Electrochemical Capacitor Potential in the Energy Industry

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Outline

- Electrochemical capacitor (EC) energy storage introduction
- Energy storage technology comparisons
- EC energy-conservation applications
- Energy-sector applications of ECs
- Storage system economics
- Summary

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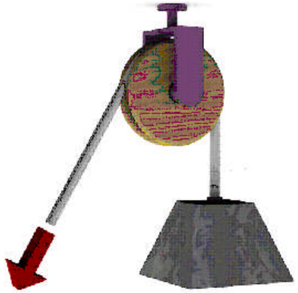
PHYSICAL ENERGY STORAGE

Typically Highly Reversible



Gravity

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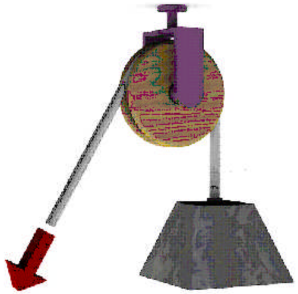

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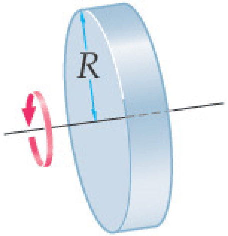

Kinetic Energy

PHYSICAL ENERGY STORAGE

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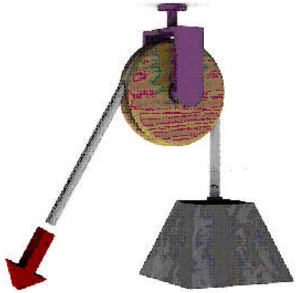

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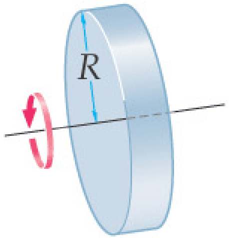

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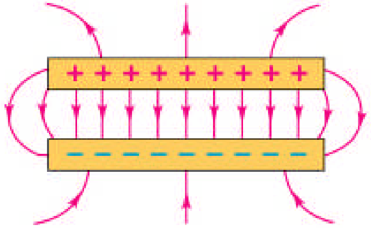

Electric Field

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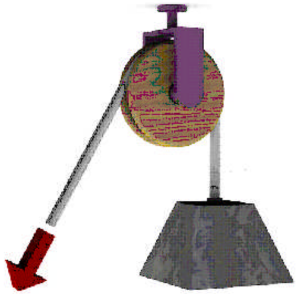

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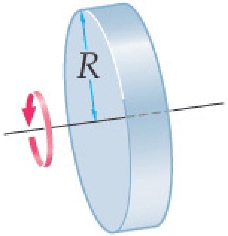

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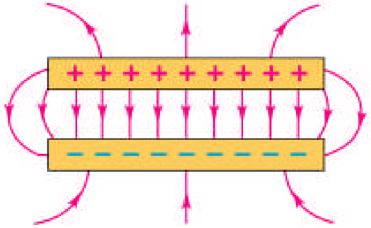

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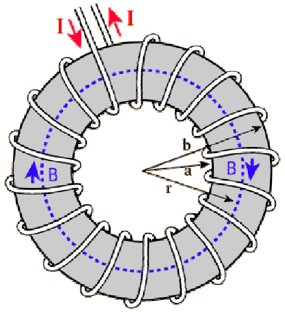

Magnetic Field

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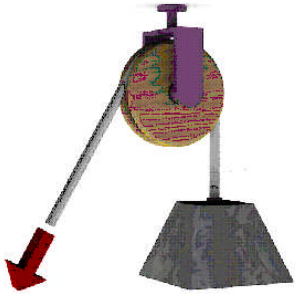

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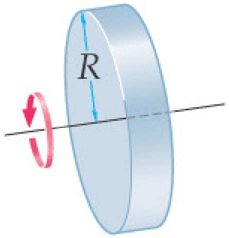

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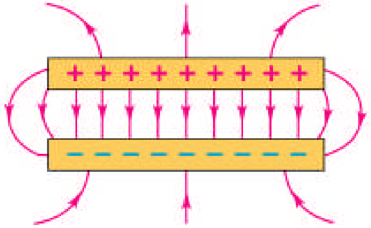

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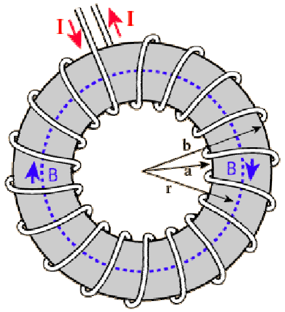

Magnetic Field

Mechanical

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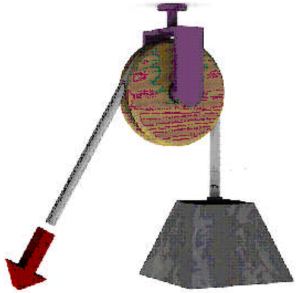
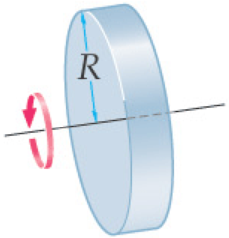


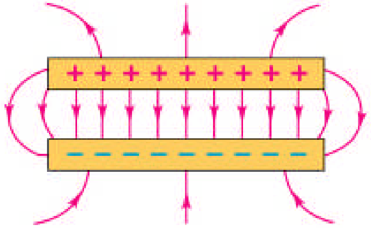
Gravity

Pumped Hydro



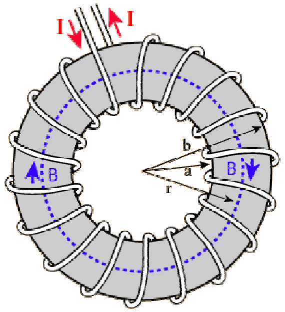
Kinetic Energy

Flywheel



Electric Field

Capacitor



Magnetic Field

SMES

Mechanical

CAES

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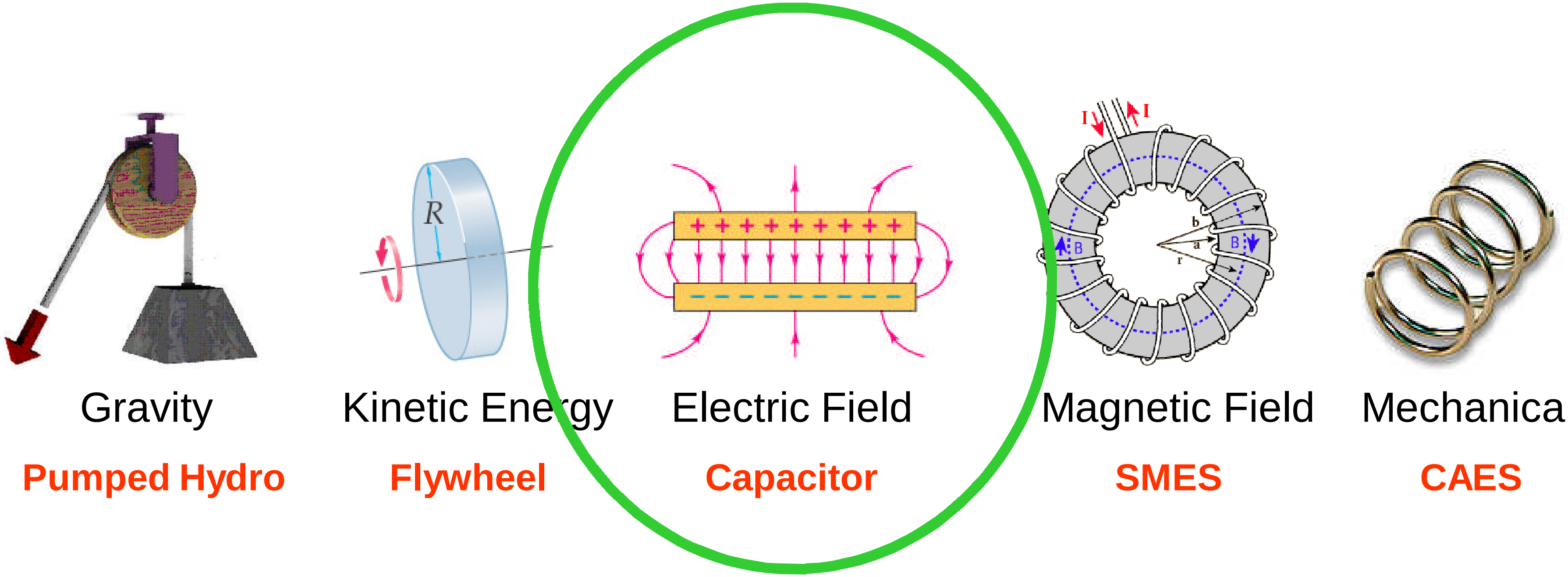

Gravity	Kinetic Energy	Electric Field	Magnetic Field	Mechanical
Pumped Hydro	**Flywheel**	**Capacitor**	**SMES**	**CAES**

No moving parts

Essentially no maintenance

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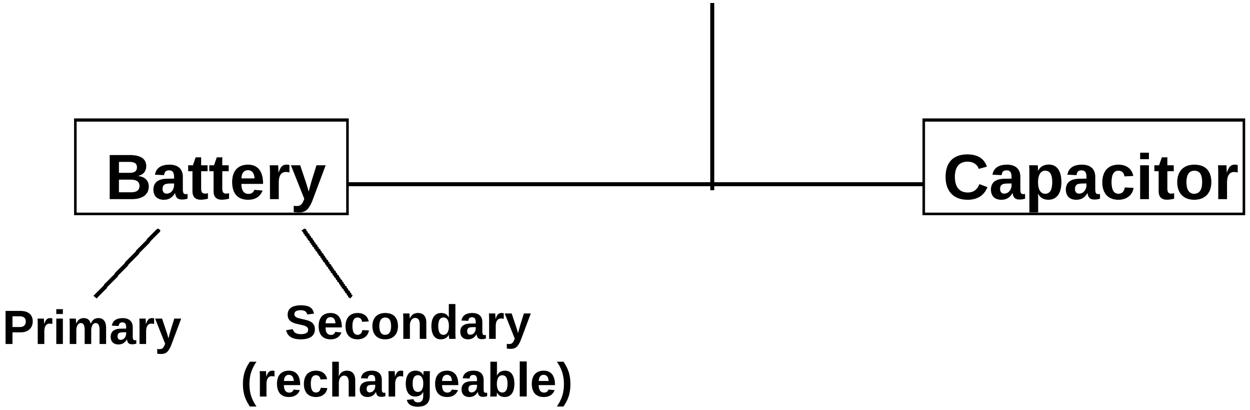
ENERGY STORAGE COMPONENTS

Battery

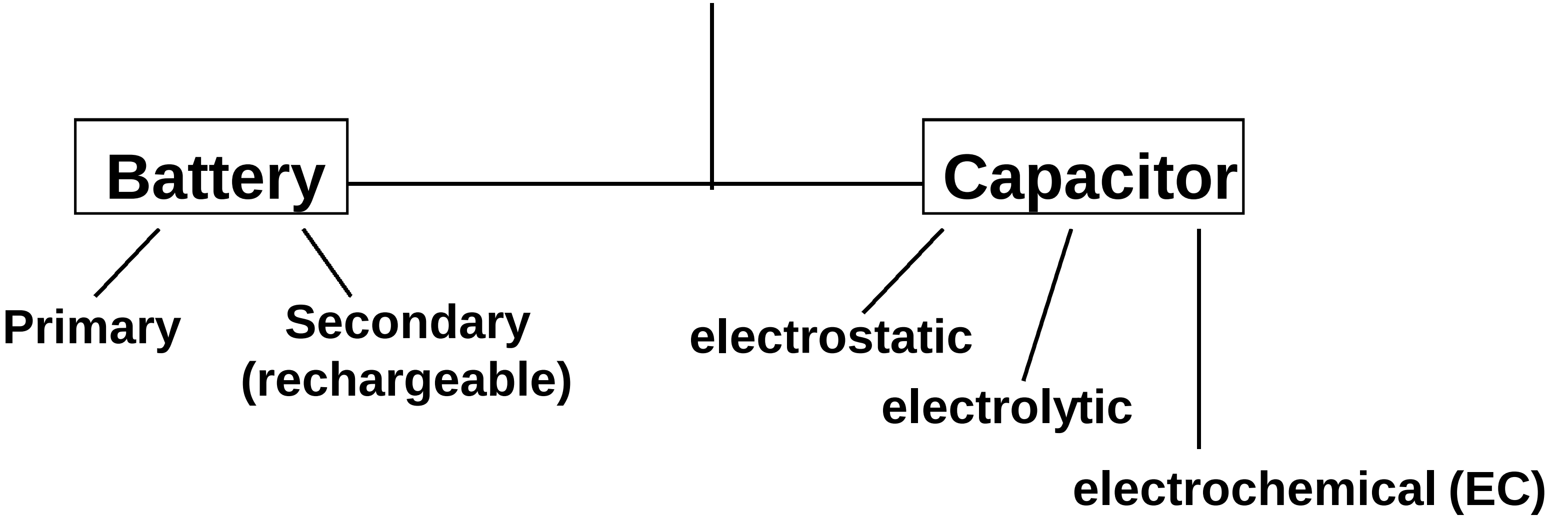
Capacitor

ENERGY STORAGE COMPONENTS



- **Battery**
  - **Primary**
  - **Secondary (rechargeable)**
- **Capacitor**

ENERGY STORAGE COMPONENTS



Battery

Primary

Secondary
(rechargeable)

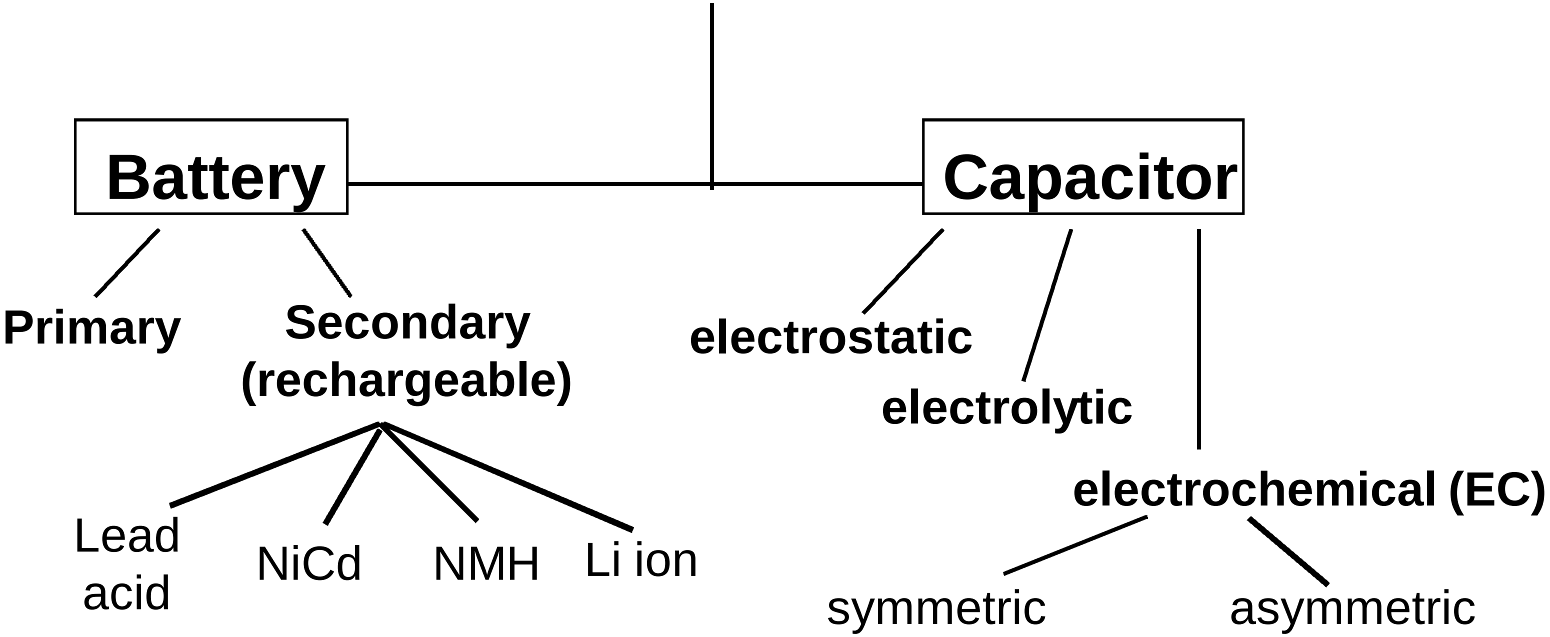
Capacitor

electrostatic

electrolytic

electrochemical (EC)

ENERGY STORAGE COMPONENTS



Battery

Primary

Secondary (rechargeable)

Lead acid

NiCd

NMH

Li ion

Capacitor

electrostatic

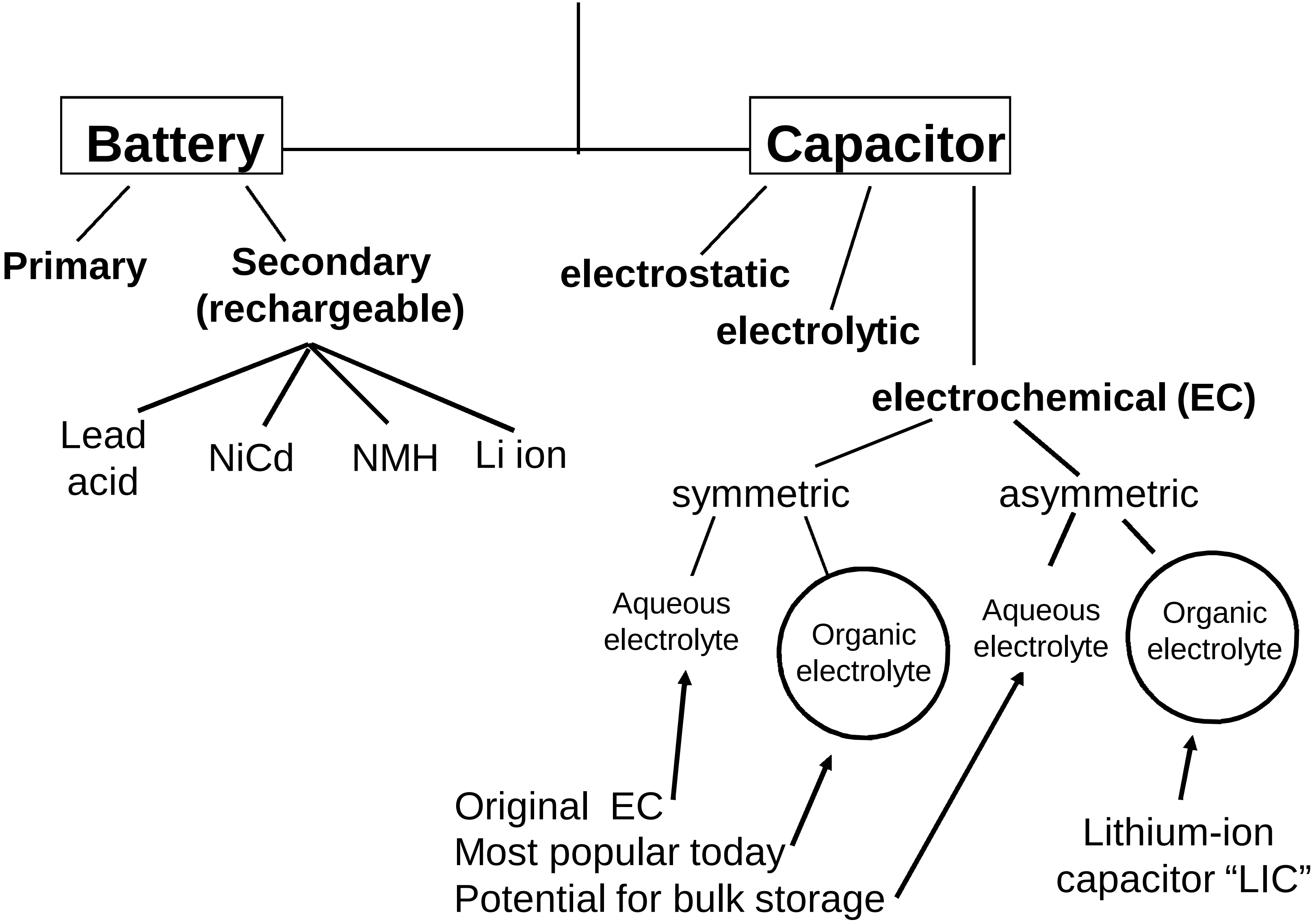
electrolytic

electrochemical (EC)

symmetric

asymmetric

ENERGY STORAGE COMPONENTS



Battery

Primary

Secondary (rechargeable)

Lead acid

NiCd

NMH

Li ion

Capacitor

electrostatic

electrolytic

electrochemical (EC)

symmetric

Aqueous electrolyte

Organic electrolyte

asymmetric

Aqueous electrolyte

Organic electrolyte

Original EC

Most popular today

Potential for bulk storage

Lithium-ion capacitor "LIC"

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Energy Storage Technology Comparison

STORAGE TECHNOLOGY			Specific Energy (Wh/kg)
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Electrolytic Capacitor			0.05
Electrochemical Capacitor (EC)			5

Energy Storage Technology Comparison

STORAGE TECHNOLOGY	**Charge/ discharge time** (s)	**Cycle Life** (80% DOD)	**Specific Energy** (Wh/kg)
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- Often called **Supercapacitors** or **Ultracapacitors**

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- Original market—volatile computer memory backup (CMOS)

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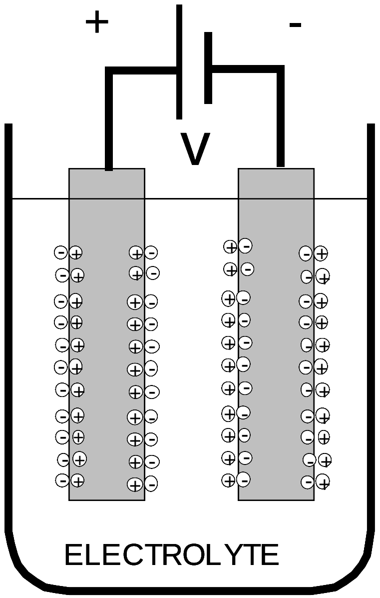
- Appreciation of other performance features in the 1990s
  - **High power (especially on charging)**
  - **High cycle-life**
  - **Long operational life**
  - **Reliable**
  - **Safe**

DOUBLE LAYER CAPACITOR CONCEPT



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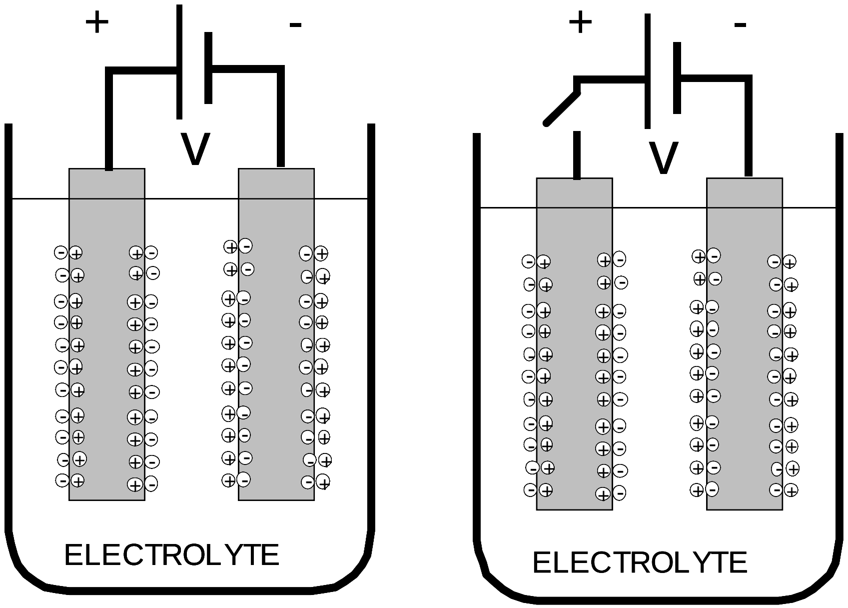

- Discovered by Helmholtz in 1800s
- C ~ 10 $\mu F/cm^2$ on electrode surface
- Physical charge storage (not chemical)
- Voltage limited--electrolyte decomposition potential
- High-surface-area electrodes--large capacitances

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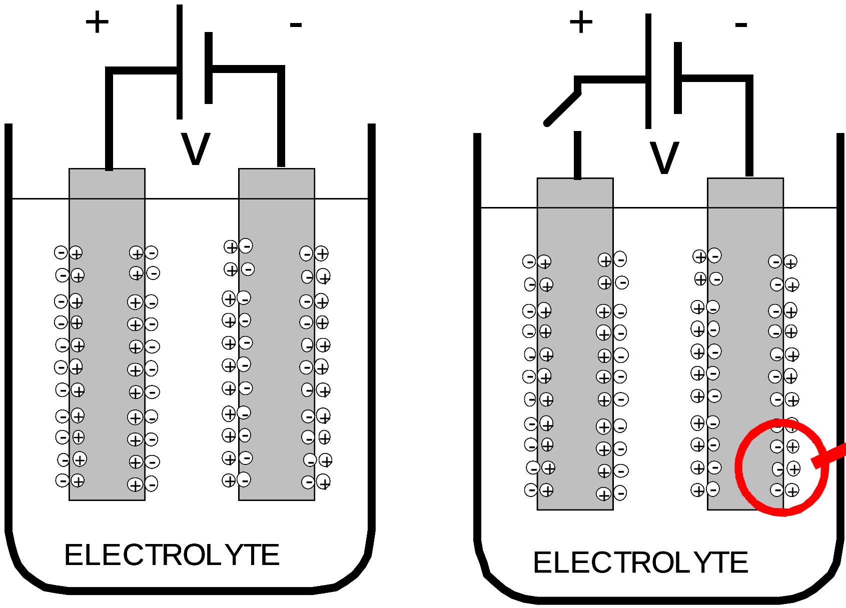

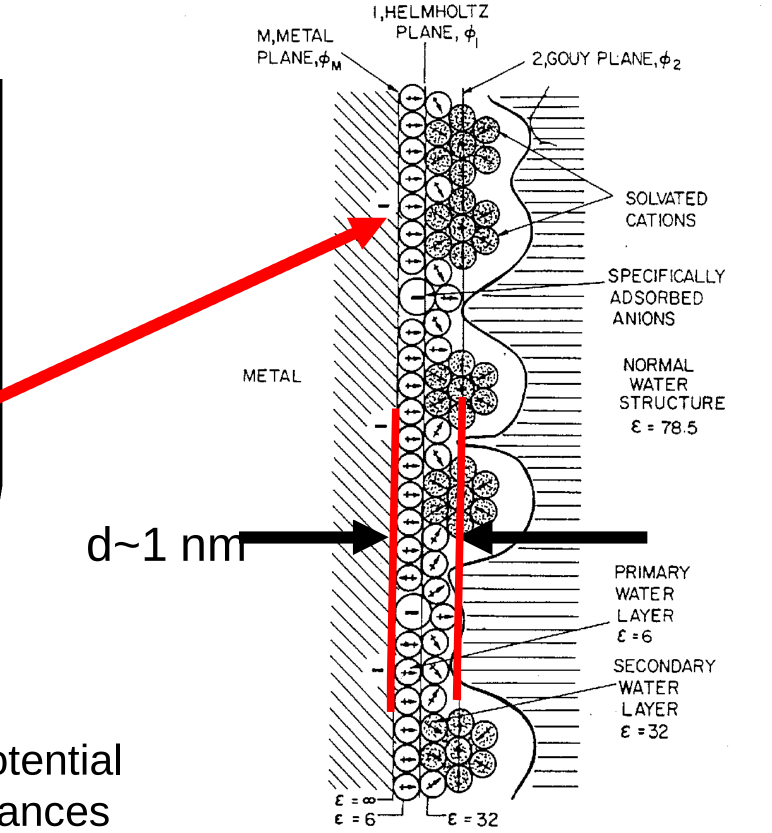

Fig. 6. Solvent adsorption model of the double-layer according to Devanathan, Bockris and Müller (52). (*Proc. Roy. Soc. London* A274, 55.)

Electric Double Layer

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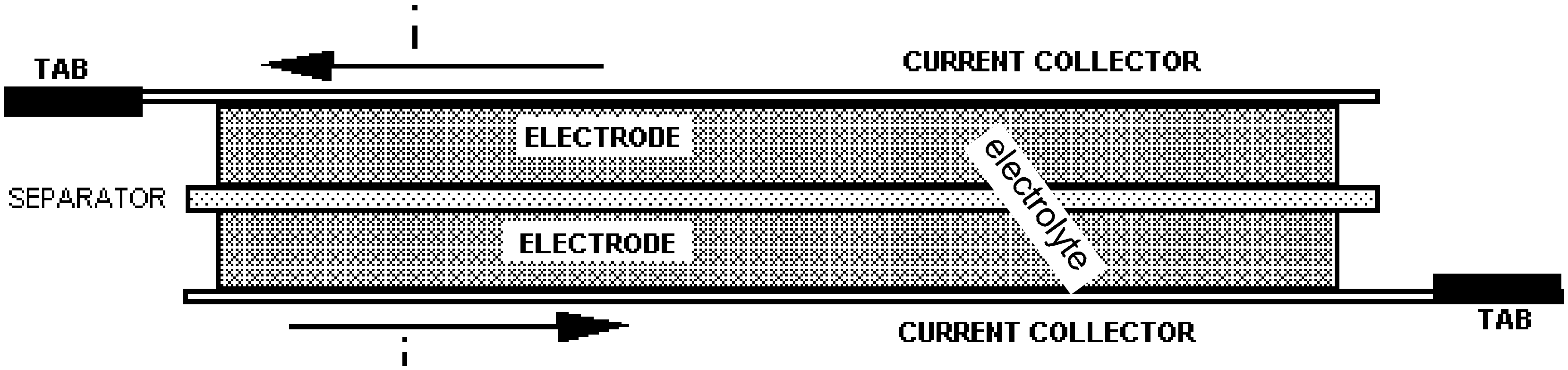
Typical Electrochemical Capacitor Construction



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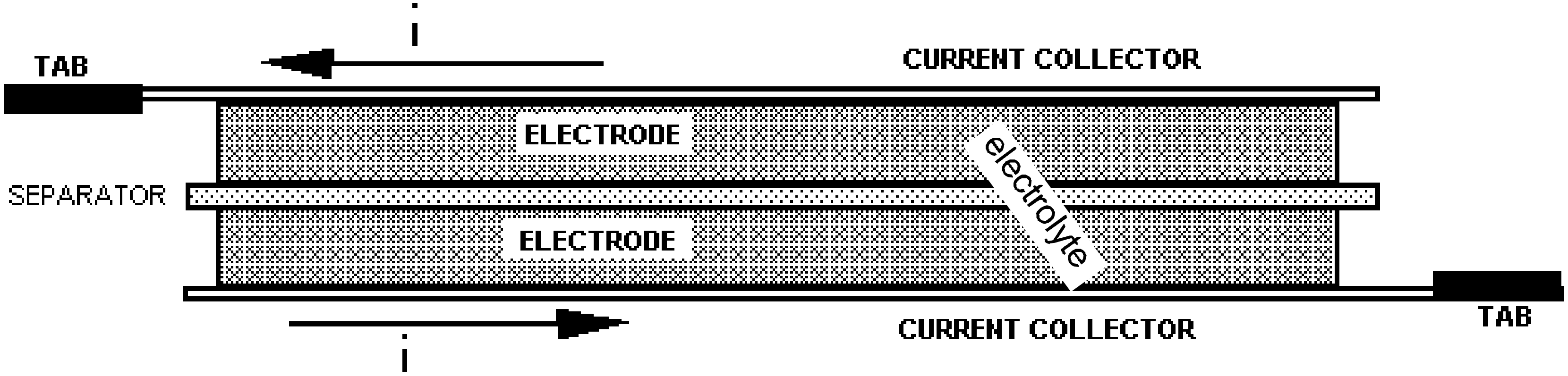

Electrodes typically ~1500 m^2/g
C/M > 100 F/g

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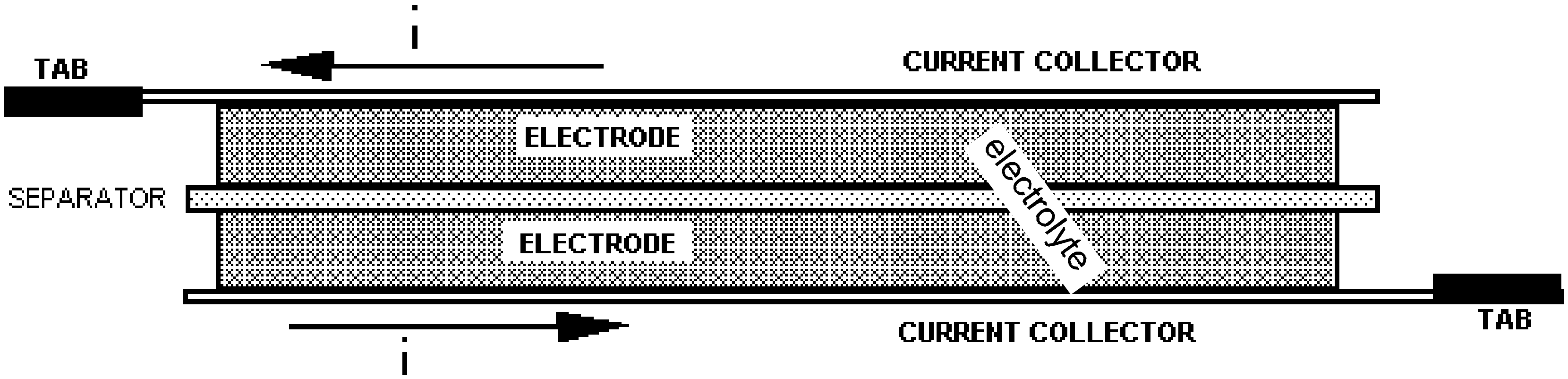
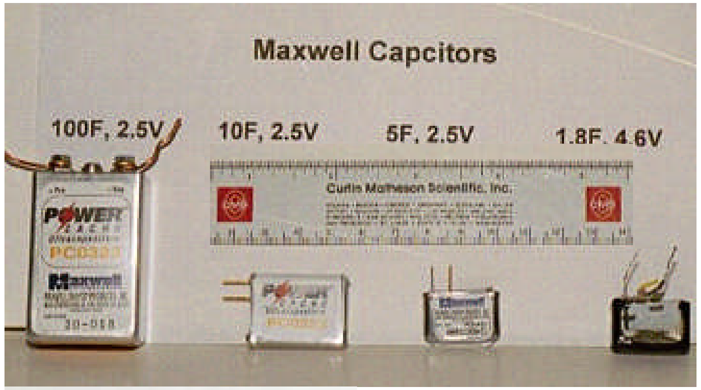


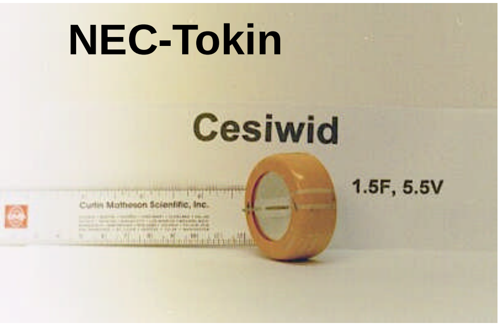
Electrodes typically ~1500 m^2/g
C/M > 100 F/g

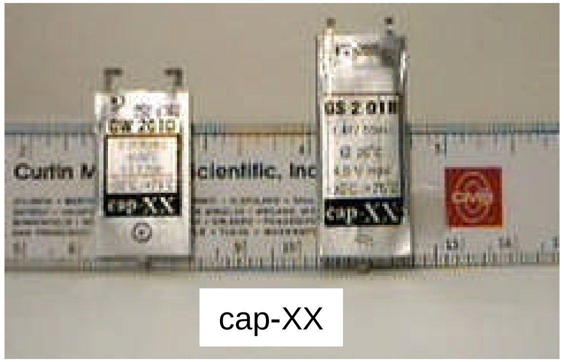
~3000 F, 2.85 V
> 10^6 cycles, >2000 hr life @ 65 ^oC
~1 second response time

Small Electrochemical Capacitor Products



NEC-Tokin



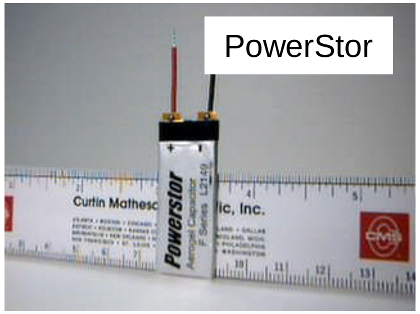


cap-XX

FastCAP

General Capacitor

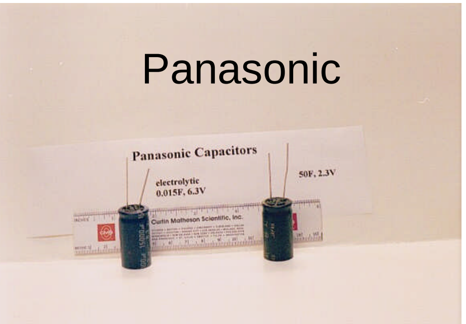
PowerStor



Danionics

ELNA

Panasonic



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Large EC Products


ELIT

Maxwell


Nippon Chemi-Con

Eaton

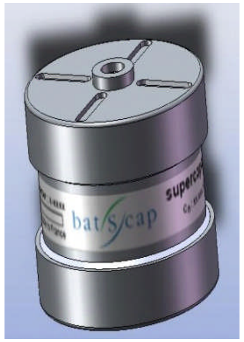
Ioxus

LS Mtron

Wima


ESMA

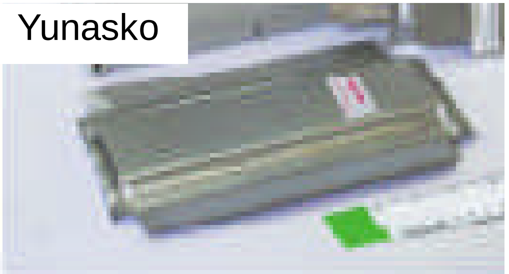
Meiden



Batscap

JSR Micro

Yunasko



EC -- Battery Comparison

PROPERTY	BATTERY	EC
Storage mechanism	Chemical	Physical

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Charge rate	Limited by reaction rates	Very high, same as discharge rate
Cycle life limitations	Physical stability, chem. reversibility	Side reactions
Life limitation	Thermodynamic stability	Side reactions

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Energy Storage Technology Comparison

STORAGE TECHNOLOGY	**Charge/ discharge time** (s)	**Cycle Life** (80% DOD)	**Specific Energy** (Wh/kg)
Lead Acid Battery	**10^{+4}**	**$>10^{+2}$**	**30**

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Li-ion Battery	**10^{+2}**	**$>10^{+3}$**	**100**
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Energy Storage Technology Comparison

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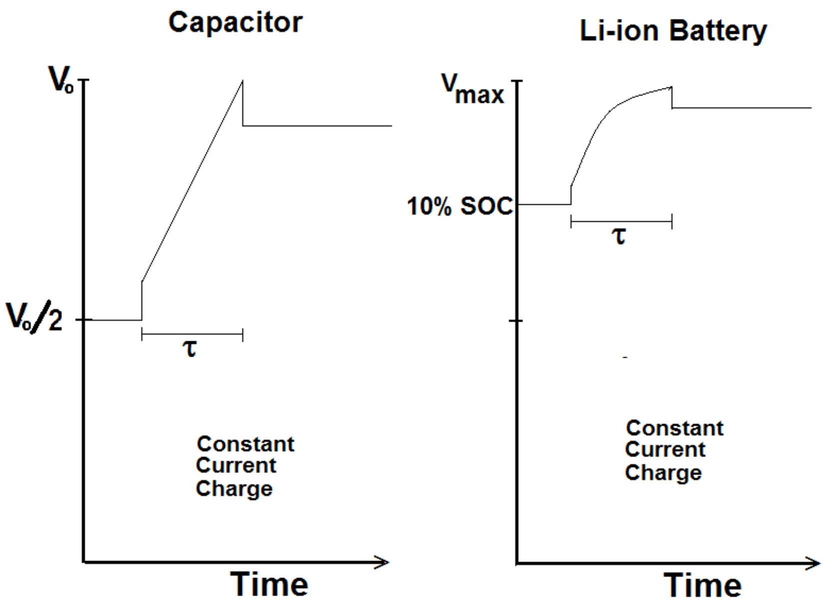
Energy Storage Technology Comparison

STORAGE TECHNOLOGY	Charge/ discharge time (s)	Cycle Life (80% DOD)	Specific Energy (Wh/kg)	COST ($/kWh)
Electrostatic Capacitor	10^{-9}	$>10^{+15}$	0.001	2,000,000
Electrolytic Capacitor	10^{-4}	$>10^{+10}$	0.05	1,000,000
Electrochemical Capacitor (EC)	1	$>10^{+6}$	5	20,000
Li-ion Battery	10^{+2}	$>10^{+3}$	100	1,000
Lead Acid Battery	10^{+4}	$>10^{+2}$	30	100

Capacitor--Battery Charging Comparison

3000 F capacitor and 12 Ah Li-ion battery

Regenerative Energy Measurement



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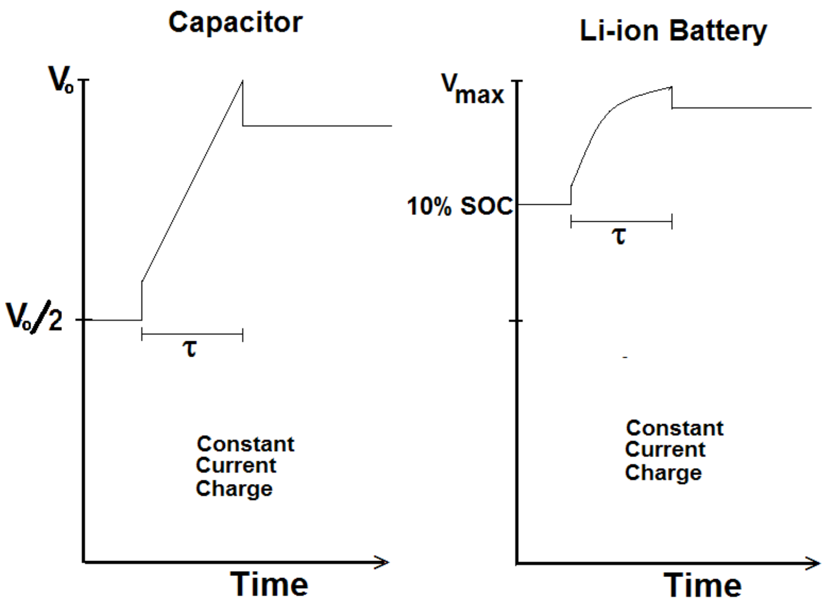

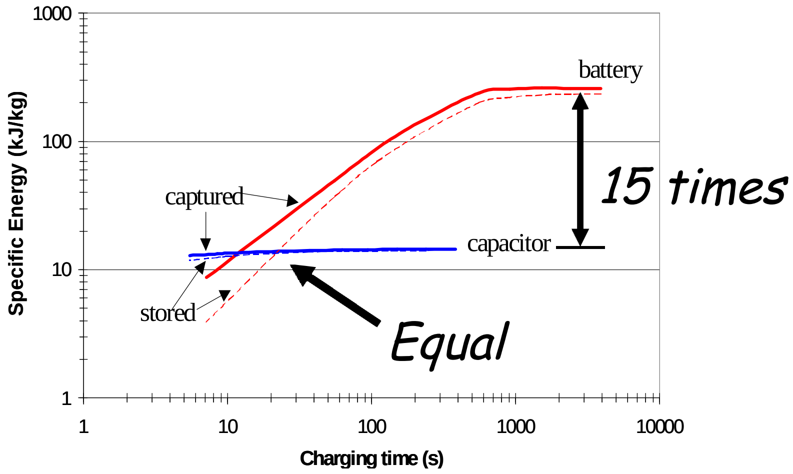

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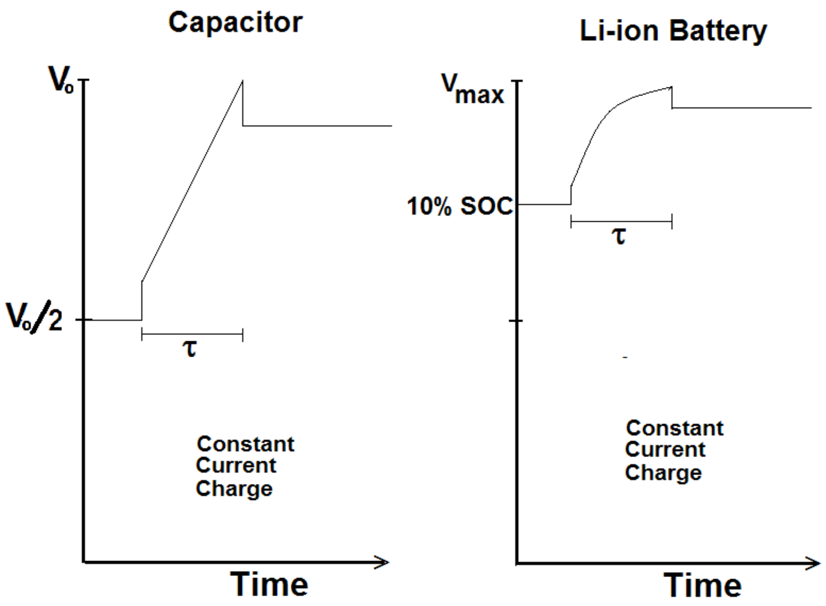

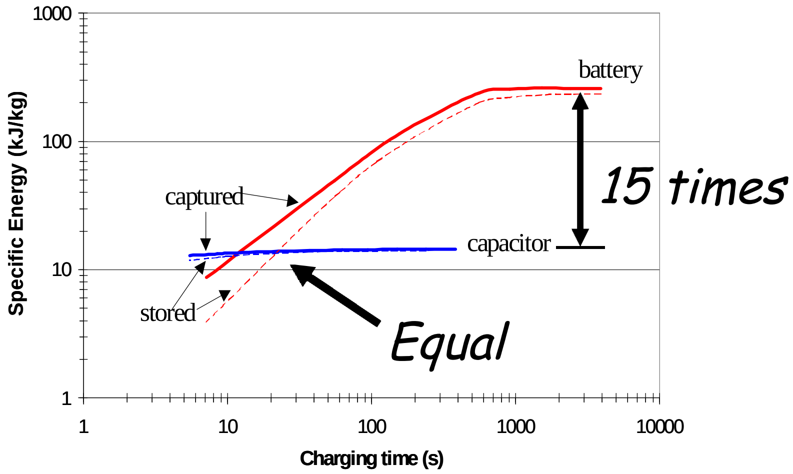

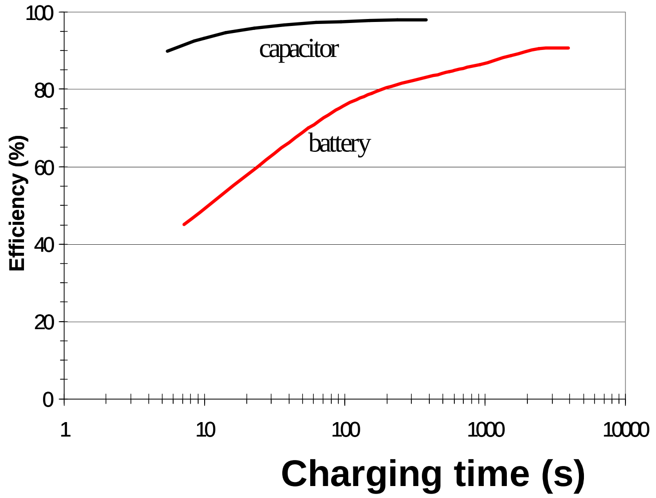

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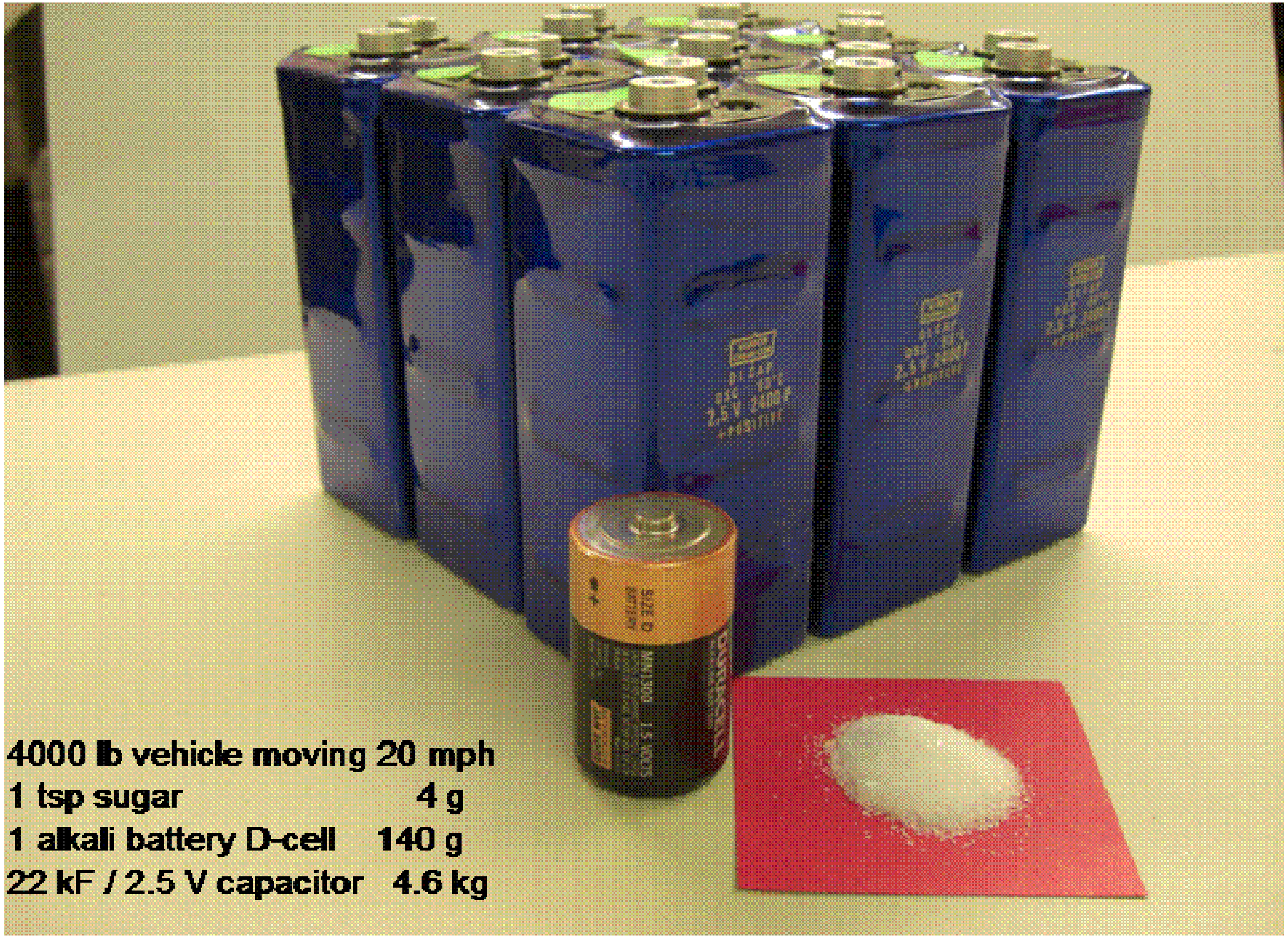
EC Summary

- Extraordinarily high specific capacitance ~100 F/g
- High energy compared with conventional capacitors
- Low unit-cell voltage, ~1 to 3 V
- Response time typically ~1 s
- Expensive on an energy basis (compared with batteries)
- Powerful compared with batteries, especially during charge
- Unlimited cycle life in most application

70 kJ of Stored Energy



4000 lb vehicle moving 20 mph

1 tsp sugar	4 g
1 alkali battery D-cell	140 g
22 kF / 2.5 V capacitor	4.6 kg

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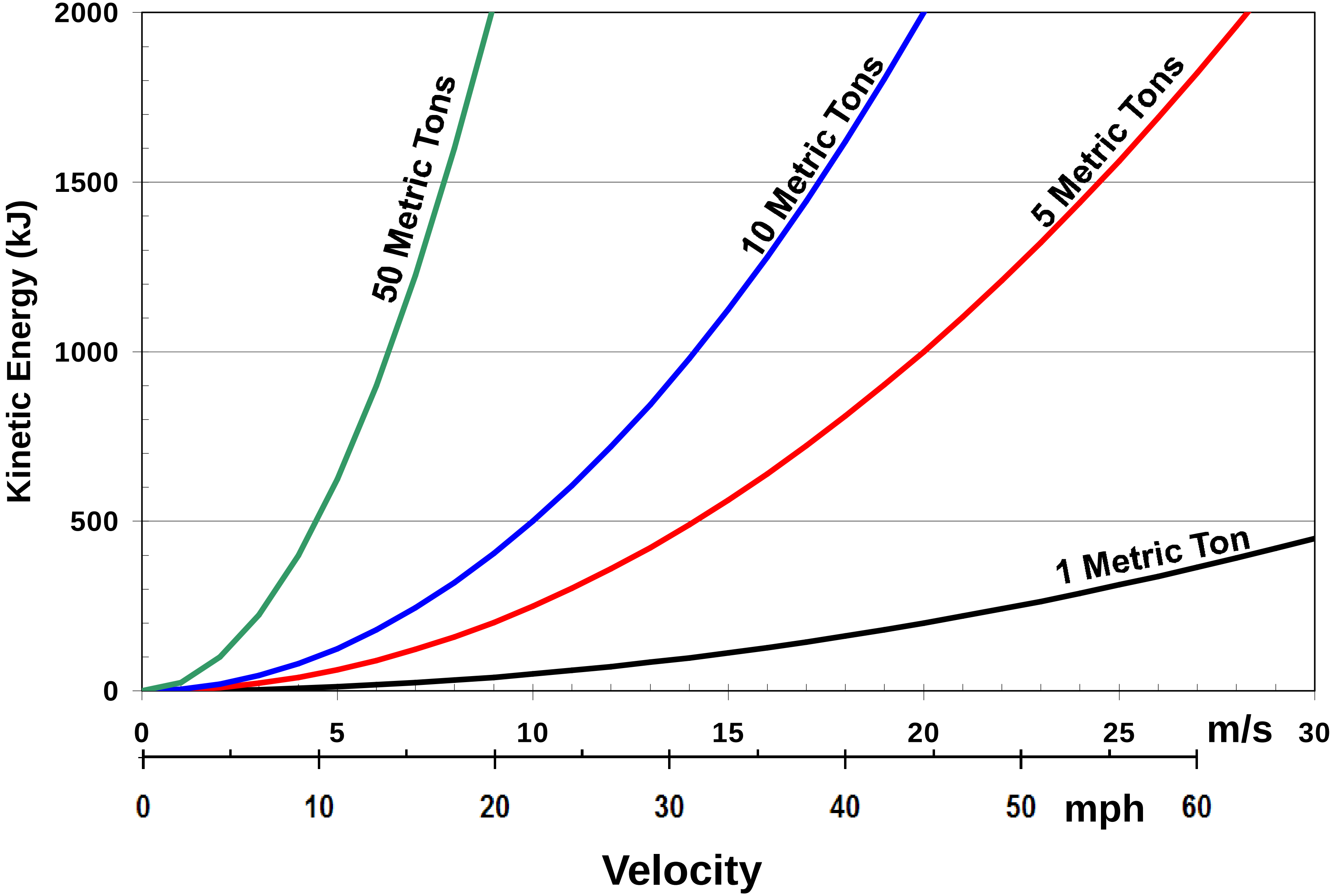
- Summary

Energy of Motion: $E = \frac{1}{2} MV^2$



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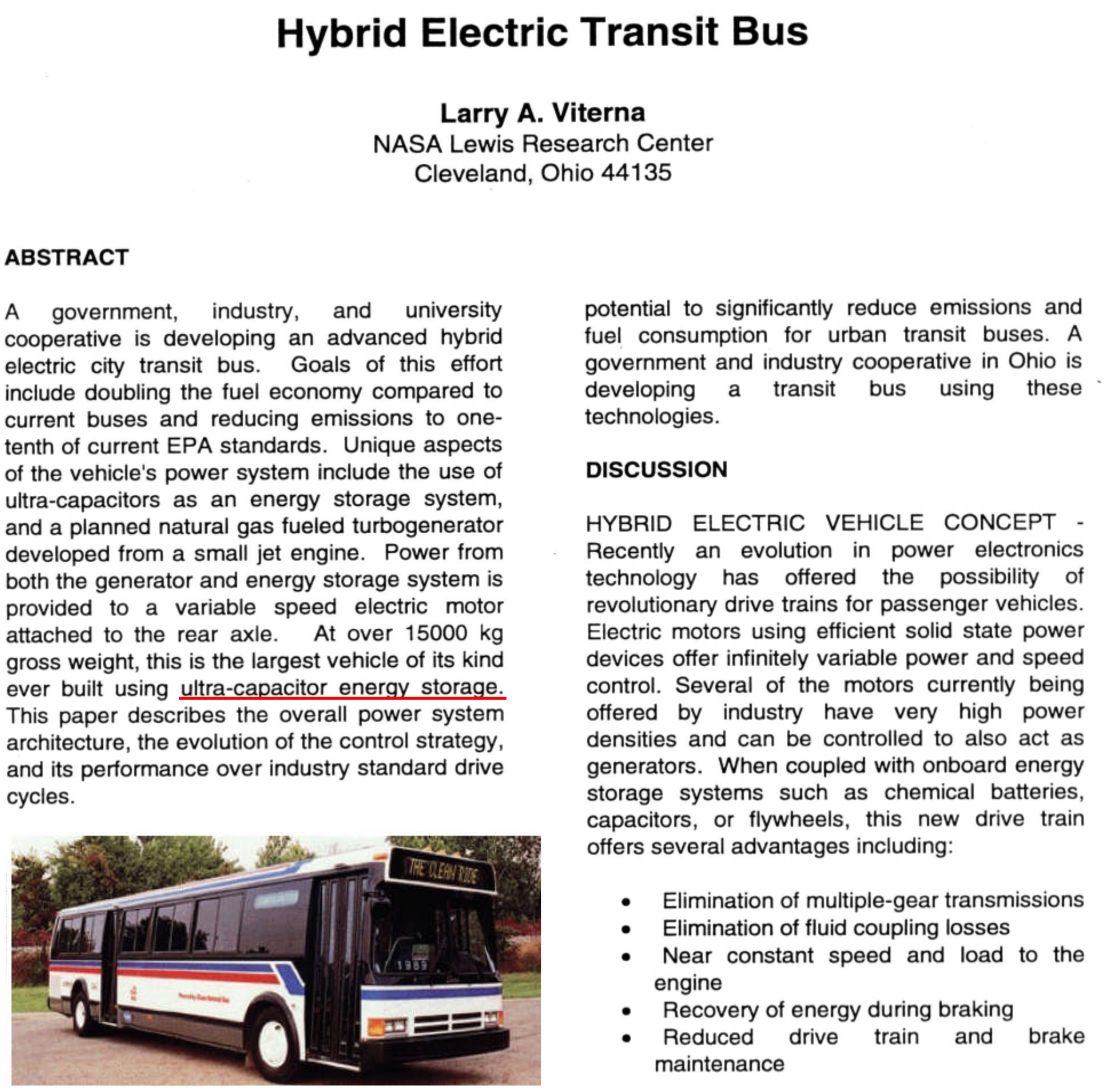


Hybrid Electric Transit Bus

Larry A. Viterna
NASA Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A government, industry, and university cooperative is developing an advanced hybrid electric city transit bus. Goals of this effort include doubling the fuel economy compared to current buses and reducing emissions to one-tenth of current EPA standards. Unique aspects of the vehicle's power system include the use of ultra-capacitors as an energy storage system, and a planned natural gas fueled turbogenerator developed from a small jet engine. Power from both the generator and energy storage system is provided to a variable speed electric motor attached to the rear axle. At over 15000 kg gross weight, this is the largest vehicle of its kind ever built using ultra-capacitor energy storage. This paper describes the overall power system architecture, the evolution of the control strategy, and its performance over industry standard drive cycles.

potential to significantly reduce emissions and fuel consumption for urban transit buses. A government and industry cooperative in Ohio is developing a transit bus using these technologies.

DISCUSSION

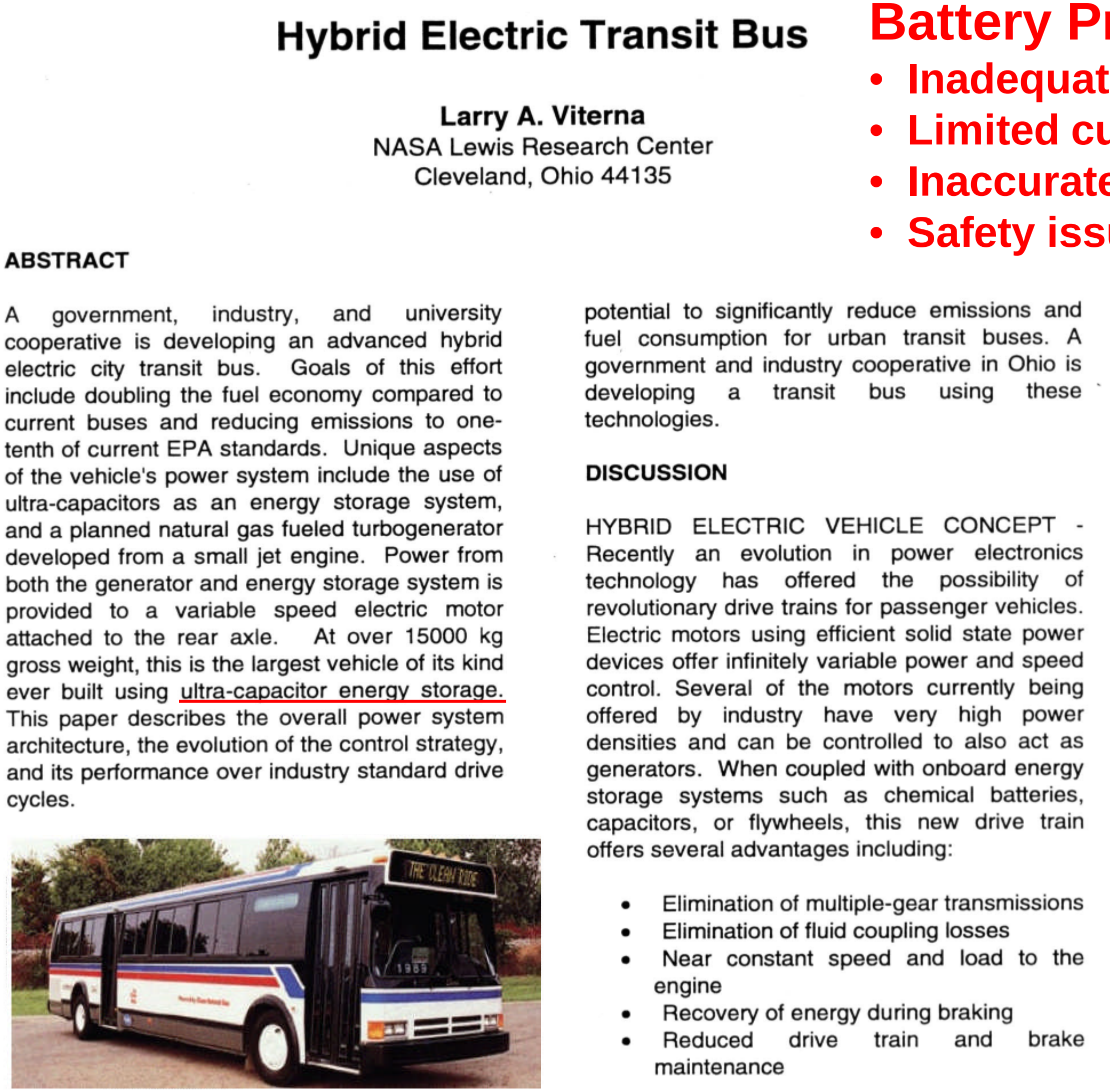
HYBRID ELECTRIC VEHICLE CONCEPT - Recently an evolution in power electronics technology has offered the possibility of revolutionary drive trains for passenger vehicles. Electric motors using efficient solid state power devices offer infinitely variable power and speed control. Several of the motors currently being offered by industry have very high power densities and can be controlled to also act as generators. When coupled with onboard energy storage systems such as chemical batteries, capacitors, or flywheels, this new drive train offers several advantages including:

- Elimination of multiple-gear transmissions
- Elimination of fluid coupling losses
- Near constant speed and load to the engine
- Recovery of energy during braking
- Reduced drive train and brake maintenance

NASA Report TM-113176

First Large Capacitor Hybrid Vehicle (1997)

- **20 F, 400 V system**
- **~1.6 MJ stored energy (440 Wh)**



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Battery Problems Listed:

- Inadequate life
- Limited current (discharge and charge)
- Inaccurate measurement of SOC
- Safety issues

First Large Capacitor Hybrid Vehicle (1997)

- 20 F, 400 V system
- ~1.6 MJ stored energy (440 Wh)

NASA Report TM-113176

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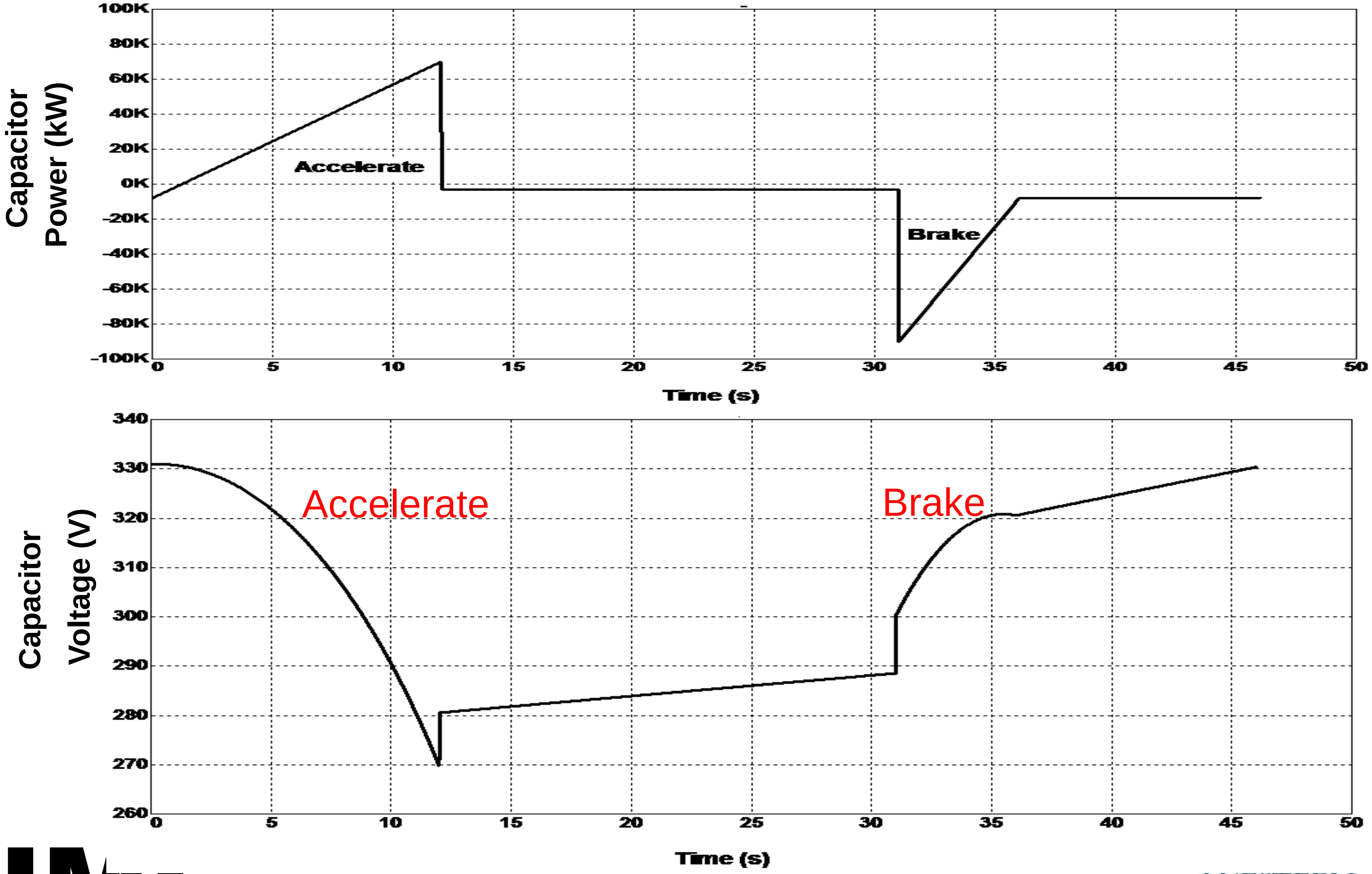
NASA Hybrid Gas-Electric Transit Bus with EC Storage

46 second Repeating Power Profile
25 F capacitor, series resistance ~0.04 ohm (RC~1 s)

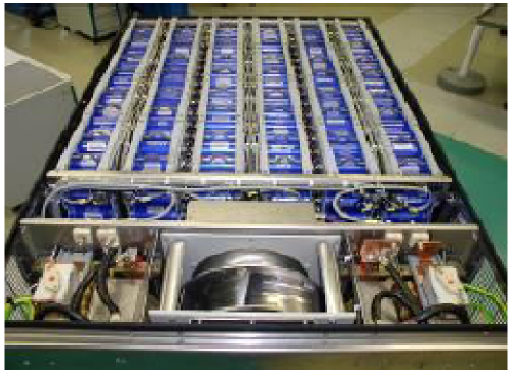


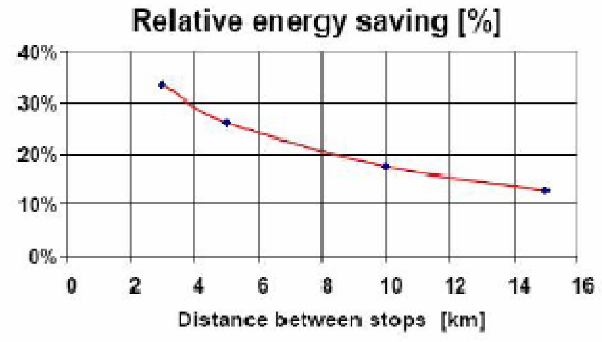
Crosspoint Kinetics Next Generation Electric Hybrid System with EC Storage

Subway Train with Capacitor Storage

December, 2008

Korean Railroad Research Institute announces installation of BOOSTCAP-based braking energy recuperation module for urban subway system.





Komatsu PC200-8 Hybrid Excavator with EC Storage

- Electric motor turret rotation
- Capacitor energy storage
- Regenerative turret braking

Komatsu PC200-8 Hybrid Excavator with EC Storage

- Electric motor turret rotation
- Capacitor energy storage
- Regenerative turret braking

- Introduced 2008
- Typically yields >30% fuel savings
- Now selling 3rd generation model
- World-wide sales >2500 units

Caterpillar 6120B H FS Hybrid Mining Shovel

- 1400 Tons
- Bucket volume 46 to 65 m^3 (size depends on material density)
- IC engine power 4500 hp (3360 kW)
- Machine power 8,000 hp (using IC engine + energy storage)
- 48 MJ capacitor energy storage (4700 cells each rated at 3000 F, 2.7 V)

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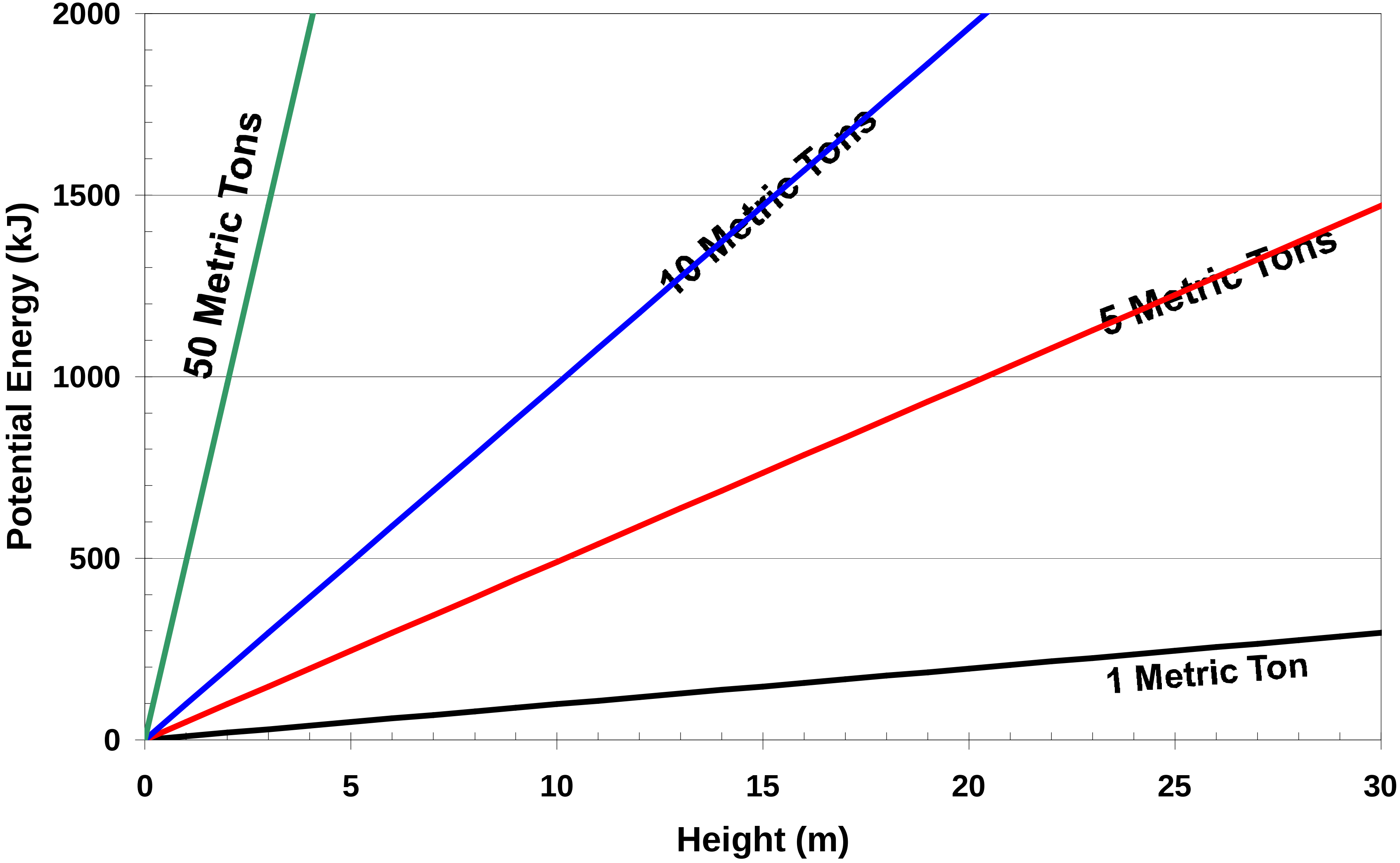
- Regen energy capture during swing deceleration and boom-down movement
- ~25% fuel savings achieved over non-hybrid version

Energy of Location: E = MgH



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Container Ship at Port

Up to 7,600 40-ft containers
Container mass up to 40 MT
Ship load up to 157,000 MT
Load can fill 35 100-car trains

Hybrid Rubber Tired Gantry Crane with EC Storage

7 MJ Capacitor--Efficient Regenerative Energy Capture

~40 % Fuel Saving / Significant Emission Reduction


Capacitor storage

Source: T. Furukawa, NCC

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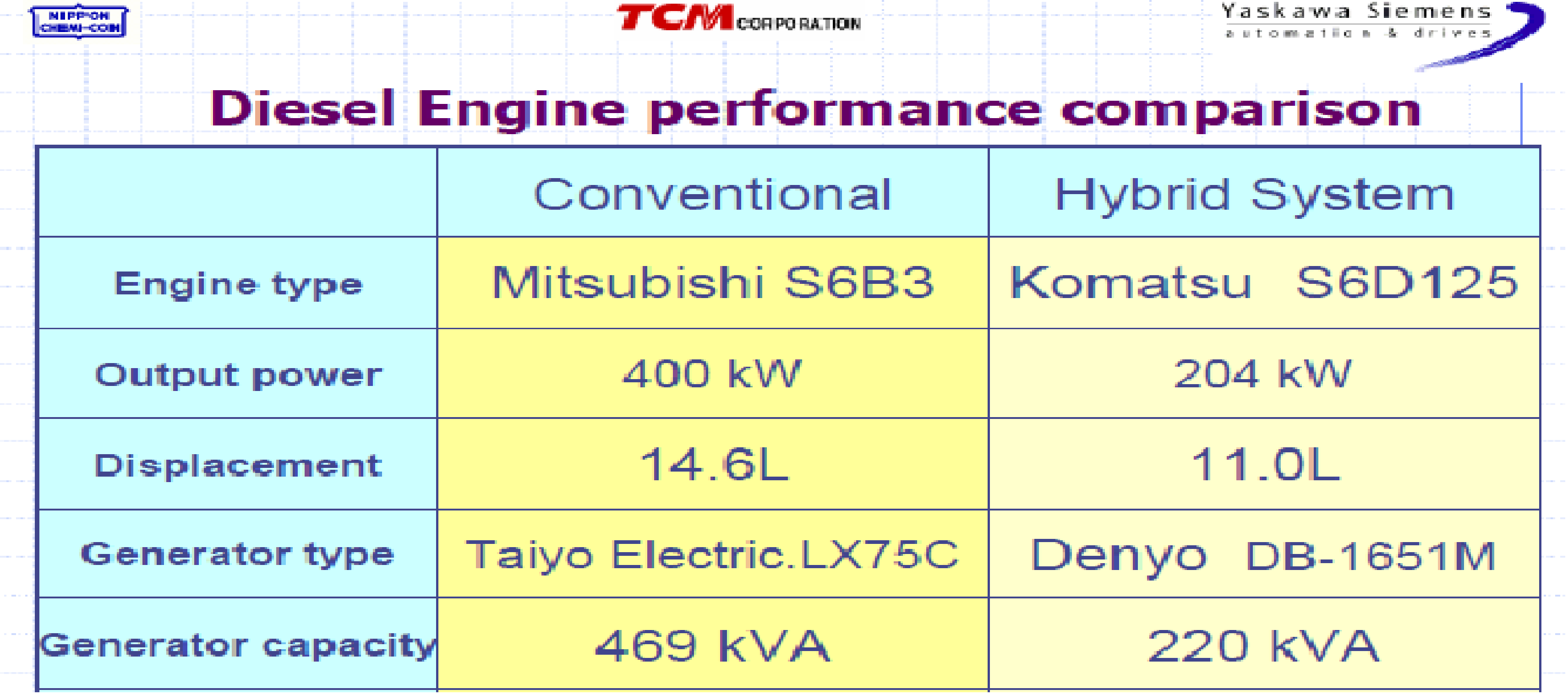
Hybrid Rubber Tired Gantry Crane with EC Storage



NIPPON CHEMI-CON

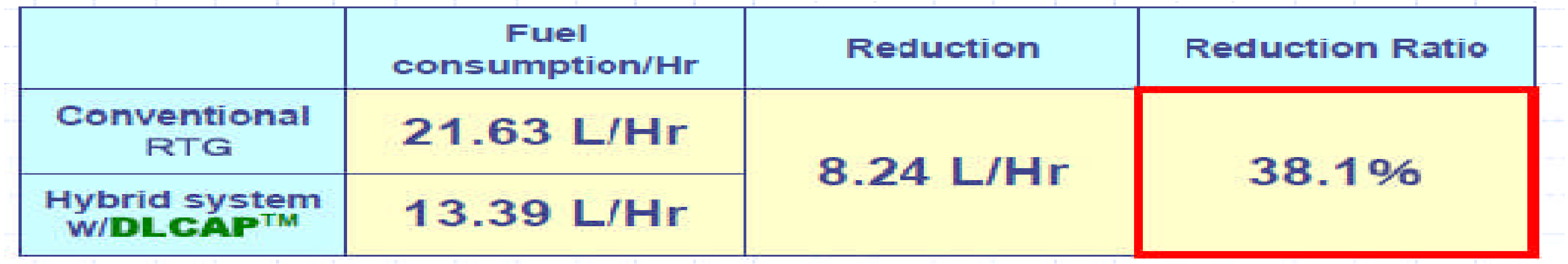
TCM CORPORATION

Yaskawa Siemens
automation & drives

Diesel Engine performance comparison

	Conventional	Hybrid System
Engine type	Mitsubishi S6B3	Komatsu S6D125
Output power	400 kW	204 kW
Displacement	14.6L	11.0L
Generator type	Taiyo Electric.LX75C	Denyo DB-1651M
Generator capacity	469 kVA	220 kVA

RESULTS



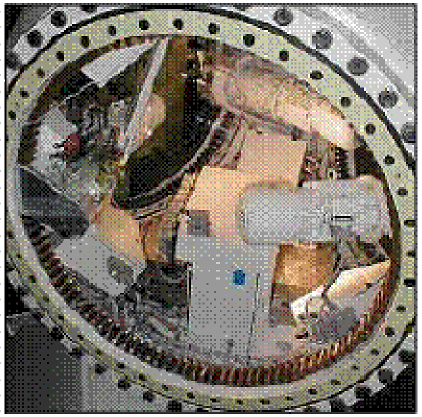
	Fuel consumption/Hr	**Reduction**	**Reduction Ratio**
Conventional RTG	**21.63 L/Hr**	**8.24 L/Hr**	**38.1%**
Hybrid system w/DLCAP™	**13.39 L/Hr**		

Source: T. Furukawa, NCC

Outline

- Electrochemical capacitor (EC) energy storage introduction
- Energy storage technology comparisons
- EC energy-conservation applications
- Energy-sector applications of ECs
- Storage system economics
- Summary

ECs for Wind Turbine Emergency Pitch Control



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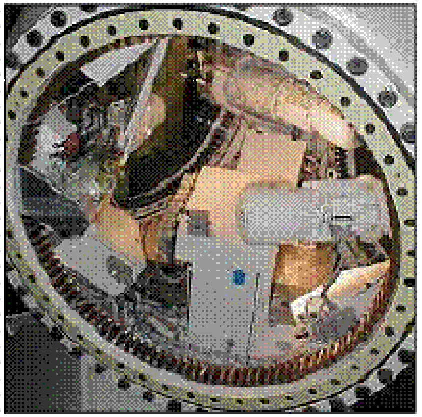
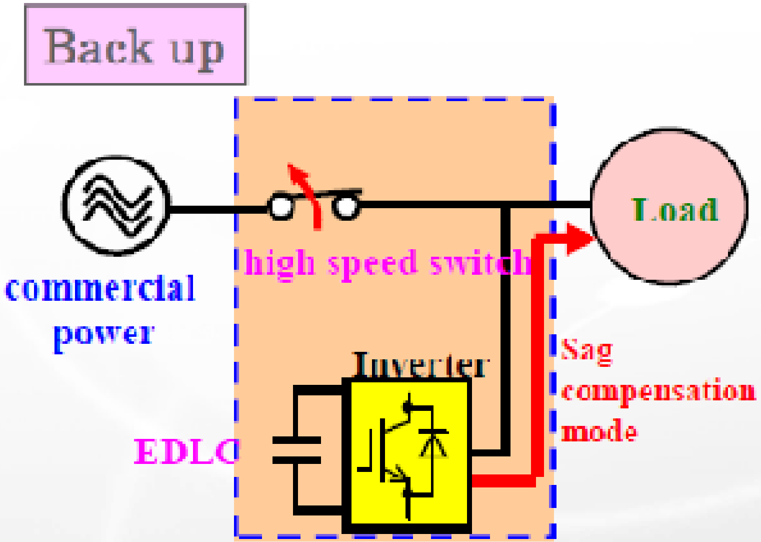


Attractive EC features

- **High reliability**
- **Long operational-life**
- **Maintenance-free**
- **Low-temperature operation**
- **High power performance**
- **Safe**
- **High cycle-life**

EC Voltage Compensation System



Rated Output	10,000kVA
Dip comp. time	1sec
Rated Voltage	3φ 6,600V
Operation	On-line method
Switch over	No interruption (Less than 2msec)
Storage	EDLC
Efficiency	over 99%

Module
600S1-70C-11P
292×600×395H

EDLC Panel

System(W:28m-H:2.6m-D:2.3m)

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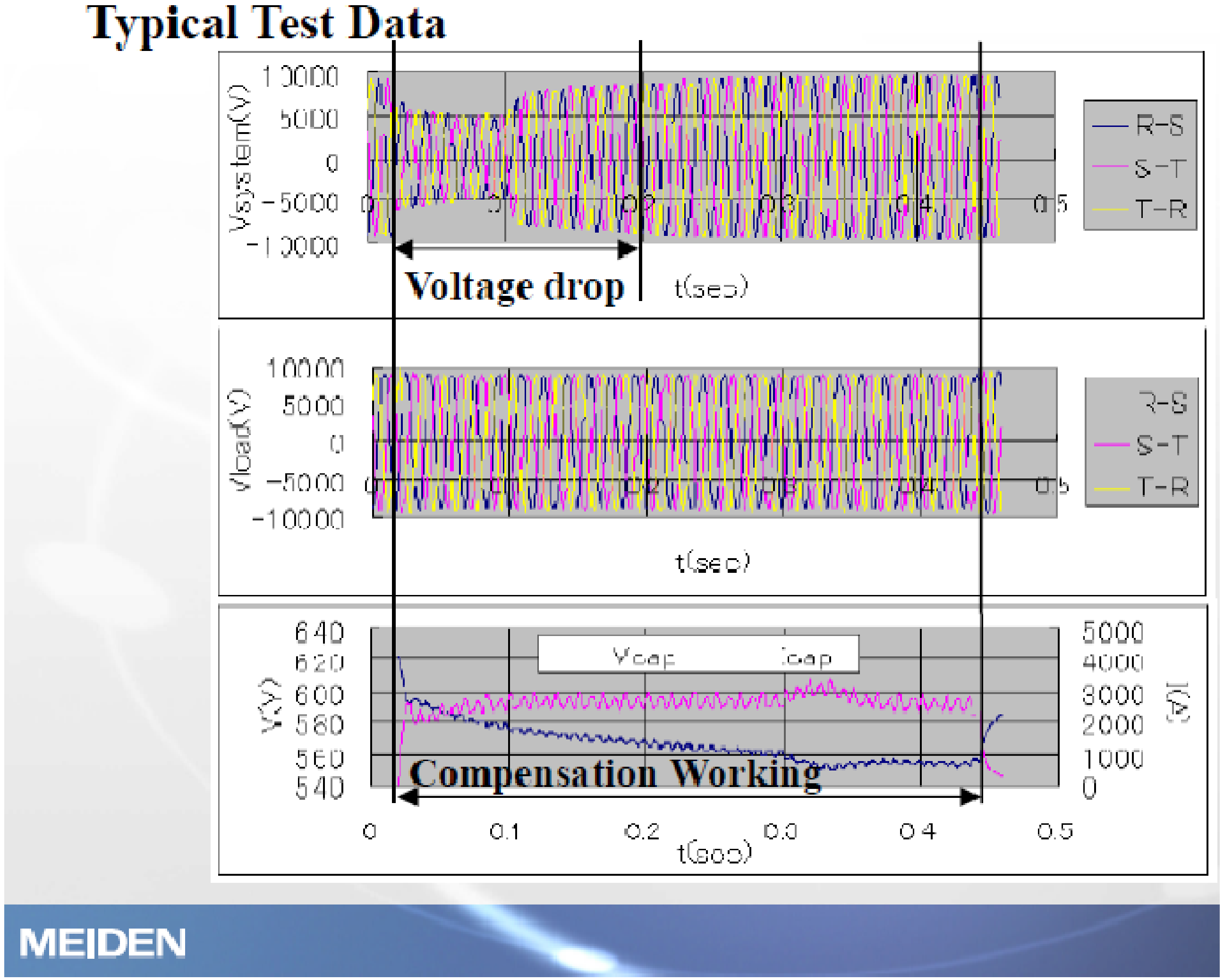
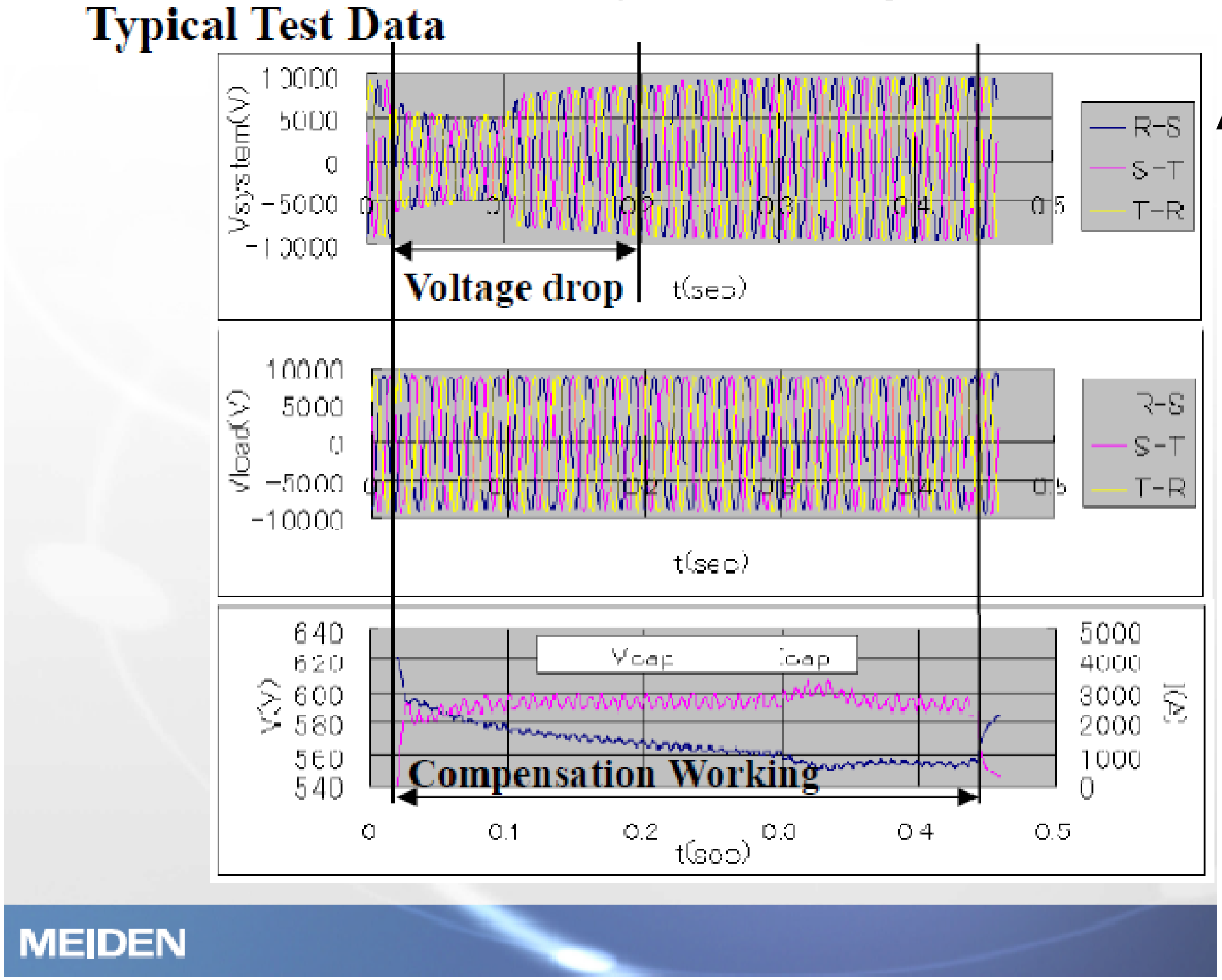
EC Voltage Compensation System



Typical Test Data

EC Voltage Compensation System



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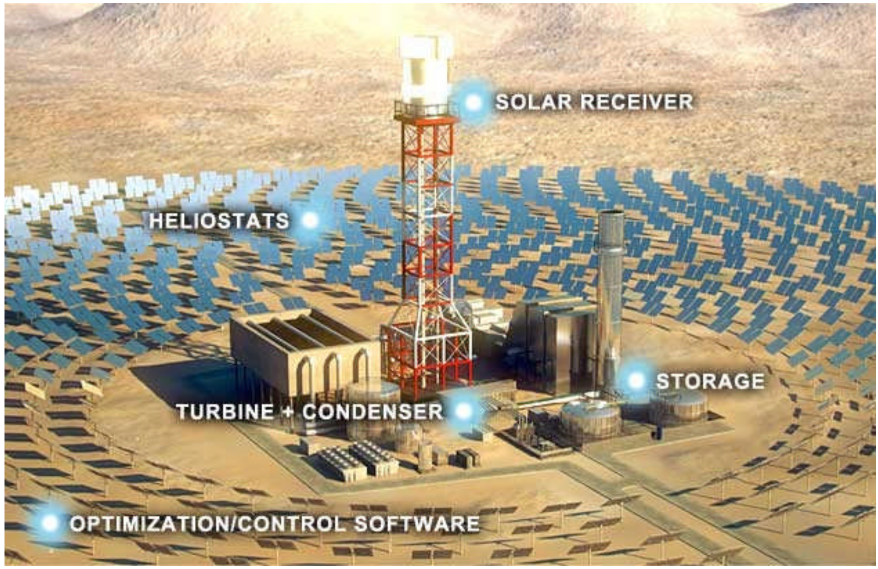
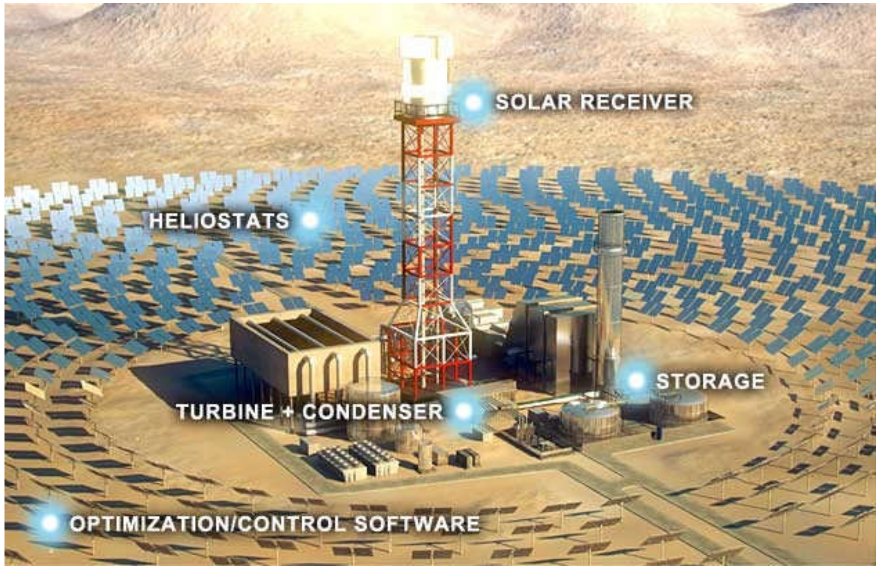
ECs for Solar Thermal Electricity Generation



Ivanpah, California, USA

- completed in 2013 by Brightsource
- 377 MW output
- three 137-meter-tall towers
- 300,000 mirrors track the sun all day

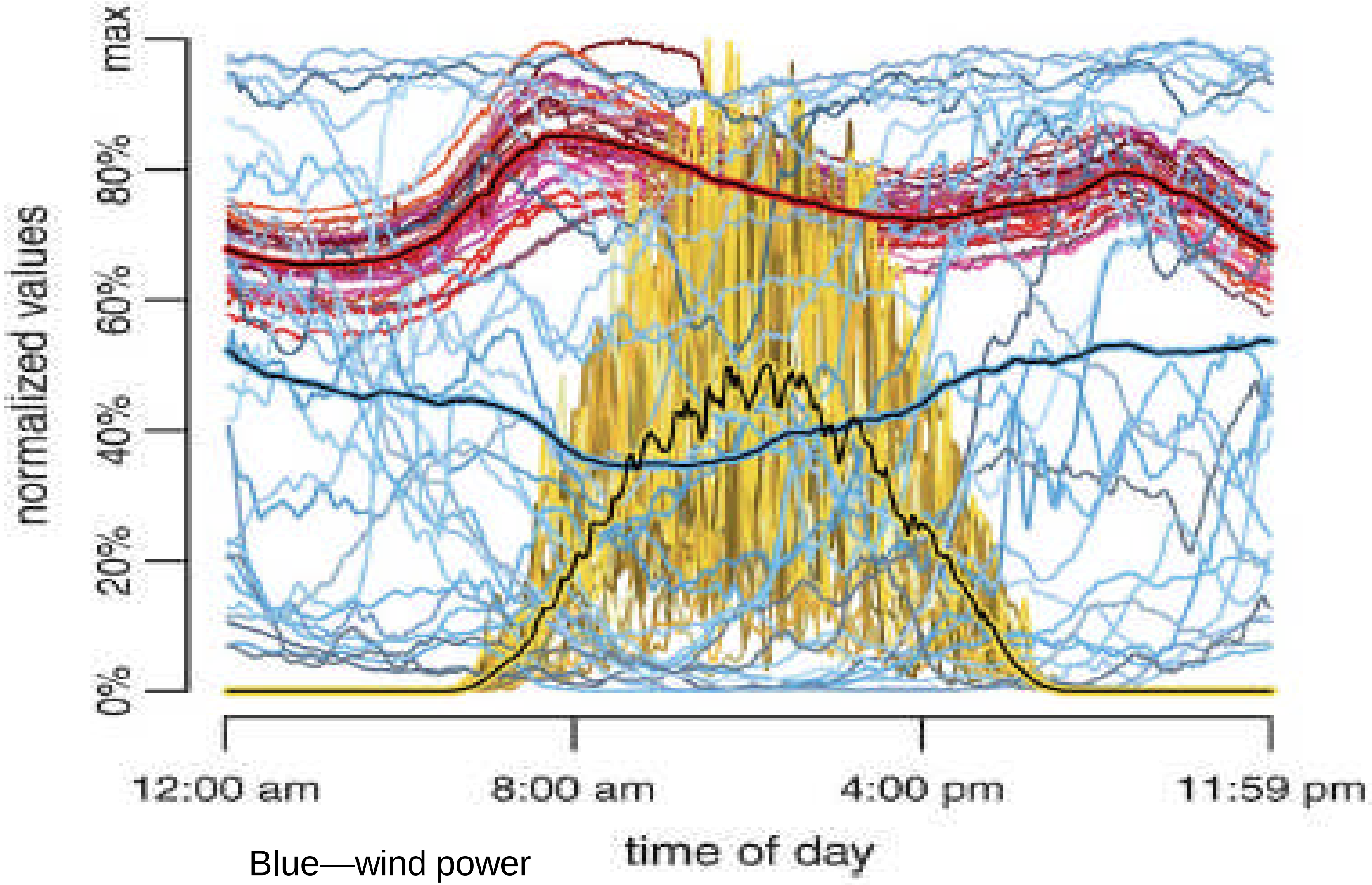
ECs for Solar Thermal Electricity Generation



Ivanpah, California, USA

- completed in 2013 by Brightsource
- 377 MW output
- three 137-meter-tall towers
- 300,000 mirrors track the sun all day
- ***each mirror requires electrical power***
- ***EC stored energy used for mirror control***

Renewable Energy Generation/Demand Example



Blue—wind power
Gold—solar power
Red—power demand
(Black lines—averages)

30 days of data
April 2010
Bonneville Power Admin.

Energy Environ. Sci., 2013, **6**, 2804–2810

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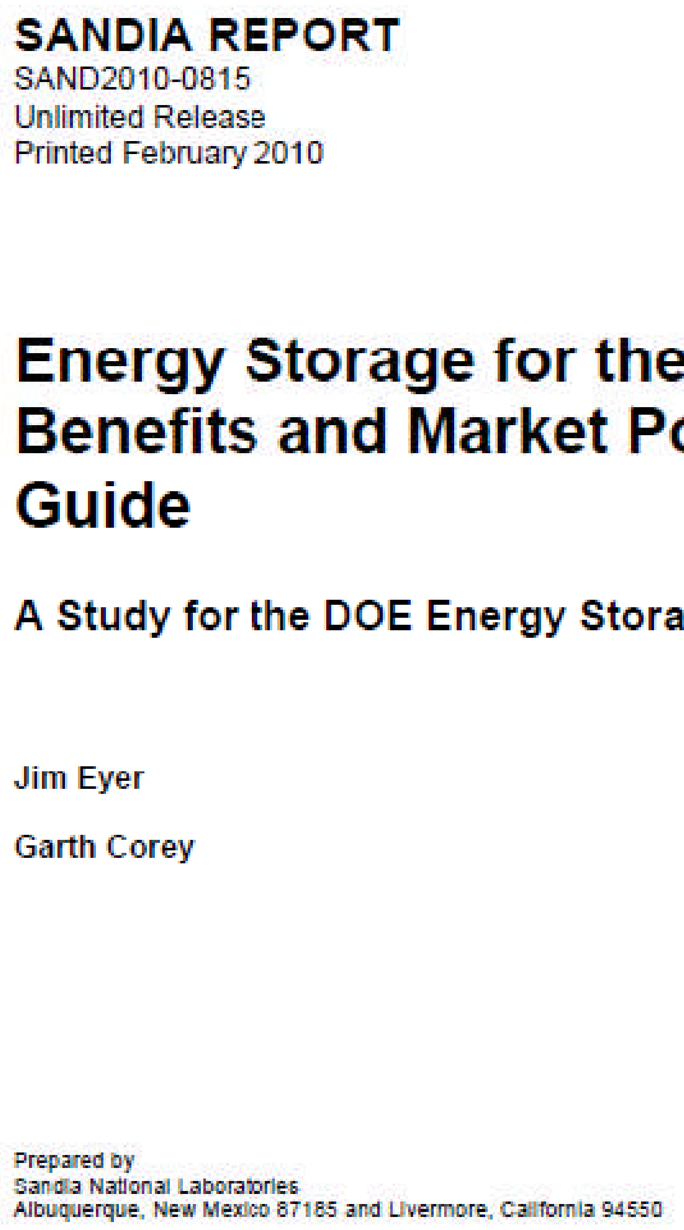


SANDIA REPORT
SAND2010-0815
Unlimited Release
Printed February 2010

Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide

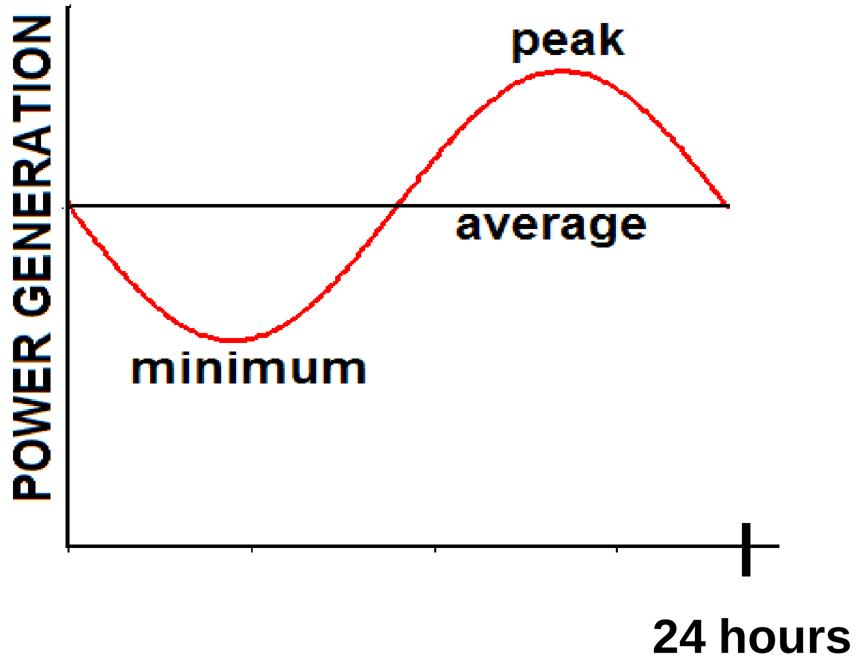
A Study for the DOE Energy Storage Systems Program

Jim Eyer

Garth Corey

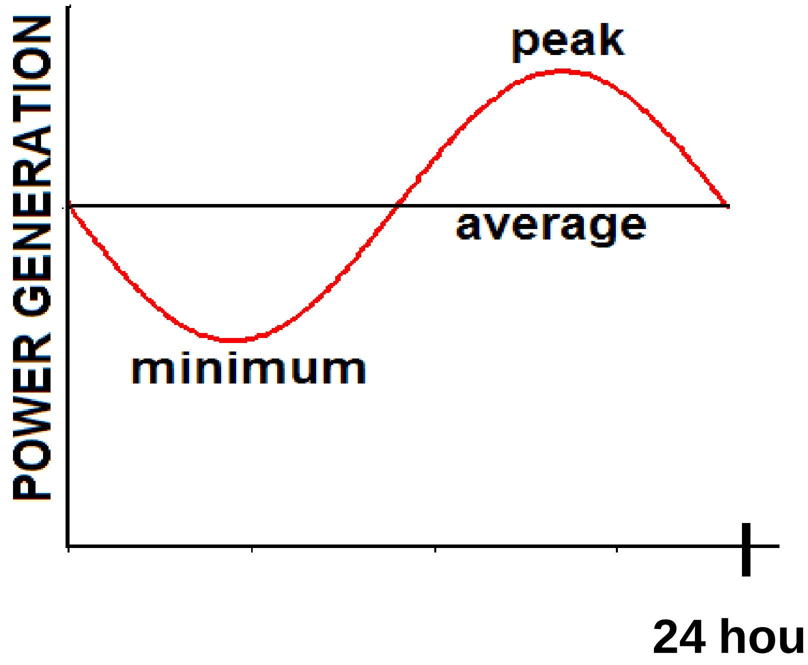
Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Time Shifting—Day/Night Storage



NO STORAGE

Time Shifting—Day/Night Storage



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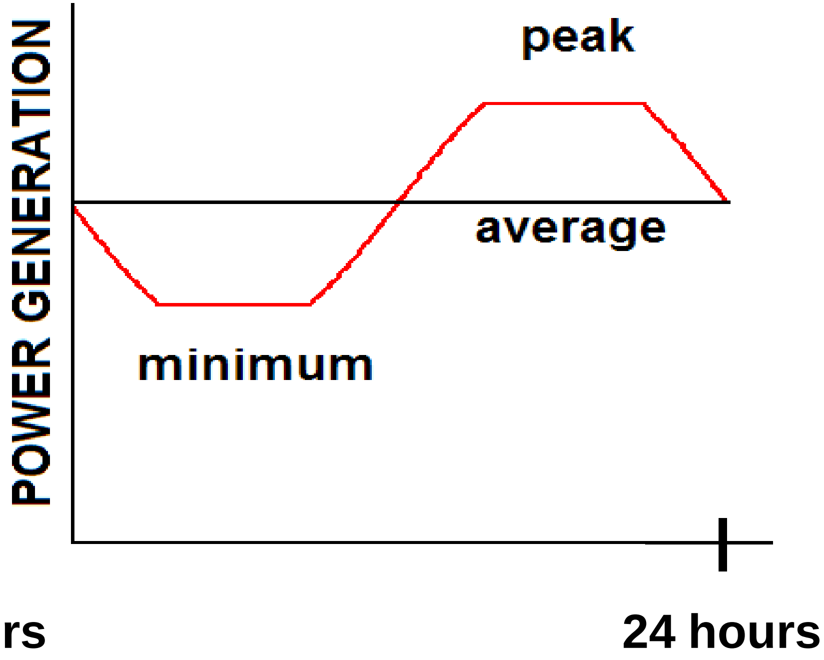
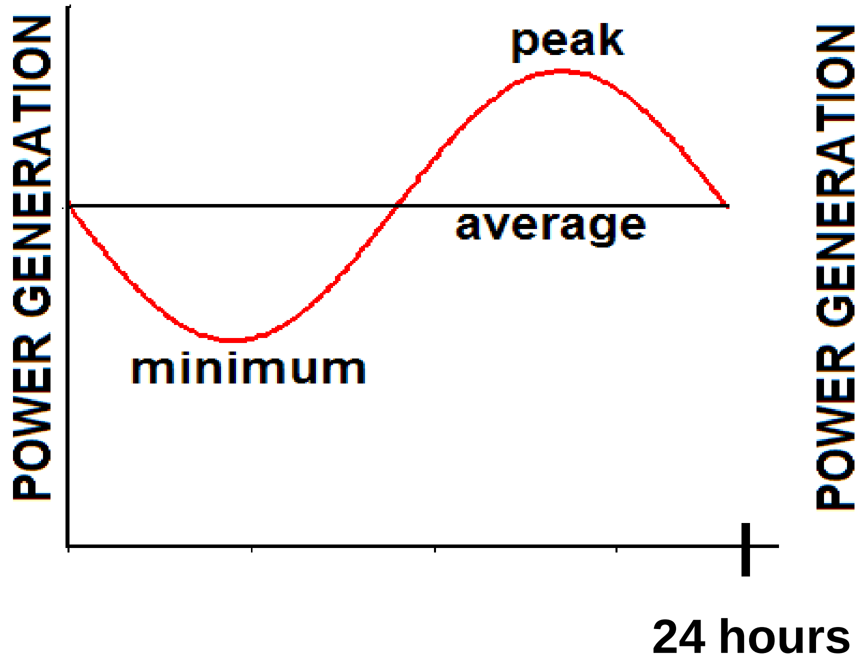
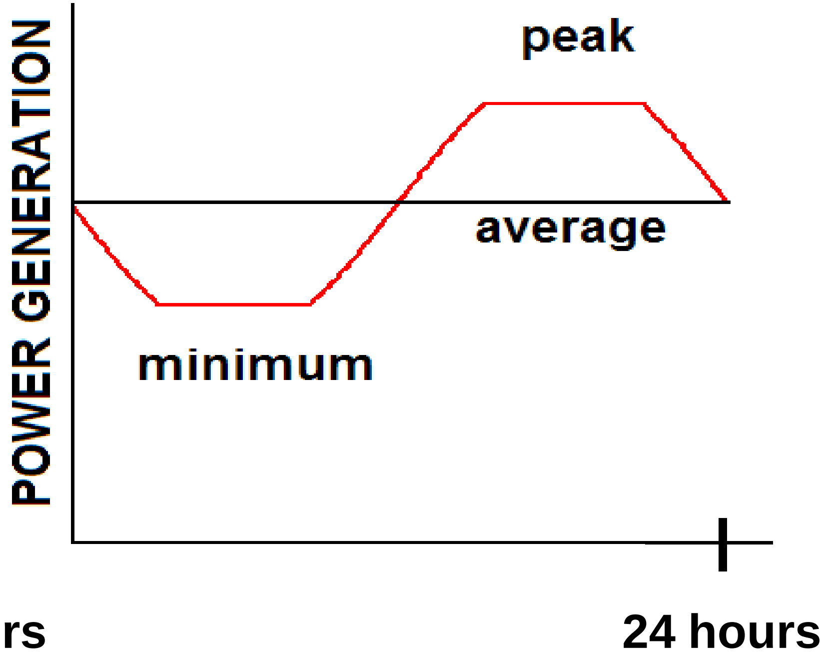


WITH STORAGE

Time Shifting—Day/Night Storage





NO STORAGE **WITH STORAGE**

20 years at 1 cycle per day, five days per week requires ~5000 cycles

Day-Night Energy Storage Systems

- Used with the electric power grid

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- Mass and volume of storage--low direct importance (stationary)

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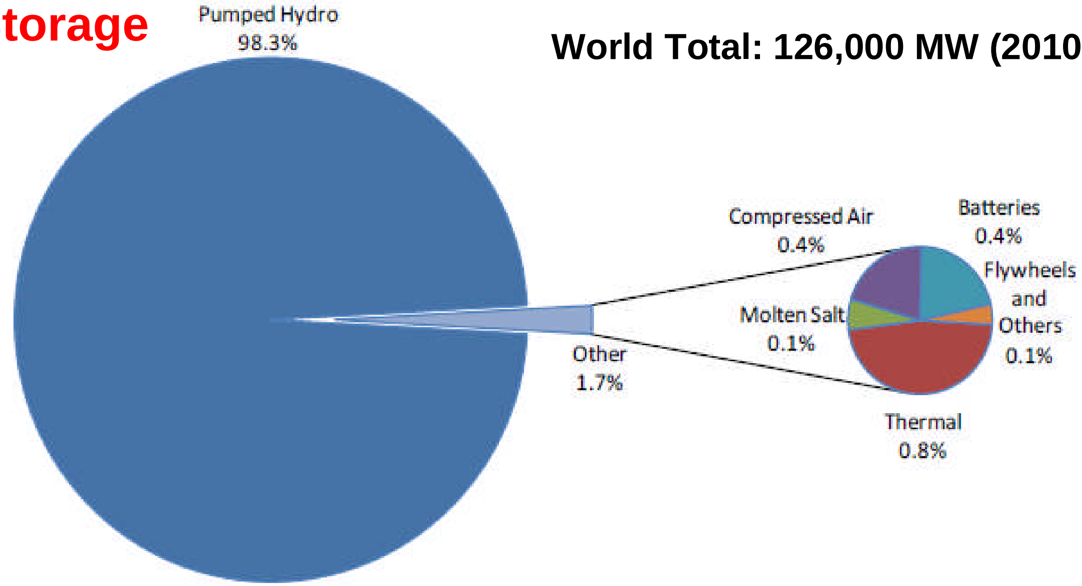
World Energy Storage 2010

World Total: 126,000 MW (2010)



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Source- California Energy Storage Alliance. “Energy Storage: Bolstering California’s Economy with AB 2514” page 3.

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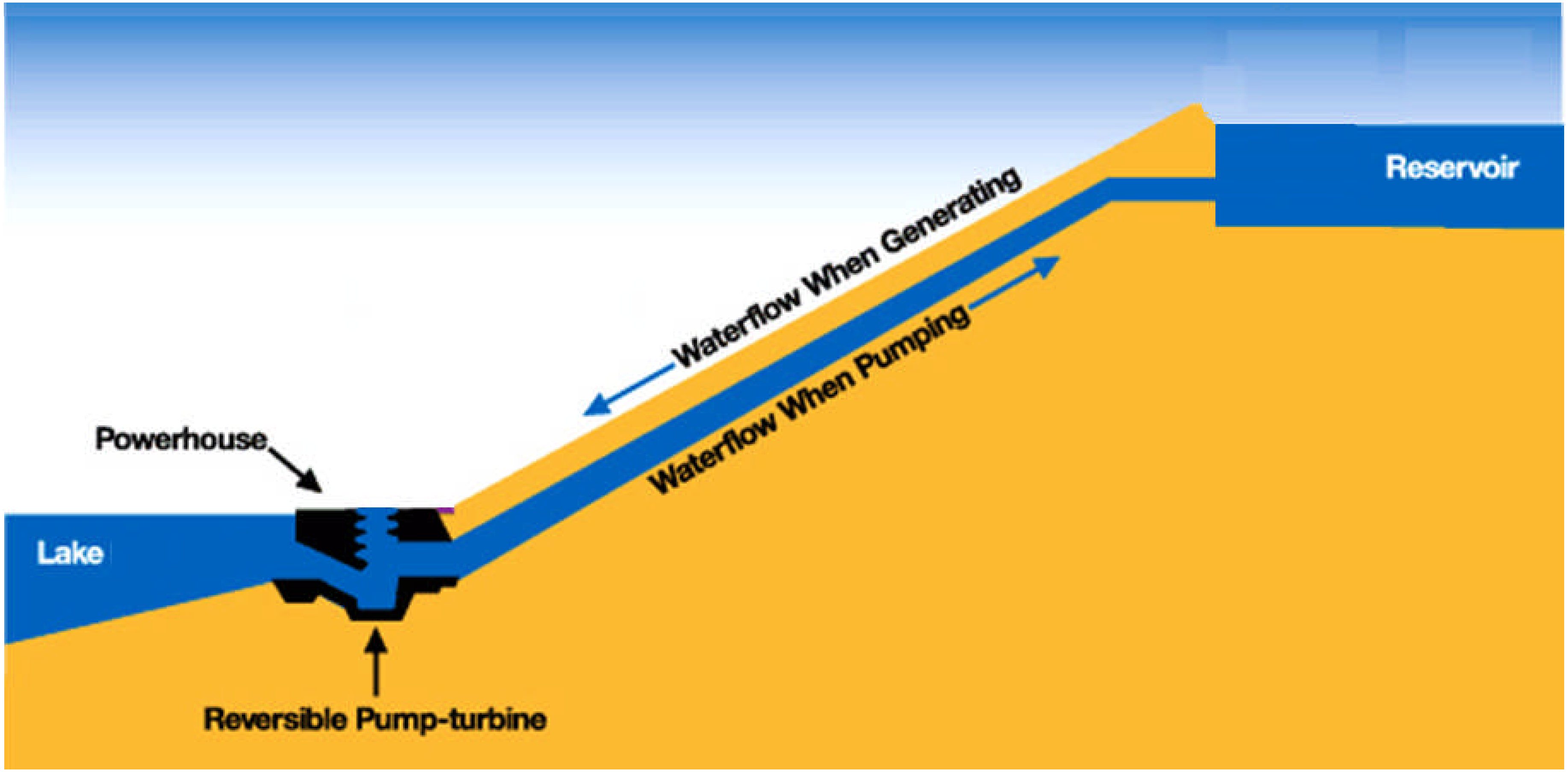
Pumped Hydroelectric Storage Schematic



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Pumped Hydroelectric Energy Storage

Station	Country	Capacity (MW)
Bad Creek Hydroelectric Station	United States	1,065
Bailianhe Pumped Storage Power Station	China	1,200
Baoquan Pumped Storage Power Station	China	1,200
Bath County Pumped Storage Station	United States	3,003
Blenheim-Gilboa Hydroelectric Power Station	United States	1,160
Castaic Power Plant	United States	1,566
Chaira Hydropower Cascade	Bulgaria	1,455
Coo-Trois-Ponts Hydroelectric Power Station	Belgium	1,164
Dinorwig Power Station	United Kingdom	1,728
Drakensberg Pumped Storage Scheme	South Africa	1,000
Edolo Pumped Storage Plant	Italy	1,000
Entracque Power Plant	Italy	1,317
Goldisthal Pumped Storage Station	Germany	1,060
Grand'Maison Dam	France	1,800
Guangdong Pumped Storage Power Station	China	2,400
Heimifeng Pumped Storage Power Station	China	1,200
Helms Pumped Storage Plant	United States	1,200
Hohhot Pumped Storage Power Station	China	1,224
Hongping Pumped Storage Power Station	China	1,200
Huizhou Pumped Storage Power Station	China	2,448
Imaichi Pumped Storage Plant	Japan	1,050
Ingula Pumped Storage Scheme	South Africa	1,332
Kazunogawa Pumped Storage Power Station	Japan	1,200
La Muela II Pumped Storage Power Station	Spain	1,772
Liyang Pumped Storage Power Station	China	1,500
Ludington Pumped Storage Power Plant	United States	1,872
Malta-Reisseck Power Plant Group	Austria	1,026
Markersbach Pumped Storage Power Plant	Germany	1,045
Matanoagawa Dam	Japan	1,200
Mingtan Pumped Storage Hydro Power Plant	Taiwan	1,602
Minhu Pumped Storage Hydro Power Station	Taiwan	1,008
Muddy Run Pumped Storage Facility	United States	1,071

Station	Country	Capacity (MW)
Northfield Mountain	United States	1,080
Okawachi Pumped Storage Power Station	Japan	1,280
Okukiyotsu Pumped Storage Power Station (1 & 2)	Japan	1,600
Okumino Pumped Storage Power Station	Japan	1,500
Okutataragi Pumped Storage Power Station	Japan	1,932
Okuyahagi Pumped Storage Power Station	Japan	1,125
Okuyoshino Pumped Storage Power Station	Japan	1,206
Omarugawa Pumped Storage Power Station	Japan	1,200
Presa de Aldeadávila	Spain	1,243
Presenzano Hydroelectric Plant	Italy	1,000
Pushihe Pumped Storage Power Station	China	1,200
Qingyuan Pumped Storage Power Station	China	1,280
Raccoon Mountain Pumped-Storage Plant	United States	1,652
Rocky Mountain Hydroelectric Plant	United States	1,095
Roncovalgrande Hydroelectric Plant	Italy	1,016
Sardar Sarovar Dam	India	1,450
Shimogo Pumped Storage Power Station	Japan	1,000
Shin Takasegawa Pumped Storage Station	Japan	1,280
Shintoyone Pumped Storage Power Station	Japan	1,125
Siah Bishe Pumped Storage Power Plant	Iran	1,040
Tai'an Pumped Storage Power Station	China	1,000
Tamahara Pumped Storage Power Station	Japan	1,200
Tianhuangping Pumped Storage Power Station	China	1,836
Tongbai Pumped Storage Power Station	China	1,200
Tumut-3	Australia	1,800
Vianden Pumped Storage Plant	Luxembourg	1,296
Xiangshuijian Pumped Storage Power Station	China	1,000
Xianyou Pumped Storage Power Station	China	1,200
Xilongchi Pumped Storage Power Station	China	1,200
Yangyang Pumped Storage Power Station	South Korea	1,000
Yixing Pumped Storage Power Station	China	1,000
Zagorsk Pumped Storage Station	Russia	1,200

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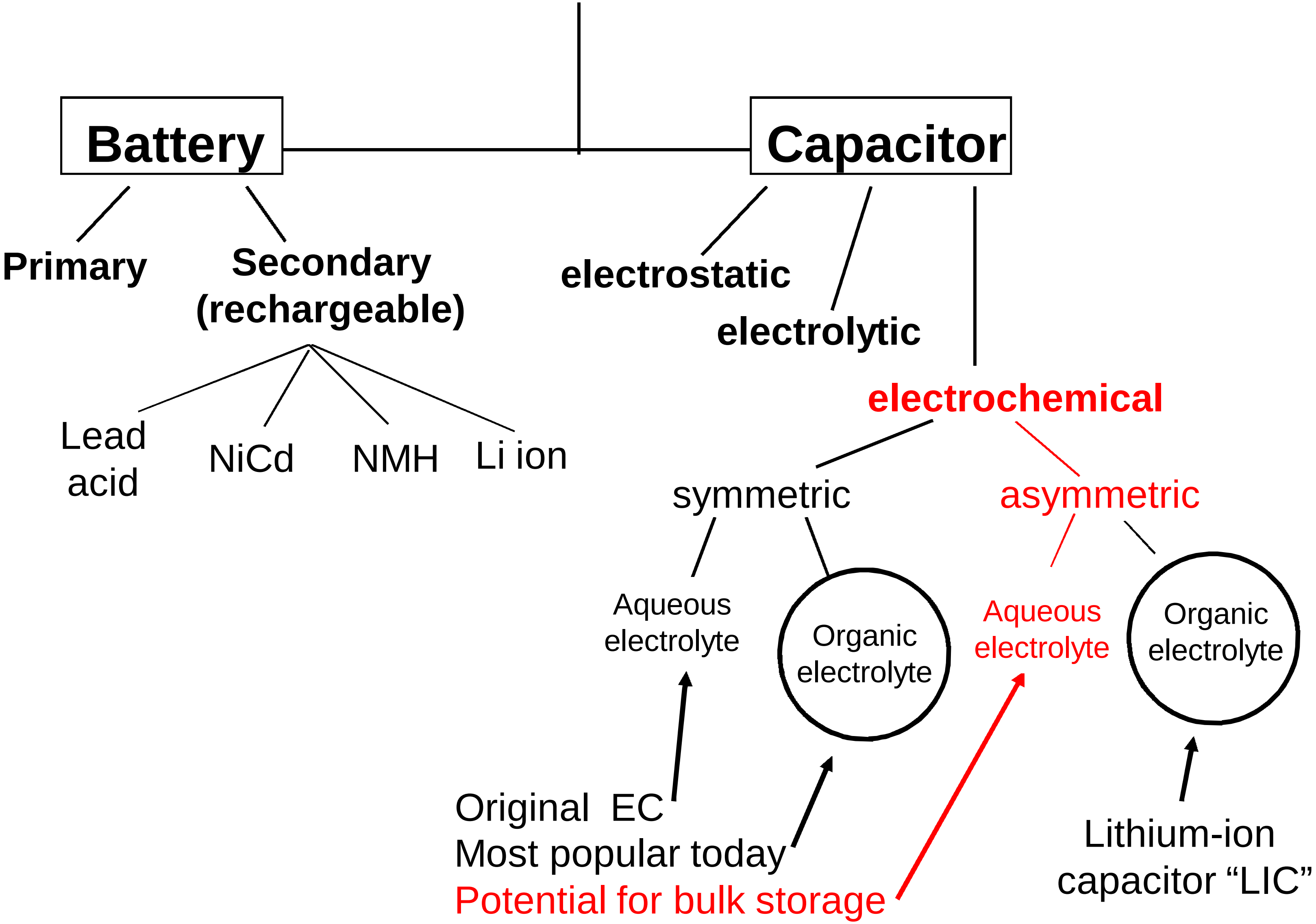
Source: Wikipedia accessed 1-11-2018

Case Western Reserve University | Great Lakes Energy Institute

Tumut 3 Power Station

1st pumped hydroelectric station in New South Wales

ENERGY STORAGE COMPONENTS



Battery

Primary

Secondary (rechargeable)

Lead acid

NiCd

NMH

Li ion

Capacitor

electrostatic

electrolytic

electrochemical

symmetric

Aqueous electrolyte

Organic electrolyte

asymmetric

Aqueous electrolyte

Organic electrolyte

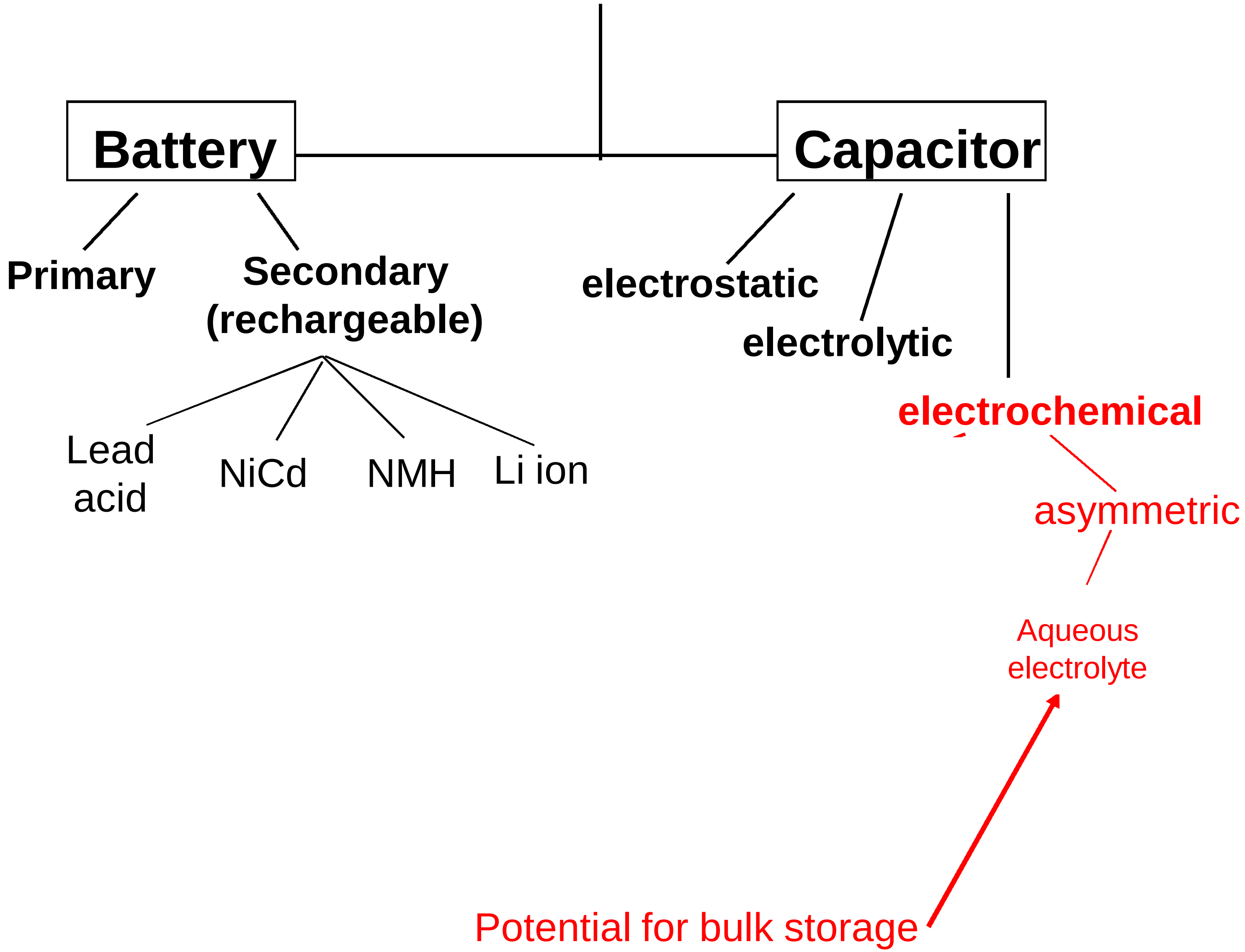
Original EC

Most popular today

Potential for bulk storage

Lithium-ion capacitor “LIC”

ENERGY STORAGE COMPONENTS



Battery

Primary

Secondary (rechargeable)

Lead acid

NiCd

NMH

Li ion

Capacitor

electrostatic

electrolytic

electrochemical

asymmetric

Aqueous electrolyte

Potential for bulk storage

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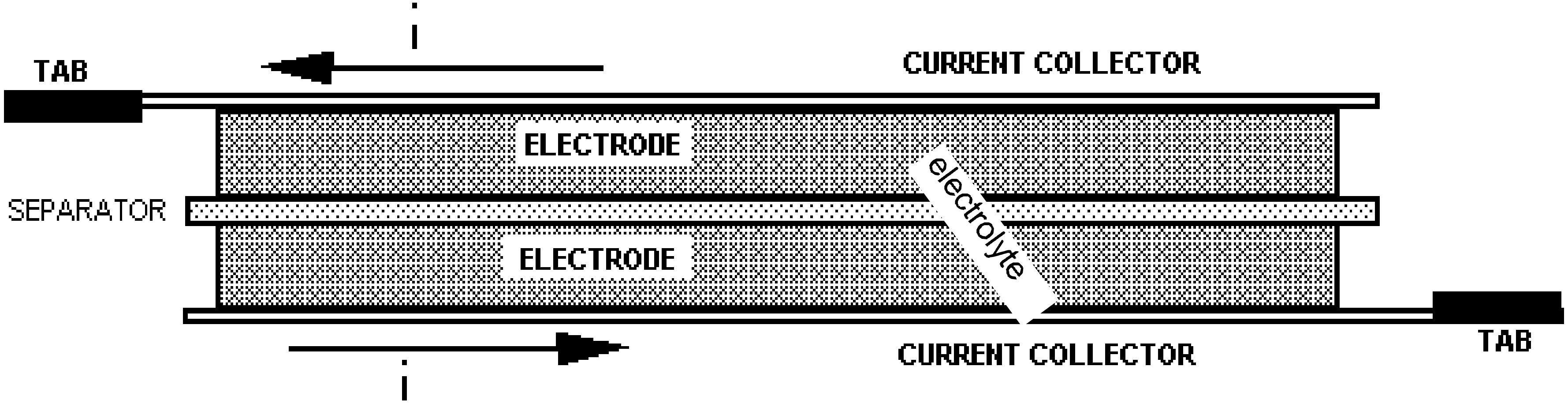
Typical EC Cell Cross-section



SYMMETRIC EC

Both electrodes same materials (usually activated carbon) and each about same thickness

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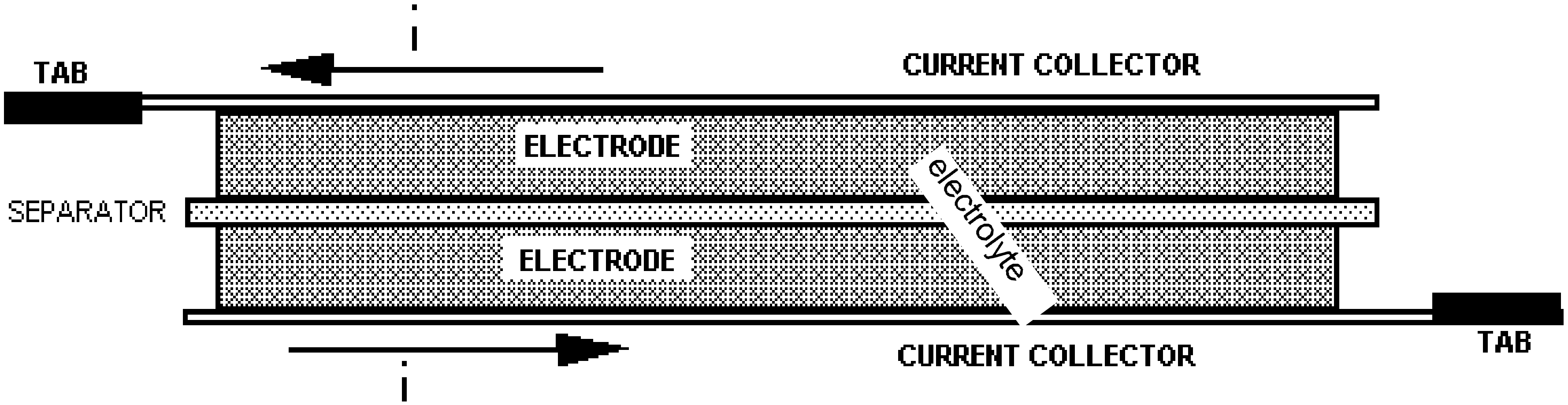
Typical EC Cell Cross-section



SYMMETRIC EC

Both electrodes same materials (usually activated carbon) and each about same thickness

ASYMMETRIC EC

Positive and negative electrodes are different materials with capacity of one electrode much greater than other

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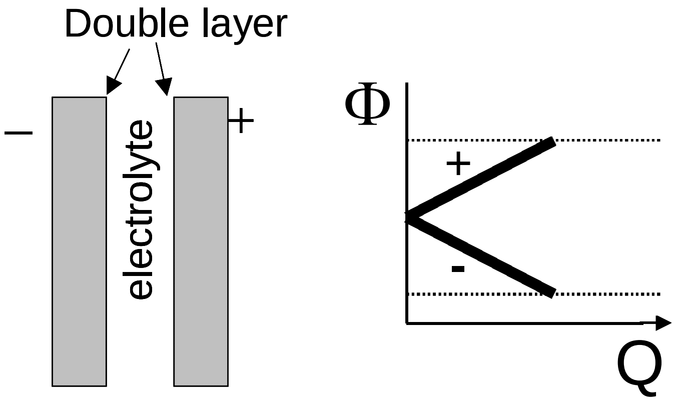
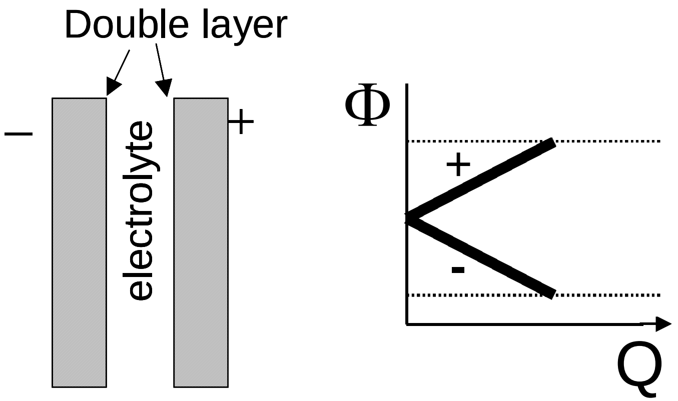
Asymmetric Electrochemical Capacitors

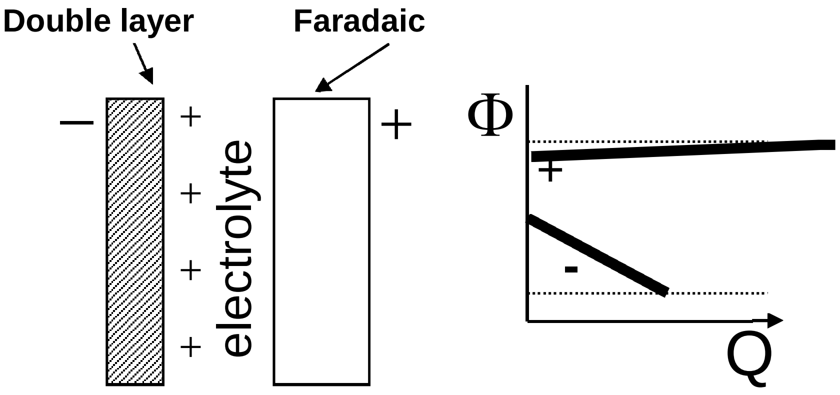


Symmetric design

Asymmetric Electrochemical Capacitors

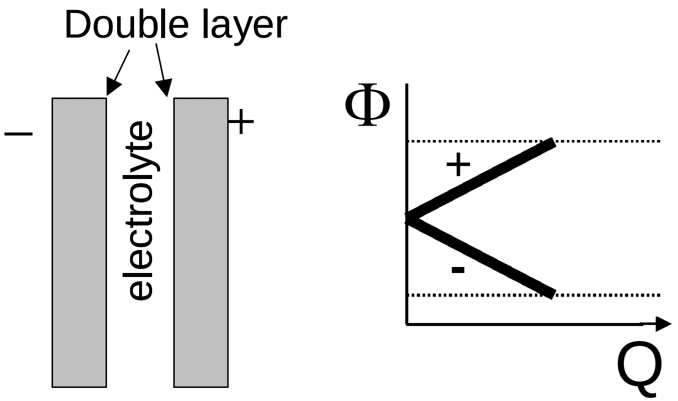


Symmetric design

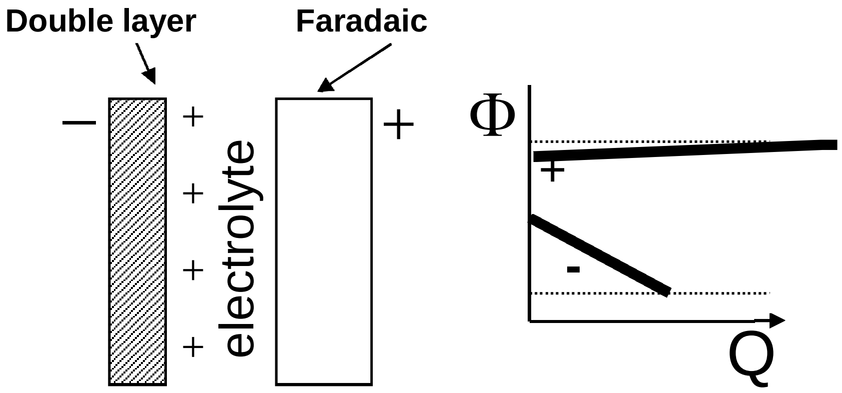


Asymmetric design

Asymmetric Electrochemical Capacitors



Symmetric design

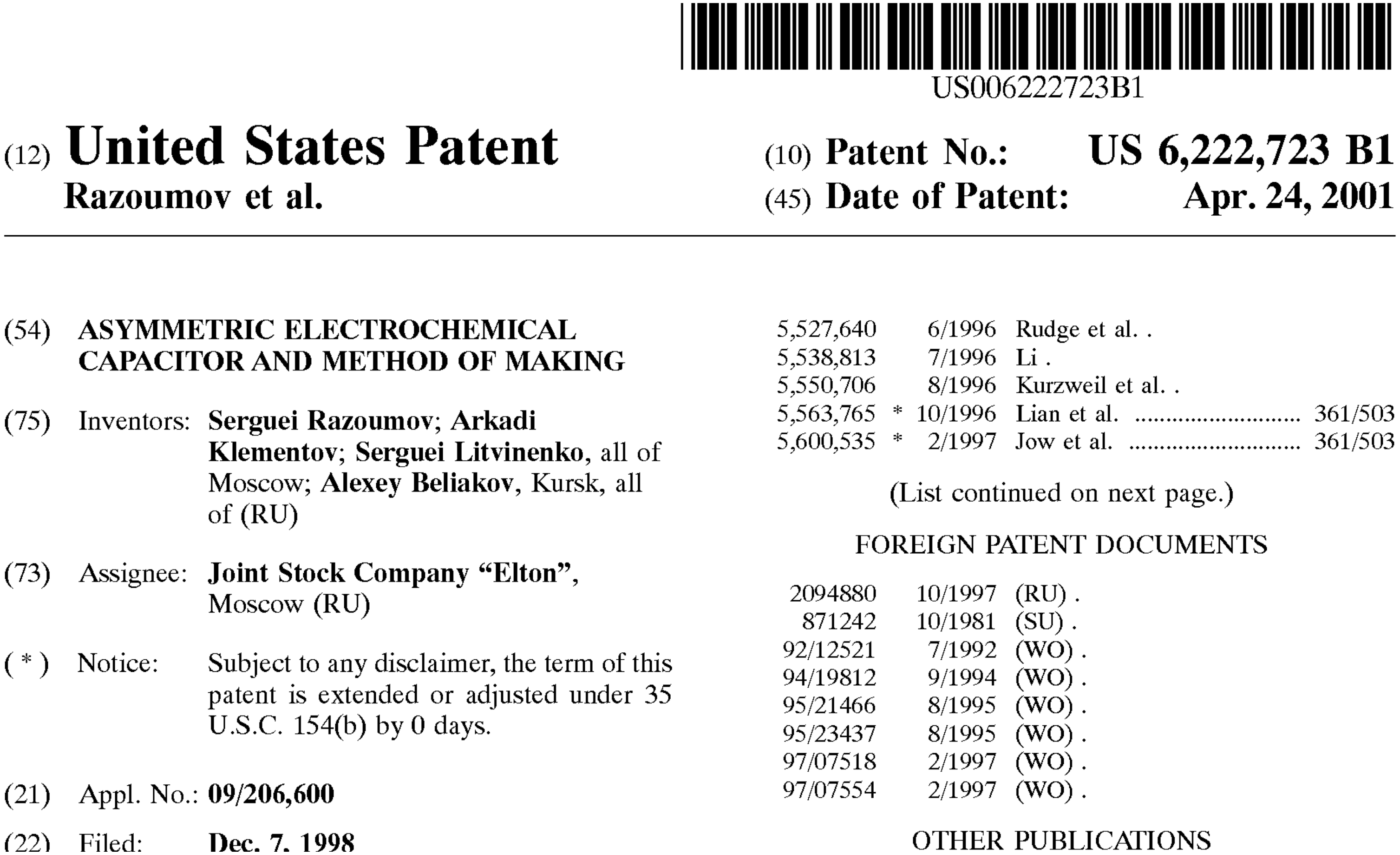


Asymmetric design

Asymmetric ECs

- Lower cost than symmetric design
- Asymmetry ratio establishes cycle life
- Low embedded energy
- Safe--locate anywhere (e.g. building basement)
- Size scalable
- Low projected energy storage costs (<$0.07/kWh)

Asymmetric Electrochemical Capacitor



US006222723B1

(12) **United States Patent**
Razoumov et al.

(10) **Patent No.:** **US 6,222,723 B1**
(45) **Date of Patent:** **Apr. 24, 2001**

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(54) **ASYMMETRIC ELECTROCHEMICAL CAPACITOR AND METHOD OF MAKING**

(75) Inventors: **Serguei Razoumov**; **Arkadi Klementov**; **Serguei Litvinenko**, all of Moscow; **Alexey Beliakov**, Kursk, all of (RU)

(73) Assignee: **Joint Stock Company "Elton"**, Moscow (RU)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/206,600**

(22) Filed: **Dec. 7, 1998**

5,527,640		6/1996	Rudge et al. .	
5,538,813		7/1996	Li .	
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(List continued on next page.)

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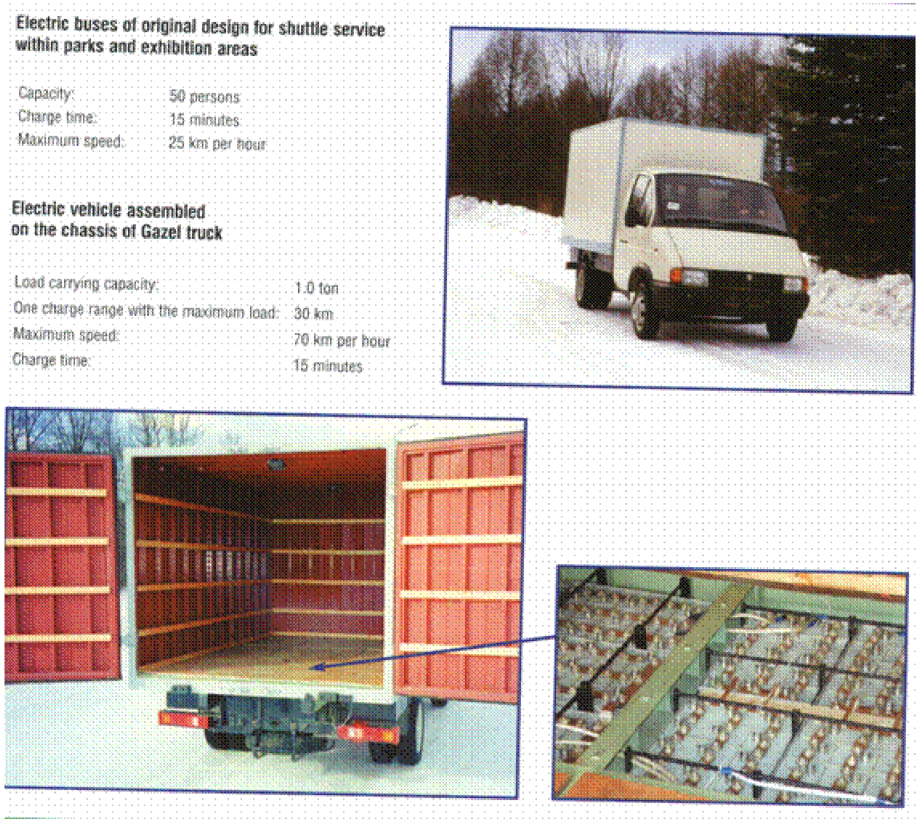
95/21466	8/1995	(WO) .
95/23437	8/1995	(WO) .
97/07518	2/1997	(WO) .
97/07554	2/1997	(WO) .

OTHER PUBLICATIONS

Early Capacitor Powered Electric Bus and Truck



Electric buses of original design for shuttle service within parks and exhibition areas

Capacity:	50 persons
Charge time:	15 minutes
Maximum speed:	25 km per hour

Electric vehicle assembled on the chassis of Gazel truck

Load carrying capacity:	1.0 ton
One charge range with the maximum load:	30 km
Maximum speed:	70 km per hour
Charge time:	15 minutes

~1993 ELTON Bus

30 MJ, 190 V, NiOOH/KOH/C storage system
15 km range, 25 km/hr, 15 minute charge
circle route operation in large Moscow park

~1995 Gazel Truck

30 MJ ELTON NiOOH/KOH/C EC, 70 km/hr
30 km range, 15 minute charge
factory to warehouse operation

Characteristics of Asymmetric ECs

(aqueous electrolyte)

- + Tolerant to over-voltage conditions
- + Voltage self-balance in series strings
- + Electrode drying unnecessary
- + Low-cost packaging possible since water not contaminant
- + Very low self-discharge rate is possible
- + High electrolyte salt concentration possible

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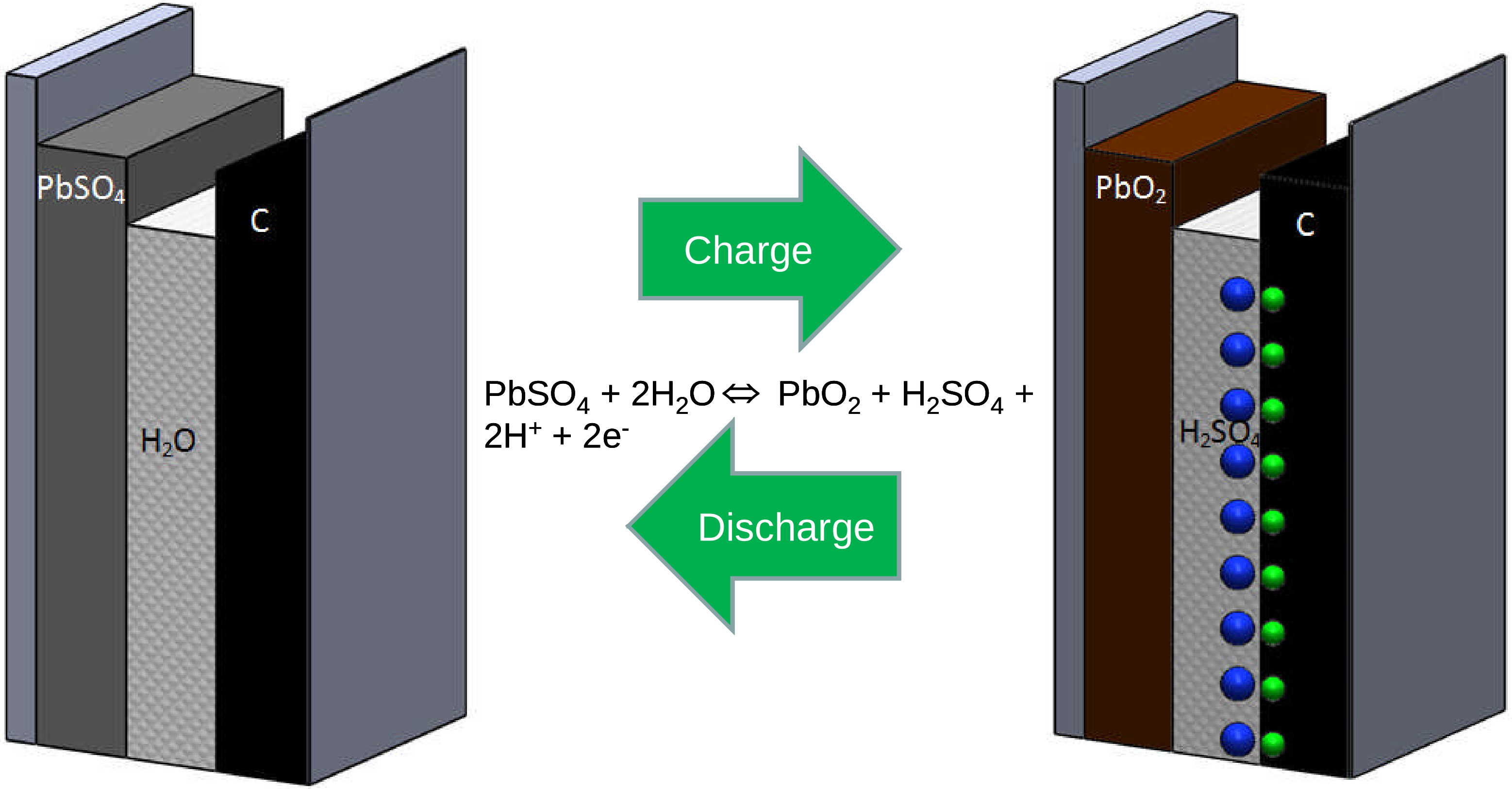
- \+ Very low self-discharge rate is possible
- \+ High electrolyte salt concentration possible
- \- Longer response times (lower power)
- \- Cycle life lower than symmetric EC—set by asymmetry ratio
- \- Cannot be discharged to and held at 0 V

ELTON Pb/C Asymmetric Electrochemical Capacitor
for the
Electric Grid



$PbSO_4 + 2H_2O \Leftrightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^-$

ELTON

C_{neg} up to 1600 F/g due to the small size of H^+ and its low-level interaction with activated carbon structure

<$0.10/kWh projected storage cost

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for the
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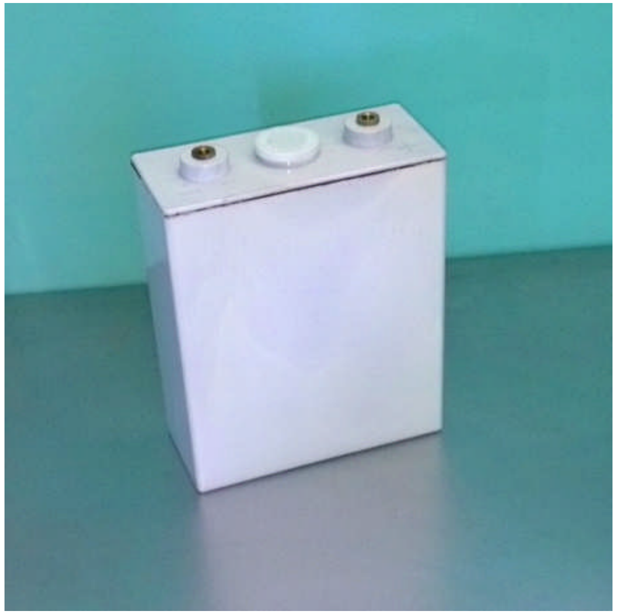
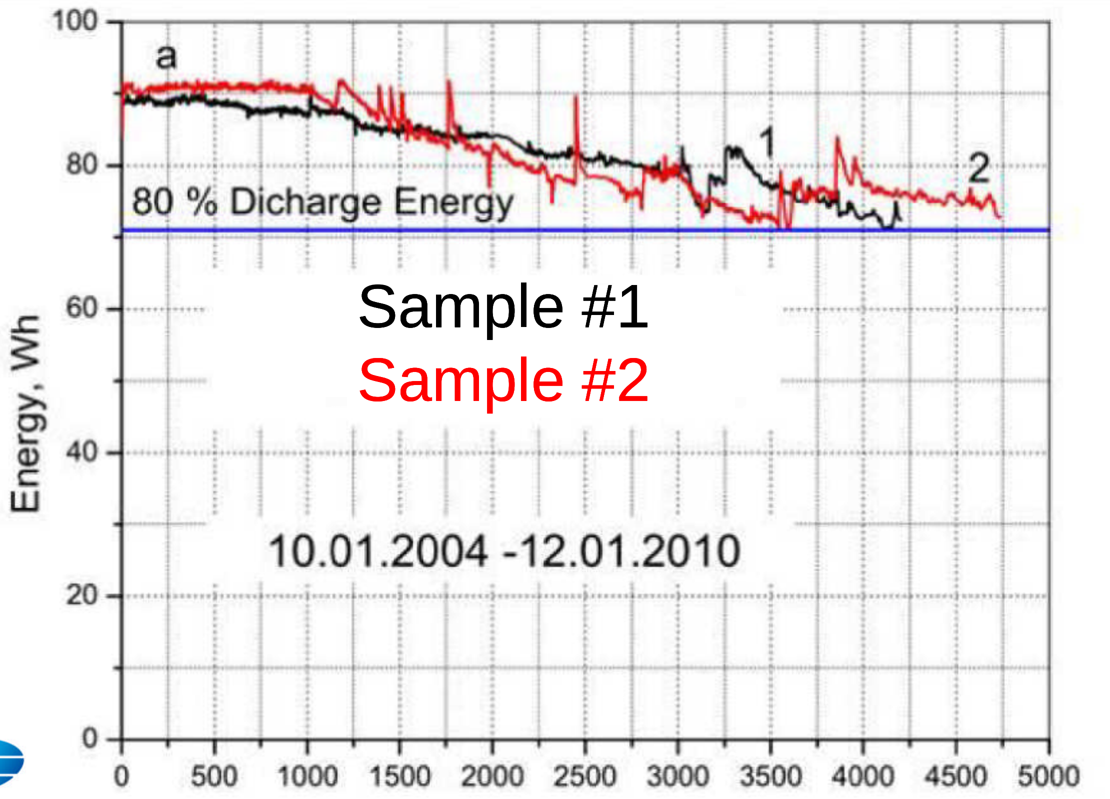


Pilot prototype
ELTON HES-340F1

ELTON



C/5 discharge, 25 ^{o}C, 100% DOD

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Decommissioned Power Plants

Fill Decommissioned Power Plants with Capacitors

Note:

- Empty building
- Transmission switchyards often intact
- Extends life of capital investment
- Promotes removal of inefficient plants
- Permitting should not be difficult

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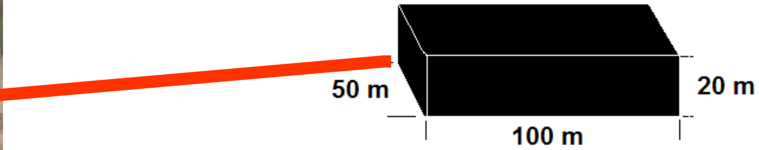

50m x 100m x 20m = **100,000 m^3**

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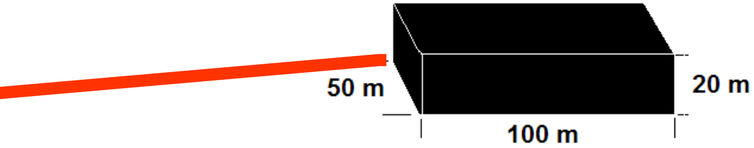

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Pb-C capacitor: **50 Wh/l** = 50 kWh/m^3

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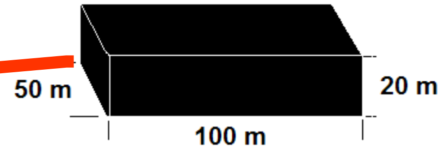
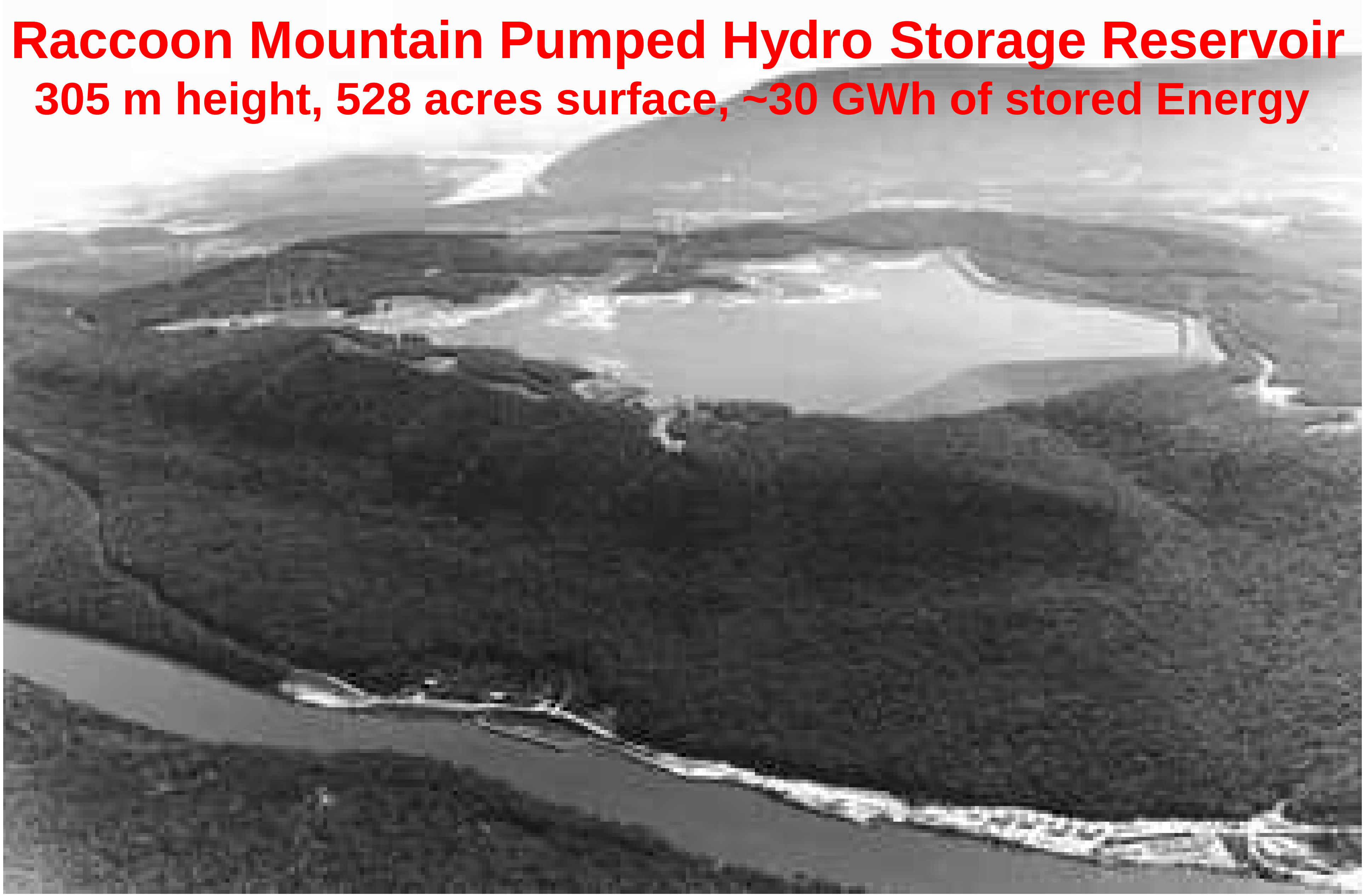


50m x 100m x 20m = **100,000 m^3**
Pb-C capacitor: **50 Wh/l** = 50 kWh/m^3

⇒ 100,000 m^3 storage volume could deliver **5,000** MWh of electricity
i.e. 1000 MW for 5 hours

Raccoon Mountain Pumped Hydro Storage Reservoir

305 m height, 528 acres surface, ~30 GWh of stored Energy



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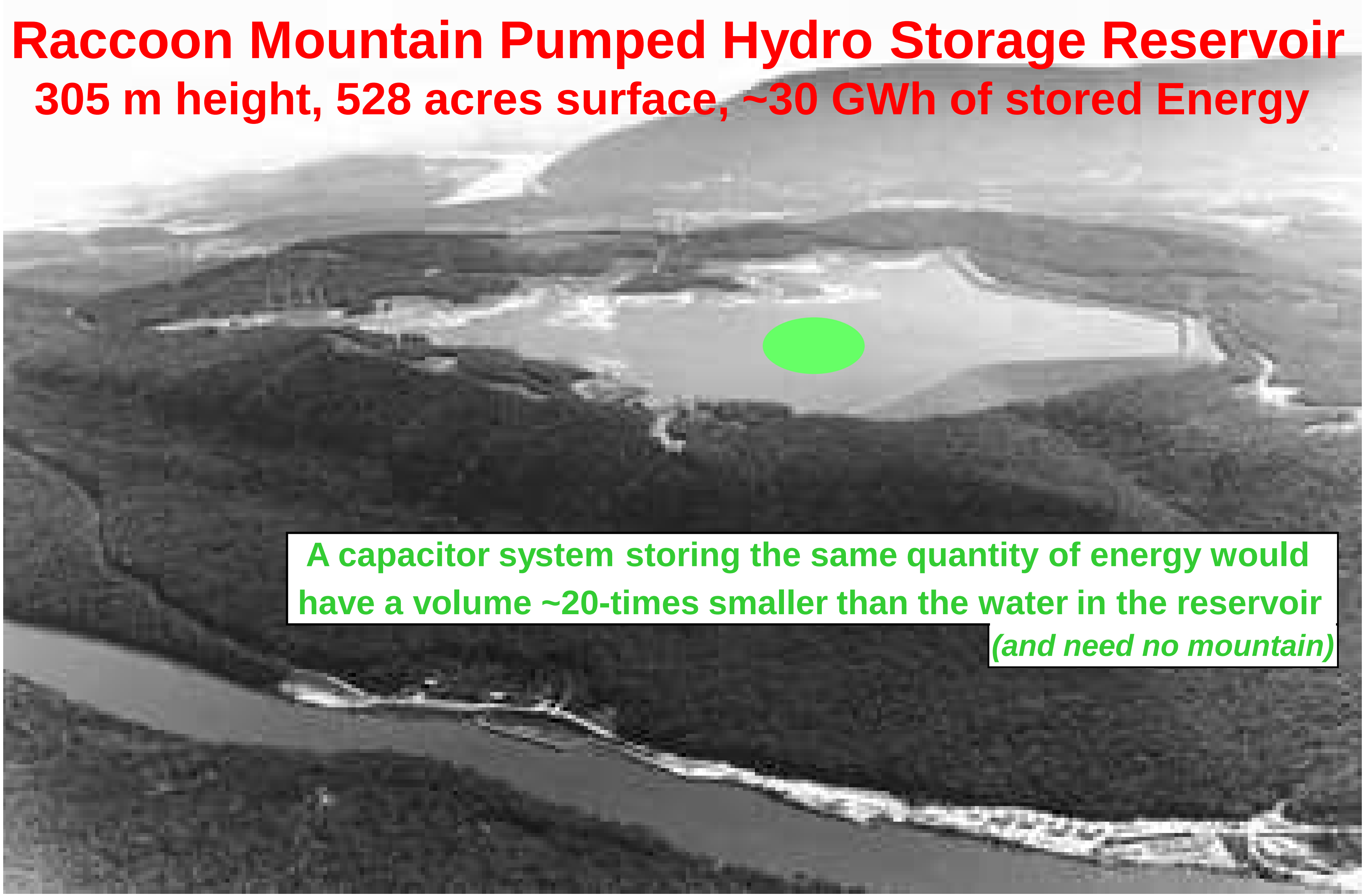

A capacitor system storing the same quantity of energy would have a volume ~20-times smaller than the water in the reservoir

(and need no mountain)

Summary: Capacitors for Day/Night Storage

- **Energy storage cost ($/kWh) is the most important metric (not energy density)**

- **EC storage systems can be scaled to any size**

- **Projected asymmetric EC storage costs < $0.10/kWh**

- **ECs can satisfy other grid needs (like fast regulation**

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- **(Mountain and water are not needed)**

Outline

- Electrochemical capacitor (EC) energy storage introduction
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Business Case for Capacitor Hybridization

Example: 40,000 lb city transit bus

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- **CAPACITOR TECHNOLOGY HAS LOWER LIFE-CYCLE COST**

Energy Storage Technology Value

Barnhart and Benson “Returned Energy” concept

$$\text{ESOI} = \frac{\text{Energy stored}}{\text{Embodied energy}} = \frac{(\text{capacity})\lambda\eta D}{(\text{capacity})\varepsilon_{\text{gate}}} = \frac{\lambda\eta D}{\varepsilon_{\text{gate}}}$$

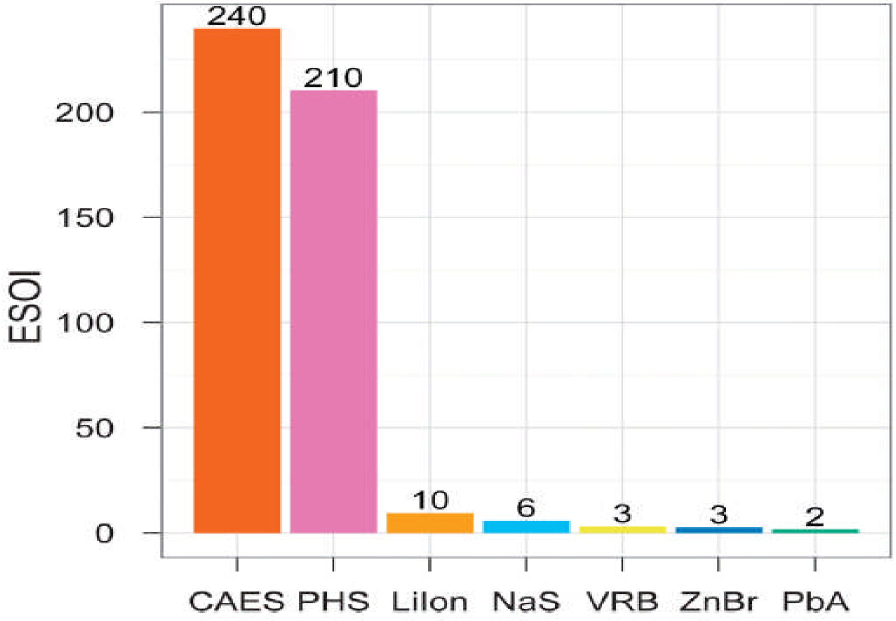
ESOI = Energy Stored On Invested

λ = cycle life

η = round-trip efficiency

D = depth-of-discharge

$\varepsilon_{\text{gate}}$ = dimensionless— ratio of embodied energy to stored energy



CAES = compressed air energy storage
PHS = pumped hydroelectric storage
LiIon = lithium ion battery
NaS = sodium sulfur battery
VRB = vanadium redox flow battery
ZnBr = zinc-bromine flow battery
PbA = lead-acid battery

Source: C.J. Barnhart and S.M. Benson, “**On the importance of reducing the energetic and material demands of electrical energy storage**”, Energy Environ. Sci., DOI: 10.1039/c3ee24040a (Jan. 30, 2013).

Conclusions from Barnhart and Benson Study

$$\mathrm{ESOI} = \frac{\text{Energy stored}}{\text{Embodied energy}} = \frac{(\text{capacity})\lambda\eta D}{(\text{capacity})\varepsilon_{\text{gate}}} = \frac{\lambda\eta D}{\varepsilon_{\text{gate}}}$$

ESOI = Energy Stored On Invested

λ = cycle life

η = round-trip efficiency

D = depth-of-discharge

$\varepsilon_{\text{gate}}$ = dimensionless ratio of embodied energy to stored energy

- Increase cycle life of storage—most effective way to reduce energy intensity
- Current R&D focus on reducing costs is insufficient to create a viable bulk energy storage technology
- R&D focus should be on bulk energy storage technologies showing potential for the largest ESOI values

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  - Power for emergency pitch control of wind turbines
  - Power to move sun-tracking mirrors

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  - Power for emergency pitch control of wind turbines
  - Power to move sun-tracking mirrors
- Electrochemical capacitors have good potential for:
  - Day/night energy storage
  - Fast regulation of grid power
  - Load leveling renewable energy generation

ELECTROCHEMICAL CAPACITOR COMPANY WEBSITES

Accessed 9-2017

Product Name	WEB-SITE
BEST CAP	www.avx.com/prodinfo_productdetail.asp?I=917&ParentID=42
Batscap	www.blue-solutions.com/
CAP-XX	www.cap-xx.com
MAXCAP	www.kanthal.com/en/products/resistors-and-capacitors/capacitors/
DLCAP	www.chemi-con.co.jp/e/index.html
PowerStor	www.cooperet.com/3/PowerStor.html
DYNACAP	www.elna.co.jp/en/capacitor/double_layer/index.html
GOLD	www.industrial.panasonic.com/www-ctlg/ctlg/qABC0000_WW.html
iCAP	www.ioxus.com
ULTIMO	www.jmenergy.co.jp
BOOSTCAP	www.maxwell.com
SUPERCAPACITOR	www.nec-tokin.com/english/product/dl_capacitor.html
EVerCAP	www.nichicon.co.jp/english/index.html
LS Ultracapacitor	www.ultracapacitor.co.kr/
XELLED EDLC	www.vina.co.kr/new_html/eng/product/info.asp?cate1=10