US Energy Resources for Electricity Generation

2014 U.S. ELECTRICITY GENERATION

- Coal: 39%
- Natural gas: 27%
- Nuclear: 19%
- Hydro: 6%
- Other renewables: 7%
- Others: 2%

Electricity generation by fuel, 1990-2040
(trillion kilowatthours per year)

From www.wikipedia.org and www.eia.gov
Demand of an Electric Power System

• System load level:
  – Base (min.) load: 6GW.
  – Peak (max.) load: 15GW.
  – Intermediate loads: in between

• Observations:
  – Daily demands of two seasons have similar patterns. Why?
  – Geographic location?
• Peak-generation plants:
  – Gas turbine plants & pumped-storage hydropower plants

• Intermediate-power plants:
  – Quickly responding to changes in demand
  – Hydropower & some fossil plants

• Base-power plants:
  – 100% power output at all times
  – Nuclear & coal-fired power plants
Power Generations
Principal Components of a Thermal Power Plant

- Generation of electricity by releasing of heat energy

\[ \eta_{\text{overall}} = (1 - \frac{T_{\text{out}}}{T_{\text{in}}}) \times \eta_{\text{others}} \approx (1 - \frac{293\,\text{K}}{823\,\text{K}}) \times 70\% = 0.644 \times 70\% = 45\% \]
Coal-fired steam turbine power plant

• Generation of electricity
  1. Boiler burns pulverized coal to produce high P&T steam
  2. Turbines (HP-MP-LP) convert heat of flowing steam to mechanical energy spinning a generator
  3. Generator converts mechanical energy to electric energy

• Concerns:
  – Low efficiency: $\eta < 45\%$
  – Takes several hours to start up
  – Environmental concerns (major emitters of $\text{CO}_2$)
Efficiency of a Coal-fired Power Plant

\[ \eta = \frac{12}{30} = 40\% \]
Gas turbine power plant

- Also called combustion turbine and operates like a jet engine
- $\eta \rightarrow 46\%$
- Start quickly in minutes (used for peak load)
- Usually used in a combined-cycle or co-generation power plant to utilize the heat left with exhaust.
Combined-cycle power plant

- Higher overall efficiency (\(\eta > 60\%\))

**Figure 1.4**
Schematic of a combined-cycle power plant.
Nuclear Power Plant

- Steam power plant except that the boiler is replaced by a nuclear reactor, e.g. BWR (boiling-water reactor) and PWR (pressurized-water reactor)
- $\eta \approx 30\%$
- Take days to start up once shut down

(Source: Wikipedia.org)
Hydropower Plant

- Generated electric power:

\[ P_W = \frac{E_P}{t} = \frac{V \rho gh}{t} = q \rho gh \]

\[ P_o = \eta P_W = \eta q \rho gh = 9.81 q h \eta \ (kW) \]

\( \eta \) - overall efficiency (~90%)

\( h \) – effective head of water (m)

\( q \) – rate of flow (m\(^3\)/s)

\( \rho \) - density of water \( \approx 1000 \text{kg/m}^3 \)

\( g \approx 9.81 \text{m/s}^2 \)

Norris Dam: 1\textsuperscript{st} major TVA project built in the mid-1930s

(source: wikipedia.org)
Types of Hydropower Plants

• Run-of-the-river plants
  – Use the nature flow of rivers
  – Cheap; very little environmental impact
  – Power outputs may have seasonal fluctuations

• Pumped-storage plants
  – Typically have two reservoirs at two elevations
  – Energy storage function: during off-peak times, the generator can operate as a synchronous motor (pump) to save surplus electricity by elevating water
  – Fast: a few minutes from startup to full power
Solar Power

• Photovoltaic (PV)
  – Photoelectric effect: Light->electricity ($\eta \sim 15\%$)

• Concentrated solar power (CSP)
  – Light->heat->electricity
    • Parabolic dish concentrators
      (Dish Stirling, $\eta \sim 30\%$)
    • Parabolic Troughs,
    • Solar Tower
Direct Normal Solar Radiation (Two-Axis Tracking Concentrator)

Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40 km resolution. See http://www.nrel.gov/gis/fll_csp.html for documentation for more details.

Produce by the Electric & Hydrogen Technologies & Systems Center - May 2004
Wind Power Plants

• Generated electric power:

\[ P_W = \frac{E_K}{t} = \frac{mv^2}{2t} = \frac{A \rho vt \cdot v^2}{2t} = \frac{A \rho v^3}{2} = \frac{\pi D^2 \rho v^3}{8} \quad \text{(W)} \]

Wind power per m²:

\[ \frac{P_W}{A} = \frac{\rho v^3}{2} \approx 0.6 v^3 \quad \text{(W / m²)} \]

\[ P_O = \eta C_P P_W = \eta C_P \frac{\pi D^2 \rho v^3}{8} \quad \text{(W)} \]

\( C_P \) – power coefficient \( \approx 0.4 < 16/27 \) or 0.59 (Betz Limit)

\( \rho \) – air density \( \approx 1.2 \text{kg/m}^3 \) at 70°F
Wind Resources and Transmission Lines

The remaining states use data from the 1987 "Wind Energy Atlas of the United States".

Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Marginal</td>
<td>200 - 300</td>
<td>5.6 - 6.4</td>
<td>12.5 - 14.3</td>
</tr>
<tr>
<td>3</td>
<td>Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
</tr>
<tr>
<td>5</td>
<td>Excellent</td>
<td>500 - 800</td>
<td>7.5 - 8.0</td>
<td>16.5 - 17.9</td>
</tr>
<tr>
<td>6</td>
<td>Outstanding</td>
<td>800 - 1600</td>
<td>8.0 - 8.8</td>
<td>17.9 - 19.7</td>
</tr>
<tr>
<td>7</td>
<td>Superb</td>
<td>900 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.5</td>
</tr>
</tbody>
</table>

* Wind speeds are based on a Weibull k value of 2.0

Transmission Lines
- 345 - 499 kV
- 500 - 699 kV
- 700 - 799 kV
- 1000 (DC)

Source: POWERmap, nrel.gov/.wind/
Question

• Which of these generation resources utilize steam turbines in generating electric power?
  – Coal-fired power plant
  – Combined-cycle power plant
  – Pressurized water nuclear reactor
  – Offshore wind farm
  – Solar Tower
  – Parabolic trough solar farm
Power Generation and Delivery
Why Interconnect?

1. Stability
2. Continuity of service
3. Economy

Figure 24.6
Three networks connected by four tie lines.
Structure of an AC Power System

• **Generation**
  – Low voltages <25kV due to insulation requirements

• **Transmission system**
  – Backbone system interconnecting major power plants (11~35kV) and load center areas
  – 161kV, 230kV, 345kV, 500kV, 765kV, etc.

• **Sub-transmission system**
  – Transmitting power to distribution systems
  – Typically, 35/69kV-138kV

• **Distribution system**
  – Typically, 4kV-34.5kV

United States transmission grid
Source: FEMA
US Electric Industry Structure

- 3,195 utilities in the US in 1996. Fewer than 1000 engaged in power generation

<table>
<thead>
<tr>
<th>Categories</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>240+, 66.1% of electricity</td>
<td></td>
</tr>
<tr>
<td><strong>Publicly owned utilities</strong></td>
<td>Nonprofit state and local government agencies, including Municipals, Public Power Districts, and Irrigation Districts, e.g. NYPA, LIPA,</td>
</tr>
<tr>
<td><strong>Federally owned utilities</strong></td>
<td>Tennessee Valley Authority (TVA), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), etc.</td>
</tr>
<tr>
<td>~1000, 3.1%</td>
<td>Owned by rural farmers and communities</td>
</tr>
<tr>
<td><strong>Non-utilities</strong>, 11.9%</td>
<td>Generating power for own use and/or for sale in wholesale power markets, e.g. Independent Power Providers (IPPs)</td>
</tr>
<tr>
<td><strong>Cooperatively owned utilities</strong></td>
<td></td>
</tr>
</tbody>
</table>
NERC (North American Electric Reliability Corporation)

• As a non-government organization, formed by the electric utility industry in 1968 to promote the reliability of bulk power systems in North America.

• From 2007, FERC (U.S. Federal Energy Regulatory Commission) granted NERC the legal authority to enforce reliability criteria with all users, owners, and operators of bulk power systems in the U.S.

• NERC Membership is mandatory. Member companies comply with NERC’s Reliability Standards (approved by FERC) to promote reliable operations and avoid costly monetary penalties if caught non-compliant (visit http://www.nerc.com for more information)
System Control Centers

Duke Energy Control Center
(source: Patrick Schneider Photo.Com)

TVA Control Center
(source: TVA.com)
Hiring Companies

• Power utilities, e.g.
  – TVA, TVA distributors (e.g. KUB, LCUB, etc.), Duke Energy, Southern Company (Georgia Power, Alabama Power, Gulf Power and Mississippi Power), etc.

• Independent System Operators
  – PJM, SPP, ISO New England, NYISO, Midwest ISO, CAISO and ERCOT

Positions: planning/operation engineers
Hiring Companies (cont’d)

• Manufacturers and service providers
  – GE, ABB, Siemens, Alstom, Texas Instruments, etc.

Positions: R&D, engineers, consultants, etc.
Hiring Companies (cont’d)

• Government and Non-profit organizations
  – US DOE and National Laboratories (ORNL, PNNL, NREL, etc.)
  – NERC
  – EPRI (Electric Power Research Institute)

Positions: scientists, engineers, analysts, etc.
• Read Ch. 24 and Ch. 25.0-25.3
• Answer Questions 24-1 ~ 24-8 (submission is not needed)