ELEC6221: Power Generation: Technology and Impact on Society

Coal-fired Steam Power Plants
Environmental Consideration
Coal fired power plant

• Coal burning power plant technology
• Steam Power Plants
  • Rankine Cycle
  • Boiler technology
  • Steam turbine technology
  • Generators
• Emission control – ash, S, NO\textsubscript{x}, CO\textsubscript{2}
• Advanced coal burning power plant technology
• Environmental effects of coal combustion
• Cost comparison

Pulverised coal power plant - Germany

Fluidised bed coal power plant - Mexico
Boiler technology (pressure parts)

**Feed Water Pump**
The first step is to get a constant supply of water at high pressure into the boiler. Since the boiler is always at a high pressure. 'Boiler feed water pump' pumps the water at high pressure into the boiler from the 'feed water tank'.

**Pre-Heating**
'Feed water heaters', using extracted steam from the turbine, adds a part of the heat even before the water enters the boiler.

**Economiser**
The flue gases, having passed through the main boiler, will still be hot. The energy in these flue gases can be used to improve the thermal efficiency of the boiler. To achieve this the flue gases are passed through an Economiser. These are a set of coils made from steel tubes located in the tail end of a boiler. The hot gases leaving the boiler furnace heat the water in the coils. The water temperature is slightly less than the saturation temperature. From the economiser the water is fed to the 'drum'.

**Drum**
The drum is a large cylindrical vessel that functions as the storage and feeding point for water and the collection point for water and steam mixture. This is the largest and most important pressure part in the boiler and weighs in the range 250 Tons for 600 MW power plant.
Boiler technology (pressure parts)

**Water Walls**

- Boiling takes place in the ‘Water Walls’ which are water filled tubes that form the walls of the furnace. Water Walls get the water from the ‘downcomers’ which are large pipes connected to the drum. The downcomers and the water wall tubes form the two legs of a water column.

- As the water heats up in the furnace a part of the water in the water-wall tubes becomes steam. This water steam mixture has a lower density than the water in the downcomers. This density difference creates a circulation of water from the drum, through the downcomers, water walls and back to the drum. Steam collects at the upper half of the drum. The steam is then sent to the next sections.

- The temperature in the drum, downcomers and water wall is at the saturation temperature.
Boiler technology (pressure parts)

**SuperHeater**
- Steam from the drum passes to the SuperHeater coils placed in the Flue gas path. The steam temperature increases from the saturation temperature till the maximum required for operation. The superheated steam then finally goes to the turbine.
- Final Superheater temperatures are in the Range of 540 to 600 °C for large power plants and SuperHeated steam pressures are around 175 bar.
Boiler technology (pressure parts)

Reheater

- Steam from the exhaust of the first stage turbine goes back to the boiler for reheating and is returned to the second stage.
- Reheater coils in the flue gas path do the reheating of the returned steam. The reheat steam is at a much lower pressure than the superheated steam but the final reheater temperature is the same as the superheated steam temperature.
- Reheating to high temperatures improves the output and efficiency of the Power Plant.
- Final Reheater temperatures are normally in the range of 560 to 600 °C. Reheat steam pressures are normally around 45 bar.
**Boiler technology (coal system)**

**Coal Storage**
Coal received from the mines is stored in the coal yard adjacent to the power plant. It is then conveyed on a daily basis to the boiler and stored in a ‘Coal Silo’. ‘Coal feeders’ continuously feed the required amount of coal to the ‘Coal Pulverisers’.

**Coal Pulverisers** grind the coal to a very fine powder to make it burn easily. Pulverisers have steel rollers or steel balls which crush the coal between them into a fine powder. This powder is easy to burn. Coal contains moisture. Hot air from the Primary Air Fans dry the coal in the pulverisers. This makes the burning easy and efficient. This air also carries the dry coal powder from the pulverisers to the burners in the boiler furnace. In the burners the coal powder is mixed with the required amount of combustion air and burned in the furnace.

**Primary Air Fan** supplies the air to the pulverisers for drying and transporting coal. This air called the Primary air also is heated in the Air Heater.
Boiler technology (air system)

Air system
Correct amount of air is the most essential ingredient for Combustion. More air or less air both makes the combustion process inefficient.

**Forced Draft Fan** supplies most of the Combustion air. This fan takes air from the atmosphere and blows it into the furnace through air ducts. The Air Heater heats the air before it enters the Furnace.

**Air Heater** utilises the heat of the hot flue gases that leave the boiler to heat the combustion air. Hot air improves the efficiency of combustion. The Air Heater works on the regenerative principle. Steel plates alternatively placed in the hot flue gas path and then in the air path heats the cold air entering the Air Heater.

**Primary Air Fan** supplies the air to the pulverisers for drying and transporting coal. This air called the Primary air also is heated in the Air Heater
Boiler technology (flue gas system)

Flue gas system
Coal burns in the furnace giving out heat and forming flue gases.

**Induced Draft Fan.** The hot flue gases from the furnace is drawn out by the Induced draft fan. The gases passes through the various heating surfaces of the boiler, the Electrostatic Precipitator and discharges to the atmosphere at the top of the stack. Induced Draft Fan provides the energy for this flow of flue gases. The Induced Draft Fan is normally located adjacent to the Stack.

**Electrostatic Precipitators** capture the fly ash in the flue gases without letting them out into the atmosphere. High voltage electrodes placed in the gas path ionise the ash particles which collects on collecting electrodes and falls into ash hoppers.

**Stack** or the Chimney disperses the hot gases and any other particles at a great height. The height enables a very large dispersion area and regulates emission concentrations at ground levels to the level acceptable to humans and vegetation. Stack heights for large power plants are around 250 to 280 meters.

**Balanced Draft** The Forced Draft fan and the Induced Draft fan operate in such a way that the air pressure in the furnace is at zero relative pressure i.e.: at atmospheric pressure. This is called the ‘Balanced Draft system’.
Boiler technology

• Applied thermodynamics [electronic resource] by Onhar Singh.

Turbine technology

Complex Design!
Turbine technology

• The steam turbine first appeared in power applications at the end of the nineteenth century.
  – Before that steam power was derived from steam-driven piston engines.

• The steam turbine has features of a hydropower turbine and a windmill.
  – Extract energy from a moving fluid
  – Hydro turbine, the water remains in the liquid phase and neither its volume nor its temperature changes during energy extraction
  – Steam turbine, energy extraction is from a gas (steam)
  – It involves both the pressure and the temperature of the fluid falling
  – This has a profound effect on the turbine design

• It is impossible to extract all the energy from steam using a turbine with a single set of turbine blades.
  – Instead, a steam turbine utilises a series of sets of blades, called stages.
  – Each stage is followed by a set of stationary blades (usually called nozzles) which control the steam flow to the next stage.
Turbine technology

An ideal steam turbine is considered to be an isentropic process, or constant entropy process, in which the entropy of the steam entering the turbine is equal to the entropy of the steam leaving the turbine.

To maximize turbine efficiency the steam is expanded, generating work, in a number of stages. These stages are characterized by how the energy is extracted from them and are known as either impulse or reaction turbines. Most steam turbines use a mixture of the reaction and impulse designs. Typically, higher pressure sections are impulse type and lower pressure stages are reaction type.

An impulse turbine has fixed nozzles that orient the steam flow into high speed jets. These jets contain significant kinetic energy, which the rotor blades, shaped like buckets, convert into shaft rotation as the steam jet changes direction (constant cross section area type from blade inlet to exit). A pressure drop occurs across only the stationary blades, with a net increase in steam velocity across the stage.

In the reaction turbine, the rotor blades themselves are arranged to form convergent nozzles. This type of turbine makes use of the reaction force produced as the steam accelerates through the nozzles formed by the rotor. Steam is directed onto the rotor by the fixed vanes of the stator. It leaves the stator as a jet that fills the entire circumference of the rotor. The steam then changes direction and increases its speed relative to the speed of the blades. A pressure drop occurs across both the stator and the rotor (varying cross section area type from blade inlet to exit), with steam accelerating through the stator and decelerating through the rotor, with no (or small) net change in steam velocity across the stage but with a decrease in both pressure and temperature, reflecting the work performed in the driving of the rotor.
Turbine technology

• Applied thermodynamics [electronic resource] by Onhar Singh.

Generators

The turbine shaft is coupled to a generator which converts the rotary mechanical motion into the electrical energy that the plant is designed to provide. All utilise a coil of a conducting material, usually copper, moving in a magnetic field to generate electricity.
Generators

- The generators used in most power stations are designed to deliver an alternating current (AC) to a power grid.
  - It determines the speed at which the generator rotates. This must be an exact multiple of the grid frequency (normally grids operate at either 50 or 60 Hz). For grids operating at 50Hz the generator speed is 3000 rpm. The equivalent 60 Hz machine rotates at 3600 rpm.
  - This speed, in turn, determines the operating speed of the steam turbine. Large low-pressure steam turbines may operate at half these speeds.

- Generators may be as large as 2000MW, and large generators are normally built to suit a particular project.
  - Modern generators operate with an efficiency of greater than 95%.
  - The remaining 5% of the mechanical input energy from the turbine is usually lost as heat within the generator windings and magnetic components.
    - Even though the percentage is small, this still represents an enormous amount of energy; perhaps 50 MW in a 1000-MW machine. Hence generators require very efficient cooling systems in order to prevent them overheating. A variety of cooling mediums are used, including hydrogen which is extremely efficient because of its low density and high specific heat.

- The broad outline of generator design has changed little over a century.
  - However new materials have improved efficiencies. The latest developments involve the use of superconducting materials to reduce energy and increase efficiencies.
Environmental Impact of Coal Plants

• The combustion of coal to generate energy is an inherently dirty process
  – The combustion product is primarily carbon dioxide, one of the main greenhouse gases.
  – High-temperature combustion also produces NO\textsubscript{x}, both from nitrogen contained within the coal and from atmospheric nitrogen
  – All natural coals contain some sulphur, this emerges as sulphur dioxide, a potent chemical that is converted into acid in the atmosphere
  – Incombustible mineral material in the coal is left as ash and slag which must be disposed of harmlessly
  – And some mineral and particular material escapes with the flue gases into the atmosphere; this can contain trace metals such as mercury which are potentially harmful.
Coal Combustion Waste (CCW)

\[ C_x H_y + \left( x + \frac{y}{4} \right) O_2 + 3.76 \left( x + \frac{y}{4} \right) N_2 \rightarrow Heat + x CO_2 + \frac{y}{2} H_2 O + 3.76 \left( x + \frac{y}{4} \right) N_2 \]

Chemical coal structure

+ Sulphur
+ heavy metals (i.e. mercury)
+ incombustible matter

High temperature combustion

Unwanted dirt

CO\textsubscript{2}, NO\textsubscript{x}, 2SO\textsubscript{2} + O\textsubscript{2} = 2SO\textsubscript{3}, SO\textsubscript{3} + H\textsubscript{2}O = H\textsubscript{2}SO\textsubscript{4}, Hg
other metals, ash
Emissions control strategies – coal washing

Coal washing involves grinding the coal into smaller pieces and passing it through a process called gravity separation.

- Removing inorganic impurities

- Cleaning coal prior to combustion can significantly reduce the levels of sulphur emissions from a power plant as well as reducing the amount of ash and slag produced
  - This can have a beneficial effect on plant performance and maintenance schedules.
  - It has been estimated that boiler availability improves by 1% for every 1% reduction in ash content.
  - The main approach to physical coal cleaning has been outlined on the figure above.

- One disadvantage of coal cleaning is that it leads to a loss or between 2% and 15% of the coal with the coal waste. However it is possible to burn this coal waste in a fluidised-bed combustion (FBC) plant.
Emissions control strategies - $\text{NO}_x$  

- $\text{NO}_x$ are generated by a reaction between oxygen and nitrogen contained in air during combustion
  
  - This NOx production is strongly affected by two factors
    
    - the temperature at which the combustion takes place
    - the amount of oxygen available during combustion
  
  - Controlling these parameters provides a way of controlling the quantity of $\text{NO}_x$ generated.

- Simple design of a low $\text{NO}_x$ burner.
  
  - An initial combustion region for the pulverised-coal particles where the proportion of oxygen is kept low. When this happens, most of the available oxygen is captured as carbon dioxide during the coal combustion process, leaving little to react with nitrogen.
  
  - Some more air needed to burn the coal completely, it is being admitted to the combustion region after most of the combustion has been completed.

- The initial combustion zone is normally the hottest region in the furnace.

- As the combustion gases leave this zone they start to cool. At this stage, further air can be admitted
Emissions control strategies – NO\textsubscript{x} reduction

Low nitrogen oxide burners

It is not possible to reduce the nitrogen content of the fuel before combustion by physical cleaning since it is combined within the organic matter of the fuel. Instead, nitrogen oxides can be removed during combustion. Low nitrogen oxides burners ensure that the fuel is burnt in low oxygen concentrations, such that any nitrogen oxides produced are reduced to nitrogen gas. This staged combustion procedure (as it is commonly known) can reduce the level of NO\textsubscript{x} produced by 30–55%.

Once initial combustion has taken place, further air is added to the combustion chamber to ensure that the fuel is completely burnt. The air admitted at this stage in the furnace is called 'over-fire-air'. When used in conjunction with a low NO\textsubscript{x} burner, the use of over-fire-air can lead to a reduction in NO\textsubscript{x} levels of 40–60%. Such burners can be installed on either new or existing power plants.

Another strategy which can reduce the NO\textsubscript{x} level even further is called re-burning. More coal, or natural gas, is introduced into the combustion gases after they have left the combustion zone. The effect is to remove some of the oxides of nitrogen that have been formed. Overall reductions of up to 70% can be achieved.

Nitrogen oxides capture

Emissions of nitrogen oxides, can also be reduced by treating the smokestack gases.

One method involves mixing the flue gases with ammonia, converting the nitrogen oxides to nitrogen and water. This process (selective non-catalytic reduction) can be fitted to existing and new power plants, and can achieve an emissions reduction of up to 80 to 90%.
Emissions control strategies – NO\textsubscript{x} capture

Emissions of nitrogen oxides, can also be reduced by treating the smokestack gases. One method involves mixing the hot (between 870°C to 1200°C) flue gases with ammonia, converting the nitrogen oxides to nitrogen and water. This reaction will occur spontaneously and is called selective non-catalytic reduction (SNCR).

At lower temperatures a special metal catalyst is necessary to stimulate the reaction therefore the process is called selective catalytic reduction (SCR).

Typical flue gas temperatures are 340–380°C.

SNCR can be fitted to existing and new power plants, and can achieve an emissions reduction between 35% and 60% of the NO\textsubscript{x} from the flue gas stream.

SCR can be fitted to existing and new power plants, this method can remove up 70-90% of the NO\textsubscript{x} emissions.

However SCR can be fitted to power plants that use only low sulphur coals (less than 1.5% sulphur), even with low sulphur coal SCR can lead to the formation of sulphur trioxide which becomes highly corrosive on contact with water when it forms sulphuric acid.

SCR is also more expensive.

"SCR technology has been used commercially in Japan since 1980 and in Germany since 1986 on power stations burning mainly low-sulphur coal and in some cases medium-sulphur coal. There are now about 15 GWe of coal-fired SCR capacity in Japan and nearly 30 GWe in Germany, out of a total of about 53 GWe worldwide. During the 1990s SCR demonstration and full-scale systems have been installed in US coal-fired power plants burning high-sulphur coal. Their commercial use has followed the introduction of stringent limits to regulate NOx emissions in each country." IEA Clean Coal Centre, London
Emissions control strategies – sulphur dioxide removal

There is no strategy similar to low NO\textsubscript{x} burners that can be used to control the emission of sulphur dioxide. If sulphur is present in coal it will be converted into sulphur dioxide during combustion. The sulphur can be captured either before the coal is burnt using a coal-cleaning process, or after combustion using some chemical reagent inside the power plant.

There are many chemicals that are potentially capable of capturing sulphur dioxide from the flue gases of a power station but the cheapest to use are lime and limestone. Both are calcium compounds which will react with sulphur dioxide to produce calcium sulphate. If the latter can be made in a pure enough form it can be sold into the building industry for use in wallboards.

The cheapest method of capturing sulphur dioxide is to inject one of these sorbent materials into the flue gas stream as it exists the furnace. The reaction then takes place in the hot gas stream and the resultant particles of calcium sulphate, and of excess sorbent, are captured in a filter downstream of the injection point.

Depending on the point of injection of the sorbent, this method of sulphur removal can capture between 30% and 90% of the sulphur in the flue gas stream. The cheapest, and least effective method (30–60% capture efficiency) is to inject the sorbent directly above the furnace. Injection later in the flue gas stream is more expensive but can remove up to 90% of the sulphur.
Emissions control strategies – sulphur dioxide removal

The **Flue Gas Desulfurization (FGD)** unit comprises a specially constructed chamber through which the flue gas passes. A slurry of water containing 10% lime or limestone is sprayed into the flue gas where it reacts, capturing the sulphur dioxide. The slurry containing both gypsum and un-reacted lime or limestone is then collected at the bottom of the chamber and recycled. Typical wet scrubbing systems can capture up to 97% of the sulphur within the flue gas. With special additives, this can be raised to 99% in some cases. Wet scrubbers can easily be fitted to existing power plants, provided the space is available. Wet scrubbing technology is technically very complex.

The reaction taking place in wet scrubbing using a (limestone) slurry produces (calcium sulfite) and can be expressed as:

\[
\text{CaCO}_3 \text{ (solid)} + \text{SO}_2 \text{ (gas)} \rightarrow \text{CaSO}_3 \text{ (solid)} + \text{CO}_2 \text{ (gas)}
\]

When wet scrubbing with a Ca(OH)\(_2\) (lime) slurry, the reaction also produces CaSO\(_3\) (calcium sulfite) and can be expressed as:

\[
\text{Ca(OH)}_2 \text{ (solid)} + \text{SO}_2 \text{ (gas)} \rightarrow \text{CaSO}_3 \text{ (solid)} + \text{H}_2\text{O} \text{ (liquid)}
\]

When wet scrubbing with a Mg(OH)\(_2\) (magnesium hydroxide) slurry, the reaction produces MgSO\(_3\) (magnesium sulfite) and can be expressed as:

\[
\text{Mg(OH)}_2 \text{ (solid)} + \text{SO}_2 \text{ (gas)} \rightarrow \text{MgSO}_3 \text{ (solid)} + \text{H}_2\text{O} \text{ (liquid)}
\]

To partially offset the cost of the FGD installation, in some designs, the CaSO\(_3\) (calcium sulfite) is further oxidized to produce marketable CaSO\(_4\) · 2H\(_2\)O (gypsum). This technique is also known as forced oxidation:

\[
\text{CaSO}_3 \text{ (solid)} + \text{H}_2\text{O} \text{ (liquid)} + \frac{1}{2}\text{O}_2 \text{ (gas)} \rightarrow \text{CaSO}_4 \text{ (solid)} + \text{H}_2\text{O}
\]
Emissions control strategies – particulate removal

There are two principal systems for removing particulates from the flue gas of a coal-fired power station, **electrostatic precipitators (ESPs)** and fabric (baghouse) filters.

**Electrostatic Precipitation**

It utilises a system of plates and wires to apply a large voltage across the flue gas as it passes through the precipitator chamber. This causes an electrostatic charge to build up on the solid particles in the flue gas; as a result they are attracted to the oppositely charged plates of the ESP where they collect. Rapping the plates caused the deposits to fall to the bottom of the ESP where they are collected and removed. A new ESP will remove between 99.0% and 99.7% of the particulates from flue gas.

**Bag Filters**

Bag filters, or baghouses, are tube-shaped filter bags through which the flue gas passes. Particles in the gas stream are trapped in the fabric of the bags from which they are removed using one of a variety of bag-cleaning procedures. These filters can be extremely effective, removing over 99% of particulate material.

They are generally less cost effective than ESPs for collection efficiencies up to 99.5%. Above this, they are more cost effective.
Emissions control strategies – Carbon dioxide

There are a number of methods of carbon dioxide capture under development. These can be broadly classified under chemical absorption, physical absorption and membrane separation.

Chemical absorption involves using a chemical to capture and bind carbon dioxide. This chemical is then transferred to a processing plant where it treated to remove the carbon dioxide which is captured and stored. The chemical agent is then recycled through the power plant.

Physical absorption involves absorbing the carbon dioxide within a solid compound which is placed in its path in the flue gas stream. The solid is then treated, usually at low pressure, to remove the carbon dioxide, which is stored.

Membrane separation involves exploiting the properties of a special membrane which will allow carbon dioxide to pass through it but will not pass oxygen or nitrogen.

Storage of CO₂ is a greater technical challenge than the capture of it!!

1. One use is for enhanced oil recovery. This involves pumping carbon dioxide into oil reservoirs under pressure to force out additional oil.
2. Stored in underground caverns
3. Stored in saline aquifer or at the bottom of the oceans under extreme pressure (solid state).
Reduction of Carbon dioxide

Subcritical 500MW
Eff = 34.3%

Ultra Supercritical 500MW
Eff = 43.4%

Ref: “The future of Coal” – An Interdisciplinary MIT Study - 2007
Reduction of Carbon dioxide

Ref: “The future of Coal” – An Interdisciplinary MIT Study - 2007
Advanced coal burning power plant technology

The traditional coal-fired power plant suffers two primary drawbacks:

- The overall efficiency is limited
- It is a major source of pollution

There are strategies that can be applied to the traditional plant to dramatically reduce the levels of pollution produced. However, there is little that can be done to increase its efficiency apart from raising the steam pressure and temperature. This requires expensive materials and may not be cost effective in the near future.

The most important technologies available for coal power plants are:

- Fluidised Bed Combustion (FBC)
- Integrated Gasification Combined Cycle (IGCC).
Fluidised Bed Combustion power plant

• If a layer of sand, of finely ground coal, or of another fine solid material is placed in a container and high-pressure air is blown through it from below, the particles, provided they are small enough, become entrained in the air and form a floating, or fluidised, bed of solid particles above the bottom of the container. This bed behaves like a fluid in which the constituent particles constantly move to and from and collide with one another. As a type of reactor, this offers some significant advantages.
  – The fluidised bed was used first in the process industries to enhance the efficiency of chemical reactions between solids by simulating conditions of a liquid-phase reaction.
  – Only later was its application for power generation recognised. Its use is now widespread, and the fluidised bed can burn a variety of coals as well as other poorer fuels such as coal-cleaning waste, petroleum coke, wood and other biomass.

• A fluidised bed used for power generation contains only around 5% coal or fuel. The remainder of the bed is primarily an inert material such as ash or sand.

• The temperature in a fluidised bed is around 950°C, significantly lower than the temperature in the heart of a pulverised-coal boiler.

• This low temperature helps minimise the production of NOx.

• A reactant such as limestone can also be added to the bed to capture sulphur, reducing the amount of sulphur dioxide released into the exhaust gas.

• One further advantage of the fluidised bed is that boiler pipes can be immersed in the bed itself, allowing extremely efficient heat capture (but also exposing the pipes to potentially high levels of erosion).
Fluidised Bed Combustion power plant

- Coal
- Limestone
- Atmospheric circulating fluidized-bed boiler
- Cyclone
- Combustion chamber partition
- Secondary air
- Air
- Ash
- Steam
- Fabric filter
- Fly ash
- Stack
- To boiler feedwater
- Generator
- Solid waste to disposal
- Steam turbine
Fluidised Bed Combustion power plant

- There are several designs for fluidised-bed power plants.
- The simplest is called a bubbling-bed plant. This, and a second, more complex plant called a circulating fluidised bed can both operate at atmospheric pressure.
- The circulating bed can remove 90–95% of the sulphur from the coal while the bubbling bed can achieve between 70% and 90% removal. Maximum energy conversion efficiency is 43%, similar to that of a traditional pulverised coal plant.
- However such high efficiencies can only be achieved with larger plants that can employ larger, and generally more efficient, steam turbines under optimum steam conditions.
- A third type of fluidised-bed design, called the pressurised fluidised bed, was developed in the late 1980s and the first demonstration plants employing this technology were constructed in the mid-1990s. The pressurised bed is like a bubbling bed, but operated at a pressure of between 5 and 20 bar (1 bar is equivalent to atmospheric pressure).
- Operating the plant under pressure allows some additional energy to be captured by venting the exhaust gases through a gas turbine. This provides a higher efficiency (currently up to around 45–46%) while maintaining the good emission performance of the atmospheric pressure fluidised bed. The largest pressurised fluidised-bed plant in operation is a 360 MW unit in Japan.
- Atmospheric fluidised-bed power plants with boiler capacities of over 400MW are commercially available. These can provide supercritical steam to gain the best efficiency. The technology is still under active development, with the prospect of more efficient capture of pollutants coupled with an efficiency of around 50% within the next 10–15 years.
- A standard fluidised-bed power plant can meet the emission-control requirements in many regions of the world without further emission-control measures. However in regions with the most stringent regulations capture technologies are required. These are likely to include NO\textsubscript{x}, sulphur oxides (SO\textsubscript{x}) and particulate capture measures. The techniques employed to provide additional emission control are the same as those used in a conventional coal-fired power station.
Integrated Gasification Combined Cycle power plant

- The second type of advanced coal-burning plant, the IGCC plant, is based around the gasification of coal.
  - Coal gasification is an old technology. It was widely used to produce town gas for industrial and domestic use in the USA and Europe until natural gas became readily available. Modern gasifiers convert coal into a mixture of hydrogen and carbon monoxide, both of which are combustible.
  - Gasification normally takes place by heating the coal with a mixture of steam and oxygen (or, in some cases, air). This can be carried out in a fixed bed, a fluidised bed or an entrained flow gasifier.

- The process that takes place in the gasifier is a partial combustion of the coal. Consequently it generates a considerable amount of heat. This heat can be used to generate steam to drive a steam turbine. The gas produced, meanwhile, is cleaned and can be burned in a gas turbine to produce further electricity. Heat from the exhaust of the gas turbine is used to raise additional steam for power generation. This is the basis of the IGCC plant.
  - An IGCC power plant can achieve an efficiency of 45%. In addition it can remove 99% of the sulphur from the coal and reduce the emissions of NOx to below 50 ppm.
  - Several demonstration projects were built in the mid- and late 1990s, with unit sizes up to around 110MW.
  - The technology has yet to make an impact in the main power generation market. Further development is required to enable gasification to realise its full potential. This will include effective technologies for cleaning the hot exhaust gas before it enters the gas turbine stage of the IGCC plant. Hot gas cleanup will allow an IGCC plant to operate at optimum efficiency.

- Another area that could prove attractive is underground gasification. This involves the controlled burning of coal in the seams underground where it is found. Air is injected through a borehole into the seam and the gasification product is extracted from a second borehole. Underground gasification avoids many of the pollution problems associated with coal combustion while requiring little advanced technology. However the technique is nowhere near commercial application.
Integrated Gasification Combined Cycle power plant
Environmental effects of coal combustion

Global Trends in Major Greenhouse Gases to 1/2003

Global trends in major long-lived greenhouse gases through the year 2002. These five gases account for about 97% of the direct climate forcing by long-lived greenhouse gas increases since 1750. The remaining 3% is contributed by an assortment of 10 minor halogen gases, mainly HCFC-22, CFC-113 and CCl₄.

Environmental effects of coal combustion

Emissions from coal plants
- CO$_2$ 73%
- NO$_x$ 80%
- SO$_x$ 93%
- Radioactive elements (5884 tones U-235, 2mil tones Th)
- Heavy Ions

## Environmental effects of coal combustion

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<th>Year</th>
<th>OECD (U.S.)</th>
<th>Non-OECD</th>
<th>Total</th>
<th>OECD (U.S.)</th>
<th>Non-OECD</th>
<th>Total</th>
<th>Total Emissions (Billion Metric Tons CO₂)</th>
<th>Emissions from Coal (Billion Metric Tons CO₂)</th>
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<td>5.06 (2.59)</td>
<td>9.76</td>
<td>14.8</td>
<td>40</td>
<td></td>
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<tr>
<td>2025</td>
<td>16.5 (7.59)</td>
<td>23.5</td>
<td>40.0</td>
<td>5.42 (2.89)</td>
<td>10.9</td>
<td>16.3</td>
<td>41</td>
<td></td>
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<tr>
<td>2030</td>
<td>17.5 (8.12)</td>
<td>26.2</td>
<td>43.7</td>
<td>5.87 (3.23)</td>
<td>12.2</td>
<td>18.1</td>
<td>41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison of different technologies


- Coal plant
  - Pulverised fuel (PF) steam plant;
  - Circulating fluidized-bed combustion (CFBC) plant;
  - Integrated gasification combined-cycle (IGCC) plant;
- Gas plant
  - Open-cycle gas turbine (OCGT) plant;
  - Combined-cycle gas turbine (CCGT) plant;
- Nuclear fission plant.
- Biomass (poultry litter)
  - Bubbling fluidized-bed combustion (BFBC) plant;
- Wind turbines
  - Onshore
  - Offshore
- Wave and Marine
Cost of generating electricity

Effect of carbon dioxide emission costs (zero to £30 per tonne)
Prices for electricity

**Strike prices for new renewable energy projects in 2016-18**
Price per megawatt hour the government has guaranteed for electricity*

<table>
<thead>
<tr>
<th>Technology</th>
<th>Price (£/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore wind</td>
<td>125</td>
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<tr>
<td>Advanced conversion technologies (waste)</td>
<td>110</td>
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<tr>
<td>Hinkley Point nuclear</td>
<td>100</td>
</tr>
<tr>
<td>Onshore wind</td>
<td>75</td>
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<tr>
<td>Large solar</td>
<td>50</td>
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<tr>
<td>Current wholesale price</td>
<td>25</td>
</tr>
</tbody>
</table>

*Prices represent the average price per MWh agreed by the Department for Energy and Climate Change for projects commissioned for 2016/17 and 2017/18 during round one of CFD auctions in February 2016.

Source: DECC, Ofgem