Batteries

- Batteries are electrochemical cells, each consisting of two electrodes immersed in an electrolyte.
  - Electrode material
    - Contains the electrochemical energy of the battery
  - Electrolyte
    - Contributes to the internal conduction of charge between the electrodes: An ionic conductor.
    - No conductions of electrons
  - Separator
    - Mechanical separation within the electrolyte of the anode and cathode electrodes
    - Permeable to the electrolyte: ionic conductivity,
  - The characteristics of a battery are decided by the combination of electrode materials and the electrolyte being used

Batteries (cont.)

- Stationary applications
  - Mature technologies
    - Lead-acid (vented and valve regulated)
    - Nickel-cadmium
  - Technologies about to be scaled up from portable
    - NiMH
    - Lithium ion
    - Lithium polymer
  - Technologies not previously commercialized
    - Flow batteries
    - Sodium-sulfur

Commercial availability

Now

2-4 years?

1-3 years?

Batteries (cont.)

- Availability: Very good, i.e. offer a large combination of technologies with different characteristics, including variations in quantities, sizes, designs and costs. (Compatible with user requirements.)
- Costs: Varies a lot between different battery technologies
  - Least expensive: Lead-acid (from ~100 $/kWh) followed by nickel-cadmium (initial costs)
- Environmental aspects: Some problems exists
  - Possible hydrogen gassing in some designs can be an explosion hazard
  - Hazardous elements involved (acid or alkaline solutions etc)
  - Lead and cadmium highly toxic: Future ban of cadmium may come into practice
- Applications: Power quality, UPS, load leveling and traction (minutes to hours discharge).
- Pilot plants: A lot of commercial sites and pilot plants exists world-wide utilizing several battery technologies
  - Lead-acid: Several tens of MWh/MW plants exists, e.g. a 40 MWh/10 MW-site (CHINO) in California
  - Nickel-cadmium: A 40 MW plant under construction in Fairbanks, Alaska.
  - Sodium-sulfur: Several Japanese demonstration sites exist (e.g. two of 48 MWh/6 MW size)
  - Flow batteries: Several multi MWh/MW sites are built, including a 120 MWh/14,75 MW plant under construction (Regenesys)

Batteries (cont.)

Battery type		Cell voltage (nominal/open)	Energy density		Power density		Operating temp.	Efficiency	Self-discharge (loss/month)	Calendar life	Cycle life	Cost	Maturity	Types available
System	Type	[V]	[Wh/kg]	$[Wh/dm^3]$	[W/kg]	$[W/dm^3]$	[?C]	[%]	[%]	[year]	[cycles]	[$/kWh]		
Lead acid	SLI (starting, lighting, ignition)	2,0/2,1	35	70			-40 to 55	80 1)	20-30 (Sb-Pb) 2-3 (maint. free)	3-6	up to 700		Very good	30-200 Ah
	Traction	2,0/2,1	25	80	200		-20 to 40	65 3)	4-6	6	1500	215 2)	Very good	45-200 Ah pr positive plate
	Stationary	2,0/2,1	10-20	50-70			-10 to 40	84	-	18-25	-	100-150 1) 200-700 13)	Very good	5-400Ah up to 1440 Ah per positive plate
NiCd	Vented pocket plate	1,2/1,29	20	40			-20 to 45	60	5	8-25	up to 2000		Very good	prismatic to 1300 Ah
	Vented sintered plate	1,2/1,29	30-37	58-96	330-460	730-1250	-40 to 50	65 3) 4)	10	3-10	up to 2000	300-400	Very good	1,5-100 Ah
	FNC (fiber nickel Cd))	1,2/1,35	10-40	15-80			-50 to 60	55-65	10-15	5-20	up to 10000		Good	450 Ah
NiMH		1,2/1,4	75	240	200 12)	320 5)	-20 to 50	65 3)	15-25 <10% @48h	2-5	up to 600 up to 1000 12)	1500 2) 300-400 12)	Good	prismatic to 100 Ah
Li-ion		4,0/4,1	150	400	700-1300	2000-3000 640-2900 5)	-20 to 50	95	2	-	3000+	>600 13) ~1000 14)	Good	cylindrical or prismatic to 100 Ah
Li-polymer			200 3)	220 6)	100 3) 315 6)			65			1000+ 6)		Modest	
NaS		-/2,076-1,78	53-116	40-170	9-15	14-21	310-350	75-80 1) >86 8)	No self-discharge	15 8)	>2250 8)	50-100 1) 140-1100 9)	Modest	Battery modules up to 5421 kWh/50 kW/ 3624 Ah (NKG, Japan)
Metal-air	Zn/air	1,0-1,2	120-180	160-180	10-200			50			200		Poor 7)	-
Vanadium-Redox		1,2/1,5	20	20	20-25		Ambient	60-75	5-10		3000	175-190 11) 12) 600 12)	Modest	Several multi-kW syst., incl. 1,5MWh/3MW and 5 MWh/5MW (Jp)
Regenesys		1,25/1,4	10	10	20-25		Ambient	60-75	5-10		2000	175-190 10)	Modest	Pilot plants of 5-100 kWh exists; 120 MWh/14,75 MW under construction
Zinc/bromine		1,60/1,83	65 70 1)	60 75 1)	90		25-40	60-65	-		1250	100-200 1)	Modest/ good	Several hundred kWh installations, a 4 MWh/1 MW (Jp)

Source (if no other references are indicated): Linden D., Reddy T.R.: Handbook of batteries. Third edition. New York, McGraw-Hill. 2001. ISBN 0-07-135978-8.

1) Hurwitch J.H., Carpenter C.A.: Technology and application options for future battery power regulation. IEEE Transaction on Energy Conversion, vol 6, No. 1, 1991. pp. 216-223

2) Gage T.B.: Lead-acid batteries: Key to electric vehicle commercialization. Experience with design, manufacture and use of EV's. IEEE 2000. pp.217-222.

3) Riley R.Q.: Electric and hybrid vehicles: A technology overview. http://www.solardome.com/solardome51.html

4) Not specified for different types of NiCd, but NiCd in general.

5) ESA: Technologies for energy storage. IEEE PES stationary Battery committee. 2000.

6) Vincent C.A.: Lithium batteries IEE Review, March 1999. pp. 65-68

7) Applies to electrical rechargeable metal/air batteries

8) NKG home site: http://www.ngk.co.jp/english/products/nas/nas2.htm

9) Estimated costs depending on the production volume: Highest cost show T5-cell [used in Ohito Substation (6 MW)] at a mass production of 48 MWh/year, lowest cost shows mass production of 1600 MWh/year. (Kamibayashi M.: Advanced sodium-sulfur (NAS) battery system.IEEE Power Engineering Society, Winter Meeting, 2001.)

10) Børresen, B.: Elektrokjemisk energilagring. EEU-kurs. 08.01.2002. NTNU.

11) Skyllas-Kazakos M., Menictas C.:The vanadium redox battery for emergency back-up applications. IEEE Intelec –97. 1997. pp 463-471.

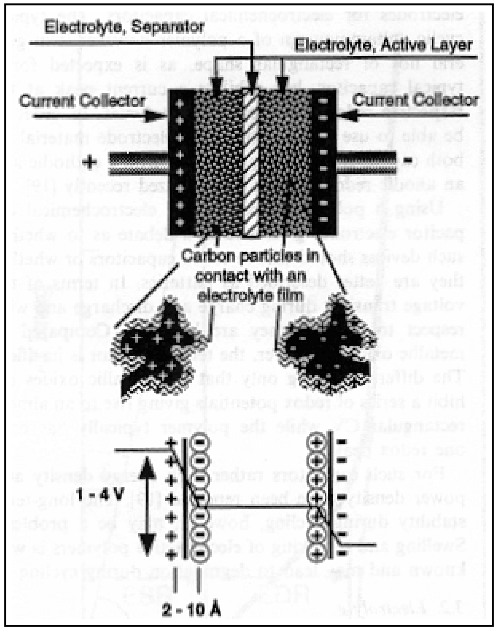
12) Hunt, G L: The great battery search. IEEE Spectrum nov 1998. pp 21-26 12)

13) http://www.electricitystorage.org/technology/

14) Nourai A.: Bulk Electricity Storage Technologies. ESA mini meeting. November, 2001.

Electrochemical capacitors

- Two electrodes separated by an electrolyte
- Energy is stored in an electrochemical double layer (Helmholtz layer) at the interface between the solid electrode and the electrolyte
- Electrostatic charge process: Ideally, the charge process does not involve any electron across the electrode interface



The double layer capacitance C of an electrode immersed in an electrolyte:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

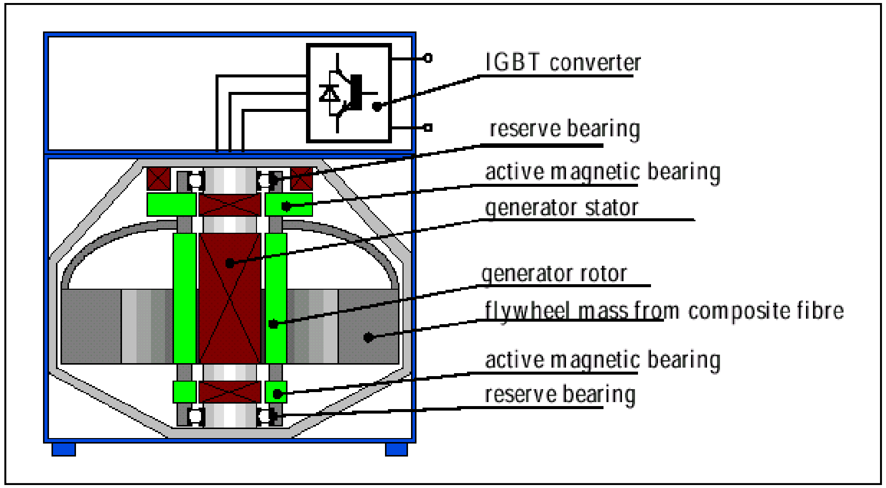
Two types of electrochemical capacitors exist:
- one which charges and discharges the interfacial double-layer
- one where the charge-discharge mechanism involves charges across the double layer (pseudo-capacitor or redox capacitor)

Electrochemical capacitors

- Availability: Low voltage, high capacitance devices commercial available. Devices with higher voltages are available, but to a less extent.
- Costs: Expensive (approx. tens of 1000 $/kWh), but cost is expected to decrease as the market increase (DOE goal production cost: 1000 $/kWh in 2000, 650 $/kWh in 2004)
- Environmental aspects: Non-toxic, do not contain heavy metals, easy to dispose. Tests indicate very rugged components against overcharge or overdischarge problems (gassing, gas pressure causing electrolyte spilling etc.)
- Applications: Power quality and UPS (seconds to minutes discharge), complementary storage with batteries, fuel cells or diesel electric systems.
- Pilot plants: A prototype design from Saft was able to store 46 Wh during a 120 A charge betwen 75 and 135 V and delivered 40 Wh with an energy eficiciency of 86 %.

Flywheels

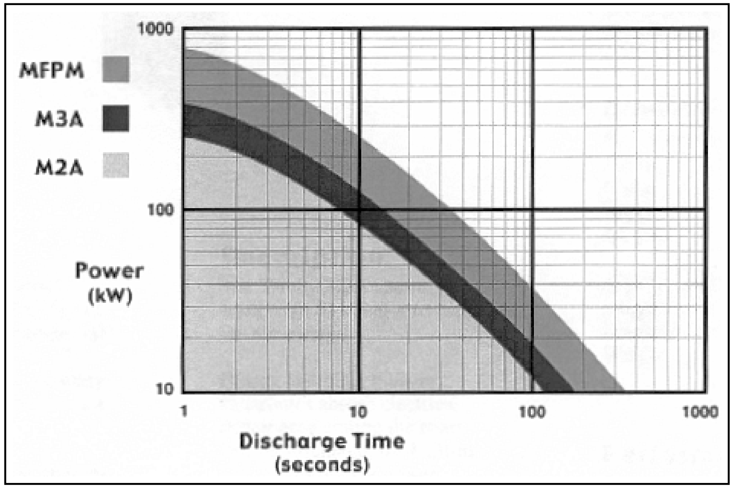
- Electromechanical storage system
- The kinetic energy related to the moment of inertia and angular velocity: $E_k = \frac{1}{2} I \omega^2$
- Electrical energy converted from or into kinetic energy through an electrical machine: Charging increases speed of rotor, discharging decreases the rotor speed



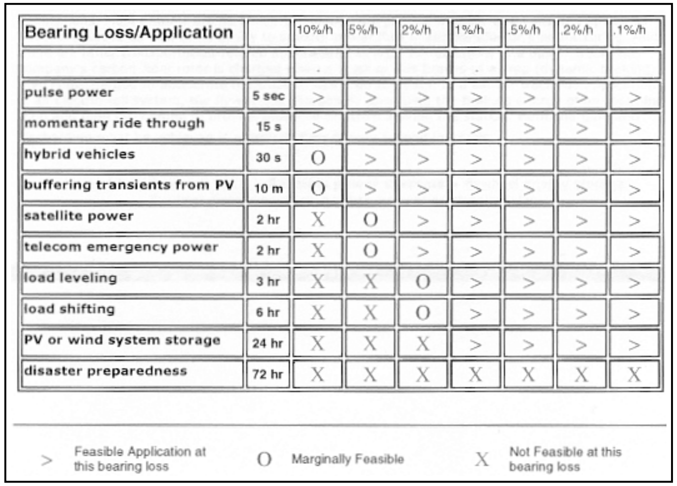
Low speed flywheels:
- steel rotor
- conventional bearings
- speeds of ~7000 rpm
High speed flywheels:
- composite rotor
- conventional or magnetic bearings
- speeds of ~40000 rpm
Very high speed flywheels:
- high speed composite rotors
- high temperature superconducting bearings
- speeds of >100000 rpm

Flywheels (cont.)

- Availability: Low-speed flywheels available, high-speed flywheels hardly available
- Costs (dependent on energy):
  - Low-speed (1650 kW) : ~300 $/kW, ~300 $/kWh
  - High-speed (750 kW) : ~25000$/kW, ~350 $/kW
- Environmental aspects: Safety problem if mechanical damage of rotor?
- Applications: Power quality, battery replacement in UPS (discharge in seconds to minutes)



Relation of power and discharge time for three flywheels from AFS Trinity



Bearing Loss/Application		10%/h	5%/h	2%/h	1%/h	.5%/h	.2%/h	.1%/h
pulse power	5 sec	>	>	>	>	>	>	>
momentary ride through	15 s	>	>	>	>	>	>	>
hybrid vehicles	30 s	O	>	>	>	>	>	>
buffering transients from PV	10 m	O	>	>	>	>	>	>
satellite power	2 hr	X	O	>	>	>	>	>
telecom emergency power	2 hr	X	O	>	>	>	>	>
load leveling	3 hr	X	X	O	>	>	>	>
load shifting	6 hr	X	X	O	>	>	>	>
PV or wind system storage	24 hr	X	X	X	>	>	>	>
disaster preparedness	72 hr	X	X	X	X	X	X	X

\> Feasible Application at this bearing loss

O Marginally Feasible

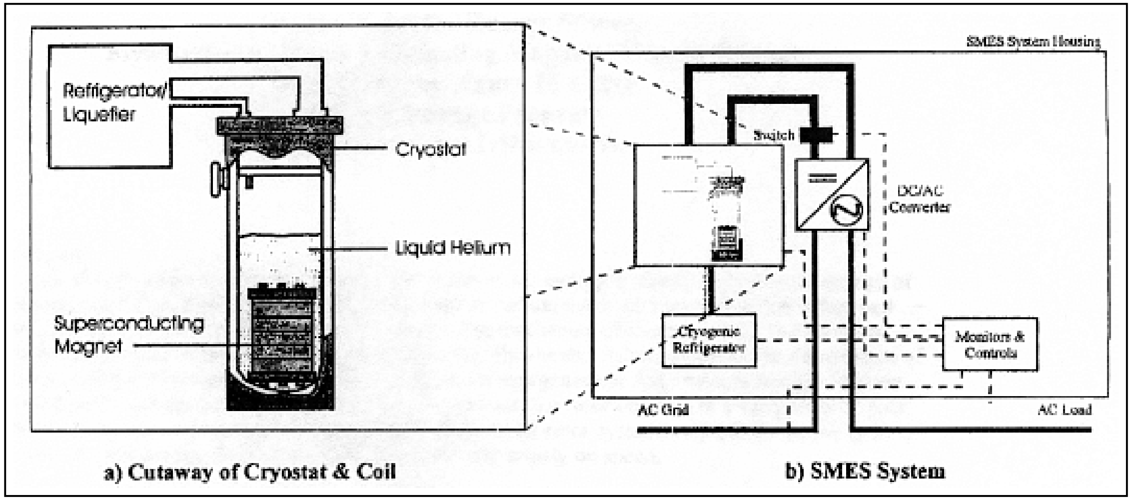
X Not Feasible at this bearing loss

Possible flywheel applications and their restrictions due to bearing losses (Source: AFS Trinity)

- Pilot plants: 200 MJ/20 MW flywheel energy storage (low-speed) installed in Japan 1996. (Used for frequency regulation.)

Superconducting magnetic energy storage (SMES)

- Stores energy in the magnetic field associated with the current flowing through superconducting wires in a large magnet



a) Cutaway of Cryostat & Coil **b) SMES System**

$$E = \int \vec{B} \cdot d\vec{H} = \frac{B^2}{2\mu_0\mu_r}$$

$E = \frac{1}{2}LI^2$

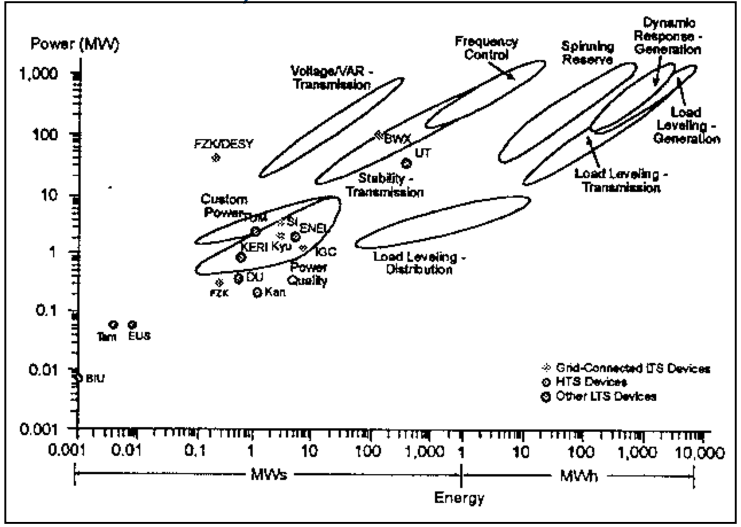
$V = L dI/dt$

$P = dE/dt = LI dI/dT = VI$

µ-SMES: SMES-device with limited energy content, typical 1-10 MJ, i.e. 0,28-2,8 kWh

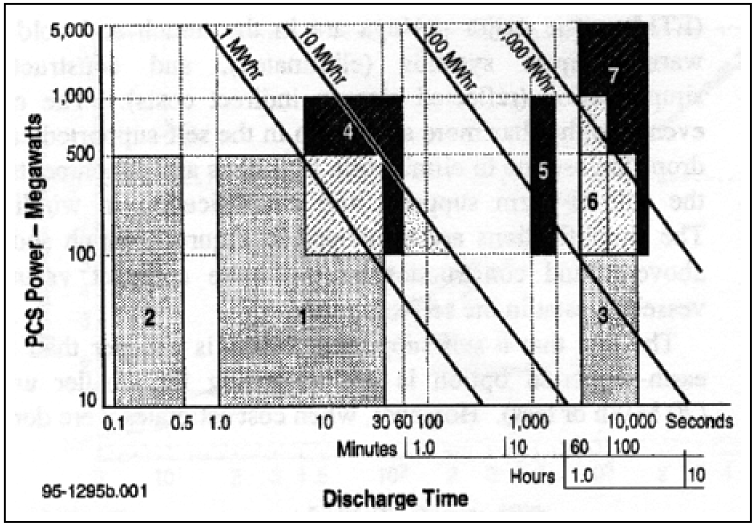
SMES (cont.)

- Availability: Poor (one manufacturer worldwide)
- Costs: Very high. µ-SMES: ~2,4 M$/kWh, ~670 $/kW
- Environmental aspects: DC magnetic field in proximity to magnet. Possible health effect?
- Applications: Transmission stability, voltage/VAR support, power quality (discharge in seconds)



SMES projects 1998 world-wide

Source: Giese R F: Superconducting energy systems.
Argonne National Laboratory. Argonne, 1994.



SMES applications

Source: Luongo C A: Superconducting storage systems: An overview.
IEEE Transactions on Magnetics, vol 32, no 4, 1996, pp 2214-2223.

Legend:

Transmission substation applications:
1. Transmission stability
2. Voltage/VAR support
3. Load leveling)

Generation system application:
4. Frequency control
5. Spinning reserve
6. Dynamic response
7. Load leveling

- Pilot plants: More than ten D-SMES (µ-SMES) devices has been sold last two years in USA

Summary

Applications:

Energy storage		Typical power rating [MW]	Typical discharge time	Application
Electrochemical capacitor		0,0001-0,1	seconds to minutes	Power quality, UPS, complementary storage to batteries, fuel cells, diesel electric etc.
Battery	Lead acid	0.001-50	minutes to hours	Power quality, reliability, frequency control, reserve, black start, UPS
	Advanced (VRLA, NaS, Li)	0,001-1	minutes to hours	Various, including utility energy storage
	Flow batteries	0,1-100	minutes to tens of hours	Power quality, reliability, peak shaving, reserve, energy management, integration of renewables
Flywheel		0,005-1,5	seconds to minutes	Power quality, battery replacement in UPS
SMES		0,01-2	$\leq$ seconds	Transmission stability, voltage/VAR support, power quality

Characteristics:

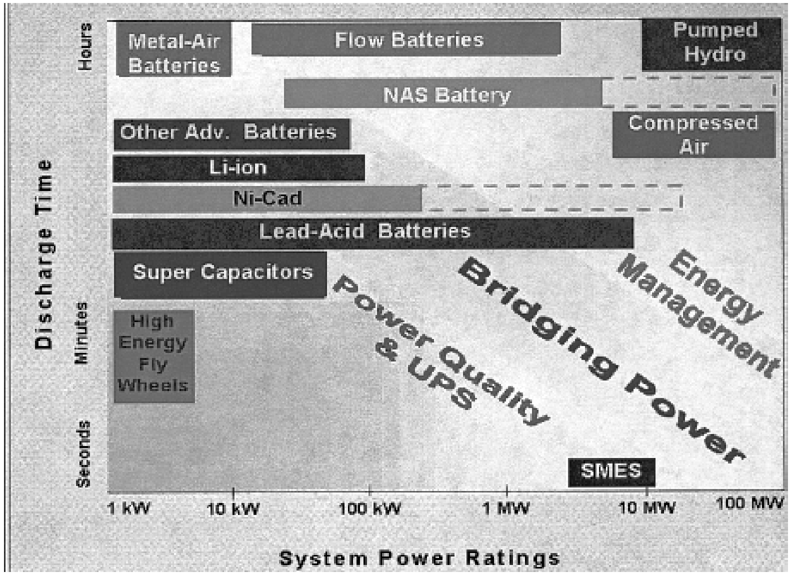
Energy storage	Energy density		Power density		Efficiency [%]	Life time [cycles|years]	Recharge time	Maintenance	Maturity
	[Wh/kg]	[Wh/dm^3]	[W/kg]	[W/dm^3]					
Electrochemical capacitors	1-10	0,01-20	400-4000	10^2-10^6	90-95	$>10^5$|>10	Seconds to minutes	None	Good, increasing
Batteries	10-200	10-400	20-600	10-1000	50-95	500-10^4|2-20	Minutes to hours	From weeks to none	Very good
Flywheels	30-200	1-?	180-30000	125-667	88-93	10^5|20	Minutes	Months to annual	Good/modest, increasing
SMES	4 –75	-	10^3-10^5	-	90-99	$>10^5$|20	Minutes (μ-SMES)	Annual	Poor, increasing slowly

Availability, cost and environmental impact

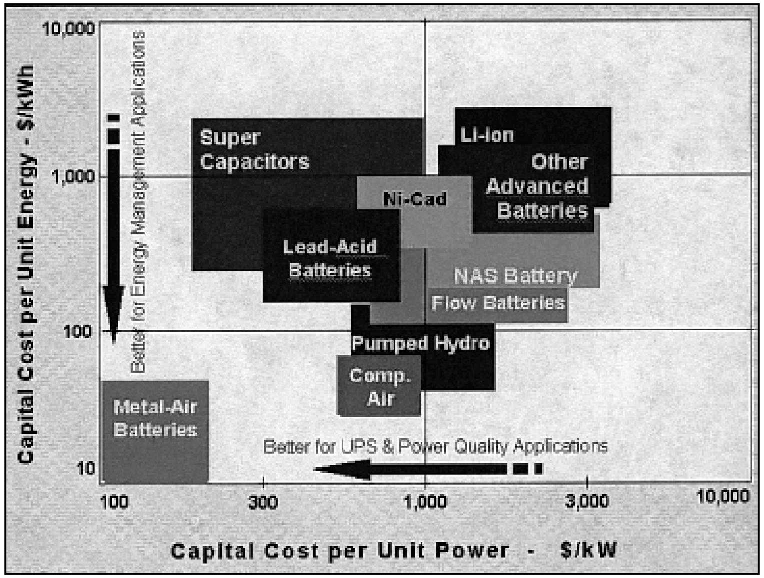
Energy storage		Capital costs [\$/kWh | \$/kW]	Availability	Environmental impact
Electrochemical capacitors		83500 | 250-1000	Good	Very good
Battery	Lead acid	200-700 | 240-700 [1)]	Very good	Modest to very good Depending on type of battery. (Future ban of cadmium?)
	Advanced (VRLA, NaS, Li)	Very varying dependent of technology, but always more expensive than lead-acid	Good to very good (depending on technology)	
	Flow batteries	175-600 | -	Modest	
Flywheel		300-25000 | 300-500	Low-speed flywheel available High-speed flywheel hardly available	Good. Uncertainty: Safety problem on mechanical damage of rotor?
SMES		~2,4 million | ~670	Poor. One manufacturer worldwide	Good (Magnetic field in surroundings of superconductor. Possible health effect?)

1) Based on cost of plants >1MW in the world in 1995 (1995$)

Summary (cont.)



Guidelines typical applications of energy storages

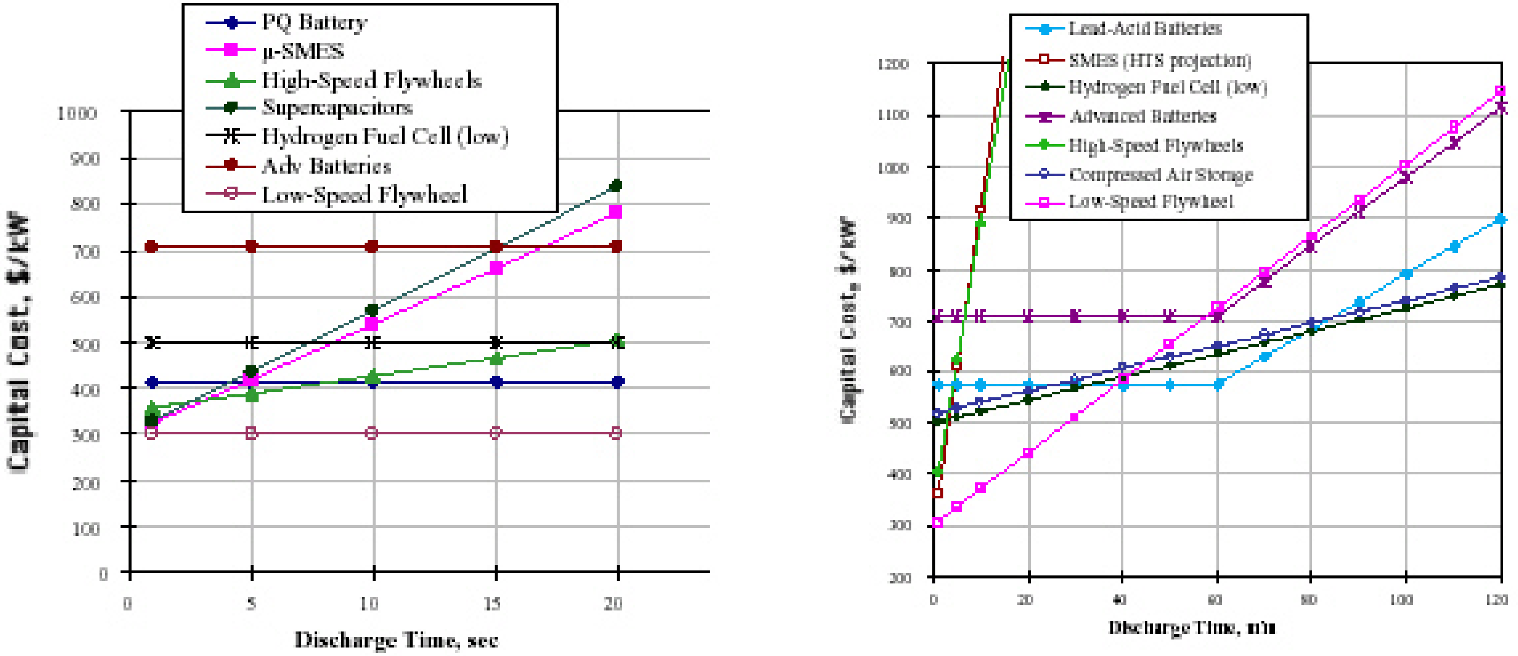


Capital cost comparison of energy storages

Source of illustrations: Nourai A.: Bulk Electricity Storage Technologies.
ESA mini meeting. November, 2001

Life cycle cost is the meaningful parameter for cost comparisons. Depends strongly on applications, i.e. difficult to find from literature

Summary (cont.)



Power Quality
(very short time:
0 - 20 sec, 1 – 4 MW)

Distributed Utility Applications
and Renewables Matching
(short time: 10 min. to 2 hours, <2 MW)

Capital cost [$/kW] vs. discharge time for different energy storage technologies

(Source: Boys J. D., Clark N.: Flywheel energy storage and super conducting magnetic energy storage systems.
IEEE Power engineering society summer meeting (PES 2000), July 2000.)