Electricity Overview
Energy Markets Are Interconnected

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Source: LLNL 2014. Data is based on DOE/EIA-0045(2014-01), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant “heat rate.” The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 85% for the residential and commercial sectors, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Topics

• Electricity Capacity and Usage
• Electricity generation & transmission
• Energy Conversions in Electricity Generation
• CO₂ Production & Possible Sequestration
Electricity Capacity and Usage

• US: 1 million MW generating capacity.
  ▪ 2,000 medium-sized power plants.

• Four trillion kWh produced.
  ▪ Power for about 250 million homes.
  ▪ 2.5 billion tons of CO2 -- over 40% of total US source.

• Growth projections to 2030: 1.5 – 2%/yr.
  ▪ 2% = 35 year doubling rate!

<table>
<thead>
<tr>
<th>2012 Energy Usage</th>
<th>Quads</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>0.0408</td>
<td>0.1%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>8.05</td>
<td>20%</td>
</tr>
<tr>
<td>Hydro</td>
<td>2.67</td>
<td>7%</td>
</tr>
<tr>
<td>Wind</td>
<td>1.36</td>
<td>3%</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.163</td>
<td>0.4%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>9.31</td>
<td>23%</td>
</tr>
<tr>
<td>Coal</td>
<td>17.4</td>
<td>44%</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.429</td>
<td>1.1%</td>
</tr>
<tr>
<td>Petroleum</td>
<td>0.218</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total</td>
<td>39.6408</td>
<td></td>
</tr>
</tbody>
</table>
U.S. Electric Power Plants

http://www.eia.gov/state/
Electricity Generation in Colorado

- 11.2 GW total capacity
- Total electricity generated (2012) – 52.6 TWh
- As part of Colorado Clean Air Clean Jobs Act Xcel plans...
  - Retire 593 MW of coal-fired generation
  - Replace with new 569-MW natural gas plant built on the Cherokee site
  - Switch 4th unit at Cherokee Plant and Arapahoe Unit 4 from using coal to natural gas
  - Reduce emissions from 951 MW of coal-fired generation by installing modern emissions controls


http://www.eia.gov/state/maps.cfm?src=home-f3
Europe’s total generation capacity: 800 GW

Countries
- Germany
- France
- Belgium
- Netherlands
- Austria
- Switzerland
- UK
- Spain
- Portugal
- Italy
- Norway
- Denmark
- Finland
- Sweden
- Poland
- Czech Republic
- Slovakia
- Hungary
- Romania
- Bulgaria
- Balkan (5)
- Greece

Generation structure 2007
- Wind: 37 GW
- Other renewables: 53 GW
- Water: 185 GW
- Gas/Oil: 201 GW
- Hard coal: 131 GW
- Lignite: 60 GW
- Nuclear: 136 GW

Sources: BCG, RWE

Factbook – Generation Capacity in Europe
Electricity generation & transmission

Generation, Transmission, & Distribution

Voltage levels in transmission and distribution are based on efficiency/cost trade-offs

Figure 3.1 Conventional power generation, transmission, and distribution system.

- Typical residential wiring
  - One of the distribution phases (4 kV in the example shown) dropped to two 120 V circuits using transformer with a center-tapped secondary
  - Available AC voltages 120Vrms and 240Vrms (single phase)
U.S. Power Grids

- 986 GW total capacity (2006)
- 275,000 miles of transmission lines
Demand Fluctuations

• Electric supply & transmission is an on-demand system – flip a switch & the electricity is there to do what is required.

• Types of power plants
  - Base load plants
    (e.g., coal or nuclear)
  - Intermediate
    (e.g., hydro or combined-cycle)
  - Peaking
    (e.g., combustion gas turbines)
Demand Fluctuations

- Base load
  - Take a very long time to bring up to full capacity - on the order of hours (limited by steam cycle/turbine) – cannot respond quickly to changes in demand
  - But electricity is cheaper
  - Coal plants can cycle, some will drop to 50% load, in response to predictable demand changes (such as overnight)

- Peaking
  - Combustion turbine can come on line very quickly – can be from a few to 30 minutes depending on size
  - Combustion turbines supplement renewable sources, such as wind energy or solar
Energy Conversions in Electricity Generation

Chemical (e.g. coal)
- Heat → steam flow → mechanical → electrical

Nuclear

Carnot efficiency limit of heat engines
$\eta < 1 - \frac{T_C}{T_H} < 70\%$

Hydro and wind
- Water flow → mechanical → electrical
- Air flow → mechanical → electrical

Betz efficiency limit:
$\eta < 60\%$

Photovoltaic
- Radiation → electrical

Material bandgap efficiency limit:
$\eta < 50\%$
Concept of Electricity Generation

- Convert rotational mechanical energy to electricity by cutting lines of magnetic force
- Faraday’s law of electromagnetic induction:

$$\varepsilon = -N \frac{\partial \Phi_B}{\partial t}$$

Electricity Generation From Boiler & Steam Cycle

- Heat source
  - Combustible materials
    - Coal
    - Natural gas
    - Biomass
  - Non-combustibles
    - Nuclear pile (fission)
    - Concentrated solar
- Boiler efficiency limited by exhaust temperature of stack gas
  - Generally have 20% excess oxygen
  - Special mechanical design to minimize NOx formation

Electricity Generation From Gas Turbine

- Take advantage of the ability of natural gas and its exhaust to directly spin a turbine
  - Directly provides the rotational mechanical energy
  - Fuel gas at high starting pressure
  - Air flow to control outlet exhaust temperature
    - Great excess of oxygen above stoichiometric amount
- Extremely hot exhaust gas still possesses potential energy for additional electricity generation

GPSA Engineering Data Book, 12th ed., 2012
CCGT – Combined Cycle Gas Turbine

- Heat recovery on the back end of the gas turbine uses exhaust as heat source to steam cycle
  - HRSG – Heat Recovery Steam Generation
  - Auxiliary firing in HSRG takes advantage of high oxygen content in the turbine exhaust
- CCGT plants can have efficiencies of 55% or greater
- Commercially proven at hundreds of installations

http://www.nippc.org/technology/index.tpl?cntid=105475498113479
Integrated Gasification/Combined Cycle - IGCC
Typical Industrial CO₂ Emissions

- Power: 54%
- Gas Processing: 12%
- Cement: 15%
- Refineries: 5%
- Ammonia: 3%
- Ethylene: 2%
- Hydrogen: 2%
- Iron & Steel: 6%
- Ethylene Oxide: 1%
Can We Can Sequester the CO₂?

- Carbon sequestration schemes (aka carbon capture and storage – CCS) involve injecting the CO₂ into underground storage cavities.
  - Typically depleted natural gas wells.
- Two trials ongoing in the North Sea and Canada.
  - Also used for enhanced oil recovery but the CO₂ doesn’t all stay down in EOR.
- Still issues.
  - Costs? Capture, pumping, piping, injection wells.
  - Safety? CO₂ is a toxic, heavier-than-air gas. A leak in a valley would lead to widespread asphyxiation.
  - Will the CO₂ stay underground?
  - Does it force methane out of the ground?
CO₂ Capture and Sequestration
“Study places CO2 capture cost between $34 and $61/ton”

*Oil & Gas Journal*, Oct. 12, 2009