Energy Storage

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Mechanical Engineering 483
Alternative Energy Engineering II

February 10, 2009

Outline

- Types of energy storage and measures
- Operation of electric power plants with limited ability to store electrical energy
- Battery operation and limits
- Energy *versus* power metrics for energy storage
- Other systems: flywheels, compressed air, supercapacitator, pumped hydro

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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

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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

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Energy Storage Measures

- Energy per unit mass (kJ/kg; Btu/lb$_m$)
- Energy per unit volume (kJ/m^3; Btu/ft^3)
- 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

http://www.eere.energy.gov/afdc/altfuel/fuel_comp.html

Electric Plants

- Base load plants run continuously
  - Produce load that is required 24/7
  - Most efficient plants
- Peak load plants
  - Used to satisfy demand peaks
  - Often gas turbines that are less efficient
  - Hydroelectric plants run as peak plants because of limited resource
- Distributed Generation – large users generate their own power

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Electricity Load

- Power demand varies by day and hour
  - CA energy, peak MW growth: 1.25%, 1.35%
- Renewable Portfolio Standards require utilities to have renewable generation
  - 20% of retail sales by December 31, 2010 in California (transmission problems?)
  - Papers from WCS AWMA October 2007 conference in next five slides
    - CA Energy Commission – Dave Ashuckian
    - SC Edison – James Woodruff

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LADWP Electricity Rates

- Residential normal meter: $0.07288/kWh
- Residential time-of-service meter
  - Monday–Friday, 1–5 pm: $0.14377/kWh
  - Monday–Friday, 10 am–1 pm: $0.08793/kWh
  - All other times: $0.03780/kWh
- Other services have demand charge (per kW) but lower service charge
  - High season (June to October) extra
  - Also have different rates for interruptible or non-interruptible

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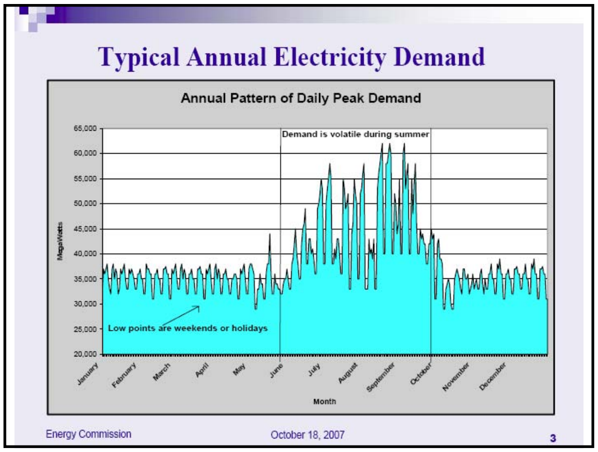
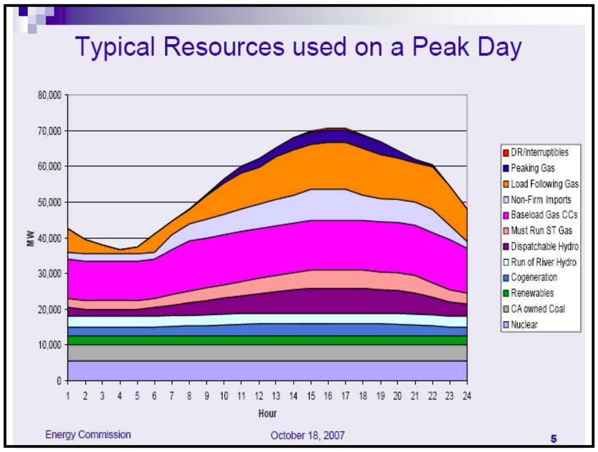
http://www.ladwp.com/ladwp/cms/ladwp001646.jsp



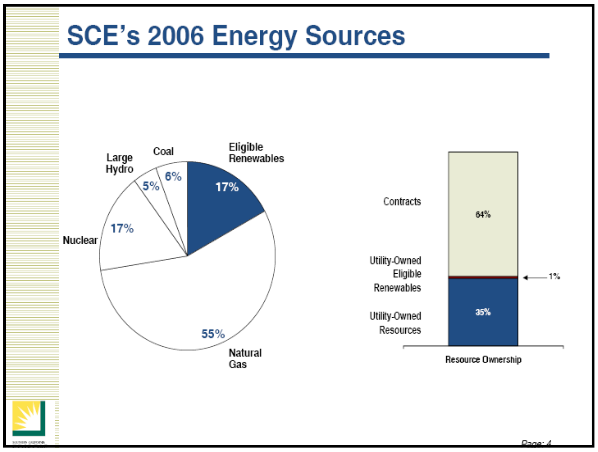
Typical Annual Electricity Demand

Energy Commission October 18, 2007

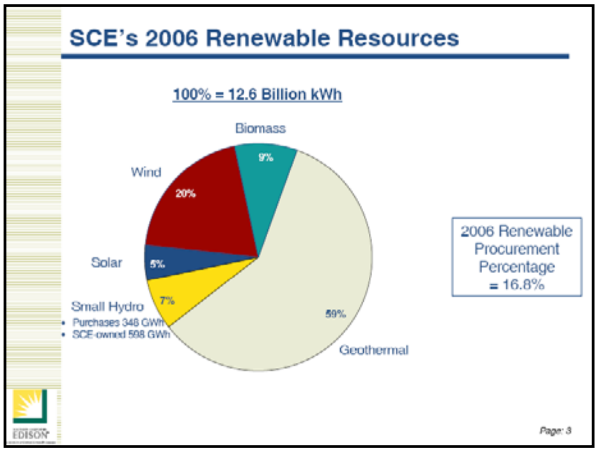


Typical Resources used on a Peak Day

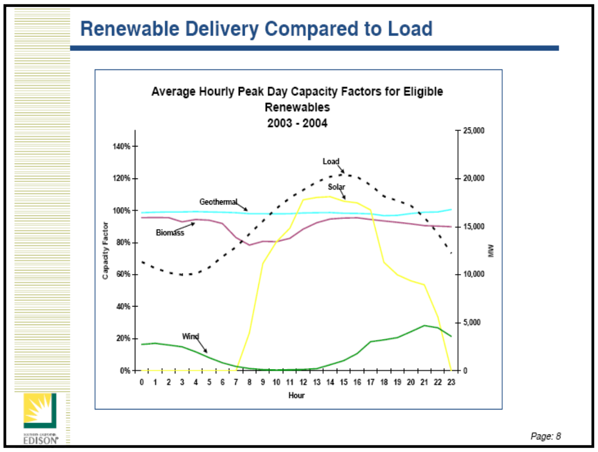
Energy Commission October 18, 2007



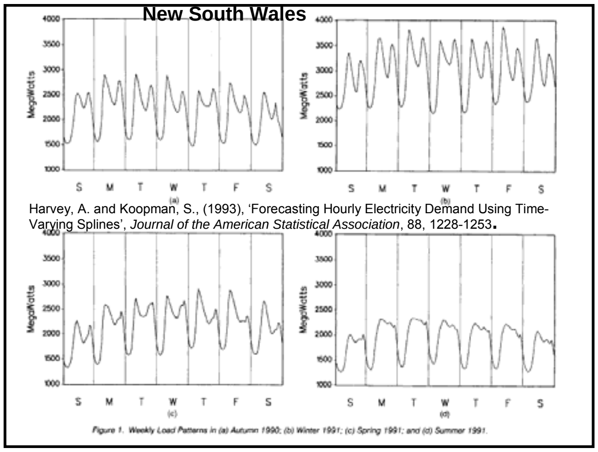
SCE's 2006 Energy Sources



SCE's 2006 Renewable Resources



Renewable Delivery Compared to Load



New South Wales

Harvey, A. and Koopman, S., (1993), 'Forecasting Hourly Electricity Demand Using Time-Varying Splines', *Journal of the American Statistical Association*, 88, 1228-1253.

Figure 1. Weekly Load Patterns in (a) Autumn 1990; (b) Winter 1991; (c) Spring 1991; and (d) Summer 1991.

Analysis of Alternatives

- Following charts from paper by Oxford Environmental Change Institute
- Conclude that alternative and energy supplies can, when properly planned, meet needs for peak power
  - – Based on models of supply and demand
  - – Wind, solar photovoltaic, and domestic combined heating and power (dCHP)
    - dCHP not a renewable, but an alternative

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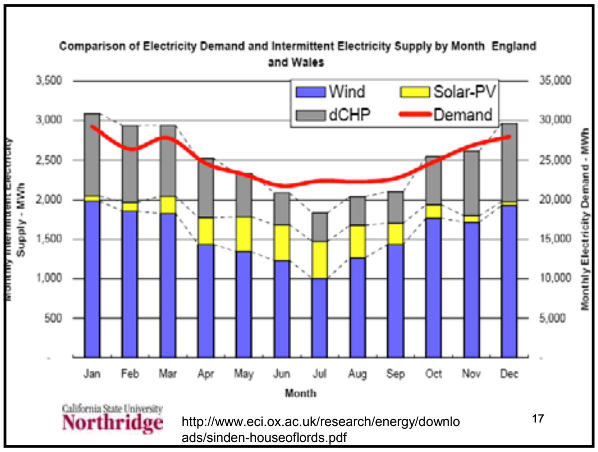

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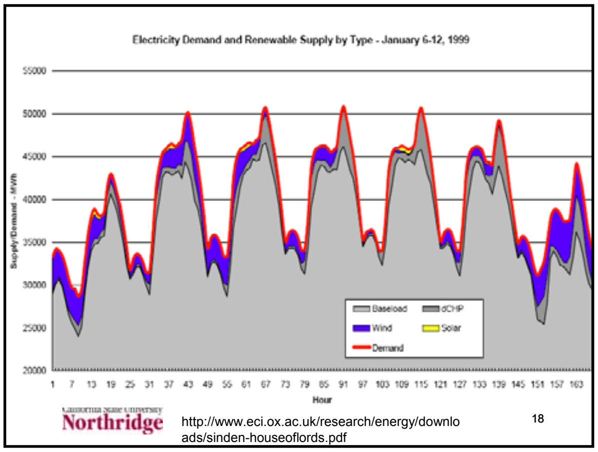
http://www.eci.ox.ac.uk/research/energy/downloads/sinden-houseoflords.pdf



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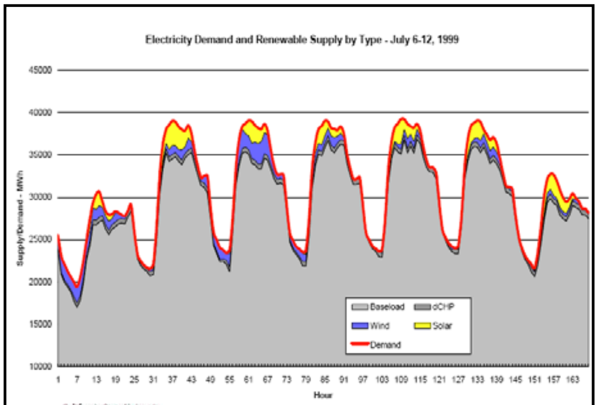


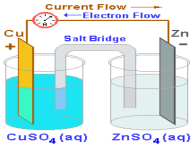
http://www.eci.ox.ac.uk/research/energy/downloads/sinden-houseoflords.pdf

Supplemental Slides

- Slides 52 and later will not be covered in lecture
  - Provide information on electrical generation system in US
  - Note sources of energy for generation
  - Shows electricity costs in various states
  - Discuss changes in electricity industry to encourage nonutility generators
  - Considers deregulation of electricity generation in late 1990s with successes and failures

Battery Basics

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

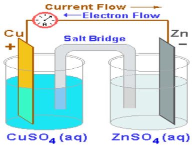


- At anode (right)
  - $Zn \rightarrow Zn^{++} + 2e^-$
  - Zn^{++} ions into $ZnSO_4$ in solution
  - electrons into circuit

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
  - $Cu^{++} + 2e^- \rightarrow Cu$ (0. 34 v)
  - $Zn^{++} + 2e^- \rightarrow Zn$ (–0.76 v)
  - Zinc reaction is reversed
  - Potential difference is 1.10 v

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^o
- Actual potential ΔE

$$\Delta E = \Delta E^o - \frac{RT}{nF} \ln Q$$

  - R = 8.414 J/gmmol·K, T = temperature in K
  - F = 96485.3415 A·s/gmmol (Faraday const)
  - n = electrons in reaction
  - Q depends on concentrations

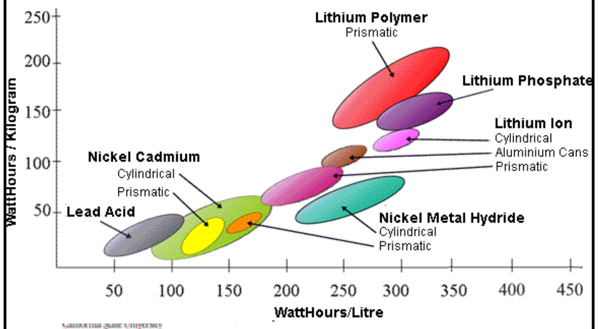
Battery Types

- **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

Solar System Batteries

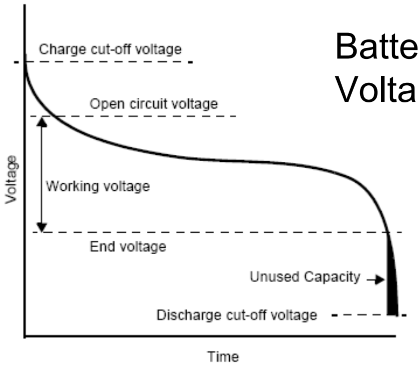
- Optional – home systems can sell excess power to utility
- Can provide power during evening hours for systems not linked to grid
- Also provide back-up power in cases of blackout
- Lead-acid batteries uses because of low cost

Battery Properties

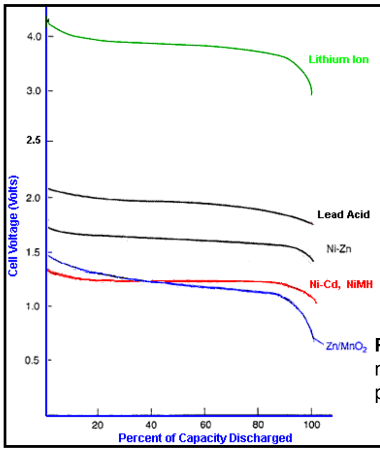


http://www.mpoweruk.com/chemistries.htm

Battery Voltages



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



Discharge

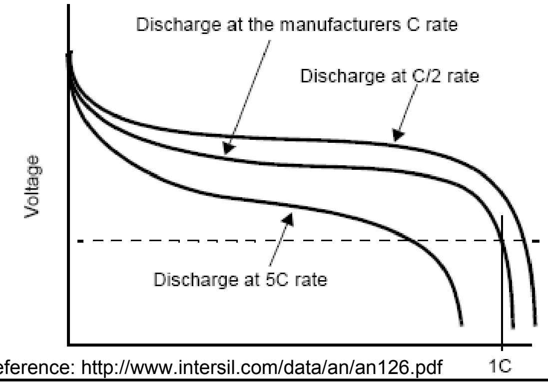
- Discharge patterns: similar with different batteries

Reference: http://www.mpoweruk.com/performance.htm

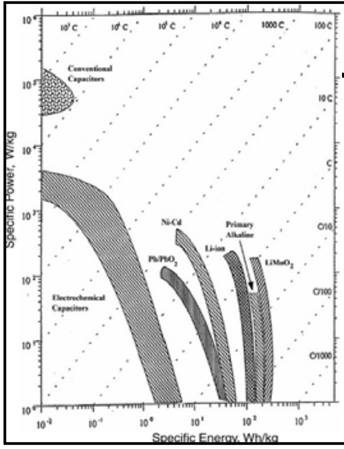
Battery Discharge Rates

- 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

Battery Discharge Rates

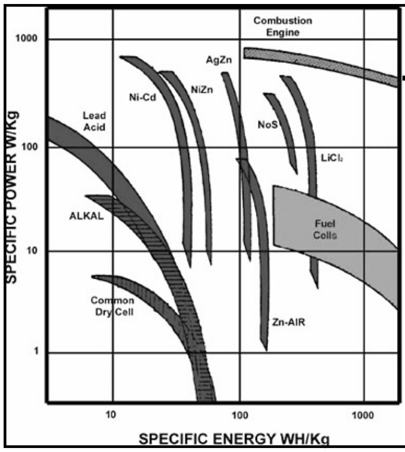


Reference: http://www.intersil.com/data/an/an126.pdf



Rate Effect

- Higher discharge rates give lower energy
- Reference: http://www.nap.edu/books/0309087007/html/64.html

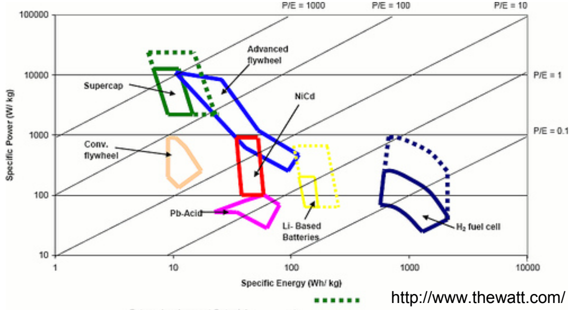


Compare

Batteries versus other motive power

http://www.nap.edu/books/0309092612/html/40.html

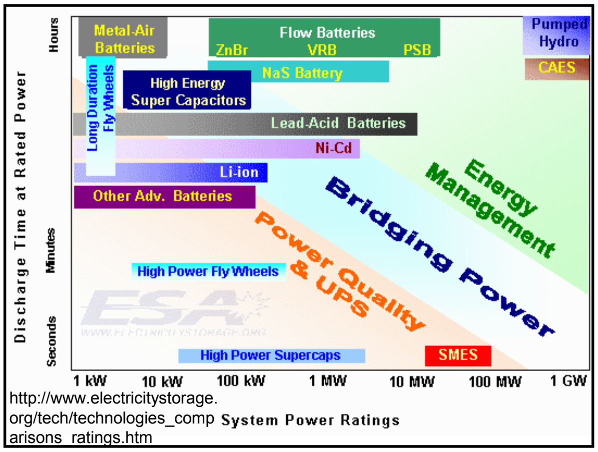
Ragone Plot



http://www.thewatt.com/modules.php?name=News&file=article&sid=926&mode=nested

Utility Storage Applications

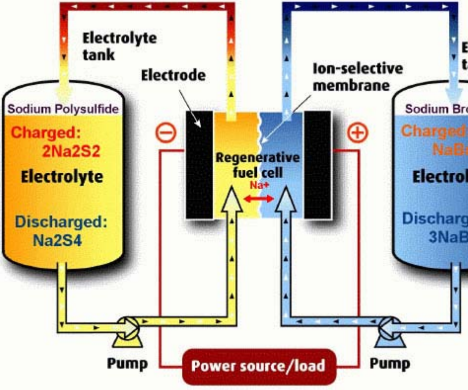
- **Power Quality:** applied for seconds or less, as needed, to assure continuity of quality power.
- **Bridging Power:** seconds to minutes to assure continuity of service when switching from one source to another.
- **Energy Management:** decouple the timing of generation and consumption of electric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



http://www.electricitystorage.org/tech/technologies_comparisons_ratings.htm

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

Schematic

http://www.electricitystorage.org/tech/technologies_technologies_psb.htm

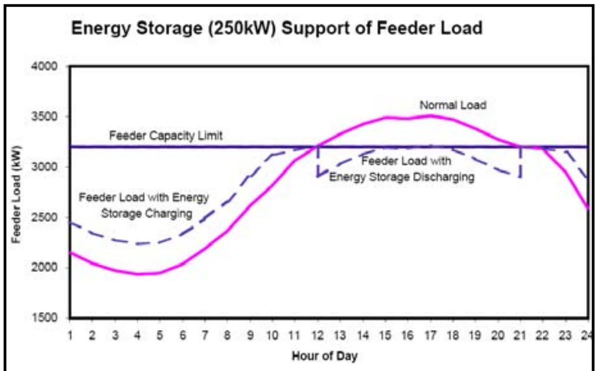
PSB Battery Reactions

- Charging reactions
  - $Na_2S_4 + 2e^- + 2Na^+ \rightarrow 2Na_2S_2$
  - $3NaBr \rightarrow 2e^- + 2\ Na^+ + NaBr_3$
- Discharge reactions
  - $2Na_2S_2 \rightarrow Na_2S_4 + 2e^- + 2Na^+$
  - $NaBr_3 + 2e^- + 2\ Na^+ \rightarrow 3NaBr$
- External power charges electrolyte so that tanks contain Na_2S_2 and $NaBr_3$
- Charged electrolytes power flow

VRB

Installation

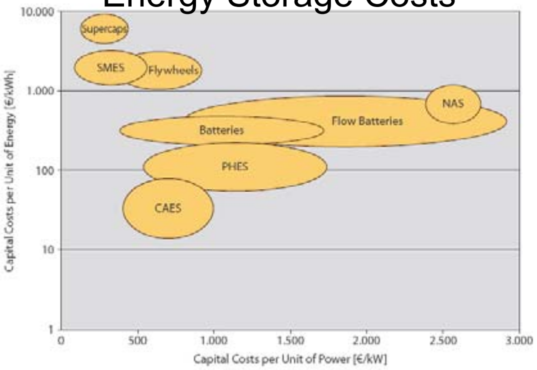
(Reference next chart)



- Flow battery increases transmission capacity

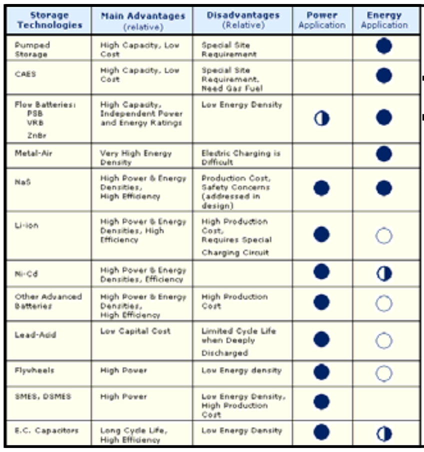
http://www.energy.ca.gov/pier/notices/2005-02-24_workshop/07%20Kuntz-VRB%20PacifiCorp%20Flow%20Battery.pdf

Energy Storage Costs



http://www.leonardo-energy.org/drupal/files/2007/Briefing%20paper%20-%20Flow%20batteries.pdf?download

Store



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: PSB 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	●	◑

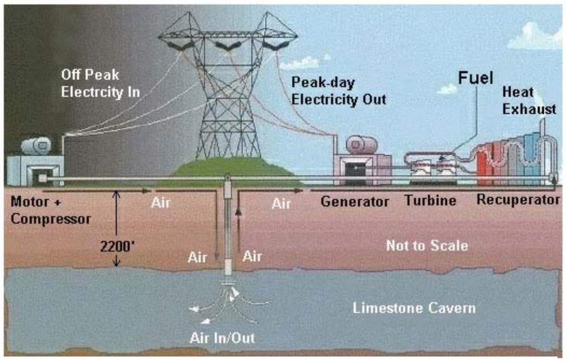
- Symbols
  - fully capable
  - reasonable
  - feasible, but not quite…
  - not feasible

•http://www.electricitystorage.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/kW; comes online in 14 mins
  - 2700 MW (planned) Norton, OH
    - 1500 psi air pressure, 2200 ft underground

http://www.electricitystorage.org/tech/technologies_technologies_caes.htm



http://www.electricitystorage.org/tech/technologies_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

Flywheels

- Store kinetic energy
  - Exchanged with motor-generator set
  - $E = I\omega^2/2 \quad I = kmR^2$
    - k = ½ 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

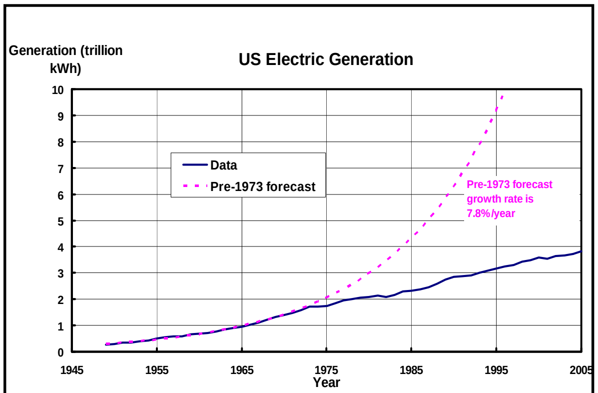
- Superconducting magnetic energy storage
- Store energy in magnetic field
- High power output for a short period of time (similar to supercapacitors)
- Requirement for extremely low temperatures to maintain superconductivity
- Used in some utility applications

Thermal Energy Storage

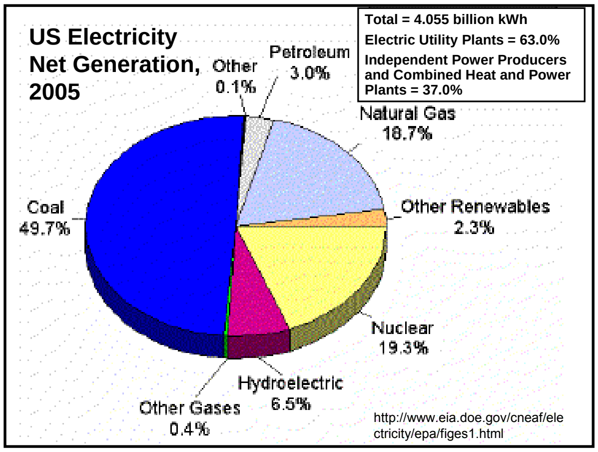
- Used to shift energy use from peak
  - Especially used to reduce air conditioning loads during summer
  - Run air conditioning compressors during off peak hours to provide cold temperature energy storage in ice or eutectic salts
  - Use stored energy during peak hours to provide cooling without any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

Supplemental Slides

- Following slides not covered in lecture
- Provide more information on electrical utility system in US and CaliforniaNote sources of energy for generation
  - Show electricity costs in various states
  - Discuss changes in electricity industry to encourage nonutility generators
  - Consider deregulation of electricity generation in late 1990s with successes and failures



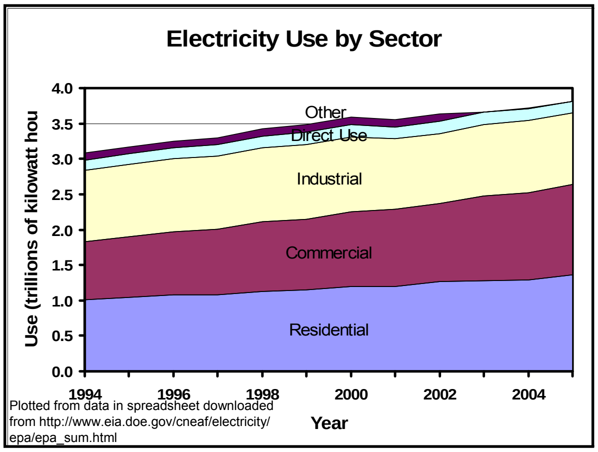
Plotted from spreadsheet data downloaded from http://www.eia.doe.gov/emeu/aer/elect.html



US Electricity Net Generation, 2005

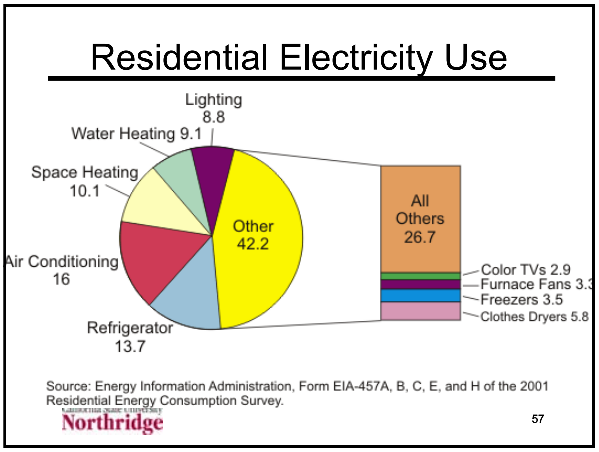
Total = 4.055 billion kWh
Electric Utility Plants = 63.0%
Independent Power Producers and Combined Heat and Power Plants = 37.0%

http://www.eia.doe.gov/cneaf/electricity/epa/figes1.html



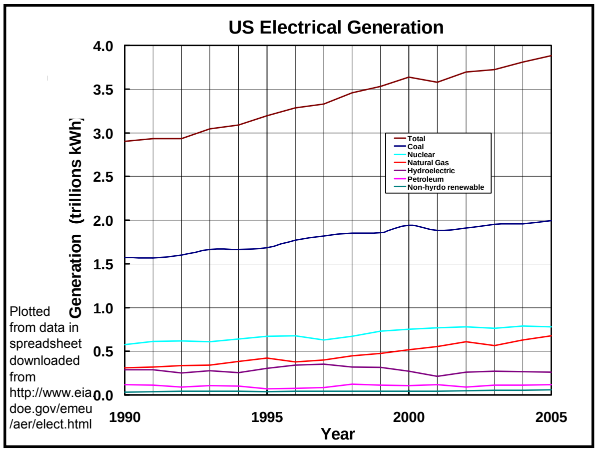
Electricity Use by Sector

Plotted from data in spreadsheet downloaded from http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html



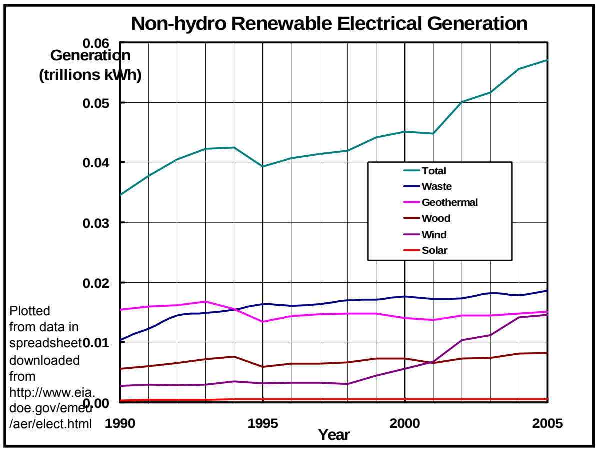
Residential Electricity Use

Source: Energy Information Administration, Form EIA-457A, B, C, E, and H of the 2001 Residential Energy Consumption Survey.



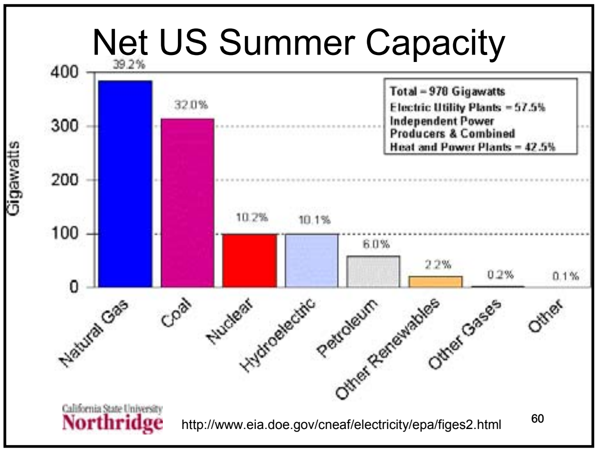
US Electrical Generation

Plotted from data in spreadsheet downloaded from http://www.eia.doe.gov/emeu/aer/elect.html



Non-hydro Renewable Electrical Generation

Plotted from data in spreadsheet downloaded from http://www.eia.doe.gov/emeu/aer/elect.html

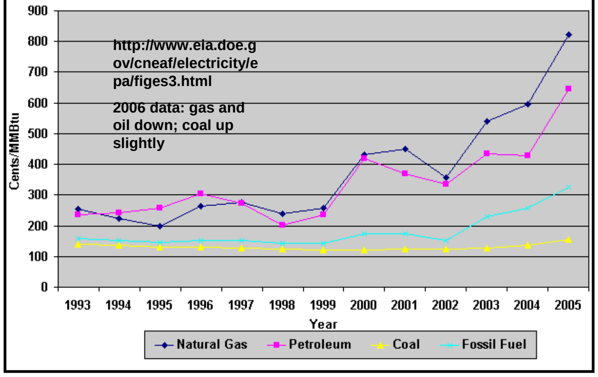


Net US Summer Capacity

Total = 970 Gigawatts
Electric Utility Plants = 57.5%
Independent Power Producers & Combined Heat and Power Plants = 42.5%

http://www.eia.doe.gov/cneaf/electricity/epa/figes2.html

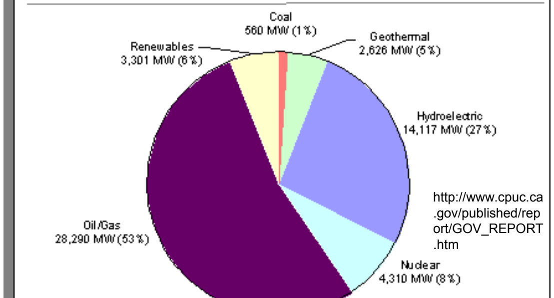
Electric Industry Fuel Costs



http://www.eia.doe.gov/cneaf/electricity/epa/figes3.html

2006 data: gas and oil down; coal up slightly

California Generation Capacity by Fuel Type

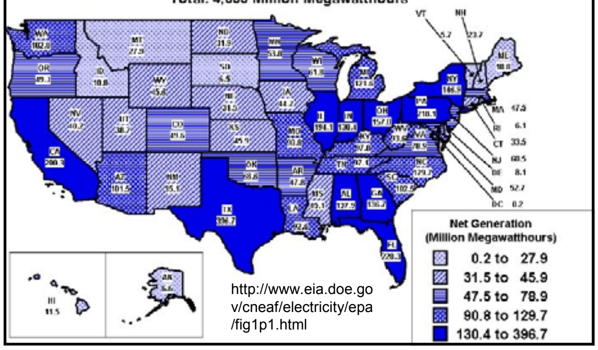


http://www.cpuc.ca.gov/published/report/GOV_REPORT.htm

Source: Based upon data from the California Energy Commission Database of California Power Plants (http://www.energy.ca.gov/database/index.html#powerplants)

Net Electricity by State 2005

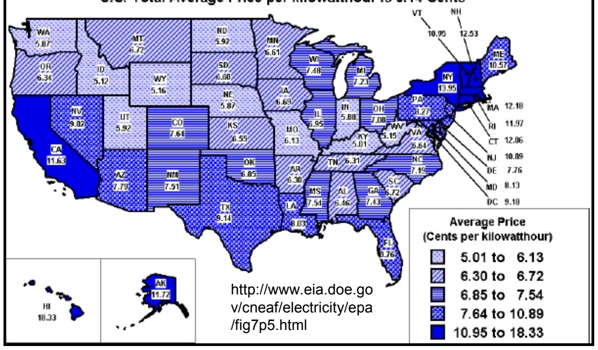
Total: 4,055 Million Megawatthours



http://www.eia.doe.gov/cneaf/electricity/epa/fig1p1.html

Retail Electric Costs 2005

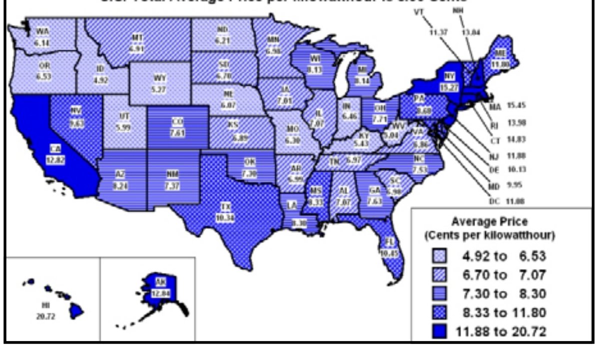
U.S. Total Average Price per kilowatthour is 8.14 Cents



http://www.eia.doe.gov/cneaf/electricity/epa/fig7p5.html

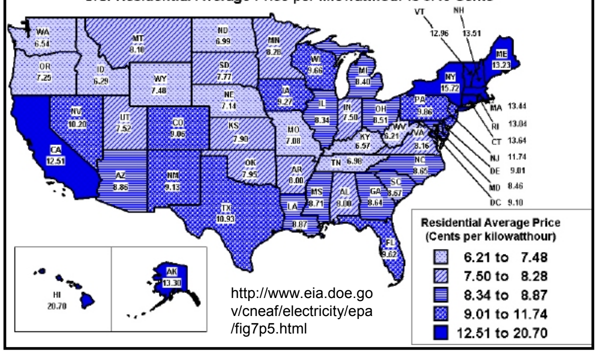
Retail Electric Costs 2006

U.S. Total Average Price per kilowatthour is 8.90 Cents



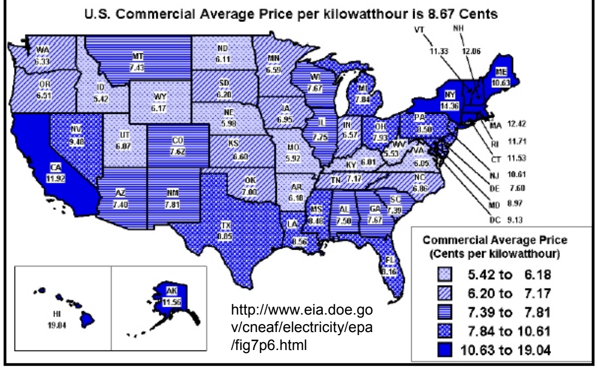
Residential Electric Costs 2005

U.S. Residential Average Price per kilowatthour is 9.45 Cents



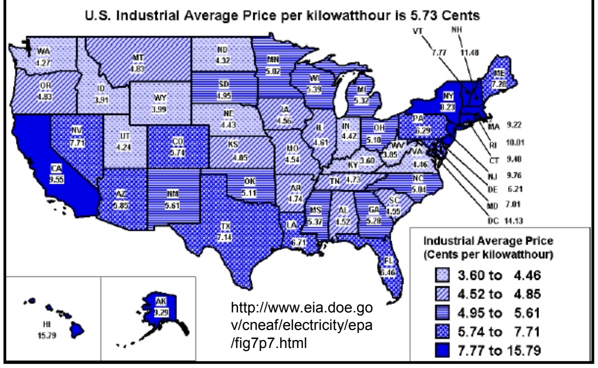
http://www.eia.doe.gov/cneaf/electricity/epa/fig7p5.html

Commercial Electric Costs 2005



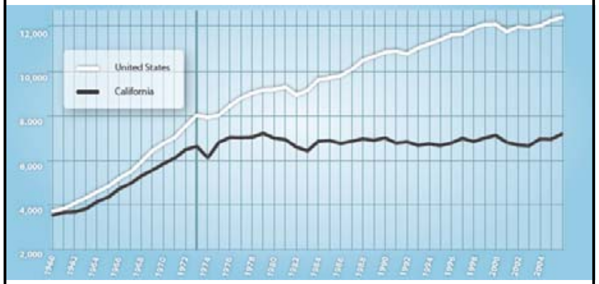
http://www.eia.doe.gov/cneaf/electricity/epa/fig7p6.html

Industrial Electric Costs 2005



http://www.eia.doe.gov/cneaf/electricity/epa/fig7p7.html

Electricity Sales (kWh/person)



http://www.energy.ca.gov/2007publications/CEC-100-2007-008/CEC-100-2007-008-CMF.PDF Figure ES-2

A Brief History

- Initial development of industry
  - Generation mostly by investor-owned, regulated monopolies
  - Some publicly owned utilities and rural cooperatives
  - Large industries generate for their own use
- PURPA 1978 brings in other generators
- EPAct 1992 deregulates generation at Federal level

Who Makes Electricity?

- Traditional electric utilities
  - 239 investor owned utilities supply about 75% of ultimate customers
  - 2,009 publicly owned utilities
  - 912 consumer owned rural electric cooperatives
  - 10 Federal electric utilities
- About 2,110 non-utility power producers as shown on next chart

http://www.eia.doe.gov/cneaf/electricity/page/prim2/toc2.html

Non-utility Electric Producers

- Facilities qualifying under 1978 Public Utility Regulatory Policies Act (PURPA)
- Cogeneration facilities producing steam and electricity, doing other business
- Independent power producers who sell electricity wholesale
- Exempt wholesale generators under 1992 Energy Policy Act (EPACT)
- http://www.eia.doe.gov/cneaf/electricity/page/prim2/toc2.html

Government Agencies

- Federal Energy Regulatory Commission (FERC) regulates interstate transmission of electricity, oil and gas
- State public utilities commissions regulate investor-owned utilities in state
- State Independent System Operators (ISO) operates transmission ines
- California Energy Commission (CEC) one-stop permits for new power plants

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What is PURPA?

- Public Utility Regulatory Policies Act 1978
  - Requires utilities to change rate structures from earlier ones that encouraged use
    - Costs per kWh declined with use based on model valid from 1950-1970
  - Convert from oil to gas
  - Require utilities to purchase power from qualified facilities (QFs) who generated it
    - Includes, solar, wind and biomass generation
    - Among requirements to be a QF is the production of electricity and heat with stipulated efficiency

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Effects of PURPA

- Started the development of a new industry: non-utility power producers
- Merged well with development of stationary gas turbine technology for cogeneration
- California incentives linked to PURPA made it an international leader for solar and wind electricity (about 85% of world wind and 95% of world solar in 1990)

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1992 Energy Policy Act

- Required owners of transmission lines to accept power from other generators for ultimate customers ("wheeling")
- Federal Energy Regulatory Commission passed enabling regulations in 1996
- California legislature passed restructuring legislation same year
- History of deregulation has been mixed

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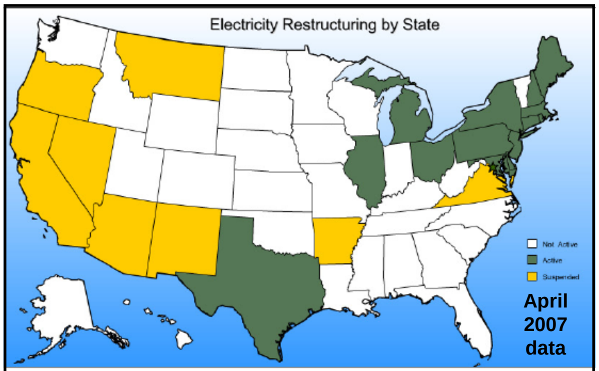

April 2007 data

http://www.eia.doe.gov/cneaf/electricity/page/restructuring/restructure_elect.html

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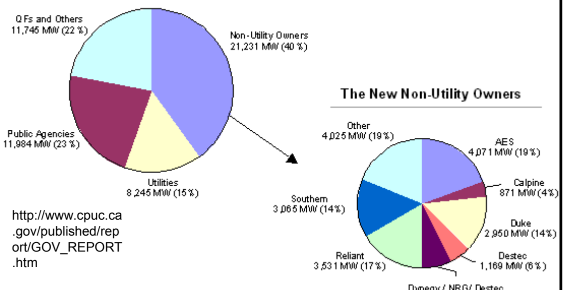
Who Owns Generation In California?



http://www.cpuc.ca.gov/published/report/GOV_REPORT.htm

Source: Based upon data from the California Energy Commission Database of California Power Plants (http://www.energy.ca.gov/database/index.html#powerplants)

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The California Experience

- Law passed in 1996
  - 10% decrease in rates mandated until utilities paid off existing debt
- Open market started March 31, 1998
- Average wholesale price was \$19.73/MWh compared to \$24/MWh before deregulation
- SDG&E first to raise prices on July 1, 1999
  - Wholesale price increases to \$500/MWh in May 2000 (billed to SDG&E customers)

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The California Experience II

- Price caps drives electricity sales outside of California
  - Aluminum smelters made more money by shutting down and selling electricity
- Wholesale price escalations not felt by LADWP, SCE, and PG&E customers
  - Companies losing 20 to 30 cents on each kWh they sold
  - PG&E bankrupt, SCE close to it

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The California Experience III

- January 17, 2001 governor directs DWR to enter into long-term contracts
  - Contract price was \$70/MWh when wholesale spot price was about \$300/MWh
  - Later spot prices declined to \$35/MWh
- Price increases due to manipulations by companies like Enron and real cost increases because of price increases in natural gas

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The California Experience IV

- What went wrong?
  - Manipulation by power suppliers
  - Fuel cost increases
  - Customers shielded from price increases
    - When customers had to pay higher prices, electricity use decreased
  - Lack of new power plants to meet demand
    - Capacity increases not provided
- Current status http://www.ferc.gov/industries/electric/indus-act/wec.asp

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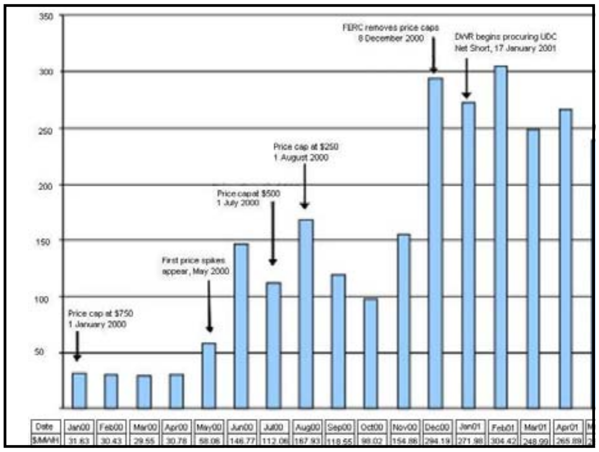
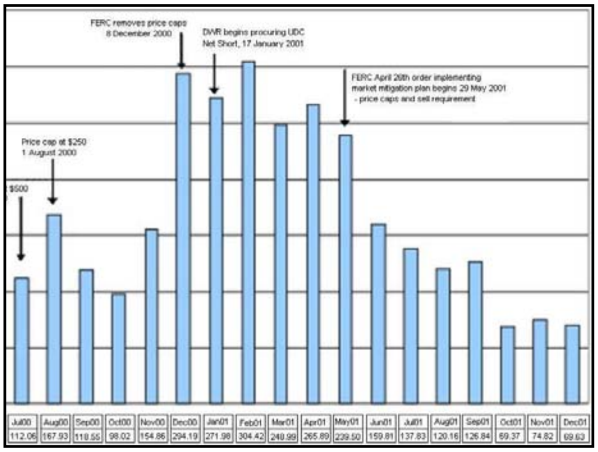
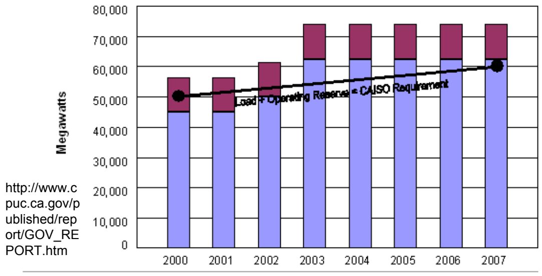




The Pennsylvania Experience

- Legislation did not require utilities to divest generation facilities and allowed long-term contracts
- State is net exporter of electricity
- Originally considered success story, just the opposite of California
- Subsequent price increases – utilities control large fraction of generation
- Prices still lower than before deregulation

California Relies On Imports



http://www.cpuc.ca.gov/published/report/GOV_REPORT.htm

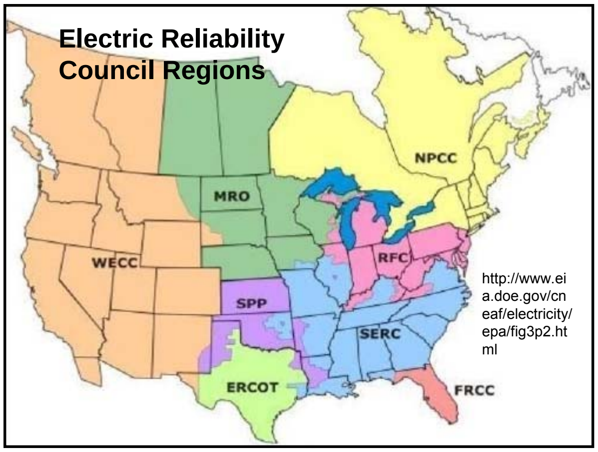
	2000	2001	2002	2003	2004	2005	2006	2007
🟥 Max Import Capacity	11,260	11,260	11,260	11,260	11,260	11,260	11,260	11,260
🟦 Max Avail. Gen. Capacity	45,565	45,602	50,011	62,861	62,878	62,861	63,190	63,180
Load Forecast + OR	***49,209***	***50,188***	***51,463***	***53,602***	***54,462***	***55,306***	***56,177***	***57,928***

Source: California Independent System Operator

Reliability Councils

- Set up to share power in a region
- Link producers to produce system reliability
  - ERCOT – Electric Reliability Council of Texas
  - FRCC – Florida Reliability Coordinating Council
  - MRO – Midwest Reliability Organization
  - NPCC – Northwest Power Coordinating Council
  - RFC – Reliability First Corporation
  - SERC – Southern Electric Reliability Council
  - SPP – Southwest Power Pool
  - WECC – Western Energy Coordinating Council

Electric Reliability Council Regions



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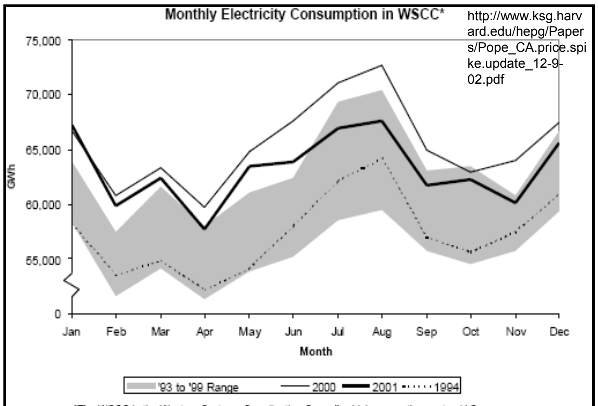
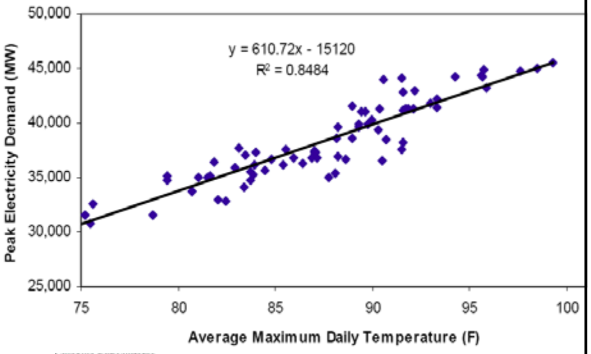


http://www.ksg.harvard.edu/hepg/Papers/Pope_CA.price.spike.update_12-9-02.pdf

*The WSCC is the Western Systems Coordinating Council, which covers the westen U.S. and portions of Canada and Mexico.

California Climate *vs.* Demand



http://www.energy.ca.gov/2005publications/CEC-500-2005-201/CEC-500-2005-201-SF.PDF