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ELECTRICITY GENERATION AND TRANSMISSION

Michael W. Golay, Professor of Nuclear Science and Engineering

Lab4energy International 2014, January 10 at MIT

ORGANIZATION OF PRESENTATION

- Why interest in renewable electricity generation technologies?
  Answer: To reduce climate change
- What are the renewable electricity generation technologies?
- How do the electrical generation technologies compare?
- What is a typical national industrialized country electrical production system like?
- What is the electrical grid?
- What influences are causing the grid to change?
  - Free markets
  - Use of renewable generation technologies
  - Smart grid?

FUNDAMENTAL SOURCES OF ENERGY USED BY DIFFERENT ENERGY TECHNOLOGIES

Energy Source	Fundamental Nuclear Energy Source
Solar	Gravitationally confined solar fusion reactions transmitted via photons
Fossil Fuels	Gravitationally confined solar fusion reactions transmitted via photons and stored in biomass
Geothermal	Naturally-occurring radioactive decays of materials within the Earth and Gravitational Work
Tidal	Nuclear reactions following the Big Bang Sustaining Current Gravitational Work
Nuclear Fission	Neutron-induced fission reactions of heavy nuclei
Nuclear Fusion	Nuclear fusion reactions of light nuclei

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CLIMATE CHANGE AND ELECTRICITY

Electricity-Related Emissions are:

- The largest single source of CO_2 in industrialized countries
- Produced from combustion of fossil fuels in electrical generation
- Associated with most current electrical generation
- Likely to continue for several decades

Nuclear, Solar and Geothermal Electrical Generation Technologies do not Emit Large Amounts of CO_2

- Nuclear and hydroelectric generation typically rank after coal and natural gas as electricity sources
- Other renewable electricity generation technologies are of minor importance, but are growing rapidly

All Generation Technologies Face Environmental, Social, and Economic Barriers to Larger Scale Use

RENEWABLE ELECTRICITY TECHNOLOGIES

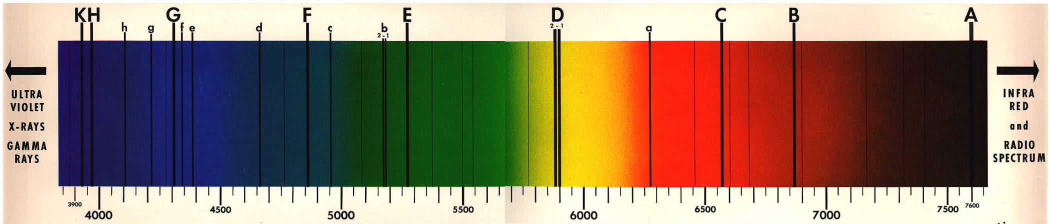
Technology	Phenomena				
Solar	Nuclear fusion-generated energy reaches Earth from sun as photons				
• Thermal	Collector materials absorb photons and become heated*	⟹	Heat engine working fluid becomes heated from collector*	⟹	Rankine cycle generation of AC electricity†
• Biomass	Solar photons are absorbed by plants in photosynthesis processes	⟹	Harvested plants are used as chemical feedstocks by synfuels or dried and burned†	⟹	Rankine cycle generation of AC electricity†
• Photovoltaic (PC)	Superconducting collector materials absorb photons, mobilizing electrons-hole pairs in the form of DC electric current*				
• Hydroelectric	Photons are absorbed in water, causing heating and evaporation into the atmosphere†	⟹	Atmospheric water vapor condenses and falls to earth, where it collects in water bodies†	⟹	Collected water flows downward through a turbine that turns an AC electric generator *
• Wind	Photons are absorbed in terrestrial materials that become heated*	⟹	Heat is transferred to atmospheric air that rises and flows as wind*	⟹	The wind flows through a turbine that turn a DC electric generator*
Geothermal	Radioactive decay reactions within the Earth heat magma that flows toward the Earth's surface, heating the crust†	⟹	Groundwater flowing in the crust is heated, and then withdrawn at the power plant†	⟹	Steam, heated by the groundwater, is used in a Rankine cycle for generation of AC electricity*

Energy form produced:
* Work/electricity: AC = alternating current electricity, DC = direct current electricity
† Heat

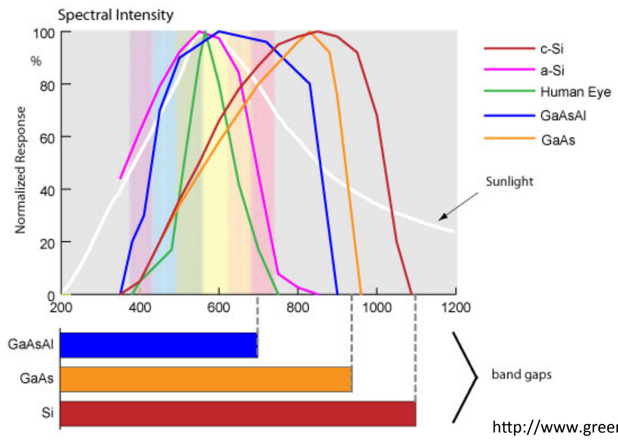
SOLAR ENERGY

- From sun, above Earth's atmosphere 1200 W/m^2
- At Earth's surface
  - Maximum 1000 W/m^2
  - Average 250 W/m^2
- Average at latitude 45° in April 400 W/m^2
- Seasonal variation ± 25–50% of mean (average)
- Causes of interruption of solar insolation
  - Clouds
  - Dust
  - Rain
  - Night

SOLAR SPECTRUM AND PV SPECTRAL SENSITIVITY



www.coseti.org



http://www.greenrhinoenergy.com

PHOTOVOLTAIC

http://en.wikipedia.org/wiki/Photovoltaics

http://www2.dupont.com/Photovoltaics/en_US/news_events/imagegallery.html

STATIONARY SOLAR PHOTOVOLTAIC ARRAY

http://www.southeastern.edu/admin/phys_plant/green/solarpanel/

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ADVANCED TWO AXIS SOLAR TRACKER

http://suntotal.en.made-in-china.com/product/wblmIRgKEMYd/China-Advanced-Two-Axis-Solar-Tracker-Sy-Bat-C-.html

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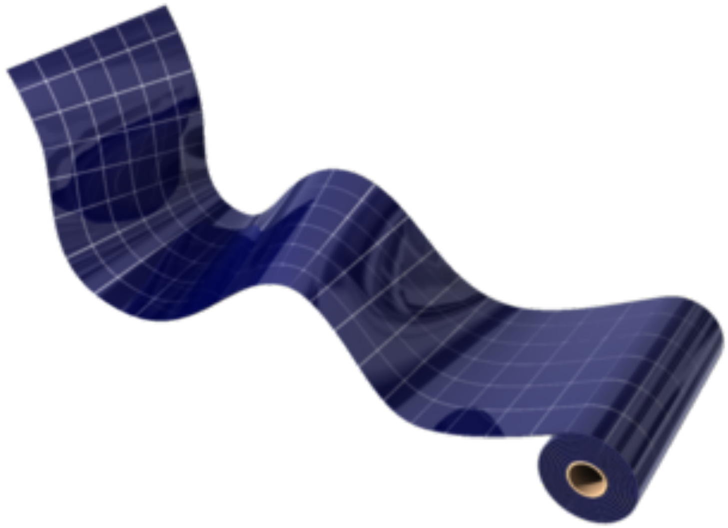
FLEXIBLE PV MODULES



http://www.micel-films.com/flexible-photovoltaic-modules-104.html

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FLAT PLATE SOLAR THERMAL COLLECTOR

http://www.directindustry.com/prod/maharishi-solar-technology/flat-plate-solar-thermal-collectors-54437-716227.html

PARABOLIC TROUGH SOLAR THERMAL POWER PLANT

http://science.howstuffworks.com/environmental/green-tech/energy-production/solar-thermal-power.htm

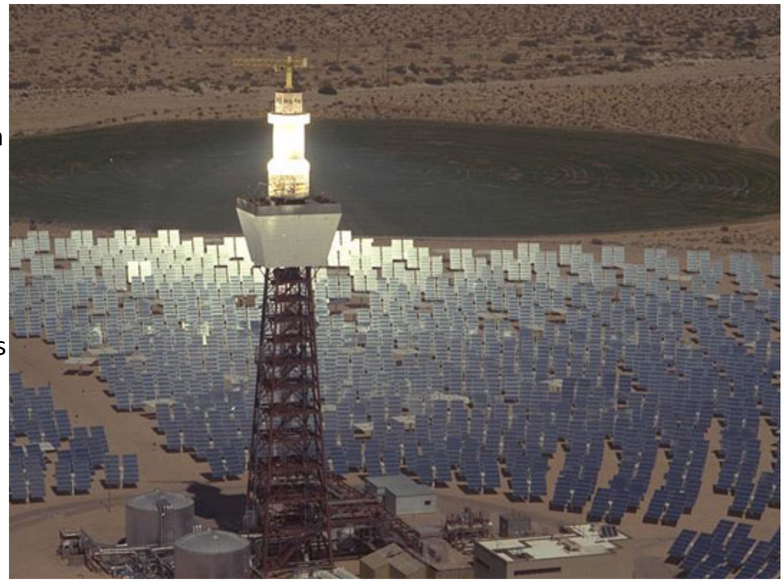
http://www.greenenergyreporter.com/renewables/solar/solar-thermal-generated-electricity-future-dominating-technology/

THERMAL SOLAR POWER PLANT

http://papundits.wordpress.com/2009/07/25/the-problem-with-solar-thermal-power/

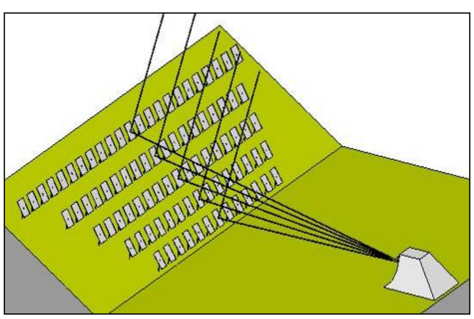
MOLTEN SALT SOLAR PLANT

The Department of Energy just invested $737 million into the Crescent Dunes Solar Energy Project in Nevada, which will generate energy well into the night by using molten salt as an energy storage medium. To do this the plant will focus nearly 20,000 heliostats upon a solar power tower filled with salt, heating the material to 1,050 degrees Fahrenheit. Once it has been heated the salt will retain its thermal energy for a long time, and it can be mixed with water to produce steam on demand, which can be used to drive turbines to produce electricity.



http://inhabitat.com/nevadas-new-molten-salt-solar-plant-will-produce-power-long-after-the-sun-sets/

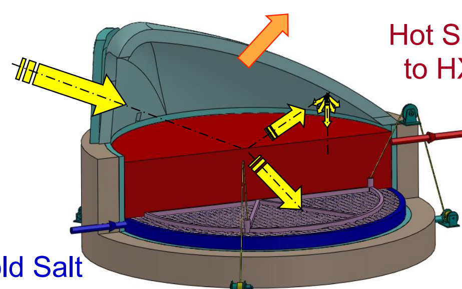
Two Component System



Light Reflected From Hillside Heliostats to CSPonD System

(Not to scale)

Flat Land Options Exist



Light Collected Inside Insulated Building With Open Window

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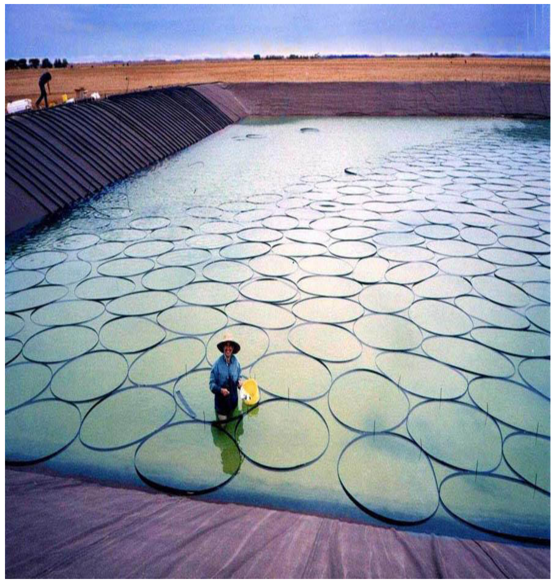
SOLAR POND, PYRAMID HILL, VICTORIA, AUSTRALIA



http://www.eng.usf.edu/~hchen4/Solar%20Thermal.htm

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WIND TURBINES

www.sme.org

hobbiezones.com

www.latimes.com

GEOTHERMAL LARDERELLO, TUSCANY, ITALY

Pipework for geothermal power generation in Valle del Diavolo (Devil's Valley), Larderello.

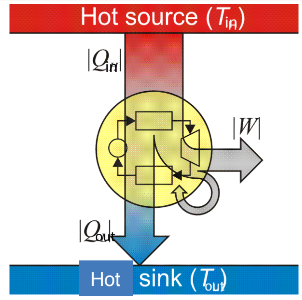
Larderello is a Volcanically active area, renowned for Its geothermal productivity, now producing 10% of the world's entire supply of geothermal electricity, amounting to 4,800 GWh per year and powering about a million Italian households. Its geology makes it uniquely conducive to geothermal power production, with hot granite rocks lying unusually close to the surface, producing steam as hot as 202°C (396 °F).

http://en.wikipedia.org/wiki/Larderello

GEOTHERMAL POWER PLANT AT THE GEYSERS NEAR SANTA ROSE, CA

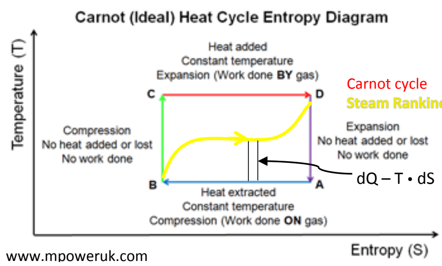
http://pubs.usgs.gov/gip/dynamic/geothermal.html

HEAT ENGINE EFFICIENCY



en.wikipedia.org

- Heat Source, T_{in}
- Input Heat, Q_{in}
- Work, $W = F \times \Delta X$ (F = Force, X = Distance)
- Output Heat, $Q_{out} = Q_{in} - W$
- Hot Sink, T_{out}
- Carnot Efficiency $= \dfrac{W}{Q_{in}} = \dfrac{Q_{in} - Q_{out}}{Q_{in}} = \dfrac{T_{in} - T_{out}}{T_{in}} < 1$
- Is the highest efficiency possible using heat source at T_{in} and hot sink at T_{out}
- Result: Heat work are both forms of energy, but Work < Q_{in}



www.mpoweruk.com

ELECTRICITY GENERATOR EFFICIENCIES

Technology	T-max (ºC)	Thermal Efficiency	
Steam-Rankine	500	0.40	
Fossil-Combined Brayton (Gas Turbine) and Rankine	700	0.60	
Nuclear-Rankine			
LWR	300	0.33	
Liquid Metal or Molten Salt	500	0.40	
Geothermal-Rankine	200	0.25	
Solar Thermal	700-300	0.60-0.33	
Solar PV*		0.10-0.30**	Based upon photon energy flux
Wind*		0.45-0.59**	Based upon wind kinetic energy flux
Hydro-electric		0.90**	Based upon water potential energy flux

*Direct conversion system, not a heat engine

$$**\text{Efficiency} = \left[\frac{\text{Work}}{\text{Energy} - \text{In}}\right]$$

RENEWABLE ELECTRICITY TECHNOLOGIES, continued

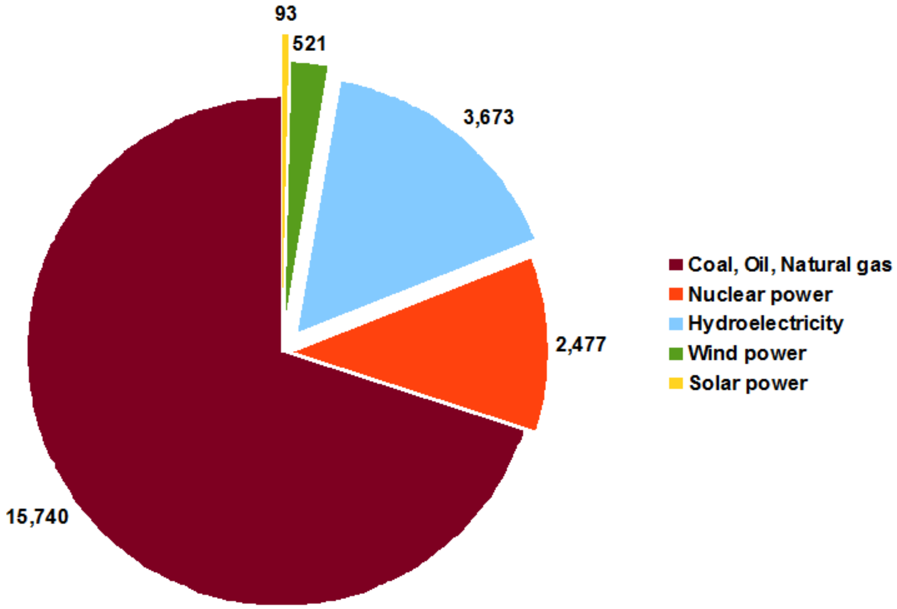
Technology	Economics/Costs			Environmental Costs					Dispatchable Generation?	Hazards
	Fuel	O&M*	Capital	Land	Water	Pollutants	Labor	Ecological		
Solar										
Thermal	Free	Moderate	High	High	Low	Low	Low	Low	Quasi	Low
Biomass	Free	Moderate	High	High	High	High-Fertilizers	High	High	Yes	High
Photovoltaic	Free	Moderate	High	High	Low	Low	Low	Low	No	Low
Hydroelectric	Free	Low	High	High	Low	Low	Low	High	Yes	High
Wind	Free	Low	High	Moderate	Low	Low	Low	Birds	No	Moderate
Geothermal	Free	Moderate	High	Low	Low	Moderate-Brine	Low	Low	Yes	Low

*Operations and Maintenance

ENVIRONMENTAL EFFECTS OF ENERGY SOURCES

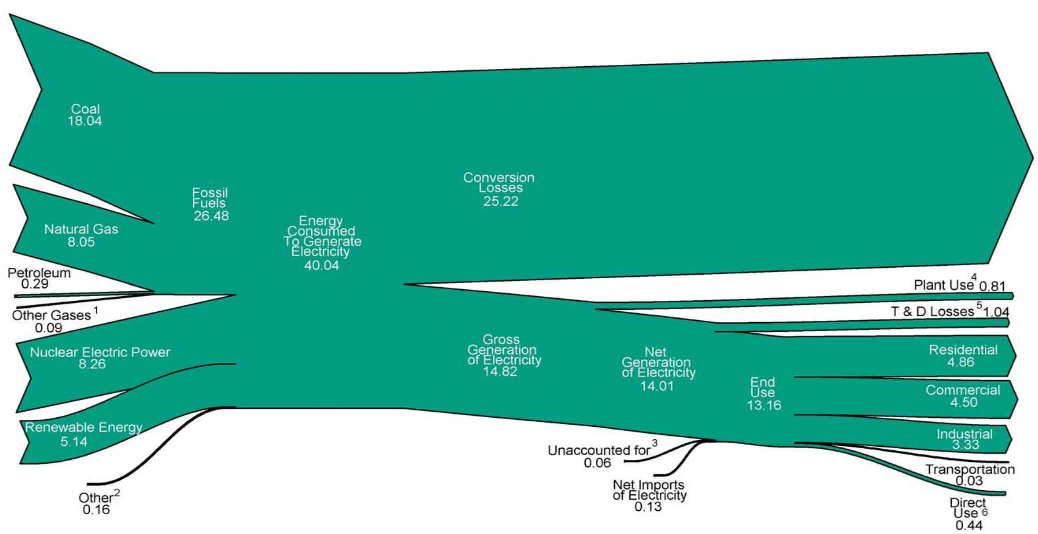
FUEL / PHASE	Coal	Petroleum	Natural Gas	Nuclear	Hydro	Solar Terrestrial Photovoltaic	Solar Power Tower	Wind	Fusion	Geothermal
Extraction	Mining Accidents Lung Damage	Drilling-Spills (off-shore)	Drilling	Mining Accidents Lung Damage	Construction	Mining Accidents	- -	- -	He, H², Li Production	- -
Refining	Refuse Piles	Water Pollution	- -	Milling Tails	- -	- -	- -	- -	- -	- -
Transportation	Collision	Spills	Pipeline Explosion	- -	- -	- -	- -	- -	- -	- -
On-Site										
Thermal	High Efficiency	High Efficiency	High Efficiency	Low Efficiency	- -	Low Efficiency Ecosystem Change	Ecosystem Change	- -	- -	Low Efficiency
Air	Particulates-SO_2, NO_x	SO_2, NO_x	NO_x	BWR Radiation Releases	- -	- -	- -	- -	- -	H_2S
Water	Water Treatment Chemicals	Water Treatment Chemicals	Water Treatment Chemicals	Water Treatment Chemicals	Destroys Prior Ecosystems	Water Treatment Chemicals	Water Treatment Chemicals	- -	Tritium in Cooling Water	Brine in Streams
Aesthetic	Large Plant Transmission Lines	Large Plant Transmission Lines	Large Plant Transmission Lines	Small Plant Transmission Lines	Small Plant Transmission Lines	Poor Large Area	Poor Large Area	Large Area Large Towers Noise?	Small Area	Poor Large Area
Wastes	Ash, Slag	Ash	- -	Spent Fuel Transportation Reprocessing Waste Storage	- -	Spent Cells	- -	- -	Irradiated Structural Material	Cool Brine
Sprecial Problems	- -	- -	- -	- -	- -	Construction Accidents	- -	Bird, Human Injuries	Occupational Radiation Doses	- -
Major Accident	Mining	Oil Spill	Pipeline Explosion	Reactor Cooling	Dam Failure	Fire	- -	- -	Tritium Release	- -

WORLD ELECTRICITY GENERATION (TWh), 2012



commons.wikimedia.org

ELECTRICITY FLOW, 2011 (Quadrillion Btu)



[1] Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.
[2] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).
[3] Data collection frame differences and nonsampling error. Derived for the diagram by subtracting the "T & D Losses" estimate from "T & D Losses and Unaccounted for" derived from Table 8.1.
[4] Electric energy used in the operation of power plants.
[5] Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 7 percent of gross generation.
[6] Use of electricity that is 1) self-generated, 2) produced by either the same entity that consumes the power or an affiliate, and 3) used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment. Direct use is exclusive of station use.

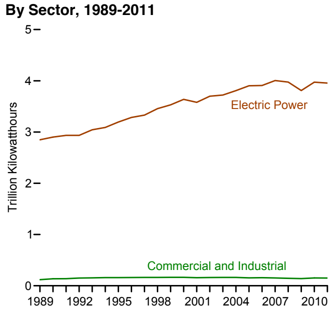
Notes: • Data are preliminary. • See Note, "Electrical System Energy Losses," at the end of Section 2. • Net generation of electricity includes pumped storage facility production minus energy used for pumping. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 8.1, 8.4a, 8.9, A6 (column 7), and U.S. Energy Information Administration, Form EIA-923, "Power Plant Operations Report."

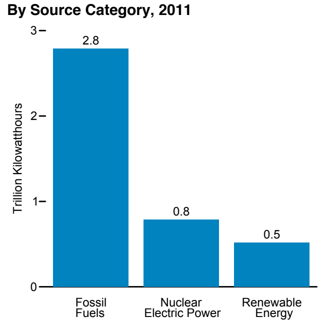
Energy Information Administration / Annual Energy Review 2011; http://www.eia.doe.gov/emeu/aer/diagram5.html

ELECTRICITY NET GENERATION, TOTAL (ALL SECTORS)

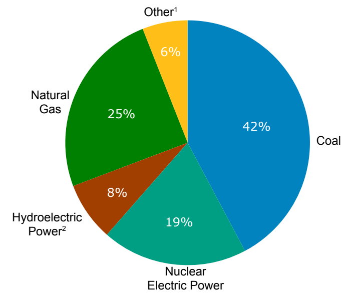
By Sector, 1989-2011



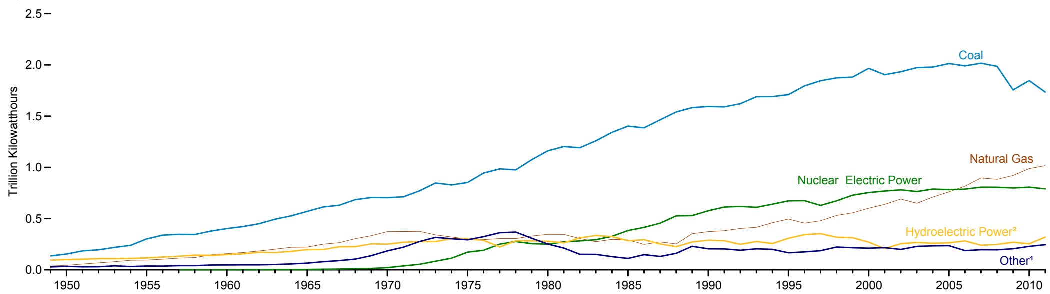
By Source Category, 2011



By Source, 2011



By Source, 1949-2011



[1] Wind, petroleum, wood, waste, geothermal, other gases, solar thermal and photovoltaic, batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

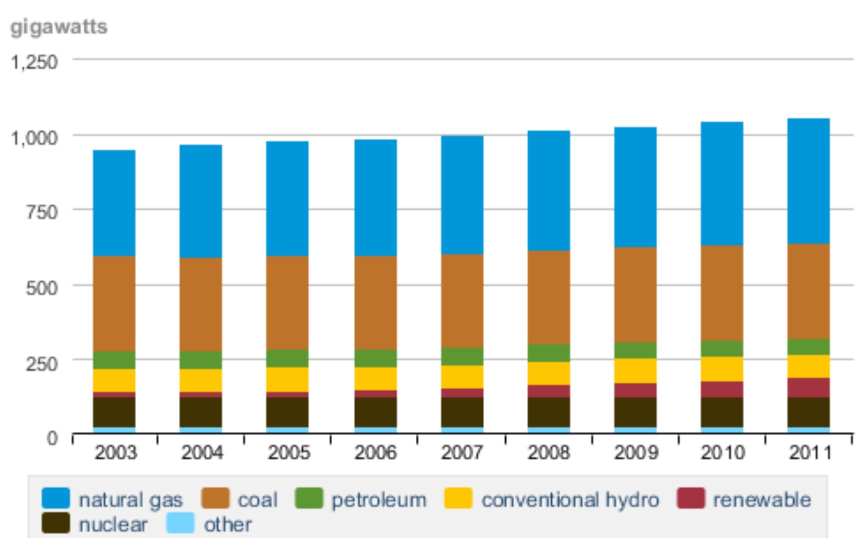
[2] Conventional hydroelectric power and pumped storage.

Note: Sum of components may not equal 100 percent due to independent rounding.

Sources: Tables 8.2a, 8.2b, and 8.2d.

Energy Information Administration / Annual Energy Review 2011: http://www.eia.doe.gov/emeu/aer/elect.html

TOTAL NET SUMMER CAPACITY BY FUEL TYPE, 2003-2011



eia U.S. Energy Information Administration, Form EIA-860, Annual Generator Report

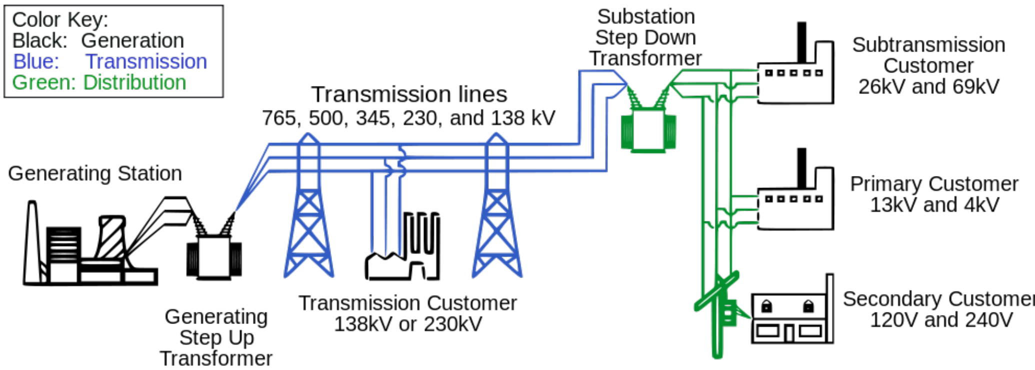
NUCLEAR GENERATING UNITS

http://www.nrc.gov/reactors/operating/map-power-reactors.html

ELECTRIC TRANSMISSION SYSTEMS

- Organizationally
  - Were historically created by local electric utility companies for providing their electricity to their customers
  - Are evolving into regional and national scale systems, providing electricity from many producers to many customers
  - Are changing from regulated monopolies to free markets, resulting in much great complexity
- Technologically
  - Are handling many more combinations of generators and consumers over larger distances
  - Are accommodating greater use of non-dispatchable renewable generation technologies, bringing greater complexity
  - Are introducing "smart" grid technologies, permitting more optimized, stable grid operation, and control of electricity consumption

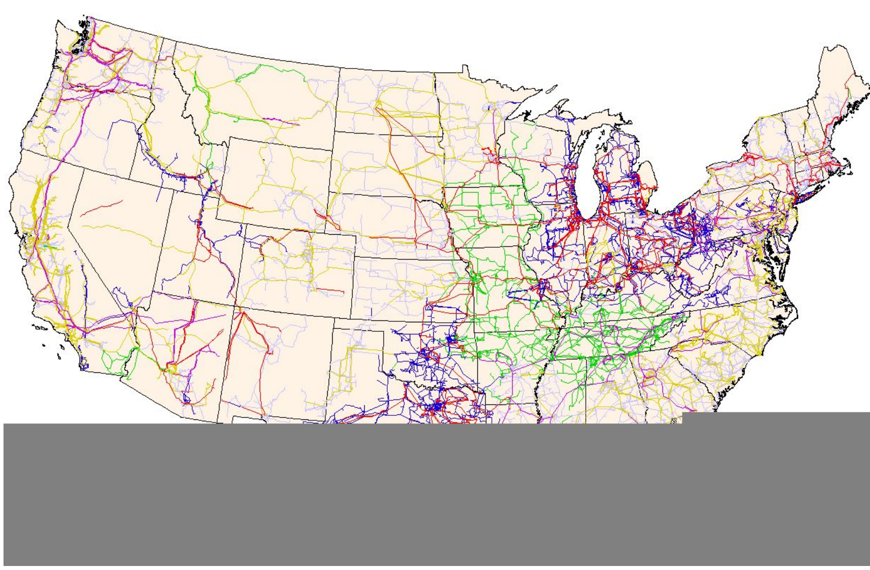
ELECTRICAL GRID



http://commons.wikimedia.org

US TRANSMISSION GRID

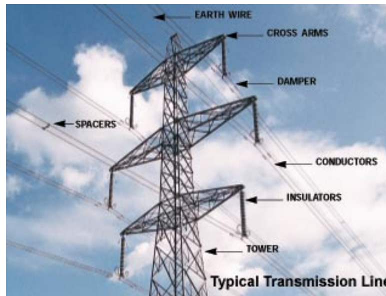
l appears, you may have to delete the image and then insert it again.



tli.umn.edu

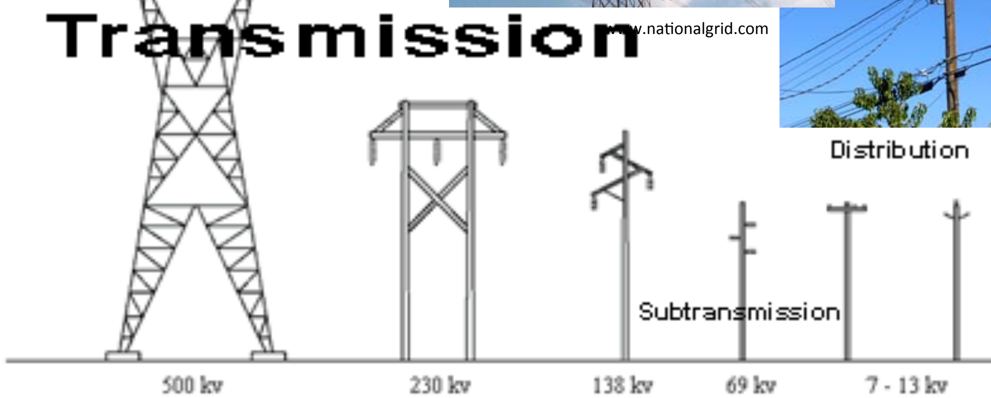
www.geni.org

TYPICAL TRANSMISSION LINE STRUCTURES AND FEATURES



www.nationalgrid.com

www.osha.gov



www.osha.gov

POWER GENERATOR

Pilstick 18PC4-2B HFO Second hand power plant equipment.

Manufacture: DEUTZ GERMANY
Type: 6M640
Rated Output: 6350KW
Year: 1992
Running Hours: 30695h

Mechanical Part
Lub. Oil Supply Systems
Cooling System
Fuel Oil Supply Systems
Compress-Air Systems
Exhaust Gas System
Electrical Part
Low-voltage Distribution Panels
Control, Measuring & Protection Panel

http://www.traderscity.com/board/products-1/offers-to-sell-and-export-1/pilstick-18pc4-2b-power-plant-generator-180622/

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SWITCHYARD: GRAND COULEE DAM PROJECT

xroads.virginia.edu

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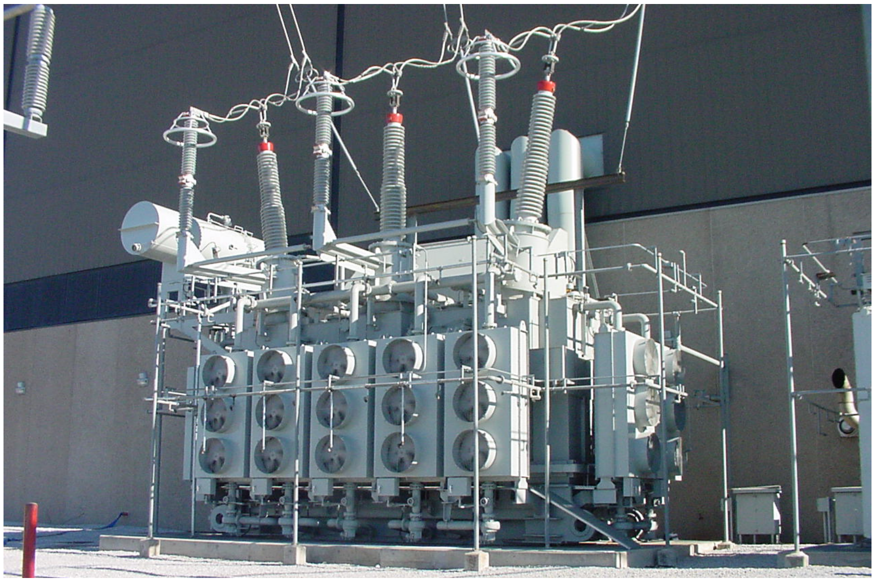
MAIN POWER TRANSFORMER



powerplantmen.wordpress.com

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ELECTRICAL SUBSTATION

A 115 kV to 41.6/12.47 kV 5 MVA 60 Hz substation with circuit switcher, regulators, reclosers and control building at Warren, Minnesota. This substation shows elements of low-profile construction; apparatus is mounted on individual columns.

en.wikipedia.org

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ROLE OF GENERATION TECHNOLOGIES ON THE GRID

Technology	Use Priority	Use Rationale	Typical Duty Cycle*
Renewable: Solar PV, Wind, Geothermal, Hydro	1	Lowest marginal generating cost, fuel is free	0.2 – 0.30
Base Load: Nuclear, Coal, Natural Gas (combined cycle	2	High capital cost, low operating cost, low fueld cost	0.90 – 0.95
Intermediate Load: Natural Gas, Coal, Petroleum	3	Intermediate capital cost, higher operating cost, more expensive fuel	0.3 – 0.7
Peaking Load: Pumped Hydro, Gas Turbines, Diesel Generators	4	Low capital cost, high operating cost, expensive fuel	< 0.3

*Fraction of a year in service

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INTEGRATION OF RENEWABLE ENERGY SOURCES WITH THE GRID

- Generating assets are dispatched in order of increasing marginal electricity production costs (i.e., fuel and operating costs)

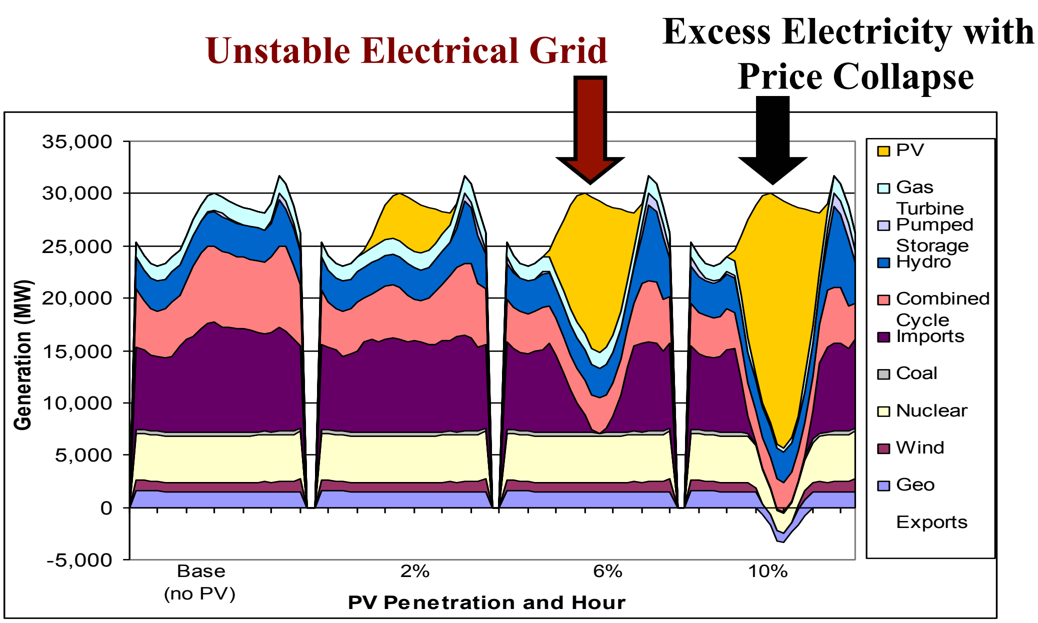
⇒ Renewables, Geothermal, Nuclear, Natural Gas, Diesel

- However, solar PV and wind are not dispatchable (i.e., cannot be turned on at-will) and can shut down suddenly

⇒ Back-up dispatchable assets are needed also

- Consequences: Large-scale use of solar PV and wind electrical generators greatly increases the required capital investment in whole-grid generating assets
- Large scale electricity storage would be valuable, but is now unavailable
- Production of hydrogen for use in synfuels could become important

Adding Solar and Wind To Electricity Grid Creates Challenges



California Daily Spring Electricity Demand and Production with Different Levels of Photovoltaic Electricity Generation

NOTES ON FIGURE

- Far left figure shows mix of electricity generating units supplying power on a spring day in California today. The figures to the right shows the impact on grid of adding PV capacity assuming it is dispatched first—low operating cost.
- Percent PV for each case is the average yearly fraction of the electricity provided by PV. Initially PV helps the grid because PV input roughly matches peak load. Problems first show up on spring days as shown herein when significant PV and low electricity load.
- With 6% PV, wild swings in power supply during spring and fall with major problems for the grid. By 10% PV on low-electricity-demand days PV provides most of the power in the middle of the day.
- California has a free market in electricity. In a free market PV producers with zero production costs will accept any price above zero. As PV grows, revenue to PV begins to collapse in the middle of the day. Collapsing revenue limits PV new build. Large-scale PV also destroys base-load electricity market while increasing market for peak power when no sun. In the U.S. that is getting filled with gas turbines. Similar effects at other times with large wind input.
- This is the problem with a low-carbon grid as renewables become significant
- Bottom line, low carbon grid with renewables has major challenges as outlined by recent OECD report. Implies different requirements for future nuclear plants to fully compete.

UNITED STATES ELECTRICAL GRID FACTORS

Grid Stage	Voltage (kV)	Length (km)
Distribution System	3.3–25	
Subtransmission System	33–132	4,000,000
Transmission System, AC	115–765*	200,000
Transmission System, DC	500	2200

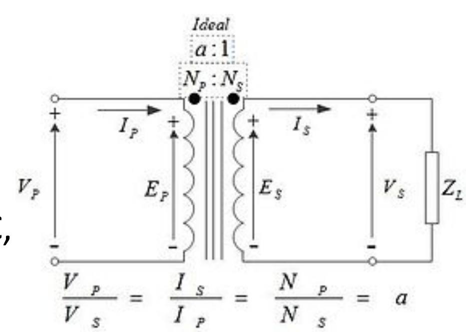
* Rate of loss ≤ 0.7%/100km

- Total Losses = 6%

$$\frac{\text{Power}-\text{Trans}}{\text{Power}-\text{Load}} = \alpha^2 \left(\frac{R_{Trans}}{R_{Load}}\right) << 1$$

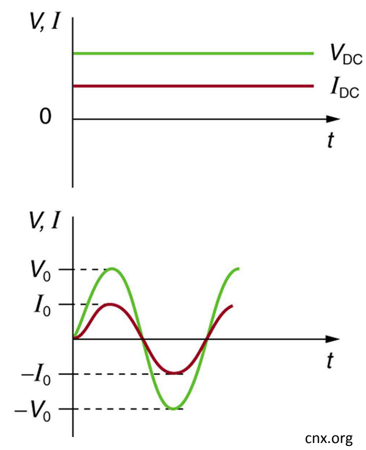
Small

- Maximum distance ~ 4000km for AC, 7000km for DC



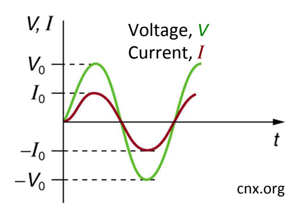
TRANSMISSION OF ALTERNATING CURRENT (AC) AND DIRECT CURRENT (DC) ELECTRICITY

- Alternating Current
  - Maintaining system stability over large distances is expensive, difficult (must balance reactive and real power components)
  - Transmission at high voltage is easier via use of transformers
- Direct Current
  - Maintaining system stability over large distances is easier (current and voltage have steady values)
  - Transmission at high voltage is more difficult as high voltage requires rectification using thrystors (a kind of diode) and high voltage AC inputs



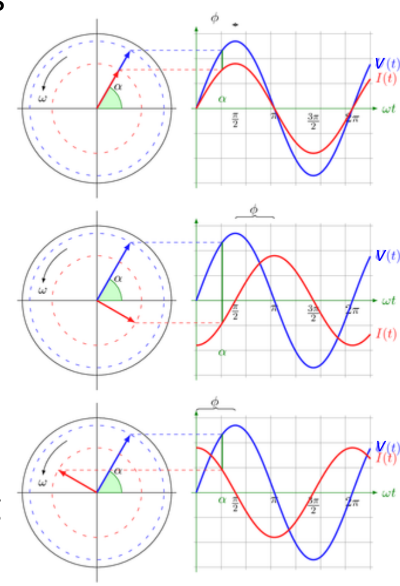
cnx.org

ALTERNATING CURRENT (AC)



cnx.org

- Phase Angle, $\phi = \phi(R, C, L)$
- Independent control of $V(t)$ and $I(t)$ allows E to be constant on grid, while I can vary
- Factors of AC + DC
- Resistance R: $V = IR$
- Factors of AC
- Inductance: $V = L\dfrac{dI}{dt}$
- Capacitance: $V = C\int I\,dt$
- AC permits voltage changes using transformers
- DC permits voltage changes via combining generators



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ALTERNATING CURRENT, continued

- Grid Performance Requirements
  - Current flow is determined by parallel impedance ratios
  - Current flow is constrained by current, thermal, stability limits
  - Load and generation must match (effectively no storage)
  - Voltage must be spatially uniform
  - AC frequency must be constant
  - Generators must be synchronized

SMART GRID FEATURES

- Grid Operation
  - Tailoring demand
  - Monitoring and controlling grid components
  - Controlling grid current flow

  } Optimizing grid performance while maintaining stability
- At Customer Interface
  - Time-of-day price information and load control
  - Grid stability-based load control

SUMMARY

- Electricity Generation
  - Fossil-fueled technologies dominate worldwide electricity generation
  - Nuclear and hydroelectric generation are the main current non-fossil technologies
  - Other renewable electricity technologies may become important in the future, but face important barriers
- Electrical Grid
  - National electrical grids reflect the evolution of the electricity industry from local to national scales over 120 years
  - Electrical grids are changing due to
    - Introduction of competitive electricity markets
    - Increased use of renewable generation technologies
    - Introduction of "smart grid" technologies