


Energy Storage


Larry Caretto
Mechanical Engineering 496ALT
Alternative Energy

February 12, 2009



Outline


- Review last week
- Why do we store energy?
- What kind of energy is stored?
- Fuels as energy storage
- Batteries
- Thermal energy storage
- Electrical energy storage
- Mechanical energy storage



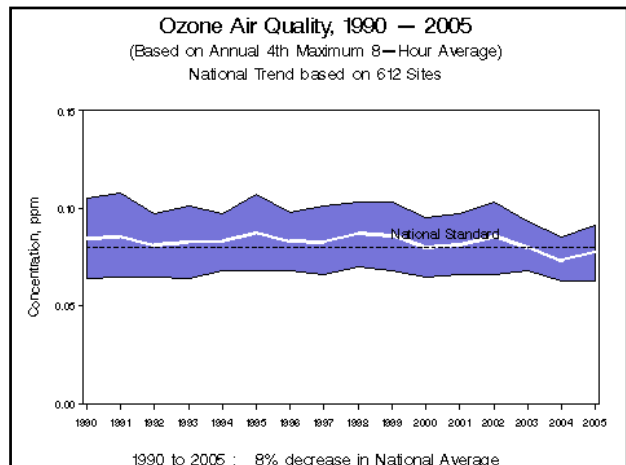
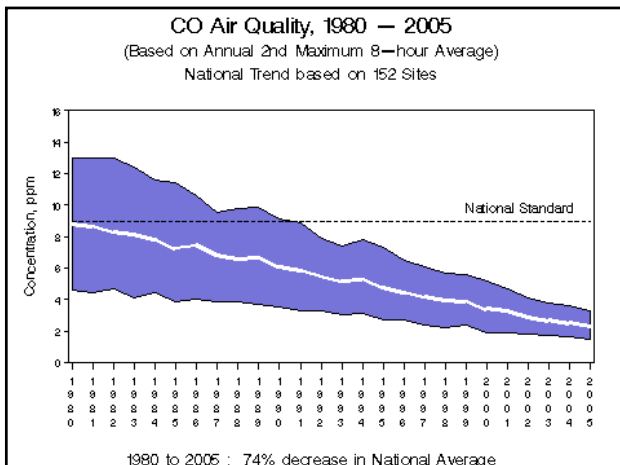
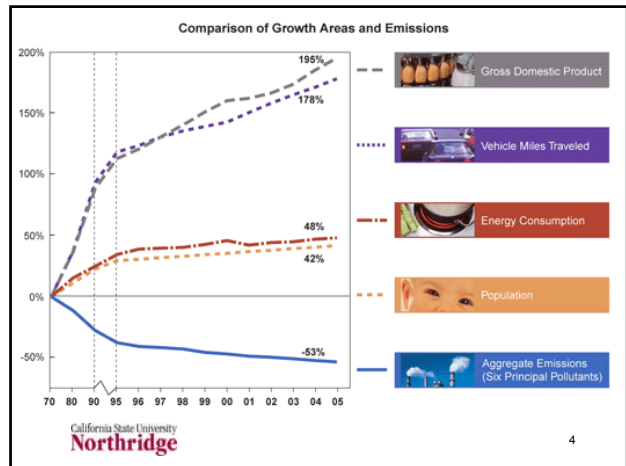
2

Air Pollution

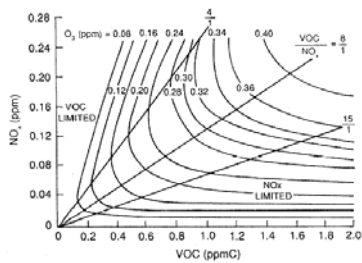
- Clean Air Act requirements
 - National ambient air quality standards for criteria pollutants
 - States must submit plans (state implementation plans or SIPs) to achieve standards by date
 - Toxic pollutants by separate process
 - Acid rain program by 1990 CAA amendment
 - Mobile vs stationary sources
 - Permitting requirements
 - Fossil fuel combustion biggest source



3



Ozone Production



California State University
Northridge

7

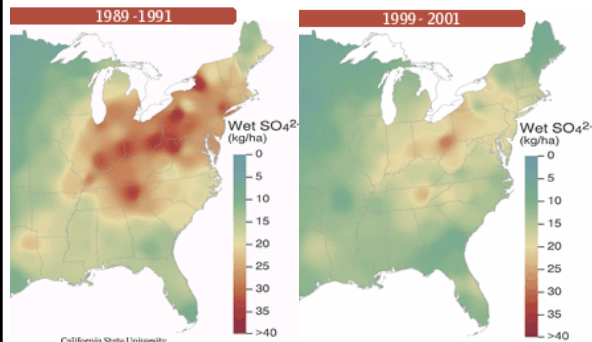
Cap-and-Trade Programs

- Emission requirements set for all sources in an area
- Sources have three options
 - Comply with emission limits
 - Produce excess emissions and buy credits from others who generate credits
 - Reduce emissions beyond requirements to generate credits for sale
- Alternative to “command and control”

California State University
Northridge

8

Acid Deposition Results



California State University
Northridge

9

Ozone Layer and Greenhouse

- Stratospheric ozone reduces UV radiation reaching planet's surface
- Chlorofluorocarbons (CFCs) reach stratosphere and destroy ozone
- Natural balance between solar radiation reaching earth and IR radiation leaving
- Balance upset by human activities producing “greenhouse gases”, especially CO₂ from fossil fuel combustion

California State University
Northridge

10

IPCC 2007 reports

- Intergovernmental Panel on Climate Change under United Nations
 - Regular assessment reports (latest 2007)
 - Reports have three separate reports and synthesis report
 - Physical Science Basis, Impacts, Adaptation and Vulnerability, and Mitigation of Climate Change
 - 2007 report has strongest conclusions about effects and human contribution

California State University
Northridge

11

Greenhouse Gases

- CO₂ accounts for 86% of all GHG
- To reduce CO₂ emissions seek carbon free fuels, alternative energy sources such as solar or wind
 - Energy conservation also helps
- Carbon capture and sequestration (CCS) removes CO₂ from exhaust and stores underground
 - R&D required to reduce costs

California State University
Northridge

12

Why do we store energy?

- To be able to respond to changes in demand in a more efficient manner
 - Electricity use fluctuates over seasons and hours of the day
 - Natural gas use fluctuates over seasons
- Most transportation (land, sea, air) needs to carry onboard energy supplies
- Solar and wind use energy storage to balance generation with use

What kinds of energy stored?

- Fuel containers store fuel energy
- Batteries and supercapacitors store electrical energy
- Flywheels and compressed air systems store mechanical energy
- Thermal energy storage as latent or sensible heat used in heating and cooling systems

Energy Storage Measures

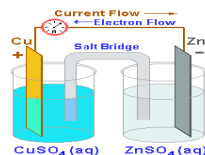
- Energy per unit mass (kJ/kg; Btu/lb_m)
- Energy per unit volume (kJ/m³; Btu/ft³)
- Rate of delivery of energy to and from storage (kW/kg; Btu/hr·lb_m)
- Efficiency (energy out/energy in)
- Life cycles – how many times can the storage device be used
 - Particularly important for batteries

Fuel Energy

- Volumetric energy storage in Btu/gallon
 - Gasoline: 109,000 to 125,000
 - Diesel fuel: 128,000 to 130,000
 - Biodiesel: 117,000 to 120,000
 - Natural gas: 33,000 to 38,000 at 3,000 psi, 38,000 to 44,000 at 3,600 psi, and ~73,500 as liquefied natural gas (LNG)
 - 85% ethanol in gasoline: ~80,000
 - 85% methanol in gasoline: 56,000 to 66,000
 - Hydrogen: ~6,500 at 3,000 psi, ~16,000 at 10,000 psi, and ~30,500 as liquid
 - Liquefied petroleum gas (LPG): ~84,000

Battery Basics

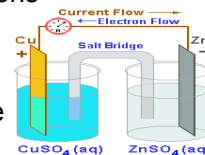
- Zinc/copper cell
- At cathode (left)
 - $\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}$
 - Cu^{2+} ions from CuSO_4 in solution
 - electrons from circuit
- Salt bridge transfers SO_4^{2-} ions
- At anode (right)
 - $\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}^-$
 - Zn^{2+} ions into ZnSO_4 in solution
 - electrons into circuit



Battery Terms

Reduction at cathode: positive pole, accepts circuit electrons
 Oxidation at anode: negative pole, supplies circuit electrons

Copper deposits on cathode



Zinc goes into solution at anode

Higher electrode potential

Salt bridge completes circuit in solution

Lower electrode potential

Battery Terms II

- Cell voltage based on standard reduction potentials (gain of electrons)
- When two half-cells are joined the reaction with the smaller reduction potential is run in reverse
 - $\text{Cu}^{++} + 2\text{e}^- \rightarrow \text{Cu}$ (0.34 v)
 - $\text{Zn}^{++} + 2\text{e}^- \rightarrow \text{Zn}$ (-0.76 v)
 - Zinc reaction is reversed
 - Potential difference is 1.10 v

California State University
Northridge

19

Nernst Equation

- Cell potentials are based on a standard concentration (1 gram mole per liter), pressure (1 atm) and temperature (25°C)
- Call this potential ΔE^0
- Actual potential ΔE

$$\Delta E = \Delta E^0 - \frac{RT}{nF} \ln Q$$
 - $R = 8.414 \text{ J/gmmol}\cdot\text{K}$, $T = \text{temperature in K}$
 - $F = 96485.3415 \text{ A}\cdot\text{s/gmmol}$ (Faraday const)
 - $n = \text{electrons in reaction}$
 - Q depends on concentrations

California State University
Northridge

20

Battery Types

- **Nickel Cadmium** mature, relatively low energy density, long life, lower cost, and high discharge rate
- **Nickel-Metal Hydride**: higher energy density than NiCd but lower cycle life
- **Lead Acid**: most economical where weight is not important
- **Lithium Ion**: high energy density and light weight
- **Lithium Ion Polymer**: Li-ion in smaller packaging

California State University
Northridge

21

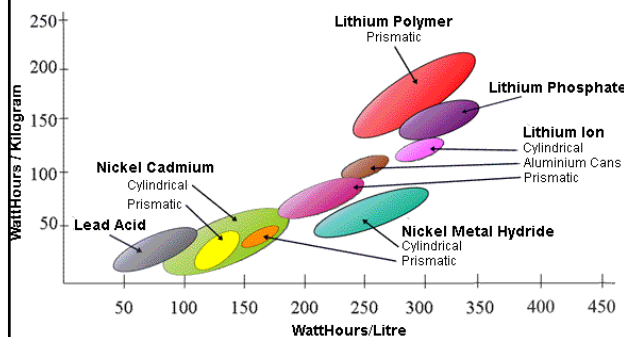
Solar System Batteries

- Optional – home systems can sell excess power to utility
- Can provide power during evening hours for systems not linked to grid
- Also provide back-up power in cases of blackout
- Lead-acid batteries uses because of low cost

California State University
Northridge

22

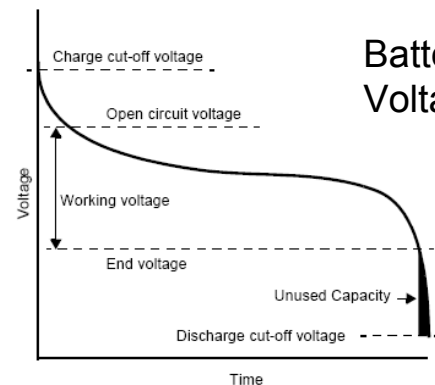
Battery Properties



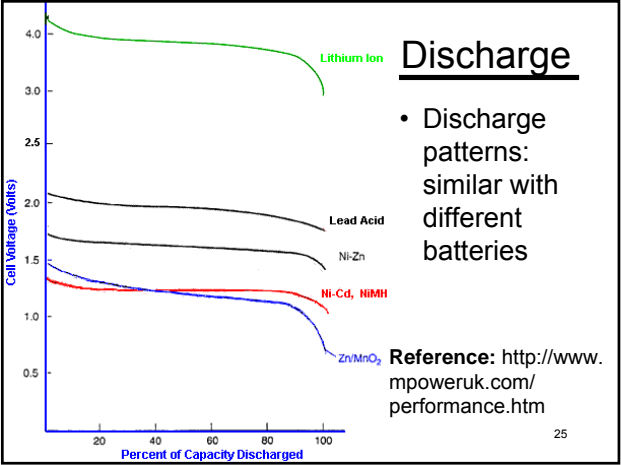
California State University
Northridge

<http://www.mpoweruk.com/chemistries.htm> ²³

Battery Voltages



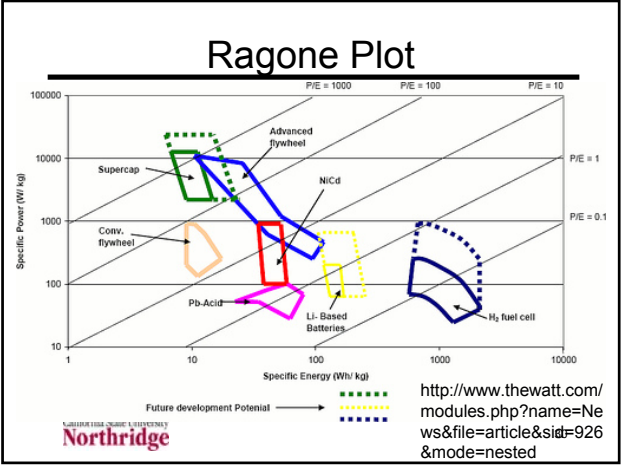
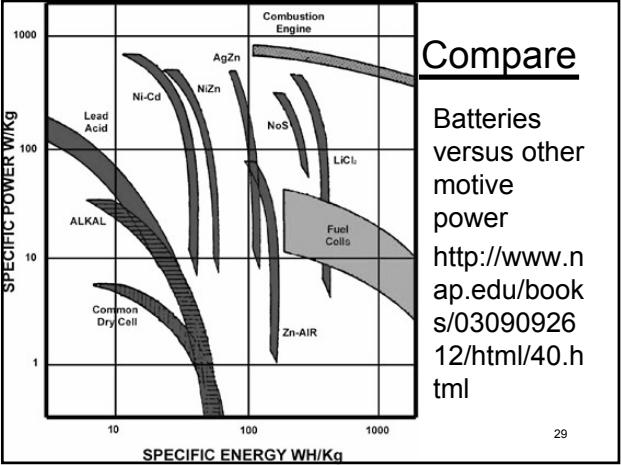
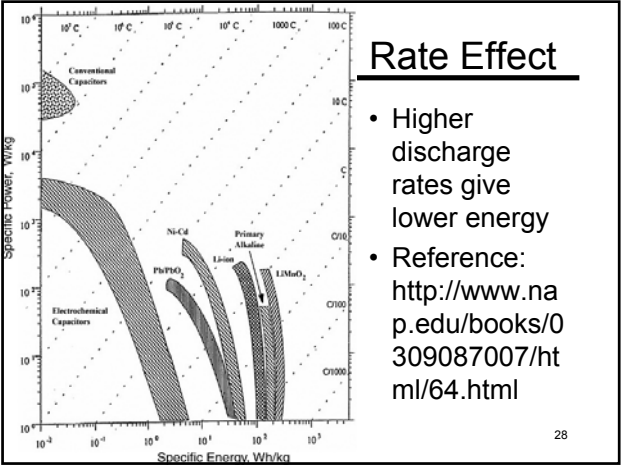
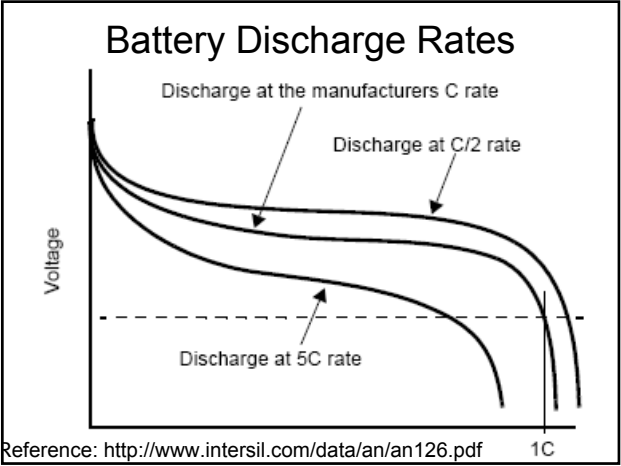
Reference: <http://www.intersil.com/data/an/an126.pdf>



Battery Discharge Rates

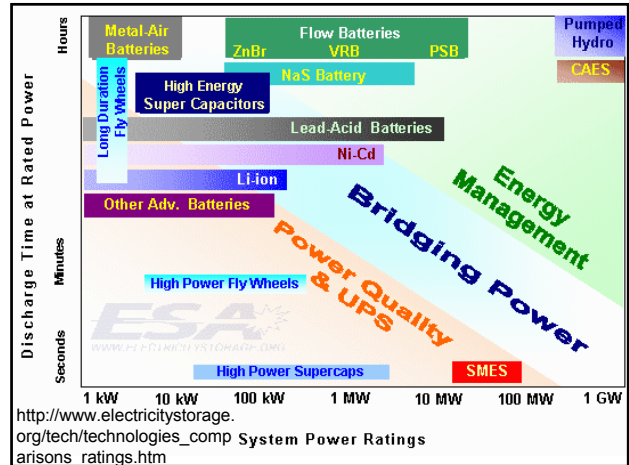
- Manufacturer rates battery to have certain energy at specified discharge rate known as the “C rate”
- Discharge at higher rates (e.g. 1.5C, 2C, 10C, etc.) reduced capacity
- Discharge at lower rates (e.g., C/1.5, C/2, C/10) increases capacity
- Similar effect for charging battery

California State University Northridge



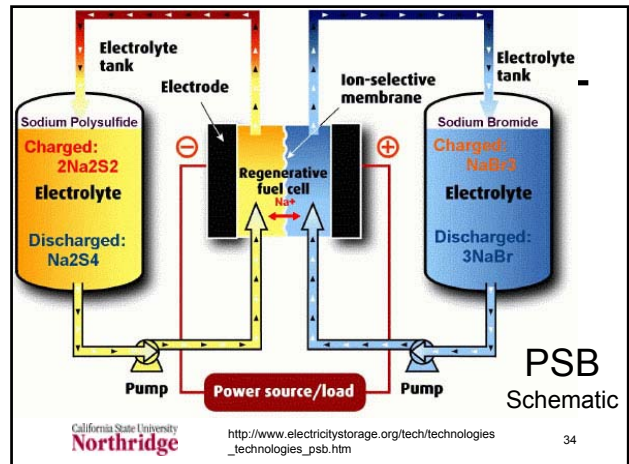
Utility Storage Applications

- **Power Quality:** applied for seconds or less, as needed, to assure continuity of quality power.
- **Bridging Power:** seconds to minutes to assure continuity of service when switching from one source to another.
- **Energy Management:** decouple the timing of generation and consumption of electric energy



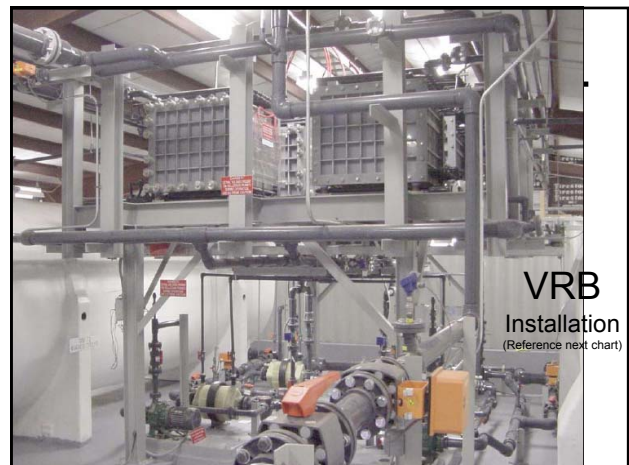
Flow Batteries

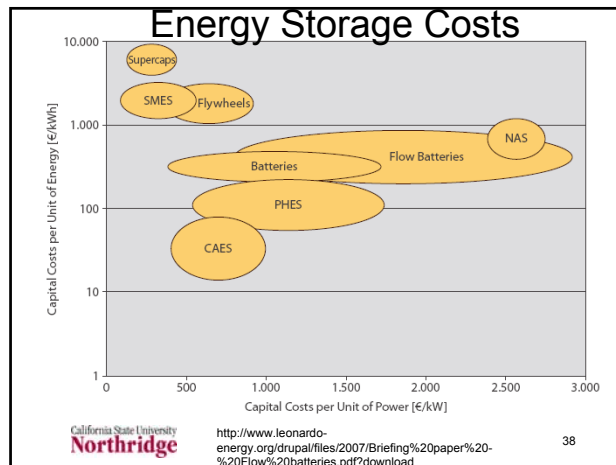
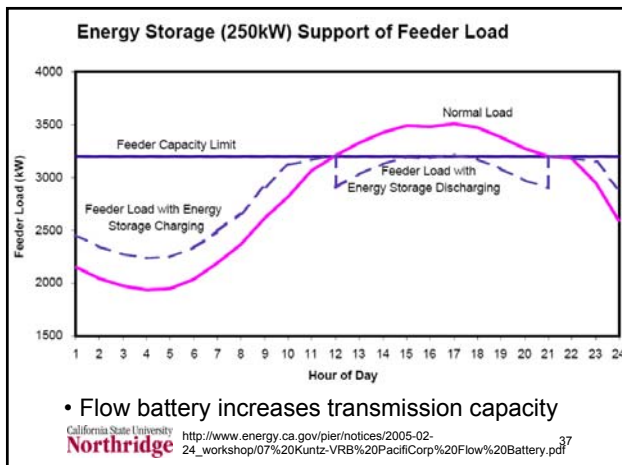
- Charge and discharge electrolyte placed in storage tanks
 - Polysulfide Bromide battery (PSB)
 - Vanadium Redox battery (VRB)
 - Zinc bromide
- Decouples energy capacity (due to storage tank size) and power (due to cell size)
- Sometimes described as fuel cells



PSB Battery Reactions

- Charging reactions
 - $\text{Na}_2\text{S}_4 + 2e^- + 2\text{Na}^+ \rightarrow 2\text{Na}_2\text{S}_2$
 - $3\text{NaBr} \rightarrow 2e^- + 2\text{Na}^+ + \text{NaBr}_3$
- Discharge reactions
 - $2\text{Na}_2\text{S}_2 \rightarrow \text{Na}_2\text{S}_4 + 2e^- + 2\text{Na}^+$
 - $\text{NaBr}_3 + 2e^- + 2\text{Na}^+ \rightarrow 3\text{NaBr}$
- External power charges electrolyte so that tanks contain Na₂S₂ and NaBr₃
- Charged electrolytes power flow





Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PFB, VRB, ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	●	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	●
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	●

Store

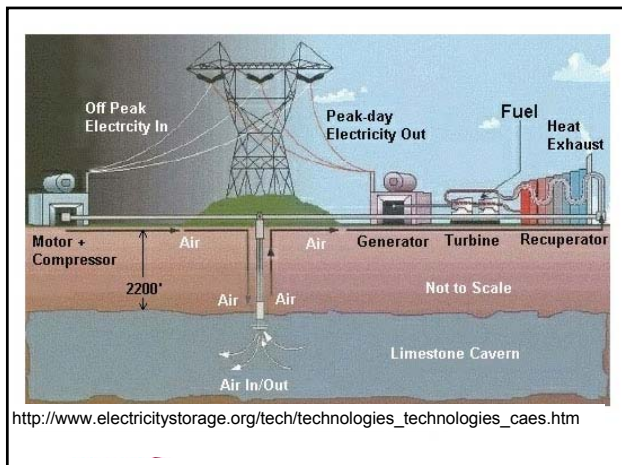
- Symbols
- fully capable
- reasonable
- feasible, but not quite...
- not feasible

• http://www.electrictystorage.org/tech/technologies_comparisons.htm

Compressed Air

- CAES: Compressed air energy storage
- Gas turbine with compressed air stored in caverns; later combustion/expansion
- Electricity peak shaving
 - 290 MW, Hundorf, Germany, 1978
 - 110 MW, McIntosh, AL, 1991
 - \$591/kWh; comes online in 14 mins
 - 2700 MW (planned) Norton, OH
 - 1500 psi air pressure, 2200 ft underground

California State University Northridge http://www.electrictystorage.org/tech/technologies_caes.htm



Pumped Hydro

- Used by power companies to provide peak energy
- Pump water uphill during off-peak hours
- Use potential energy to generate power during peak periods
 - Same equipment used for pumping and generation
 - Efficiency range is 70% to 85%
 - 1566 MW in Castaic

California State University Northridge

Flywheels

- Store kinetic energy
 - Exchanged with motor-generator set
 - $E = I\omega^2/2$ $I = kmR^2$
 - $k = 1/2$ for solid disk uniform thickness
 - $k = 1$ for wheel loaded at rim (bicycle tire)
 - Centrifugal force = $mR\omega^2$ can tear flywheel apart so materials that are less dense are better
 - Carbon fiber disks, loaded at rims, are state of the art

Flywheels II

- Efficiency is about 80% for energy out divided by energy in
- Can store energy for up to six months
- Demonstration systems for power quality by Beacon in NY and CA
- Safety is a concern for use on cars
 - Large weight of containment vessels reduces flywheel advantage of light weight

Pentadyne Power

- Company in Chatsworth makes flywheel energy storage products
 - Used for uninterruptible power supply
 - 63 cm x 83 cm x 180 cm
 - 590 kg weight
 - Can link units
 - > 99.8% efficiency
 - Sizes from 65 to 1000 kVA



Supercapacitors

- Alternative material structures to conventional capacitors using
- Provides similar function: $CE = Q$
 - $Q =$ charge, $C =$ Capacitance, $E =$ voltage
 - Materials provide larger capacitance
- Capable of rapid charging/discharge
- Do not store energy for long times
- Extremely large cycle life

SMES

- Superconducting magnetic energy storage
- Store energy in magnetic field
- High power output for a short period of time (similar to supercapacitors)
- Requirement for extremely low temperatures to maintain superconductivity
- Used in some utility applications

Thermal Energy Storage

- Used to shift energy use from peak
 - Especially used to reduce air conditioning loads during summer
 - Run air conditioning compressors during off peak hours to provide cold temperature energy storage in ice or eutectic salts
 - Use stored energy during peak hours to provide cooling without any electrical compressor input