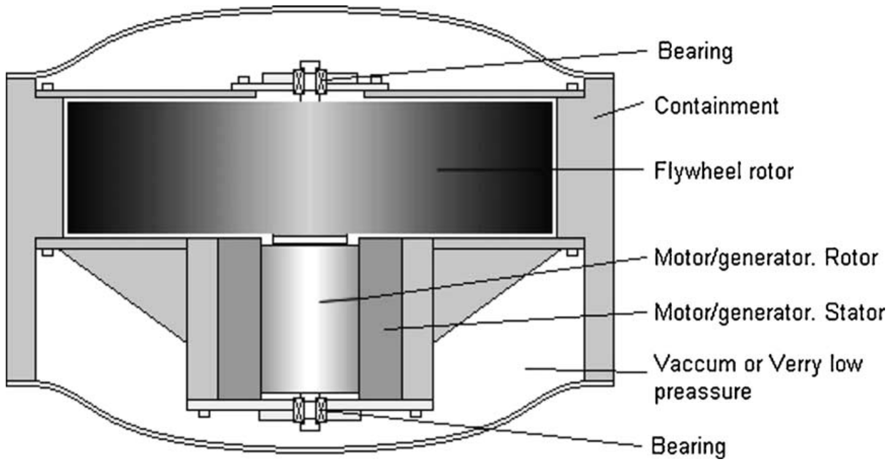
- Flywheels mechanically coupled to the transmission have been applied as KERS (kinetic energy recovery systems) in motorsports.

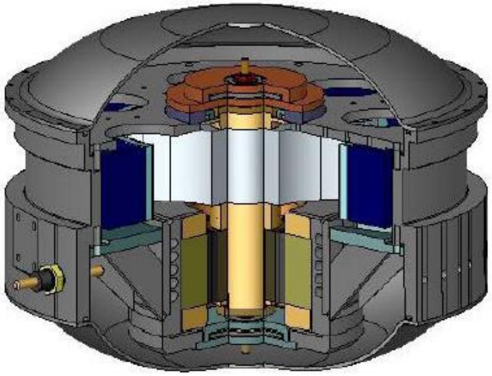
Flywheel unit combined with the TOROTRAK CVT as auxiliary drive for F1 racers

J. Hampl. Concept of Mechanically Powered Gyrobus. Transaction on Transport Sciences. Vol. 6. No1. pp 27-38, 2013.

Flywheels

- To circumvent the difficulty to connect directly the flywheel to the car propulsion system, a common approach consists in coupling an electric machine to the flywheel directly or via a transmission: One makes a ‘mechanical battery’





Flywheels Energy Systems

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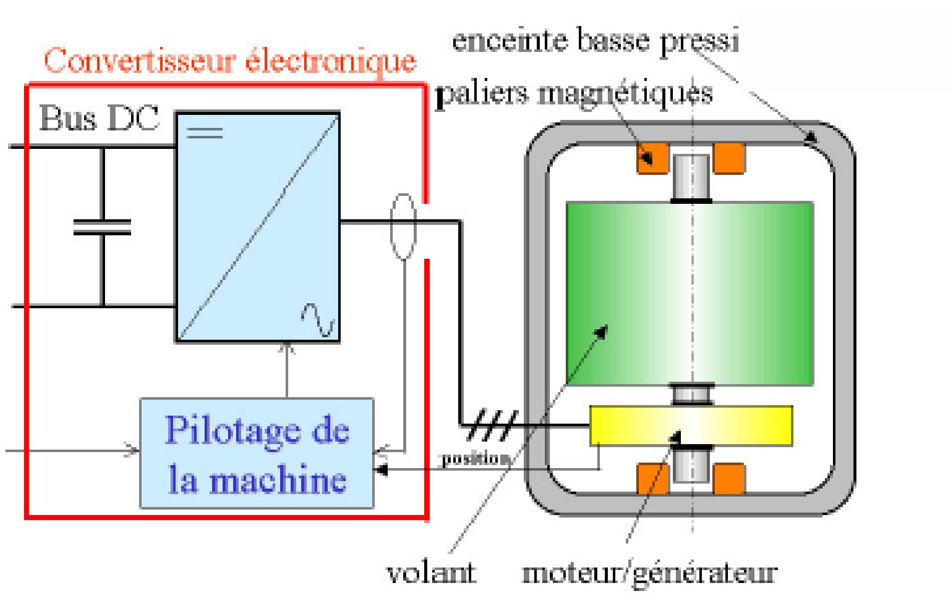
Flywheels

- The electric machine operates as the energy input / output port converting the mechanical energy into electrical energy and vice-versa



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

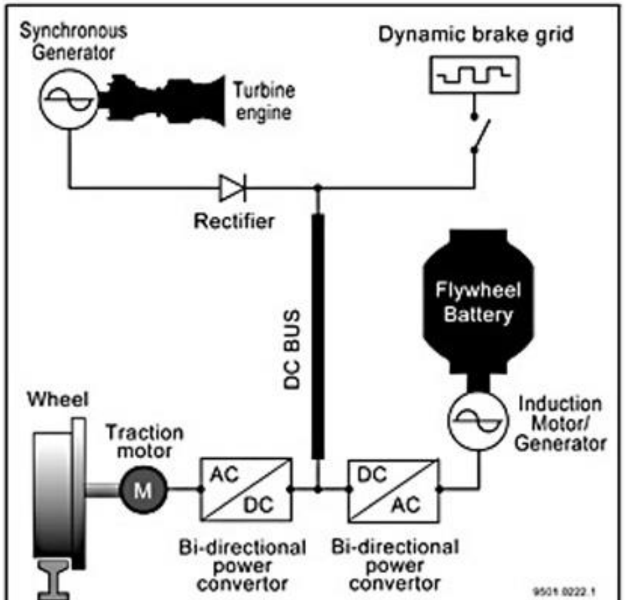
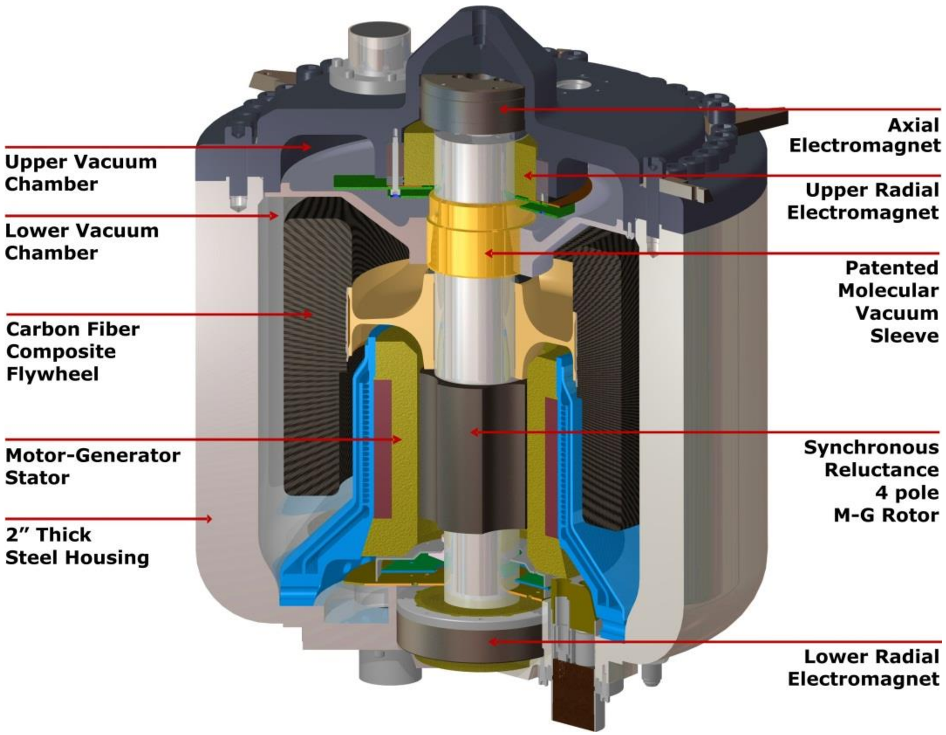


Figure 1. ALPS power flow schematic

Flywheels

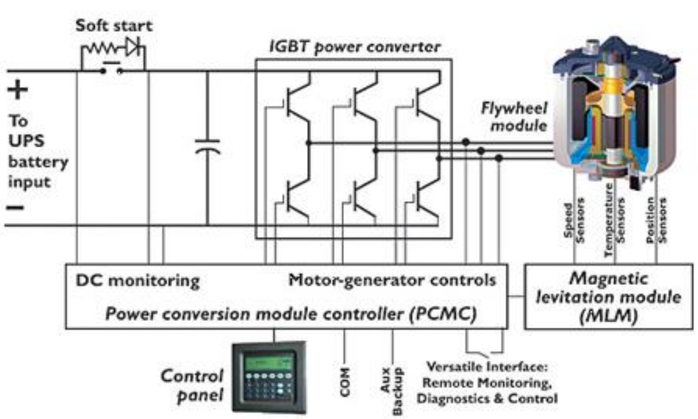
- In order to reduce the friction (hence, losses) the disc is usually in a vacuum chamber and uses magnetic bearings.



Pentadyne flywheel

Flywheels

http://www.vyconenergy.com



VYCON Direct Connect (VDC)

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.

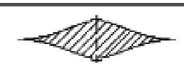
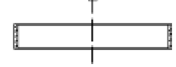
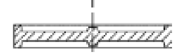
Flywheels

- 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

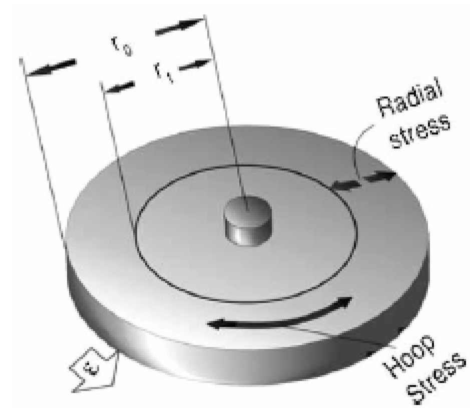
- Disc shape and material: the maximum energy density *e* per unit mass and the maximum tensile stress are related by:

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

- 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

$$e_m = K\sigma_{max}/\rho \qquad (1)$$

- and

$$E_k = \frac{1}{2} J\omega^2 \qquad (2)$$

- and

$$J = m\,R^2 \qquad (3)$$

- then, from (2) and (3)

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

- So, replacing (1) in (4) it yields that max speed is related to the material properties

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

Flywheels

- However, maximum 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

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

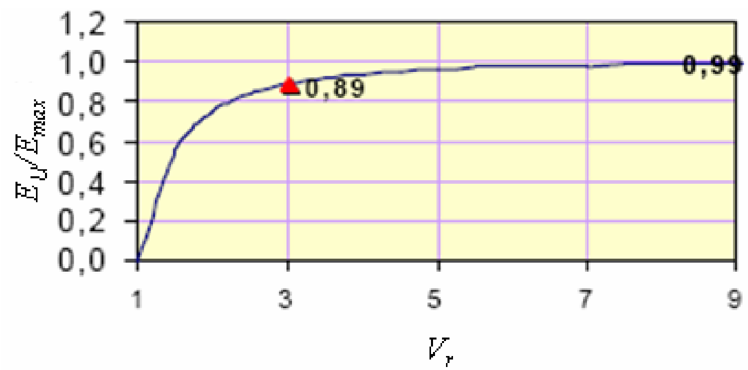

Fig. 4: Evolution in useful energy vs. V_r

Flywheels

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

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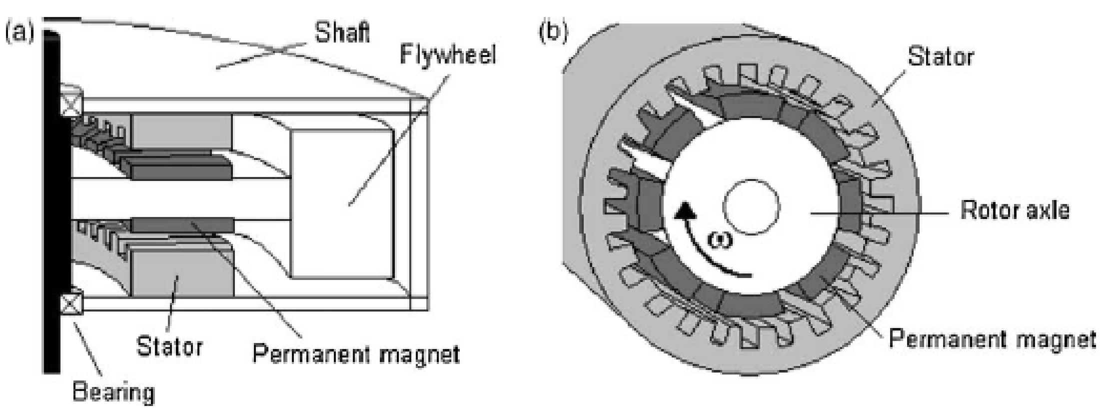
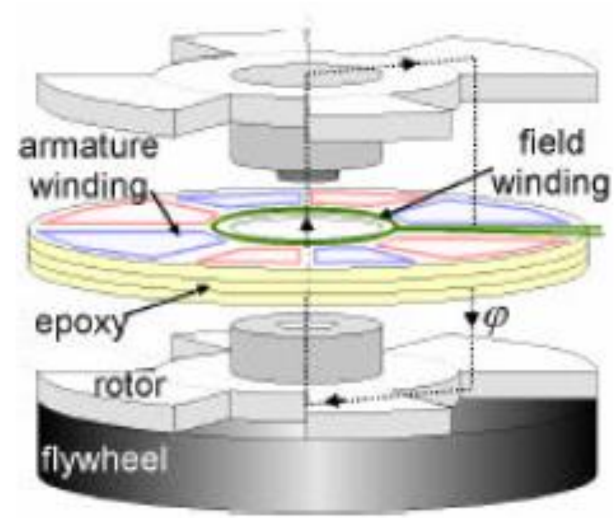


Fig. 3. (a) show an AFPM machine arrangement and (b) show an RFPM machine arrangement.

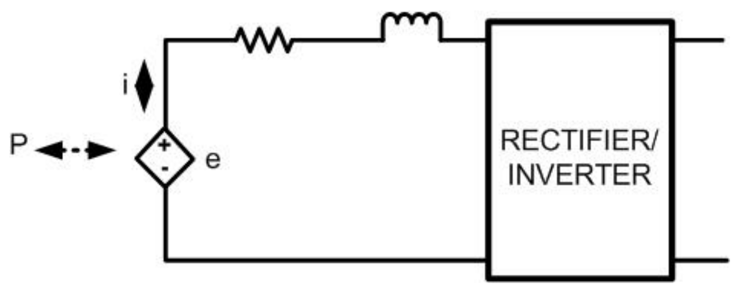


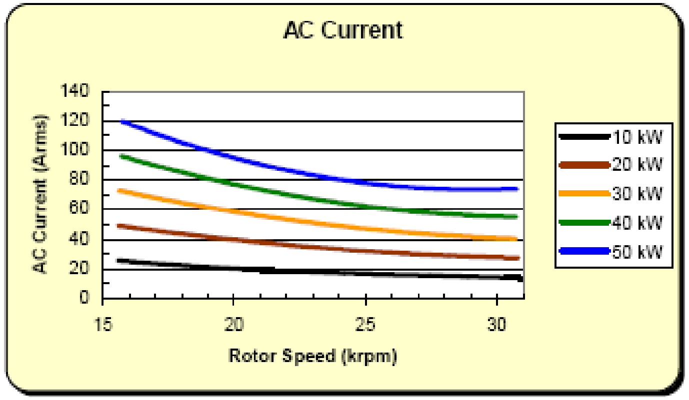
Overview of the homopolar axial synchronous motor/generator

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

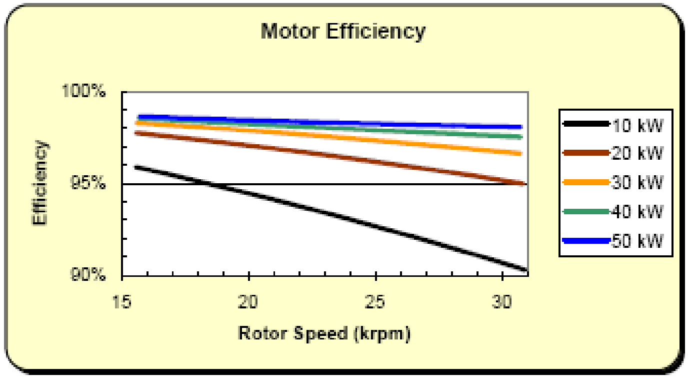
Flywheels

- 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

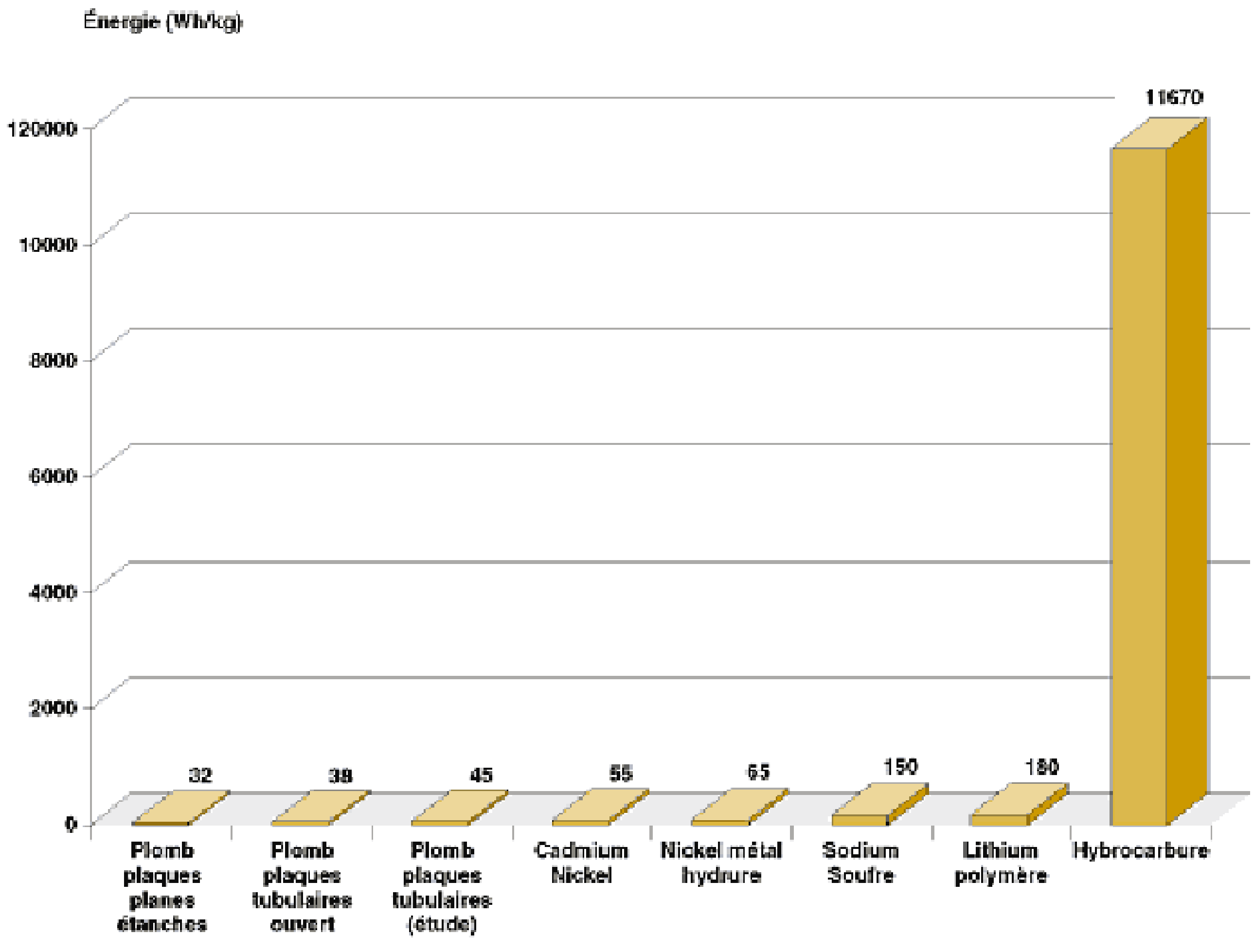
Energy and peak power storages

- Performance criteria for selection (decreasing importance):
  - Specific energy (W.h/kg)
  - Specific power (W/kg)
  - Number of charge cycles
  - Lifetime
  - 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

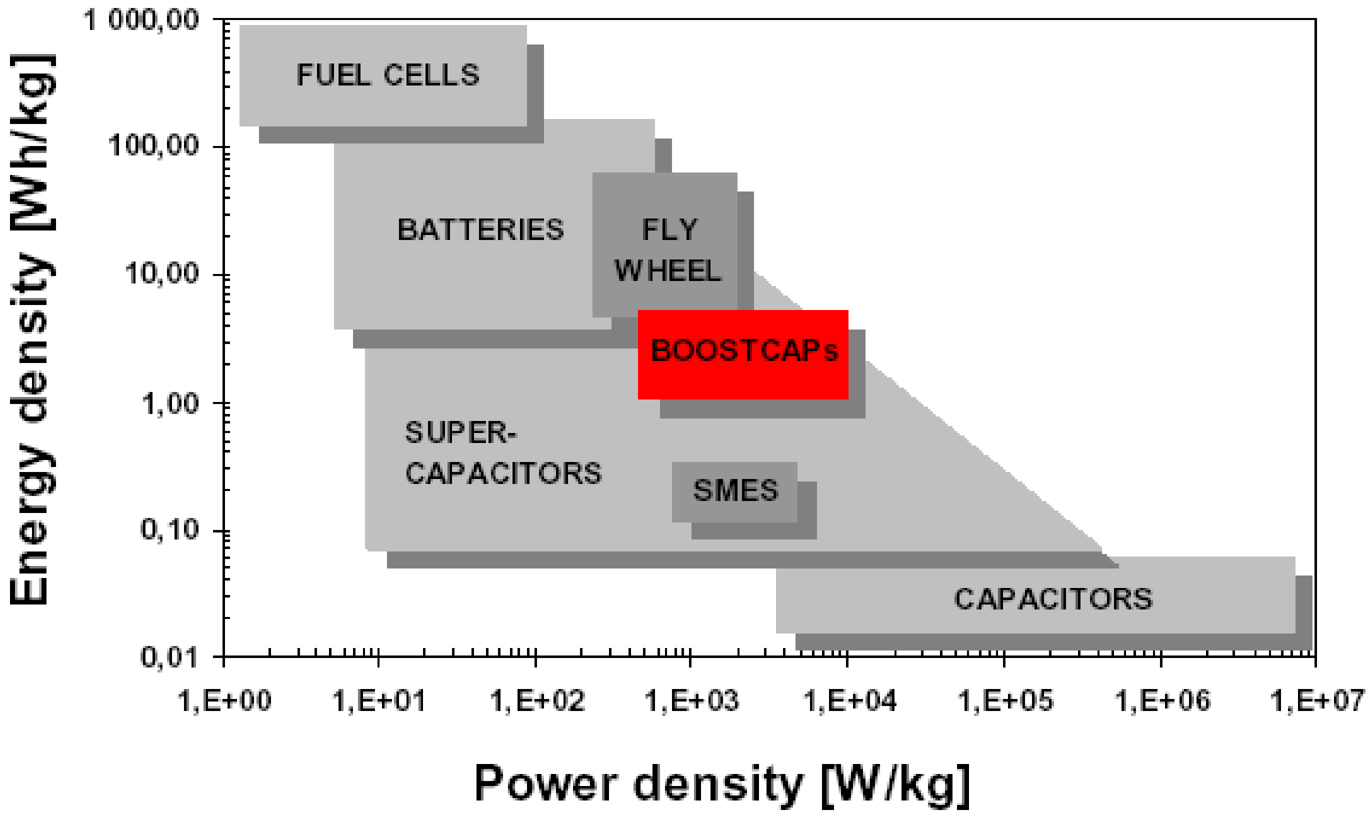


Problem of batteries w.r.t. fuels

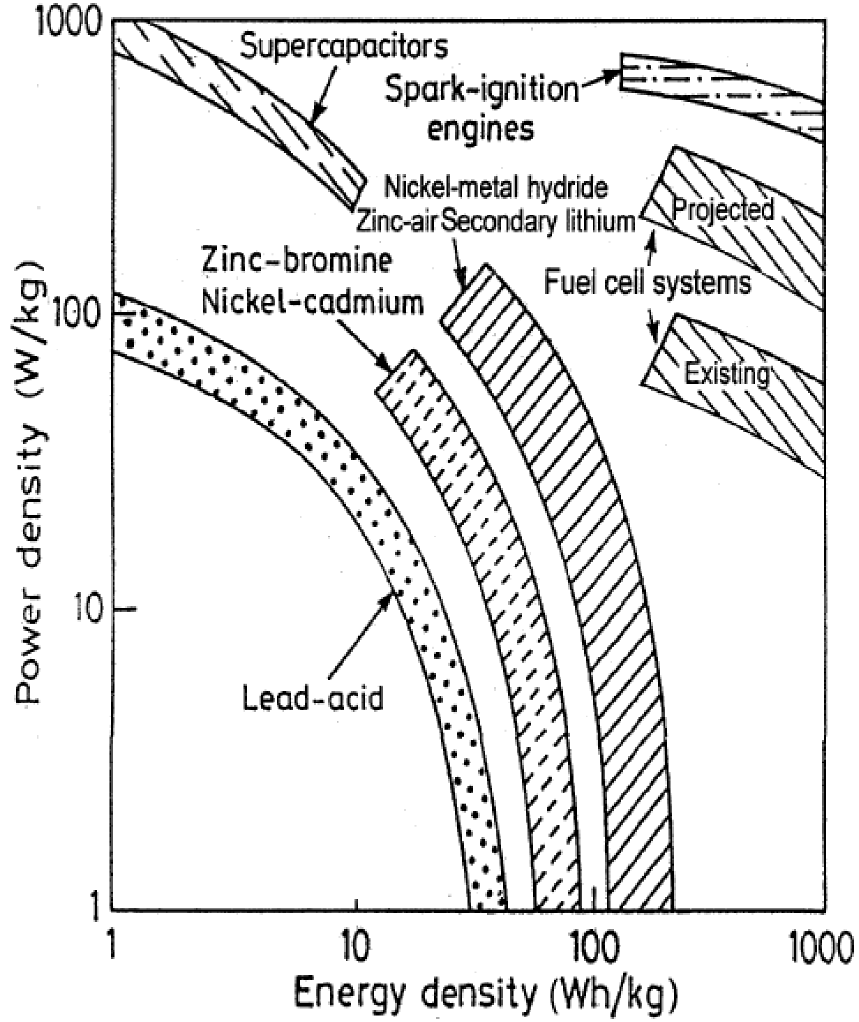
Fuel	Gasoline	Diesel	Li-Ions
Specific energy / PCI [W.h/kg]	11.833	11.667	105
Mean conversion efficiency in vehicle [%]	12	18	80
Specific energy at wheel [W.h/kg]	1420	2100	84

Facteur 200!

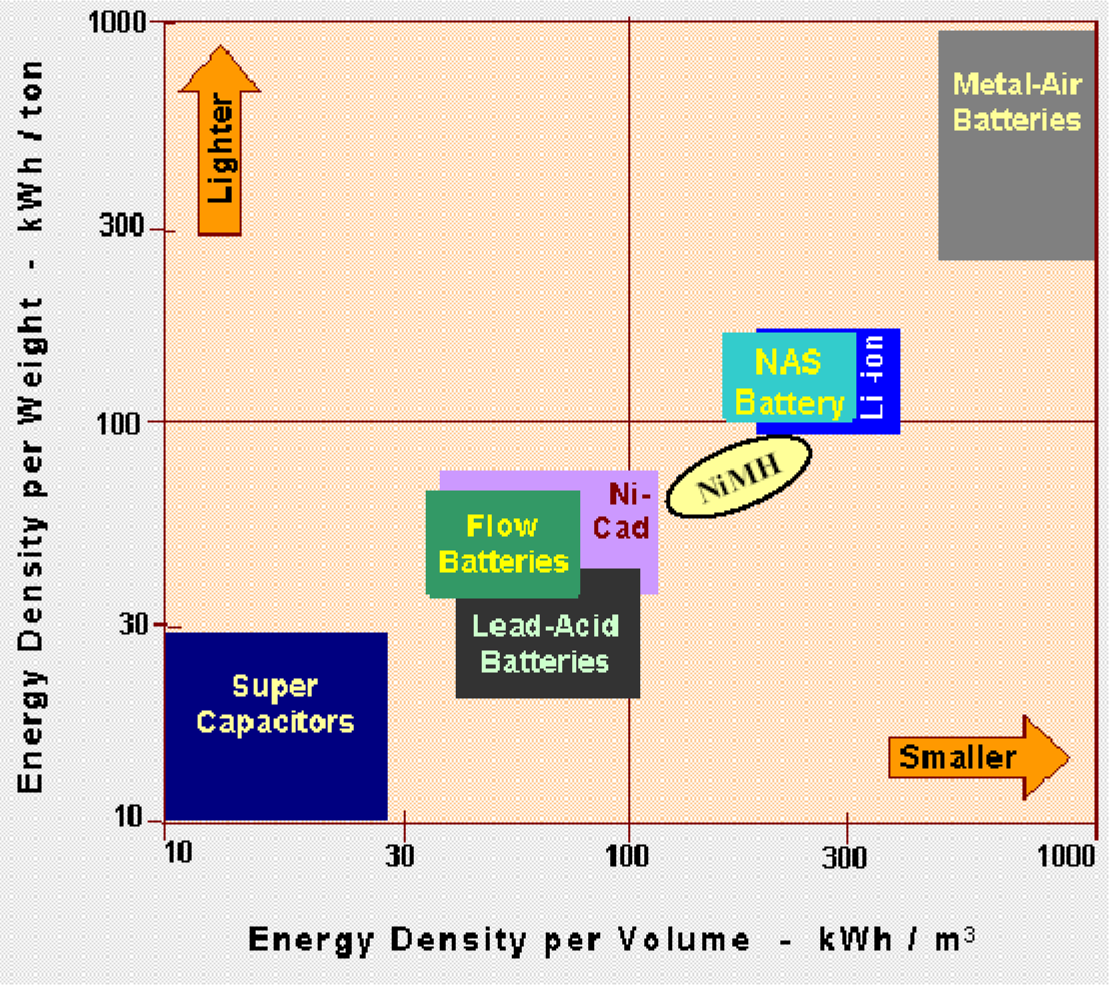
Energy density vs power density



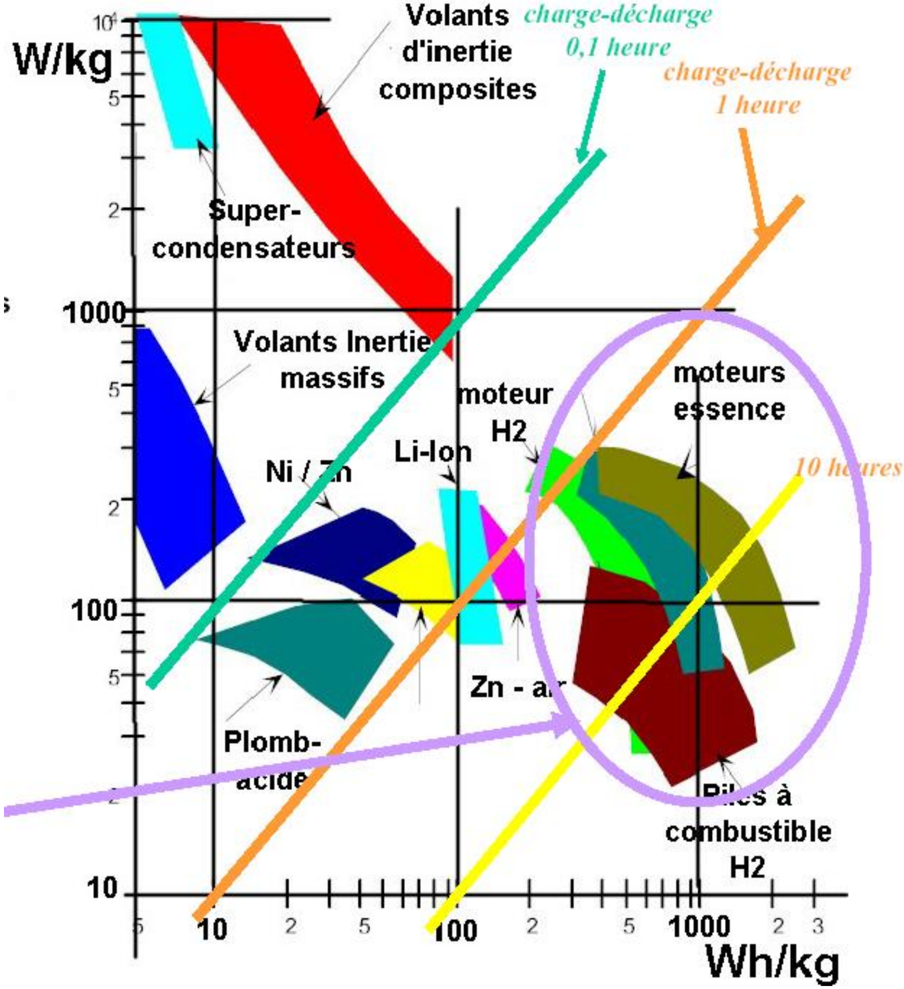
Energy density vs power density



Energy per volume / per weight

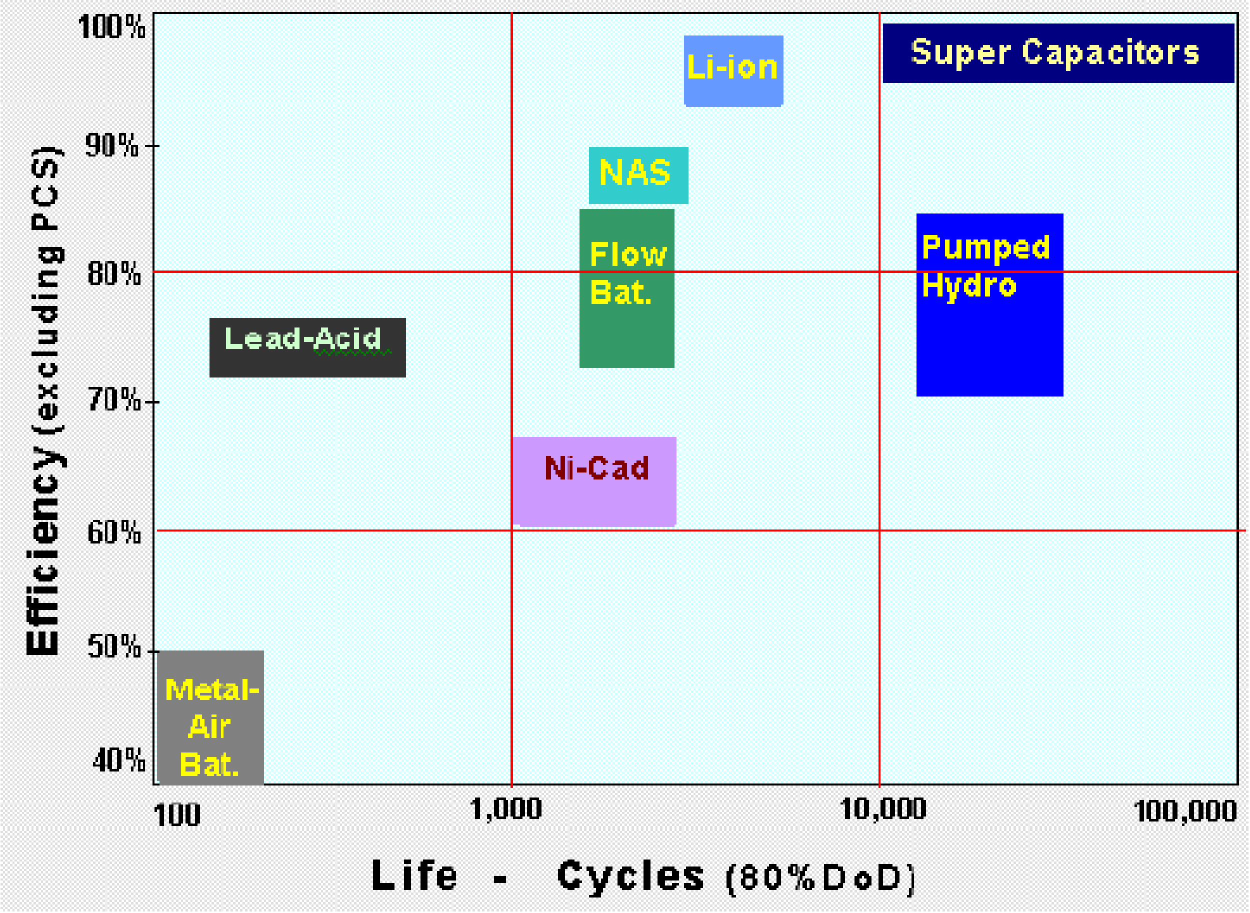


Discharge characteristic time



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

Efficiency vs life cycles



Investment cost