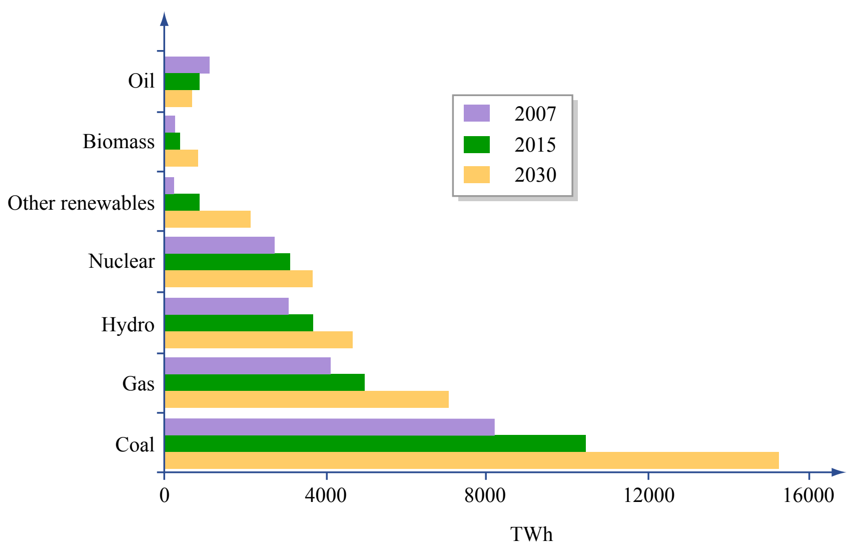
Electricity production



World electricity generation by fuel in the Reference Scenario

Source: World Energy Outlook 2009

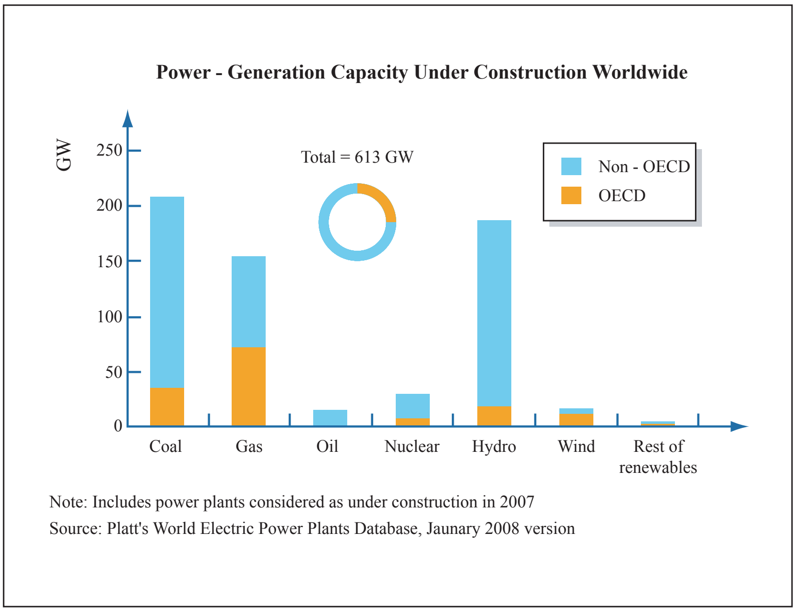


Image by MIT OpenCourseWare.

Source: World Energy Outlook 2008

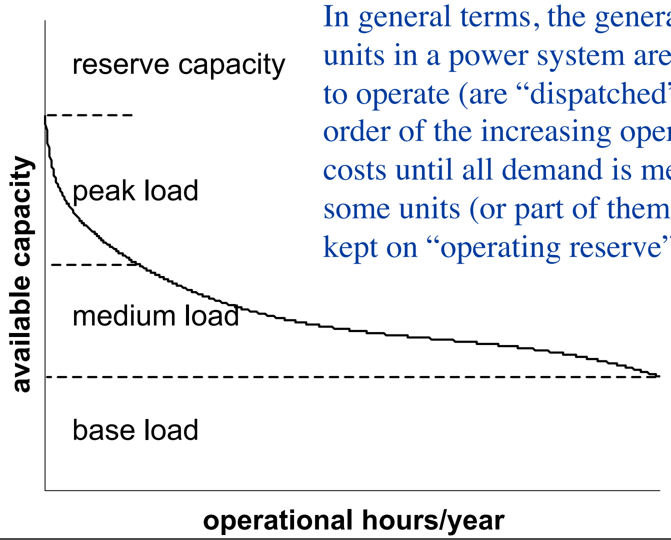
Generation technologies

- Hydro plants
  - with reservoir
  - run-of-the-river
  - pump storage
- Thermal plants
  - Nuclear
  - Coal, oil
  - Gas
    - simple cycle
    - combined cycle
- Other plants: wind, thermo solar, photovoltaic, fuel cells, biomass, geothermal, wave & tidal power, etc.

Why a mix of generation technologies?

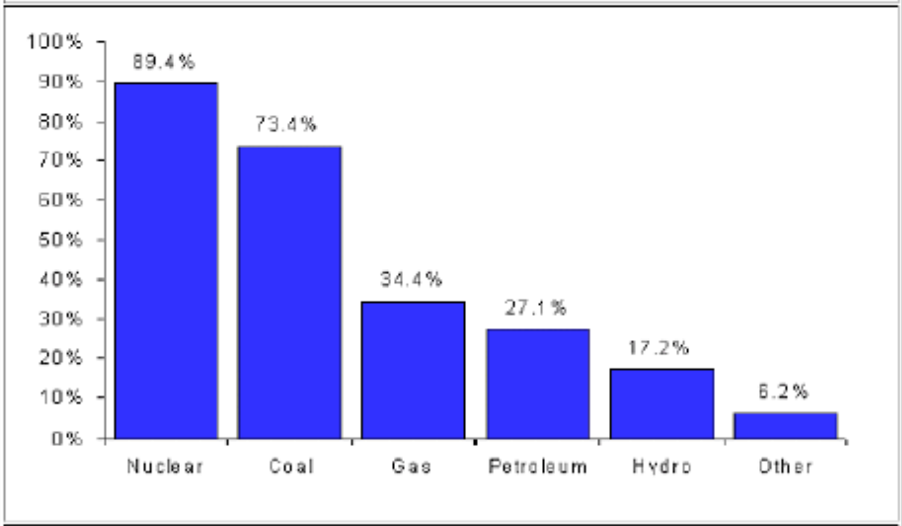
- Economic reasons
  - The uneven demand profile provides opportunities for the different technologies, since they offer different combinations of fixed & variable costs
- Strategic / political reasons
  - Fuel diversification is a reasonable strategy
- Environmental reasons
  - Generation technologies have very diverse environmental impacts

Load-duration curve



In general terms, the generating units in a power system are called to operate (are "dispatched") in order of the increasing operating costs until all demand is met & some units (or part of them) are kept on "operating reserve"

Figure 5. Average Capacity Factor by Energy Source, 2001



Source: Energy Information Administration, Form EIA-906, "Power Plant Report."

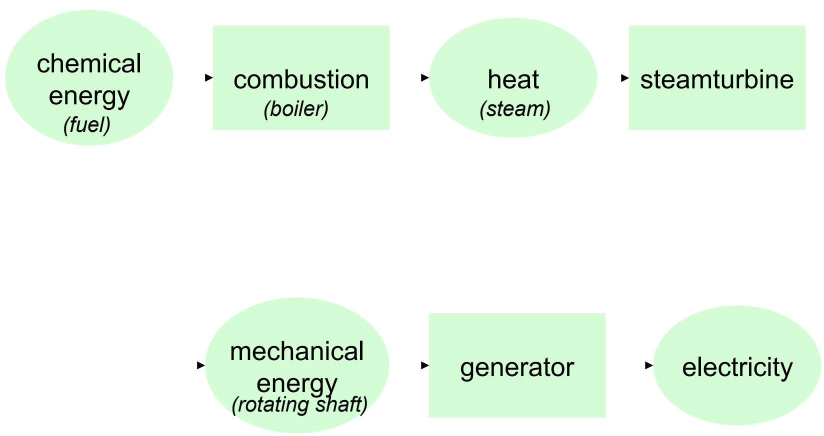
Pros & Cons of different sources of electricity

"An energy policy for Europe", EU, January 2007

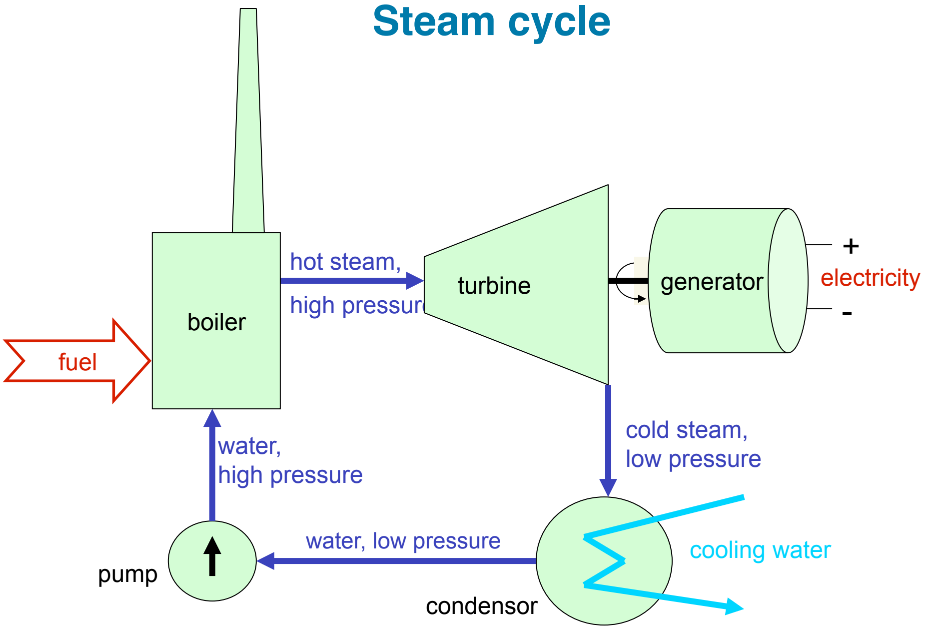
Energy sources	Technology considered for the cost estimate	2005 Cost (€ / MWh)	Projected Cost 2030 (€ / MWh with €20-30/tCO2)	GHG emissions (Kg CO2eq/MWh)	EU-27 Import dependency 2005	EU-27 Import dependency 2030	Efficiency	Fuel price sensitivity	Proven reserves / Annual production
		Source IEA							
Natural gas	Open cycle gas turbine	45 – 70	55 - 85	440	57%	84%	40%	Very high	64 years
	CCGT (Combined Cycle Gas Turbine)	35 - 45	40 - 55	400			50%	Very high	
Oil	Diesel engine	70 - 80	80 - 95	550	82%	93%	30%	Very high	42 years
Coal	PF (Pulverised Fuel with flue gas desulphurisation)	30 - 40	45 - 60	800	39%	59%	40-45%	medium	155 years
	CFBC (Circulating fluidized bed combustion)	35 - 45	50 - 65	800			40-45%	medium	
	IGCC (Integrated Gasification Combined Cycle)	40 - 50	55 - 70	750			48%	medium	
Nuclear	Light water reactor	40 - 45	40 - 45	15	Almost 100% for uranium ore		33%	low	Reasonable reserves: 85 years
Biomass	Biomass generation plant	25 - 85	25 - 75	30	nil		30 - 60%	medium	Renewable
Wind	On shore	35 - 175 35 – 110	28 - 170 28 – 80	30			95-98%	nil	
	Off shore	50 - 170 60 – 150	50 - 150 40 – 120	10			95-98%		
Hydro	Large	25 - 95	25 - 90	20			95-98%		
	Small (<10MW)	45 - 90	40 - 80	5			95-98%		
Solar	Photovoltaic	140 - 430	55 -260	100			/		

N EN

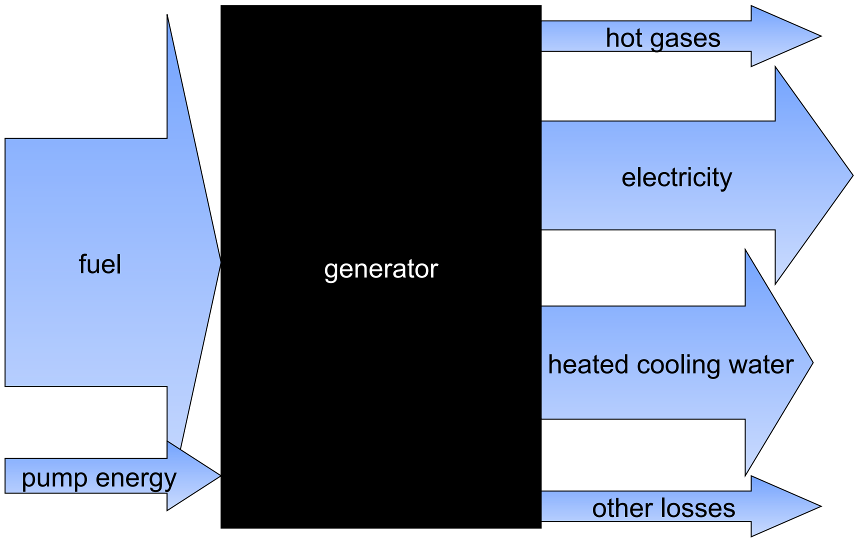
Principle of a thermal unit



Steam cycle



Energy balance



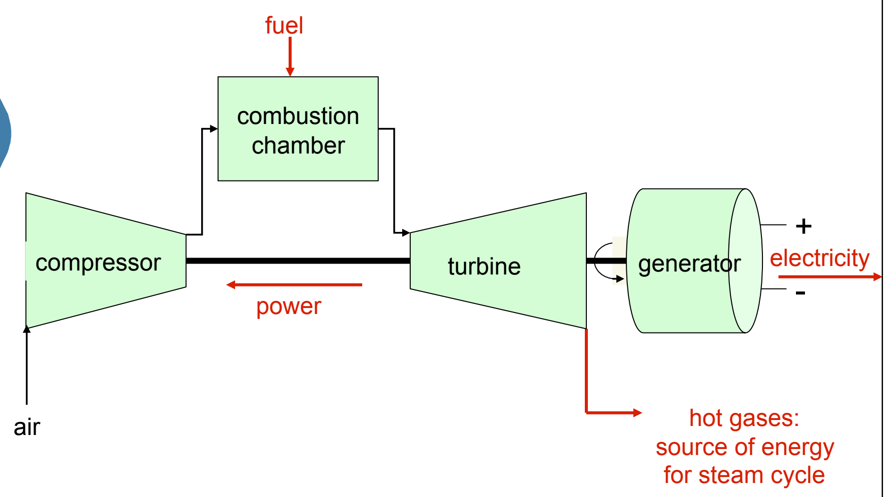
Combined-cycle units

Gas turbine development led to combined-cycle units: 'steam and gas'. Such units have high (electric) efficiencies (up to 60%).

Sale of heat less important

Smaller units make on-site electricity production competitive

Combined-cycle generator



The electricity distribution network

Distribution

- One can distinguish between **subtransmission** & true **distribution** networks
- **Subtransmission** networks cover a region & they have a some kind of meshed topology. They feed distribution networks & some large consumers
- **Distribution** networks must reach every single end consumer
  - Rural distribution networks have a radial topology
  - Urban distribution networks are meshed but they are operated radially

Storage

Main properties of electric storage technologies

Technology	Typical Capacity	Response time	Discharg e time	Efficiency	Life time	Developm ent stage	Application
Batteries	1kW – 50MW		1 min – 3h	65-75%	2-10 years	Premature /matures	Uninterruptible power supply, RE fluctuation reduction, spinning/standing reserve
Compressed air energy systems (CAES)	25MW – 2.5GW	15 min from cold start	2-24 h	55%	15-40 years	Mature	Spinning/standing reserve, energy arbitrage
Super magnetic energy storage (SMES)	10kW – 1MW		5sec – 5min	95%	~30 years	Premature	Uninterruptible power supply, power quality
Hydrogen Fuel Cell Storage System (HFCSS)	1kW – 10GW	Depends on a fuel cell	0.01 sec-days	~40%	5-10years	Prototype	RE fluctuation reduction, spinning/standing reserve
Supercapacitors	< 150 kW		1sec-1min	85-95%	~10 years	Premature	Uninterruptible power supply, power quality
Pumped storage	20MW – 2GW	1 min (if standing) 10 sec (if spinning)	4-10h	55-85%	~50 years	Mature	Spinning / standing reserve,
Flywheels	5kW – 3MW		15sec-15min	90-95%	~20 years	Mature	Power quality

Electricity supply comprises many activities…

Supply of electricity
Classification of the required activities

Generation
Ordinary Generation
Special Generation
Ancillary services

Network
Transmission
Investment planning
Construction
Maintenance planning
Maintenance
Operation of transmission network
Distribution
Investment planning
Construction
Maintenance planning
Maintenance
Operation of distribution network

Transactions
Wholesale Market
Free Contracts
Standardized Contracts
International Exchanges
Retail market
Supply to qualified consumers
Supply to captive consumers
Complementary Activities
Settlement
Billing
Metering

Coordination
Operation of the Electric Power System
Operation of the Organized Market

Commercialization (retailing, supply *(UK)*)

Diversity of services:

- Retailers of captive consumers
- Retailers of consumers that are qualified to choose supplier
  – and choose supplier
  – but stay with the regulated tariff *(if any)*
- Traders
- Brokers

System Operation

- Coordination activity at system level: To guarantee system security while meeting the market requirements
- System Operator (SO) implements the dispatch of generation & determines the network operation, subject to prescribed technical rules
- SO applies prescribed criteria for network access & informs about estimated access conditions in the short, medium & long run

Market Operation *(power exchange, PEX)*

- PEX facilitates transactions among agents in an organized market
  - In principle, this is a non regulated activity
- Typically: management of day ahead transactions
  - Hourly (typically) matching of purchasing & selling bids for the next day
- Also: management of other markets
  - Shorter term: intra-daily markets, regulation market, etc.
  - Longer term: future contracts, forward contracts
- Economic settlement of transactions

Service quality

Different dimensions of quality of service

- Technical quality of the product
  - Continuity of supply
  - Technical characteristics of the waveform
    - Over-voltages, harmonics, mini-interruptions, flicker
- Commercial quality of service
  - Connection / disconnection time, response to queries, metering, general attention to customers, other services

Quality of service at delivery

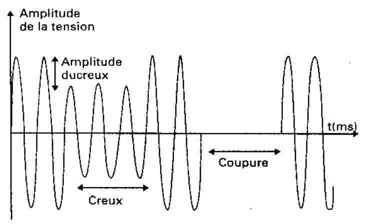


Figure 1. **Creux et coupures.**

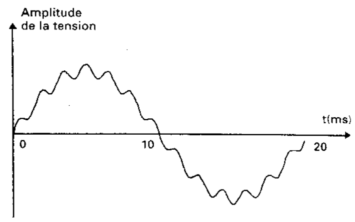


Figure 2. **Harmoniques.**

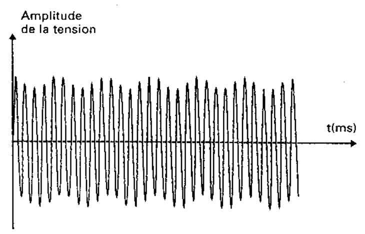


Figure 3. **Flicker.**

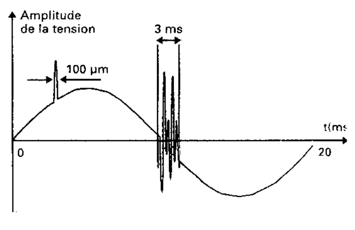


Figure 4. **Surtensions.**

Quality of service at wholesale level

- Metric 1: **Non served energy** (NSE)
  - Annual non served demand (MWh) in the entire system because of service interruptions (longer than 1 minute) at wholesale (i.e. transmission network) level

    Typical reference value that has been used in centralized generation expansion planning: 1day equivalent of non-served demand/10 years
- Metric 2: **Average interruption time**
  - This is the NSE divided by the average power (MW) supplied by the system, and it is expressed in minutes

    TIM = 8760 x 60 x NSE / E

    E = annual supplied system demand (MWh)

    Typical reference value could be 15 m/year (e.g. Spain)

Quality of service of the transmission network

- The unavailability of a network can be measured by the total amount of time that its lines, transformers & control devices have not been available during the year.

  Computation of the Unavailability Index (UI) *(a component of the remuneration of transmission may be related to this index):*

$$UI = \frac{\sum_{i=1}^{n} t_i \cdot PN_i}{T \sum_{i=1}^{n} PN_i} \cdot 100 \qquad \textit{Reference value = 3\%}$$

ti= Unavailable time for the ith component (line, transformer or control device) (hours)

n= Total number of lines, transformers and control devices in the transmission network

T= Duration of the considered time period (hours)

PNi= Rated capacity (MW) of the lines, transformers and control devices

Environmental implications of electricity supply & consumption

References: For instance see J.W. Tester et al. "Sustainable energy. Choosing among options", MIT Press, 2005.

Environmental implications

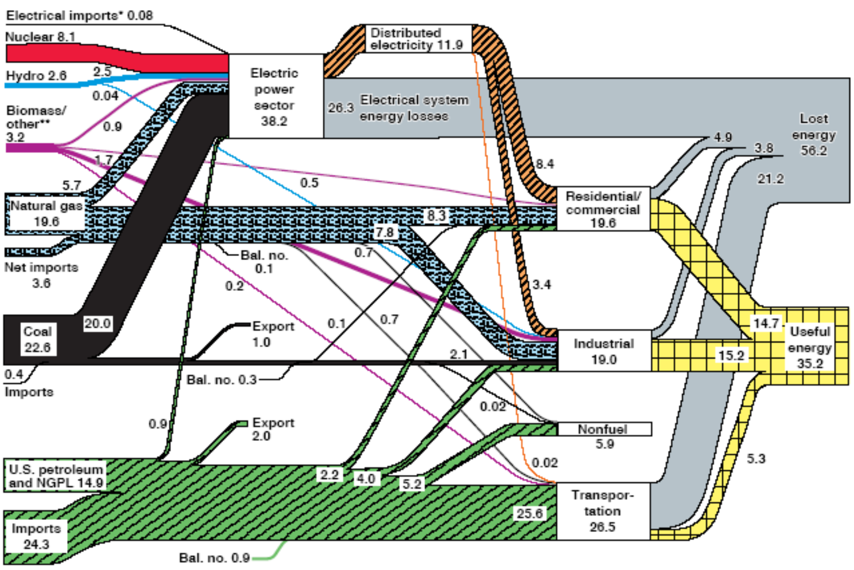
- No technology is free from environmental impact, although the type & extent of the impacts are widely different
  - The entire life cycle has to be considered
    - Mining, fuel processing, manufacturing of plant components, electricity production, emissions, wastes, dismantling
    - E.g., some not well known results
      - Embedded energy content of a PV module *(polycristalline wafer)* takes 2 years of operation to recover (*much less with the newer thin film techniques being currently pursued)*
      - According to some studies a nuclear plant takes 5 years to recover the energy spent during construction & fuel manufacturing

from J. W. Storm (CERN 3.4.06)
(http://ihp-lx2.ethz.ch/energy21/CERN-3Apr06.ppt)

Environmental implications *(cont.)*

- All thermal plants *(fossil, nuclear, biomass, high temperature thermosolar)* need some cooling, since a large fraction of the primary energy is rejected to the environment
  - From “once-through” cooling to cooling towers & dry cooling *(expensive & some loss of efficiency)*
  - Use of the reject heat: cogeneration & trigeneration

Figure 1. U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~97 Quads



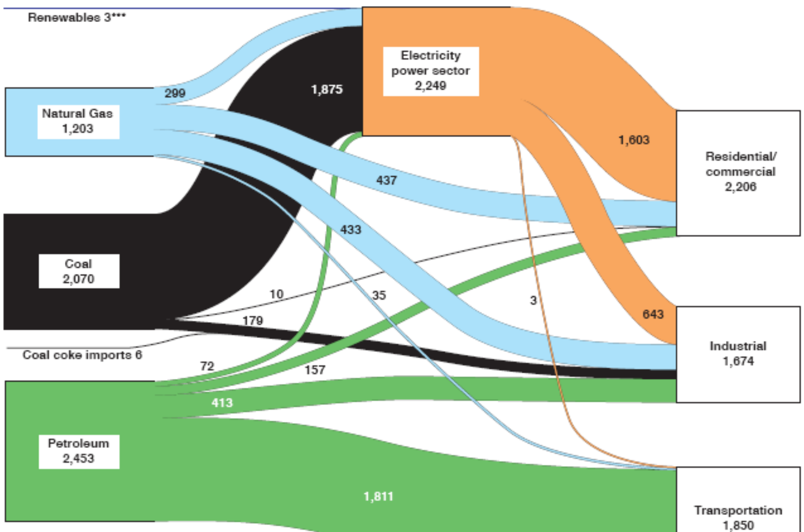
Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002.*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow

Environmental implications *(cont.)*

- Waste
  - Radioactive materials (high, medium, low intensity)
  - Ash & sludge (coal power plants)
  - Dismantling the plant at end of useful life
- Airborne emissions
  - CO_2 (all fossil plants during operation; but the complete load cycle should be considered)
  - SO_2 (>90% typically captured with scrubbers)➔waste
  - NOx (depending on the combustion temperature)
  - Particulates (>99% can be captured, although not the sub-micron-sized ones)

Fig. 7. U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO_2**



Source: Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2002*, Tables 4–10.
*Includes adjustments of 42.9 million metric tons of carbon dioxide from U.S. territories, less 90.2 $MtCO_2$ from international and military bunker fuels.
**Previous versions of this chart showed emissions in metric tons of carbon, not of CO_2.
***Municipal solid waste and geothermal energy.
Note: Numbers may not equal sum of components because of independent rounding.

Lawrence Livermore National Laboratory, May 2004
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Environmental implications *(cont.)*

– Land area requirements, e.g.:

- Typically 2 km^2 for a large fossil plant (plus any mining requirements, for coal) vs. 0.2 km^2 for natural gas plants or for nuclear plants (plus the surrounding "exclusion zone")
- Hydropower: E.g. Hoover Dam (1500 MW) inundates 640 km^2 while a high temperature concentrated solar plant in the US southwest desert would require ~50 km^2 to produce the same energy annually. *(Source J.W. Tester book, Ch. 13)*
- Wind: ~ 3 to 4 MW/km2
- High-temperature thermosolar with parabolic through systems in a good region (2500 kWh/yr.m^2 available solar energy): 0,5 km^2 of collector surface area for a 100 MWe plant operating with 12% solar to electric efficiency
- Fotovoltaic: 5 MW/km2 (non movable panels) for 10 GWh/(yr. km^2) in a good Spanish site

Environmental implications *(cont.)*

– Visual impact, noise, environmental degradation, hazards for wildlife, health threats

- The NYMBY effect *(benefits typically do not accrue to those most disturbed by the plant)*
- Potential incentive mechanisms to reduce opposition
- We have to make choices!!!

Environmental implications *(cont.)*

Case example:

- In Spain, the power sector is responsible for
  - 90% of SO2 & NOx emissions from large combustion facilities (>50 MWt)
  - 68% & 23% of the total emissions of SO2 & NOx
  - 25% of total CO2 emissions
  - 95% of the high level radioactive waste
- Note that
  - Electricity price does not include most environmental costs
  - Economic efficiency & sustainability require these environmental costs to be internalized

Outline *(next session)*

- Background
- The technological perspective
- **The economic & managerial perspectives**
  - Time scales
    - Expansion planning
    - Operation planning
    - Operation
    - Protection & control
  - Economic data & orders of magnitude

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