Energy and Environment
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Fossil-fueled power plants

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Fossil-fueled power plants

• The worldwide average efficiency is about 35%
• Gas turbine power plants achieve a thermal efficiency 25–30% range.
• More advanced power plants exist today that use a combination of Brayton and Rankine cycles.
• Combined cycle power plants can achieve an efficiency of about 45%.
• The relatively low thermal efficiency of power plants is due to two factors
  – the heat needs to be rejected to a cold reservoir
  – Heat losses through walls and pipes, frictional losses, and residual heat escaping with the flue gas
In a fossil-fuelled power plant:

- The chemical energy inherent in the fossil fuel is converted to raise the enthalpy of the combustion gases. Enthalpy is transferred to a working fluid (usually, water/steam). The enthalpy is converted to mechanical energy in a turbine. The mechanical energy of the turbine shaft is converted to electrical energy in a generator.
The major components of a fossil fuelled power plant are as follows:

- Fuel storage and preparation
- Burner
- Boiler
- Steam turbine
- Gas turbine
- Condenser
- Cooling tower
- Generator
- Emission control
Fuel Storage and Preparation

Coal

• Coal is delivered to power plant by rail or ship or barge
• Usually, power plant have several weeks of coal stock on site
• A 1000-MW power plant of thermal efficiency 35%, consumes 10,000 tons of coal per day
• Some coal-fired power plants are situated near coal mines (mine-mouth plants).
• Even these plants store at least a month’s supply of coal near the plant.
• When coal arrives by rail, it is usually carried by a unit train, consisting of a hundred wagons filled with coal, at 100 tons per wagon. The wagons are emptied by a rotary dump, and the coal is carried by conveyors to a stockpile, or directly to the power plant.
• Coal is delivered to a plant in feed size of the pulverizing mill in few to ten centi-meters per coal lump.
• In the United States and many other countries, coal is washed at the mine.
• Washing of coal removes much of the mineral content of the coal (including sulfur)
Most modern steam power plants fire pulverized coal. The raw coal from the stockpile is delivered on a conveyor belt directly to a pulverizing mill. Such mills are either of the rotating ring, rotating hammer, or rotating ball type. The mill reduces the raw coal lumps to particles smaller than 1 millimeter.

The pulverized coal is stored in large vertical silos from whence it is blown pneumatically into the burners at a rate demanded by the load of the plant.
Burner

- The role of the burner is to provide a proper mixing of fuel and air.
- The mineral matter (which forms ash) is blown out of the boiler by forced or natural draft and is later captured in particle collectors.
- About 10% of the mineral matter falls to the bottom of the boiler as bottom ash.
- When the bottom of the boiler is filled with water, the bottom ash forms a wet sludge.
- This forms a slag which hinders heat transfer.
- The slag needs to be removed from time to time by blowing steam jets against it or by mechanical scraping.
- Coal burns relatively slowly, oil burns faster, and gas burns the fastest.
- For complete combustion (carbon burn-out), excess air is required.
- Pulverized coal requires 15–20% excess air.
• Burning coal emits harmful waste such as carbon dioxide, sulphur dioxide, nitrogen oxides, sulphuric acids, arsenic and ash
• Coal emits twice as much carbon dioxide when compared with natural gas
• The burning of coal has led to acid rain in some regions
• Coal can be cleaned and turned into a liquid or gas but this technology has yet to be fully developed (IGCC)

\[
\text{C (as Coal) + O}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}
\]

• Around 10% of coal is ash
• Coal ash is hazardous and toxic to human beings and other living things
• Coal ash contains the radioactive elements uranium and thorium
• Coal ash and other solid combustion by-products are stored locally and escape in various ways that expose those living near coal plants to radiation and environmental toxic
The boiler is the central component of a fossil-fueled steam power plant.

Water tube boilers can be designed to exploit any heat source and are generally preferred in high-pressure applications since the high-pressure water/steam is contained within small diameter pipes which can withstand the pressure with a thinner wall.

Fire-tube boilers usually have a comparatively low rate of steam production, but high steam storage capacity. Fire-tube boilers mostly burn solid fuels, but are readily adaptable to those of the liquid or gas variety.
Biomass combustion in boiler

Biomass has a number of characteristics that makes it more difficult to handle

• The low energy density is the main problem in handling and transport of the biomass

• Biomass contain significant amounts of chlorine, sulfur and potassium

• The salts, KCl and K2SO4, are quite volatile, and the release of these components may lead to heavy deposition on heat transfer surfaces, resulting in reduced heat transfer and enhanced corrosion rates.

• The release of alkali metals, chlorine and sulfur to the gas-phase may also lead to generation of significant amounts of aerosols (sub-micron particles) along with relatively high emissions of HCl and SO2.
\[
2\text{MCl} + \text{Fe}_2\text{O}_3 + \frac{1}{2} \text{O}_2 \rightarrow \text{M}_2\text{Fe}_2\text{O}_4 + \text{Cl}_2 \quad (R1)
\]

\[
\text{Cl}_2 + \text{Fe}/\text{Ni}/\text{Cr} \rightarrow \text{FeCl}_2 \quad (R2,3)
\]

\[
2\text{FeCl}_2 + \frac{3}{2} \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 2\text{Cl}_2 \quad (R4)
\]
Steam Turbine

Advantages

• Thermal efficiency of a steam turbine is usually higher than that of a reciprocating engine
• Very high power-to-weight ratio, compared to reciprocating engines
• Fewer moving parts than reciprocating engines
• Steam turbines are suitable for large thermal power plants
• Steam contains high amount of enthalpy, this implies lower mass flow rates compared to gas turbines.
• In general, turbine moves in one direction only, with far less vibration than a reciprocating engine.
• Steam turbines have greater reliability, particularly in applications where sustained high power output is required.
Steam Turbine

Disadvantages

Although approximately 90% of all electricity generation in the world is by use of steam turbines, they have also some disadvantages.

- Relatively high overnight cost
- Steam turbines are less efficient than reciprocating engines at part load operation
- They have longer startup than gas turbines and surely than reciprocating engines
- Less responsive to changes in power demand compared with gas turbines and with reciprocating engines.
Advantages of gas turbine engines

- Very high power-to-weight ratio, compared to reciprocating engines
- Smaller than most reciprocating engines of the same power rating
- Moves in one direction only, with far less vibration than a reciprocating engine
- Fewer moving parts than reciprocating engines
- Low operating pressures
- High operation speeds
- Low lubricating oil cost and consumption
Gas Turbine

Disadvantages

• Cost is much greater than for a similar-sized reciprocating engine since the materials must be stronger and more heat resistant
• Machining operations are also more complex
• Usually less efficient than reciprocating engines at idle
• Delayed response to changes in power settings.
• Working fluid in gas turbines nitrogen, excess oxygen, water vapor, and carbon dioxide, is not recycled into the compressor and combustion chamber, instead, emitted into the atmosphere.

• In some systems, a part of the energy still residing in the exhaust gas is recovered in heat exchangers to heat up the air entering the combustion chamber in order to enhance the overall thermal efficiency of the Brayton cycle, but eventually the exhaust gas is emitted to atmosphere.
Condenser

- In heat engine cycles, after performing useful work, the working fluid must reject heat to a cold body.

- They reject a significant amount of heat into the environment.

- Between 1.5 and 3 times as much heat is rejected as the plant produces work in the form of electricity. A 1000-MW electric power plant working at 25% efficiency rejects 3000 MW of heat to the environment, whereas one working at 40% efficiency rejects 1500 MW.

- Some of that heat is added to the environment by the condensing system in a steam cycle, and the rest is added by the discharge to the atmosphere of the hot flue gas vented through the smoke stack.
Cooling Tower

- The heat rejection to surface water or atmosphere.
- Power plants usually located near a river, lake, or ocean.
- Thermal pollution and harm to aquatic organisms.
• Environmental protection agencies in many countries mandate that heat rejection occur into the atmosphere via cooling towers.
• There are two types of cooling towers: wet and dry.
• There are also combinations of wet and dry towers, as well as combinations of cooling towers and surface water cooling.
Emission Control

• If uncontrolled, Power plants emit huge quantities of air pollutants that cause pollutant levels to exceed

• A 1000-MW coal power plant, with a 10% mineral content, 2% sulfur content (not unusual), Base-loaded plant at 100% capacity and 35% thermal efficiency

• All the mineral content exits the smoke stack as particles (fly ash), and the sulfur exits as sulfur dioxide SO2

• This plant would emit 300,000 t/y of particles and 130,000 t/y of SO2

• In addition, the plant would emit abundant nitrogen oxides, products of incomplete combustion (PIC), carbon monoxide, and volatile trace metals
The control of PIC and CO is relatively easy to accomplish. If the fuel and air are well-mixed, as is the case in modern burners, and the fuel is burnt in excess air, the flue gas will contain very little PIC and CO. It is in the interest of power plants to achieve a well-mixed, fuel-lean (air rich) flame, not only for reducing the emission of these pollutants, but also for complete burn-out of the fuel, which increases the thermal efficiency of the plant. PIC and CO emissions do occur occasionally, especially during start-ups and component breakdowns, when the flame temperature and fuel–air mixture is not optimal. Under those conditions a visible black smoke produces from the smoke stack.
Particle Control

- Particles, also called particulate matter (PM), is the predominant pollutant coming from power plants if not controlled at the source. Coal and oil contain a significant fraction of incombustible mineral matter.
- The mineral matter accumulates in the bottom of the boiler as bottom ash and is discarded as solid waste or sluiced away.
- In modern pulverized coal-fired plants, the majority (≈ 90%) of the mineral matter is blown out from the boiler as fly ash.
- The fly ash contains (a) a host of toxic metals, such as arsenic, selenium, cadmium, manganese, chromium, lead, and mercury, and (b) nonvolatile organic matter (soot), including polycyclic aromatic hydrocarbons (PAHs).
- Most countries have instituted strict regulations on particle emissions from power plants.
Sulfur Control

• Coal can contain up to 6% by weight of sulfur, and oil up to 3%.
• Generally, bituminous, subbituminous, and lignite coals are used in power plants.
• They contain 0.7–3% by weight of sulfur. Residual oil used in power plants contains 0.7–2% sulfur.
• Without sulfur emission control devices, the oxidized sulfur, mainly sulfur dioxide SO2, minor quantities of SO3, and sulfuric acid H2SO4, would be emitted through the smoke stack into the environment.
• The oxides of sulfur are precursors to acid deposition and visibility impairing haze.
• Because coal-fired power plants emit the majority of all sulfur oxide emissions worldwide, operators of these plants are required to limit the emissions by either switching to low-sulfur containing fuels or installation of sulfur emission control devices.
• Three approaches to reducing sulfur emissions: before, during, and after combustion of the fossil fuel.
Before Combustion

• Coal Washing
  
  – When coal is removed from the coal seams in underground or surface mines, there is always some mineral matter included in the coal. The majority of mineral matter is composed of silicates, oxides, and carbonates of common crustal elements, such as calcium, magnesium, aluminum, and iron, but some of it contains pyrites, which are sulfides of iron, nickel, copper, zinc, lead, and other metals. Because the specific gravity of mineral matter, including the pyrites, is greater than that of the carbonaceous coal, a part of the mineral matter can be removed by “washing” the coal. Coal washing not only reduces the sulfur content of coal, but also reduces its ash content,

  – Coal washing is usually performed at the mine mouth. Typically, the crushed raw coal is floated in a stream of water. The lighter coal particles float on top, and the heavier minerals sink to the bottom. The wet coal particles are transferred to a dewatering device, generally a vacuum filter, centrifuge, or a cyclone. The coal can be further dried in a hot air stream.
Coal Gasification

- Coal can be converted by a chemical process into a gas, called synthesis gas or syngas.
- In the process of coal gasification, most of the sulfur can be eliminated.
- The clean, desulfurized syngas can be used to fuel a gas turbine or combined cycle power plant.
During Combustion

*Fluidized Bed Combustion*

Fluidized bed combustion (FBC) is the burning of coal (or any other solid fuel) imbedded in a granular material, usually limestone, riding on a stream of air. The primary aim of the development of FBC was not specifically to reduce SO2 emissions, but rather to enable the combustion of all sorts of fuel, including nonpulverizable coal, municipal solid waste, industrial and medical waste, wood, tar, and asphaltene (residue of oil refining). The admixed limestone acts as a sorbent, extracting sulfur and other impurities from the fuel.
Figure 5.10 Fluidized bed combustor, schematic.
After Combustion

• The removal of sulfur oxides from the flue gas after combustion of the fuel in a furnace or boiler is called flue gas desulfurization (FGD). There are several methods of FGD: sorbent injection and wet and dry scrubbers.
Nitrogen Oxides (NOx) Control

- The other major category of pollutants that emanates from fossil fuel combustion is nitrogen oxides, called NOx, which includes nitric oxide NO, nitrogen dioxide NO2 (and its dimer N2O4), nitrogen trioxide NO3, pentoxide N2O5, and nitrous oxide N2O.
- NOx usually implies the sum of NO and NO2.
- NOx is a malicious pollutant because it is a respiratory tract irritant and it is a pioneer to photo-oxidants, including ozone, and acid deposition.
- Control of NOx emissions from both stationary and mobile sources, including electric power plants.
- Coal and oil contain organic nitrogen in their molecular structure. When burnt, these fuels produce the so-called fuel NOx.
- All fossil fuels produce thermal Nox, from the recombination of atmospheric nitrogen and oxygen under conditions of the high temperatures, $\text{N}_2 + \text{O}_2 \leftrightarrow 2\text{NO}$.
During Combustion

- Low-NOx Burner. A low-NOx burner (LNB) employs a process called staged combustion.
- NOx formation is a function of air-to-fuel ratio (by weight) in the flame is exploited in LNB. This ratio affects the flame temperature and the availability of free radicals that participate in the NOx formation process.
- A plot of NOx concentration in the flame versus air-to-fuel ratio is given in next slide.

![Diagram of Low-NOx burner, schematic.](image-url)
• Stoichiometric conditions (air/fuel ratio ≈ 15) gives maximum NOx is formed
• Less NOx is formed both under fuel-rich and fuel-lean combustion conditions.
Combined Cycle
A combined cycle power plant can be fueled by coal, but then the coal needs first to be gasified.

The gasified coal (syngas) propels the topping cycle gas turbine.

A power plant using coal gasification and combined cycle is called an integrated gasification combined cycle plant (IGCC).

In the world wars, Germany used gasified coal as a fuel for automobiles, trucks, and military vehicles.

Coal can be gasified to low-, medium- and high-heating value syngas.

The processes differ depending upon whether air or pure oxygen is used for gasification and whether the product gas is rich or devoid of CO2.

For an IGCC plant, high-heating value syngas is preferred.
Integrated Gasification Combined Cycle (IGCC)

IGCC is a technology that uses a gasifier to turn coal or biomass into gas and to electricity

- Produce syngas (CO+H2)+ impurities (SO2, PM, NOX etc..)
- Remove impurities before combustion
  - Biomass contains alkali materials K, Na
  - Form KCl, KSO4
  - Deposition and corrosion
  - Heat xchanger lost

Scheme of a BIGCC plant to produce heat and electricity from the biomass used in an ethanol production plant
Conventional thermal power generation is extremely wasteful process.
- Efficiencies in the range 30–47%
- Over 50% of fuel value is wasted
- Heat rejected to surrounding.
- Liberates huge CO2 into the atmosphere.
The Carnot principle shows the theoretical maximum thermal efficiency of any heat engine cycle:

\[ \eta_{\text{carnot}} = 1 - \frac{T_2}{T_1} \]

\( T_1 \) is maximum temperature and \( T_2 \) is the lowest temperature available (K).

For example, if the maximum reachable temperature in a cycle is 1450 K and the cooling water minimum temperature is 285 K:

\[ \eta_{\text{carnot}} = 1 - \frac{285}{1450} = 0.803 \text{ (or 80.3\%)} \]
Poly generation concept

- In fact the maximum Carnot efficiency cannot be achieved - irreversibility in the process.
- Energy being lost in the form of waste heat.
- Waste heat is recovered and make use of it in poly generation process.

\[ \oint \frac{\delta Q}{T} = \int_{1_{\text{rev}}}^{2} \frac{\delta Q}{T} + \int_{1_{\text{rev}}}^{2} \frac{\delta Q}{T} < 0 \]

\[ \int_{1_{\text{rev}}}^{2} \frac{\delta Q}{T} + \int_{2}^{1_{\text{rev}}} \delta S = \int_{1_{\text{rev}}}^{2} \frac{\delta Q}{T} + (S_2 - S_1) < 0 \]

\[ \Delta S = (S_2 - S_1) > \int_{1_{\text{rev}}}^{2} \frac{\delta Q}{T} \]

For adiabatic processes (\( \delta Q = 0 \)) \( \Rightarrow \Delta S \geq 0 \)
Mono-generation

- Heat and electricity produced separately
- The most common way to produce electricity and heat
- E.g. power plant ($\eta=40-60\%$), heating boiler ($\eta=90-105\%$)
Co-generation

- Heat and electricity produced in a combined heat and power plant (CHP)
- Several technology solutions
- Power $\eta=20-50\%$, heat $\eta=30-60\%$, total $\eta=75-90\%$
Combined heat and power (CHP)

- CHP to serve both electricity and heat
Benefits of co-generation (combined heat and power)

- High overall efficiency from fuel to final energy (even up to 90%)
Tri-generation

- Heat, cold and electricity produced in a polygeneration plant
- Typically combines a CHP and absorption cooling
- Power $\eta=20-50\%$, heat $\eta=30-60\%$, cold $\eta=20-40\%$, total $\eta=80-90\%$
Benefits of tri generation

- Major fuel and cost savings (15-50%)
- Lower carbon emissions
- Fuel flexibility
- Utilization of local bioenergy sources
- Diverse applications
- Flexible technology options
- Power system flexibility & stability
- In municipalities often coupled to district heating (DH)
Carbon Capture and Storage (CCS)

**CCS involves:**
- Capture the emitted CO₂ from power and industrial plants
- Transportation
- Injection in underground reservoirs for storage.

**Four main technologies for CC:**
- Post-combustion capture
- Pre-combustion capture
- Oxy-fuelling
- Chemical looping

**A significant energy penalty to the base plant.**

- After CO₂ is captured, it should be compressed for transportation through high-pressure pipelines or ships, and finally stored into geological formations such as depleted gas reservoirs, saline formations and deep unmineable coal seams.
The 30-MW power plant was commissioned in Schwarze Pumpe in September 2008 by the company Vattenfall and is intended to serve as a test to be applied in commercial-size CCS power plants (250–350 MW).
Group discussion

Discuss with your friends about fossil fuel power plants (5 minutes)

1. About 50-75% of input energy in fossil fueled power plants is wasted as exhaust ...
2. Fossil fueled power plants produce SOx, NOx, particulate matters, toxic organic and inorganic by-products which are very harmful to the public health..
3. Globally less than 10% electricity comes from renewable sources..
4. Resource depleting rapidly ..

What should we do?
Test 1

22 Oct 2018 (Tuesday) 8.30am-9.30am
E07, DK 2