# Electricity 101: An Introduction to Electric Power Generation

**Thomas A. Sarkus**

Division Director, Project Financing & Technology Deployment Division

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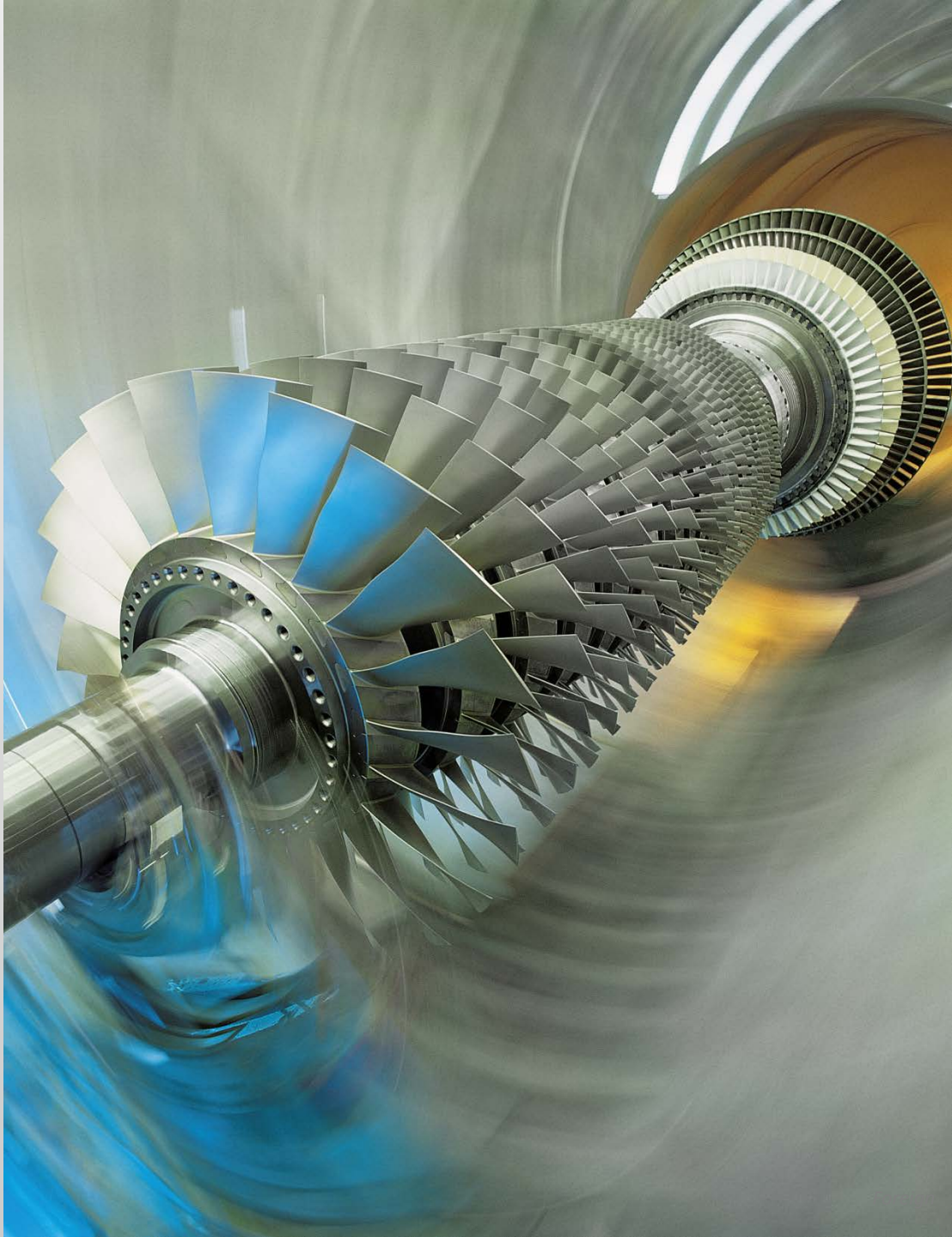


U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

# Coal & Power Class Outline (Electricity and the Grid)

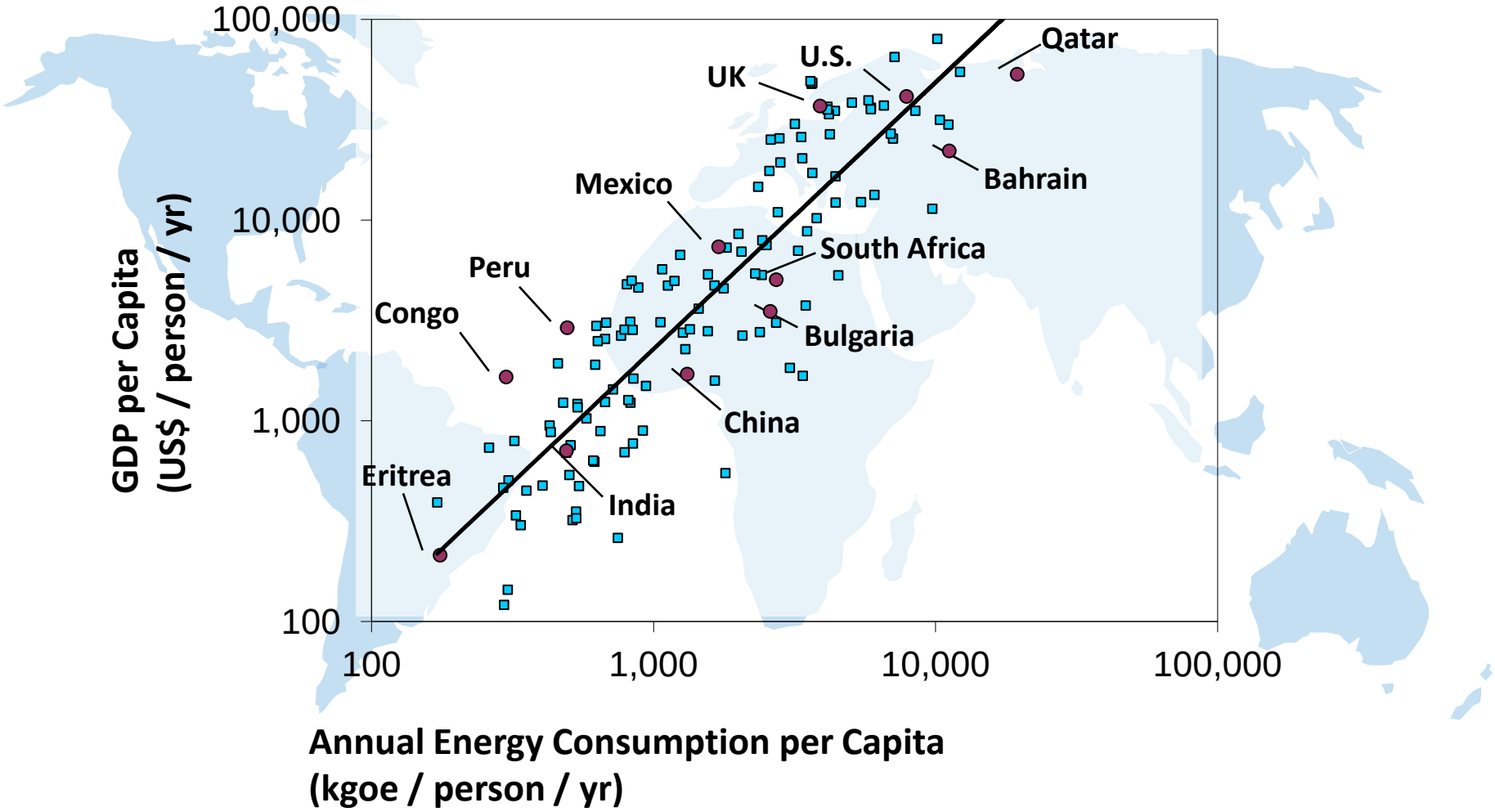
- **Electricity/Power Generation Basics (Today)**

- **Components of an Electricity System**
  - Generation (Today and the rest of the week)
  - Transmission & Distribution (Friday)
  - Load (Today, briefly)

- **Smart Grid Overview (Friday)**

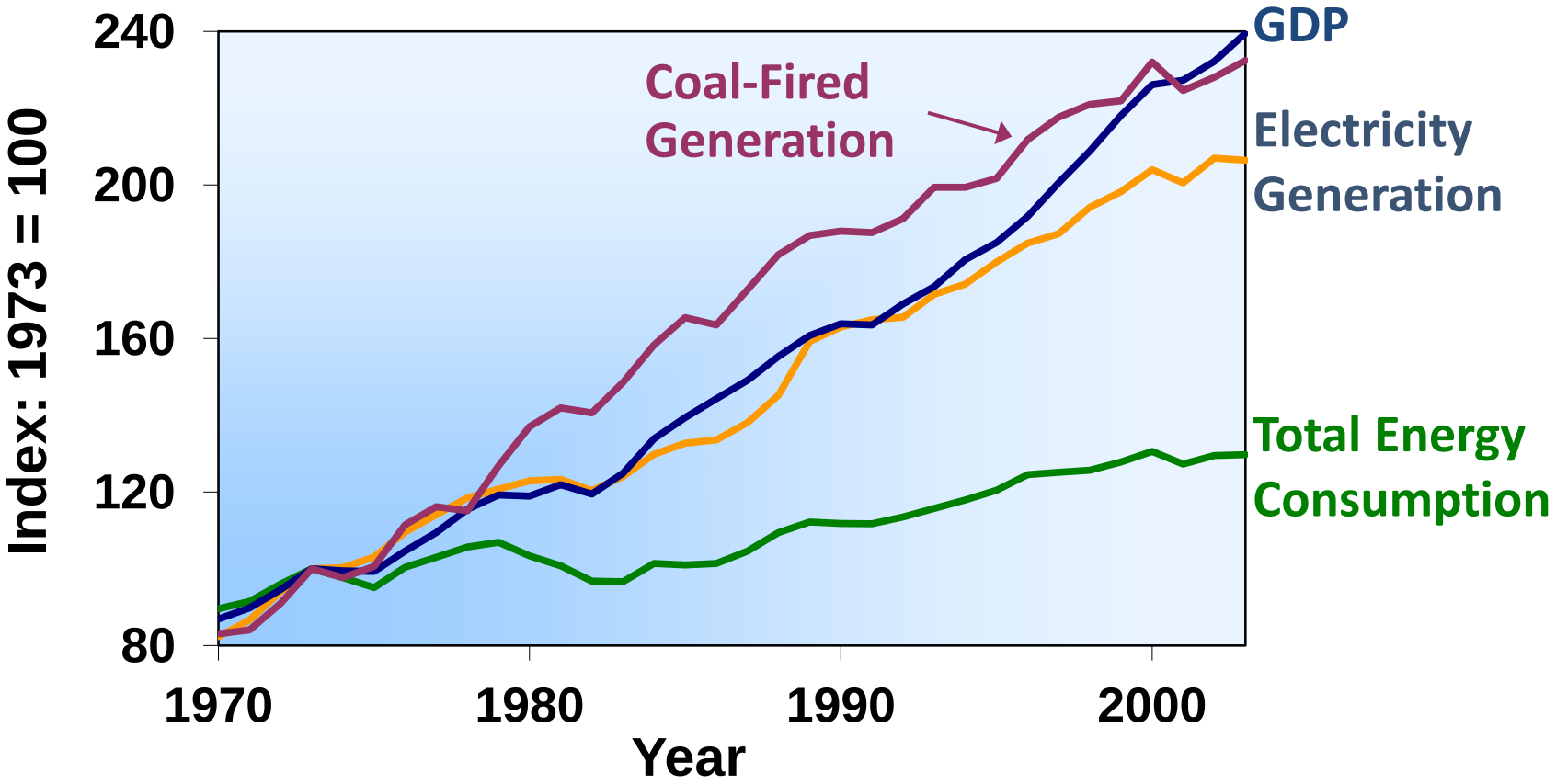
# Energy Contributes to Quality of Life

## *GDP vs. Energy Consumption*




*Development Data Group, The World Bank. 2008; Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat: IEA Statistics Division*

# Coal Use Linked to Economic Growth

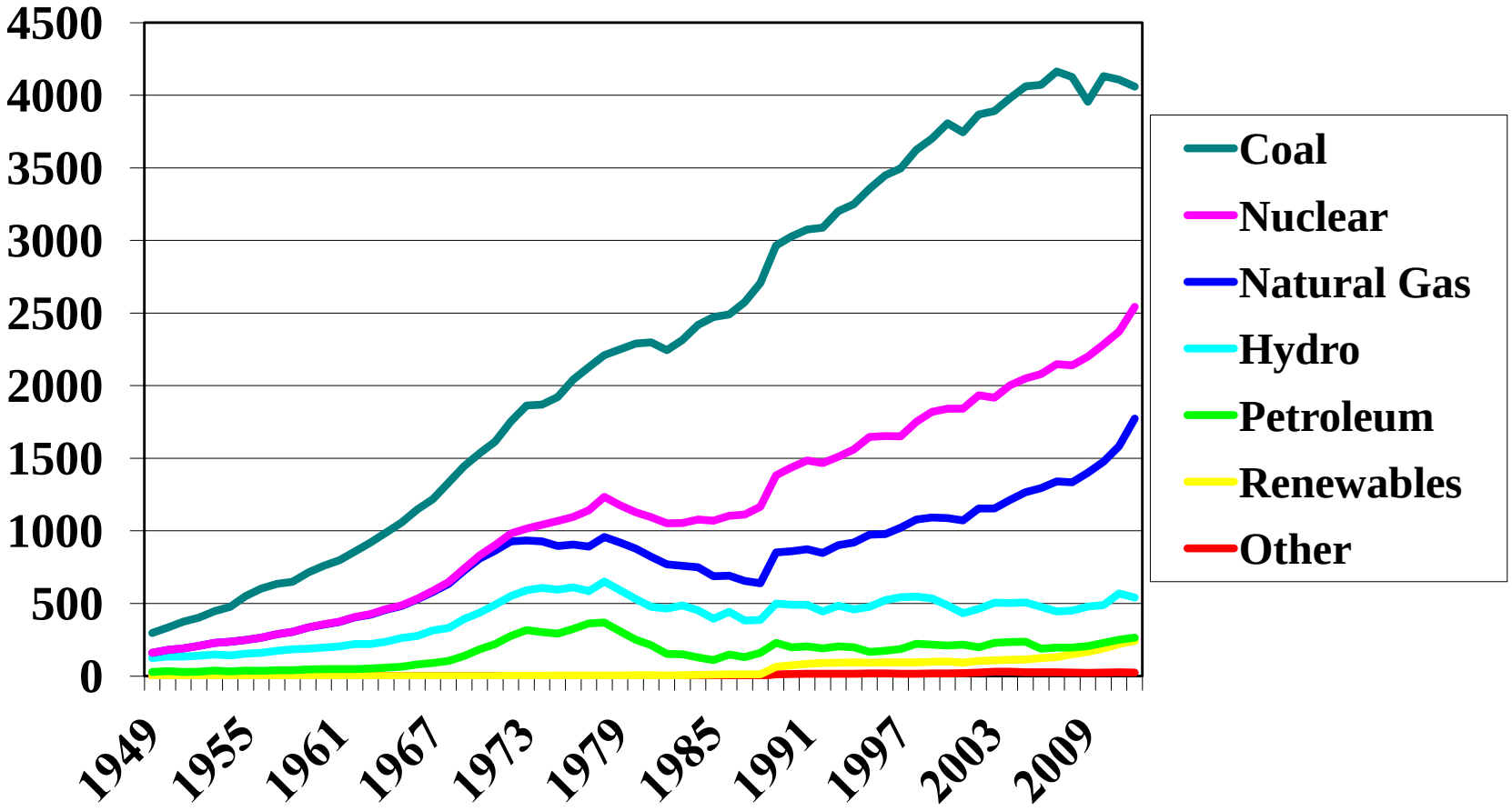



***Coal-fired generation and GDP have grown at nearly the exact same pace over last 30 years***

*GDP: U.S. DOC, Bureau of Economic Analysis*
*Energy & Electricity: EIA, Annual Energy Review 2003*

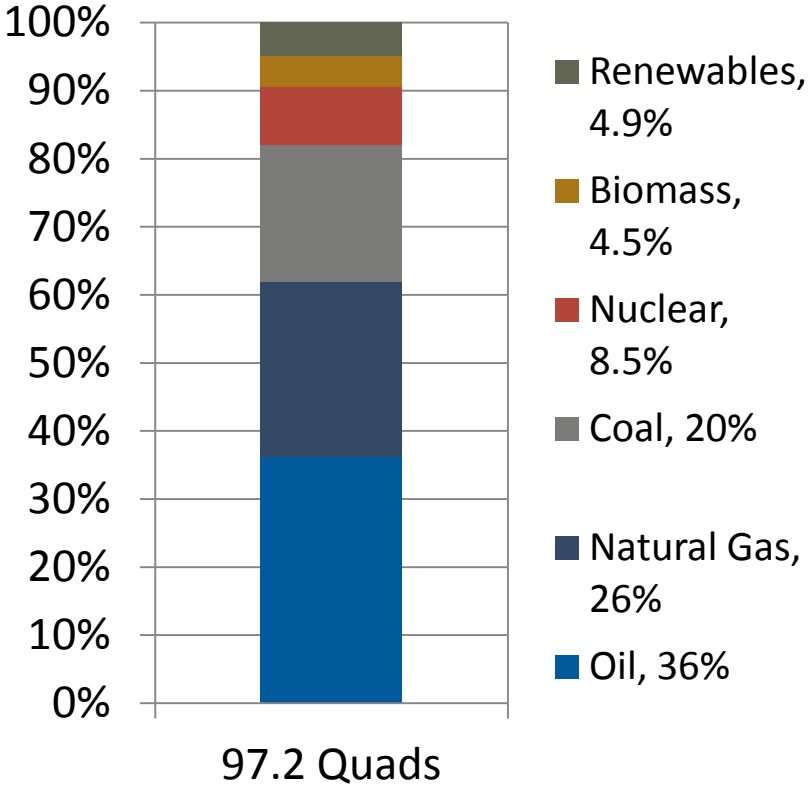
# U.S. Electricity Generation, by Source

(Billion KiloWatt-Hours)

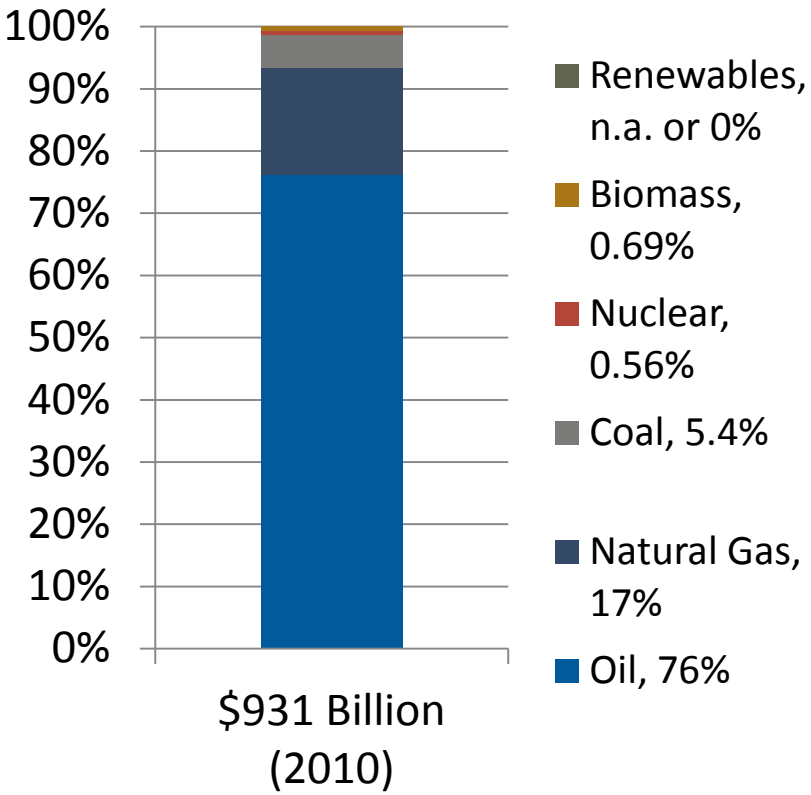


# U.S. Energy Consumption & Cost

## Consumption, Quadrillion Btu




## Consumer Expenditures, $ Billion




Source: U.S. Energy Administration, *Annual Energy Review 2011* (DOE/EIA-0384, 2011), Table 1.3 Primary Energy Consumption Estimates by Source, & Table 3.5 Consumer Expenditure Estimates for Energy by Source (most recent data listed in Table 3.5 are from 2010).

# U.S. Electric Capacity & Generation, 2011

| | Net Summer Capacity (thousand MWe) | Net Generation (billion kW-hrs) |
|---|---|---|
| Coal | 317.6 - 30.2% | 1,733.4 - 42.3% |
| Natural Gas | 415.2 - 39.5% | 1,013.7 - 24.7% |
| Nuclear | 101.4 - 9.6% | 790.2 - 19.3% |
| Hydro | 78.7 - 7.5% | 319.4 - 7.8% |
| Renewables | 61.2 - 5.8% | 194.0 - 4.7% |
| Petroleum | 51.5 - 4.9% | 30.2 - 0.7% |
| Other | 25.6 - 2.4% | 19.8 - 0.5% |
| Total | 1,051.3 - 100% | 4,100.7 - 100% |

Source: *EIA Electric Power Annual 2010*1 Tables 3.1.A & 4.2.A.

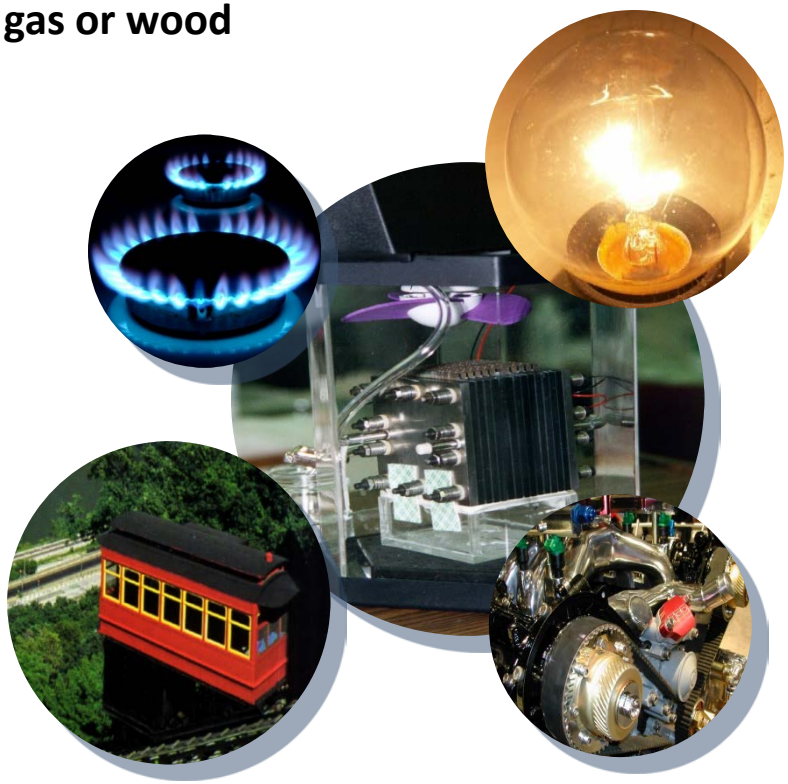
# Average Power Plant Operating Expenses for Electric Utilities, 2011 (mills/kWh)

| | Operation | Maintenance | Fuel | Total |
|---|---|---|---|---|
| Nuclear | 10.9 mills | 6.8 mills | 7.0 mills | 24.7 mills |
| Fossil Steam | 4.0 | 4.0 | 27.1 | 35.1 |
| Hydroelectric | 5.1 | 3.7 | -- | 8.9 |
| Gas Turbine & Small Scale | 2.8 | 2.9 | 38.8 | 44.5 |

Source: EIA *Electric Power Annual 2011*, Table 8.4.

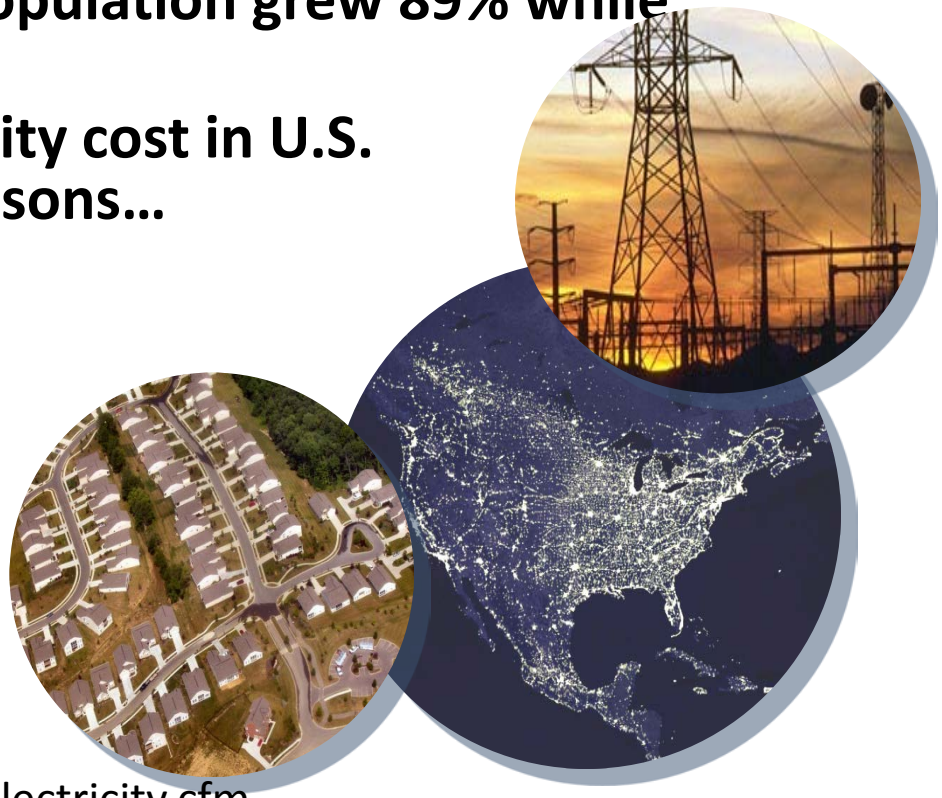
# Forms of Energy

- **Energy can neither be created nor destroyed - it can only be transformed (converted) from one form to another**
  - Chemical to thermal
    - **Home furnace using fuel oil, natural gas or wood**
  - Chemical to thermal to mechanical
    - **Automobile engine**
  - Chemical to electrical
    - **Fuel cell**
  - Electrical to mechanical
    - **Electric motor**
  - Electrical to radiant
    - **Toaster, light bulb**
  - Mechanical to electrical
    - **Generator**



# The Big Picture for Electricity

- **World electricity demand is projected to double in the next ~ 30 years [1)]**
- **Of 7B world population, ~1.4B lacked access to electricity in 2009 [1)]; another ~2B had minimal access**
- **Over the last 50 years, U.S. population grew 89% while electricity use grew 1,315%**
- **From 1985-2005, avg. electricity cost in U.S. increased 27%; some comparisons…**
  - Health Care – 185%
  - Housing – 82%
  - Food – 81%
  - Transportation – 63%
  - Clothing – 14%



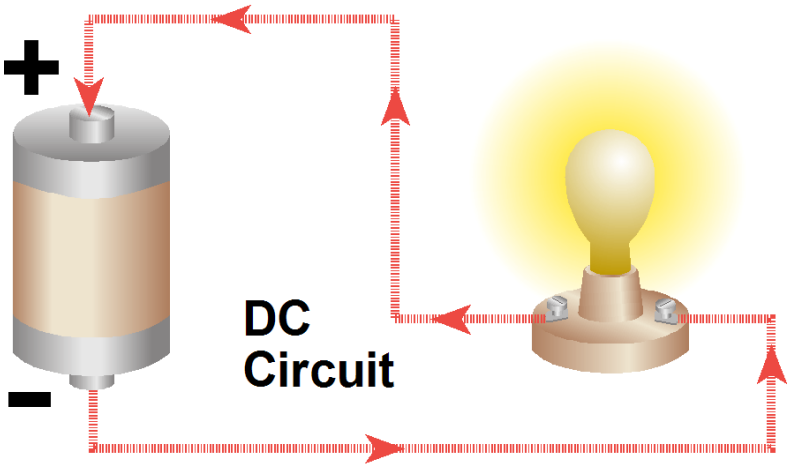
1) http://www.eia.gov/forecasts/ieo/electricity.cfm

# Basic Electric Circuit

- **Electric currents come in two types**

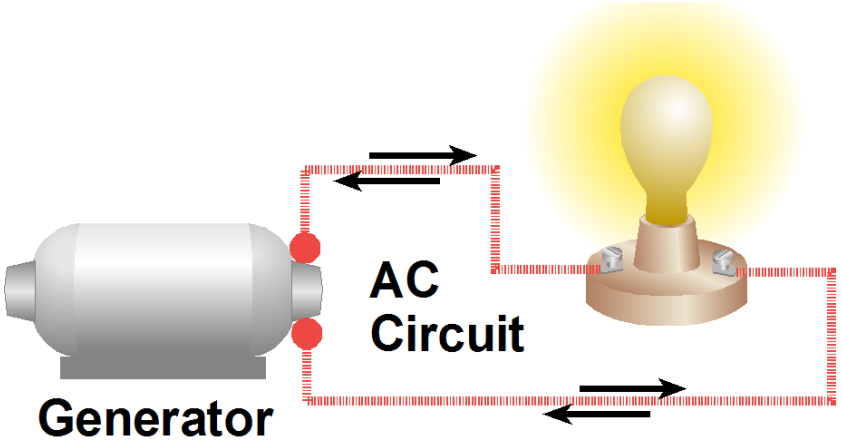
Direct current (DC)

Power flows continually in one direction, electrons from the negative terminal to the positive terminal




Alternating current (AC)

A flow of electric charge that undergoes periodic reverses in direction. Each round trip is called a cycle and in the US, the cycle for electricity is 1/60th of a second

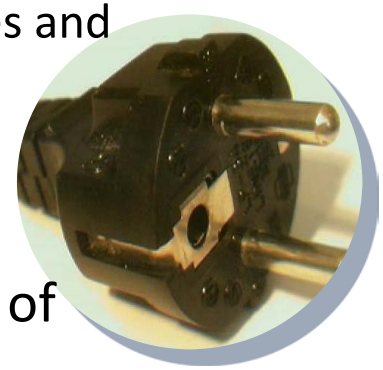


# Watt is Electricity?

- **Watt (W) – Basic unit of measure of electric power. Power (measured in Watts) equals voltage (measured in Volts) times current (measured in Amps) or Volts X Amps = W**
- **Kilowatt (kW)**
  - A unit of power equal to 1,000 W
- **Kilowatt Hour (kWh)**
  - A unit by which residential and most business customers are billed for monthly electric use. It represents the use of one kW of electricity for one hour, e.g.,
    - **A 100 W light bulb on for 10 hours**
    - **A 1,000 W heater on for 1 hour**
    - **A 10,000 W air conditioner on for 6 minutes**

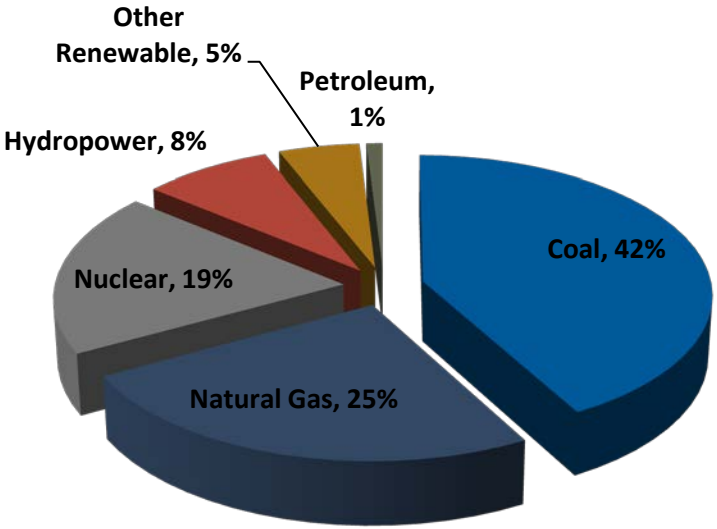
# Watt is Electricity?

- **Megawatt (MW)**
  - A unit of power equal to one million watts
- **Megawatt Hour (MWh)**
  - The use of 1 million watts (or 1,000 kilowatts) of electricity for one hour
  - This term is used most often for large-scale industrial facilities and large population centers
- **The average U.S. household uses 11.5 MWh (11,496 kWh) of electricity/yr[1]**
  - Per EIA[2], it takes 1.03 pounds of coal to make 1 kWh of electricity
  - The average U.S. household would be using 11,840 pounds of coal



1) http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3
2) http://www.eia.gov/tools/faqs/faq.cfm?id=667&t=2

# What Fuels Are Used to Generate Electricity?




## 2011 - National Fuel/Source Mix

(Mix varies significantly by region)

Note: With the recent increase in shale gas production, coal share has dropped and natural gas share has risen in electricity generation

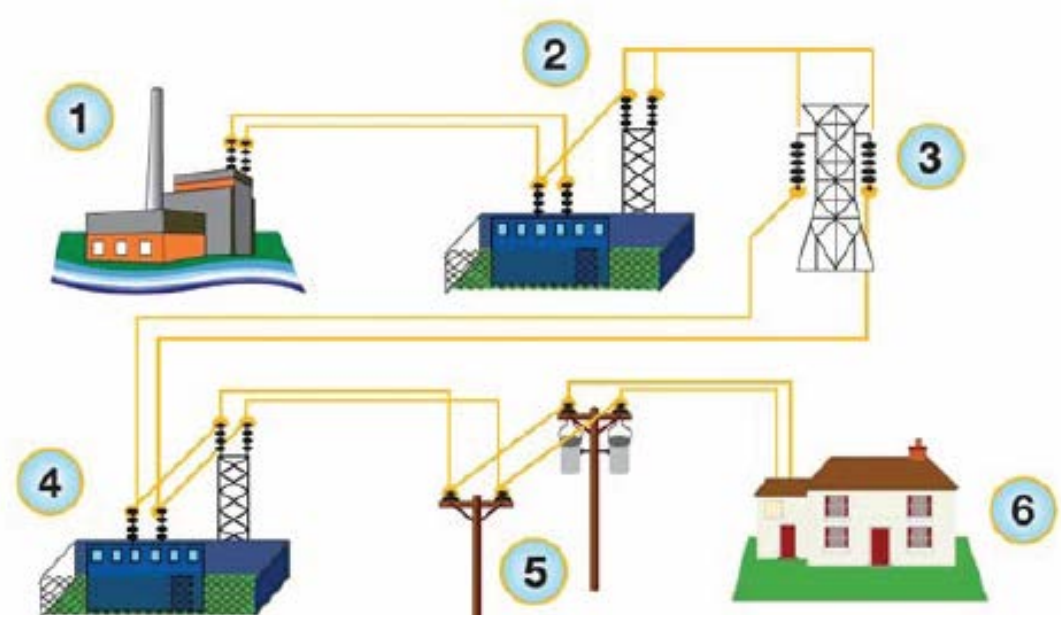
"Other Renewable" includes generation from solar, wind, geothermal, biomass (agricultural waste, municipal solid waste, landfill gas recovery, wood, pitch)

Data from: http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

# How Do I Get Electricity?

## *Fundamental Components*

1. Electricity is generated and leaves the power plant
2. Voltage is increased at a “step-up” substation
3. Energy travels along a transmission line to the area where power is needed
4. Once there, voltage is decreased or “stepped-down,” at another substation
5. A distribution power line carries the electricity
6. Electricity reaches the customer



# Efficiencies or "Lost" Energy

- **All machines, processes and systems lose some energy in the course of their use**
  - As an example, an incandescent light bulb converts less than 10% of the energy to light, and about 90% to heat
- **A subcritical pulverized coal plant has a nominal efficiency of about 37%*, but still has losses such as:**
  - Condenser – (heat loss)
  - Exhaust Gas – (heat loss)
  - Internal Power requirements – (electrical loss)
- **Also, resistance in the power lines, and small inefficiencies in transformers and power switches result in some efficiency loss**

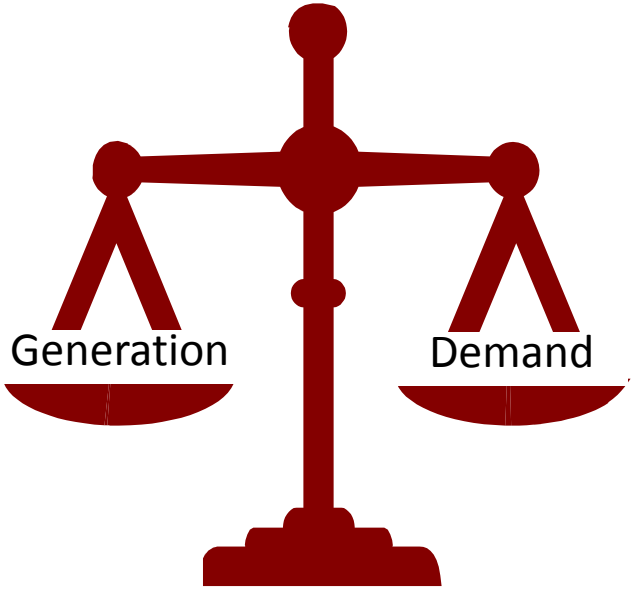
**Cost and Performance Baseline for Fossil Energy Plants, DOE/NETL-2007/1281, page4*

# Unique Characteristics of Electricity

- **Travels at the speed of light**
  - 186,000 miles / second
- **Flows through the path of least resistance**
- **Cannot be stored on a large scale**
  - Must be consumed the instant (within a second) it is created
  - Generation must closely match load / demand
  - There are some battery, flywheel, pumped hydro, etc. facilities that can store power; but not at a significant capacity, on a grid scale.

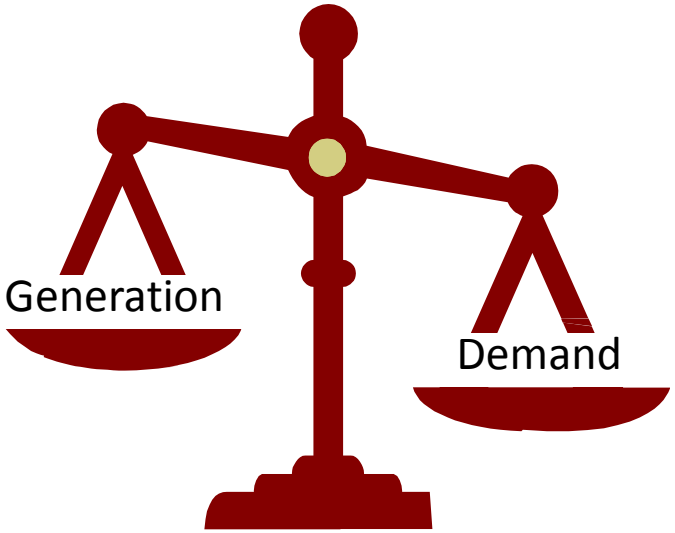
# Generation and Load Must Balance

- **Forecast demand**
- **Schedule generation**
- **Minute-to-minute automatic generation control**
- **Spinning and non-spinning reserves**

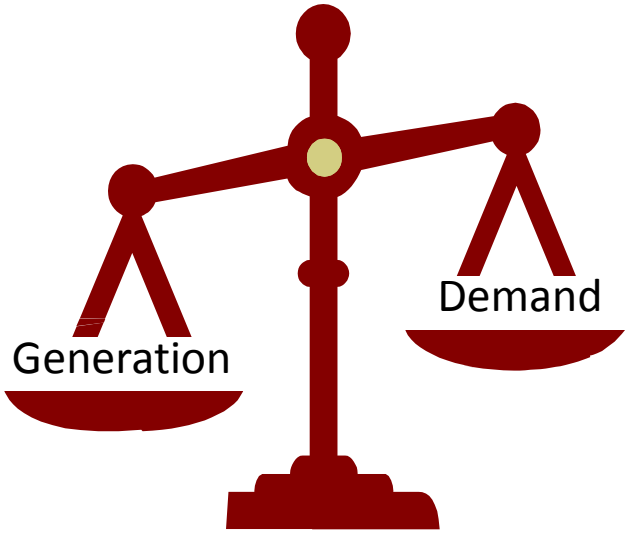


# Consequences of Generation / Load Mismatch

- **Low voltage**
- **Low frequency**
- **Dim lights**
- **Damaged motors**



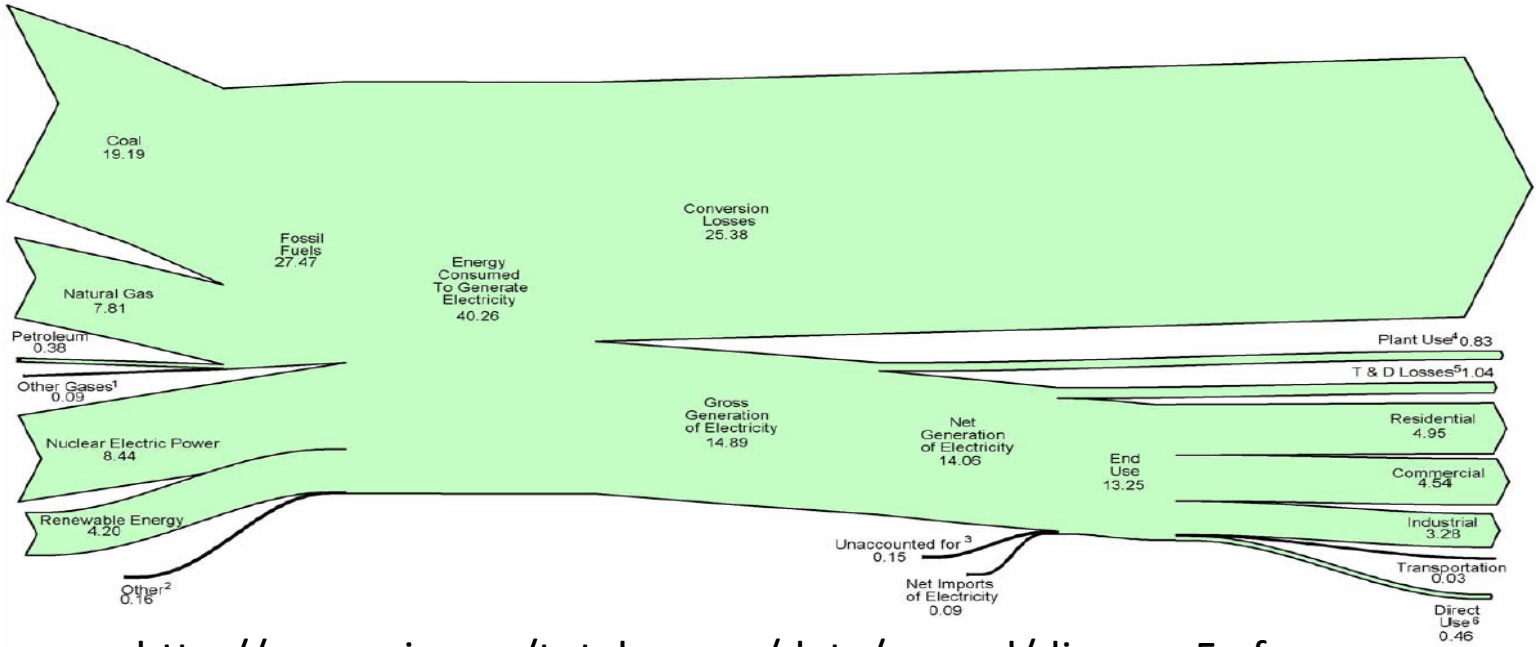

- **High voltage**
- **High frequency**
- **Damaged electronic equipment**



# Electricity Flow, 2010 (Quadrillion Btu)

In 2010, 40.26 Quads of "energy" used to produce electricity. Of this:

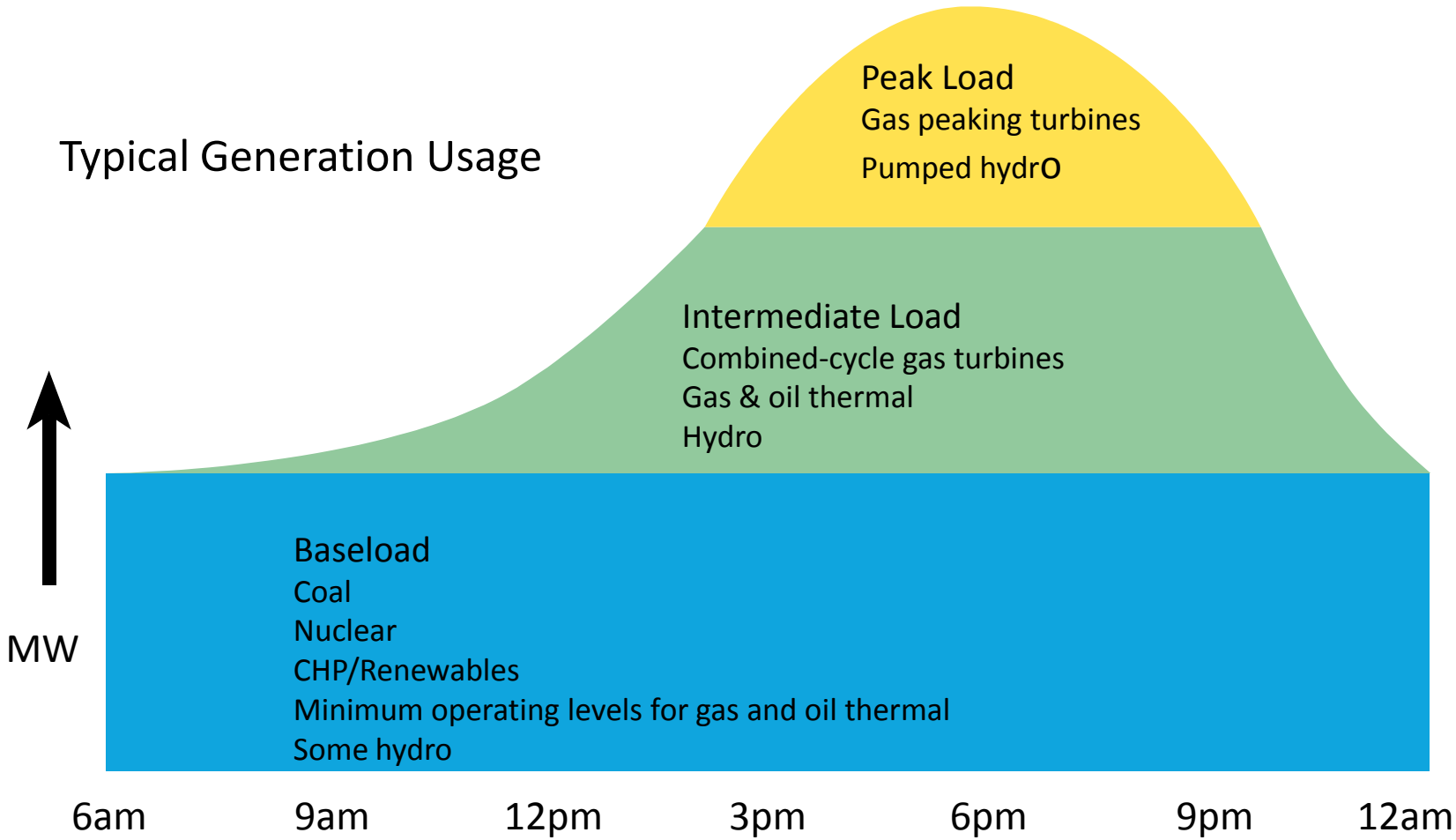
- 25.38 (~63%) Quads lost, i.e., "conversion losses"
- 14.89 (~37%) Quads of electricity produced. Of this:
  - 4.95 Quads (~33.2%) used in Residential market
  - 4.54 Quads (~30.5%) is used in Commercial market
  - 3.28 Quads (~22%) is used in Industrial market
  - 1.04 Quads (~7%) is lost in transmission and distribution (T&D)
  - 1.08 Quads (~7.25%) is "Other"



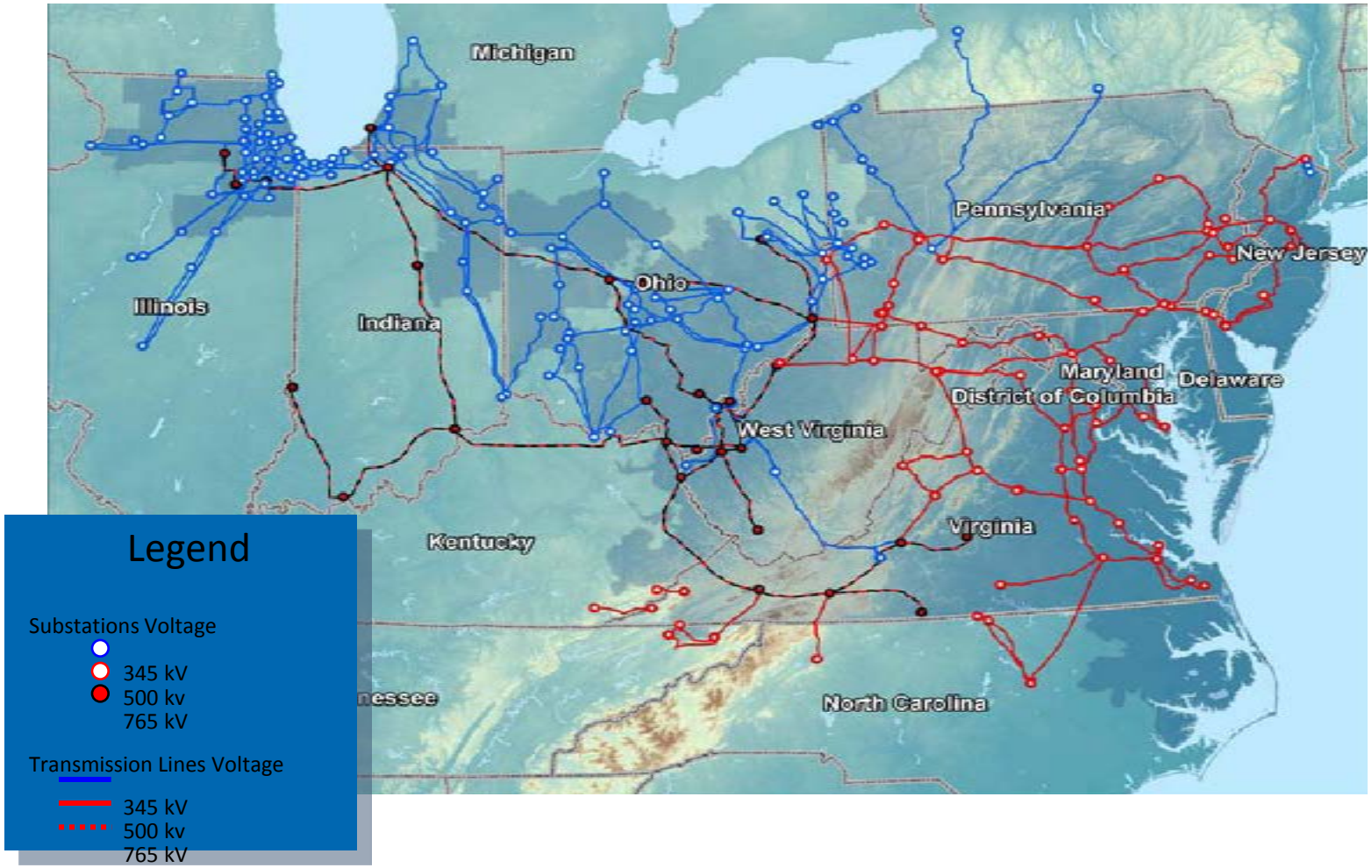



http://www.eia.gov/totalenergy/data/annual/diagram5.cfm

# Baseload, Intermediate Load and Peak Load



# PJM Transmission Backbone



# Acceptable Ranges of Voltage & Frequency in U.S.

- **Standards have been established for voltage & frequency of the power transmission & distribution system**
  - Voltage 120 VAC +/- 5%
    (114 VAC – 126 VAC in the home)
  - Frequency 60Hz +/- .01 Hz
    (1 cycle per second equals 1Hz)

# Residential Customer Expectations

- **Reliability -- Electricity will always be there**
- **Power Quality – Will not damage my stuff (or someone will pay!)**
- **Inexpensive – End of rate freeze in deregulated states is causing a crisis**
- **Constant rates – Real costs fluctuate by the hour**

# Rate Classes (2011 Data)

- **Industrial -- $0.068/kWh**
  - 728K customers in U.S. (0.5% of total customers)
  - Consumes ~26% of electric generation

- **Commercial -- $0.102/kWh**
  - 17.6M customers (12.2% of total customers)
  - Consumes ~35% of electric generation

- **Residential -- $0.117/kWh**
  - 126.1M customers (87.3% of total customers)
  - Consumes ~38% of electric generation
  - Significant regional rate variations: 34.7¢/kWH in HI; 18.3¢/kWh NY; 16.2¢/kWh NJ; 14.8¢/kWh CA; 13.4¢/kWh DC; 13.3¢/kWh MD, MI & PA; 11.8¢/kWh IL; 11.5¢/kWh FL; 11.4¢/kWh OH; 11.1¢/kWh AL, AZ & TX; 10.6¢/kWh VA; 9.4¢/kWh OK & WV; 9.3¢/kWh MO, NE & SD; 9.2¢/kWh KY; 9.0¢/kWh LA & UT; 8.3¢/kWh WA; 7.8¢/kWh ID

http://www.eia.gov/electricity/sales_revenue_price/

# How is Electricity Used in My Home?

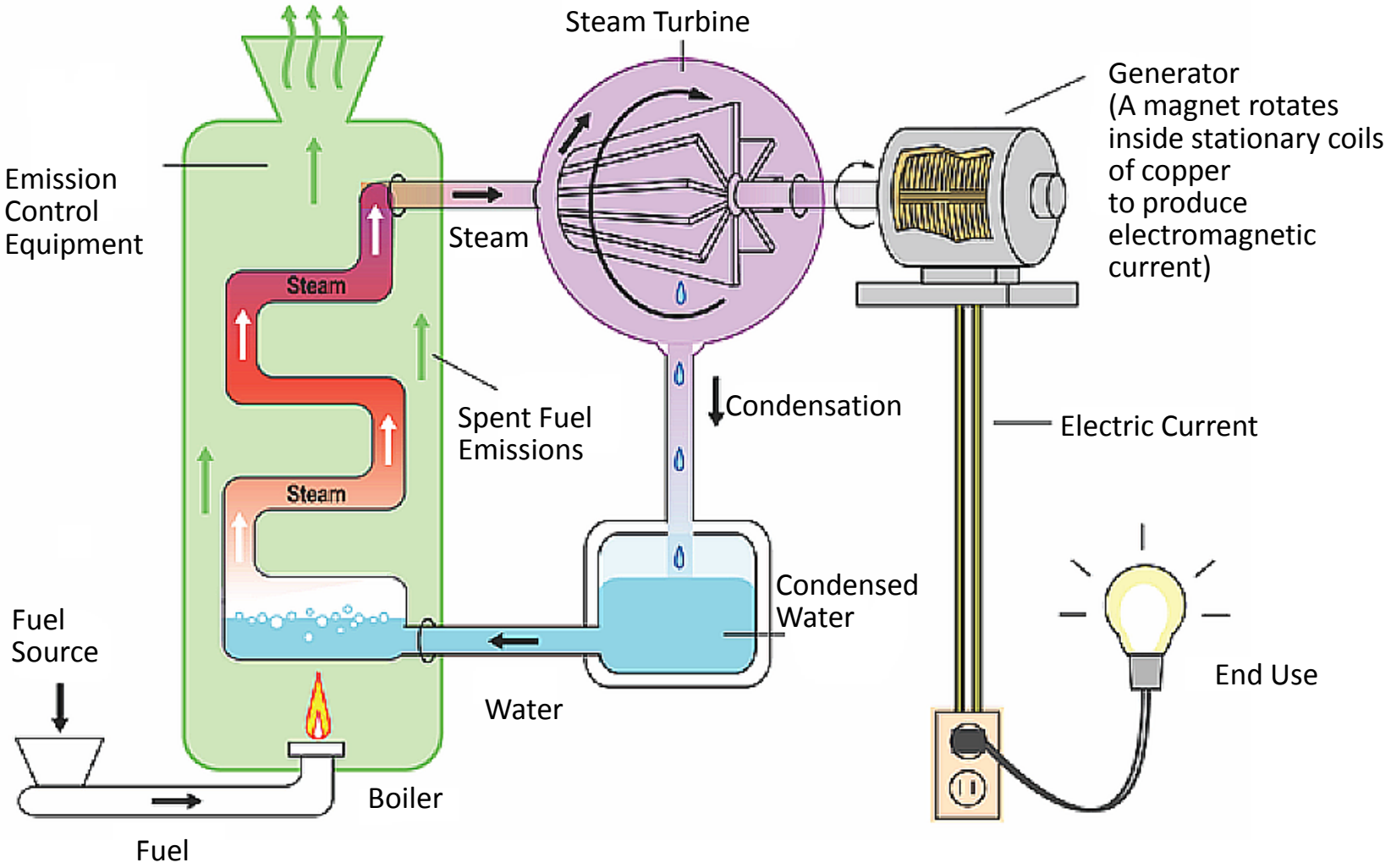
| End-Use | Quadrillion Btu | Billion KWhr | Share of Total |
|---|---|---|---|
| Space Cooling | 1.11 | 326 | 22.40% |
| Lighting | 0.71 | 207 | 14.20% |
| Water Heating | 0.44 | 129 | 8.90% |
| Refrigeration | 0.36 | 107 | 7.30% |
| Color Televisions and Set-Top Boxes | 0.34 | 100 | 6.80% |
| Space Heating | 0.29 | 84 | 5.80% |
| Clothes Dryers | 0.19 | 54 | 3.70% |
| Personal Computers and Related Equipment | 0.18 | 53 | 3.60% |
| Furnace Fans and Boiler Circulation Pumps | 0.14 | 41 | 2.80% |
| Cooking | 0.11 | 31 | 2.20% |
| Dishwashers [1] | 0.09 | 27 | 1.80% |
| Freezers | 0.08 | 23 | 1.60% |
| Clothes Washers [1] | 0.03 | 10 | 0.70% |
| Other Uses[2] | 0.9 | 264 | 18.10% |
| **Total Consumption** | 4.65 | 1,363 | 99.90% |

1) Does not include water heating
2) Includes small electric devices, heating elements, and motors not listed above

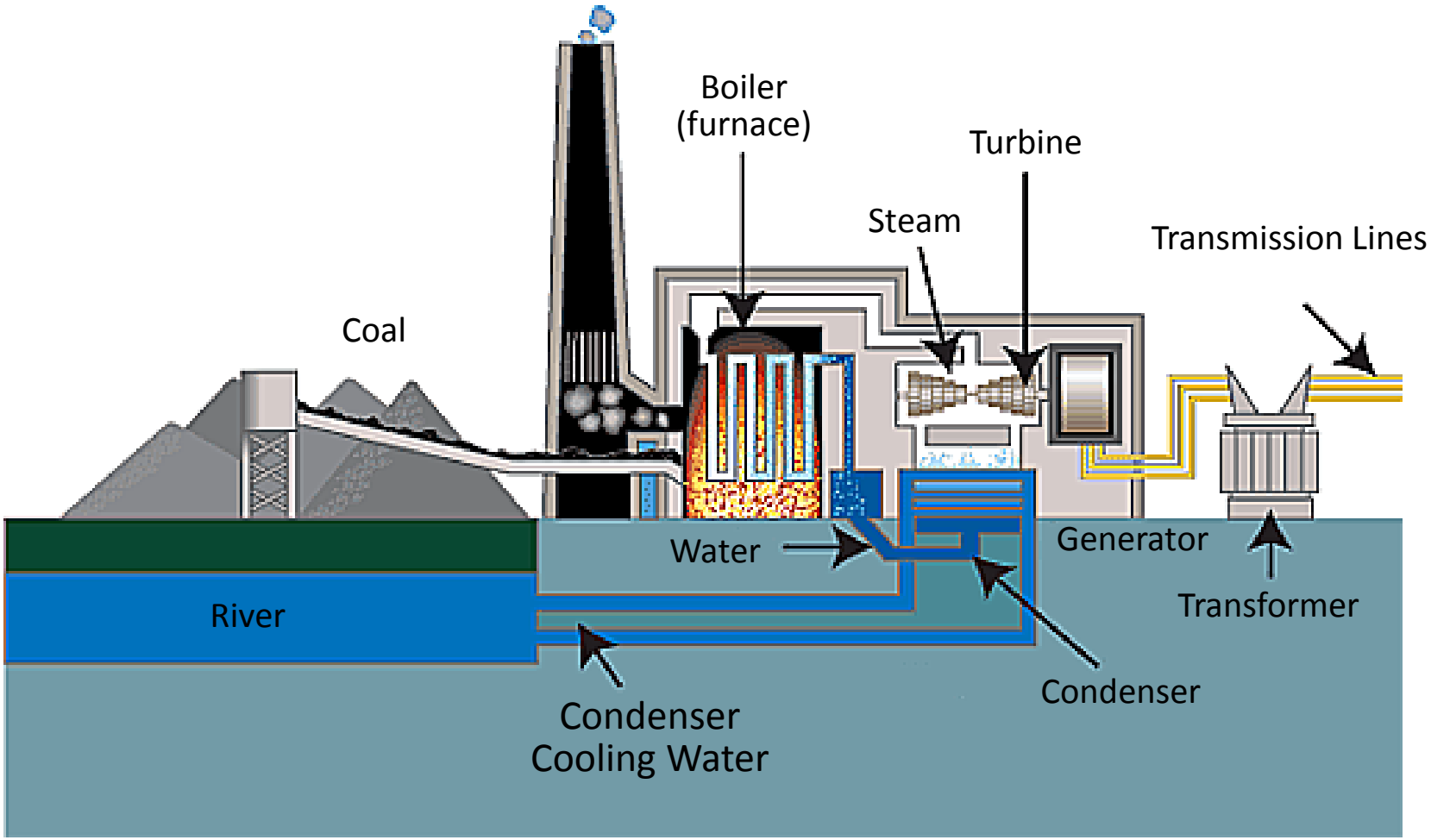
http://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3

# Generation

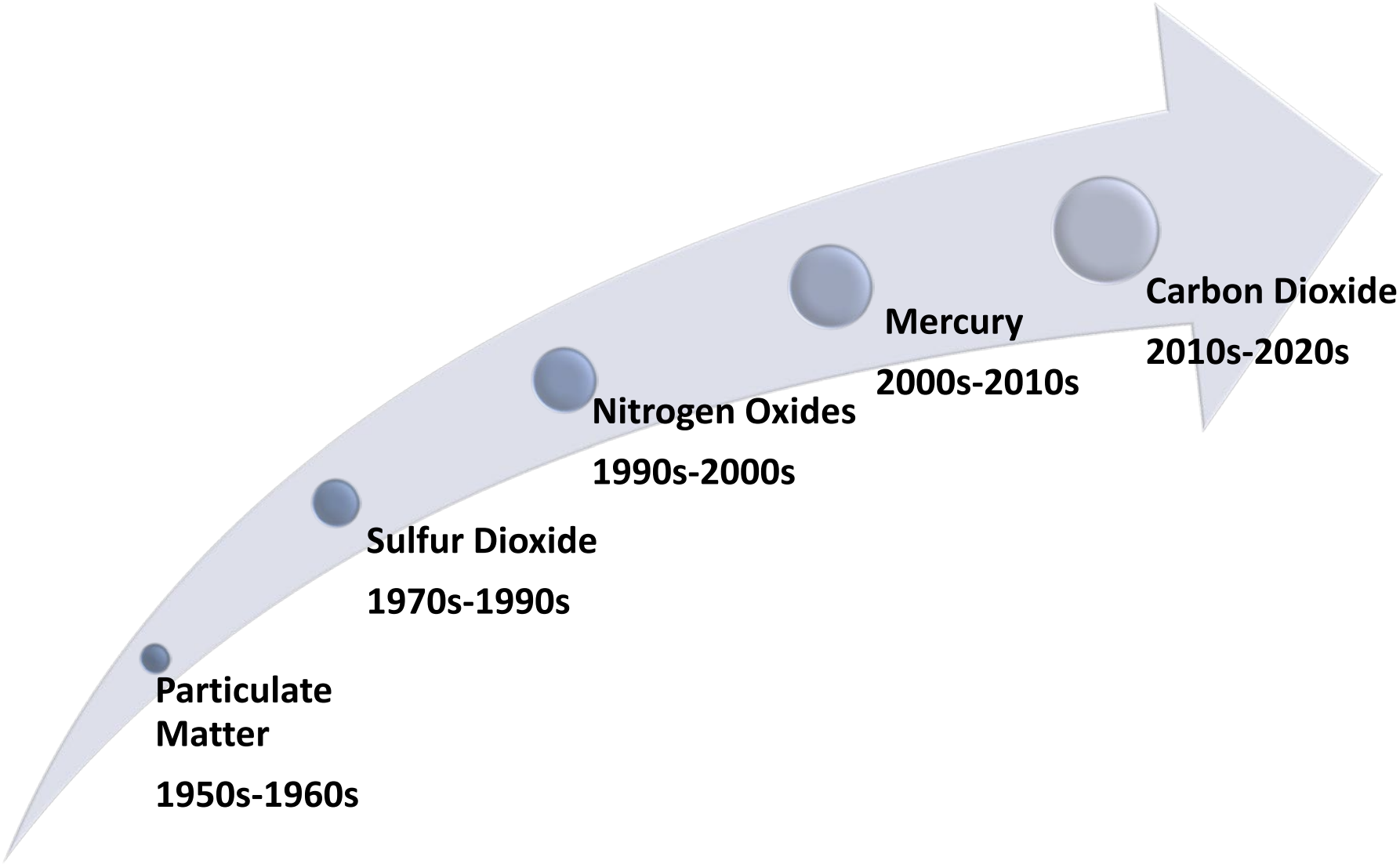
## *Generating Power and Getting It to the Consumer*



# Coal-Fired Power Plant Diagram



# Evolution of Air Pollution Controls



# Emissions Control & Efficiency Improvements

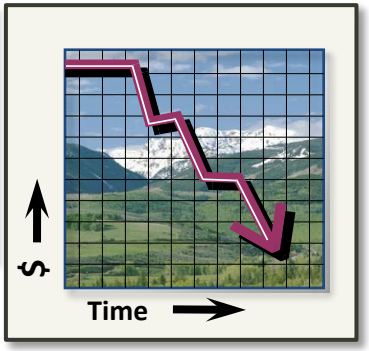
## Notable Program Successes

### Advanced Pollution Controls

- Installed on 75% of U.S. coal plants
- 1/2 to 1/10 cost of older systems

### HAPS & Hg Data

- Quantified Hazardous Air Pollutant (HAPs) Levels
- Basis for Mercury (Hg) Regulations

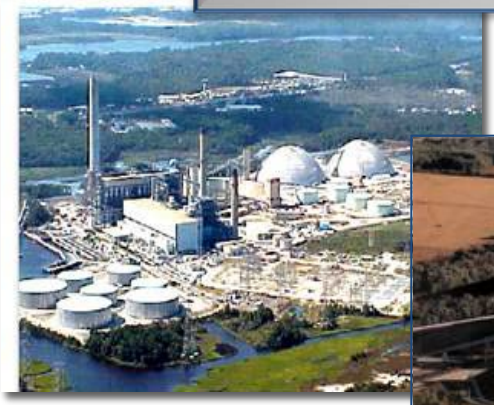



Flue Gas Desulfurization (FGD) Scrubbers

Low-$NO_x$ Burners

### Advanced Coal Power Systems

- First large (265 MW) Circulating Fluidized Bed Combustion (CFBC) power plant
- Two "super-clean" Integrated Gasification Combined Cycle (IGCC) power plants



Jacksonville CFBC

Wabash IGCC

Tampa IGCC

# Annual $CO_2$ Emissions Extremely Large

| Emissions | Total Release in the U.S., short tons per year |
|---|---|
| Mercury | 120 |
| Sulfur Dioxide ($SO_2$) | 15,000,000 |
| Municipal Solid Waste | 230,000,000 |
| Carbon Dioxide ($CO_2$) | 6,300,000,000 |

**1 million metric tons of $CO_2$:**

- Every year would fill a volume of 32 million cubic feet
- *Close to the volume of the Empire State Building*

Data sources: Mercury - EPA National Emissions Inventory (1999 data); $SO_2$ - EPA air trends (2002 data); MSW - EPA OSWER fact sheet (2001 data); $CO_2$ - EIA AEO 2004 (2002 data)

# Technological Carbon Management Options

## *Pathways for Reducing GHGs -$CO_2$*

**Reduce Carbon Intensity**

- Renewables
- Nuclear
- Fuel Switching

**Improve Efficiency**

- Demand Side
- Supply Side

**Sequester Carbon**

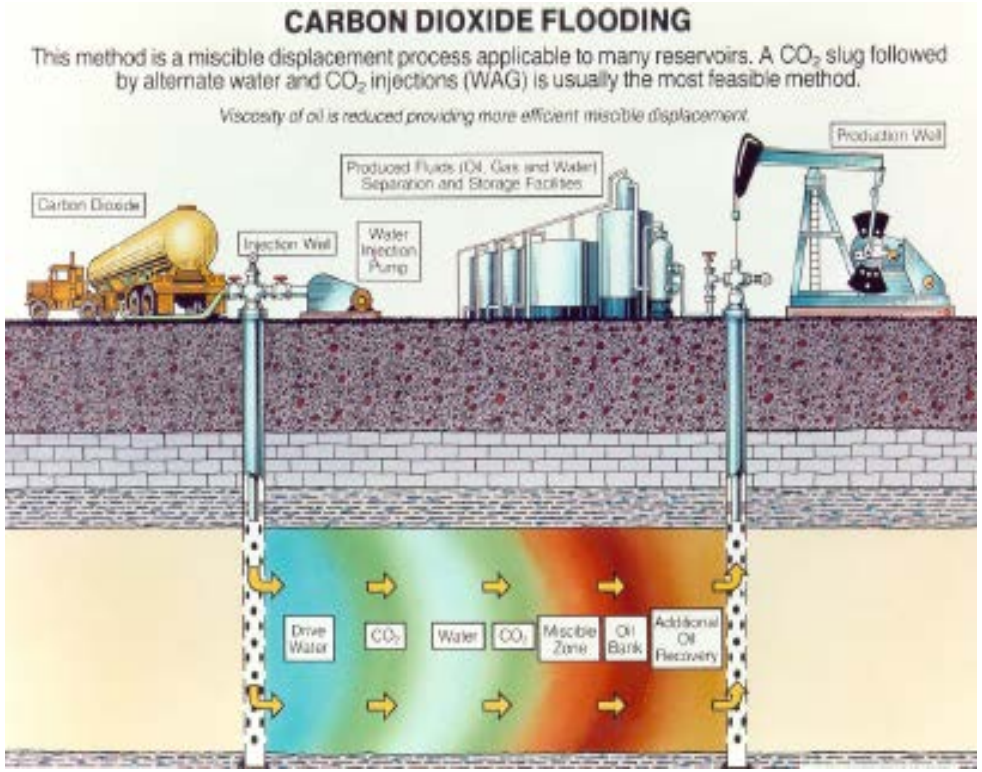
- Enhance Natural Sinks
- Capture & Store

**All options needed to:**

- Affordably meet energy demand
- Address environmental objectives

# Enhanced Oil Recovery – Beneficial Use of $CO_2$

- **EOR continually increasing its role in oil production**
  - 1 ton of injected $CO_2$ can recover 2 to 3 bbls of oil from played-out oilfields
- **Reduces cost of CCUS**
  - Oil revenues can offset CCUS costs
- **Lowers carbon footprint of transportation sector**
  - Oil produced with "next generation" $CO_2$-EOR may be better than carbon neutral
- **Increases energy supply**
  - Promotes world-wide energy security



# Comparison of Coal-Based Power Generation Platform Technologies

- **Pulverized Coal (PC) Boilers**
  - Commercialized in 1920s-1930s
  - Approximately 5000 units operating world-wide; 1100 in US
  - Unit sizes up to ~1300 MWe

- **Fluidized Bed Combustion (FBC) Boilers**
  - Commercialized in 1970s-1980s
  - Approximately 500 units operating world-wide; 150 in US (mostly small units)
  - Unit sizes up to ~ 500 MWe
  - Costs ~5-10% higher than pc units

- **Integrated Gasification Combined-Cycle (IGCC) Power Plants**
  - Commercialized in 1980s-1990s
  - 9 coal-based units operating world-wide; 4 in US (+ 2 more in 2014)
  - Unit sizes up to ~ 300 MWe
  - Costs ~10-20% higher than pc units

# Some Next Steps for Coal-Based Power Generation Platform Technologies

- **Pulverized Coal Combustion**
  - Tightened emissions controls (e.g., Hg)
  - Post-combustion $CO_2$ capture
  - ↑Temperature,↑Pressure (e.g., USC)
  - Oxy-Combustion

- **Fluidized Bed Combustion**
  - Supercritical CFB (possibly oxy-CFB)
  - Post-combustion $CO_2$ capture
  - Pressurized CFB (possibly oxy-PCFB)

- **IGCC**
  - ↓ Cost, ↑ Efficiency (e.g., larger combustion turbines)
  - Higher-$H_2$ syngas, with water-gas shift to enable CCUS
  - Polygeneration of electricity, $CO_2$ and…fertilizers, chemicals and/or fuels
  - Natural gas back-up, low rank coals, advanced gasifier designs
  - $H_2$ separation membranes, low cost $O_2$ supply, warm-gas cleanup

# Some Possible Trends & Directions

- **Increased Thermal Efficiency**
  - A practical way to address climate change concerns

- **$CO_2$ Capture with Enhanced Oil Recovery**
  - $CO_2$ capture is another way to mitigate climate change
  - EOR is presently the only way to offset $CO_2$ capture costs
  - Must participate/share in oil revenues, not just sell $CO_2$

- **Polygeneration**
  - Co-produce chemicals, fertilizers and/or fuels
  - Higher value co-products can enhance electricity revenues

- **Hybrid Technologies**
  - Coal + Gas, Gas + Renewables, Coal + Renewables

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www.fe.doe.gov

NETL

www.netl.doe.gov