The Florida Advanced Technological Education (FLATE) Center wishes to make available, for educational and non-commercial purposes only, materials relevant to the "EST1830 Introduction to Alternative/Renewable Energy" course comprised of images, texts, facilitator's notes, and other demonstration materials.

This instructional resource forms part of FLATE's outreach efforts to facilitate a connection between students and teachers throughout the State of Florida. We trust that these activities and materials will add value to your teaching and/or presentations.

FLATE
Hillsborough Community College - Brandon
10414 E Columbus Dr., Tampa, FL 33619
(813) 259-6575
www.fl-ate.org; www.madeinflorida.org; www.fesc.org

This material is based upon work supported by the National Science Foundation under Grant No. 0802434 and a Florida Energy Systems Consortium Grant. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the Florida Energy Systems Consortium.

Introduction to Alternative and Renewable Energy

EST1830

FESC Florida Energy Systems Consortium

FLATE FLORIDA ADVANCED TECHNOLOGICAL EDUCATION CENTER

1. Introductory Section

1.3 Centralized versus Distributed Electrical Generation

1.3.1 Centralized Power Generation

1.3.2 Electricity Demand Management

1.3.3 Decentralized Power Generation

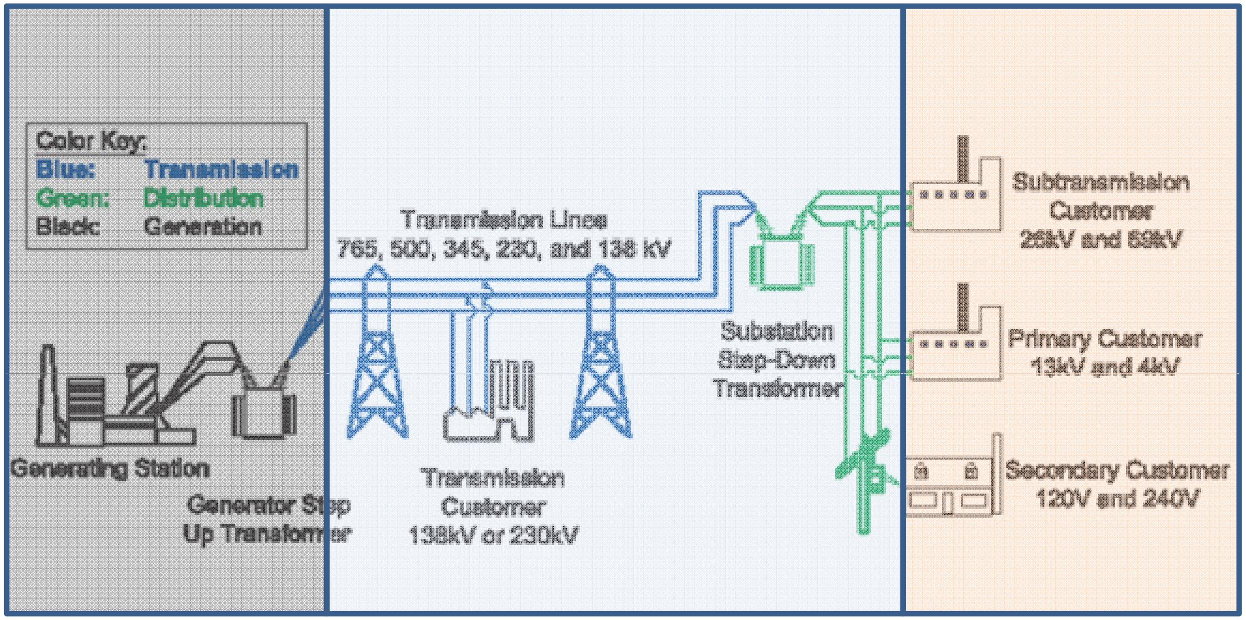
1.3.4 Load Imbalance Mitigation

1.3.1 Centralized Power Generation

Fossil Fuels, Nuclear, Hydroelectric

Centralized Generation

Supply | Transmission/Distribution | Demand



•Under current electricity distribution design , electrical energy is not typically stored.

•Generated as it is needed.

•Sophisticated controls in place to try to match electric generation with demand.

Losses: 44-68% Losses: 8%

<u>Efficiency</u>

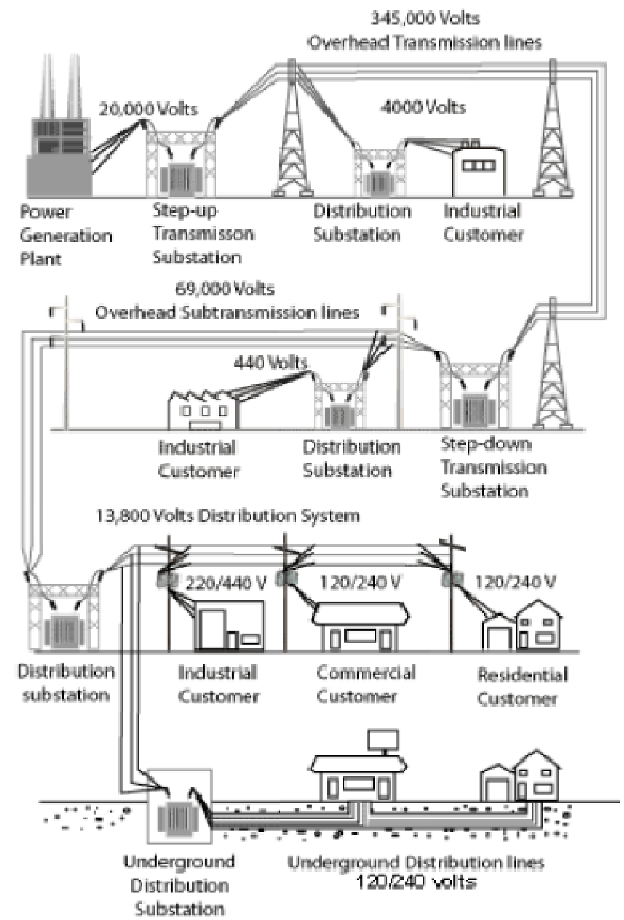
η_1=0.32-0.56 X η_2=0.92 = η_f=0.30-51

http://www.oe.energy.gov/information_center/electricity101.htm

Centralized Generation

Power Flow

- Example of 345kV flow
- Power Generation: 20kV
- Transmission
  - Step up to 345kV
  - Step down to 69kV
- Distribution
  - At distribution station step down to 13.8kV
  - Step down to 220/440V or 120/240V



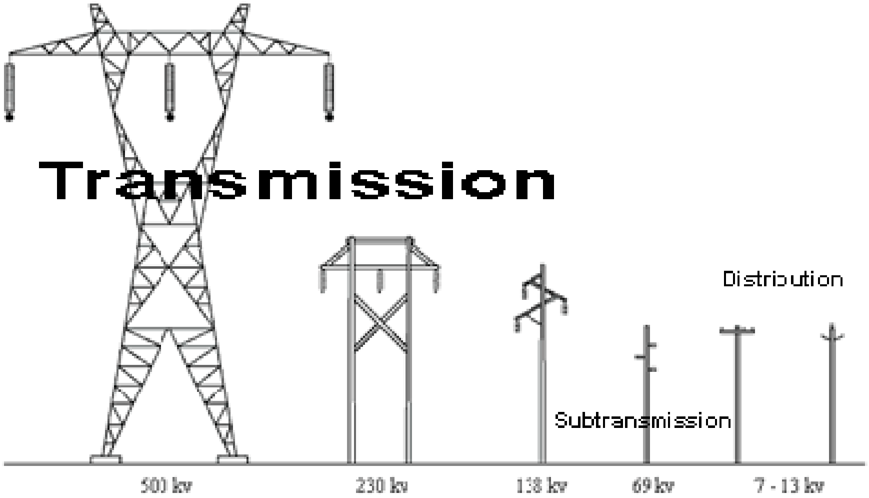
AC transmission lines carry three-phase current and use three transmission lines. DC transmission uses two lines- one for positive current and one for negative current.

http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/

Transmission

High voltage (HV) ac:	69 kV, 115 kV, 138 kV, 161 kV, 230 kV
Extra-high voltage (EHV) ac:	345 kV, 500 kV, 765 kV
Ultra-high voltage (UHV) ac:	1100 kV, 1500 kV
Direct-current high voltage (dc HV):	±250 kV, ±400 kV, ±500 kV

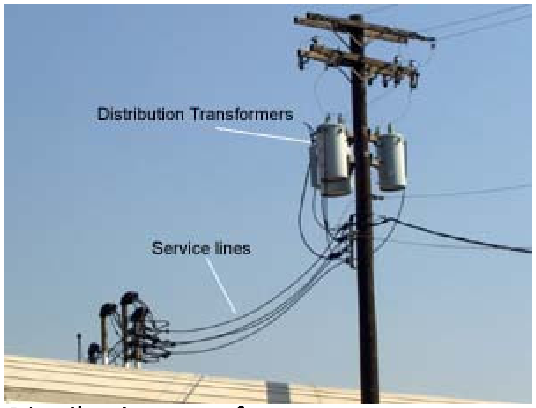
Step-up AC transmission substation



http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/

Distribution

Energy flow through a typical substation

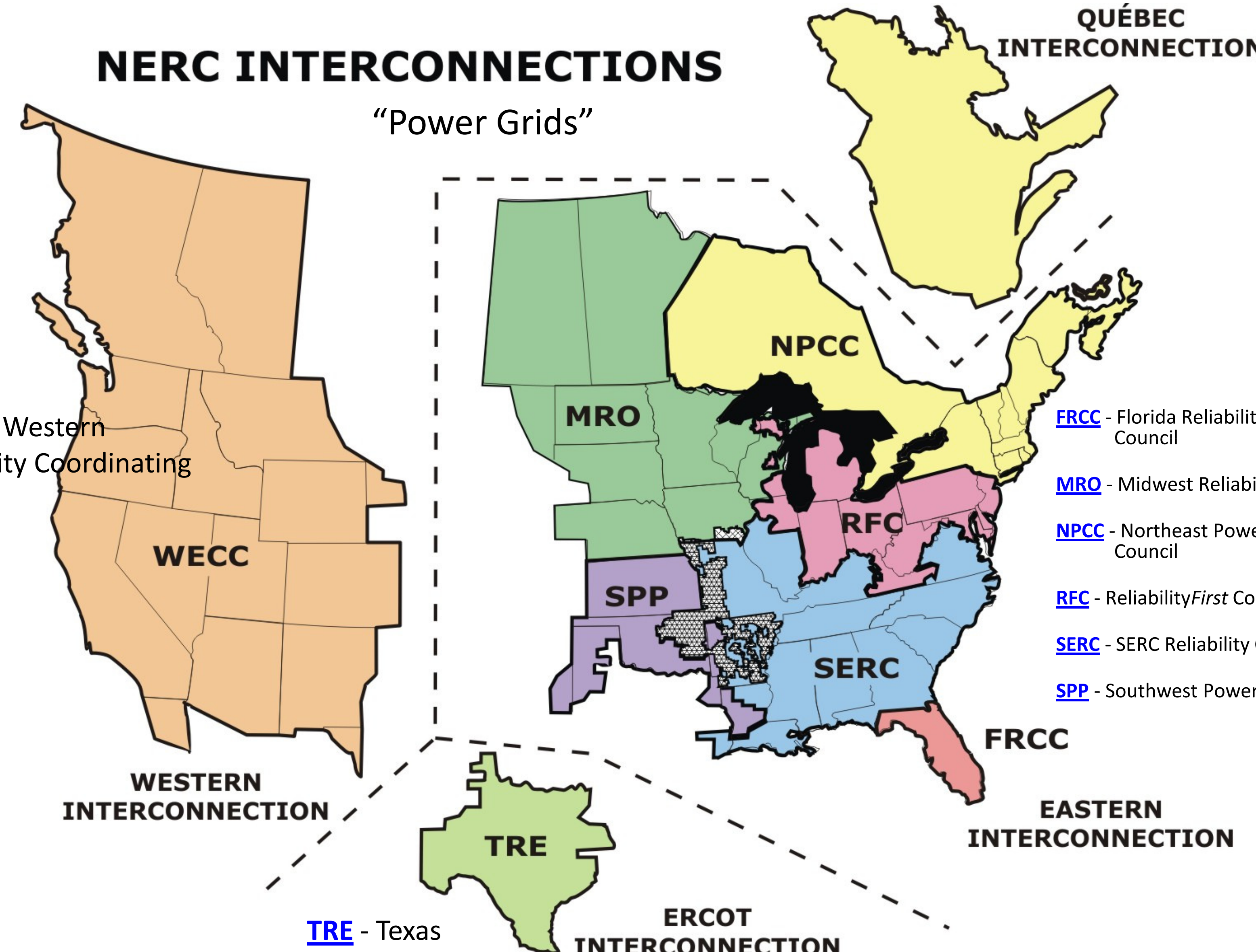


Distribution transformer to
3-phase service - commercial facility

Residential distribution transformer and service drop

http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/

NERC- North American Reliability Corporation



WECC - Western Electricity Coordinating Council

FRCC - Florida Reliability Coordinating Council

MRO - Midwest Reliability Organization

NPCC - Northeast Power Coordinating Council

RFC - Reliability*First* Corporation

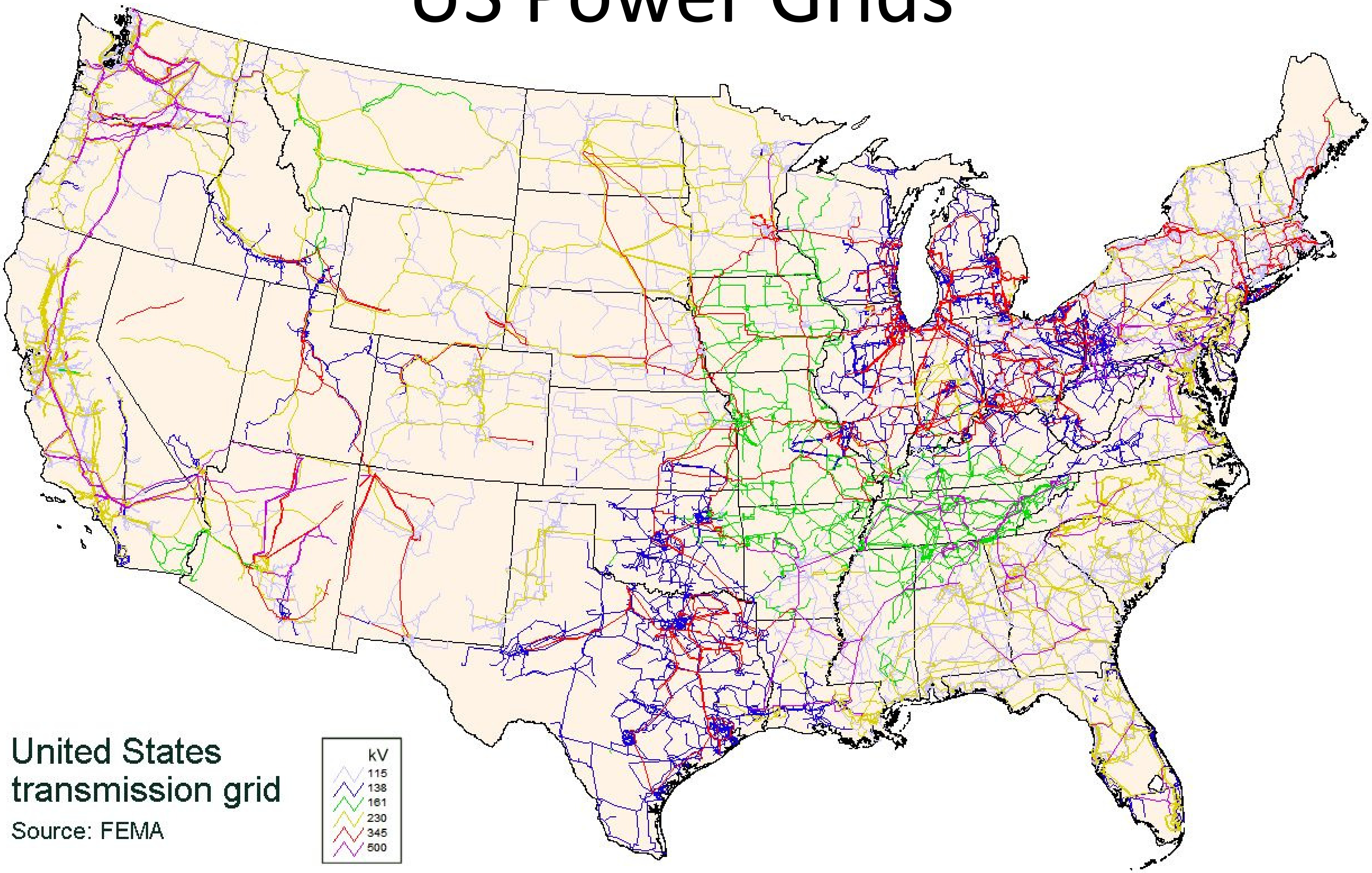
SERC - SERC Reliability Corporation

SPP - Southwest Power Pool, RE

TRE - Texas Regional Entity

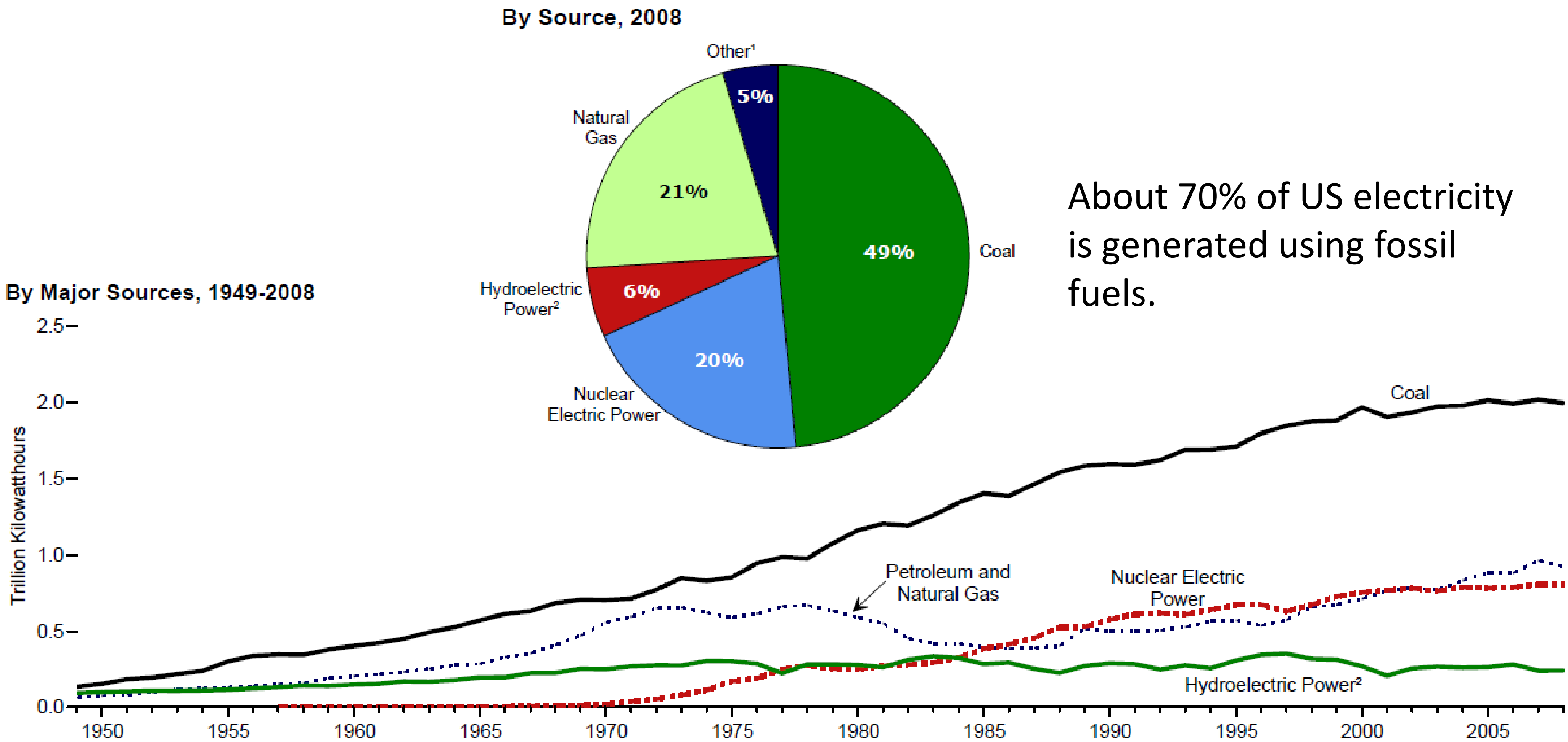
http://www.nerc.com/page.php?cid=1%7C9%7C119

US Power Grids



http://upload.wikimedia.org/wikipedia/commons/d/d4/UnitedStatesPowerGrid.jpg

Sources of Electricity



About 70% of US electricity is generated using fossil fuels.

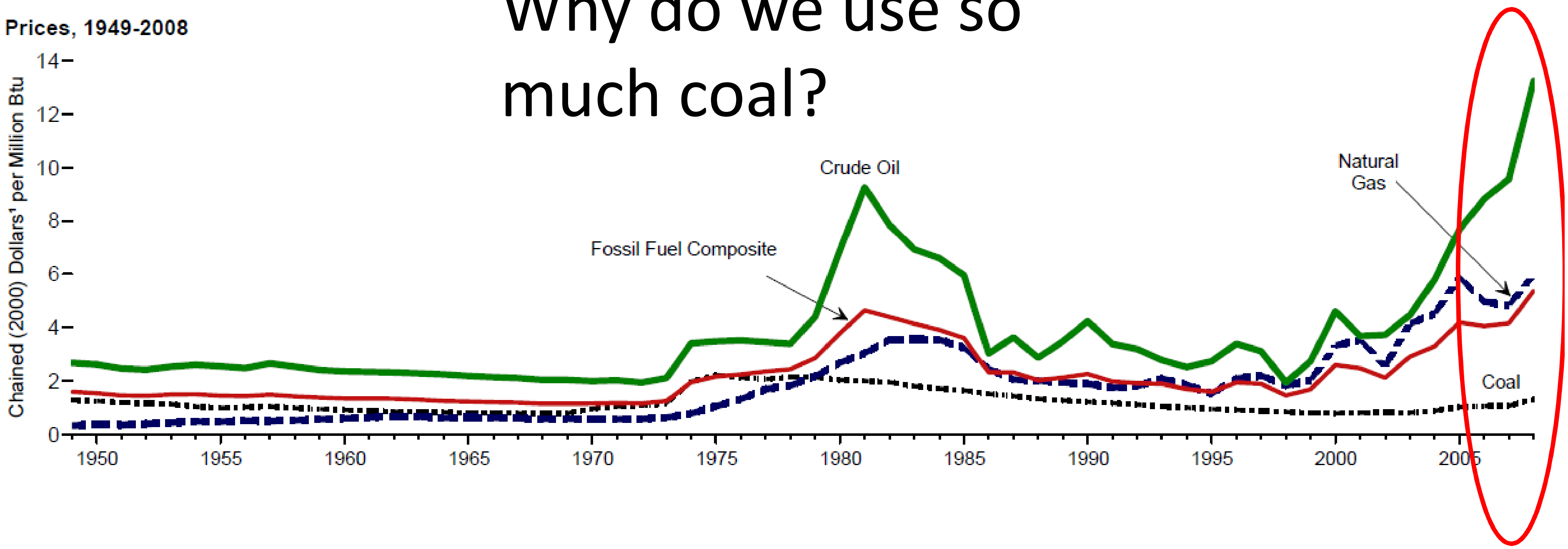
[1] Wind, petroleum, wood, waste, geothermal, other gases, solar thermal and photovolatic, batteries, chemicals, hydrogen, pitch, puchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

[2] Conventional hydroelectric power and pumped storage.
Sources: Tables 8.2a, 8.2b, and 8.2d.

Source: Annual Energy Review 2008, http://www.eia.doe.gov/aer

Sources of Electricity

Why do we use so much coal?



Prices!!

Source: Annual Energy Review 2008, http://www.eia.doe.gov/aer

Non-Renewable Power Generation

- Thermal Energy
  - Fossil fuels
    - Coal
    - Petroleum
    - Natural Gas
  - Nuclear
- Large Capacities: ≥1000MW

Coal Plant

Nuclear Plant

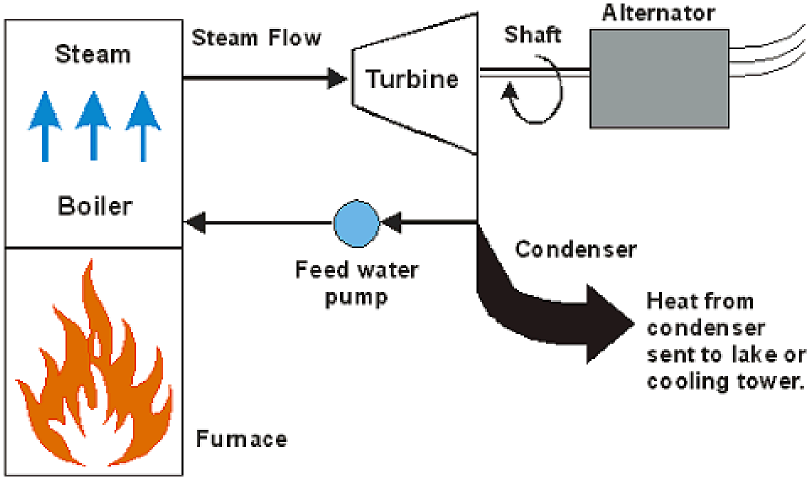
Big Bend Coal Power Plant Apollo Beach, FL; 1998 MW, TECO

http://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/power_generation_plant.html

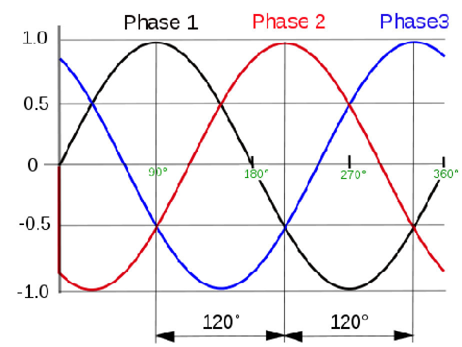
Types of Power Generators

1. Steam Units
   - Steam produced in a boiler turns a turbine to drive an electric generator.
   - What heats the boiler?
     - Fossil fuels (coal, natural gas, fuel oil), or biomass
       - Efficiency: 30-35% Heat lost to atmosphere, cooling tower, or cooling lake
     - Nuclear Fission: 33% efficiency (PWR/BWR)
2. Gas Units
   - Gas turbines and combustion engines use hot gas from burning fossil fuels to turn a turbine that drives the generator.
   - Efficiency: 35-40%....but some claim to be as high as 60% using heat recovery systems.
3. Combined Cycle Units
4. Cogenerating Units

Steam Units



•Alternator refers to the fact that electricity is generated as Alternating Current (AC)
•In US this is typically 60Hz, three phase.
•Power is conducted in three voltage waveforms about 120deg offset in time.



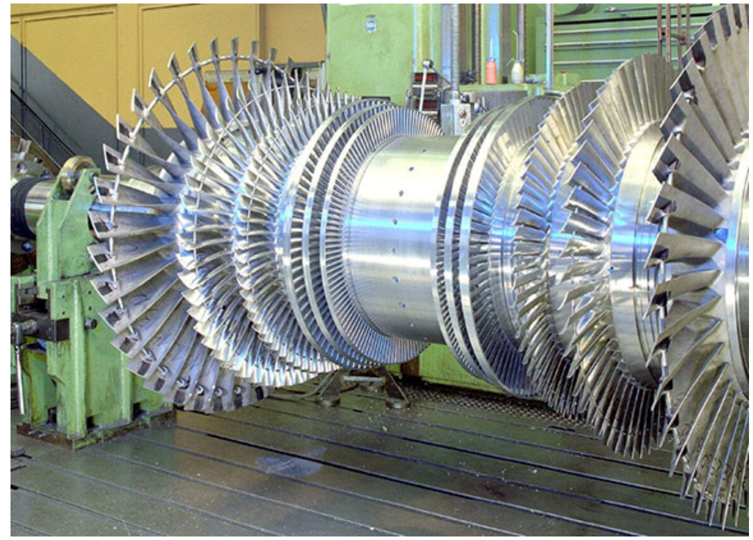
- In this diagram, furnace refers to the heat source.
- Heat sources
  - – Fossil fuels: Coal, natural gas, fuel oil
  - – Nuclear reaction: Uranium

Source: *R. Baldick, "Introduction to Electric Power Systems for Legal and Regulatory Professionals," Course Materials, The University of Texas at Austin (1999).*

http://www.eia.doe.gov/cneaf/electricity/chg_stru_update/chapter3.html

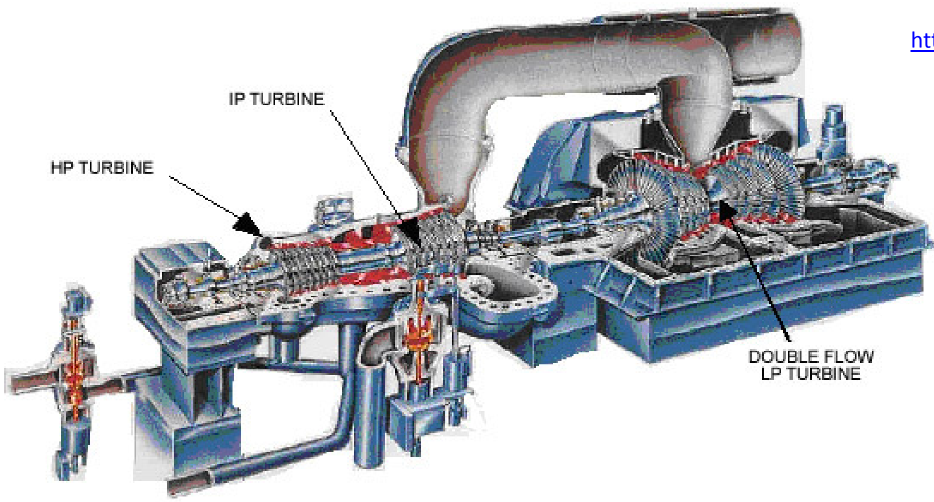
Steam Units: Turbine

- Turbines contain many blades having a radius inversely proportional to the pressure
- As the pressure falls, the radius must increase to get the same torque per section
- Multiple sections are used to allow steam at different temperatures and pressures to all contribute to turning the shaft

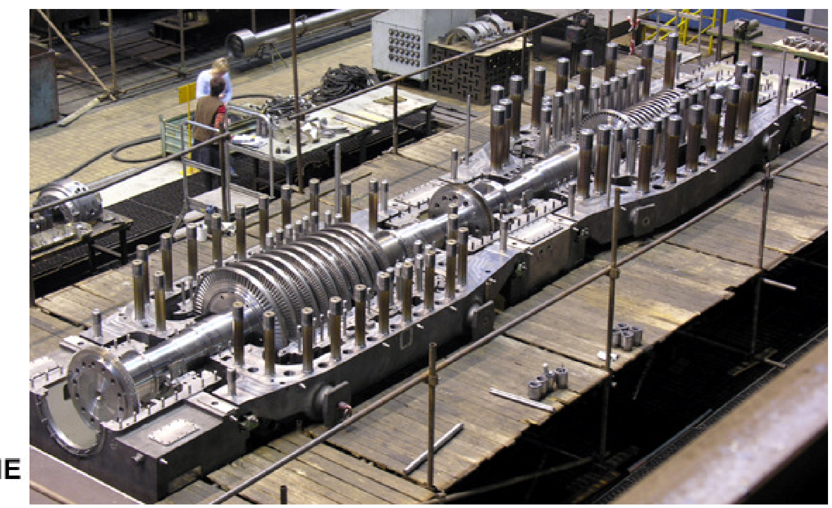


The SST-500 is a single casing, double flow steam turbine with up to 100 MW power output.

http://www.energy.siemens.com/hq/en/mechanical-drives/steam-turbines/sst-500.htm



VIEW OF THE INTERNALS OF A TYPICAL POWER STATION STEAM TURBINE



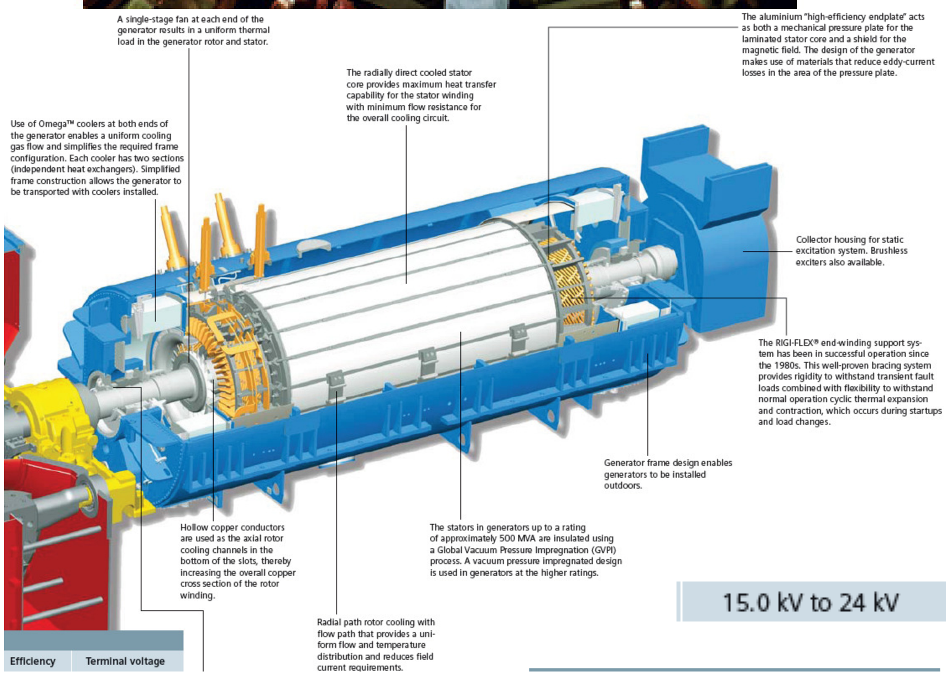
Skoda 80 MW steam turbine

http://www.skoda.cz/news/project-amager-denmark-aid2230.html

Steam Units: Generators

stator of a 225-megawatt air-cooled electrical generator to be used in a combined cycle power plant.

Good place for a bench demonstration of a generator.



http://www.energy.siemens.com/us/en/power-generation/generators/sgen-2000h-series.htm

http://www.multitek-usa.com/ProductGH.htm

Steam Units: Coal

Anthracite Coal

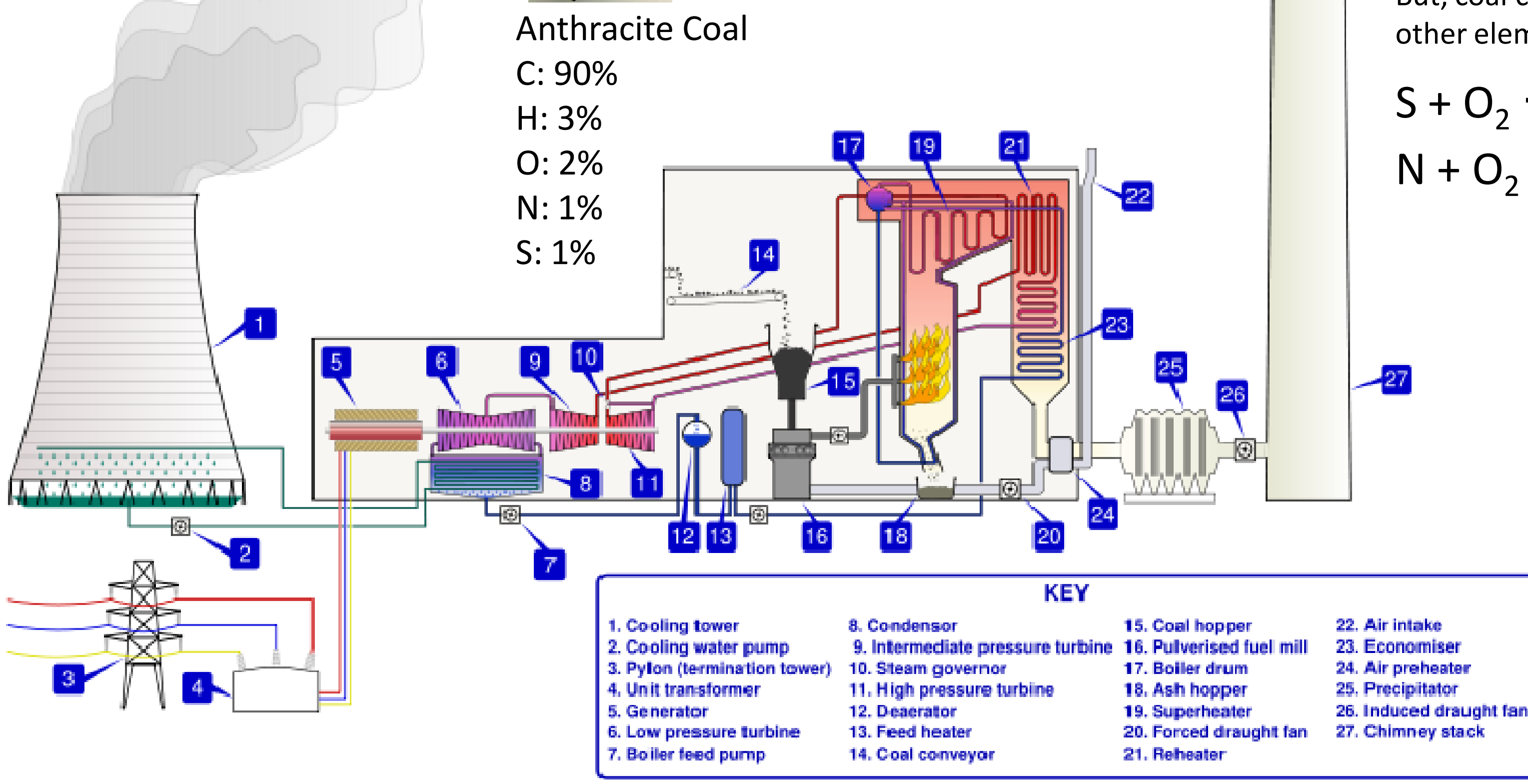
C: 90%

H: 3%

O: 2%

N: 1%

S: 1%



$C + O_2 \rightarrow CO_2$

But, coal contains other elements…so

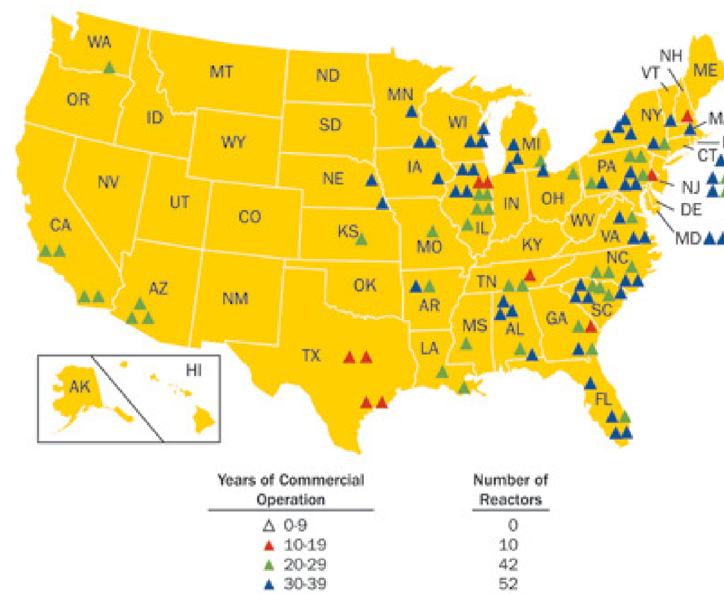
$S + O_2 \rightarrow SO_2$

$N + O_2 \rightarrow NO_2$

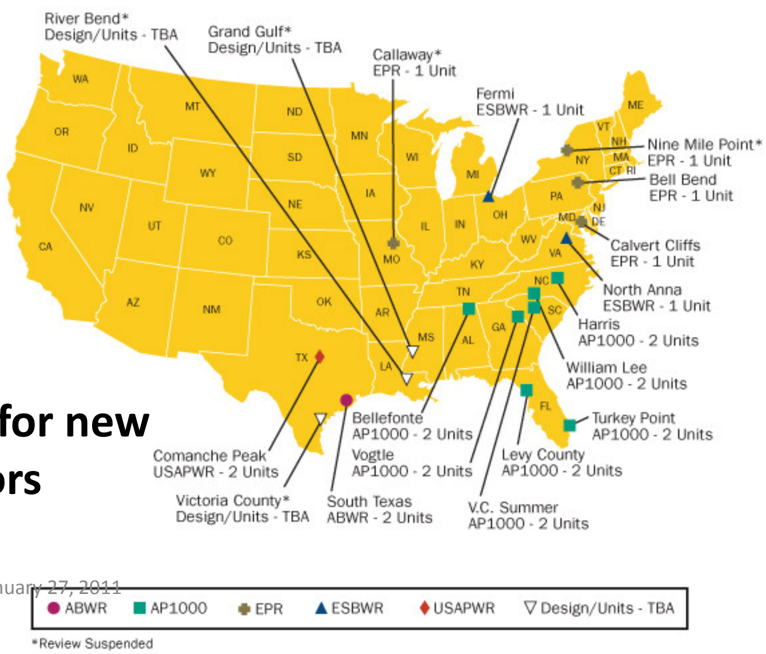
Steam Units: Nuclear

- No new nuclear power plants have been built since mid-1970s.
- In 2008: 104 operable units; 28 in permanent shutdowns *(Source: AER2008)*
- US Typical Nuclear Reactors
  - PWR: Pressurized Water Reactor
  - BWR: Boiling Water Reactor

U.S. Commercial Nuclear Power Reactors—Years of Operation



Source: U.S. Nuclear Regulatory Commission



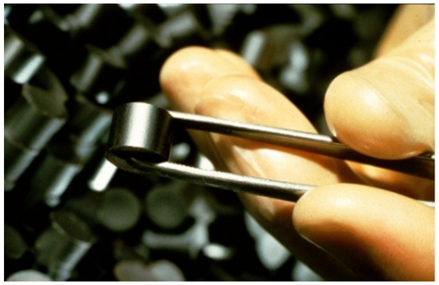
Plans for new reactors

Advanced Passive Pressurized Water Reactor (AP1000) – Twin units, 1,117 MWe each (Westinghouse International)
Advanced Boiling Water Reactor (ABWR) – 1,356 MWe (General Electric)
Economic Simplified Boiling Water Reactor (ESBWR) – 1,560 MWe (General Electric)
United States Advanced Power Reactor (US-APWR) – 1,700 MWe (Mitsubishi Heavy Industry)
United States Evolutionary Power Reactor (US-EPR) – 1,600 MWe (AREVA)

http://www.nrc.gov/reactors/new-reactors/col/new-reactor-map.html

Steam Units: Nuclear

- To make fuel for reactors, the concentration of natural uranium (U^{235}) is enriched to 3 - 5 %.
  - Because cooling water absorbs some of the neutrons needed for the nuclear chain reaction .



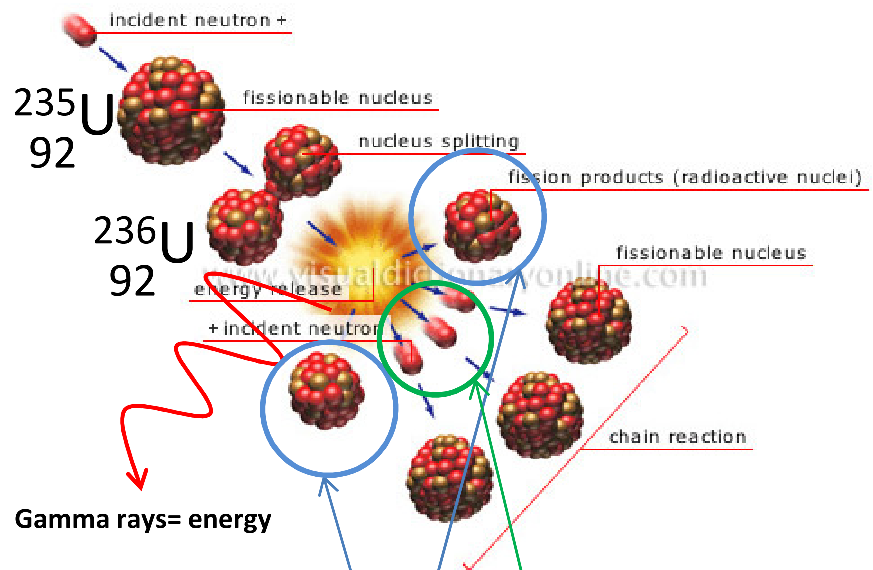
Uranium fuel pellet made from compaction of Uranium Dioxide powder. Not in enriched form here.

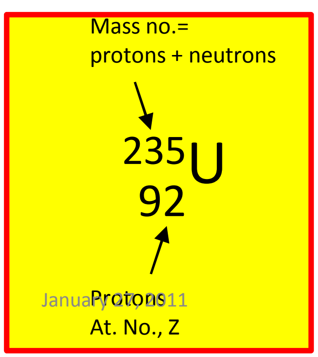
Reactor Fuel Assembly: Pellets are stacked within each rod. Several rods make up the assembly.

http://www.eia.doe.gov/cneaf/nuclear/page/intro.html

Steam Units: Nuclear

- Neutron begins chain reaction
- Reaction begins with Uranium, but the mass of all resulting atoms and particles add up to a mass less then Uranium.
- The mass is not lost…it is turned to energy according to Einstein's famous equation: $E=mc^2$
- Moderators: H_20, D_2O, Graphite (C), Beryllium
  - Slow down neutrons to help control the fission reaction





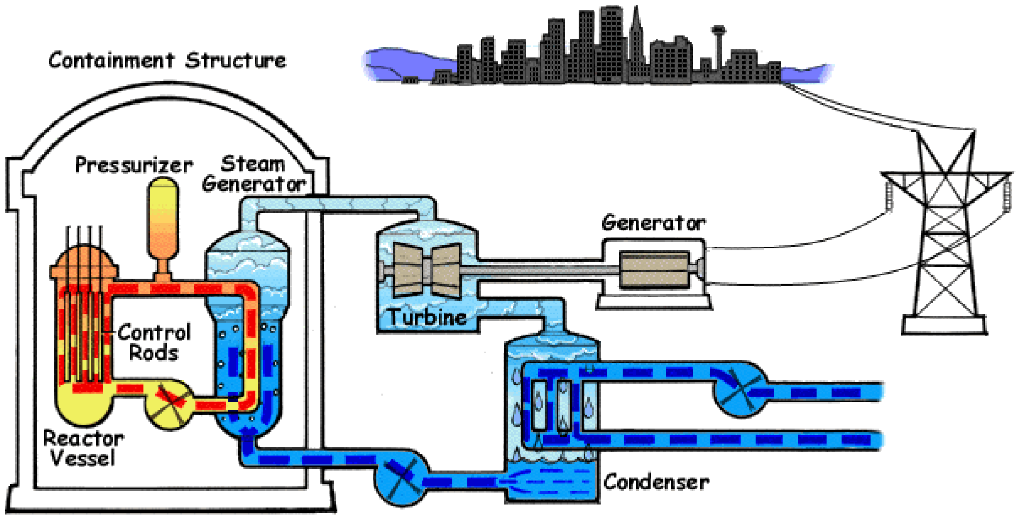
$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 180\ MeV$$

Gamma rays= energy

http://visual.merriam-webster.com/science/chemistry/matter/nuclear-fission.php

Steam Units: Nuclear

PWR: Pressurized Water Reactor

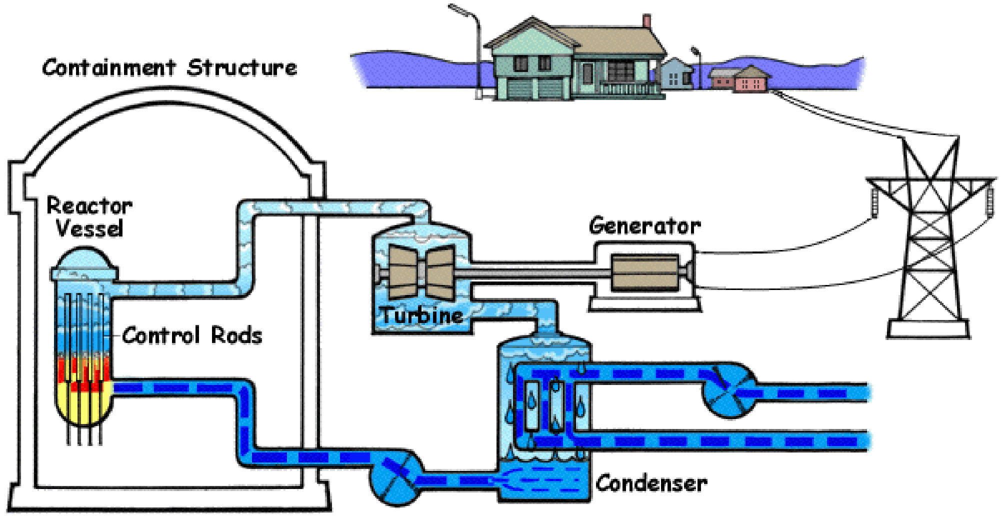


- The uranium core inside the reactor vessel creates heat,
- Pressurized water in the primary coolant loop carries the heat to the steam generator,
- Inside the steam generator, heat from the steam, and the steam line directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.
- PWRs keep water under high pressure so that it heats, but does not boil.
- Water from the reactor and the water in the steam generator that is turned into steam never mix.
- Pressurized-water reactors contain between 150-200 fuel assemblies.

http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

Steam Units: Nuclear

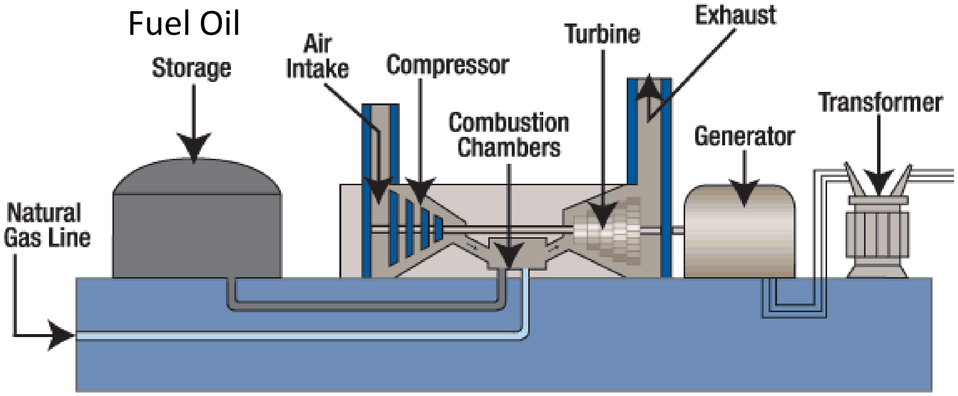
BWR: Pressurized Water Reactor



- The reactor core creates heat.
- A steam-water mixture is produced when very pure water (reactor coolant) moves upward through the core, absorbing heat.
- The steam-water mixture leaves the top of the core and enters two stages of moisture separation before steam is allowed to enter the steam line.
- Steam line directs the steam to the main turbine, causing it to turn the turbine generator, which produces electricity.
- Boiling-water reactor’s contain between 370-800 fuel assemblies.

http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

Gas Units



Natural Gas : CH_4 (mostly)

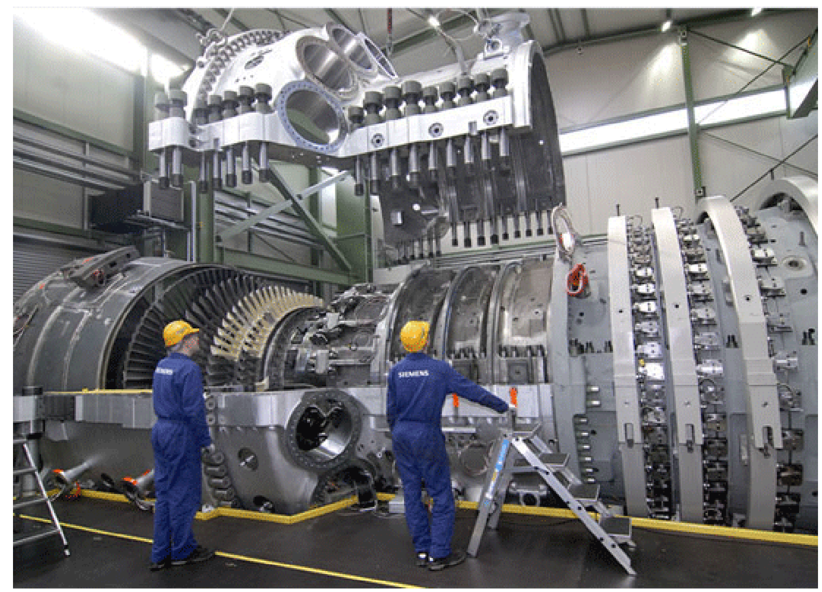
Combustion yields

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Energy}$$

But, since nitrogen is abundant in air, it is also oxidized at high temperatures…**so**

$$2CH_4 + xO_2 + N_2 \rightarrow CO_2 + 4H_2O + CO + 2NO_x + \text{Energy}$$

- Combustion turbines are designed to start quickly to meet the demand for electricity during peak operating periods.
- They are normally run with natural gas as a fuel, although low-sulfur fuel oil can also be used as needed.
- The turbines operate like a jet engine:
  - they draw in air at the front of the unit, compress it, mix it with fuel, and ignite it.
  - The hot combustion gases then expand through turbine blades connected to a generator to produce electricity.

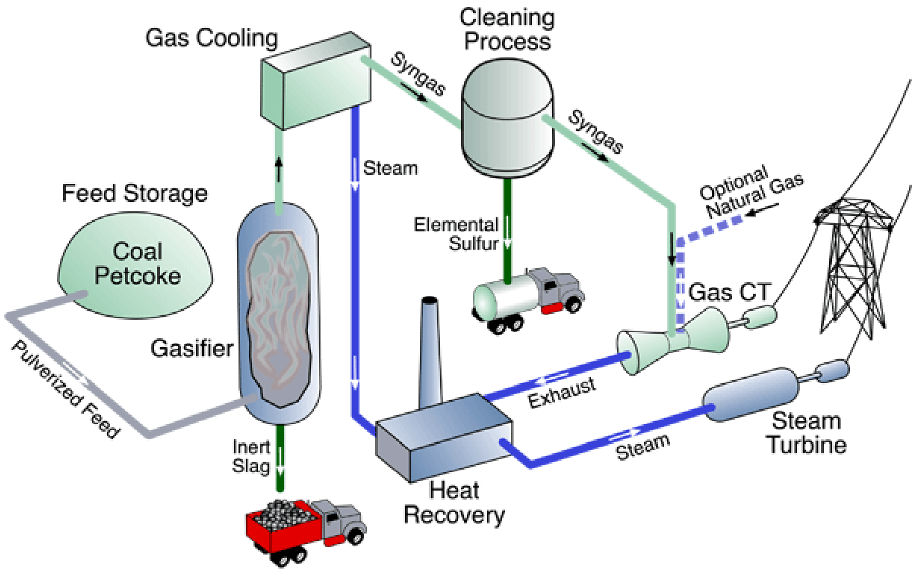


Siemens SGT-8000H series gas turbine designed to achieve more than 60% efficiency in combined cycle operation. 375MW stand-alone

http://www.tva.gov/power/cumb_turbineart.htm

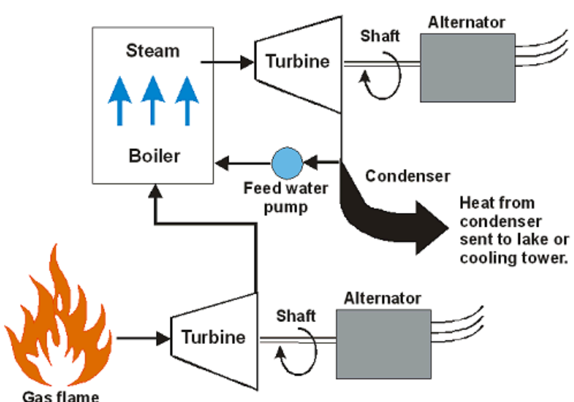
http://www2.usa.siemens.com/powergen2008/products.html

Combined Cycle Units



Integrated Gasification Combined Cycle (IGCC) plant

http://www.energy-northwest.com/generation/igcc/technical.php

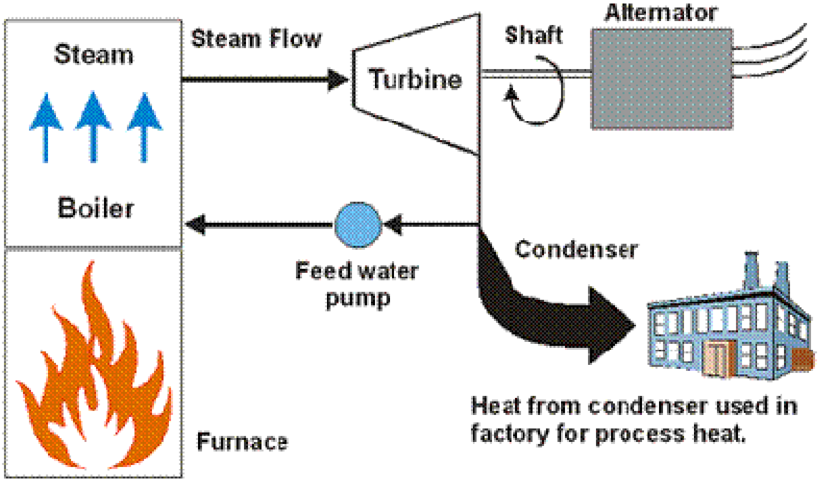


Source: *R. Baldick, "Introduction to Electric Power Systems for Legal and Regulatory Professionals," Course Materials, The University of Texas at Austin (1999).*

http://www.eia.doe.gov/cneaf/electricity/chg_stru_update/chapter3.html

- IGCC plants have two sources of power generation
  - A combustion turbine-generator
  - And a steam turbine-generator.
- A combustion turbine-generator burns the gas and generates power.
- Heat from the gasification process and exhaust from the combustion turbine-generator create steam to power a steam turbine-generator that also generates power.

Co-generation Units

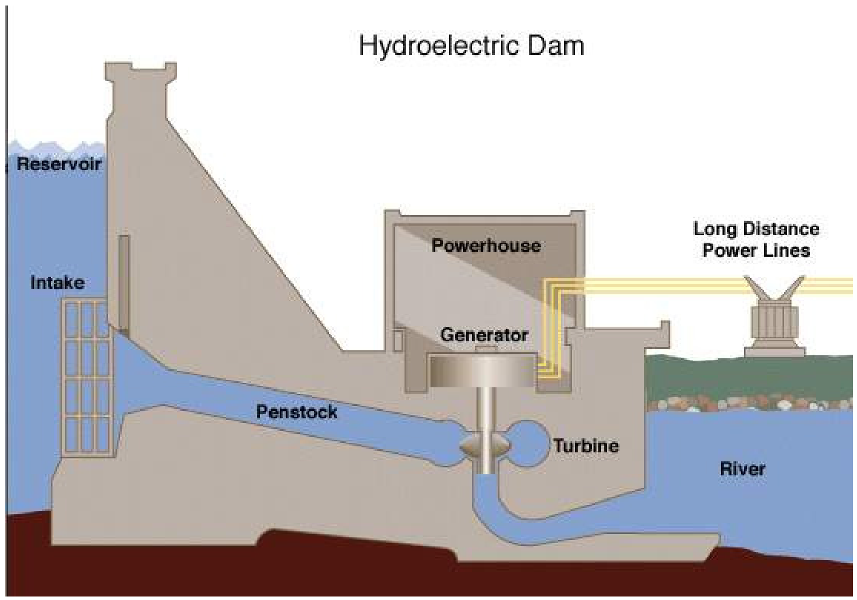


Source: *R. Baldick, "Introduction to Electric Power Systems for Legal and Regulatory Professionals," Course Materials, The University of Texas at Austin (1999).*

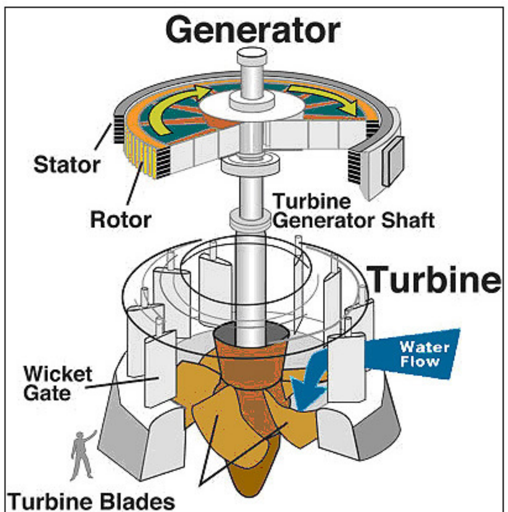
- Also known as combined heat and power generators, are facilities that utilize heat for electricity generation and for another form of useful thermal energy (steam or hot water), for manufacturing processes or central heating
- There are two types of cogeneration systems: bottom-cycling and top-cycling.
- Bottom-cycling configuration,
  - a manufacturing process uses high temperature steam first and a waste-heat recovery boiler recaptures the unused energy and uses it to drive a steam turbine generator to produce electricity.
- Two top-cycling configurations,
  1. A boiler produces steam to drive a turbine-generator to produce electricity, and steam leaving the turbine is used in thermal applications such as space heating or food preparation.
  2. A combustion turbine or diesel engine burns fuel to spin a shaft connected to a generator to produce electricity, and the waste heat from the burning fuel is recaptured in a waste-heat recovery boiler for use in direct heating or producing steam for thermal applications

http://www.eia.doe.gov/cneaf/electricity/chg_stru_update/chapter3.html

Centralized Generation: Hydroelectric



- Water is needed to run a hydroelectric generating unit.
- It's held in a lake behind the dam, and the force of the water being released from the lake through the dam spins the blades of a turbine.
- The turbine is connected to the generator that produces electricity.
- After passing through the turbine, the water reenters the river on the downstream side of the dam.



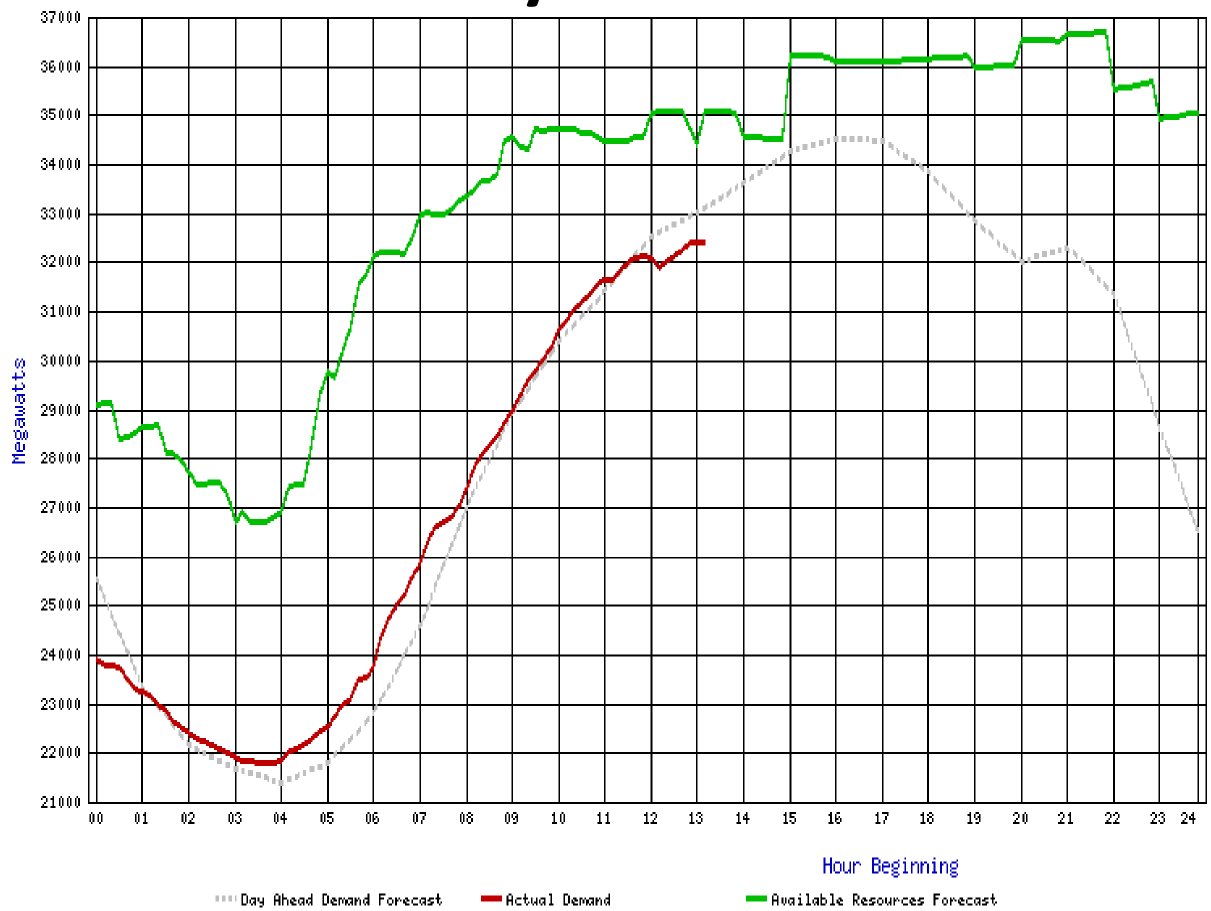
Eight Hydroelectric Generators

http://www.hooverdamcom.com/tour_itinerary.html

http://www.tva.gov/power/cumb_turbineart.htm

1.3.2 Electricity Demand Management

Daily Demand



Summer: 6/7/2010 around 1pm PST (California time)

California Independent System Operator: a non-profit corporation charged with operating the majority of California's high-voltage wholesale power grid. Balancing the demand for electricity with an equal supply of megawatts. Buys/Sells power.

http://www.caiso.com/outlook/outlook.html

Generating Loads

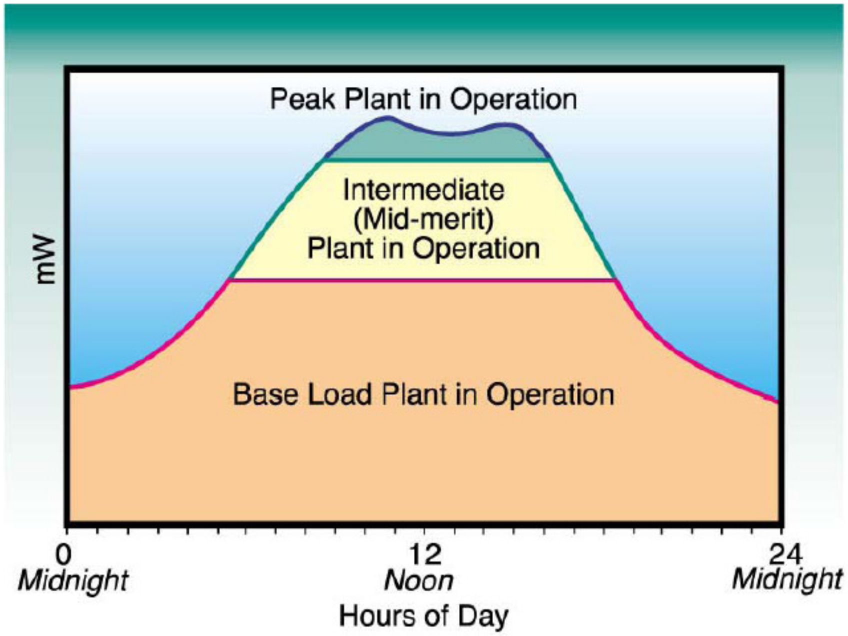
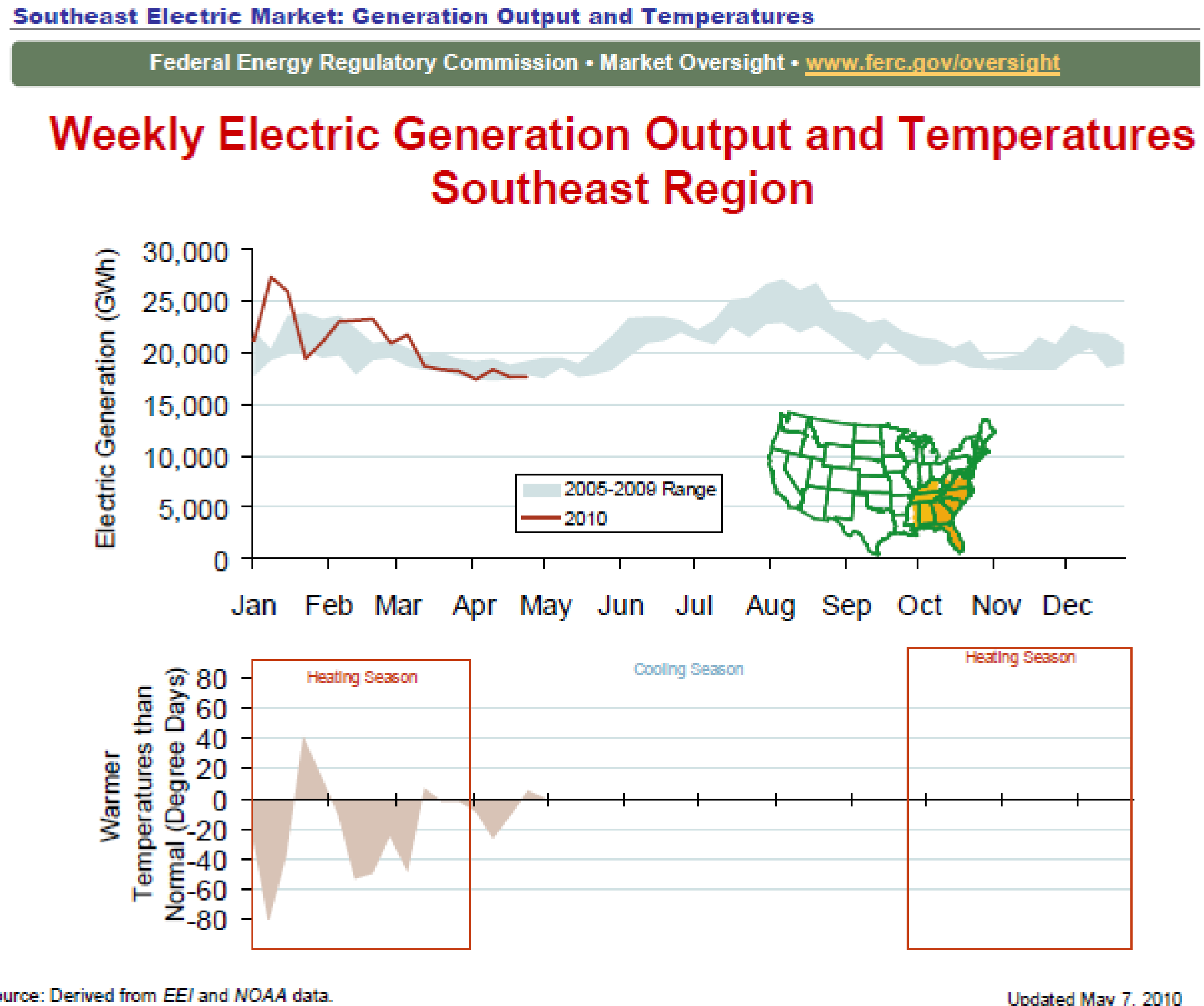


Figure 3.7. To ensure a reliable power supply, power generators operate some power plants around the clock. These plants are called base load plants. Utilities typically choose coal-fired, hydro, or nuclear plants for this continuous base-load operation because they are cheaper to run for prolonged periods. To meet demand during peak daylight hours, utilities are likely to run oil and gas-fired plants, referred to as peaking plants, which are more expensive to operate but can be started and stopped quickly. In between are intermediate or midmerit plants, which are typically combined-cycle combustion turbine plants.

- **Base-load** generating units are typically used to satisfy the base load of the system.
  - Produce electricity at a constant rate
  - Run countinuously
  - Nuclear and Coal plants are expensive to start up and shut down so these are best adapted for base load operations.
- **Intermediate-load** generating units meet system requirements that are greater than base-load but less than peak load.
  - Used during transition between Base and Peak load requirements.
  - Typically combined-cycle combustion turbine design
  - Typically use fuels with high heat content (oil/natural gas)
- **Peak-load** generating units can be brought on line quickly and are used to meet requirements during periods of greatest or peak load on the system.
  - Do not run for many hours (200-400 hrs/yr)
  - Use fuels with high heat content (oil/natural gas)
  - Normally smaller plants using gas and combustion turbines

http://www1.eere.energy.gov/femp/pdfs/primer.pdf

Yearly demand



Control Center

Figure 4.3. This photo highlights the key features of a control center. On the far right is a map. Although it is too small to show these details, the map indicates the location of power plants and transmission lines under the control of the center, usually with colored lights that indicate the status of the power plant or transmission line (e.g., red for out of service). Connections to adjacent control areas are also indicated. (Photo courtesy of Electric Reliability Council of Texas [ERCOT].)

http://www1.eere.energy.gov/femp/pdfs/primer.pdf

1.3.3 Decentralized Power Generation

AKA Distributed Generation

Distributed generation

- Distributed energy resources (DER)
  - Also called distributed generation, distributed energy, and distributed power systems
  - Small, modular, decentralized, grid-connected or off-grid energy systems located in or near the place where energy is used.
  - They are integrated systems that can include effective means of power generation, energy storage, and delivery.
  - Ie. Small generators and storage power systems.
- Typically in the range of 1 to 50MW
- Scattered throughout the power grid and connected primarily to the distribution system
- Provides power among generating users in remote isolated areas

Distributed generation: Technologies

Conventional

- Diesel Engines
- Reciprocating Engines
  - Natural Gas
- Combustion Turbine
  - Including micro-turbines
- Combined Cycle Turbine
- Low-Head Hydro
- Co-Generation units

Renewable Energy

- Fuel Cell
- Wind
- Solar Thermal
- Photovoltaics
- Small modular Biopower
- Hybrid systems

Energy Storage Systems

Batteries, Plug-in Hybrid

The right choice is determined by application, cost, environmental considerations, and system size.

Distributed generation: Technologies

Summary of Cost and Performance Parameters for Distributed Generation Technologies

Technology	Size Range (kW)	Installed Cost ($/kW)[b]	Heat Rate (BTU/kWh$_e$)	Approx. Efficiency (%)	Variable O&M ($/kWh)	Emissions[a] (lb/kWh)	
						NOx	CO2
Diesel Engine	1-10,000	350-800	7,800	45	0.025	0.017	1.7
Natural Gas Engine	1-5,000	450-1,100	9,700	35	0.025	0.0059	0.97
Natural Gas Engine w/ CHPc	1-5,000	575-1,225	9,700	35	0.027	0.0059	0.97
Dual Fuel Engine	1-10,000	625-1,000	9,200	37	0.023	0.01	1.2
Microturbine	15-60	950-1,700	12,200	28	0.014	0.00049	1.19
Microturbine w/ CHP c	15-60	1,100-1,850	12,200	28	0.014	0.00049	1.19
Combustion Turbine (CT)	300-10,000	550-1,700	11,000	31	0.024	0.0012	1.15
Combustion Turbine w/ CHP	300-10,000	700-2,100	1,100	31	0.024	0.0012	1.15
Fuel Cell	100-250	5,500+	6,850	50	0.01-0.05	0.000015	0.85
Photovoltaics	Limited by Available Space	7,000-10,000		N/A	0.002	0	0
Wind Turbine	0.2-5,000	1,000-3,000		N/A	0.01	0	0
Battery	1-1,000	1,100-1,300	--	70	0.01	d	d
Flywheel	2-1,600	400	--	70	0.004	d	d
SMES	750-5,000	600	--	70	0.02	d	d
Hybrid Systems	1-10,000	f	e	e	e	e	e

Will discuss in more detail later.

[a] Nationwide utility averages for emissions from generating plants are 0.005 lb/kWh of NOx and 1.2 lb/kWh of CO_2.

[b] The high end of the range indicates costs with NOx controls for the most severe emissions limits internal combustion technologies only.

[c] Although the electric conversion efficiency of the prime mover does not change, CHP significantly improves the fuel utilization efficiency of a DER system.

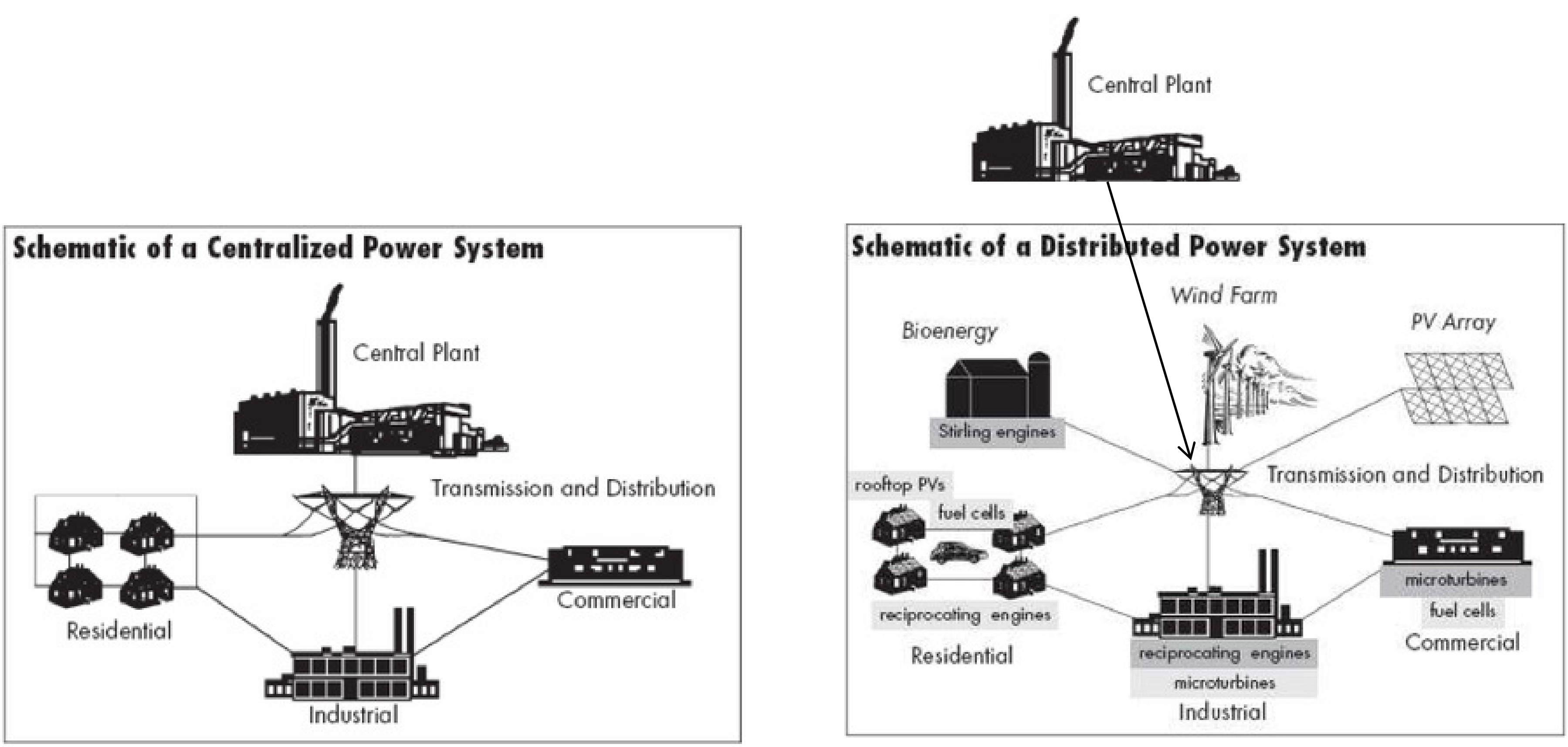
[d] Storage devices have virtually no emissions at the point of use. However, the emissions associated with the production of the stored energy will be those from the generation source.

[e] Same as generation technology selected.

[f] Add cost of component technologies.

http://www1.eere.energy.gov/femp/technologies/derchp_derbasics.html#benefits

Distributed Generation Distribution



Diesel Generator Sets

CAT C175 2-4 MW Diesel Generator Set

http://www.cat2-4mw.com/features.html

Natural Gas Reciprocating Engine

- Can burn landfill gas, bio-gas or natural gas.
- R&D with ORNL to improve efficiencies > 44%
- And to reduce NOx emmissions

50 MW Plant- Multiple Generators

CAT G3520 C- Natural gas reciprocating engine

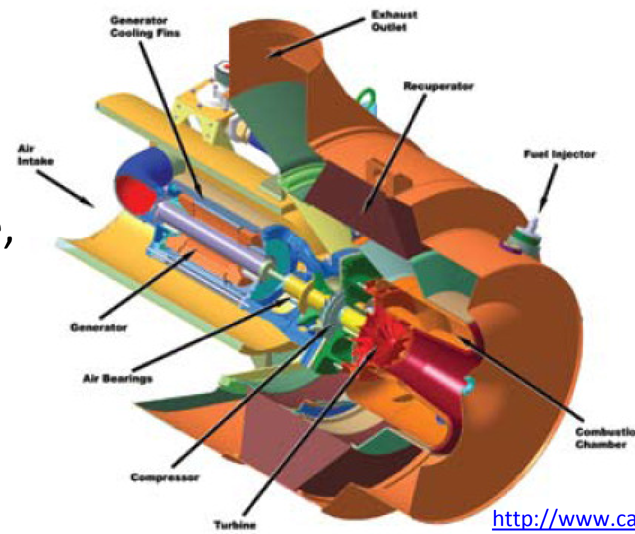
2055KW CONTINUOUS, 2889HP, 60HZ, 480V, 1800RPM, YEAR: 2007

http://www.machinerytrader.com/listingsdetail/detail.aspx?OHID=6628261

Microturbines

- Small combustion turbines approximately the size of a refrigerator with outputs of 25 kW to 500 kW.
- They evolved from automotive and truck turbochargers, auxiliary power units (APUs) for airplanes, and small jet engines.
- Most are comprised of a compressor, combustor, turbine, alternator, recuperator (a device that captures waste heat to improve the efficiency of the compressor stage), and generator.
- Fuel: Natural gas, hydrogen, propane, diesel

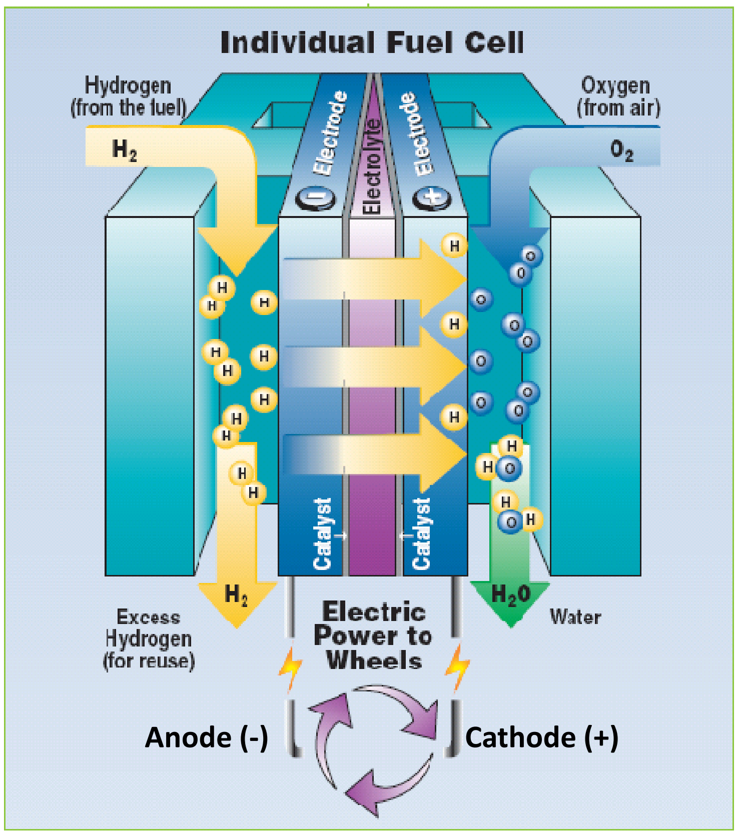
Capstone MicroTurbine®



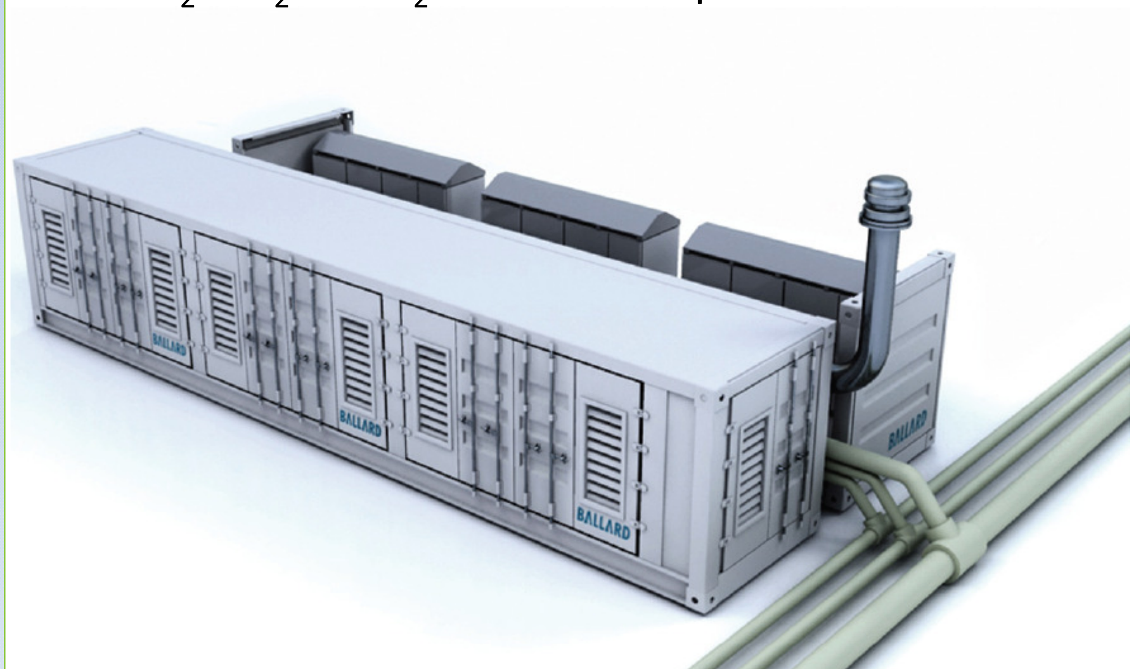
http://www.capstoneturbine.com/prodsol/products/

200kW C200 Capstone Microturbine

FuelCells



$2H_2 + O_2 \rightarrow 2H_2O$ + Electrical power + heat

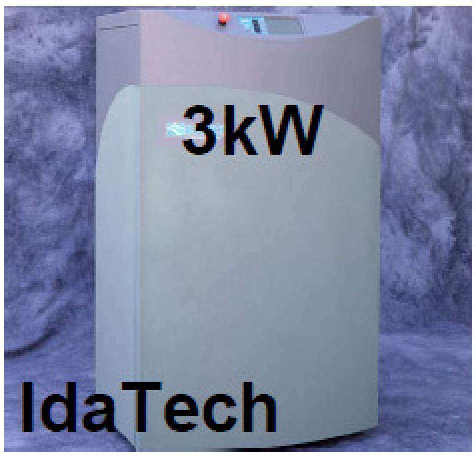


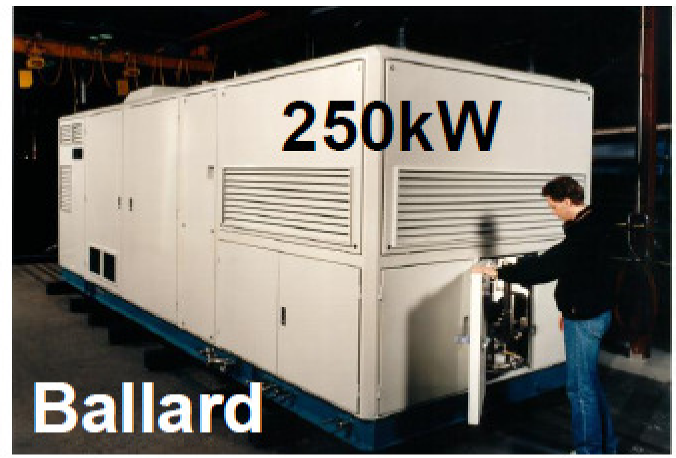
Ballard PEM Fuel Cell; 1 MW; 48% efficiency; fuel cell stacks; converts DC generation to AC output; 60Hz

http://www.ballard.com/Stationary_Power/Distributed_Power_Generation/Product_Specifications.htm

FuelCells

Stationary Power Units

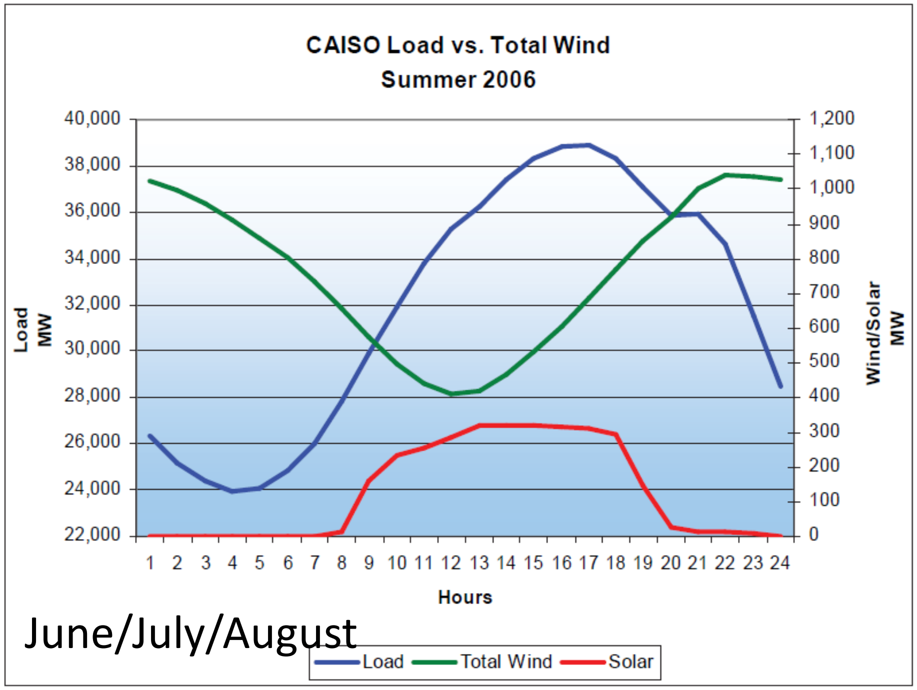


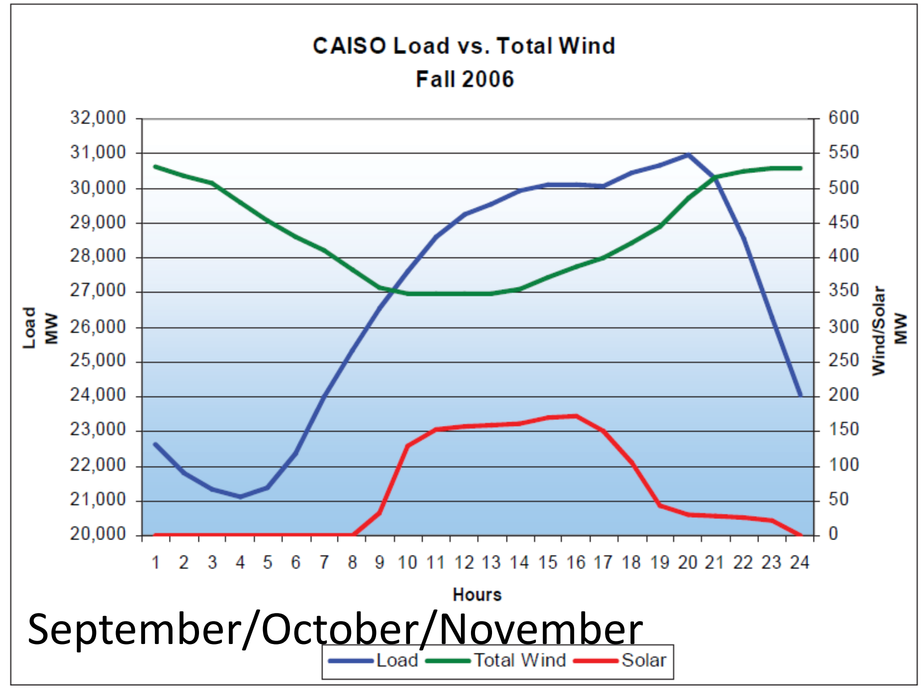


1.3.4 Load Imbalance Mitigation

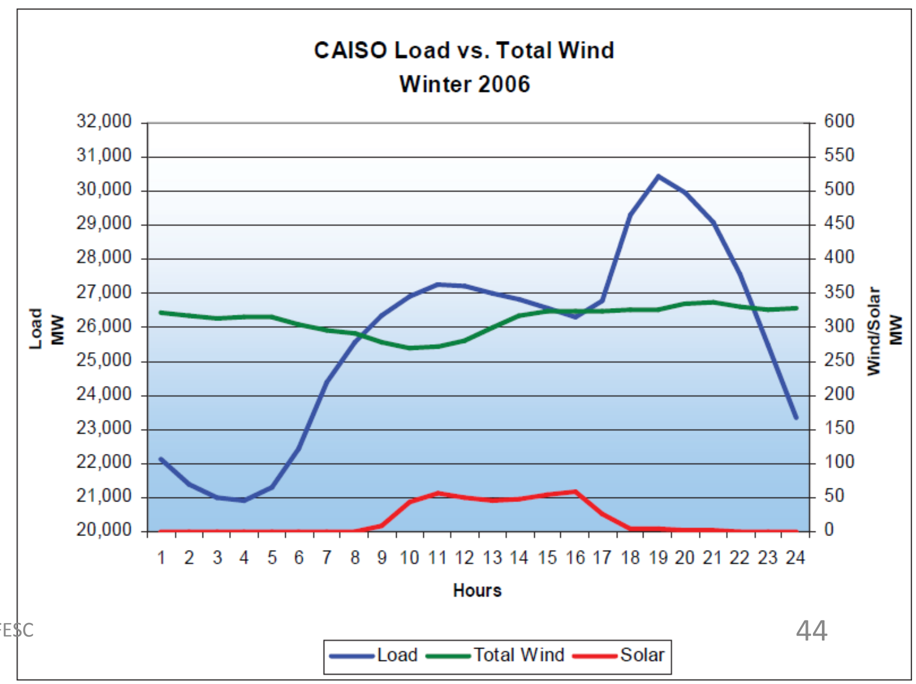
Energy Storage Systems,

Smart Grid Concept





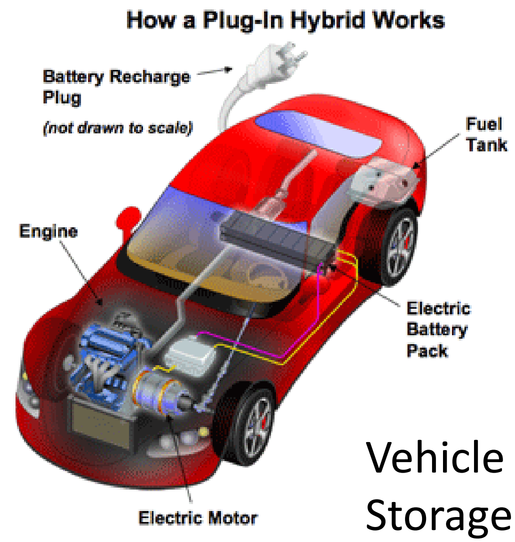
Load Imbalance, Renewables



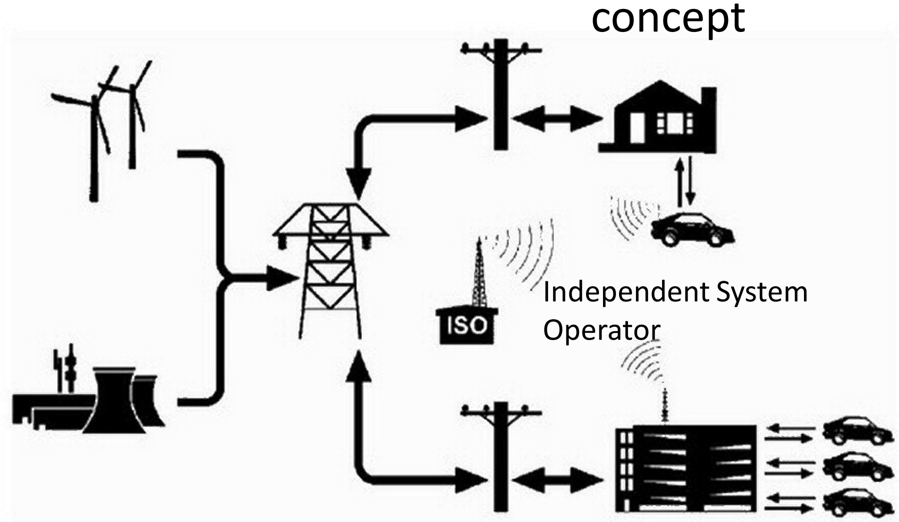
CAISO, Integration of Renewables, November 2007

Energy Storage Systems

- Pumped Hydro
- Compressed Air Energy Storage
- Flywheel storage
- Ultracapacitors
- SMES- Superconducting Magnetic Energy Storage
- Battery Storage
  - Lead Acid
  - Sodium Alumina
  - NiMH; NiCad; Lithium Ion
  - Flow Batteries
    - Vanadium Redox
    - Zinc Bromine
  - Metal Air
- Plug-in Hybrid Car with V2G storage capability [developing]
- Most technologies are in early stages of market acceptance or still being developed .



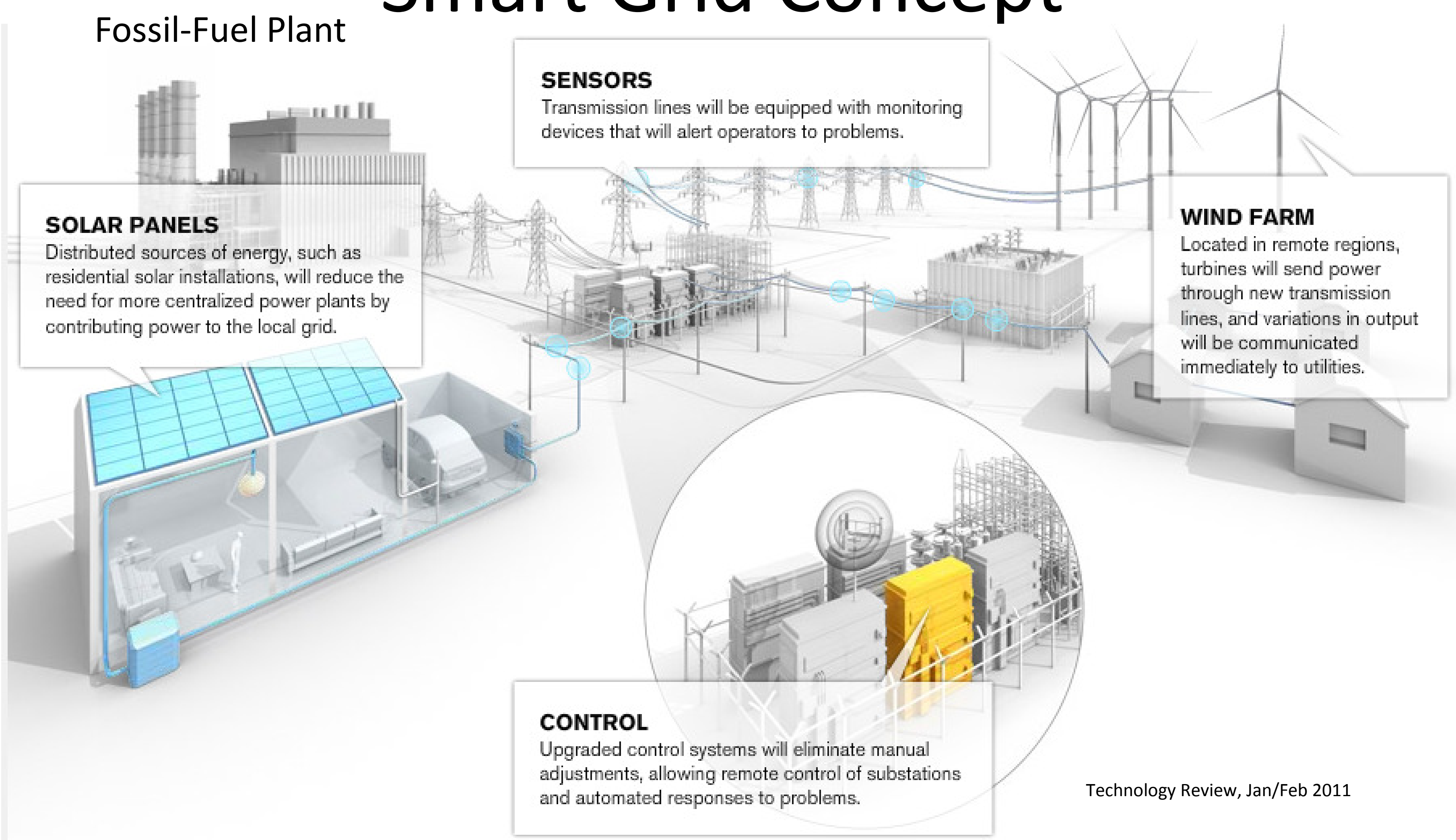
Vehicle to Grid Storage (V2G) concept



http://www.wwindea.org/technology/ch04/en/4_3_4.html

Source: *Kempton, Willett, et al., Electric Vehicles with V2G, Windtech International, 2006.*

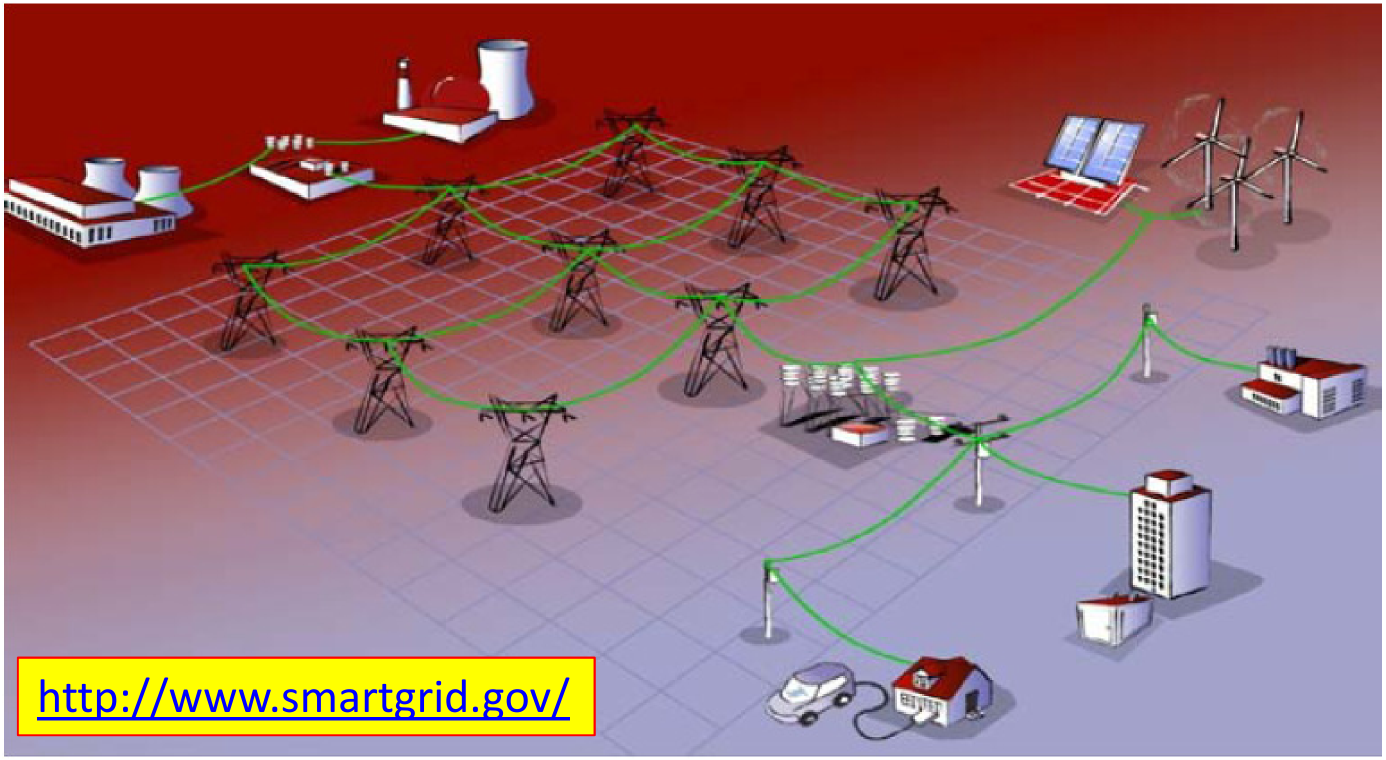
Smart Grid Concept



Technology Review, Jan/Feb 2011

Smart Grid Video- Overview http://www.netl.doe.gov/smartgrid/video.html

Smart Grid Concept



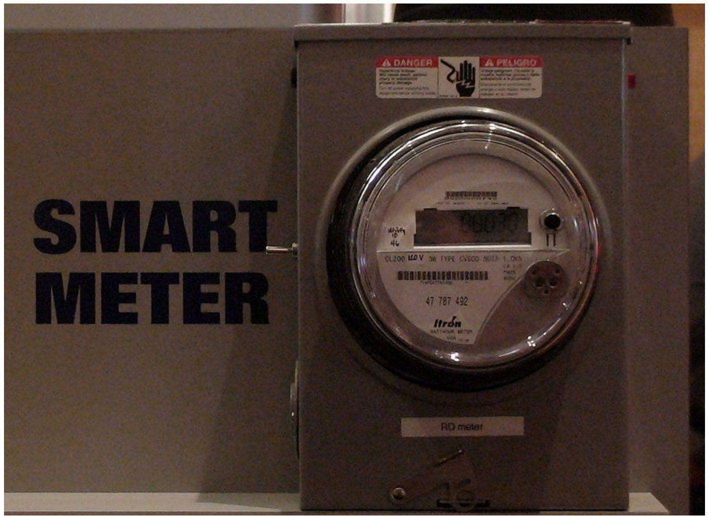
1. Uses IT to improve how electricity flows from power generators to consumers
2. Allows consumers to interact with the grid
3. Integrates new technologies into grid operation.

- Decentralized supply and control
- Two-way power flow
- Two-way information flow

- Active participation by consumers
- Accommodate energy from DER
- Anticipates and responds to system disturbances
- Optimizes asset utilization

http://www.netl.doe.gov/smartgrid/refshelf.html#Articles

Smart technology



SMART METERS: Installations allow real-time tracking and adjusting of energy consumption

http://www.scientificamerican.com/article.cfm?id=virginia-smart-meters-power-grid

http://www.scientificamerican.com/blog/60-second-science/post.cfm?id=want-to-lower-your-electric-bill-go-2009-02-11

Google announced that it's developing software called PowerMeter, which will let consumers check out their home energy use in near real-time on their computers.

Total Smart Grid funding in Florida:
$431, 724, 697

1. City of Leesburg, Florida Smart Grid Project
2. City of Quincy, FL Smart Grid Project
3. City of Tallahassee Smart Grid Project
4. Florida Power & Light Company Smart Grid Project
5. Intellon Corporation Smart Grid Project
6. JEA Smart Grid Project
7. Lakeland Electric Smart Grid Project
8. Southern Company Services, Inc. Smart Grid Project
9. Talquin Electric Cooperative, Inc. Smart Grid Project

China

- China is now building lines carrying direct current at 800 kilovolts and alternating current at 1,000 kilovolts--both world firsts.
- Plans call for a total of nine 800-kilovolt lines in China by 2020 and some $300 billion worth of grid upgrades through 2015.

Source: Fairley, Peter, *Technology Review*, Vol. 113, No. 3, pp. 36-43, May/June 2010.