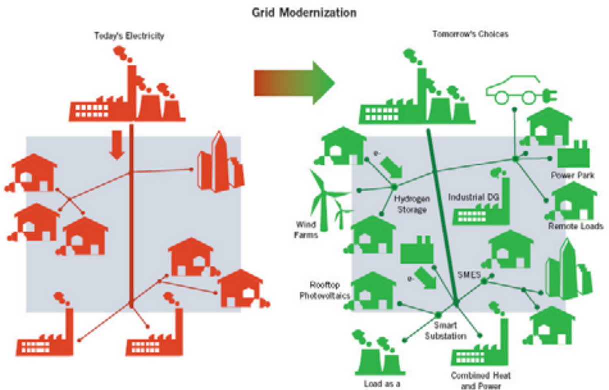
Electric Power Industry

- Electric Power Industry in US (Before 1980)
  - One of the largest enterprises
  - One of the most polluting industries
    - Emissions
      - Sulfur Oxides (SOx)
      - Carbon Dioxide (CO2)
      - Nitrogen Oxides (NOx)
  - Regulated utilities
  - Monopoly franchises
  - Vertical Integration with Generation, Transmission, and Distribution
  - Serving their own customers

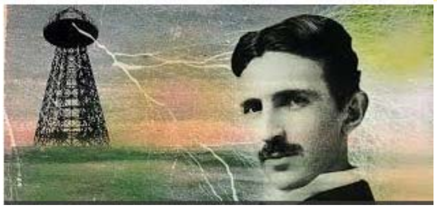
Electric Power Industry

- Electric Power Industry in US (From 1980s)
  - Own power on-site, or perhaps buy it directly from non-utility providers.
  - Break of the natural monopoly
  - Enter in to a new competitive power industry → "deregulation" → California's failed experiment →Mixed structure
  - Global warming and emission reduction mandate
  - "Smart Grid"
  - Renewable energy in to action
  - Changes in Technological and Regulatory Systems



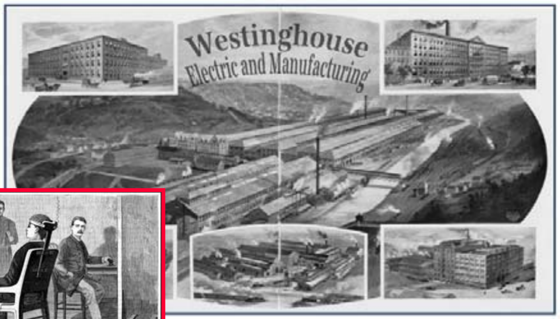
Early Pioneers

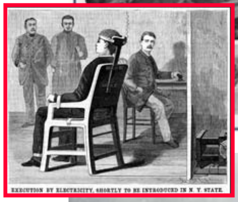
- Electricity and Magnetism
  - Has Christian Oersted, Andre Ampere, and James Clerk Maxwell
- Electro-Mechanical Conversion
  - 1831 DC Dynamo -- Maxwell, H. Pixil (France)
  - 1880s AC Generation and AC induction motor --- Nikola Tesla
- Electric Power Market
  - Thomas Edison – Edison Electric Light Company – Illumination
  - 1882 Pearl Street in Manhattan – distribution of electricity for lights → 1st investor-owned utility in the nation
  - DC system: flicker-free light, easy control of DC motors, difficulty in voltage change, low-voltage DC led to high line losses →customers are to be located nearby

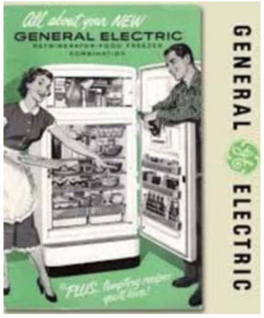


Early Pioneers

- Electric Power Market
  - George Westinghouse --- based on Tesla's AC system – Westinghouse Electric Company (1886)
  - Big feud between Westinghouse and Edison (DC vs. AC): "high voltage's safety hazard" → demonstration by Edison and Samuel Insull (assistant) of 1000V AC → led to electric chair invention
  - AC system prevailed (advantage of high voltage transmission). Edison's DC system disintegrated → new incorporation in 1892 as General Electric Company with shifted focus from a utility to manufacturing electrical equipment for utilities and customers

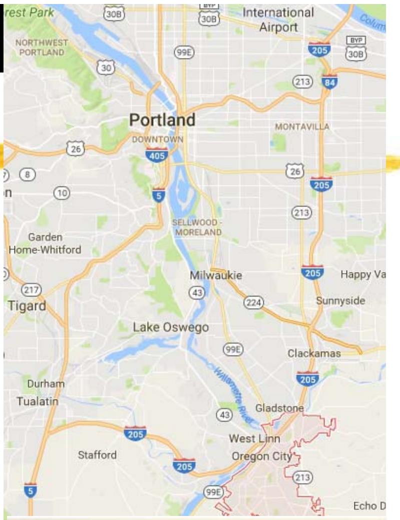






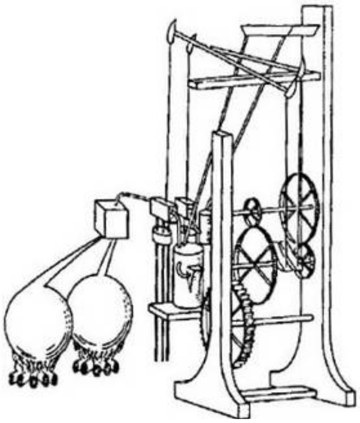
Long Distance Power Delivery

- First demonstration (1891)
  - 3-phase, 106-mile, 30kV, 75kW between Hauffen and Frankfurt, Germany
- First transmission line in the US (1890)
  - 1-phase, 3.3kV, 13 mile, Hydroelectric station (Oregon City) – Portland, OR
- Solving the flickering lamp problem
  - US --- 60Hz system is standardized (1930s)
  - 50Hz countries – Japan and some European countries
- Economy side of electric power companies (Samuel Insull)
  - Big capital investment
  - Monopoly → Regulated monopoly [franchise territory and price controlled by public utility Commissions (PUCs)]



Major Electricity Milestones - 1

- 1800 First electric battery (A. Volta)
- 1820 Relationship between electricity and magnetism confirmed (H. C. Oersted)
- 1821 First electric motor (M. Faraday)
- 1826 Ohm's law (G. S. Ohm)
- 1831 Principles of electromagnetism and induction (M. Faraday)
- 1832 First dynamo (H. Pixil)
- 1839 First fuel cell (W. Grove)
- 1872 Gas turbine patent (F. Stulze)
- 1879 First practical incandescent lamp (T. A. Edison and J. Swan, independently)



Major Electricity Milestones - 2

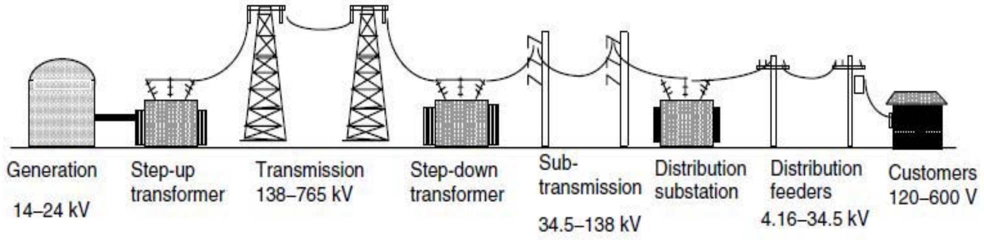
- 1882 Edison's Pearl Street Station opens
- 1883 Transformer invented (L. Gaulard and J. Gibbs)
- 1884 Steam turbine invented (C. Parsons)
- 1886 Westinghouse Electric formed
- 1888 Induction motor and polyphase AC systems (N. Tesla)
- 1890 First single-phase ac transmission line (Oregon City to Portland)
- 1891 First three-phase ac transmission line (Germany)
- 1903 First successful gas turbine (France)
- 1907 Electric vacuum cleaner and washing machines
- 1911 Air conditioning (W. Carrier)
- 1913 Electric refrigerator (A. Goss)

Major Electricity Milestones - 3

- 1962 First nuclear power station (Canada)
- 1973 Arab oil embargo, price of oil quadruples
- 1979 Iranian revolution, oil price triples; *Three Mile Island* nuclear accident
- 1986 *Chernobyl* nuclear accident (USSR)
- 1990 Clean Air Act amendments introduce tradeable SO2 allowances
- 1998 California begins restructuring
- 2001 Restructuring collapses in California; *Enron* and *Pacific Gas and Electric* bankruptcy

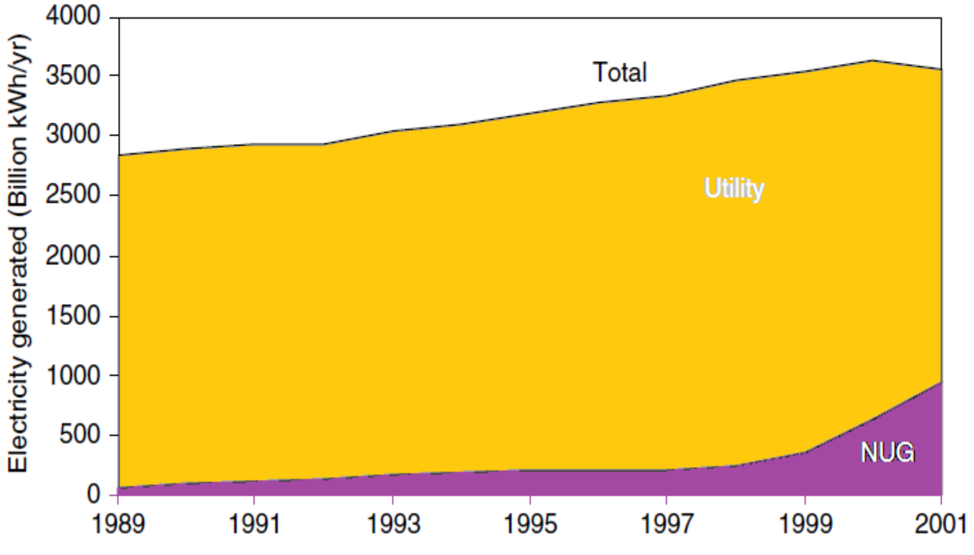
Electric Utility Industry Today

- Conventional Power System



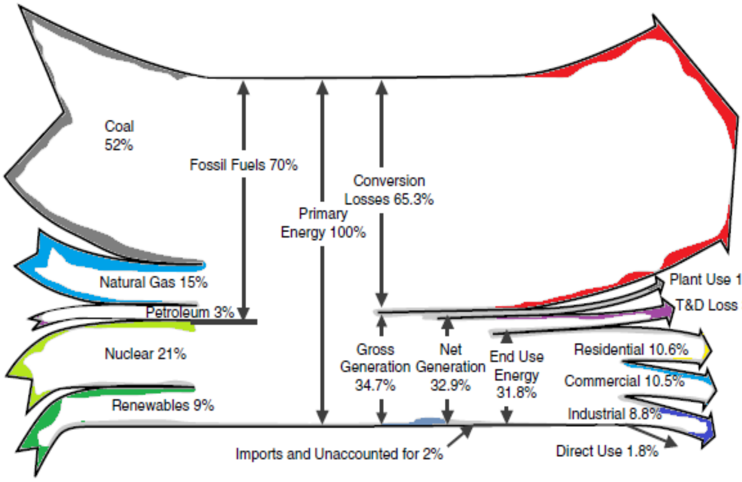
- Utilities: Regulated Monopoly Franchise over a fixed geographical area
  - Investor Owned utilities (IOUs)
  - Federally Owned Utilities: TVA, BPA, etc
  - Other Publicly Owned Utilities: State and Local Government agencies
  - Rural Electric Coop: Rural Electric Administration
- Non-Utility Generators (NUG)
  - Privately owned for own use and/or for sale to utilities

NUG Portion of Total Electricity Generation



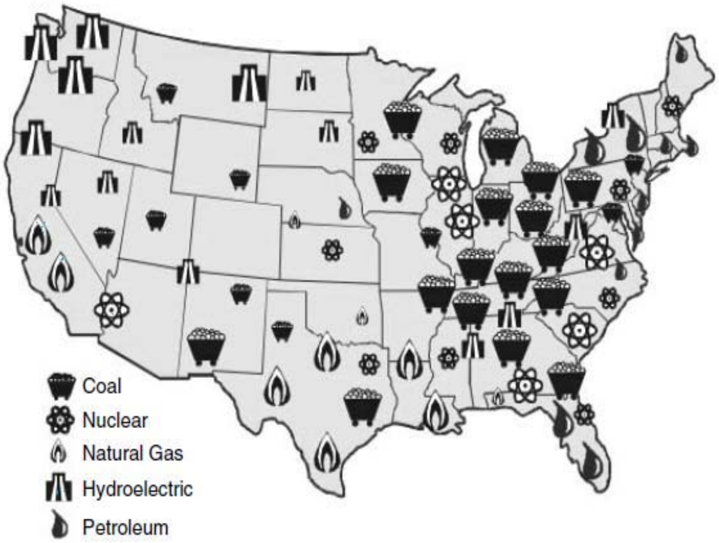
Nonutility generators have become a significant portion of total electricity generated in the United States. From *EIA Annual Energy Review 2001* (EIA, 2003).

Industry Statistics: Energy Sources & Electricity Flow



Electricity flows as a percentage of primary energy. Based on *EIA Annual Energy Review 2001* (EIA, 2003).

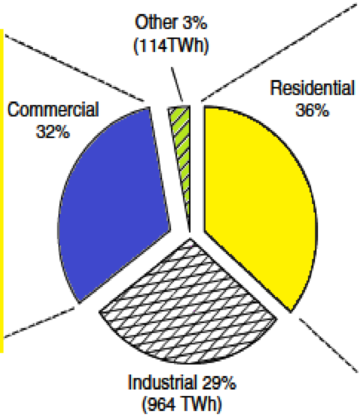
Industry Statistics: Energy Sources by States



Energy sources for electricity generation by region. Each large icon represents about 10 GW of capacity, small ones about 5 GW. From *The Changing Structure of the Electric Power Industry 2000: An Update* (EIA, 2000).

Industry Statistics: Distribution of Electricity Sales

COMMERCIAL	PERCENTAGE
Lighting	32
Space Cooling	12
Office Equipment	7
Ventilation	5
Refrigeration	5
Space Heating	3
Water Heating	3
Computers	2
Cooking	1
Other Office	9
Non-Building Uses	21
TOTAL (TWh)	1089

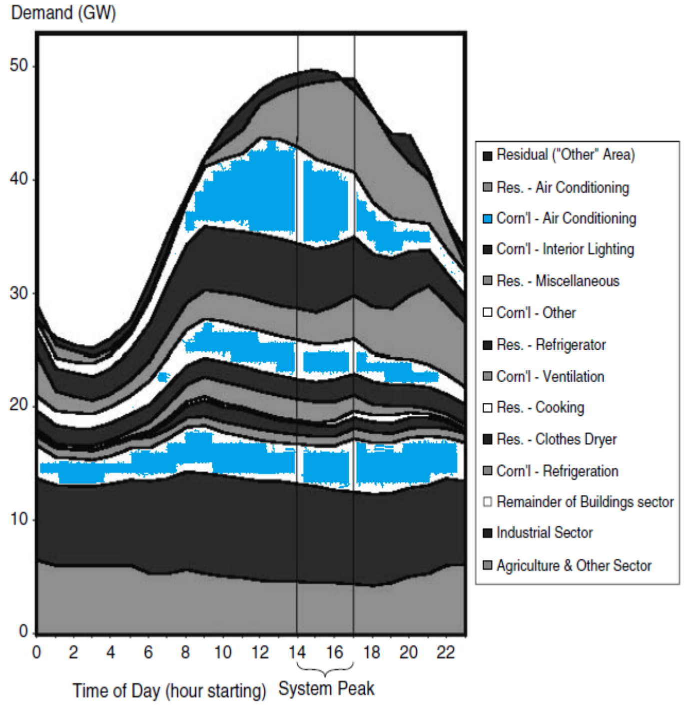


RESIDENTIAL	PERCENTAGE
Space Cooling	13
Refrigerators	11
Motors	11
Heating	10
Water Heating	10
Electronics	9
Lighting	9
Heating Elements	9
Clothes Dryers	6
Cooking	3
Freezers	3
Televisions	3
Computers	2
Clothes Washers	1
TOTAL (TWh)	1203

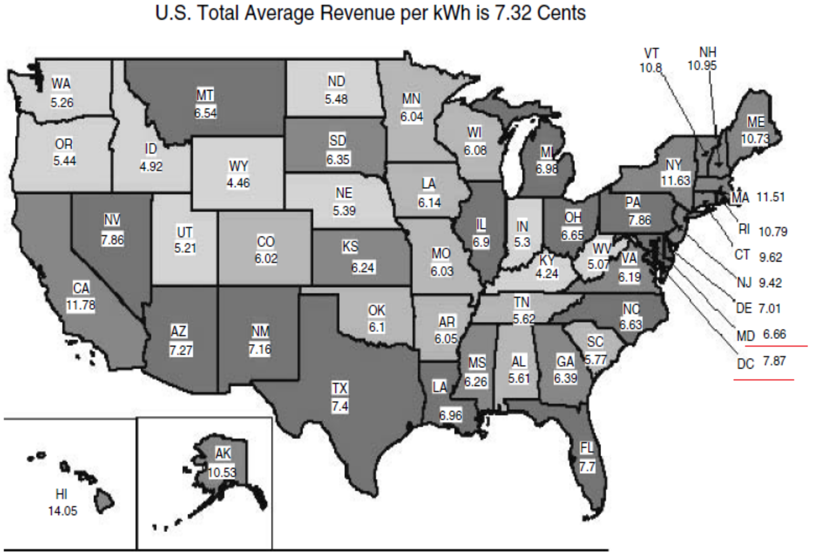
Distribution of retail sales of electricity by end use. Residential and commercial buildings account for over two-thirds of sales. Total amounts in billions of kWh (TWh) are 2001 data. From EIA (2003).

Industry Statistics: Load Profile

The load profile for the a peak summer day in California (1999) shows maximum demand occurs between 2 P.M. and 4 P.M. Lighting and air conditioning accounts for over 40% of the peak. End uses are ordered the same in the graph and legend. From Brown and Koomey (2002).

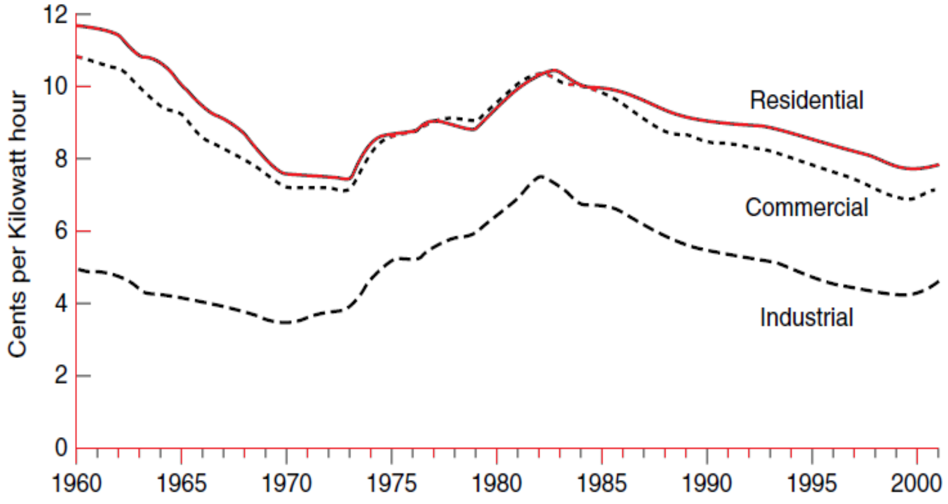


Industry Statistics: Electricity Price ($/kWh)



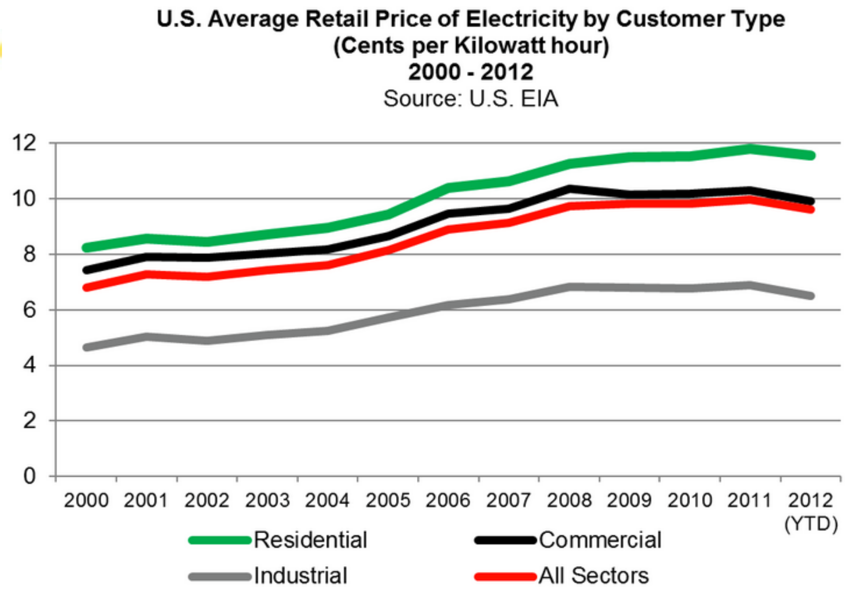
Average revenue per kilowatt-hour for all sectors by state, 2001. California in 1998 before restructuring was 9.03 ¢/kWh. *Source*: Energy Information Administration.

Industry Statistics: Price ($/kWh) Change



Average retail prices of electricity, by sector (constant $1996). From *EIA Annual Energy Review 2001* (EIA, 2003).

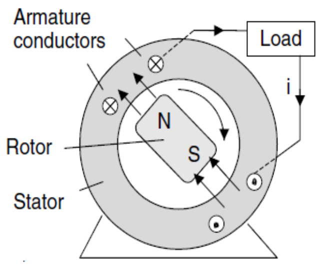
Industry Statistics: Price ($/kWh) Change

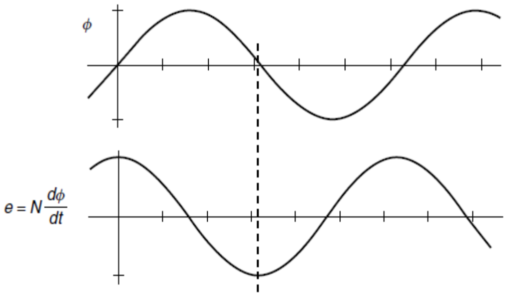


Zpryme: Learn more @ www.smartgridresearch.org

Synchronous Generators

- Simple Generator
- Theory: Electromagnetic Induction (1831) by Michael Faraday
- Rotating Magnetic Field (DC excited Rotor) + Armature (Stator)



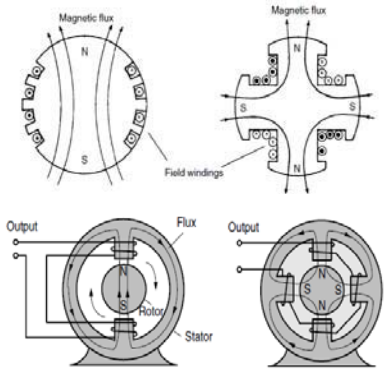


Changing flux in the stator creates an emf voltage across the windings.

Single-phase Synchronous Generators

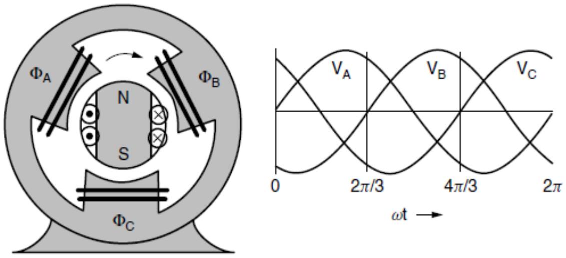
- Generation of voltage at 60 Hz
- Each revolution of the rotor gives one voltage cycle for a 2-pole generator
- The speed of rotor for 60Hz? (for a 2-pole generator)
  - 60 rps (revolutions per second) = 60 * 60 (min/sec) rpm (revolutions per minute) = **3600** rpm
  - Fixed speed machine = synchronous generator (synchronized with the utility system)
- 2-pole machine vs 4-pole machine
  - Speed for 4-pole machine for 60 Hz voltage?
  - 4-pole generator makes 2 voltage cycles per revolution →**1800** rpm
- General Equation for RPM (N_s) $N_s = \frac{120f}{p}$

Poles p	50 Hz rpm	60 Hz rpm
2	3000	3600
4	1500	1800
6	1000	1200

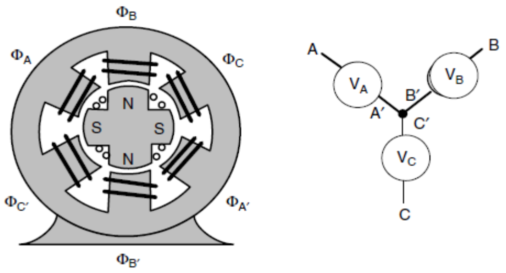


3-phase Synchronous Generators

- Single magnetic rotor (2-pole)
- 3-winding stator 120 degrees apart
- Rotor sweeps by each winding
- Induces a voltage at each winding



- 4-pole 3-phase generator
- Salient-pole rotor
- 3 pairs of stator winding
- Half the rotor speed of 2-pole machine

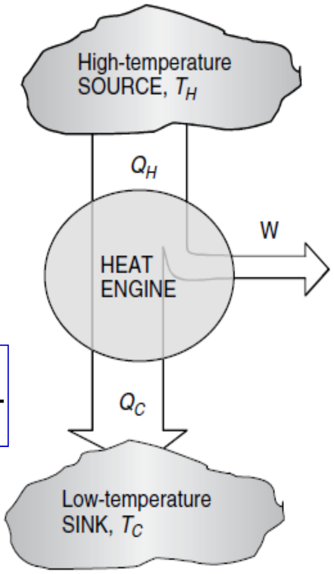


Heat Engines

- Conversion of heat into mechanical work
- Heat Sources:
  - nuclear reaction
  - fossil-fuel combustion
  - solar heater
- Heat ($\mathbf{Q}_H$) → Boiled Water → Steam → Steam Turbine Spin (Work: **W**) + Remaining Heat ($\mathbf{Q}_C$) → Other works by Remaining Heat ($\mathbf{Q}_C$)
- $\mathbf{Q}_H = \mathbf{W} + \mathbf{Q}_C$
- Thermal Efficiency = $\mathbf{W}/\mathbf{Q}_H$

$$\textbf{Efficiency} = \frac{\textbf{Net Work Output}}{\textbf{Total Heat Input}}$$

- Thermal Efficiency = $(\mathbf{Q}_H - \mathbf{Q}_C)/\mathbf{Q}_H = 1 - \mathbf{Q}_C/\mathbf{Q}_H$
- "In view of Heat" (cf. "in view of Temperature")



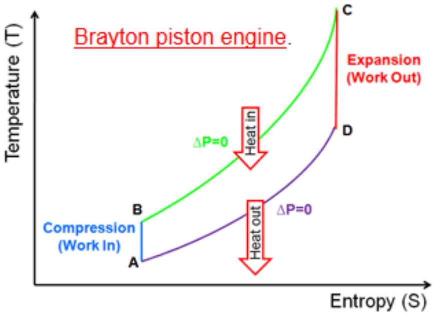
Heat Engines – Entropy Analysis (for Temperature View)

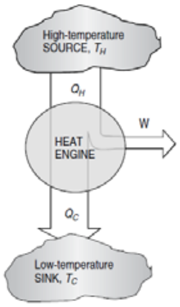
- Work done by the engine = Heat Transfer

$$\Delta S = \frac{Q}{T}$$

- Entropy Equation
  - Q: Heat removed from a large thermal reservoir
  - "Large" thermal reservoir: Temperature (T) of the reservoir does not change after the loss of Q
  - T: Absolute Temperature
  - Entropy goes down as T goes up
  - Entropy must increase in a heat engine → helps wit determination of maximum possible efficiency
- Entropy
  - Work done (W) is an idealized process, so does not increase Entropy
  - Process = Heat Transfer + Work
  - Heat Transfer → Entropy Transfer
  - Work → Entropy-Free

Brayton Heat Cycle Entropy Diagram

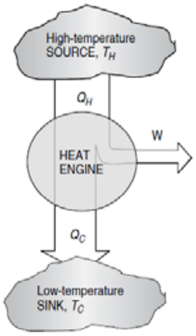




Heat Engines – Entropy Analysis

- Entropy must increase in a heat engine
- Entropy added to the low-temperature sink must exceed the entropy removed from the high-temperature reservoir (Heat engine: high-temp → Low-temp process)

$$\Delta S = \frac{Q}{T}$$

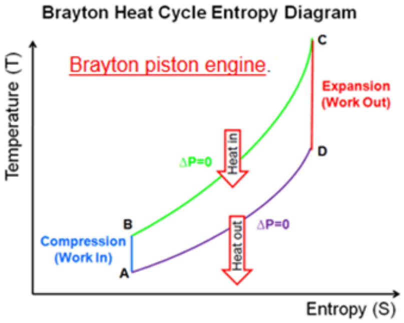


$$\Delta S_C = \frac{Q_C}{T_C} \qquad \Delta S_H = \frac{Q_H}{T_H}$$

$$\Delta S_C \geq \Delta S_H \qquad \frac{Q_C}{T_C} \geq \frac{Q_H}{T_H} \longrightarrow \frac{Q_C}{Q_H} \geq \frac{T_C}{T_H}$$

$$\text{Thermal efficiency} = 1 - \frac{Q_C}{Q_H} \leq 1 - \frac{T_C}{T_H}$$

$$\eta_{\max} = 1 - \frac{T_C}{T_H}$$ **<--- Maximum Efficiency (Efficiency Limit)**

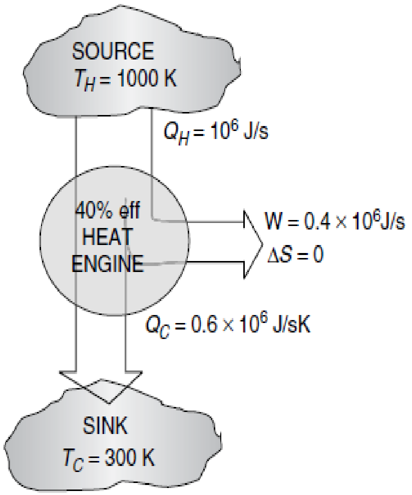

Brayton Heat Cycle Entropy Diagram

- In view of Temperature

Entropy Analysis Example

$$\boxed{K = {}^\circ\mathrm{C} + 273.15}$$

- 40% Efficient Heat Engine
- Between 1000K(727C) reservoir and 300K(27C) reservoir
- Q1: If it withdraws 10^6 J/S from the high-temp reservoir, (a) what would be the rate of loss of entropy from the reservoir; and (b) what would be the rate of gain by the low-temp reservoir
- Q2: Express the work done by the engine in watts.
- Q3: What would be the total entropy gain of the system?



Entropy Analysis Example - Solution

- $Q_H = 10^6$; $W = 0.4*Q_H$; $Q_C = 0.6*Q_H$
- $T_H = 1000K$(727C); $T_C = 300K$(27C)
- A1:

$$\Delta S_{\text{loss}} = \frac{Q_H}{T_H} = \frac{10^6\ \text{J/s}}{1000\ \text{K}} = 1000\ \text{J/s}\cdot\text{K}$$

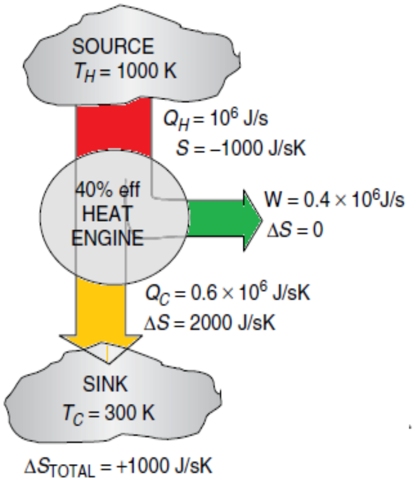
$$\Delta S_{\text{gain}} = \frac{Q_C}{T_C} = \frac{0.60\times 10^6\ \text{J/s}}{300\ \text{K}} = 2000\ \text{J/s}\cdot\text{K}$$

- A2:

$$\text{Work} = 0.40\times 10^6\ \text{J / s}\times\frac{1\ \text{W}}{\text{J / s}} = 400\ \text{kW}$$

- A3:

$$\Delta S_{\text{total}} = -1000 + 2000 + 0 = +1000\ \text{J / s}\cdot\text{K}$$

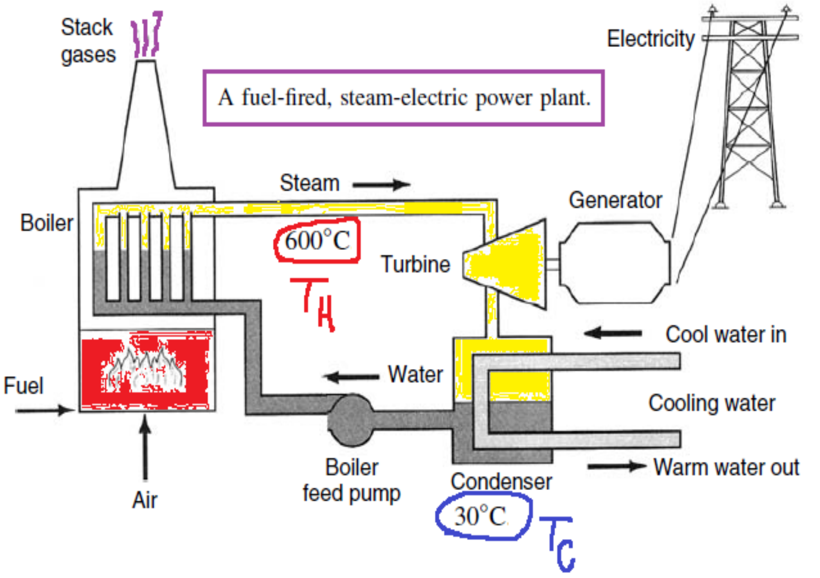


Thermodynamic Cycle

- Thermodynamic Cycle in converting heat into work
  - **Rankine Cycle**: A working fluid is alternately vaporized and condensed; Most baseload thermal power plants → steam is the working fluid
  - **Brayton Cycle**: Working fluid remains a gas throughout the cycle; Most peaking plants (on line as needed) with gas turbine.
  - **Combined Cycle**: Both of the above two cycles in use

Steam-Cycle

- Basic Steam Cycle



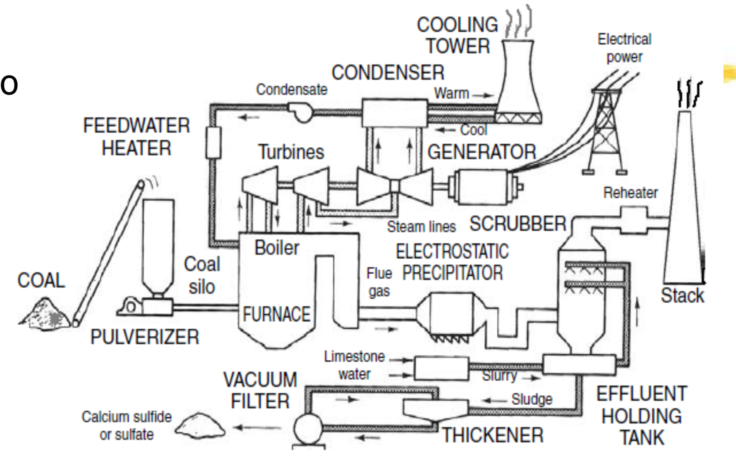
$$\eta = 1 - \frac{T_C}{T_H}$$

$$= 1 - \frac{30+273}{600+273}$$

$$= 0.65$$

Steam-Cycle

- Coal-Fired Steam Cycle
- "Heat Rate" = "Thermal Input (Btu or kJ) required to deliver 1kWh of Electrical Output"
- 1 Btu/kWh = 1.055 kJ/kWh
- Heat Rate & Efficiency



SO2 Scrubber

$$\text{Heat rate (Btu/kWh)} = \frac{3412 \text{ Btu/kWh}}{\eta}$$

$$\text{Heat rate (kJ/kWh)} = \frac{3600 \text{ kJ/kWh}}{\eta}$$

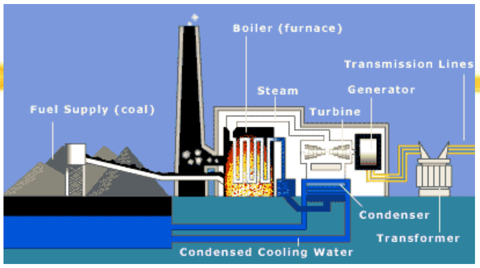
1 Btu = 3412 kWh

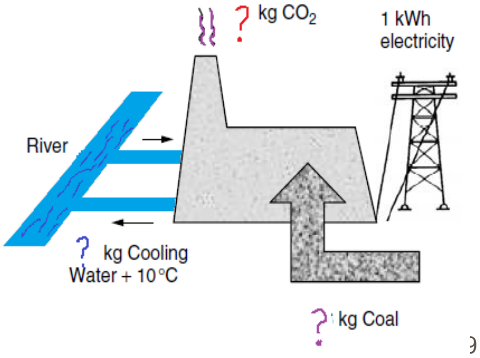
Edison's first plat
70,000 Btu/kWh
= 0.05 (efficiency)

Average steam plant
10,000 Btu/kWh
= 0.34 (Efficiency)

Material Balance - Example

- A power plant with a heat rate of 10,800 kJ/kWh
- Fuel: Bituminous Coal with 75% Carbon and a heating value (energy released when it is burned) of 27,300 kJ/kg.
- 15% of thermal losses are up the stack, and the remaining 85% are taken away by cooling water
- Q1: Find the efficiency of the plant
- Q2: Find the mass of coal that must be provided per kWh delivered
- Q3: Find the rate of carbon and CO2 emission from the plant in kg/kWh
- Q4: Find the minimum flow of cooling water per kWh if its temperature is only allowed to increase by 10 C.





Material Balance Example - Solution

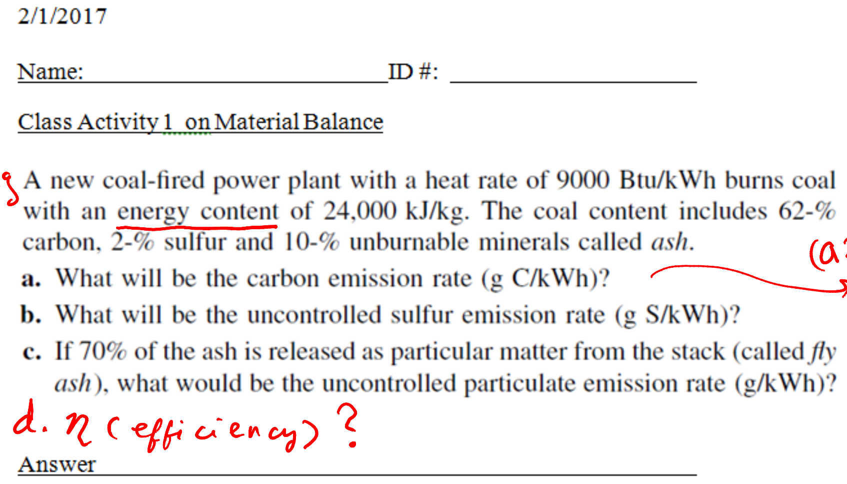
- A power plant with a heat rate of 10,800 kJ/kWh
- Fuel: Coal with 75% Carbon and a heating value of 27,300 kJ/kg.
- 15% of thermal losses are up the stack, and the remaining 85% are taken away by cooling water

$$\text{Heat rate (kJ/kWh)} = \frac{3600\ \text{kJ/kWh}}{\eta}$$

- A1:
- A2: `Coal Rate = {Heat Rate} / {Heat Value} = [kg Coal / kWh]`
- Q3:

C

Material Balance – Class Activity 1



2/1/2017

Name:________________________ID #: ____________________

Class Activity 1 on Material Balance

heating value

A new coal-fired power plant with a heat rate of 9000 Btu/kWh burns coal with an energy content of 24,000 kJ/kg. The coal content includes 62-% carbon, 2-% sulfur and 10-% unburnable minerals called *ash*.

a. What will be the carbon emission rate (g C/kWh)?

(a2) CO_2 Emission g CO_2/kWh

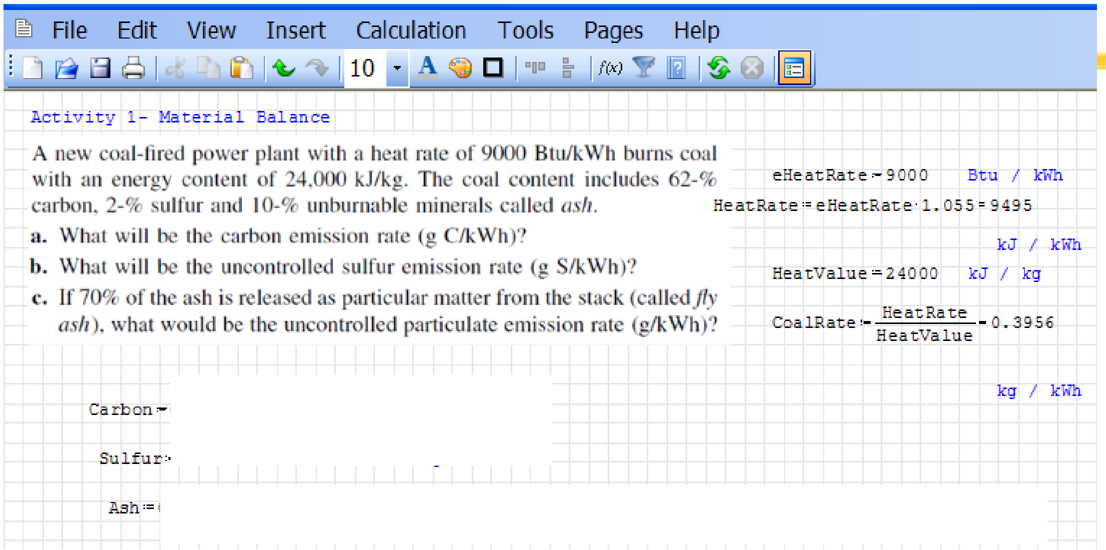
b. What will be the uncontrolled sulfur emission rate (g S/kWh)?

c. If 70% of the ash is released as particular matter from the stack (called *fly ash*), what would be the uncontrolled particulate emission rate (g/kWh)?

d. η (efficiency) ?

Answer ____

Material Balance – Class Activity 1



Activity 1- Material Balance

A new coal-fired power plant with a heat rate of 9000 Btu/kWh burns coal with an energy content of 24,000 kJ/kg. The coal content includes 62-% carbon, 2-% sulfur and 10-% unburnable minerals called *ash*.

a. What will be the carbon emission rate (g C/kWh)?

b. What will be the uncontrolled sulfur emission rate (g S/kWh)?

c. If 70% of the ash is released as particular matter from the stack (called *fly ash*), what would be the uncontrolled particulate emission rate (g/kWh)?

$eHeatRate := 9000$ Btu / kWh

$HeatRate := eHeatRate \cdot 1.055 = 9495$

kJ / kWh

$HeatValue := 24000$ kJ / kg

$CoalRate := \frac{HeatRate}{HeatValue} = 0.3956$

kg / kWh

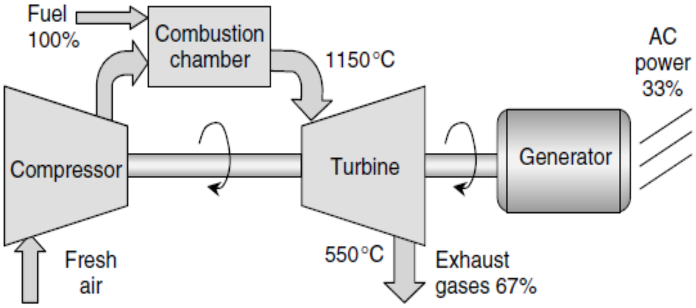
Carbon :=

Sulfur :=

Ash :=

Combustion Gas Turbines

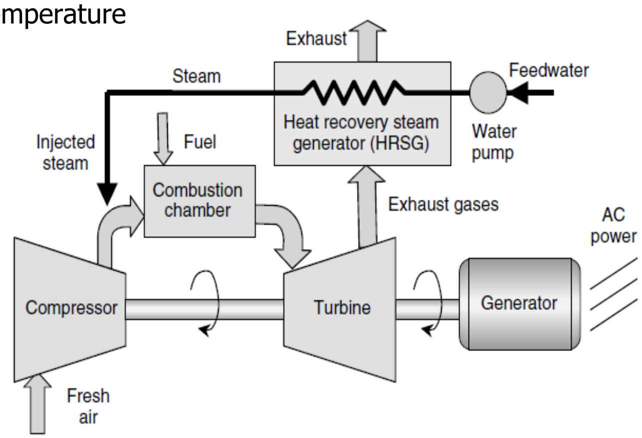
- Fuel: Natural Gas
- Compressor and Turbine shares a connecting shaft
  - ½ the rotational energy created by the spinning turbine is used to power the compressor
- Basic gas turbine



- High Efficiency Gas Turbine: Derivatives of Jet Aircraft; “Aeroderivative turbine”; small-size; quick and numerous up/down

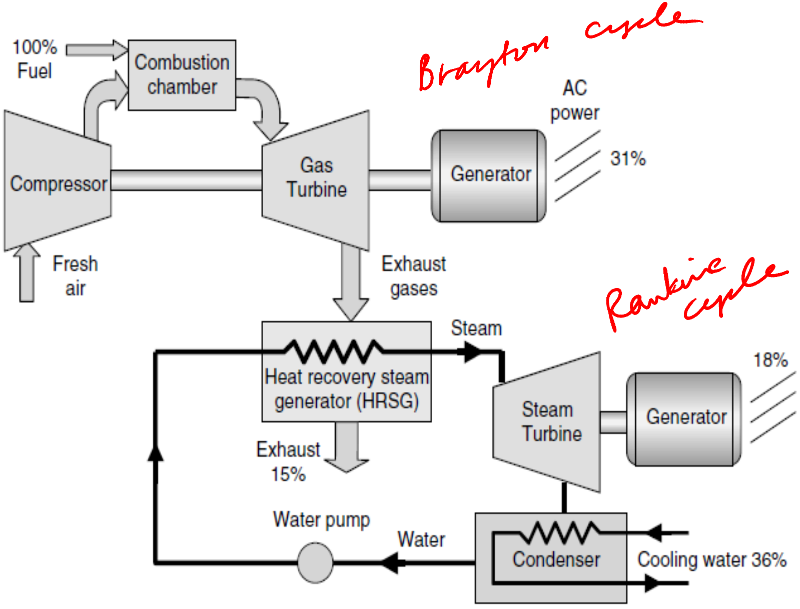
Combustion Gas Turbines

- Steam-Injected Gas Turbine (STIG)
  - Increased Efficiency by a heat exchanger
  - Heat Recovery Steam Generation (HRSG)
    - Injected Steam
    - Effect of fuel reduction
  - HRSG reduces the combustion temperature
    - Reduced NOx emission
  - Efficiency 45%
  - More Expensive



Combined-Cycle Power Plant

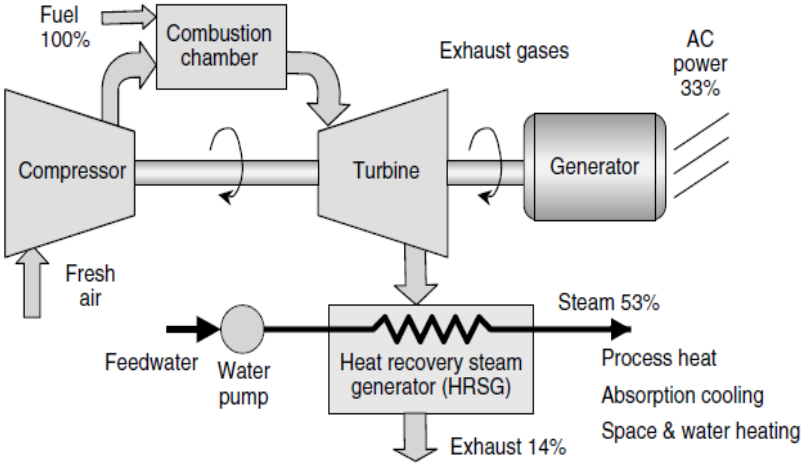
- Gas turbine waste heat can be used to power a second-stage steam turbine →Coupling a gas turbine and steam turbine → Combined Cycle Plant
- 49% Efficiency


Brayton cycle

Rankine cycle

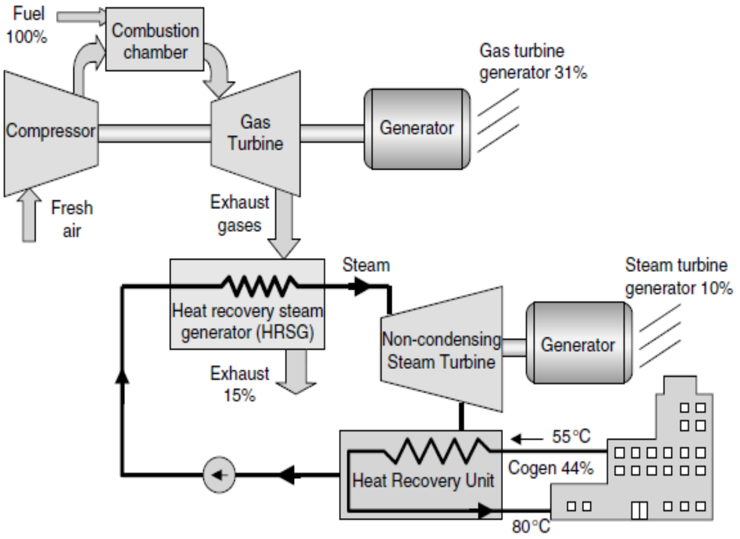
Combined-Cycle Cogeneration 1

- Gas turbine exhaust heat > 500 C
- Cogeneration: Electricity + Thermal Energy
- Use of thermal energy
  - Industrial heating
  - Space heating



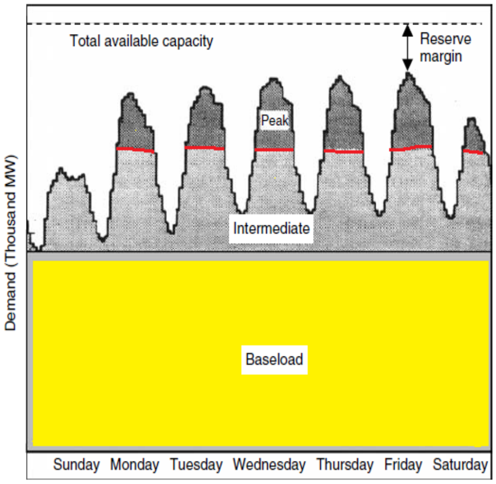
Combined-Cycle Cogeneration 2

- Cogeneration: Electricity + Thermal Energy (Steam Turbine Generation + Heating)



Roles of Different Power Plants

- Load: Daily Patterns (Day and Night), Weekly Patterns, and Seasonal Patterns
- Baseload plants:
  - Coal-fired plants
  - Hydroelectric plants
  - Nuclear plants
- Peak load plants
  - Gas turbines
- Intermediate load plants
  - Day-time operation
- Economic dispatch
  - Economic characteristics of different types
  - Cost Parameters → Screening Curve



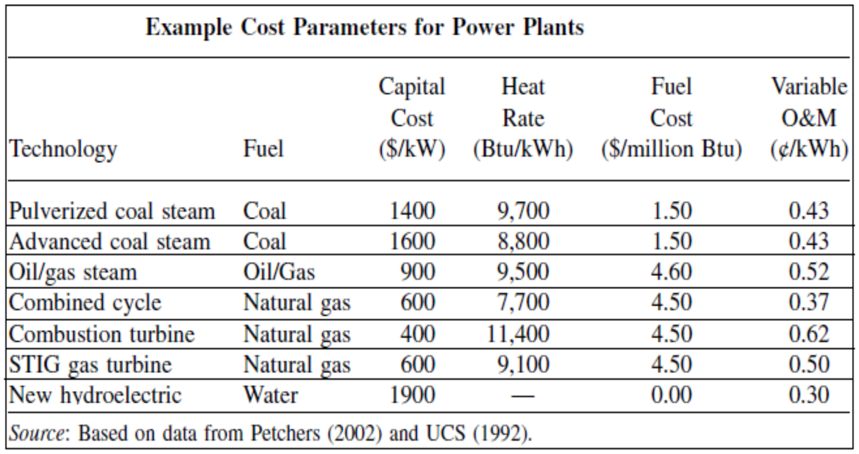
Dispatch

- **Dispatch**: "Selection process of plants to operate at a given time"
- Dispatch plants by the **operating costs** from lowest to highest
- **Renewables** (intermittent operational characteristics) (very low operating costs) should be dispatched first whenever they are available → so they are part of the baseload
- **Hydro** is useful as a dispatch-able source that may supplement baseload, intermittent, or peak loads, especially when existing facilities are down for maintenance or other reasons.

Cost Parameters

- **Screening Curve**: Annual revenue as a function of operation hours per year required to pay fixed and variable costs
- **Fixed cost**: cost must be spent even if the power plant is turned off
  - Capital costs, taxes, insurance, fixed O&M cost, etc
- **Variable cost**: added cost associated with actually running the plant
  - Fuel cost, operational O&M costs
- **Fixed Charge Rate** (**FCR**): FCR per year accounts for interest on loans, acceptable returns of investors, fixed O&M charges, taxes, etc.
  - 11 – 18% per year
- **Annualized fixed cost** ($/yr-kW) = Capital Cost ($/kW) x FCR(/year)
- **Annualized variable cost** ($/yr-kW) = [Fuel ($/Btu) x HeatRate (Btu/kWh) + O&M ($/kWh] x H/yr
  - H: Operating hour per year

Example Cost Parameters



Example Cost Parameters for Power Plants

Technology	Fuel	Capital Cost ($/kW)	Heat Rate (Btu/kWh)	Fuel Cost ($/million Btu)	Variable O&M (¢/kWh)
Pulverized coal steam	Coal	1400	9,700	1.50	0.43
Advanced coal steam	Coal	1600	8,800	1.50	0.43
Oil/gas steam	Oil/Gas	900	9,500	4.60	0.52
Combined cycle	Natural gas	600	7,700	4.50	0.37
Combustion turbine	Natural gas	400	11,400	4.50	0.62
STIG gas turbine	Natural gas	600	9,100	4.50	0.50
New hydroelectric	Water	1900	—	0.00	0.30

Source: Based on data from Petchers (2002) and UCS (1992).

Electricity Cost Example

- A pulverized-coal Steam Plant
- A fixed charge rate (FCR) = 0.16/yr
- Operating hours per year = 8000
- Q1: Find the annualized revenue required?
- Q2: What should be the price of electricity from this plant?

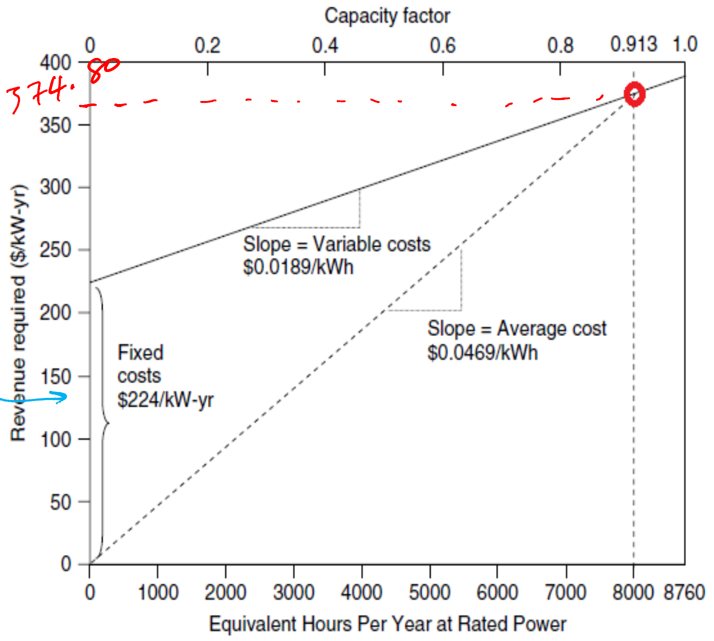
Technology	Fuel	Capital Cost ($/kW)	Heat Rate (Btu/kWh)	Fuel Cost ($/million Btu)	Variable O&M (¢/kWh)
Pulverized coal steam	Coal	1400	9,700	1.50	0.43
Advanced coal steam	Coal	1600	8,800	1.50	0.43

Plant Operation and CF(Capacity Factor)

- In the Example, the operating hours per year is assumed to be 8000 hours with full power → 760 hours of no (zero) power
- It could be that: plant operated 8760 hours per year but not always at the full power
- Annual Output (kWh/yr) = Rated Power (kW) x 8760 h/yr x CF (Capacity Factor)
- CF (in the example) = 8000/8760 = 0.9132
- Capacity Factor (CF) = {Average Power}/ {Rated Power}

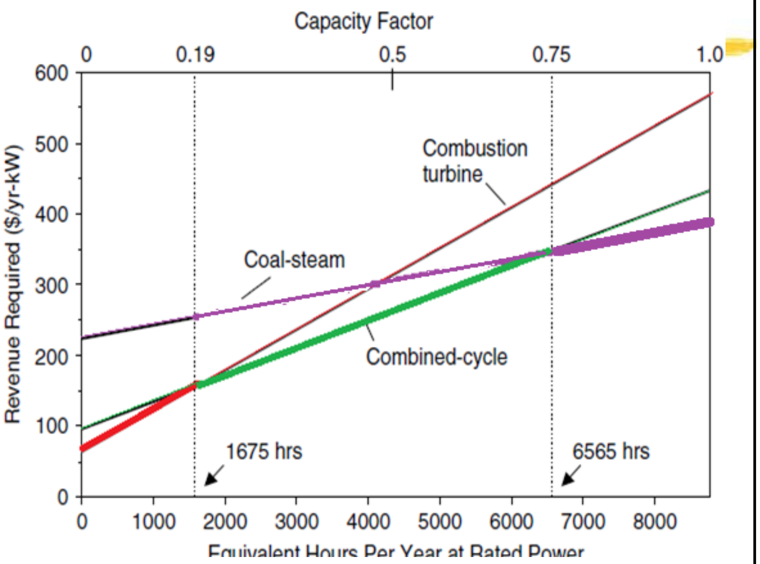
Plant Operation and CF(Capacity Factor)

- Fixed Costs = $1400/kW x 0.16/yr = **$224/kW-yr**
- Variable Costs ={ $1.5/10^6 Btu x 9700 Btu/KWh + $0.0043/kWh) x 8000 h/yr = $150.80/kW-yr = slope **$0.0189/kWh**
- Annualized revenue required = Fixed costs + variable costs = $(224+150.80)/kW-yr = $374.80/kW-yr = **$0.0469/kWh**
- **CF at the circle = 0.913**



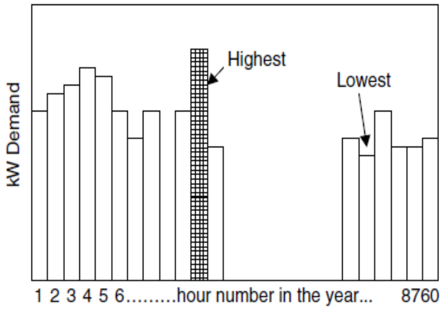
Screening Curves

- Cost curves for different power plants on the same axis
- Example Curves
- **Combustion turbine** is cheapest to build (Lowest fixed cost) but is expensive to operate (steepest variable cost slope); viable when operating no more than 1675 hours per year with CF < 0.19 → best choice for peaking plant
- **Coal-steam plant** (high capital cost and low fuel cost) is least expensive as long as it runs at least 6565 hours per year (CF > 0.75) → best choice for baseload plant
- **Combined cycle plant** is cheapest if it operates between 1675 and 6565 hours (0.19 <CF <0.75) → best intermediate load plant



Load-Duration Curves

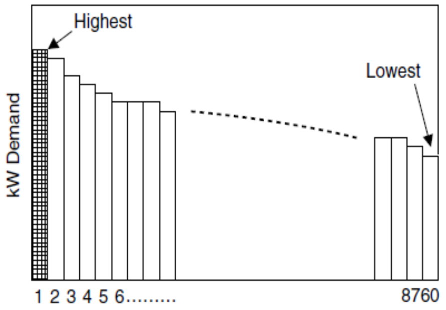
- Hourly Load Curve
  - Hourly kW demand → The area is kWh or energy used in that hour
- Load-Duration Curve
  - Rearranged Hourly load curve in the order of load magnitude



HOUR-BY-HOUR LOAD CURVE...

Area of each rectangle is kWh of energy in that hour...

Total area is kWh/yr



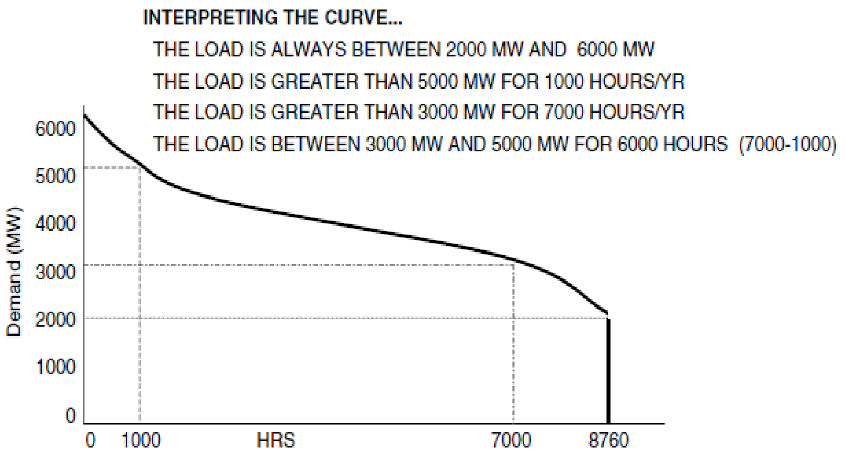
LOAD CURVE REORDERED FROM HIGHEST TO LOWEST..

Total area is still kWh/yr

"LOAD–DURATION CURVE"

Load Duration Curve

- A smooth version of a load-duration curve



INTERPRETING THE CURVE...

THE LOAD IS ALWAYS BETWEEN 2000 MW AND 6000 MW

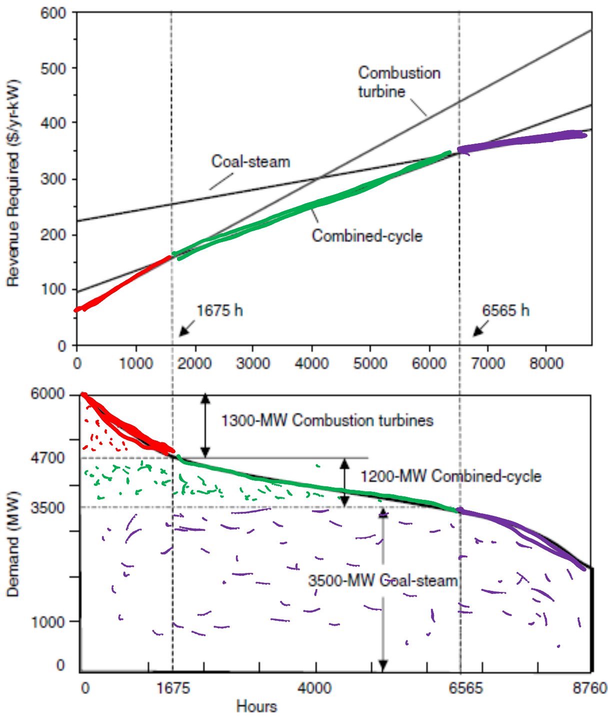
THE LOAD IS GREATER THAN 5000 MW FOR 1000 HOURS/YR

THE LOAD IS GREATER THAN 3000 MW FOR 7000 HOURS/YR

THE LOAD IS BETWEEN 3000 MW AND 5000 MW FOR 6000 HOURS (7000-1000)

Screening Curve and Load-Duration Curve

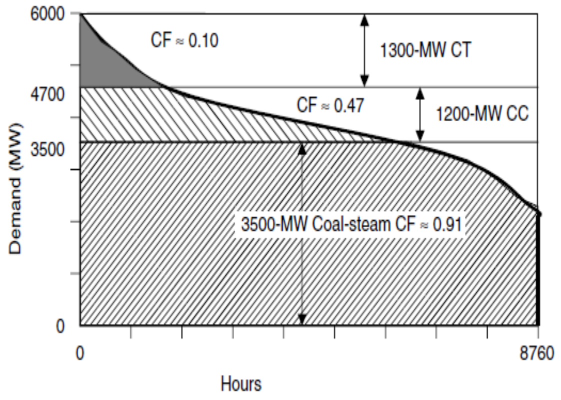
- Determination of on optimum mix of power plants
- Crossover Points for the first Cut Estimate of Generation Mix
- 0 - 6565 hours & 6565 – 8760 hours → Demand of 3500 MW → Coal-Steam
- 6565 – 1675 hours & 1675 – 0hours → Demand of 1200 MW → Combined-Cycle
- 0 - 1675 hours → Demand of 1300 MW → Combustion Turbine



CF and Generation Mix

- CF for each power plant is the fraction of the shaded area to the horizontal rectangular
- EXAMPLE of Unit Cost of Electricity for the generation mix
- The peaker plant electricity is much more expensive
  - Lower efficiency
  - Expensive fuel – natural gas
  - Capital cost is spread over so few kW-hour of output --- they are used so little

given



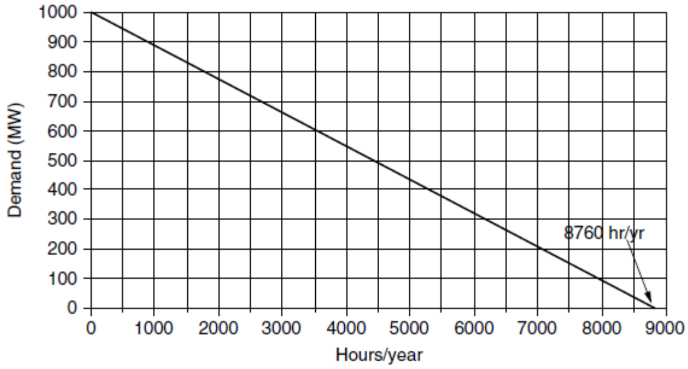
Generation Type	Rated Power (MW)	CF	Fixed Cost (million $/yr)	Variable ($/kWh)	A Output (billion kWh/yr)	B Total Cost (billion $/yr)	$\frac{B}{A}$ Unit Cost (¢/kWh)
Coal-steam	3500	0.91	784.0	0.0189			
Combined-cycle	1200	0.47	115.2	0.0390			
Combustion turbine	1300	0.10	83.2	0.0556			

calc.

Annual output (kWh/yr)
= Rated power (kW) × 8760 h/yr × CF

Class Activity - 2

Consider the following very simplified load duration curve for a small utility:

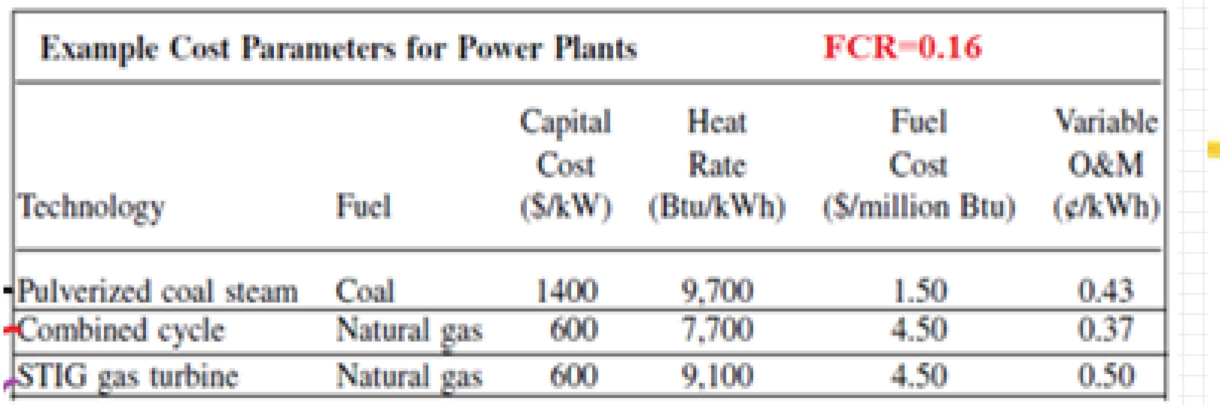


a. How many hours per year is the load less than 200 MW?

b. How many hours per year is the load between 300 MW and 600 MW?

c. If the utility has 500 MW of base-load coal plants, what would their average capacity factor be?

d. How many kWh would those coal plants deliver per year?

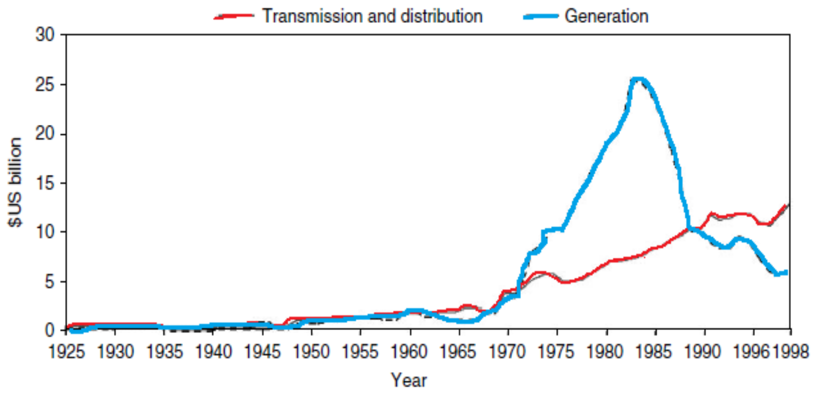


Example Cost Parameters for Power Plants FCR=0.16

Technology	Fuel	Capital Cost ($/kW)	Heat Rate (Btu/kWh)	Fuel Cost ($/million Btu)	Variable O&M (¢/kWh)
Pulverized coal steam	Coal	1400	9,700	1.50	0.43
Combined cycle	Natural gas	600	7,700	4.50	0.37
STIG gas turbine	Natural gas	600	9,100	4.50	0.50

Transmission and Distribution

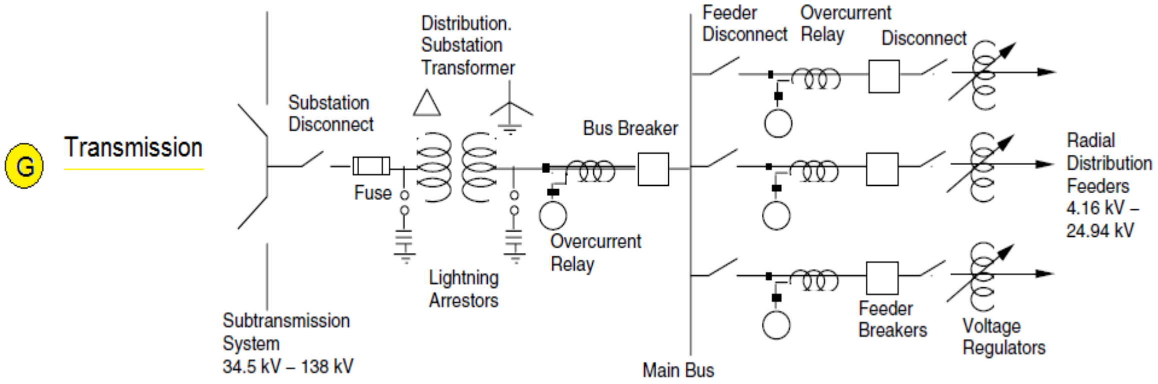
- **T&D** Construction Expenditures at US investor-owned utilities
- **Generation** Expenditures



- Generation (1970 – 1985):Huge spending for Nuclear Power Stations
- T&D (1990s): Most spent on the Distribution portion of T&D

Transmission and Distribution

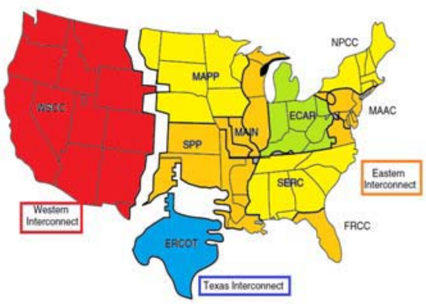
- Utility Grid System: Voltage Levels
- Distribution Systems
  - Protection and Isolation Components: Switches, Circuit Breakers, Fuses, Sectionalizers



National Transmission Grid

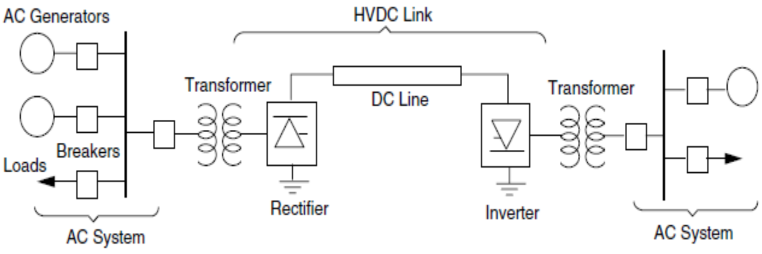
- US: 275,000 miles of transmission lines
- US Transmission Network
  - NERC (North American Electric Reliability Council) was formed after 1965 Northeastern blackout
  - 3-Major Power Grids: Eastern Interconnect, Western Interconnect, and Texas Interconnect
- 10 NERC Regions

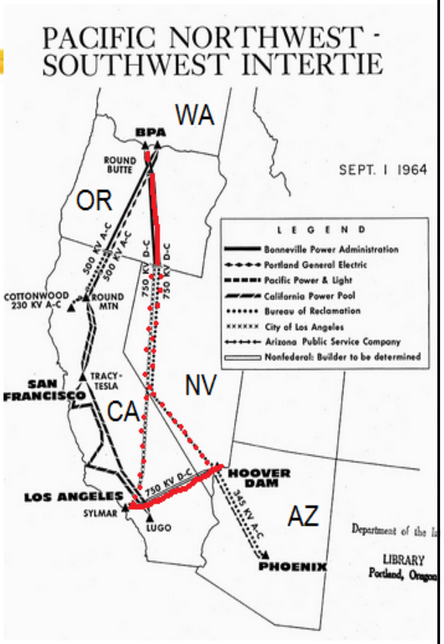
ECAR (East Central Area Reliability Coordination Agreement); ERCOT (Electric Reliability Council of Texas); FRCC (Florida Reliability Coordinating Council); MAAC (Mid-Atlantic Area Council); MAPP (Mid-Continent Area Power Pool); MAIN (Mid-America Interconnected Network); NPCC (Northeast Power Coordinating Council); SERC (Southeastern Electric Reliability Council); SPP (Southwest Power Pool); WSCC (Western Systems Coordinating Council).



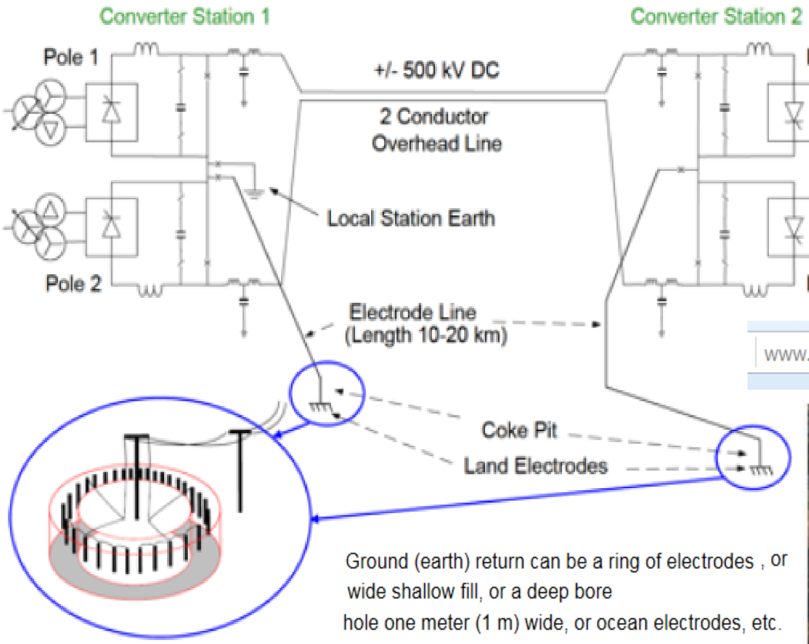
National Transmission Grid

- Transmission Configuration Types
  - 3-phase AC system (Almost all transmission system)
  - HVDC (High Voltage DC) transmission
    - More economical for 500 miles or longer tranasmission
    - Example: 600kV 6000-MW Pacific Intertie: Pacific Northwest – Southern California
    - Converters are required
      - Rectifiers and Inverters: AC – DC - AC





Pacific Intertie Ground



www.envirostudies.net/development/hvdc/

Ground (earth) return can be a ring of electrodes , or wide shallow fill, or a deep bore hole one meter (1 m) wide, or ocean electrodes, etc.

Ring of ground electrodes, 300 m radius, for 500 kV HVDC (Manitoba).

Pacific Intertie Ground

The problem with high voltage dc with earth return is in the grounding. Or getting enough ground contact to accept the current. The current will tend to dryout the local ground grid soil, at which point the grid resistance will increase. There are things you can do to increase the ground contact, like use charcoal, or some high metal supliment for the soil, but it is the same thing as increasing the ground grid size (I think it is cheeper than increasing the ground grid).

www.eng-tips.com/viewthread.cfm?qid=327869

Wiki says:

The grounding system at Celilo consists of 1,067 cast iron anodes buried in a two foot trench of petroleum coke, which behaves as an electrode, arranged in a ring of 3,255 m (2.02 mi) circumference at Rice Flats (near Rice, Oregon), which is 10.6 km (6.6 mi) SSE of Celilo. It is connected to the converter station by two aerial 644 mm2 steel-reinforced aluminum (ACSR) cables, which end at at a strainer situated at 45.4975865°N 121.0646206°W.

The Sylmar grounding system is a line of 24 silicon-iron alloy electrodes submerged in the Pacific Ocean suspended in concrete enclosures about one meter above the ocean floor. The grounding array is 48 km (30 mi) from the converter station and is connected by a pair of 644 mm2 aluminum cables.

Pacific Intertie Ground

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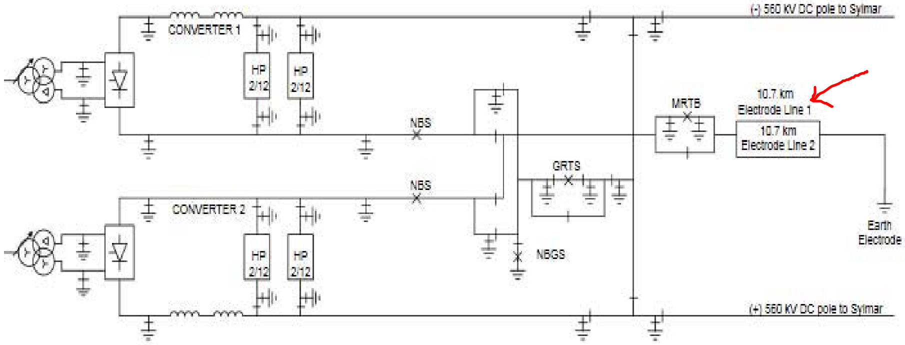
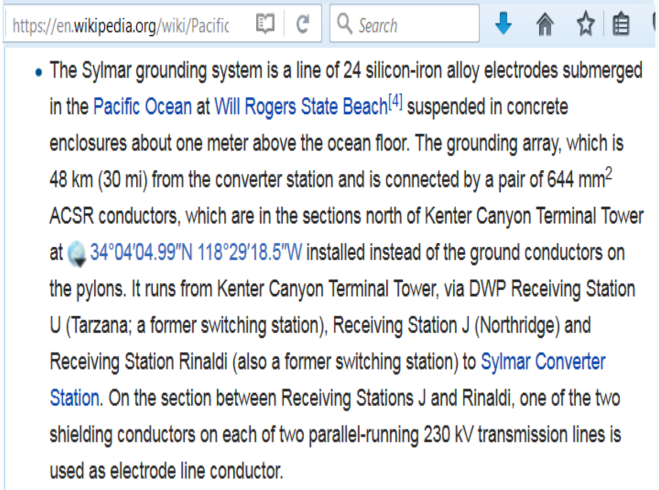


[PDF] Celilo Pacific DC Intertie Upgrade presentation - ABB
https://library.e.abb.com/.../Celilo%20Pacific%20DC%20Intertie%20Upg...

Pacific Intertie Ground

KTY: PACIFIC INTERTIE - SYLMAR OCEAN ELECTRODE LINE



- The Sylmar grounding system is a line of 24 silicon-iron alloy electrodes submerged in the Pacific Ocean at Will Rogers State Beach[4] suspended in concrete enclosures about one meter above the ocean floor. The grounding array, which is 48 km (30 mi) from the converter station and is connected by a pair of 644 mm^2 ACSR conductors, which are in the sections north of Kenter Canyon Terminal Tower at 34°04′04.99″N 118°29′18.5″W installed instead of the ground conductors on the pylons. It runs from Kenter Canyon Terminal Tower, via DWP Receiving Station U (Tarzana; a former switching station), Receiving Station J (Northridge) and Receiving Station Rinaldi (also a former switching station) to Sylmar Converter Station. On the section between Receiving Stations J and Rinaldi, one of the two shielding conductors on each of two parallel-running 230 kV transmission lines is used as electrode line conductor.

thomassnyder.ieee-lac.org/?page_id=299

Sylmar Ground Return System Replacement Proposed Project Image

Regulatory Side of Electric Power

- 1935 Public Utility Holding Company Act (PUHCA)
  - Holding Company: "A financial Shell that exercises management control of one or more companies through ownership of their stock."
  - 1929 -- 16 holding companies controlled 80% of the U. S. electricity market
  - 1935 --- PUHCA to regulate gas and electric industries and prevent holding company excesses from reoccurring
    - Many holding companies were dissolved, their geographic size was limited
    - Restricted holding companies to business within a single integrated utility
- 1978 Public Utility Regulatory Policies Act (PURPA)
  - Background: Oil shock and crisis in 1973; Driven to energy efficiency, renewable energy systems, new small inexpensive gas turbines.
  - 2 Key Provisions:
    - Certain industrial facilities and other customers were allowed to build and operate their own small on-site generators with remaining connected to the utility grid
    - Utilities were required to purchase electricity from certain qualifying facilities (QFs) at a just and reasonable price (avoided cost – open market price) : QFs < 80MW, > 75% of renewables
  - Effect: Construction of numerous renewable energy facilities, especially in California

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Regulatory Side of Electric Power

- 1992 Energy Policy Act (EPAct)
  - Open wider the electricity generation market
  - QFs were much broader: "Exempt Wholesale Generators (EWGs)" – any size, any fuel, and any generation technology, wheel their power from any location to another location
  - Key restriction to EWG: "Wholesale wheeling" -- the buyer must not be the final retail customer who uses that power
  - Note: Independent Power Producers (IPPs) can participate Retail Wheeling if states allow.
- 1997 FERC Order 888
  - Background: IPPs were often denied to transmission line access for wholesale wheeling
  - FERC Order 888 eliminated the anti-competitive practices of transmission services
  - IOUs (utilities) were required to publish nondiscriminatory tariffs for transmission access for all generators
  - FERC Order 888 encouraged formation of Independent System Operators (ISOs), non-profit entities to control of transmission facilities owned by traditional IOUs.

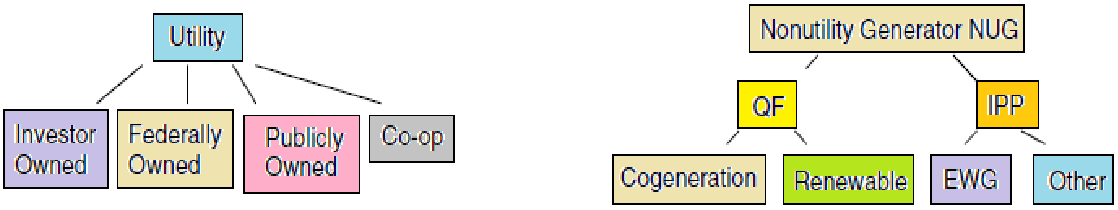
Regulatory Side of Electric Power

- 1999 FERC (Federal Energy Regulatory Commission) Order 2000
  - Breaking the vertically integrated utilities

  - Creation of Regional Transmission Organizations (TROs)
  - Promote a fully competitive wholesale power market
  - Encourage the establishment of Independent Regional Transmission Organizations (RTOs) - shifts the transmission line ownership:
    - (a) to a handful of separate transmission companies (TRANSCOs), or
    - (b) with continued utility ownership but with the control turned over to independent system operators (ISOs)

Utilities (IOUs) and Nonutility Generators (NUGs)

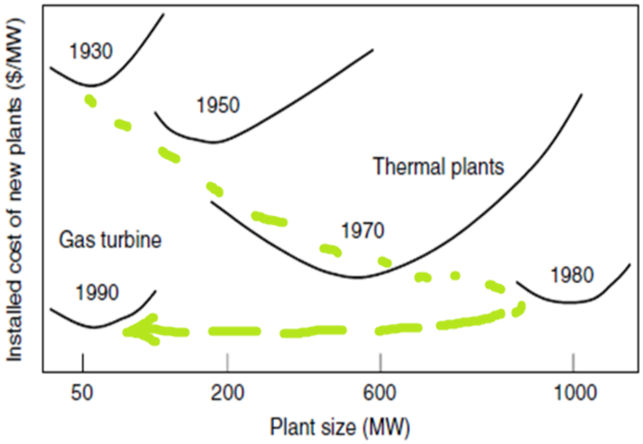
- Utilities and Non-utilities



- QF: Qualifying Facility ← PURPA
- IPP: Independent Power Producer ← EPAct
- EWG: Exempt Wholesale Generator ← EPAct, PUHCA

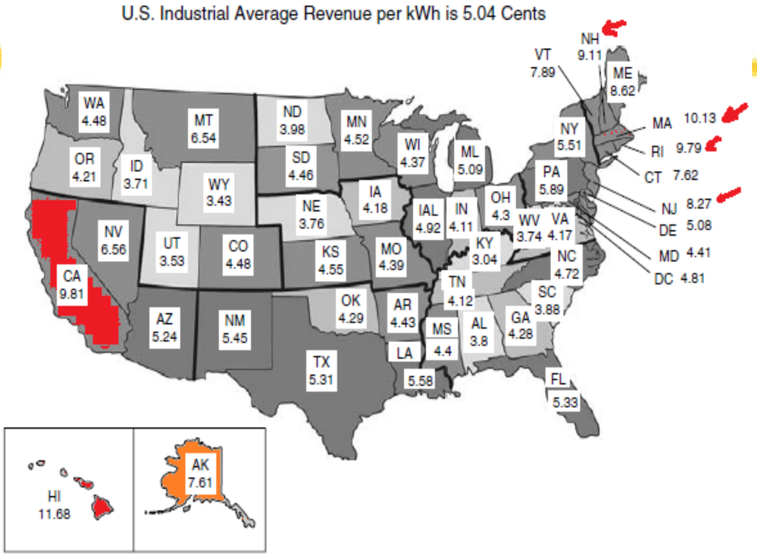
Competitive Market

- Background:
    - Successful deregulation in the industries of telecommunications, airlines, and natural gas industry → competition brings benefit
    - PURPA and EPAct: Opening up the grid to allow generators to compete for customers, thereby hopefully driving down the costs and prices → Deregulation in power industry may have the same benefit ?????
- Power industry restructuring ← motivated by emergence of new, **small gas turbine and combined-c plants** with reduced fixed costs and operating costs compared with traditional facilities already on line.



Power Industry Restructuring

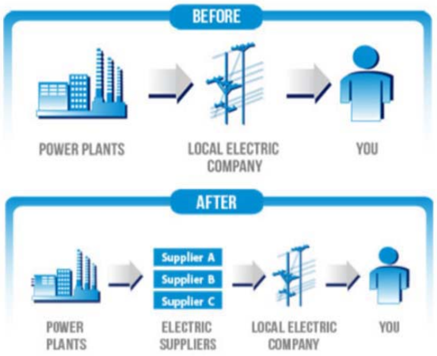
- States with high utility costs took the initiative of restructuring program
- CA: retail price was among the highest; whole sale market price was less than ¼ of the amount (power from nearby states with hydroelectricity)
- Fear of loosing industrial customers to other states with cheaper electricity rate
- CPUC 1994: Restructure Rule ("De-regulation") to reduce CA's high electricity rate



Average industrial sector revenue per kWh, 2001. California was 6.6¢/kWh in 1998, before restructuring. From EIA (2003).

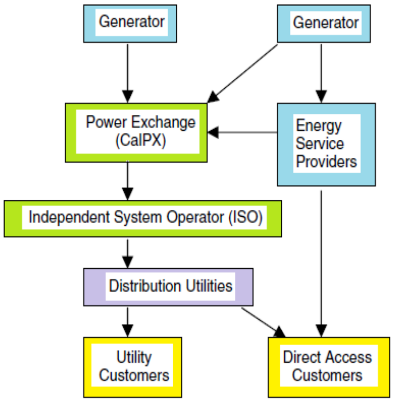
California Restructure

- 1980 California **Assembly Bill (AB) 1890**
  - Wholesale market open to competition
  - Choice to All Customers for Electricity Suppliers
  - Immediate 4-year, 10% rate reduction to Residential and Small Commercial Customers → funded by bond issuance
  - Support (with exemption and subsidy) for renewable energy, customer energy efficiency, and low-income customers
  - Rate frozen for IOUs at 1996 level → meant to give Utilities to recover costs → with the belief that, with the frozen rate, the utilities would collect more revenue than would in wholesale market
  - Utilities required to sell off their generating capacity to new generating companies which would compete to sell their power (→ which would lead to lowering prices)
  - After 4 years, (in 2002), the rate would be unfrozen.
- AB 1890 Application
  - Pacific Gas & Electric (PG&E)
  - Southern California Edison (SCE)
  - San Diego Gas & Electric (SDG&E)

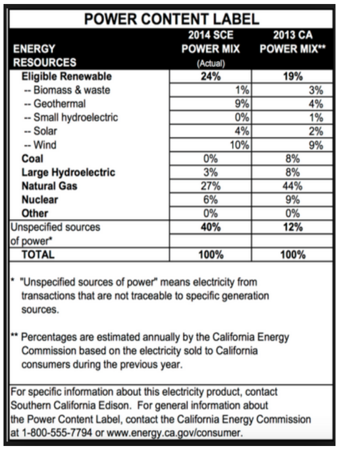


California Restructure

- Establishment of Independent System Operator (ISO) – transmission grid operation
- Set up California Power Exchange (CalPX) for daily auction



California's initial electric industry restructuring.



POWER CONTENT LABEL

ENERGY RESOURCES	2014 SCE POWER MIX (Actual)	2013 CA POWER MIX**
Eligible Renewable	**24%**	**19%**
-- Biomass & waste	1%	3%
-- Geothermal	9%	4%
-- Small hydroelectric	0%	1%
-- Solar	4%	2%
-- Wind	10%	9%
Coal	0%	8%
Large Hydroelectric	3%	8%
Natural Gas	27%	44%
Nuclear	6%	9%
Other	0%	0%
Unspecified sources of power*	**40%**	**12%**
TOTAL	**100%**	**100%**

* "Unspecified sources of power" means electricity from transactions that are not traceable to specific generation sources.

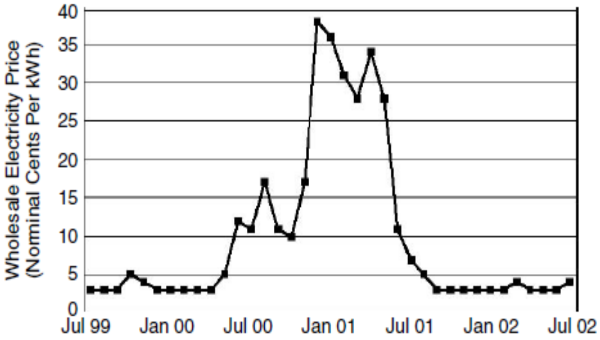
** Percentages are estimated annually by the California Energy Commission based on the electricity sold to California consumers during the previous year.

For specific information about this electricity product, contact Southern California Edison. For general information about the Power Content Label, contact the California Energy Commission at 1-800-555-7794 or www.energy.ca.gov/consumer.

- **Power Content Label:** specification of the fraction of the generation from renewables, coal, hydroelectric, natural gas, and nuclear

Collapse of California Restructure

- March 1998 Official Opening of Wholesale Electricity Market
- 1998 – 2000: Success!!
  - PG&E, SCE, and SDG&E sold off 18,000 MW generation capacity to 5 new entrants to the California market: Duke, Dynergy, Reliant, AES, and Mirant
  - Marketers of Green Power making inroads to residential market.
  - Wholesale Electricity Price = $35/MWh → $0.035/kWh (much less than the frozen retail rate)
- Summer 2000
  - August 2000: $0.17/kWh
  - One time high: $0.80/kWh
  - Factors:
    - Higher Natural Gas Price
    - Drought ← reduced generation in NW
    - Lack of new power plant construction in adjacent states
  - Principal Cause
    - Manipulation of market by generators



Collapse of California Restructure

- Generators purposely removed capacity from the grid for profit increase
  - Enron and 30 other energy companies
- Jan 2001: Rolling blackouts & wholesale price: $1.50/kWh
- May 2001: PG&E declared bankruptcy
- SCE on the brink
- CalPX shutdown
- Cal ISO began to buy power and operate
- Summer 2001
  - FERC set price cap on wholesale Power
  - CA Governor in negotiation for Long-term power contracts
  - CA's aggressive energy conservation