Maxwell Climate Change Workshop:
The US Energy Sector and CO2 Emissions

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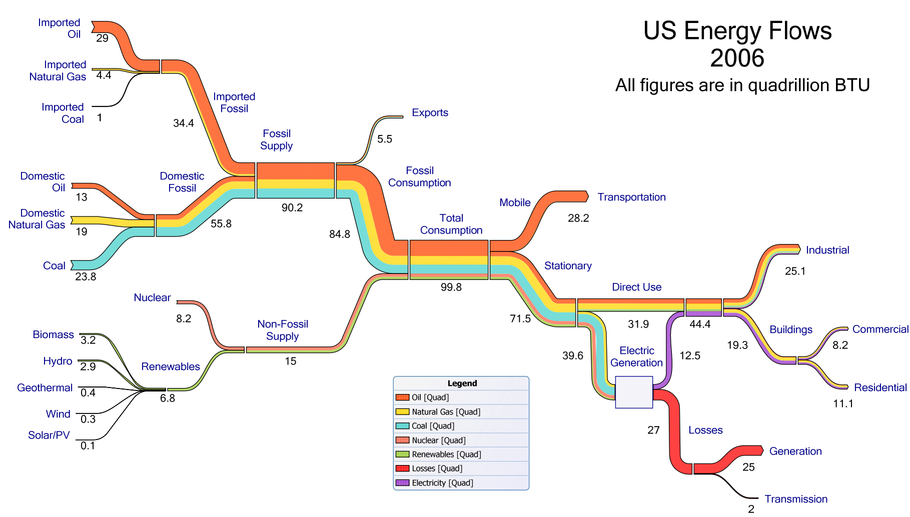
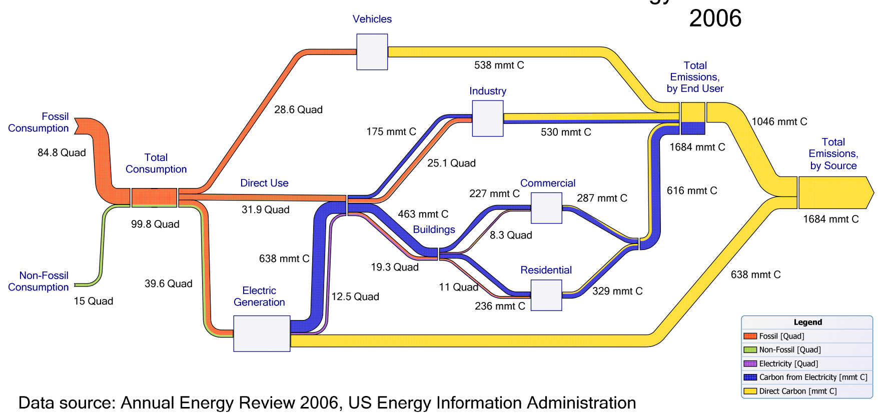


Data source: Annual Energy Review 2006, US Energy Information Administration

US Energy and Carbon Flows
2006



Data source: Annual Energy Review 2006, US Energy Information Administration

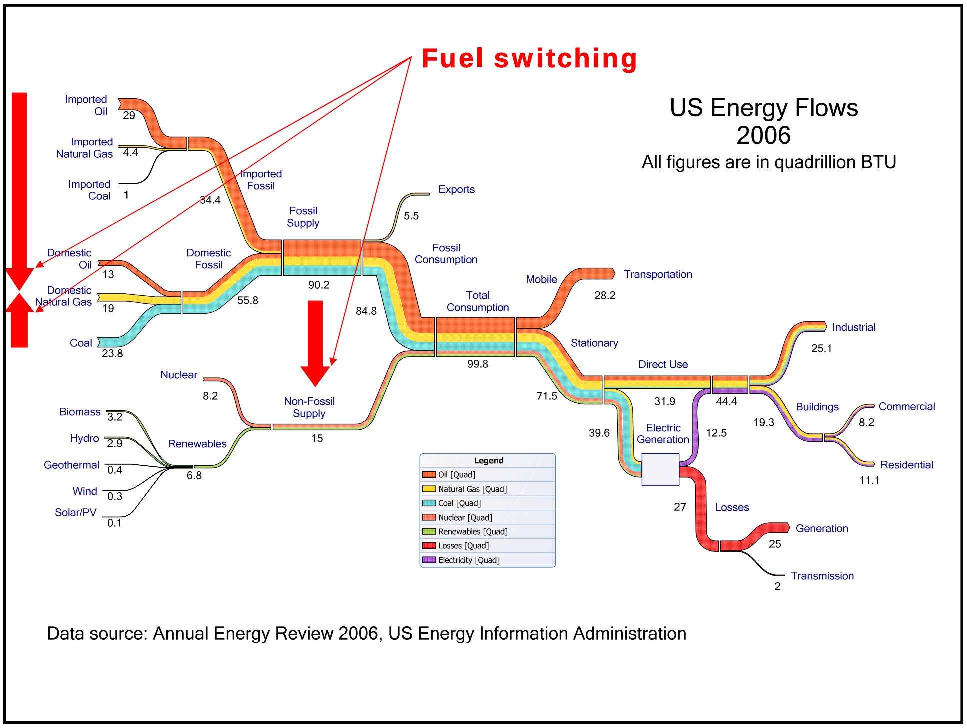
Three options for abatement

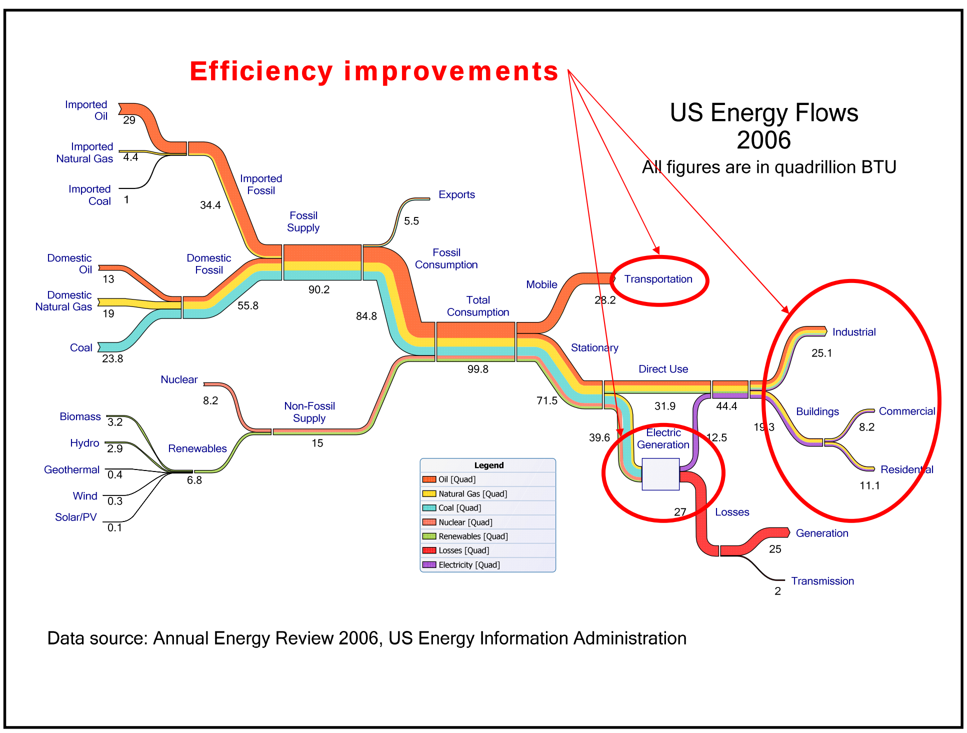
- Fuel switching
  - ⇨ *Shift to fuels with lower CO2 for equivalent energy*

    Example: coal to gas for electricity
- Efficiency improvements
  - ⇨ *Use less fuel for equivalent energy services*

    Example: better lights
- Reductions in demand for energy services
  - ⇨ *Demand lower services*

    Example: turn lights off


Fuel switching
US Energy Flows
2006
All figures are in quadrillion BTU
Imported Oil
29
Imported Natural Gas
4.4
Imported Coal
1
Imported Fossil
34.4
Fossil Supply
Exports
5.5
Domestic Oil
13
Domestic Fossil
Domestic Natural Gas
19
Coal
23.8
55.8
90.2
84.8
Fossil Consumption
Total Consumption
99.8
Mobile
Transportation
28.2
Stationary
71.5
Direct Use
31.9
44.4
Industrial
25.1
Buildings
19.3
Commercial
8.2
Residential
11.1
Electric Generation
39.6
12.5
27
Losses
Generation
25
Transmission
2
Nuclear
8.2
Non-Fossil Supply
15
Biomass
3.2
Hydro
2.9
Renewables
Geothermal
0.4
6.8
Wind
0.3
Solar/PV
0.1
Legend
Oil [Quad]
Natural Gas [Quad]
Coal [Quad]
Nuclear [Quad]
Renewables [Quad]
Losses [Quad]
Electricity [Quad]
Data source: Annual Energy Review 2006, US Energy Information Administration


Efficiency improvements
US Energy Flows
2006
All figures are in quadrillion BTU
Imported Oil
29
Imported Natural Gas
4.4
Imported Coal
1
Imported Fossil
34.4
Fossil Supply
Exports
5.5
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Fossil Consumption
Total Consumption
99.8
Mobile
Transportation
28.2
Stationary
71.5
Direct Use
31.9
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Industrial
25.1
Buildings
19.3
Commercial
8.2
Residential
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Electric Generation
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27
Losses
Generation
25
Transmission
2
Nuclear
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Non-Fossil Supply
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Biomass
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Renewables
Geothermal
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0.3
Solar/PV
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Legend
Oil [Quad]
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Nuclear [Quad]
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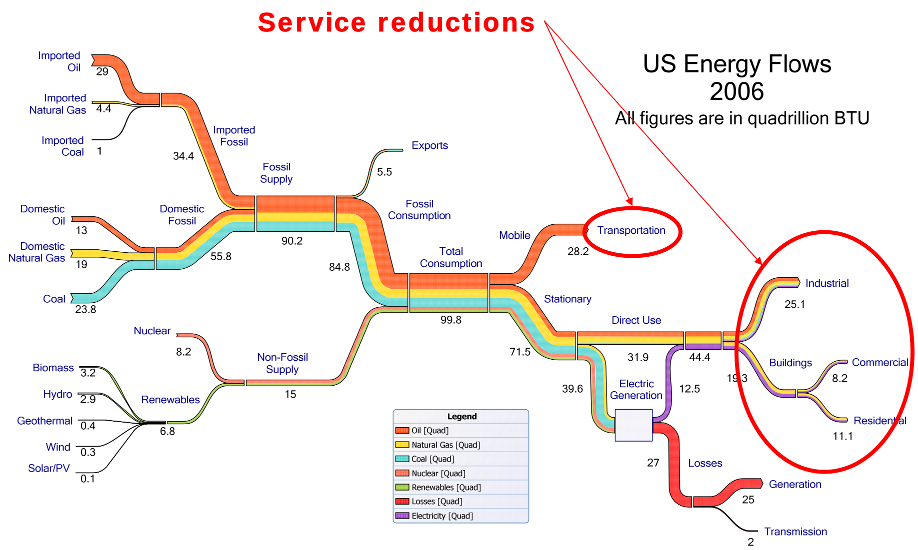
Losses [Quad]
Electricity [Quad]
Data source: Annual Energy Review 2006, US Energy Information Administration

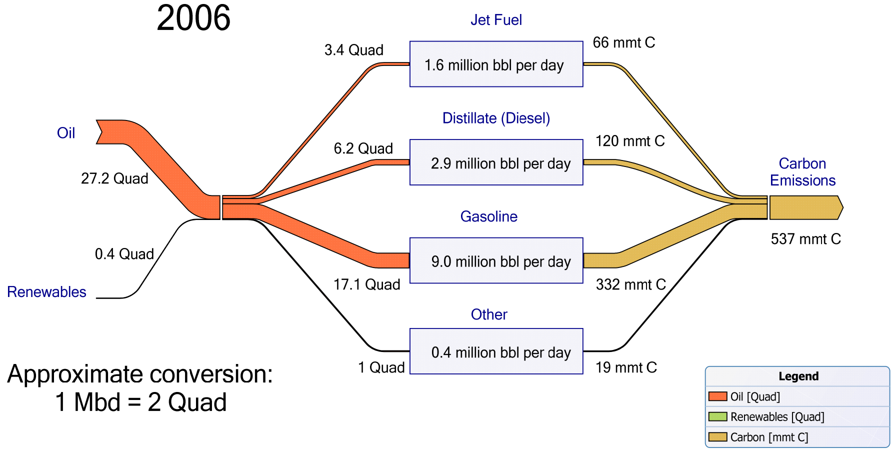


Data source: Annual Energy Review 2006, US Energy Information Administration

Vehicles

- Almost exclusively use oil
- Emissions shares by type of fuel
  - ⇨ *12% jet fuel*
  - ⇨ *22% diesel*
  - ⇨ *63% gasoline*
  - ⇨ *3% other*

US Transportation Sector
2006



Approximate conversion:
1 Mbd = 2 Quad

Data source: Annual Energy Review 2006, US Energy Information Administration

Abating vehicle emissions

- Shift fuel mix -- less CO2 per unit of energy
  - ⇨ *Toward natural gas*
  - ⇨ *Toward biofuels (really feasible?)*
  - ⇨ *Toward electricity with sequestration*
- Improve fuel efficiency -- less energy per mile
  - ⇨ *Hybrids*
  - ⇨ *Advanced diesel*
  - ⇨ *Public transportation*
- Reduce driving -- fewer miles
  - ⇨ *Live closer to work*
  - ⇨ *Change habits*

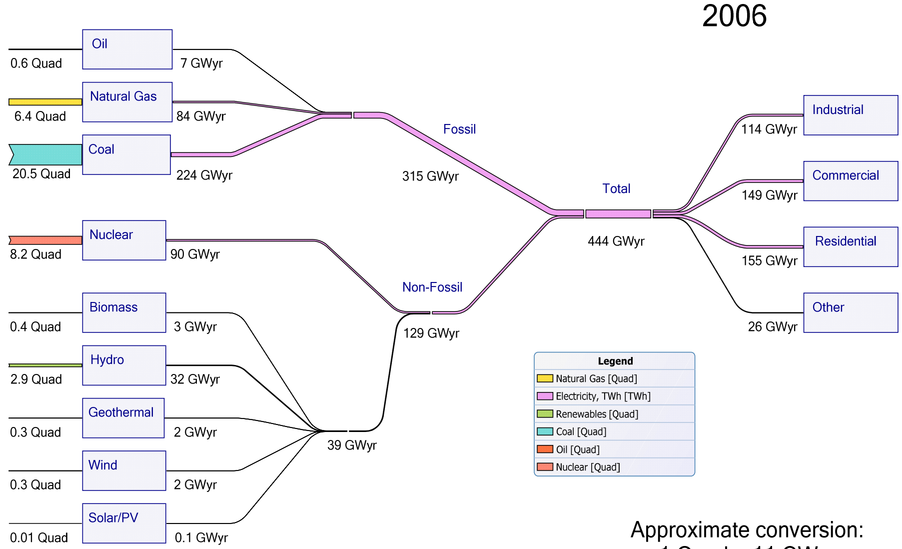
Electric sector has multiple roles

- Adapting to climate change
  - ⇨ *Higher summer temperatures*
  - ⇨ *Potentially greater peak demand for electricity*
- Implementing climate policies
  - ⇨ *Generation and delivery of renewable power*
  - ⇨ *Replace on-site fuel use in order to sequester carbon*
  - ⇨ *Support plug-in hybrids*
- Implications
  - ⇨ *Even greater role for the grid*

Electricity units

- Electric power and generating capacity
  - ⇨ *Rate of electricity generation at a point in time*
  - ⇨ *Measured in watts (W)*
  - ⇨ *1 Megawatt (MW) =10^6 watts*
  - ⇨ *1 Gigawatt (GW) = 10^9 watts*
  - ⇨ *1 Terawatt (TW) = 10^12 watts*
- Electric energy
  - ⇨ *Rate times time*
  - ⇨ *Measured in watt-hours or kilowatt-hours (kWh)*
  - ⇨ *Gigawatt-year = 8.76 x 10^12 Wh*
  - ⇨ *Gigawatt-year = 8.76 TWh*

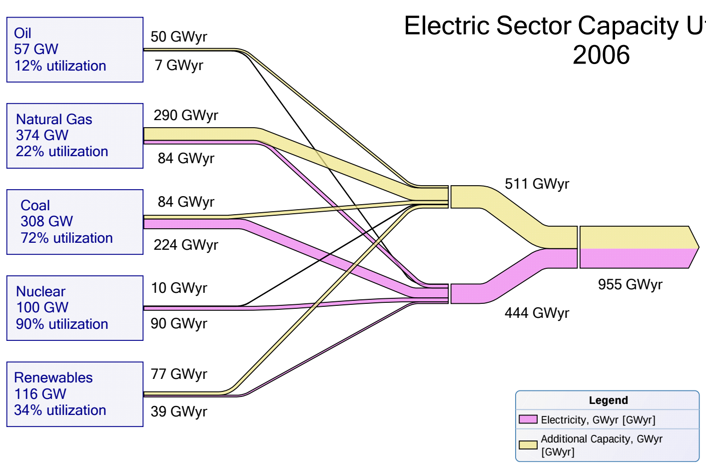
US Electricity Flows 2006



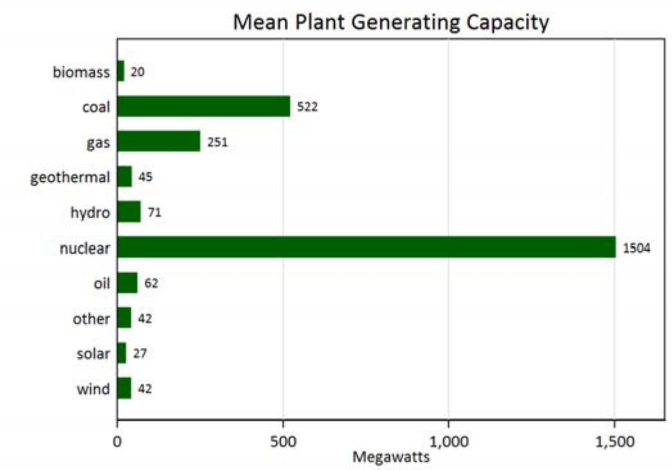
Approximate conversion:
1 Quad = 11 GWyr

Data source: Annual Energy Review 2006, Energy Information Administration

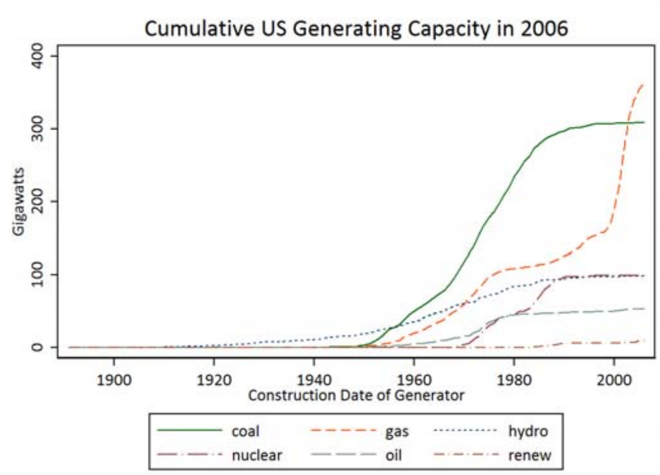
Electric Sector Capacity Utilization 2006



How large is a typical plant?



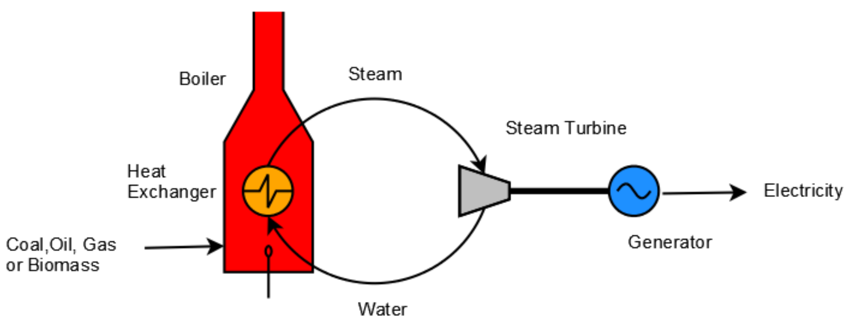
When was it built?



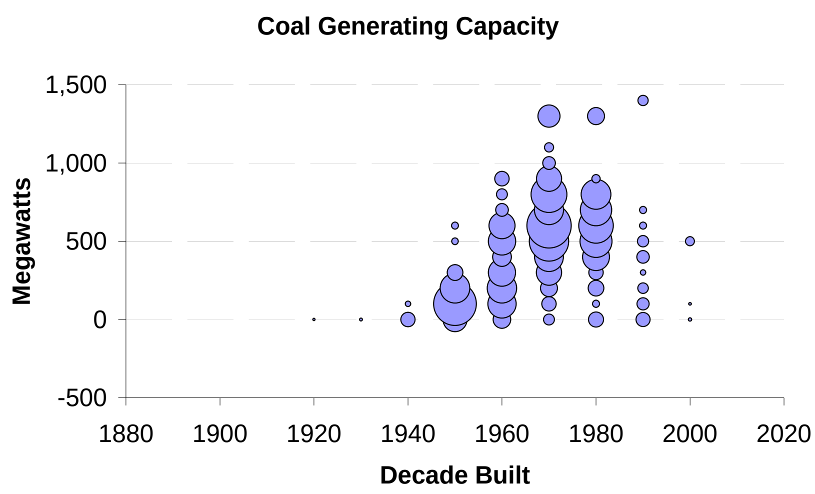
Typical coal plant

- AES Somerset on Lake Ontario
- 655 MW capacity
- Output in 2005:
  - ⇨ *91% utilization*
  - ⇨ *5.2 million MWh*
- Waste:
  - ⇨ *4.5 mmt CO2*

Conventional Thermal Power Plant



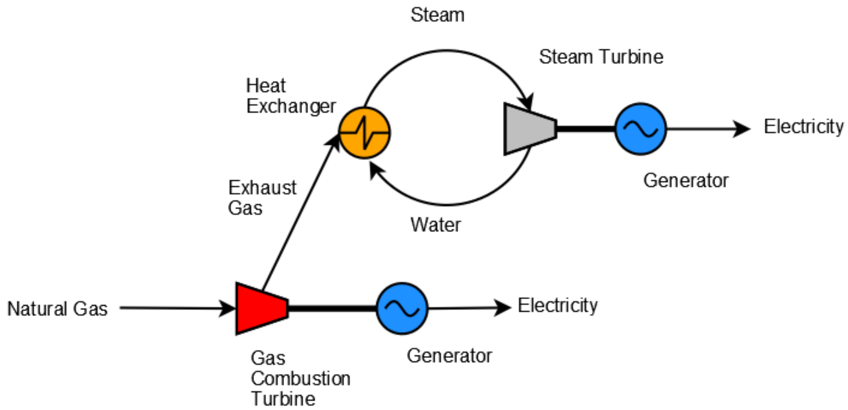
Typical Efficiency: 33%



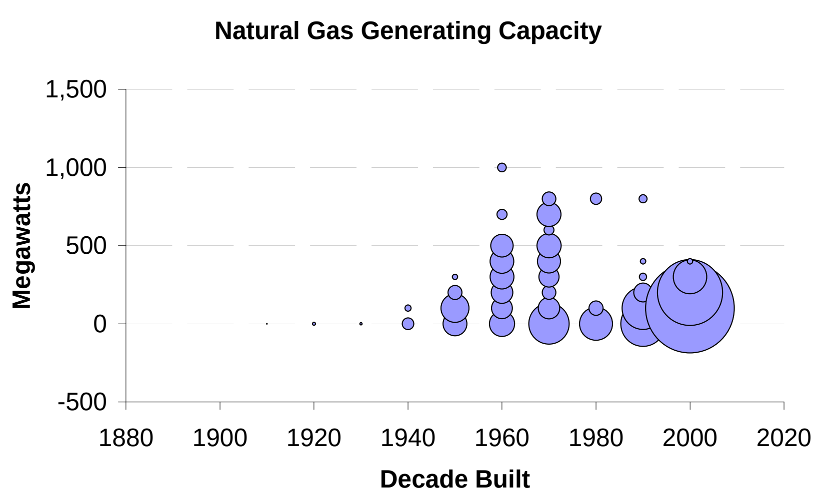
Natural gas turbine

340 MW Siemens Gas Turbine

Combined Cycle Gas Power Plant

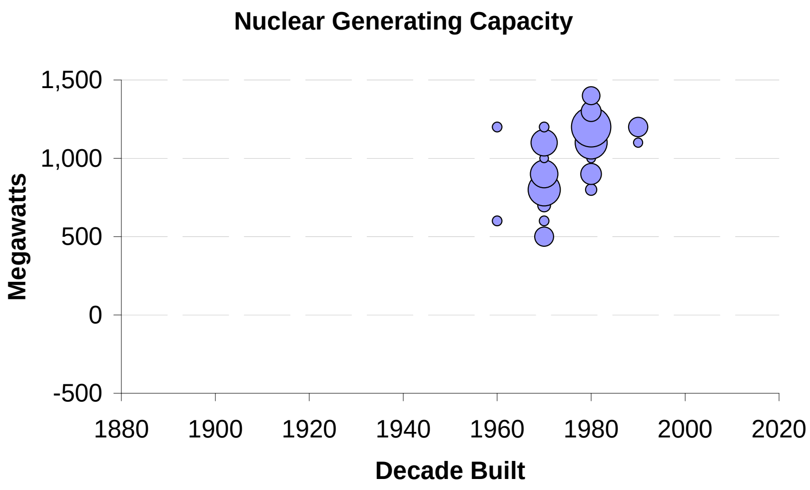


Typical Efficiency: 50%



Typical nuclear plant

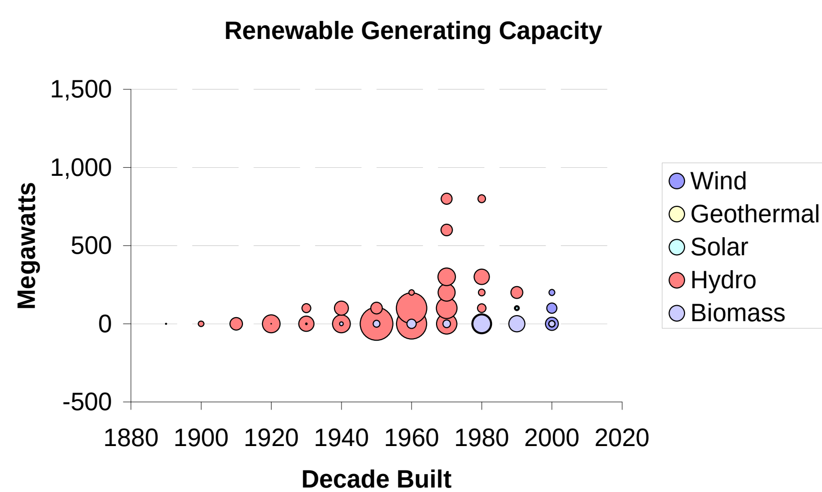
- Nine Mile Point
  - ⇨ *Northwest of Syracuse*
- Two reactors:
  - ⇨ *620 MW, 1970*
  - ⇨ *1138 MW, 1988*
- Output in 2007:
  - ⇨ *91% cap utilization*
  - ⇨ *14 million MWh*
- Waste:
  - ⇨ *0.006 lbs/MWh*
  - ⇨ *38 t/year*



Horizontal axis wind turbines

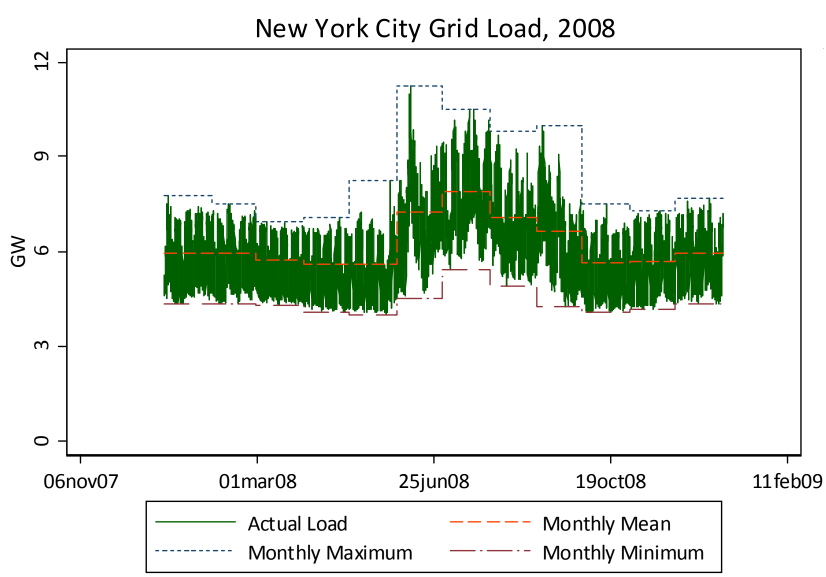
- 1.75 MW Turbine, Australia

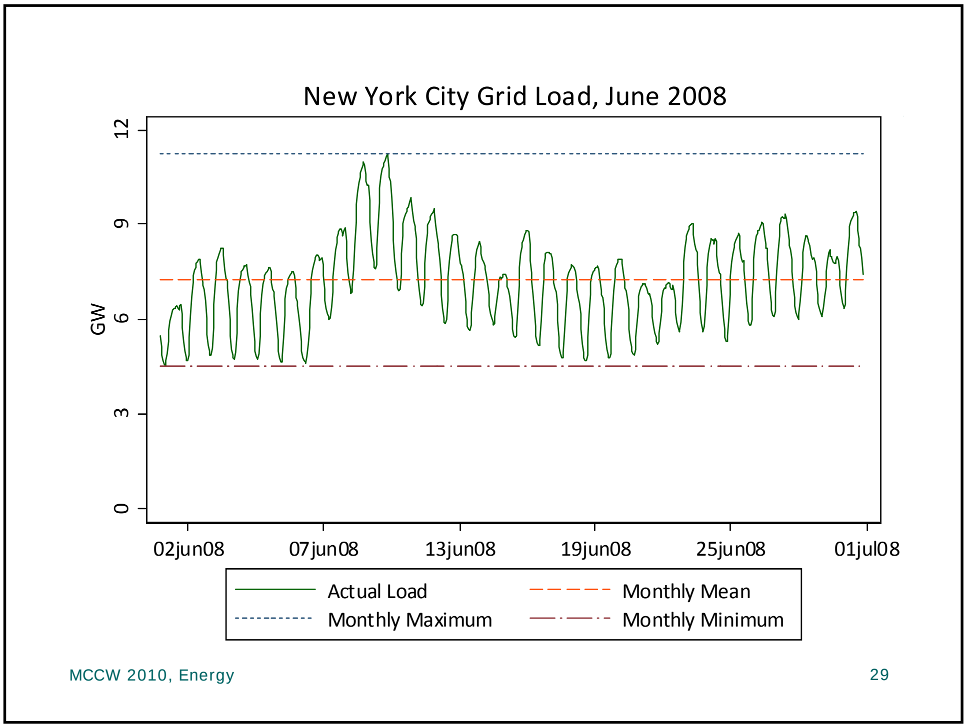
2 MW Turbine, Wales

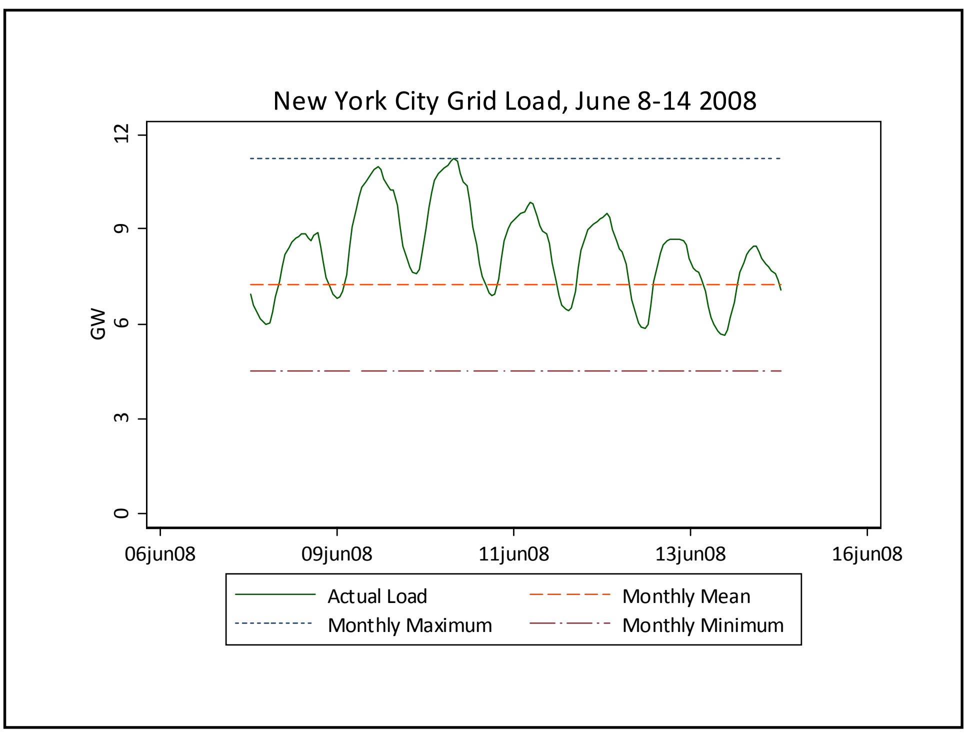


Key problem for power producers...

- Need to follow variations in demand
  - ⇨ *Electricity essentially non-storable at the grid level*
- Power demand varies strongly over the day
  - ⇨ *Higher during the day than at night*
- Also varies strongly over the year
  - ⇨ *Higher in the summer due to air conditioning*

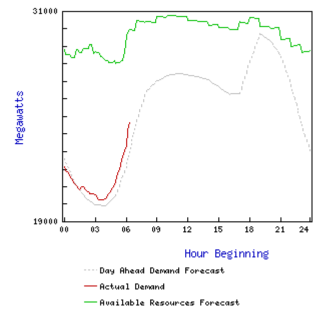



New York City Grid Load, June 2008
GW
0
3
6
9
12
02jun08
07jun08
13jun08
19jun08
25jun08
01jul08
Actual Load
Monthly Mean
Monthly Maximum
Monthly Minimum
MCCW 2010, Energy
29


New York City Grid Load, June 8-14 2008
GW
0
3
6
9
12
06jun08
09jun08
11jun08
13jun08
16jun08
Actual Load
Monthly Mean
Monthly Maximum
Monthly Minimum

Real time California ISO load curve

- Independent System Operator (ISO)
  - ⇨ *Operates part of the electrical grid*
- Data for Feb 3, 2010
- Demand (red curve):
  - ⇨ *Min about 3 am, 20 GW*
  - ⇨ *Max about 7 pm, 30 GW*
  - ⇨ *Max is 50% higher*
- Capacity (green curve):
  - ⇨ *28-32 GW*



Types of generators

- Base load
  - ⇨ *Run almost all the time*
  - ⇨ *Expensive to build, slow start, cheap to run*
  - ⇨ *Coal, nuclear*
- Peaking
  - ⇨ *Run during peak periods*
  - ⇨ *Cheap to build, quick start, expensive to run*
  - ⇨ *Gas, oil, others*
- Intermittent
  - ⇨ *Weather dependent: wind, solar, not dispatchable*

Summary of generation mix

Fuel	Capacity (GW)	Generation (GWyr)	Fossil Fuel Use (Quads)	Carbon (Mmt C)
Oil	57	7	0.6	13
Gas	374	84	6.4	93
Coal	310	224	20.5	532
Fossil total	741	315	27.5	638
Nuclear	100	90	--	--
Renewables	116	39	--	--
Total	958	444	27.5	638

Leading options for replacing fossil

- Integrated gasification combined cycle coal (IGCC)
  - ⇨ *With carbon capture and sequestration (CCS)*
- Combined cycle gas (CC)
  - ⇨ *With CCS*
- Nuclear
- Renewables
  - ⇨ *Biomass*
  - ⇨ *Hydro*
  - ⇨ *Wind*
  - ⇨ *Solar thermal, photovoltaic*

Advanced coal power plants

Integrated gasification combined cycle (IGCC)

http://www.powergeneration.siemens.com/press/press-pictures/igcc/igcc-puertollano1.htm

Cost of building new power plants

Technology	Capital cost per GW of capacity		Technology	Capital cost per GW of capacity
Coal	$2.1 B		Adv Nuclear	$3.3 B
IGCC	$2.4 B		Biomass	$3.8 B
IGCC with CCS	$3.5 B		Hydro	$2.2 B
Nat Gas CC	$0.9 B		Onshore Wind	$1.9 B
CC with CCS	$1.9 B		Solar Thermal	$5.0 B
			Solar/PV	$6.0 B

Replacing fossil completely?

- Need about 550 GW total
  - ⇨ *330 GW baseload*
  - ⇨ *220 GW peaking*
- Fossil with CCS
  - ⇨ *410 GW of IGCC CCS coal (80% utilization) = $1.4 T*
  - ⇨ *220 GW of CC CCS gas = $420 B*

  Total = $1.8T
- Intermittent renewables
  - ⇨ *1300 GW of wind (25% utilization) = $2.5 T*
  - ⇨ *220 GW of CC CCS gas = $420 B*

  Total = $2.9 T

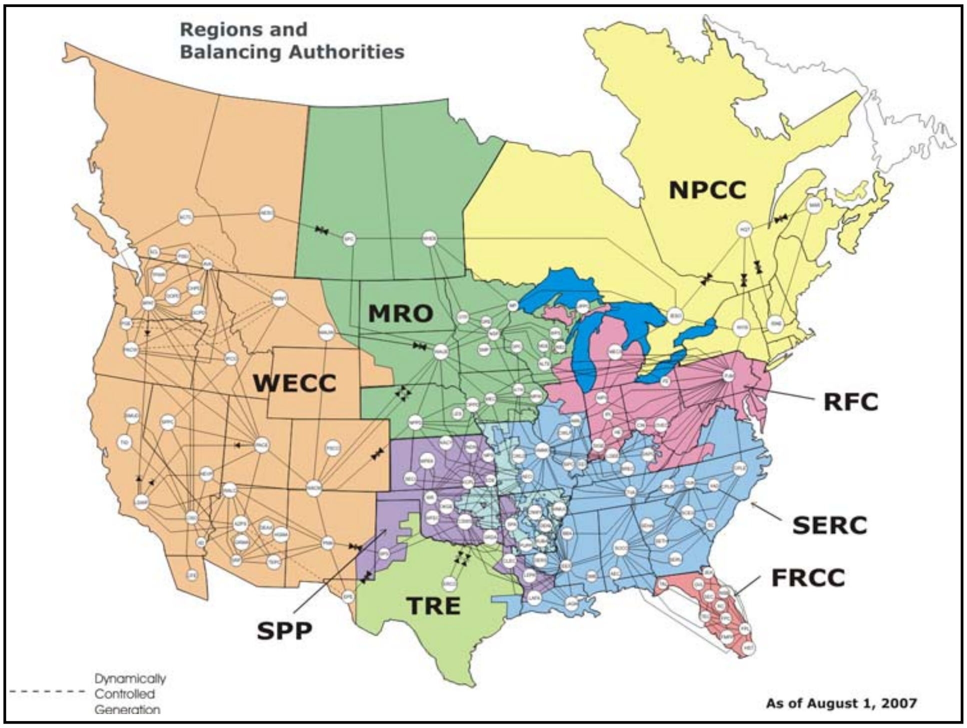
Replacing fossil capacity, continued

- Not impossible but definitely expensive
- Also, very uncertain
  - ⇨ *No large scale CCS plants*
- Population growth makes things worse

Transmission grid

- Can we get power where it's needed?

- Especially important for wind and solar
  - ⇨ *Best locations are far from cities*
  - ⇨ *Need geographic dispersion*



More grid capacity needed for wind

Variation in wholesale electricity prices due to grid congestion

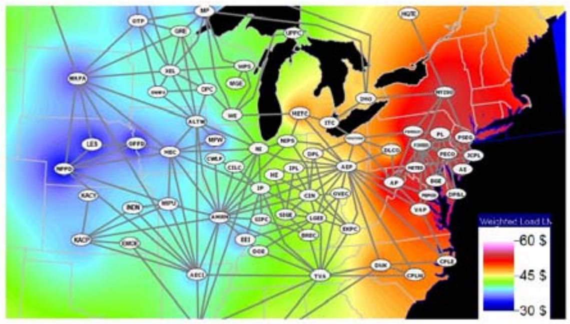


Figure 2.2-3 Contour Map of Annual Load Weighted LMP

From "2006 Midwest ISO-PJM Coordinated System Plan (CSP)," December 2006.

Very important implication

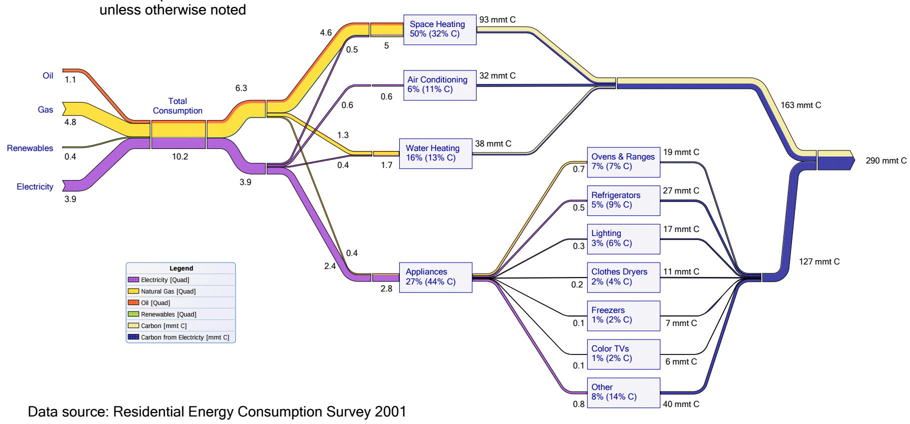
- Would be less expensive if demand were lower
- Need to reduce fuel use on the demand side

What do people do with energy?

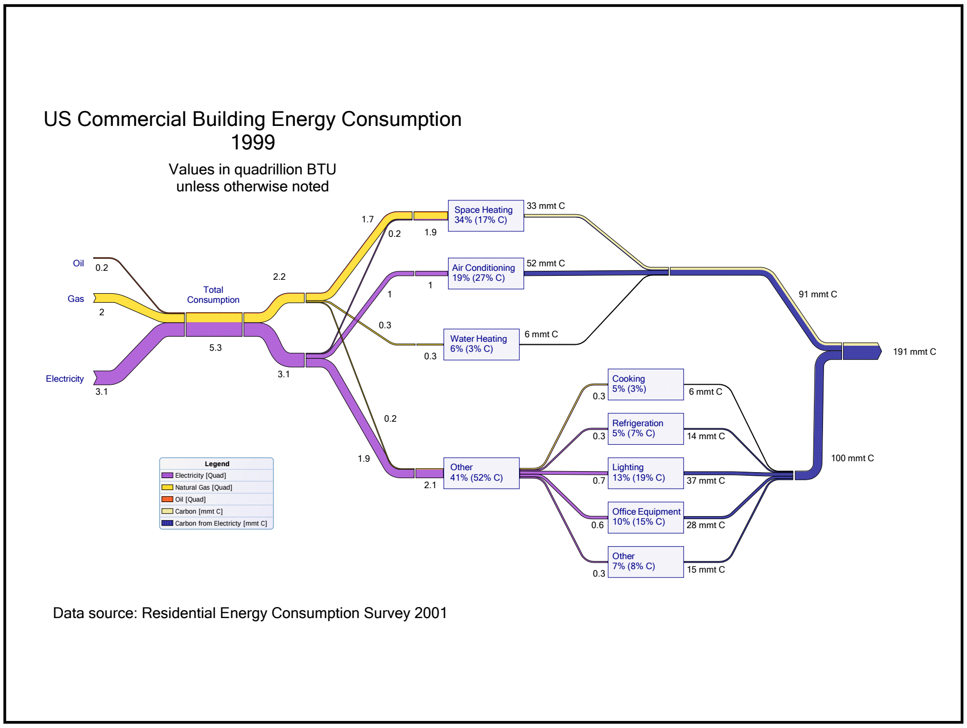
- Very quick overview of non-transportation use
- Residential and commercial
  - ⇨ *Heating*
  - ⇨ *Air conditioning*
  - ⇨ *Water heating*
  - ⇨ *Appliances*
- Industry
  - ⇨ *More difficult due to accounting for feedstocks*
  - ⇨ *Mostly in the production process*
  - ⇨ *Most of that is heating*

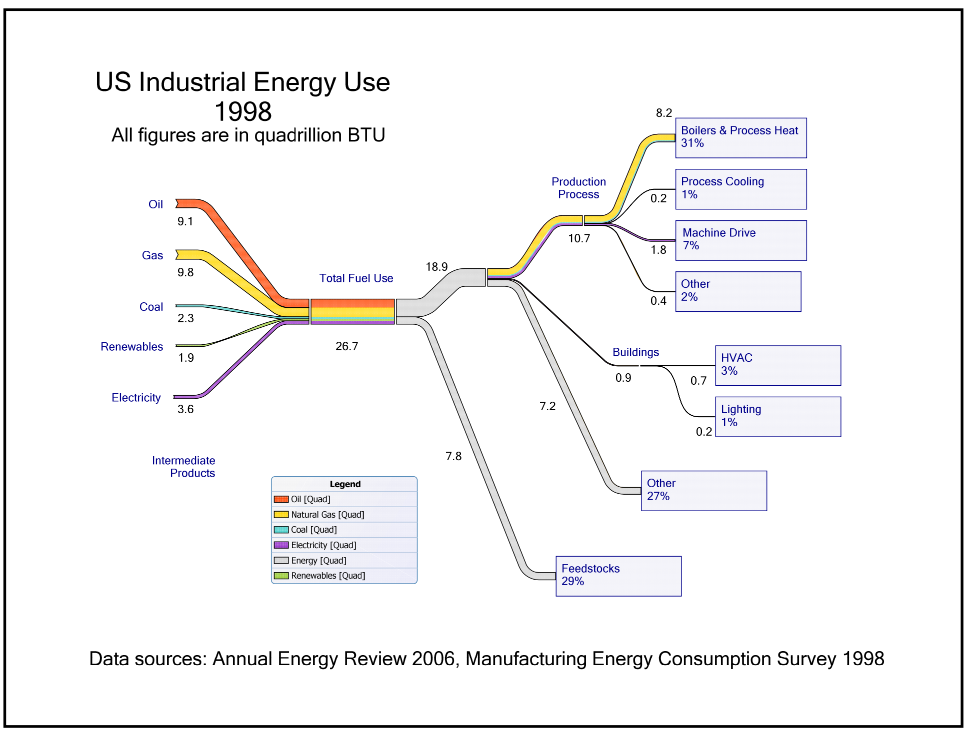
US Residential Energy Consumption
2001

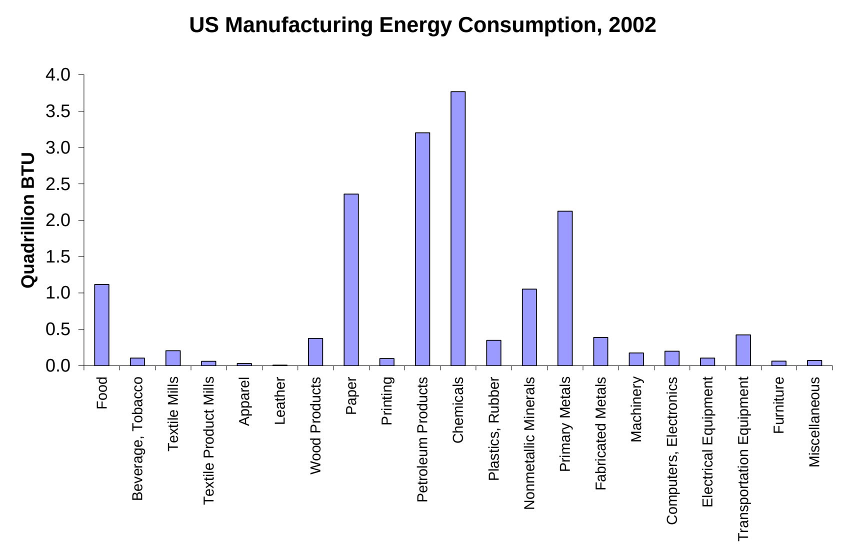
Values in quadrillion BTU
unless otherwise noted



Data source: Residential Energy Consumption Survey 2001

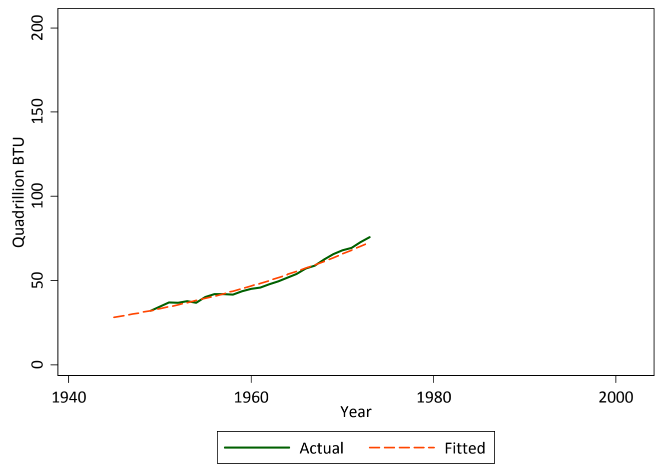

US Commercial Building Energy Consumption
1999
Values in quadrillion BTU
unless otherwise noted
Oil
0.2
Gas
2
Electricity
3.1
Total
Consumption
5.3
2.2
3.1
1.7
0.2
1.9
1
1
0.3
0.3
0.2
1.9
2.1
Space Heating
34% (17% C)
33 mmt C
Air Conditioning
19% (27% C)
52 mmt C
Water Heating
6% (3% C)
6 mmt C
Other
41% (52% C)
91 mmt C
191 mmt C
Cooking
5% (3%)
0.3
6 mmt C
Refrigeration
5% (7% C)
0.3
14 mmt C
Lighting
13% (19% C)
0.7
37 mmt C
Office Equipment
10% (15% C)
0.6
28 mmt C
Other
7% (8% C)
0.3
15 mmt C
100 mmt C
Legend
Electricity [Quad]
Natural Gas [Quad]
Oil [Quad]
Carbon [mmt C]
Carbon from Electricty [mmt C]
Data source: Residential Energy Consumption Survey 2001


US Industrial Energy Use
1998
All figures are in quadrillion BTU
Oil
9.1
Gas
9.8
Coal
2.3
Renewables
1.9
Electricity
3.6
Total Fuel Use
26.7
18.9
Production
Process
10.7
8.2
Boilers & Process Heat
31%
0.2
Process Cooling
1%
1.8
Machine Drive
7%
0.4
Other
2%
Buildings
0.9
HVAC
3%
0.7
Lighting
1%
0.2
7.2
Other
27%
7.8
Feedstocks
29%
Intermediate
Products
Legend
Oil [Quad]
Natural Gas [Quad]
Coal [Quad]
Electricity [Quad]
Energy [Quad]
Renewables [Quad]
Data sources: Annual Energy Review 2006, Manufacturing Energy Consumption Survey 1998



Historical perspective?

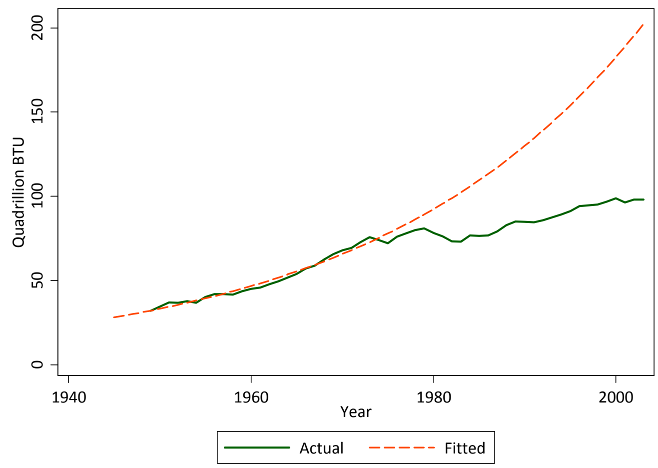
Exponential growth after WW II (3.4%)



Model used (fitted equation)

- Exponential growth at unknown rate g:
  - ⇨ *Y = A*exp(g*t)*
- Estimated over 1945-1973
- Statistical results:
  - ⇨ *Adjusted R-squared = 0.98*
  - ⇨ *Parameter g = 0.0341 (standard error 0.0010)*
- Trivial model appears to work really well:
  - ⇨ *Explains 98% of the variation*
  - ⇨ *Tightly estimated parameters*

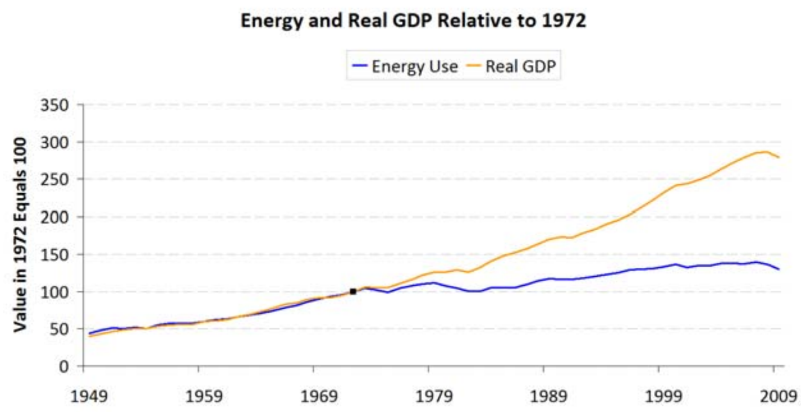
Sharp change after the energy shocks!



Two big lessons

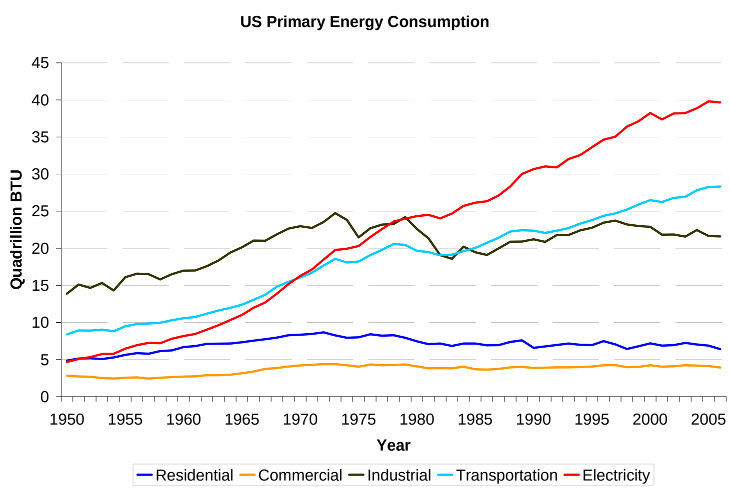
- Energy prices matter!
  - ⇨ *Price spikes:*
    Stabilized US energy consumption for about 20 years
  - ⇨ *GDP growth:*
    Slightly slower: about 0.2% per year
- Be wary about projections
  - ⇨ *Good fit does not automatically mean a model is useful*

Comparing to GDP



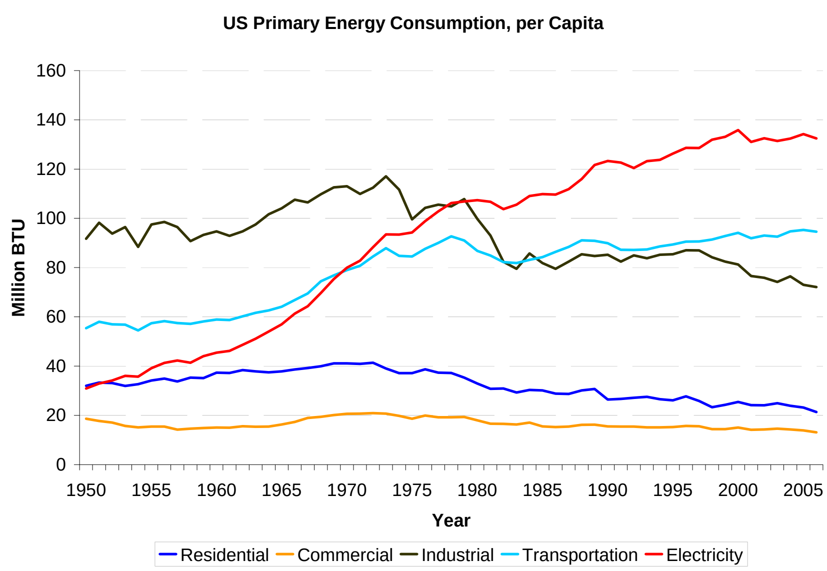
MCCW 2010, Energy 53

Changing composition of consumption



What about rates of growth?

- Low growth in primary energy:
  - ⇨ *Residential*
  - ⇨ *Commercial*
  - ⇨ *Industrial*
- Electricity and transportation
  - ⇨ *Slower post 1973*
  - ⇨ *Electricity: 6.5% annually before, 2.2% since*
  - ⇨ *Transportation: 3.5% annually before, 1.3% since*
- For reference
  - ⇨ *Population growth: 1.5% before, 1.1% since*



Implications for carbon