The first textbook was always on my desk when I was preparing these lecture notes. I also list Wikipedia, which was the source for many of the images and animations plus many useful tidbits of information.

Specific references are supplied on every slide except when the slide content is part of common mechanical engineering lore and can be found in any relevant textbook.

- Wikipedia, the free encyclopedia (http://en.wikipedia.org/wiki/Main_Page)

Module 5
Fossil-Fueled Power Plants

Thermal Power Plants in Turkey

http://www.euas.gov.tr/
• Typical size for a modern coal-fired power plant is 500 MW. Gas-fired and diesel generators could be built smaller.
• The best steam-cycle power plant efficiency is 40%. The world average is 35%.
• Gas turbine efficiency is around 25 - 30%.
• CCGT plants can achieve efficiencies as high as 45%.

Fossil Fuels

Capacity Factor

• Capacity Factor (CF) is the ratio of the actual power generation in a given period to what is theoretically possible over the same period running continuously at the full rated capacity.
• The capacity factors are usually defined over one year.
• Example
  - A 1000-MWe plant
  - Continuous production at full rating = 8760 Gwhe/y
  - The actual production in that year = 5000 Gwhe
  - Then, CF = 57%

Capacity Factors in Turkish TPPs

• The TEIAS data suggest that coal-, lignite- and gas-fired Turkish Thermal Power Plants (TPPs) achieved the following capacity factors in the year 2004:
  - Coal - 56% (Catalazgi is the only one)
  - Lignite - 35%
  - Natural gas - 26%
  - The average CF for the entire TPP sector = 27%
• The reasons for such low utilisation rates (i.e. low capacity factors) are unclear.

Types of Coal

Coal-Fired Power Plant

Fuel Supply

Coal comes by rail as crushed to <10-cm size and washed. This coal is further reduced to <1mm by the pulverizer in modern coal power plants.

Gas-fired plants usually receive the natural gas through the pipeline at about 1-4 MPa.

QUESTION – Calculate the daily tonnage for a 1000-MW coal power plant if the heating value for the coal is 25 MJ/kg.

Burner and Boiler

For complete combustion, air in excess of the stoichiometric ratio is required. Pulverised coal requires 15-20% excess air; oil and gas requires 5-10% excess air.

The fly ash needs to be captured and removed from stack gases.

Coal Power Plant

Image from wikipedia
Modern Steam Power Plants

- Condenser temperature around 30-40 °C
- Feedwater heated to 315 °C
- Steam generation at around 20 MPa (366 °C)
- Steam superheated to 565 °C and 24 MPa
- Stage 1 Turbine (High Pressure)
- Steam reheated to 500 °C and 3.7 MPa
- Stage 2 Turbine (Low Pressure)
- Turbine exhaust heats feedwater in the economiser
- The remaining steam goes to the condenser

Modern Steam Turbine

From Wikipedia

Parsons Turbine

The modern steam turbine was invented by an Anglo Irishman, Charles A. Parsons, in 1884 whose first model was connected to a dynamo that generated 7.5 kW of electricity. The above is a later Parsons model powering a Polish ship (Reference: wikipedia).
Parsons turbine was a reaction turbine. The blades of a reaction turbine are shaped and spaced to form converging nozzles between each pair of blades. The steam pressure drops steadily as the steam moves through the turbine stages and its enthalpy is converted into kinetic energy through the entire turbine.

Gustave De Laval invented the first impulse turbine by adapting the well-known Pelton wheel principle to steam turbines. The Pelton wheel was invented by Lester A. Pelton (1829-1908) in California around 1870 to convert hydrostatic pressure to mechanical energy.

The blades of an impulse turbine are bucket shaped and their function is to capture a jet impinging at a very high speed. The velocity drops across an impulse turbine stage but the pressure remains the same. Before hitting the blades on the impulse turbine rotor, the high-pressure steam goes through a stationary nozzle where it converts its high pressure to high velocity. Nozzle exit speed can be found by

\[ \frac{\dot{V}}{2} = \text{constant} \]

The force exerted on a blade is

\[ F = m(V_{\text{out}} - V_{\text{in}}) \]

The power generated by the blade

\[ W = PV_{\text{out}} - PV_{\text{in}} \]

What is the relation between blade and jet speeds to maximise power?

Gas turbines are reaction turbines. More gas turbine power plants are built with increased natural gas availability. These are usually built as combined cycle plants (CCGT) to achieve high efficiencies. They operate on Brayton cycle. The maximum temperature 1100-1200 °C, limited by modern steel alloy technology. Blade cooling is necessary against thermal stresses and corrosion. The exhaust gas is vented to atmosphere.
Condenser

• The condenser is the low temperature reservoir in the Rankine cycle
• Steam from the steam turbine is cooled in the condenser
• Two types of condensers are commonly used in modern power plants
  – Surface condensers, which are shell-and-tube heat exchangers. Steam is in the shell cooled by the water flowing through the tubes
  – Direct contact condensers, where the steam is condensed by spray-injected water and the further cooled by air in a dry cooling tower.
• Direct-contact condensers are more expensive because the spray water must be chemically treated to feedwater quality. Therefore, most large power plants use surface condensers.
• Critical design quality issues for surface condensers:
  – Low pressure drop to minimise the turbine exhaust pressure
  – Good sealing between the shell and the tubes to prevent contamination of the process steam by the cooling water
  – Resistance against corrosion
Cooling Towers

• In the past, power plants could dump their waste heat to a nearby lake or sea
• This is no longer allowed for environmental reasons because
  – The hot water destroys the local biology
  – The residual contaminants spreads over the entire body of water
• Today’s power plants use cooling towers, which transfer the plant waste heat to the air
  – Wet cooling towers – cooled by the evaporation of some of the cooling water
  – Dry cooling towers – cooled by forced convection of air over tubes of water

Wet Cooling Towers

Wet cooling towers are easy to construct therefore they are the most common type.
The scarcity of water in some places may make this type less popular in the future. A wet cooling tower for a 1000-MW may be using up water up to 20 million tonnes per year.

Wet Cooling Tower Water Balance

M – Make-up water
W – Windage losses
E – Evaporated water
C – Hot water coming from the condenser
D – Draw-off (to prevent salt accumulation)

Wet cooling towers use large quantities of water. This may not be acceptable in areas where water is scarce.
On the other hand, dry cooling towers have a high capital cost. They also impose an extra pressure drop (water flowing through the tubes) leading to reduction of plant efficiency.
Power Plant Emissions

- Coal burned in power plants is not pure carbon. It has sulphur and mineral content.
- Inefficient burners produce Products of Incomplete Combustion (PIC) and CO. This is observed as black smoke.
- The sulphur burns to SO$_2$ and mineral content becomes fly ash in the smoke stack.
- In addition, high combustion temperatures produce nitrogen oxides (NO+NO$_2$ and others, commonly referred as NOx).
- These emissions lead to very significant pollution of air: smoke and acid rain.
- The pollution is carried by wind over a large area.

How to control emissions

- PIC+CO: Better burner design should minimise these.
- Particulate matter:
  - Electrostatic Precipitator (large particles, $d_p > 2\mu m$)
  - Baghouse (for smaller particles, $d_p < 2\mu m$)
- Sulphur:
  - Before combustion:
    - Coal washing
  - During combustion:
    - Fluidised Bed Combustion
  - After combustion:
    - Sorbent injection
    - Scrubbers (wet or dry)
- NOx control:
  - during combustion:
    - Low-NOx burner (LNB)
  - After combustion:
    - Selective Reduction (with or without a catalyst)

Electrostatic Precipitator (ESP)

www.che.lsu.edu/courses/4253/spring2005/Lecture_14.ppt

Large ESP

www.che.lsu.edu/courses/4253/spring2005/Lecture_14.ppt
Collection efficiency is given by the Deutsch equation:

\[
\eta = 1 - \frac{C_e}{C_i} = 1 - e^{-\gamma}
\]

Where

- \( \eta \): Collection efficiency
- \( A \): Total plate area, \((n-1)A_p\)
- \( C_i \): Particulate matter concentration at the inlet
- \( C_e \): Particulate matter concentration at the exit
- \( w \): Speed of migrating to the plates, m/s (~0.05 \( \mu \)m)

The particles reach the terminal speed very quickly. Therefore, their migration speed is equal to the terminal velocity under the electrostatic attraction. This terminal velocity can be found by balancing the electrostatic force on the charged particle against the drag force, similar to finding the terminal velocity during free fall in air.

Fay & Golomb offer an approximate equation as

\[
w = 0.05d_p
\]

This equation gives the migration speed in terms of m/s if the particle diameter \( d_p \) is given in \( \mu \)m.

**ESP Design Parameters**

- Migration speed, \( w = 0.005 - 0.05 \) m/s
- Plate spacing, \( D = 0.3 - 0.6 \) m
- Gas velocity, \( U = 1 - 2 \) m/s
- Power density, \( 10 - 30 \) W/m²
- Capital Cost, US$30,000 – US$100,000 per scm/sec
- O&M cost, US$8,500 – US$85,000 per scm/sec

scm = standard cubic meters
Baghouse

The filtering ratio, or the total bag surface over the gas volumetric flow rate is also referred to as the superficial gas velocity and typically ranges from 0.5 to 4 m/s.

Baghouses may be installed after the ESP to trap the finer particles (<1-2 μm) that escape the ESP.

Acid Rain

Acid deposition is a general term that includes more than simply acid rain. Acid deposition primarily results from the transformation of sulphur dioxide (SO₂) and nitrogen oxides into dry or moist secondary pollutants such as sulphuric acid (H₂SO₄), ammonium nitrate (NH₄NO₃) and nitric acid (HNO₃). The transformation of SO₂ and NOx to acidic particles and vapours occurs as these pollutants are transported in the atmosphere over distances of hundreds to thousands of kilometers. Acidic particles and vapours are deposited via two processes - wet and dry deposition. Wet deposition is acid rain, the process by which acids with a pH normally below 5.6 are removed from the atmosphere in rain, snow, sleet or hail. Dry deposition takes place when particles such as fly ash, sulphates, nitrates, and gases (such as SO₂ and NOx), are deposited on, or absorbed onto, surfaces. The gases can then be converted into acids when they contact water.

Man-made Acid Rain

Fluidised-Bed Combustion

Crushed coal mixed with limestone, CaCO₃, is burned and SO₂ react with limestone to form calcium sulfite, CaSO₃, and calcium sulfate, CaSO₄. These particles (plus unburned coal and unreacted limestone) are trapped by a cyclone before being sent to the stack.

The stack gas goes through an ESP and a baghouse, before final release. Low quality coal (and other fuels like biomass) can be used at thermal efficiencies comparable to pulverised coal combustion. Limited to small plants, 10-100 MW. Sulphur capture efficiency is 40-60%.

Wet limestone scrubber

\[
\text{CaCO}_3 + \text{SO}_2 + \frac{1}{2} \text{H}_2\text{O} \rightarrow \text{CaSO}_3 + \frac{1}{2} \text{H}_2\text{O} + \text{CO}_2 \\
\text{CaSO}_3 + \frac{1}{2} \text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}
\]

A wet scrubber can remove 90-99% of the sulphur dioxide in the flue gas. It may take 2-3% of the plant electrical power output to run the scrubber. The additional cost, including capital and operating, could be as much as 10-15% on the cost of the generated electricity.

A dry scrubber is similar but does not form a sludge. The sulfite/sulfate particles are captured by an ESP placed downstream. Dry scrubbers can only capture 70-90% of the sulphur content but cost less.

Nitrogen Oxide (NOx)

Nitric oxide (NO), nitrogen dioxide (NO₂) plus various higher oxides are collectively called as NOx. NOx is a serious pollutant with health and environmental hazards. NOx can only be controlled during or after combustion.

NOx formation is maximum when the air-fuel mix is at the stoichiometric ratio. The NOx production is lower for both rich and lean mixtures.
Low-NOx Burner

NOx production is lower when the air/fuel ratio is away from the stoichiometric ratio. The unburned coal from the fuel-rich inner flame is burned in the outer flame which is fuel-lean. While the process is simple and cheap, the NOx reduction is only 30-55% and does not satisfy the new more stringent environmental standards in most countries. Post-combustion selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR) using ammonia or urea is used to achieve reductions up to 90% albeit at a cost of 3-10% added to the cost of electricity generation.

Advanced Cycles

Combined Cycles
Gasification
Cogeneration
Fuel Cells

Combined Cycle Gas Turbine

Combined efficiency can be as high as 45%. Compared to coal, the natural gas has a much more benign influence on the environment. This comes at a cost, since the natural gas is more expensive.

Integrated Gasification Combined Cycle (IGCC)

This is an experimental technology and is not yet commercially available. The coal is gasified first and then the gasified coal (syngas) is burned in a combined cycle gas turbine plant.

- **Coal Gasification**: $3C + O_2 + H_2O \rightarrow 3CO + H_2$
- **Pure oxygen** is used in this process not air. Why?
- **The heating value of the resulting syngas is around 9-18 MJ/scm.** This is not suitable for a CCGT plant. The heating value is increased by passing the mixture over a catalyst at a temperature of 400°C. This is called methanation:
  - **Methanation**: $3H_2 + CO \rightarrow CH_4 + H_2O$
  - An alternative is production of hydrogen in the **water gas shift reaction**:
    - **Water gas shift**: $CO + H_2O \rightarrow CO_2 + H_2$
  - Hydrogen can then be separated by a membrane and used in a fuel cell.
- The estimated IGCC is 40-45%, including the energies required for air separation and gasification, higher than a typical overall pulverised coal plant efficiencies of 36-38%.
- The capital cost also is expected to be much higher.
Cogeneration

If there is a need for heat energy at a relatively low temperature (too low to be used effectively exploited in a steam power plant cycle), the cogeneration can be very beneficial.

A common usage is to use the waste heat for space heating, usually over an entire district. The energy available to this purpose is

\[ Q_u = \eta_{xch}(1 - \eta_x)Q_{fuel} \]

Where \( \eta_{xch} \) is the efficiency of extracting the heat from the generator exhaust stream. \( Q_{fuel} \) is the heat content of the fuel.

Fuel Cell

- The theoretical fuel efficiency is close to 100%
- The actual efficiency is about 45-50% due to parasitic losses
- Production of hydrogen by electrolysis for water requires 18 MJ per kg of water. The electrolytic hydrogen in a fuel cell produces less electricity.
- Fuel cell hydrogen is usually generated by reforming methane.