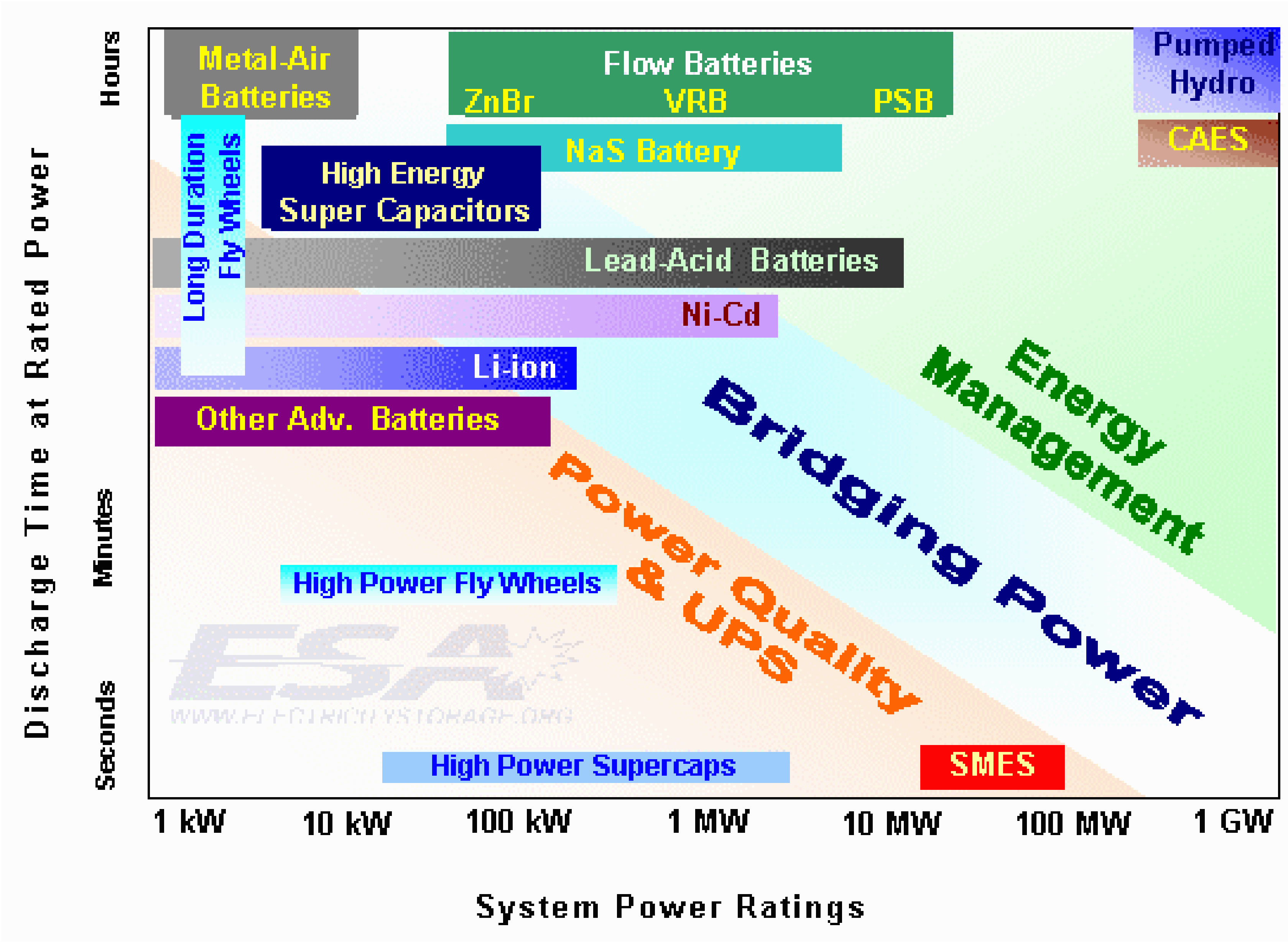
II. Energy Storage Technology Overview

- **Instructor – Haresh Kamath, EPRI PEAC**
  - **Short term - Flywheels, Cranking Batteries, Electrochemical Capacitors, SMES**
  - **Long term - Compressed Air, Pumped Hydro storage, Stationary, Flow Batteries**

Overview

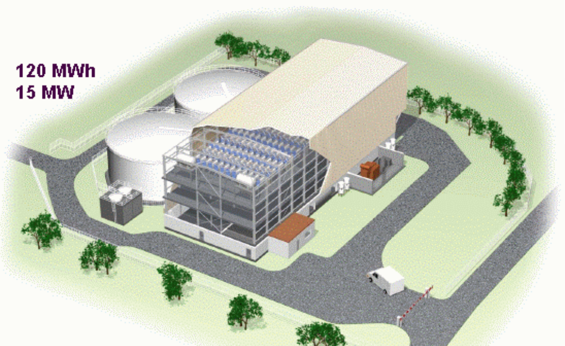
- Technology Types
  - Batteries, flywheels, electrochemical capacitors, SMES, compressed air, and pumped hydro
- Theory of Operation
  - Brief description of the technologies and the differences between them
- State-of-the-art
  - Past demonstrations, existing hurdles and performance targets for commercialization
- Cost and cost projections:
  - Prototype cost vs. fully commercialized targets

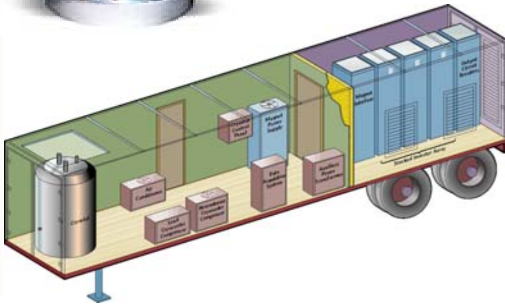
Technology Choice for Discharge Time and Power Rating (From ESA)



Maturity Levels for Energy Storage Technologies

- Mature Technologies
  - Conventional pumped hydro
  - Compressed air
  - Lead-acid batteries
- Emerging Technologies
  - Advanced Batteries
  - SMES
  - Flywheels
  - Electrochemical Capacitors

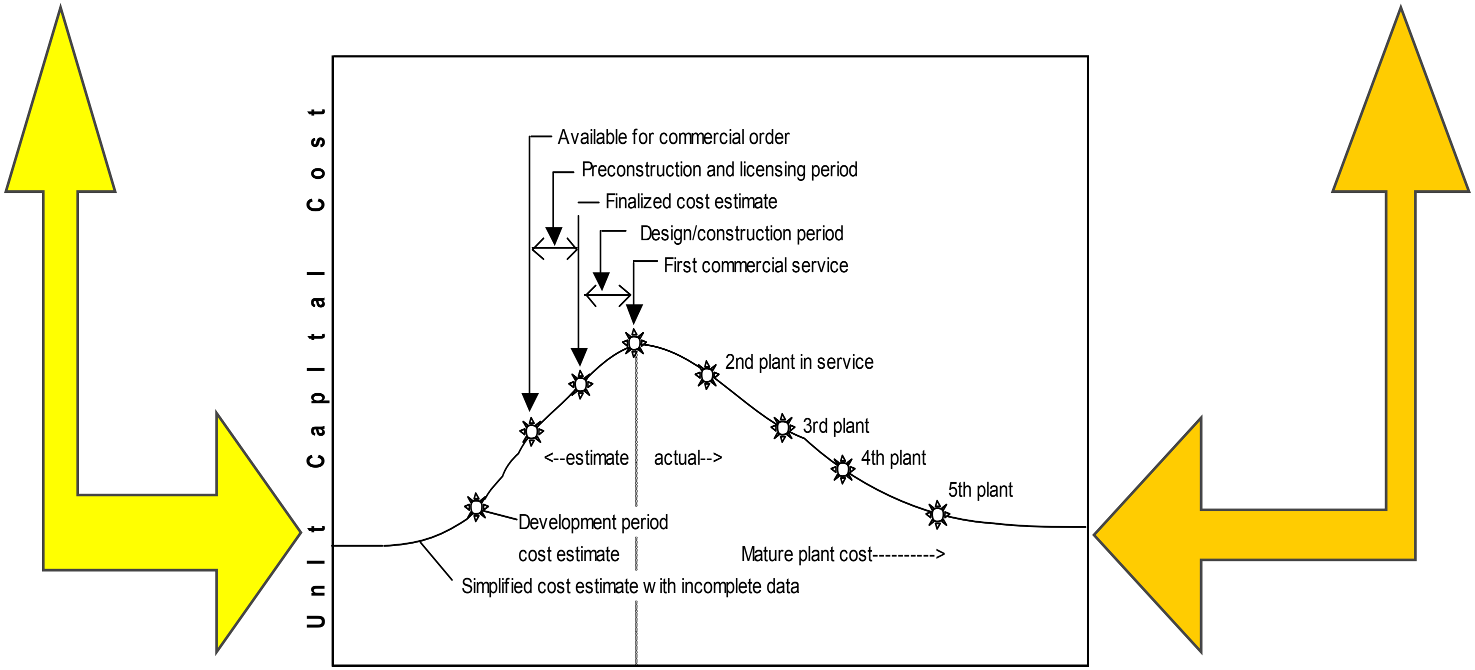




Illustrations are
Courtesy of Regenesys Technologies

Energy Storage Technology Maturity

	Concept Stage		**Demonstration Stage**		**Mature Commercial Product**	
	Energy Storage Requirment					
Power	**Seconds**	**Hours**	**Seconds**	**Hours**	**Seconds**	**Hours**
100s of MW			SMES			CAES Pumped Hydro
10s of MW	Ultra Cap Fly Wheel			Hybrid CAES Regenesys NAS Battery	SMES	Lead Acid Battery
100s of KW - Few MW		Fly Wheel Li/Metal Air Batt.	Ultra Cap	VRB Batteries ZnBr Batteries	Fly Wheel SMES	Lead Acid Battery
Several kW			Ultra Cap	Fly Wheel Li/Metal Air Batt.	Electrolitc/Advanced Capacitor	Flywheel Lead Acid Battery



Short term Storage Technologies for Bridging Power Applications

- Batteries
- Flywheels
- Electrochemical capacitors
- SMES

Batteries

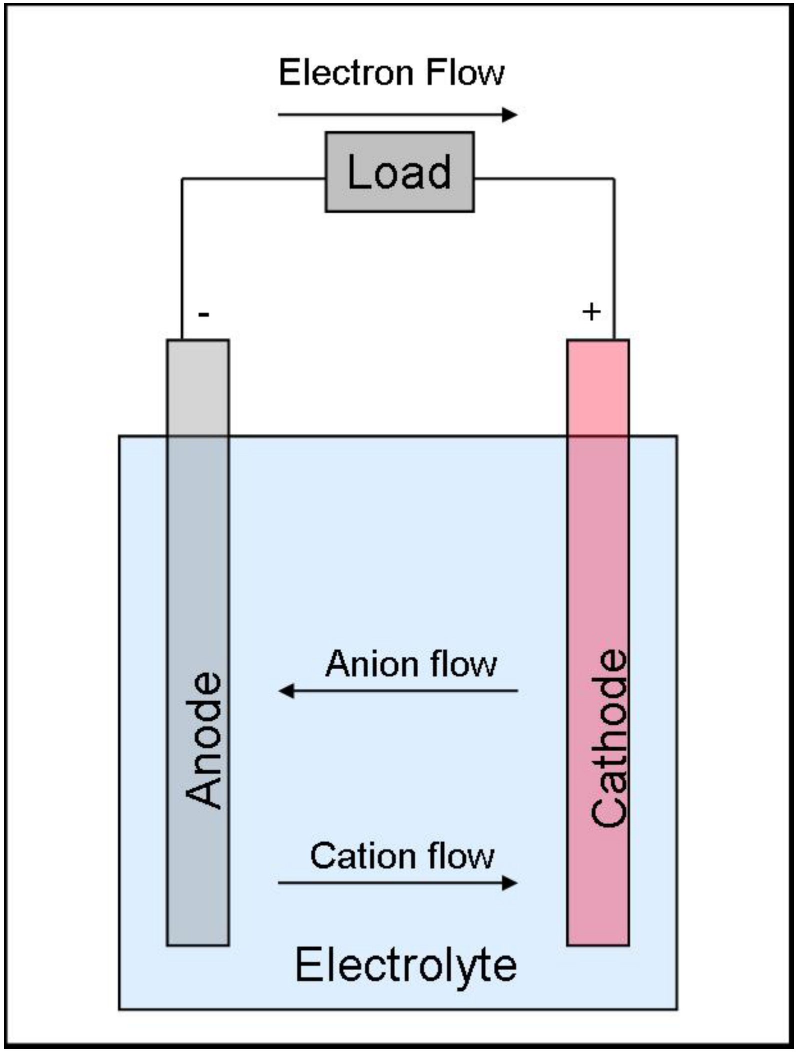
Batteries store energy chemically electrochemical reactions to produce electricity at a fixed voltage

Pros:

- Convenient voltage characteristics
- Convenient sizing
- Extensive design history

Cons:

- Limited cycle life
- Voltage and current limitations, requiring complex series/parallel systems
- Often present environmental hazard



Battery Application Suitability

- Batteries are suitable for applications that require the supply of relatively large amounts of energy storage (>1 MWh) over long periods of time (15 minutes or more), where rapid recharge is not necessary and where maintenance can be reasonably performed.
- They are not especially suitable for environmentally sensitive sites, remote locations, or applications that require rapid discharge and absorption of energy.

Battery Technologies: Levels of Maturity

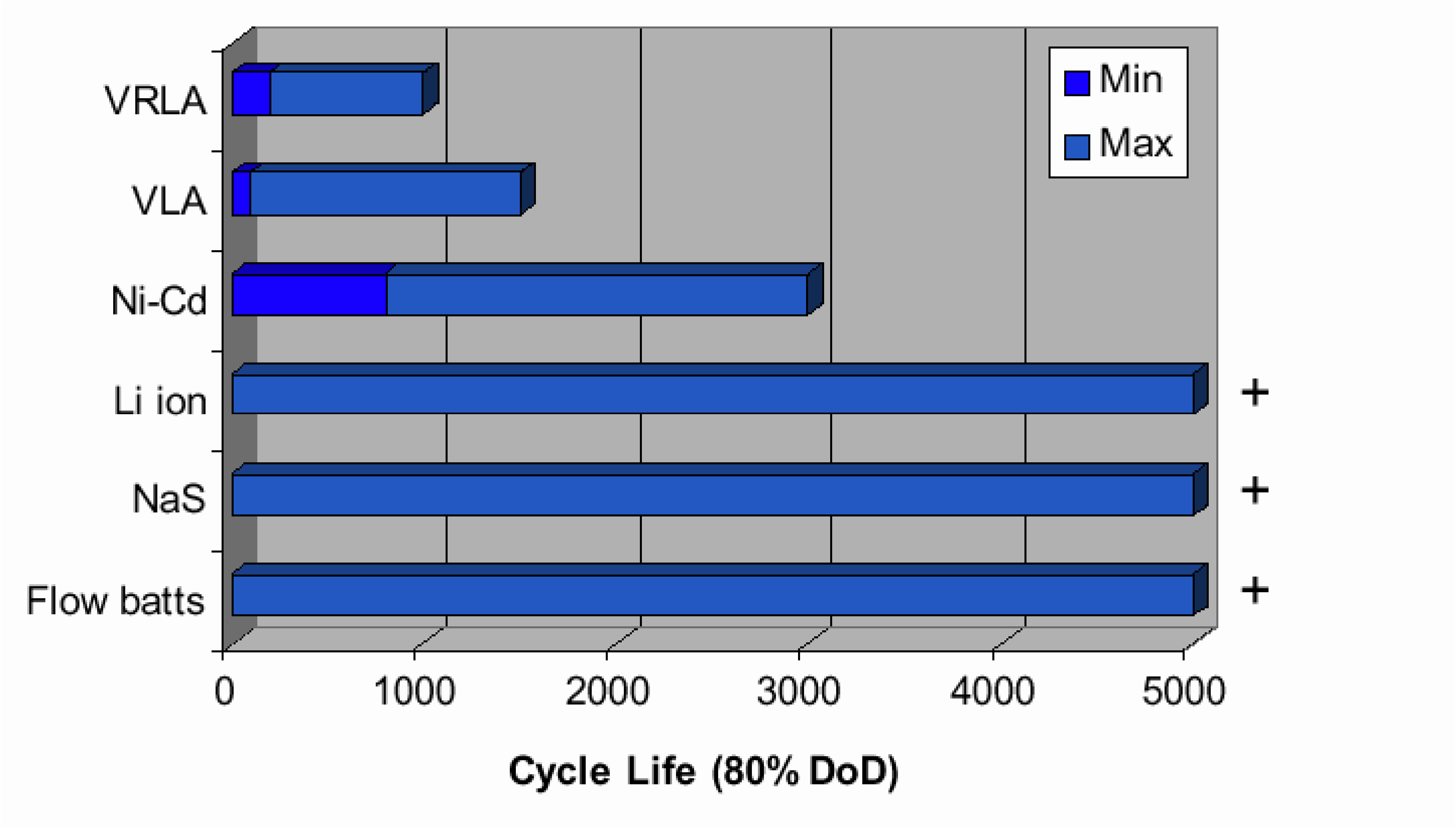
- **Mature: Significant commercial experience with several operating units**
  - Lead-Acid batteries

- **Limited Commercialization: Nascent commercial experience**
  - Nickel-Cadmium batteries

- **Demonstration: Concept verified by integrated demonstration unit**
  - Sodium-sulfur batteries

- **Pilot: Concept verified by small pilot facility**
  - Flow batteries

Cycle Life



Courtesy: Jim McDowall /SAFT

Mature Technology: Lead-Acid Batteries

Lead-Acid batteries consist of two electrodes – one lead and one lead-dioxide – immersed in sulfuric acid.

Pros:

- Mature technology – over a century old
- Familiar – the most widely-used electricity storage system on earth
- Extremely inexpensive

Cons

- Relatively low energy and power densities
- Poor cycle life
- Often requires maintenance

Lead-acid batteries should be considered the default energy technology for short-duration energy storage systems

Starting, Lighting and Igniting (SLI) Batteries

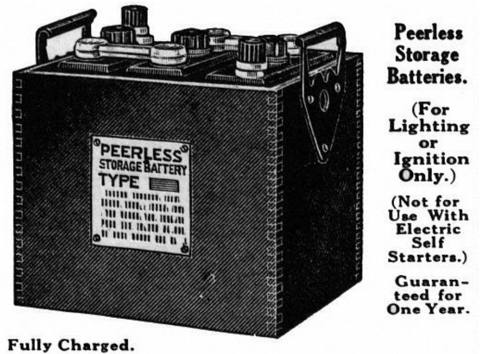
Also called cranking batteries, SLI batteries are typically used to start internal combustion engines.

Pros:

- Very inexpensive
- Extremely mature technology – changed little over a hundred years

Cons:

- Low energy density
- Very short cycle life (50-100 cycles at 100% DOD)



Peerless Storage Batteries.

(For Lighting or Ignition Only.)

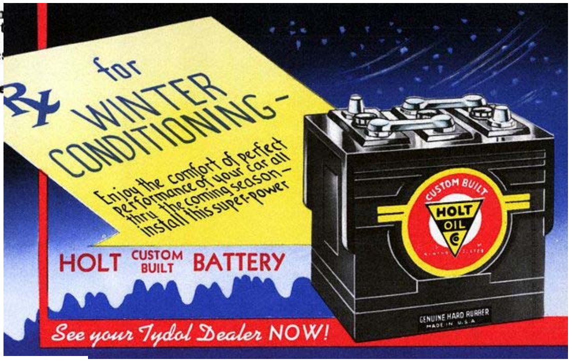
(Not for Use With Electric Self Starters.)

Guaranteed for One Year.

Fully Charged.

We furnish Peerless Storage Batteries in
two smaller sizes are for ignition only, and
sizes for both ignition and lighting. It can
from the table that the large type batterie
practical for use as lighting batteries.

Sizes and Prices of Peerless Storag



DieHard® is a registered trademark of Sears Roebuck, Inc.

Flooded Stationary Lead-Acid Batteries

Flooded stationary lead-acid batteries are long-life batteries used for critical backup applications

Pros:

- Relatively inexpensive
- Extensive design history
- Very long service life

Cons:

- Low energy density
- Regular maintenance required
- Low cycle life

Valve-Regulated Lead-Acid (VRLA) Batteries

VRLA batteries are low-maintenance batteries used for long-duration energy storage such as UPS systems

Pros:

- Relatively inexpensive
- Extensive design history
- Relatively low maintenance

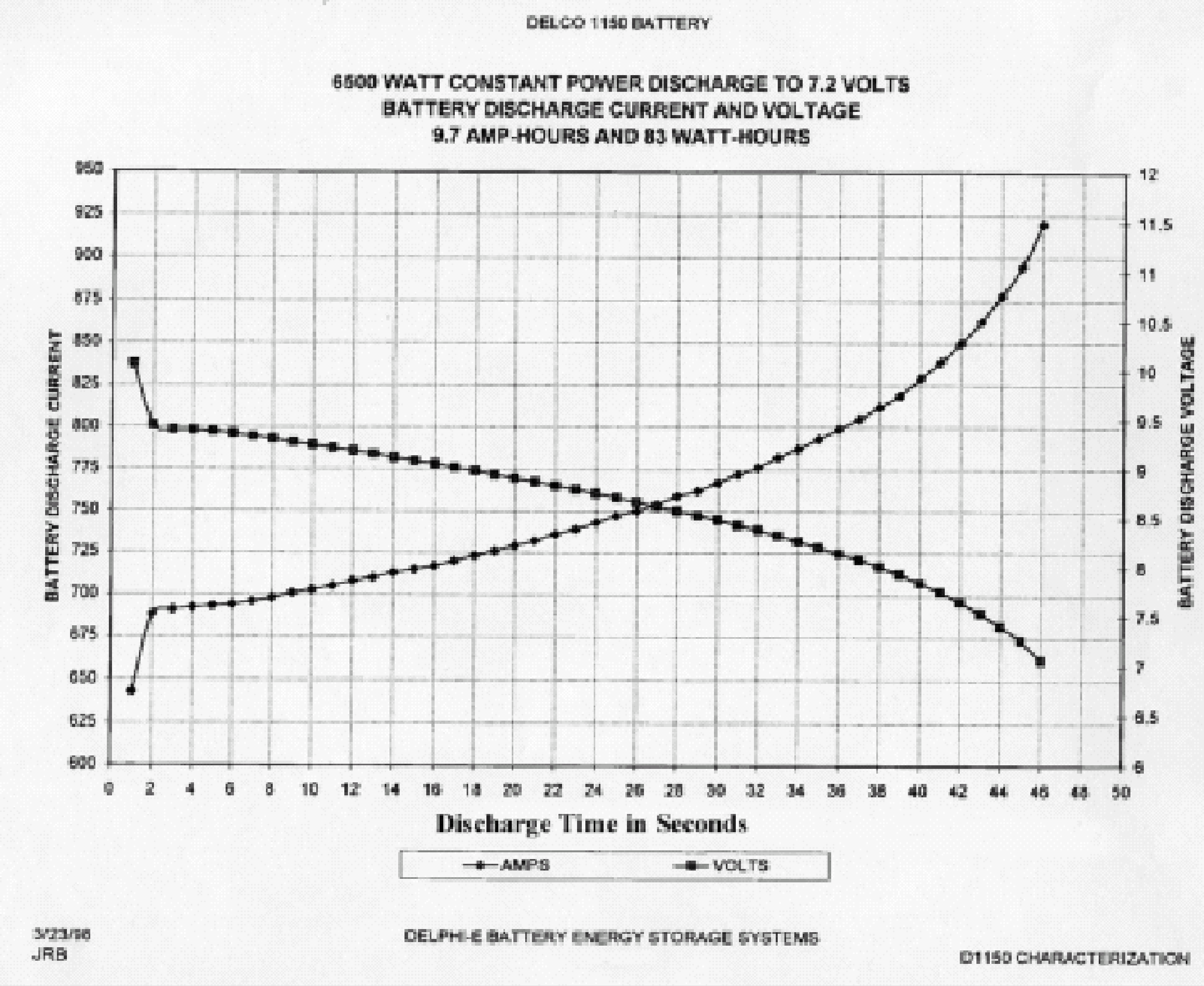
Cons:

- Low energy density
- Cycle and service life limitations

VRLA Battery technology

- Mature, work horse in utility applications
- Typical batteries used by electric utilities today are the flooded cell battery, which is more robust, and the valve-regulated, lead-acid (VRLA) battery, which requires less maintenance.
- VRLA batteries replaced many flooded cell batteries in the 1980s and early 1990s.
- In 1995, the VRLA batteries were found to suffer from a loss of capacity, effectively a life limitation, driven by the characteristic of the oxygen interaction at the negative electrode.
- Several studies suggested that there should be a life limitation of about 2 to 5 years for heavy use of VRLA batteries.
- Fortunately, a variety of solutions has allowed VRLA batteries to achieve life expectancies of over 10 years.
- Because of their widespread use, VRLA batteries are an economically viable energy storage device for a variety of utility and other applications.

High-Rate LA Battery Discharge



DELCO 1150 BATTERY

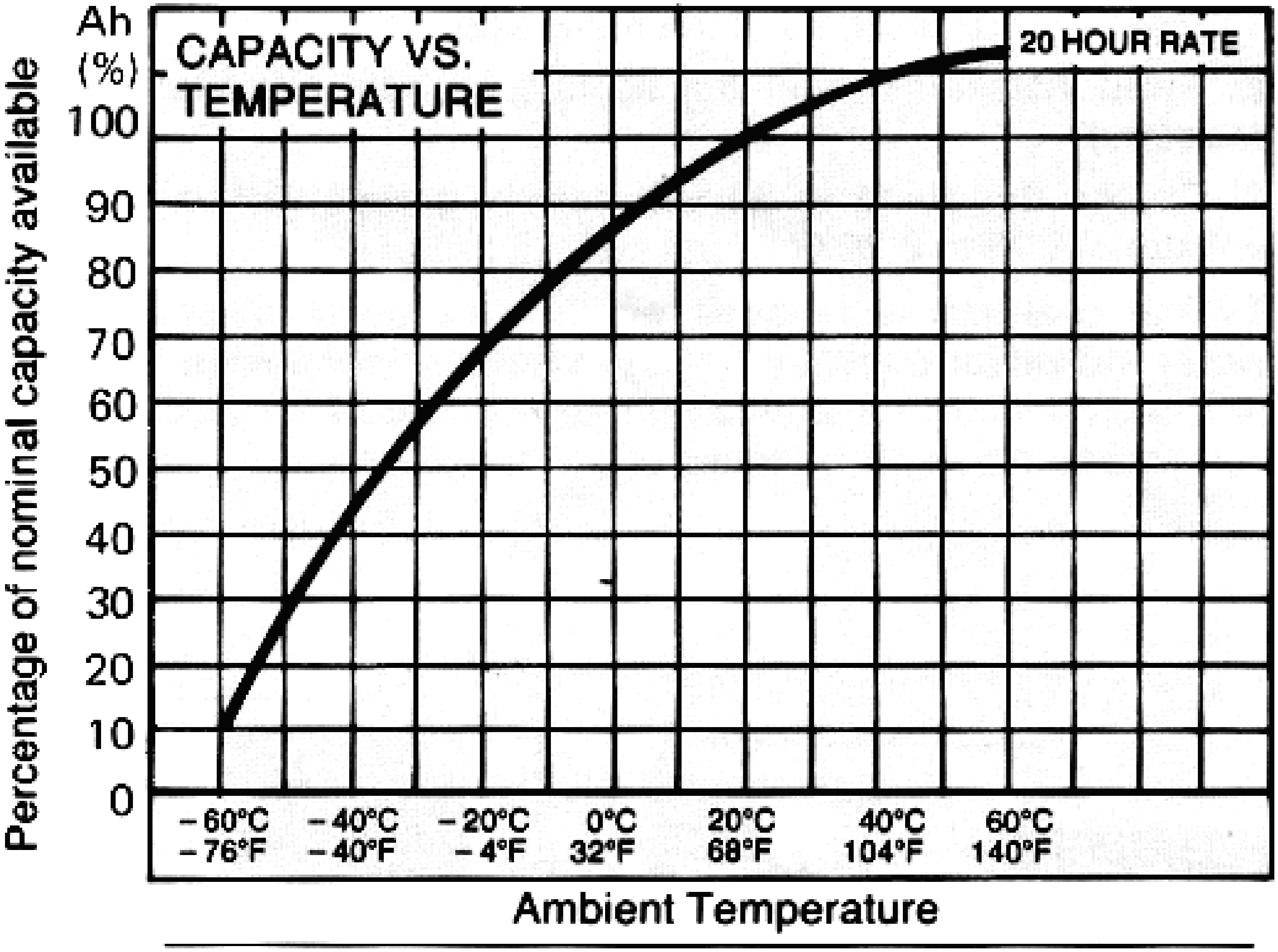
6500 WATT CONSTANT POWER DISCHARGE TO 7.2 VOLTS
BATTERY DISCHARGE CURRENT AND VOLTAGE
9.7 AMP-HOURS AND 83 WATT-HOURS

3/23/98
JRB

DELPHI-E BATTERY ENERGY STORAGE SYSTEMS

D1150 CHARACTERIZATION

Impact of Temperature on Capacity for Lead Acid Battery

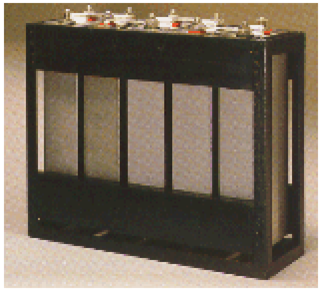


Batteries in Distributed Energy Resources

- The vast majority of energy storage systems in present-day DER devices are lead-acid batteries
  - They are cheap, readily available, and easy to integrate
  - More expensive energy storage increases the cost of already-expensive systems
- The main disadvantage is replacement cost
  - Relatively short life will affect life-cycle costing

Lead-Acid Battery Cells from an Avista PEM fuel cell

Mature Technology: Nickel-Cadmium Batteries



Nickel-Cadmium Batteries have a nickel electrode and a cadmium electrode in an aqueous potassium-hydroxide electrolyte

Pros:

- Mature technology
- Relatively rugged
- Higher energy density and better cycle life than lead-acid batteries

Cons

- More expensive than lead-acid

Emerging Technology: Sodium-Sulfur Batteries

Sodium-sulfur (NaS) batteries use molten sodium and sulfur separated by a ceramic electrolyte

Pros:

- High energy and power density
- Relatively high efficiency

Cons:

- Relatively immature technology
- High temperature produces unique safety issues

These batteries are generally not appropriate for use in DER systems.

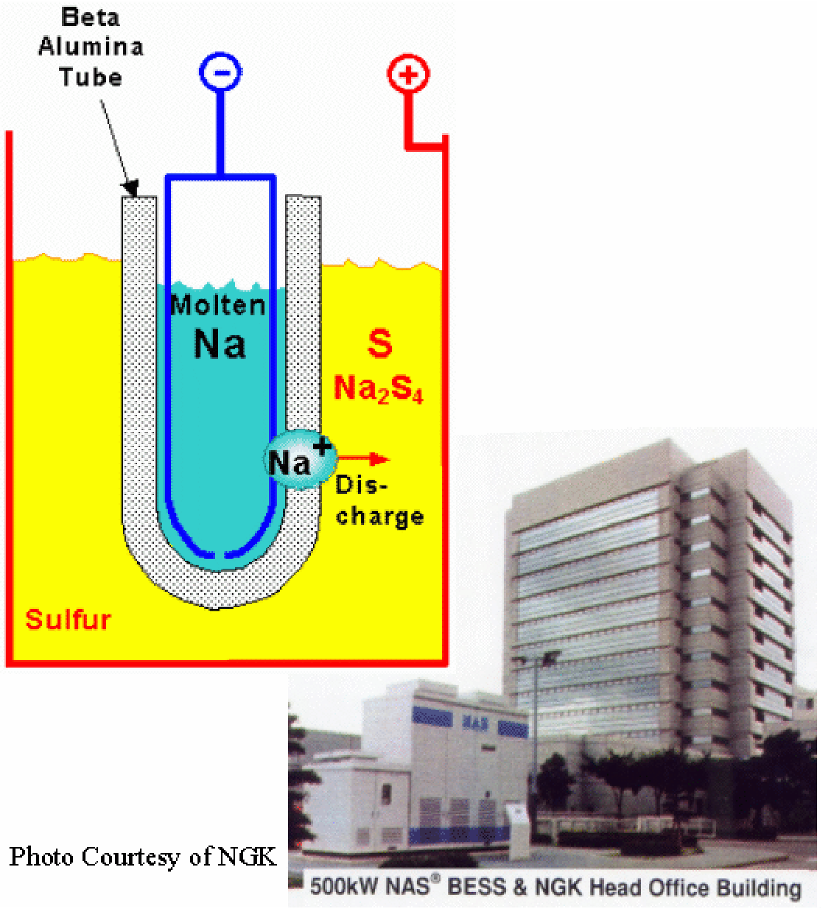


Photo Courtesy of NGK

500kW NAS® BESS & NGK Head Office Building

Flow Batteries

Flow batteries use liquid electrolytes with fixed cells to store and regenerate power

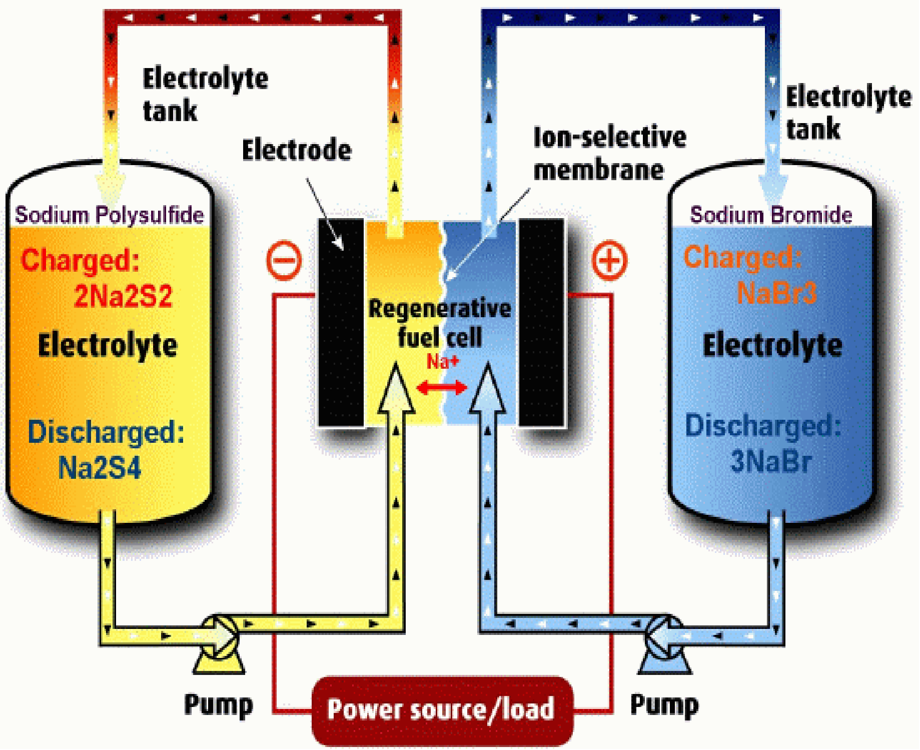
Pros:

- Energy and power sizing is independent
- Scalable for large applications
- High energy and power density

Cons:

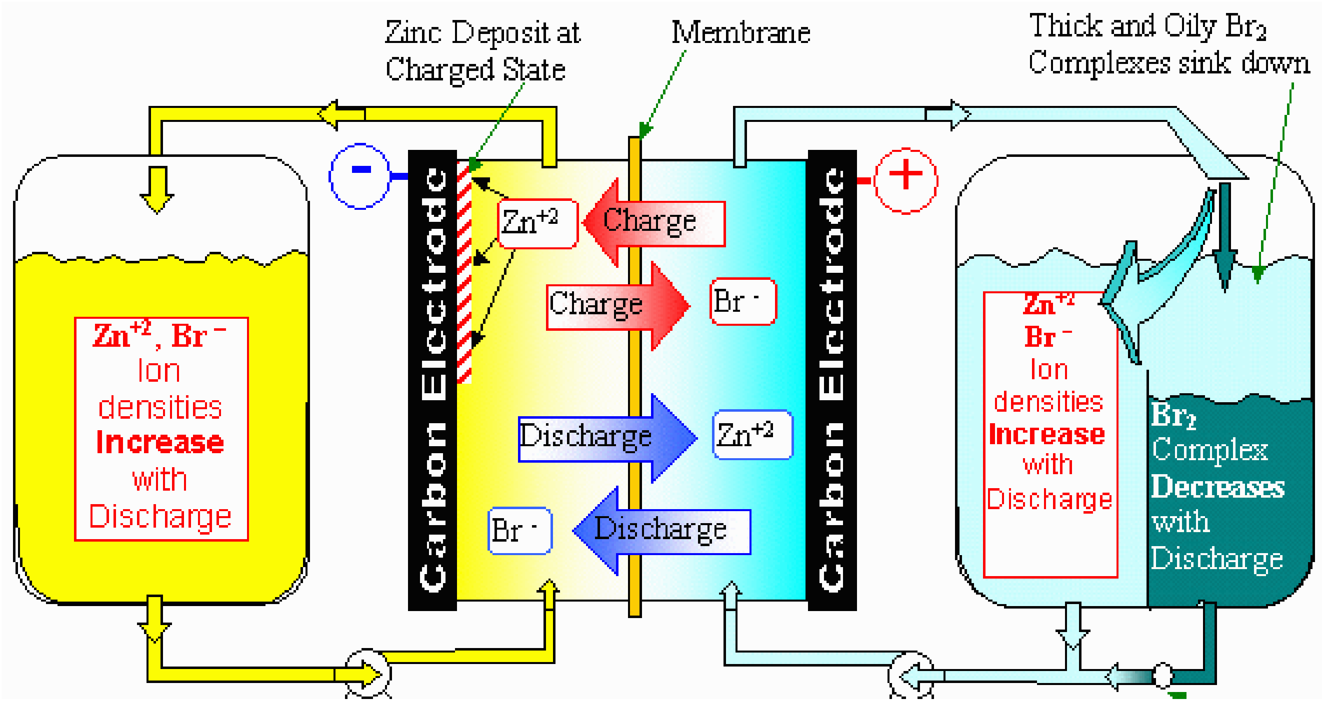
- Relatively immature technology
- High maintenance costs

These batteries are generally not appropriate for use in DER systems.



Regenesys Flow Battery

Zinc-Bromine Flow Battery



In each cell of a ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane.

Courtesy: Energy Storage Association (ESA)

Other Advanced Battery Technology

- Lithium-Ion, Metal-Air, and other battery technologies have been considered for use in DER systems
- There are still significant challenges for taking these technologies to the power and energy level required for these applications

Emerging Technologies: Flywheel

Flywheels store energy in the form of momentum in a rotating wheel or cylinder

Pros:

- High power density
- High cycle life
- Quick recharge
- Independent power and energy sizing

Cons:

- Low energy density
- Large standby losses
- Potentially dangerous failure modes

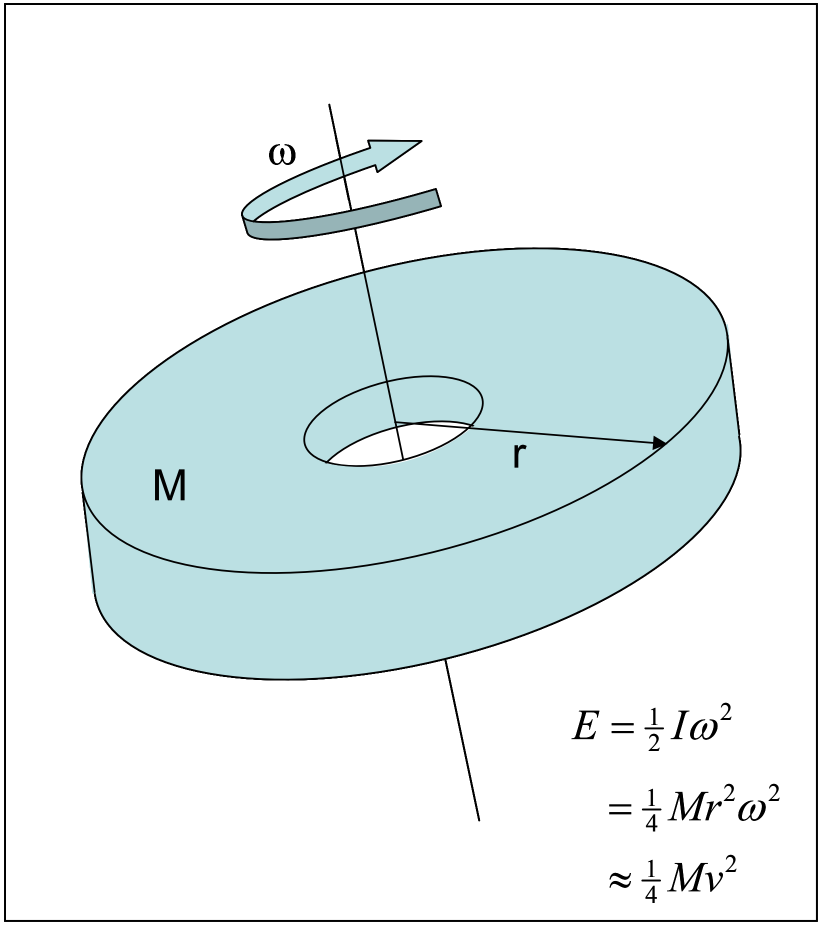
Flywheel Principles

The stored energy in a flywheel is proportional to the mass, and to the square of the tip velocity.

This leads to two approaches in flywheel design: Big, heavy wheels spinning slowly, and small, light wheels spinning quickly.

Low-speed wheels are built with steel, and rotate at rates up to 10,000 RPM.

High-speed designs store more energy but require exotic materials such as graphite and glass composites.



$$E = \tfrac{1}{2} I\omega^2$$

$$= \tfrac{1}{4} Mr^2\omega^2$$

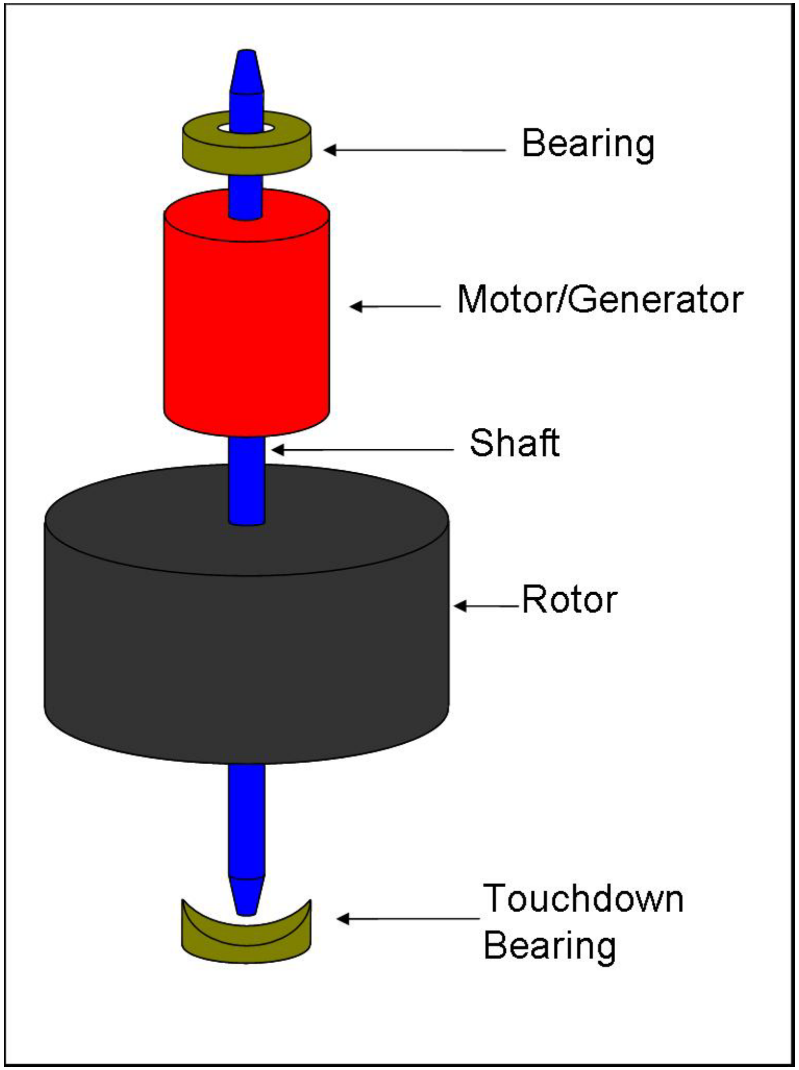
$$\approx \tfrac{1}{4} Mv^2$$

Flywheel Principles

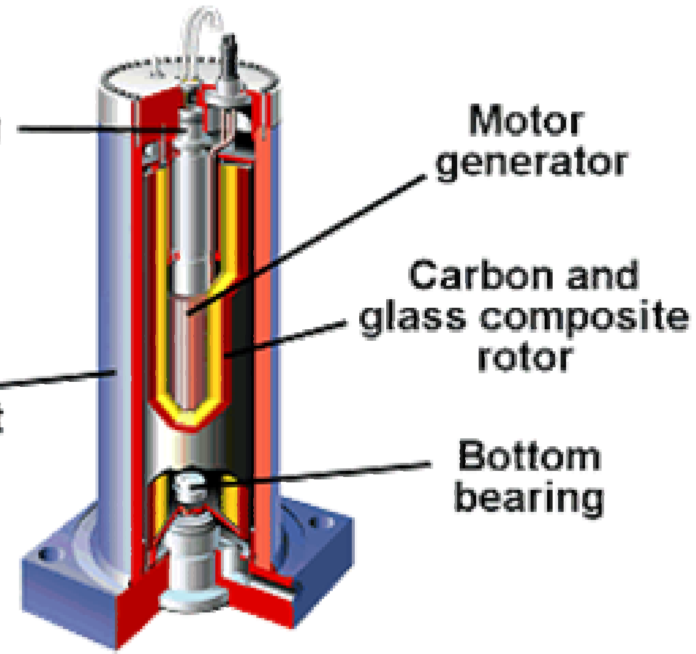
An electric motor spins the rotor to a high velocity to charge the flywheel.

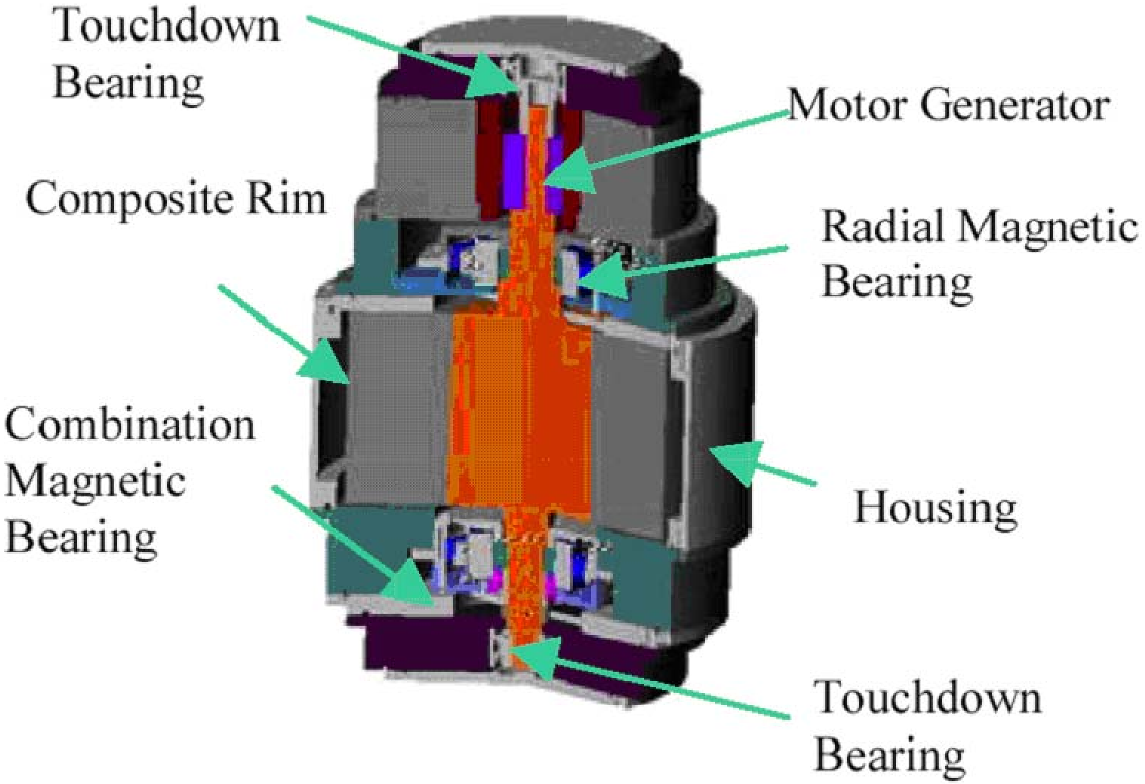
During discharge, the motor acts as a generator, converting the rotational energy into electricity.

Power electronics are used to ensure that output voltage has appropriate voltage and frequency characteristics.



Flywheel Components

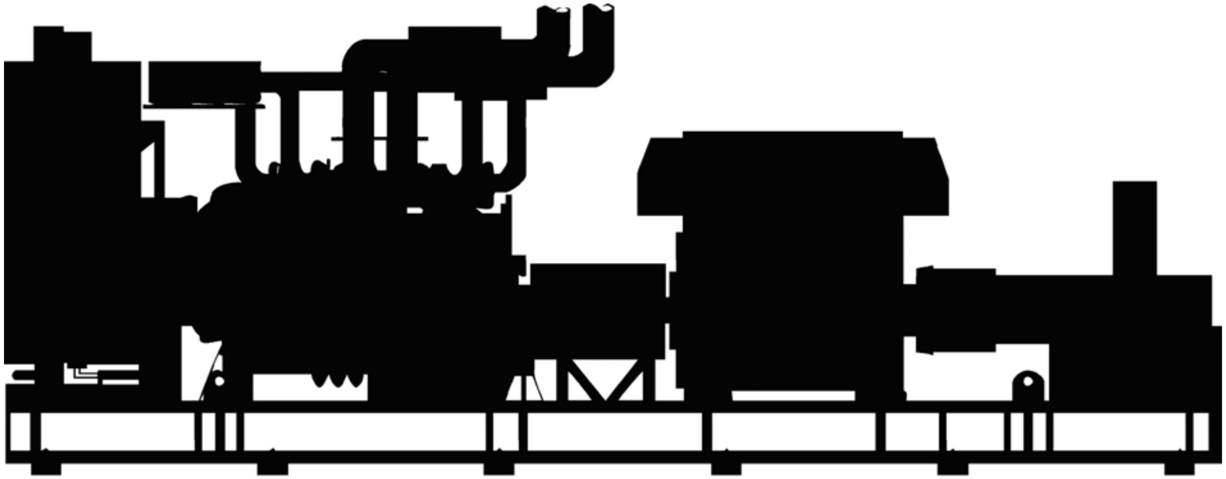




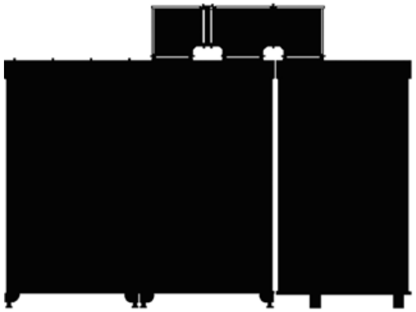
Flywheel Technology Status

- Flywheels have been seriously proposed for energy storage since the early 1970's.
- Most present installations are smaller systems used to provide bridging power for backup generators

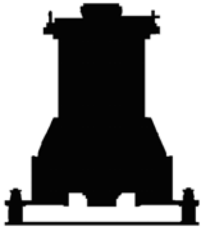
Flywheel Products



Starsine UPS



Catepillar



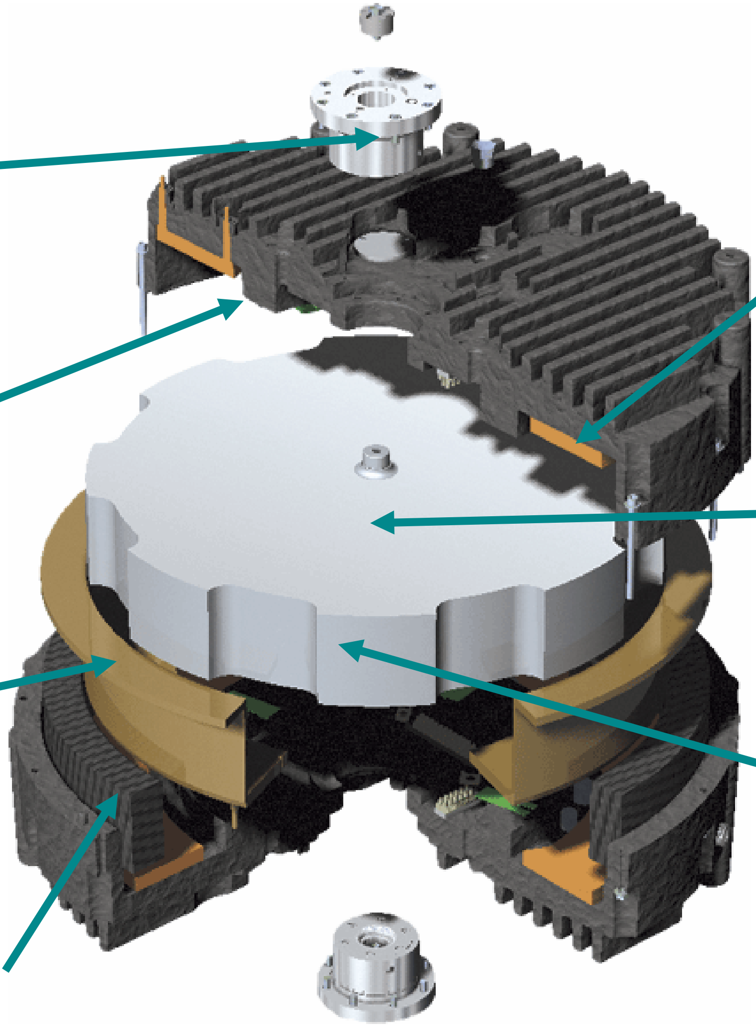
Powerbridge

Urenco
UPTpq250

Beacon
Flywheel

- **Satcon (USA),** 2200kVA, 12 sec
- Hitec (Netherlands), 2000kVA, 10 sec
- **Piller** (Germany), 1100kW, 15 sec
- **Caterpillar/Active Power** (USA), 240kW, 13.5 sec
- **Urenco** (UK), 250kW, 30 sec
- Pentadyne (USA), 120kW, 20 sec
- Trinity (USA), 100kW, 15 sec
- **Beacon Power** (USA) 2 kW, 3 hours

Active Power 240kW Flywheel (used in CAT UPS)



Field replaceable ball-bearing cartridge

Magnetic bearing integrated into field circuit

Air-gap armature

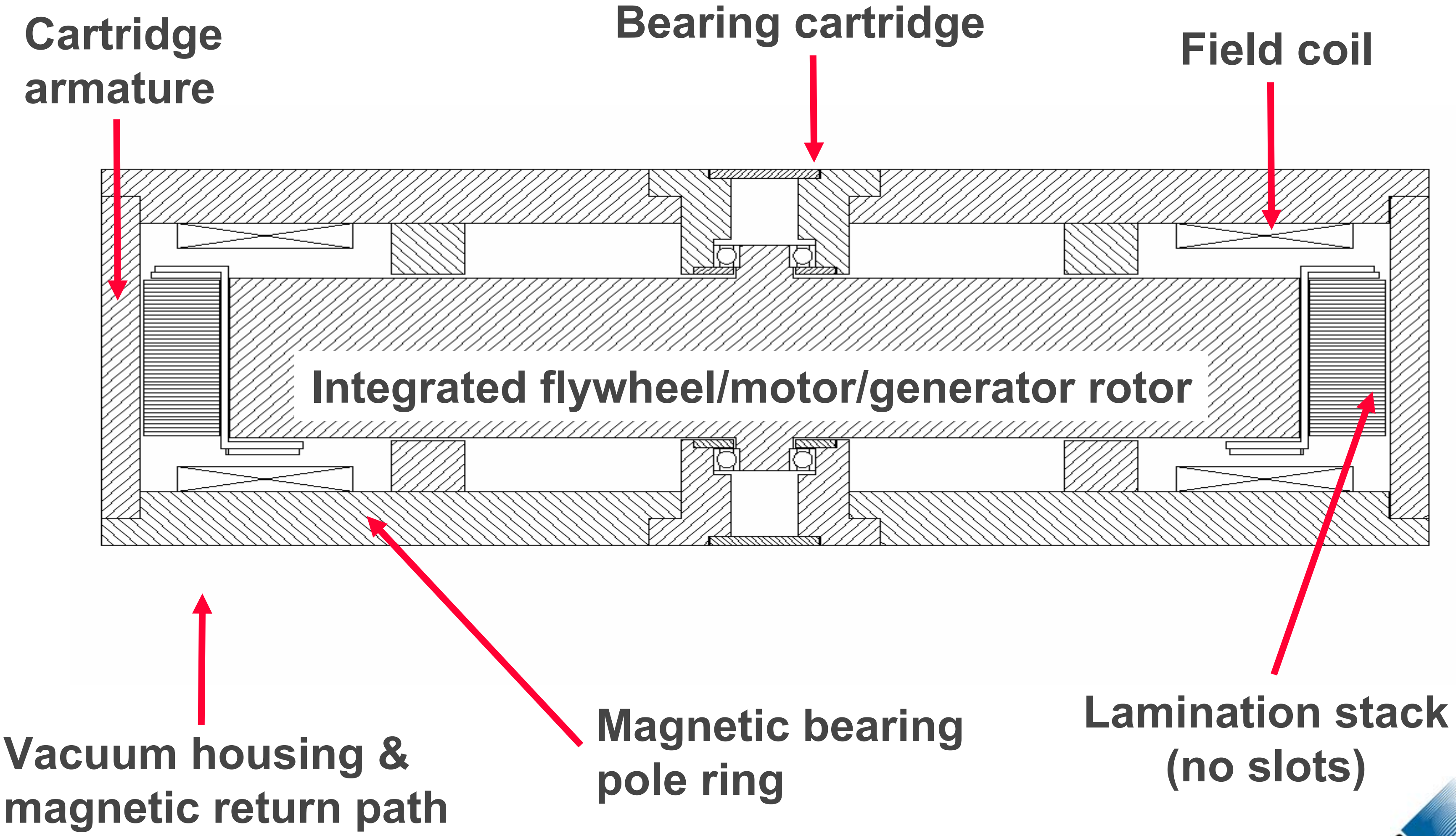
Smooth back-iron, no slots and low loss

Field coil

Flywheel, motor-generator rotor

No permanent magnets enables high tip-speed and high output power

Active Power 250kW Flywheel Cutaway View



Cartridge armature

Bearing cartridge

Field coil

Integrated flywheel/motor/generator rotor

Vacuum housing & magnetic return path

Magnetic bearing pole ring

Lamination stack (no slots)

Emerging Technologies: Electrochemical Capacitors

Electrochemical capacitors (EC), also known as supercapacitors, ultracapacitors, or electrical double-layer capacitors (EDLC), store energy in the electrical double layer at an electrode/electrolyte interface

Pros:

- High power density
- High cycle life
- Quick recharge

Cons:

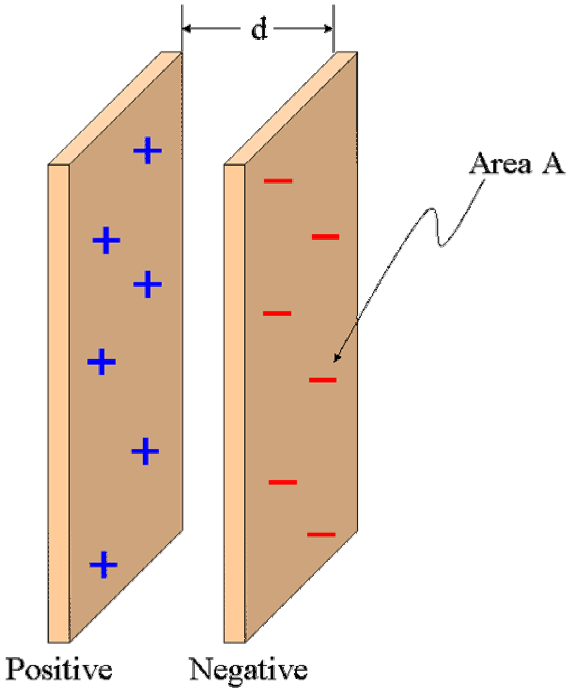
- Low energy density
- Expensive
- Sloped voltage curve requires power electronics

Capacitor Principles

Capacitors store energy through separation of electrical charge.

The energy stored in such a system is proportional to the area and the voltage squared, and inversely proportional to the distance of charge separation.

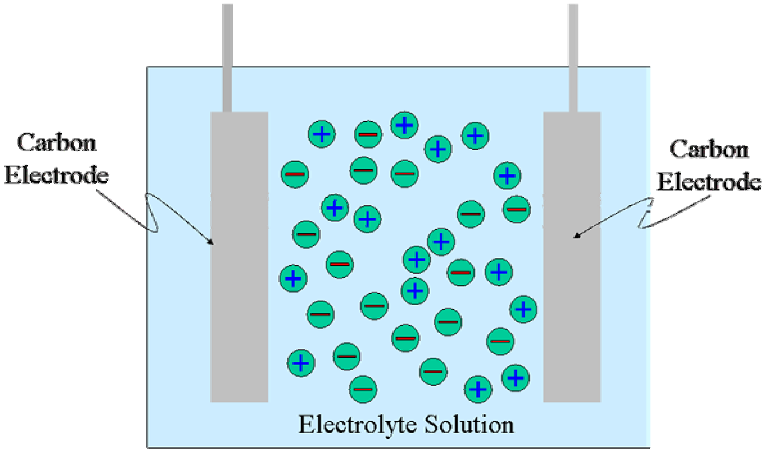
Electrochemical capacitors achieve very high capacitance and energy capacity through very high surface area and very small charge separation distance



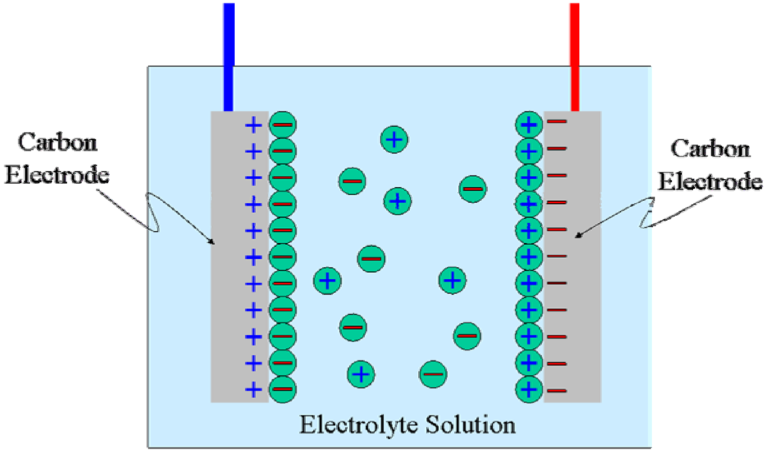
$$C = \frac{\varepsilon_0 A}{d}$$

$$E = \tfrac{1}{2} C V^2 = \frac{\varepsilon_0 A}{2d} C V^2$$

Electrochemical Capacitors



Discharged State



Charged State

A layer of charge within electrode is matched by a layer of ions that accumulate on the surface, forming a capacitor. This phenomenon is called the electrical double layer.

The separation between ions and electrode is on the order of angstroms (10^{-10} m), producing enormous capacitance.

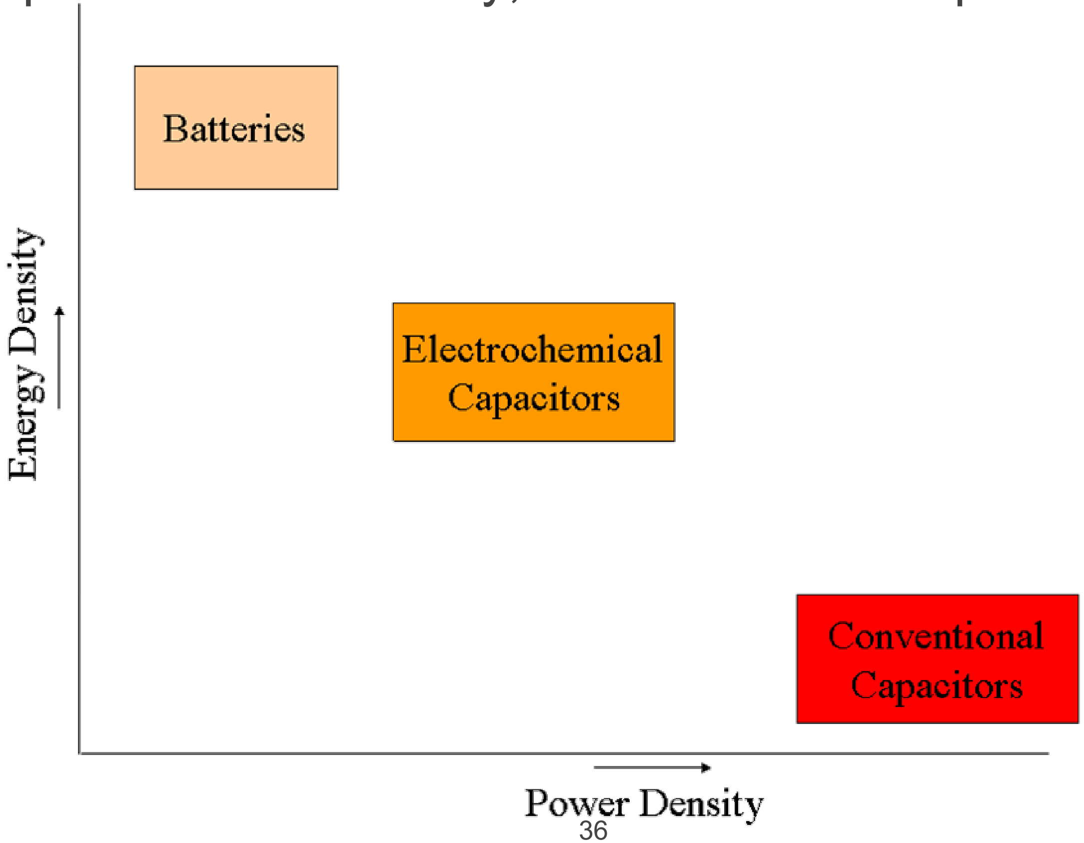
The electrodes are composed of a very high surface area material such as activated carbon (1000 to 2000 m^2/g), allowing a great deal of charge accumulation.

Parts of an Electrochemical Capacitor

- Electrodes
  - Electrodes are usually high-surface area carbons
  - Pseudocapacitive metal oxides or battery electrodes are sometimes used to provide higher capacity
- Electrolyte
  - Composed of a solvent and a salt
  - In aqueous systems, water is the solvent, and the salt is a high-conductivity electrolyte such as sulfuric acid or potassium hydroxide
  - In organic systems, there are two philosophies
    - A high-conductivity solvent such as acetonitrile is used where power performance is desired
    - A relatively poorly conductive solvent such as propylene carbonate is used where high cycle life and safety are important but power performance is not
    - In both cases, salts with large ions, such as tetraalkylammonium salts, are used to provide high energy density

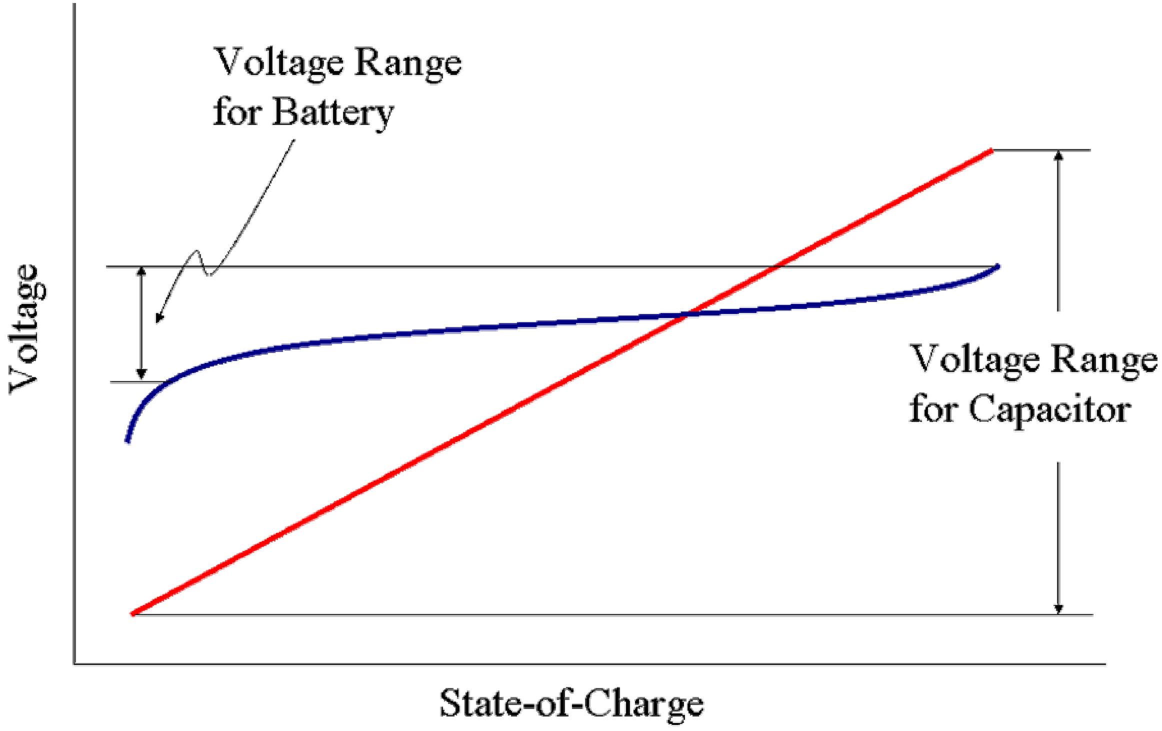
Energy and Power Density of Electrochemical Capacitors

- The energy and power densities of electrochemical capacitors fall between those of batteries and conventional capacitors
  - More energy than a capacitor, but less than a battery
  - More power than a battery, but less than a capacitor



Voltage Profile for Electrochemical Capacitors

- Electrochemical capacitors act like capacitors. Unlike batteries, the voltage varies linearly with the charge contained in the system
- The voltage range between full charge and end-of-charge is larger for ECs than for batteries. For this reason, ECs often require additional power electronics to ensure the output voltage is steady.

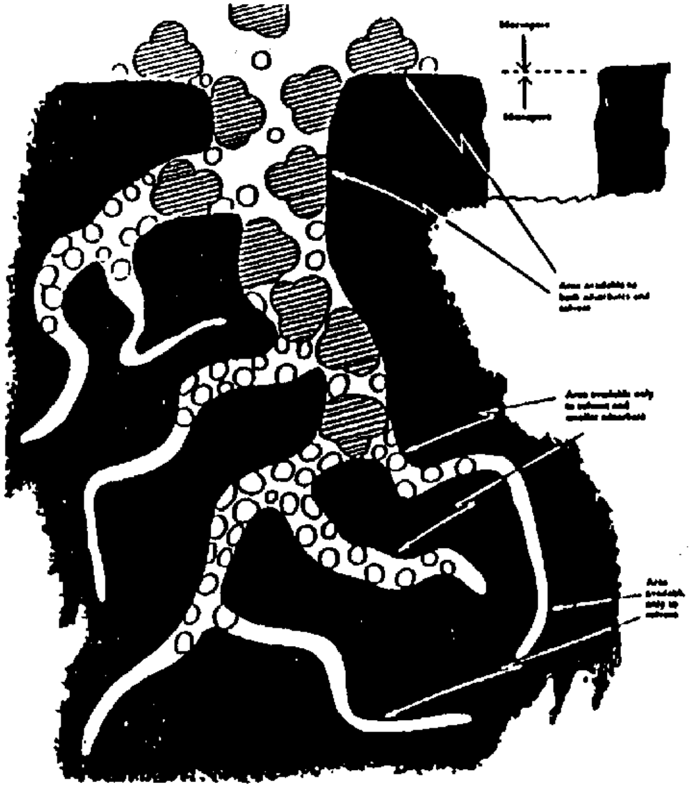


Energy Capacity Limitations of Electrochemical Capacitors

- Energy capacity of ECs is limited by surface area of electrode and number of ions in electrolyte
  - Surface area of electrode, while large, is limited
    - In theory, 1000 – 2000 m^2/g is not uncommon for high surface area carbons
    - In practice, only 30-40% of this is usable, because the remainder is in micropores too small to support electrical double layer
  - Ions in electrolyte can run out
    - In organic electrolyte systems, the solubility limit of the salt in the solvent often determines the peak capacity of the system.
    - This is rarely the limiting factor in aqueous electrolytes

Power Performance of Electrochemical Capacitors

- The electrostatic charge storage mechanism allows very high current densities
  - Unlike batteries, no chemical reactions, no rate-limiting steps
- The pulse power is limited by other factors, however
  - Tortuosity of electrode – high surface area is effected by the use of highly tortuous material, and ions cannot escape quickly
  - Internal resistance of electrolyte – some electrolytes slow down movement of ions, causing ohmic losses



Structure of a tortuous electrode

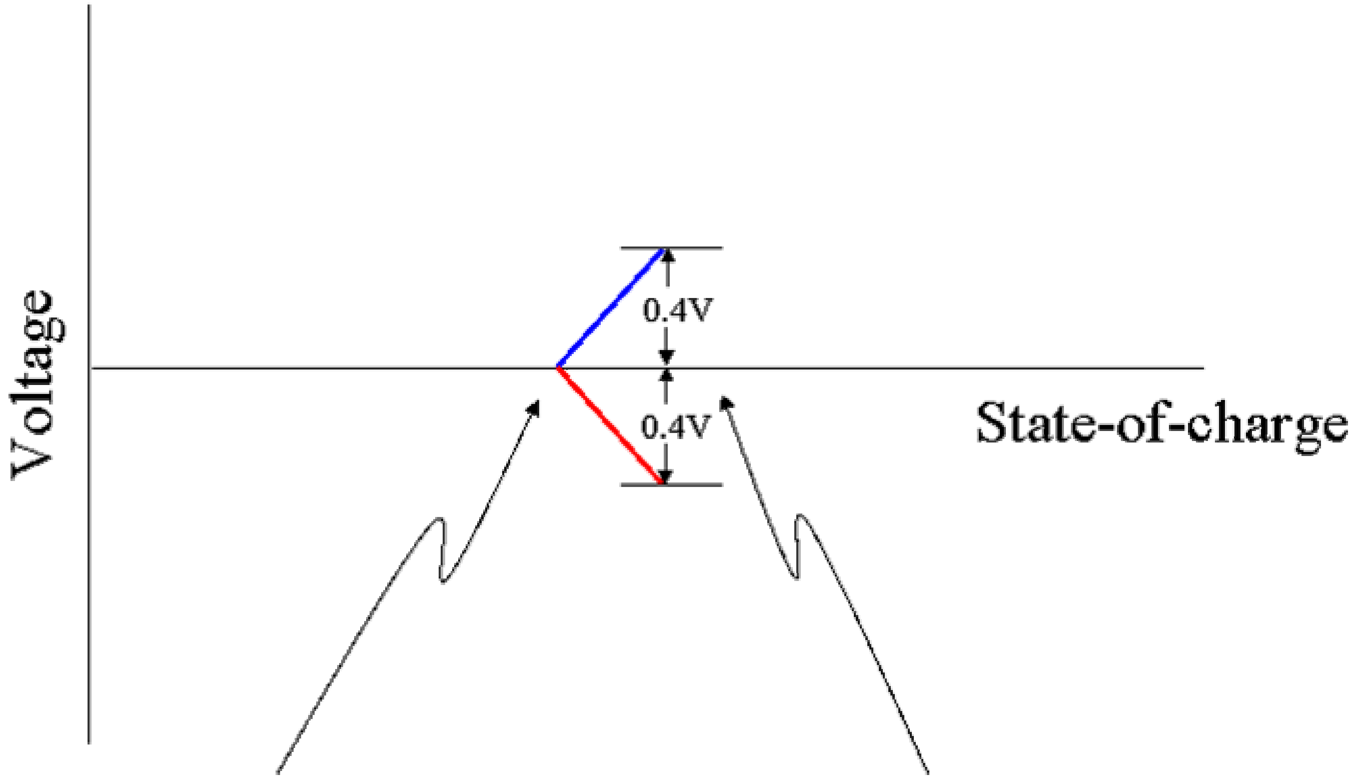
Types of Electrochemical Capacitors

- There are a number of different technologies that fall under the name “electrochemical capacitors”
  - *Symmetric ECs* use carbon for both electrodes. The charge mechanism is purely electrostatic: no charge moves across the electrode/electrolyte interface.
  - *Pseudocapacitors* use a metal oxide material for one of the electrodes. The charge mechanism is *faradaic*: charge moves across the electrode/electrolyte interface. The metal oxide electrode behaves like a capacitor, i.e. voltage varies linearly with charge.
  - *Asymmetric ECs* use a battery electrode for one of the electrodes. The battery electrode has a large capacity in comparison to the carbon electrode, so that its voltage does not change significantly with charge. This allows a higher overall cell voltage.
- Electrolyte may be aqueous or organic

Symmetric vs. Asymmetric: An example

- The symmetric capacitor on the next slide has two identical carbon electrodes
- In the asymmetric capacitor on the slide following the next, the positive electrode has been replaced with a battery electrode, while the negative electrode remains carbon
- Even though the capacitance is identical, the asymmetrical capacitor has more energy storage capacity since it operates between higher voltages

Symmetric Capacitor

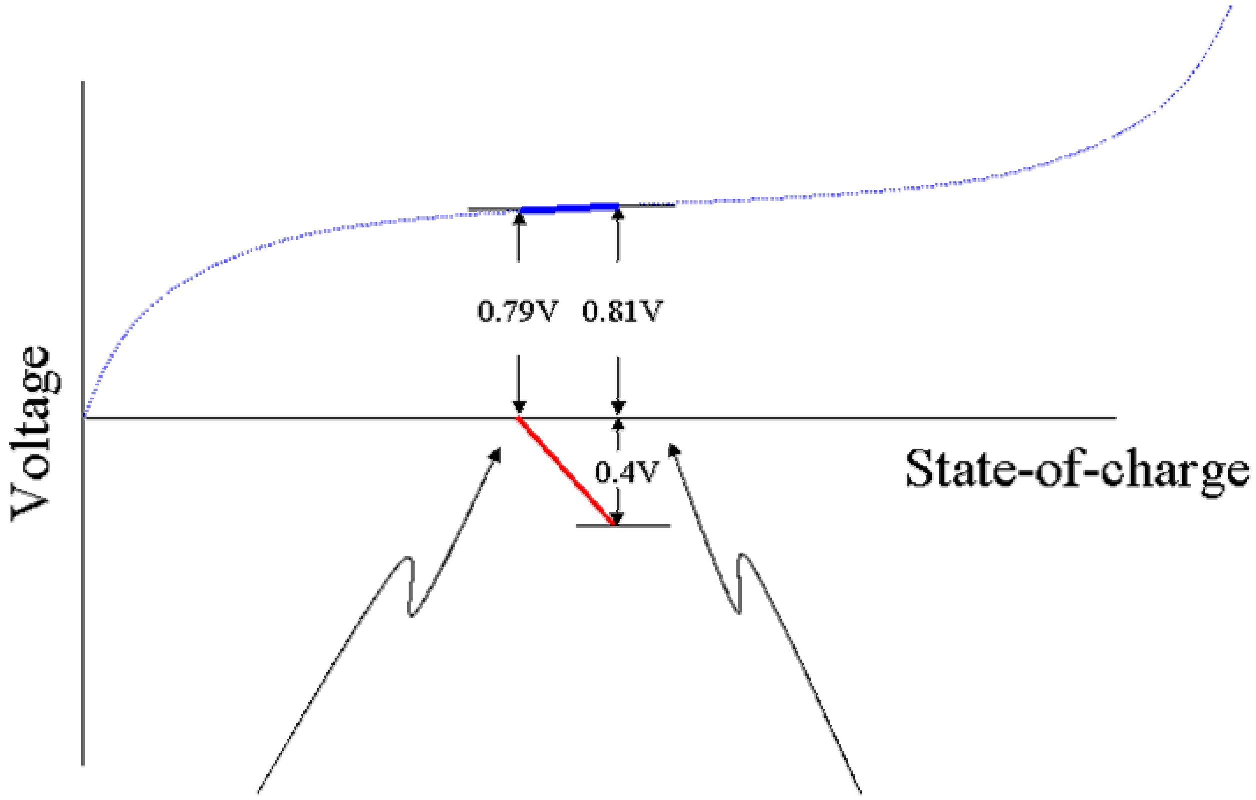


Fully discharged: V = 0 V

Fully charged: V = 0.8 V

$$E = \tfrac{1}{2}CV^2 = 0.32C$$

Asymmetric Capacitor



Fully discharged: V = 0.79 V

Fully charged: V = 1.21 V

$$E = \tfrac{1}{2}CV_2^{\,2} - \tfrac{1}{2}CV_1^{\,2} = 0.84C$$

Symmetric vs. Asymmetric (cont'd)

- In practice, asymmetric capacitors tend to be capable of higher capacitance than symmetric capacitors
  - The battery electrode is physically much smaller than the carbon electrode
  - This allows more space in the case for a carbon electrode
- Many symmetrical capacitors, however, allow a higher voltage than present asymmetrical capacitors
  - At present, most asymmetrical capacitors use aqueous electrolytes, which are limited by the gassing voltage of the water (between 1.3V and 1.7V per cell)
  - Symmetric capacitors using organic electrolytes can achieve much higher voltages (up to 2.7V per cell)
- There are few asymmetric capacitors using organic electrolytes, but this is a very active area of research

Advantages of Electrochemical Capacitors over Batteries

- ECs tend to have much longer cycle life than batteries
  - No chemical reactions translates to a stable electrode matrix and no wear-out
  - Cycle life greater than 100,000 cycles is achievable
- ECs have higher efficiency than most batteries
  - No chemical reactions translates to high coulombic efficiency
  - Few irreversible processes
  - Energy efficiencies of over 90% have been demonstrated

Electrochemical Capacitor Technology Status

- Currently viable for bridging power (seconds) in the hundreds of kW power range.
- Smaller (several kW) power range, long term energy storage (hours) application of electrochemical capacitors for residential peak shaving is another application that is currently under consideration.
- Use of ECs for multi-MW utility T&D applications that require several hours of energy storage (peak shaving, load leveling, etc.) is not feasible at present.

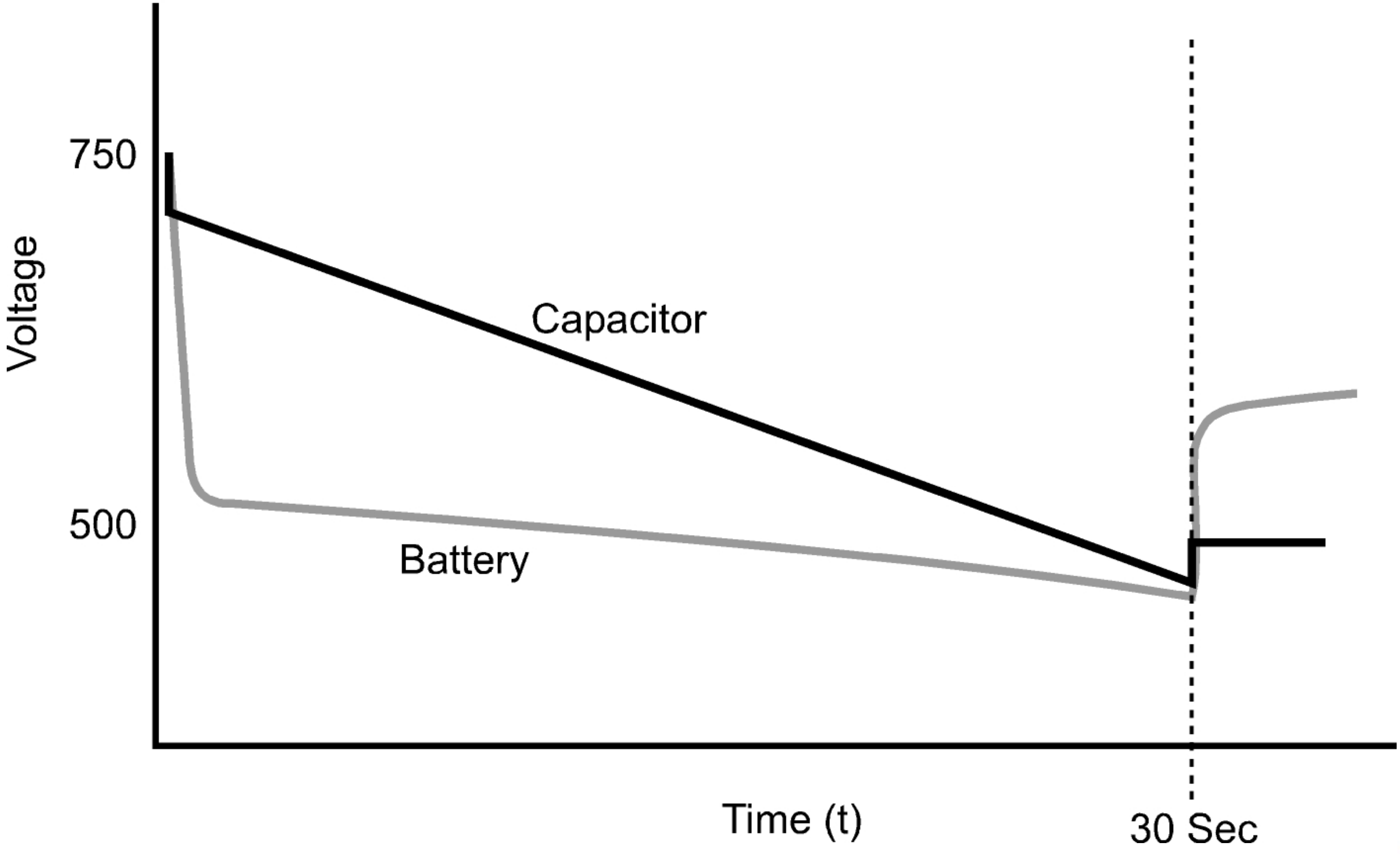
Electrochemical Capacitor Products

- ECOND (Russia) - 60F, 16V (Symmetric aqueous)
- ELIT (Russia) - 0.8 F, 310 V, 19 kg (Symmetric aqueous)
- EPCOS (Germany) - 5000F at 2.5V to 150F at 42 V (Symmetric organic)
- ESMA (Russia) - 1000F @ 14.5V module (Asymmetric aqueous)
- Maxwell Capacitor (USA) - 2700F, 2.5 V (Symmetric organic)
- NESS Capacitor (Korea) - 5000 F, 2.7 V (Symmetric organic)
- Nissan Diesel (Japan) - 35F, 346Vdc module (module) (Symmetric organic)
- Power Systems (Japan) - 65F, 54V module (Symmetric organic)
- Panasonic (Japan) - 2000 F, 2.3 V (Symmetric organic)
- SAFT (France) - 3200 F, 2.5 V (Symmetric organic)
- Shizuki Electric (Japan) - 75F, 54V module (Symmetric organic)

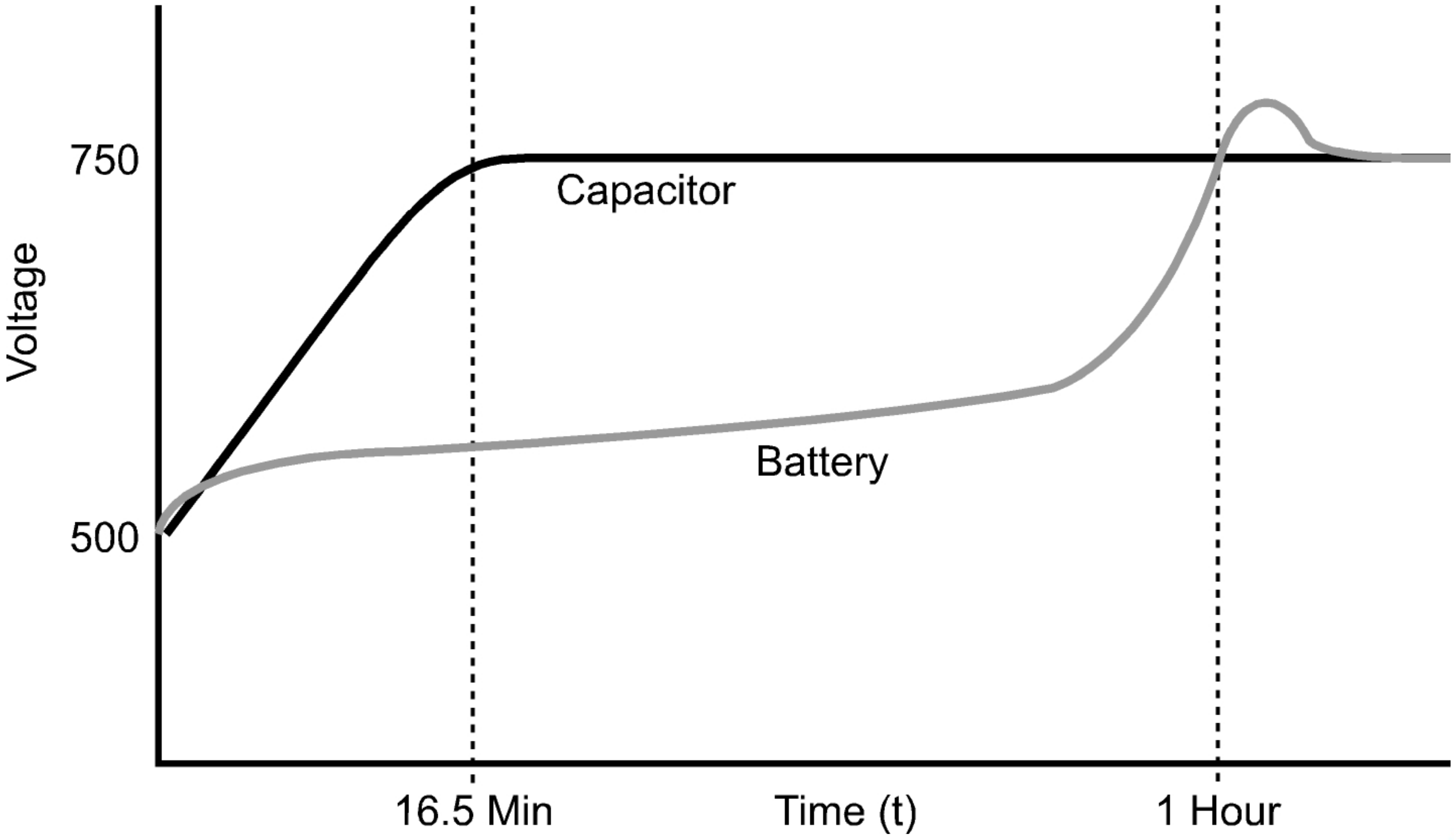
Comparison between Delco Battery and ESMA Electrochemical Capacitor

- 48, 12V Delco 1150 cranking type batteries at 576 V 30-sec at 250 kW
- 14, 42V ESMA 30EC402 electrochemical capacitor at 588V, 30-sec discharge at 250 kW

Discharge Characteristic of 1150 Battery and 30EC402 Capacitors in a high-discharge application



Recharge Characteristics with Auxiliary 8kW Charger



Emerging Technologies: Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in the magnetic field produced by current flowing through a superconducting coil.

Pros:

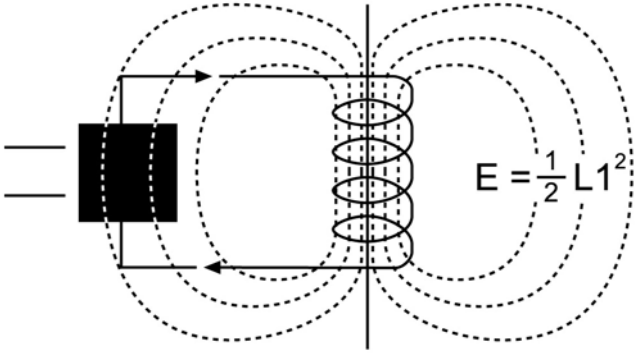
- High Power
- Quick recharge

Cons:

- Low energy density
- Large parasitic losses
- Expensive

Superconducting Magnetic Energy Storage (SMES)

- The SMES energy-storage principle is based on inductive energy storage in the magnetic field produced by current flowing through a superconducting coil.
- The DC current is converted to three-phase AC output using a solid-state power-conditioning system.
- The first experimental SMES device (10 MW / 30 MJ) was installed in 1979 on the Bonneville Power Administration system for transmission stabilization of the Pacific Intertie



SMES System Components

- A SMES system consists of four major subsystems, plus miscellaneous equipment for system control, data collection, and so on.
- The major subsystems are:
  - Conductor coil that carries the circulating current
  - Power electronics system that controls the flow of current into and out of the coil to charge and discharge the SMES
  - Cooling equipment that maintains the coil at a low enough temperature to maintain superconductivity
  - Physical structure that supports the coil against magnetic forces during SMES operation.

SMES Technology Status

- Currently viable for short-term power (seconds) in the 1-10 MW power range
- Proposed applications are in PQ and transmission support
- Several demonstration projects have shown the capability of the technology in these applications.
- High initial cost is the major obstacle for the technology

SMES Operational Experience

Industry Operational Dates	Customer/ Load / Location	SMES Unit	Power Supplied
March 1993 – Present	CYANCO / Ammonia Production Furnace / Winnemucca, NV	PQ DC	730 kVA, 1.0MJ
May 1995 – Present	Brookhaven National Laboratory / Accelerator / Upton, NY	PQ AC	1.4 MVA, 2.4MJ
May 1995 – Present	McClellan U.S. Air Force Base / Computer-Controlled Semiconductor Test Apparatus / Sacramento, CA	PQ AC	750 kVA, 2.4MJ
July 1996 – Present (Gray) June 1997 – Present (Blue)	Tinker U.S. Air Force Base / Computer Data Center / Tinker, OK	Dual PQ DC Dual PQ DC	4 of 2.4 MJ each
Oct. 1996 – Jan. 1998	ESKOM Utility / South Africa	PQ AC	1.4 MVA
April 1997 – Present	SAPPI – Stanger Paper Mill / Paper Machine / Stanger, South Africa	PQ VR	750 kVA, 2.4MJ
May 1997 – June 1999 April 1998 – June 1999	Amerimark, Owens Corning Plastics / Plastic Film Extruder / Fairbluff, NC	PQ AC PQ AC	750 kVA, 2.4MJ 1400 KVA, 4MJ
May 1999	STEWEAG Utility / Substation Equipment / Gliesdorf, Austria (Relocated from ESKOM)	PQ AC	1.4 MVA
June 1999	CP&L Solution Center / Demonstration Test Stand / North Carolina	PQ AC	1.4 MVA

Mature Technologies: Compressed Air Energy Storage (CAES)

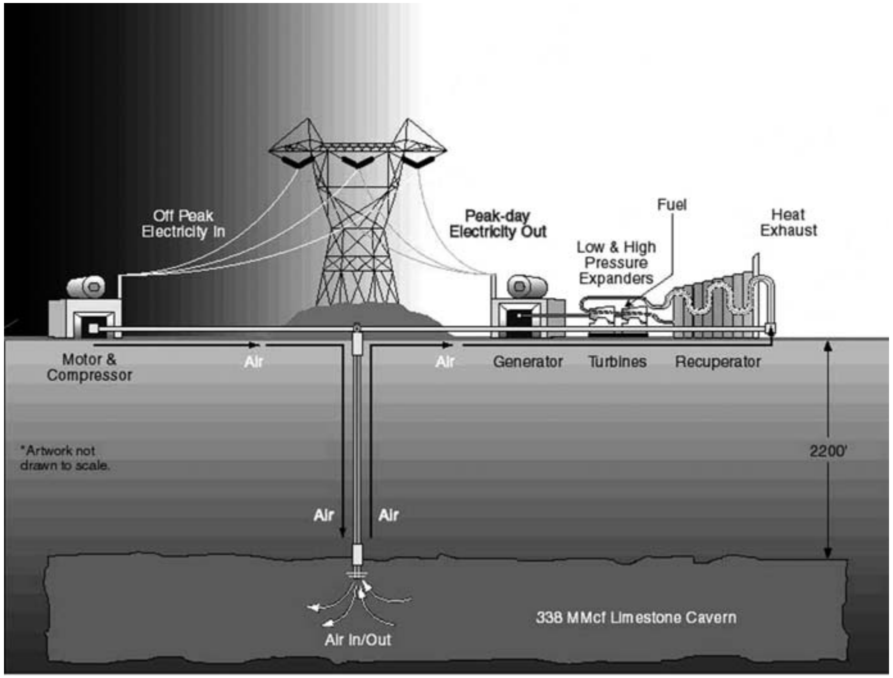
Air is compressed and stored in large underground spaces, and is later used in gas turbine generators

Pros:

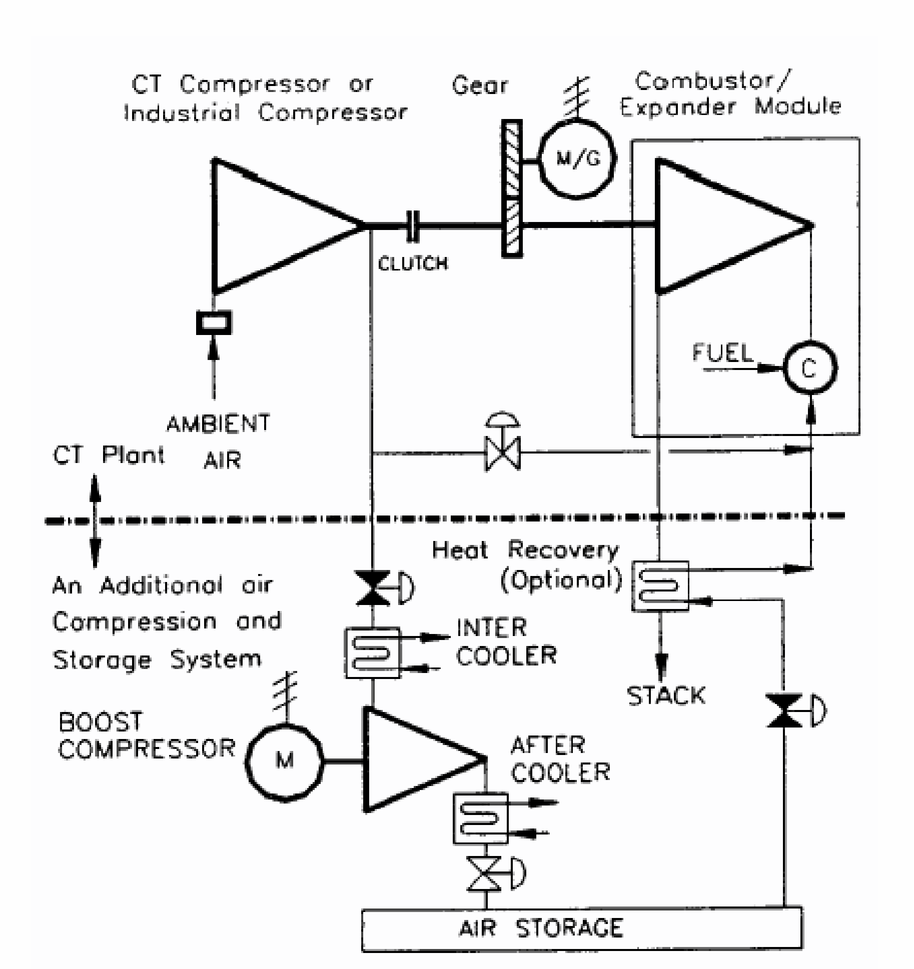
- Huge energy and power capacity

Cons:

- Requires special location
- Expensive to build and maintain
- Slow start – an unlikely candidate for distributed resources



Emerging Smaller Hybrid CAES Systems



- Smaller Hybrid Systems (<50 MW)
- Above Ground
- For small CAES systems it is possible to use the pipes used for conventional gas transmission as the energy storage medium.
- These pipes are typically 48” in diameter and operate at pressures up to 2500 psi, which is well over the maximum required for combustion turbines.
- Total Plant Cost $700-$750/kW

Mature Technologies:
Pumped Hydroelectric Storage

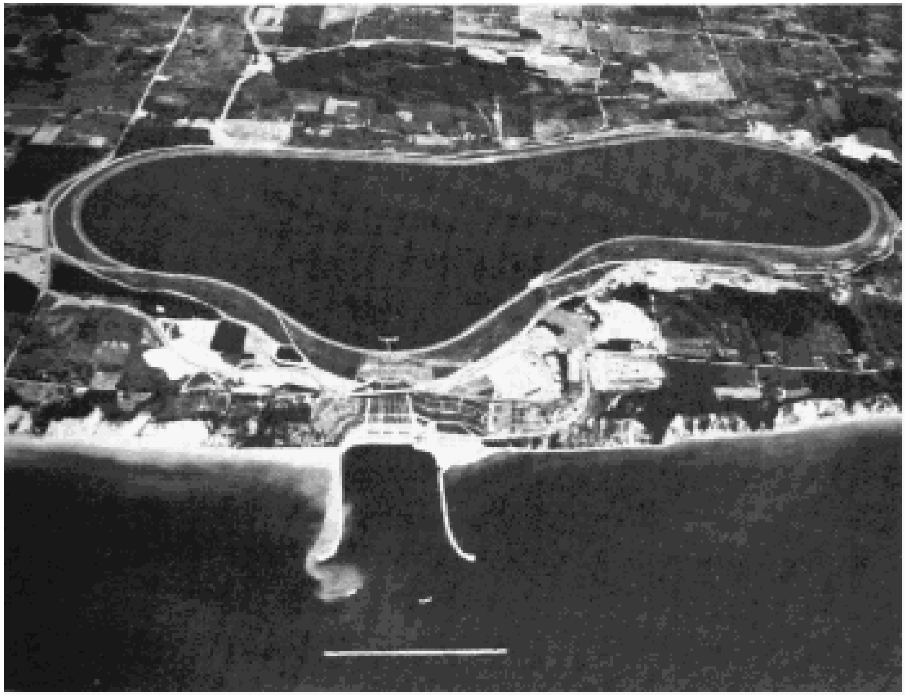
Water is pumped from low elevations to higher elevations to store energy as gravitational energy, and run down through hydroelectric turbines to generate electricity

Pros:

- Huge energy and power capacity

Cons:

- Requires special locations
- Expensive to build
- Not suitable for DER



The world's largest hydro-storage facility al Ludington, Michigan, uses Lake Michigan as the lower reservoir and an artificial lake 100 m higher as the upper reservoir. This plant can deliver 2000 MW at full power and can store 15,000 MWh of energy

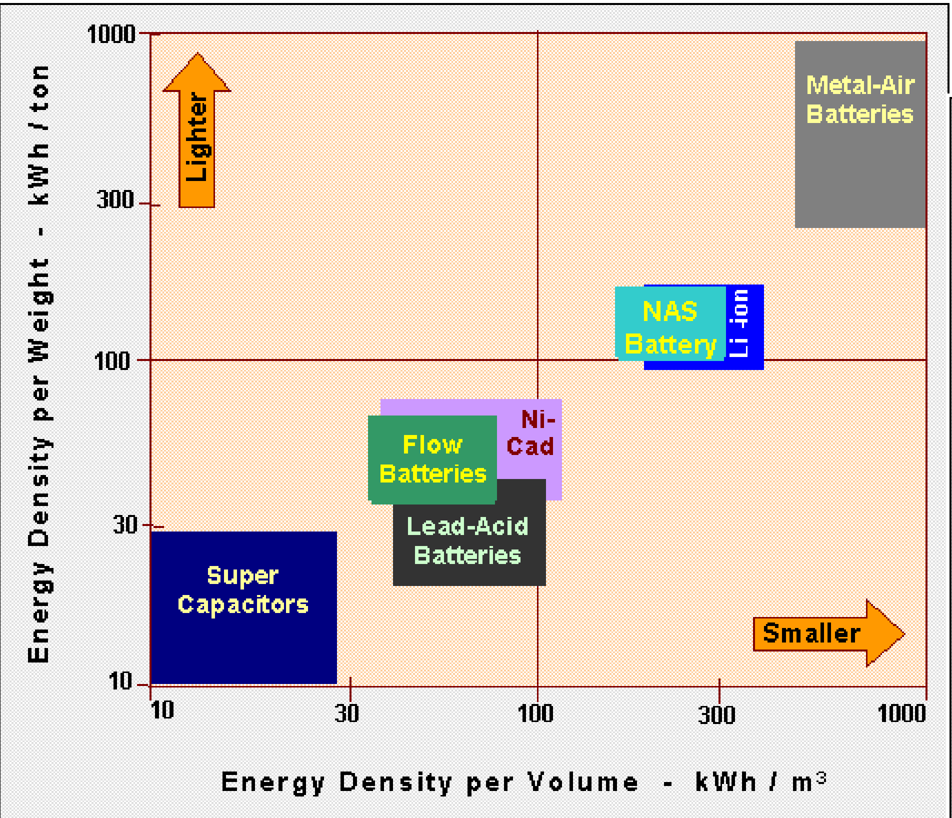
Energy Storage Technologies for Use in Distributed Energy Resource Applications

Storage Technology	**Available kW range for the storage technology**	**Suitability for 2 second to 2 minute Applications**	**Additional Power Conversion Necessary?**	**Replace-ments in 20- year lifespan**	**Comments**
Lead Acid Batteries	1kW to 2000kW	Full Range	No	4-6	Trade off on duration is lifecycle vs depth of discharge (i.e. shorter duration = longer life)
Nickel Chemistry Batteries	1kW to 2000kW	Full Range	No	1-2	More expensive than lead-acid, with improved cycle life
Lithium Ion Batteries	1 kW to 10 kW	Full Range	No	1-2	Not yet available in size range applicable to DER
Sodium Sulfur Batteries	100kW to 1000kW	Full Range	No	Unknown	Most applications are for longer duration energy storage; not thought to be cost-effective for storage with DER
Flow Batteries	1000kW to 5000kW	Not used for this Window	No	Unknown	Applications are for longer term energy storage

Energy Storage Technologies for Use in Distributed Energy Resource Applications, cont.

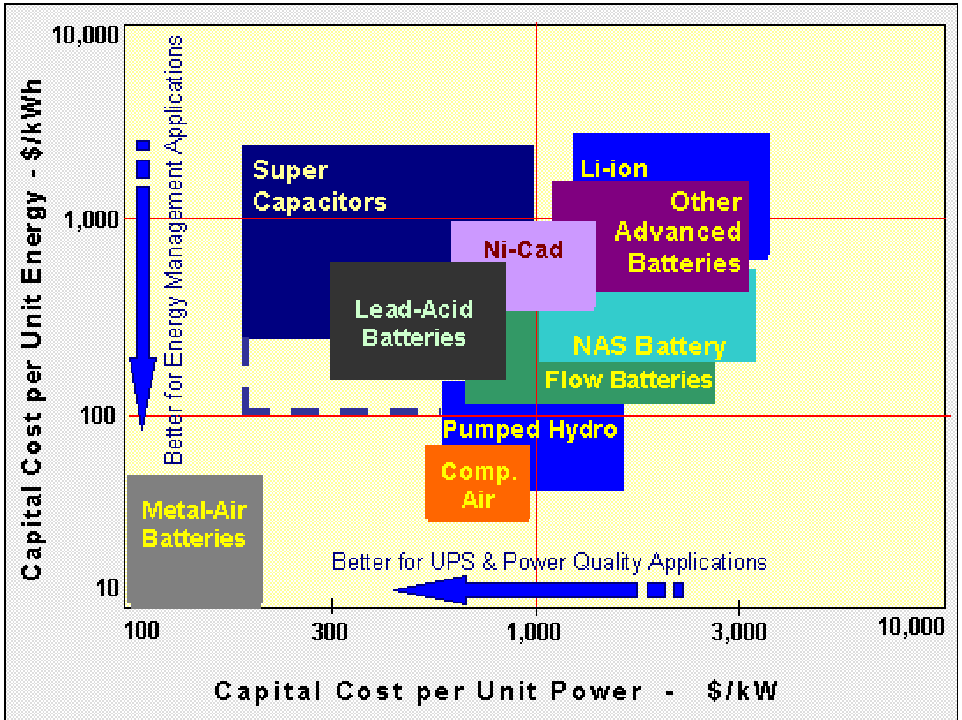
Storage Technology	Available kW range for the storage technology	Suitability for 2 second to 2 minute Applications	Additional Power Conversion Necessary?	Replace-ments in 20- year lifespan	Comments
Low Speed Flywheel	100kW to 2000kW	Full Range	Yes	Maintenance Only	Mature technology with proven performance history
High Speed Flywheel	1kW to 250kW	30 sec max	Yes	Maintenance Only	This technology is most suitable to short duration
Electrochemical Ultracapacitor	2kW to 250kW	2- 30 sec max	Yes	Unknown	In theory, has a very long cycle life. Technology is relatively new and unproven
Electrolytic Capacitors	1kW to 250kW	2 sec max	Yes	None	Most electrolytic ride through applications are rated for less than 1 second due to high cost

Technology Comparison



Notes:

The above energy densities are based on input energy. The output energy densities depend on the charge / discharge efficiency that varies from 75% for most flow batteries to almost 100% for supercapacitors and most advanced batteries.



Notes:

1) The costs of most energy storage technologies are changing as they evolve. The cost ranges in this chart include approximate values in mid-2001 and the expected mature values in a few years.

2) Life cycle cost is a more meaningful index than just the capital cost but the life of a battery strongly depends on the application and, therefore, the life and life cycle cost need to be evaluated for each case.

Courtesy: Energy Storage Association (ESA)