Electricity production


Image by MIT OpenCourseWare.
**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”
**Pros & Cons of different sources of electricity**


<table>
<thead>
<tr>
<th>Energy sources</th>
<th>Technology considered for the cost estimate</th>
<th>2005 Cost (€/MWh)</th>
<th>Projected Cost 2030 (€/MWh)</th>
<th>GHG emissions (t CO₂eq/MWh)</th>
<th>EU-27 Import dependency</th>
<th>Efficiency</th>
<th>Fuel price sensitivity</th>
<th>Reserves / Annual production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>Open cycle gas turbine</td>
<td>45 - 70</td>
<td>55 - 85</td>
<td>440</td>
<td>57%</td>
<td>84%</td>
<td>40%</td>
<td>Very high</td>
</tr>
<tr>
<td></td>
<td>CCGT (Combined Cycle Gas Turbine)</td>
<td>35 - 45</td>
<td>40 - 55</td>
<td>400</td>
<td>38%</td>
<td>93%</td>
<td>30%</td>
<td>Very high</td>
</tr>
<tr>
<td>Oil</td>
<td>Diesel engine</td>
<td>70 - 80</td>
<td>80 - 95</td>
<td>550</td>
<td>82%</td>
<td>6%</td>
<td>30%</td>
<td>Very high</td>
</tr>
<tr>
<td>Coal</td>
<td>HT (Turbine Fuel with flue gas desulphination)</td>
<td>30 - 40</td>
<td>45 - 60</td>
<td>800</td>
<td>20%</td>
<td>90%</td>
<td>40%</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>CFB (Circulating Fluid Bed combustion)</td>
<td>35 - 45</td>
<td>50 - 65</td>
<td>800</td>
<td>20%</td>
<td>90%</td>
<td>40%</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>IGCC (Integrated Gasification Combined Cycle)</td>
<td>40 - 50</td>
<td>55 - 70</td>
<td>750</td>
<td>20%</td>
<td>90%</td>
<td>40%</td>
<td>medium</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Light water reactor</td>
<td>40 - 45</td>
<td>40 - 45</td>
<td>15</td>
<td>Almost 100%</td>
<td>33%</td>
<td>Low</td>
<td>Almost 85%</td>
</tr>
<tr>
<td>Biomass</td>
<td>Biomass conversion plant</td>
<td>25 - 40</td>
<td>25 - 75</td>
<td>30</td>
<td>20%</td>
<td>93%</td>
<td>Medium</td>
<td>30 - 60%</td>
</tr>
<tr>
<td>Wind</td>
<td>On shore</td>
<td>35 - 150</td>
<td>38 - 170</td>
<td>30</td>
<td>20%</td>
<td>93%</td>
<td>Medium</td>
<td>30 - 60%</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>50 - 170</td>
<td>52 - 150</td>
<td>10</td>
<td>20%</td>
<td>93%</td>
<td>Medium</td>
<td>30 - 60%</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>25 - 85</td>
<td>25 - 40</td>
<td>20</td>
<td>20%</td>
<td>93%</td>
<td>Medium</td>
<td>30 - 60%</td>
</tr>
<tr>
<td></td>
<td>Small (&lt;10MW)</td>
<td>45 - 90</td>
<td>40 - 10</td>
<td>52</td>
<td>20%</td>
<td>93%</td>
<td>Medium</td>
<td>30 - 60%</td>
</tr>
<tr>
<td>Solar</td>
<td>Photovoltaic</td>
<td>140 - 430</td>
<td>35 - 260</td>
<td>100</td>
<td>20%</td>
<td>Medium</td>
<td>Low</td>
<td>30 - 60%</td>
</tr>
</tbody>
</table>

Source: Energy Information Administration, Form EIA-860, "Power Plant Report."
Principle of a thermal unit

- Chemical energy (fuel)
- Combustion (boiler)
- Heat (steam)
- Steam turbine
- Mechanical energy (rotating shaft)
- Generator
- Electricity
Steam cycle

1. Boiler
   - Hot steam, high pressure
   - Water, high pressure

2. Turbine
   - Hot steam, high pressure

3. Generator
   - Electricity
   - Cold steam, low pressure

4. Condenser
   - Water, low pressure
   - Cooling water

Energy balance

1. Fuel
2. Generator
   - Hot gases
   - Electricity
   - Heated cooling water
   - Other losses
3. Pump energy
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

- Fuel is fed to the combustion chamber, where it combusts and generates hot gases.
- The hot gases power the turbine, which drives the compressor and the generator.
- The generator produces electricity.
- Air is drawn into the compressor and compressed before being fed to the combustion chamber.
- Hot gases from the combustion chamber are used as a source of energy for the steam cycle.
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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Typical Capacity</th>
<th>Response time</th>
<th>Discharge time</th>
<th>Efficiency</th>
<th>Life Time</th>
<th>Development Stage</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries</td>
<td>1kW – 50MW</td>
<td>1 min – 3h</td>
<td>65-75%</td>
<td>2-10 years</td>
<td>Premature</td>
<td>Mature</td>
<td>Uninterruptible power supply, RE fluctuation reduction, spinning/standing reserve</td>
</tr>
<tr>
<td>Compressed air energy systems (CAES)</td>
<td>25MW – 2.5GW</td>
<td>15 min from cold start</td>
<td>2-24 h</td>
<td>55%</td>
<td>15-40 years</td>
<td>Mature</td>
<td>Spinning/standing reserve, energy arbitrage</td>
</tr>
<tr>
<td>Super magnetic energy storage (SMES)</td>
<td>10kW – 1MW</td>
<td>5sec – 5min</td>
<td>96%</td>
<td>~30 years</td>
<td>Premature</td>
<td>Uninterruptible power supply, power quality</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell Storage System (HFCSS)</td>
<td>1kW – 1GW</td>
<td>Depends on a fuel cell</td>
<td>0.01 sec-days</td>
<td>~40%</td>
<td>5-10 years</td>
<td>Prototype</td>
<td>RE fluctuation reduction, spinning/standing reserve</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>&lt; 150 kW</td>
<td>1sec – 1min</td>
<td>85-85%</td>
<td>~10 years</td>
<td>Premature</td>
<td>Uninterruptible power supply, power quality</td>
<td></td>
</tr>
<tr>
<td>Pumped storage</td>
<td>20MW – 20GW</td>
<td>1 min (if standing)</td>
<td>4-10h</td>
<td>56-85%</td>
<td>~50 years</td>
<td>Mature</td>
<td>Spinning / standing reserve,</td>
</tr>
<tr>
<td>Flywheels</td>
<td>1MW – 3MW</td>
<td>15sec – 15min</td>
<td>90-95%</td>
<td>~20 years</td>
<td>Mature</td>
<td>Power quality</td>
<td></td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>
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: 1 day 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
  - \[ \text{TIM} = \frac{8760 \times 60 \times \text{NSE}}{E} \]
  - \( E \) = 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):

\[
\text{UI} = \frac{\sum_{i=1}^{n} t_i \cdot P_{Ni}}{T \cdot \sum_{i=1}^{n} P_{Ni}} \times 100
\]

- \( t_i \) = 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)
- \( P_{Ni} \) = Rated capacity (MW) of the lines, transformers and control devices

Reference value = 3%
Environmental implications of electricity supply & consumption


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 (polycrystalline 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://hp4x3.ethz.ch/energy/21/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 ~87 Quads
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
  - CO2 (all fossil plants during operation; but the complete load cycle should be considered)
  - SO2 (>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 — 5,652* Million Metric Tons of CO2**
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 \(\sim 50\) km\(^2\) to produce the same energy annually. *(Source J.W. Tester book, Ch. 13)*
  • Wind: \(\sim 3\) to 4 MW/km\(^2\)
  • 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/km\(^2\) (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