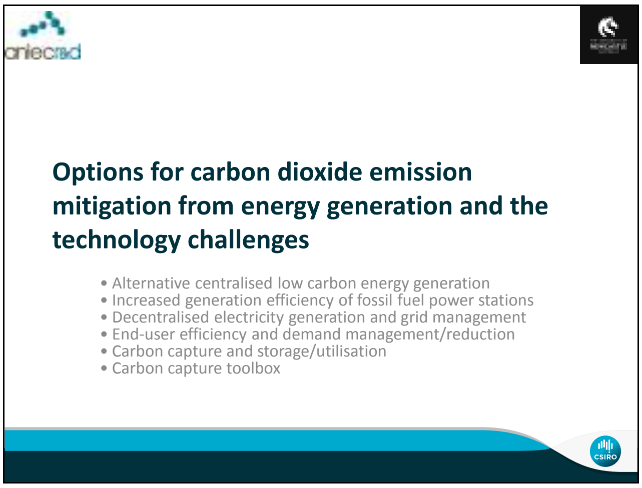
Options for CO_2 emission mitigation from energy generation and the technology challenges



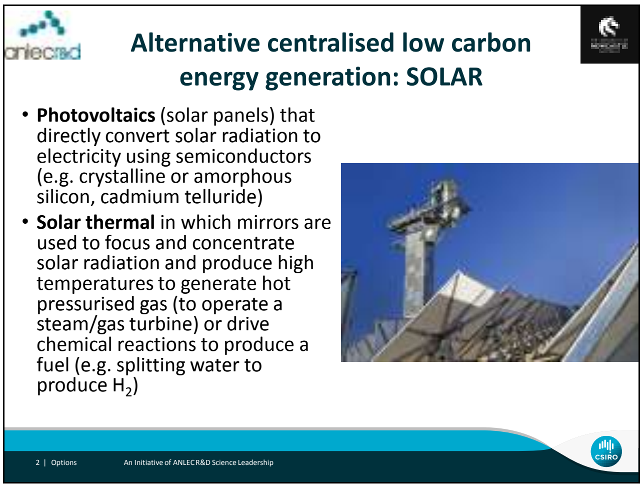
There are a whole host of ways that the CO_2 emissions from energy generation can be reduced. In terms of large scale centralised electricity generation there are renewable energy options like solar, wind and hot rocks. You can also improve the efficiency of fossil fuel power stations by using gas instead of coal or increased steam temperatures.

But, are large power plants often hundreds of kilometres from where the electricity is used the best way to do it? What about decentralised electricity generation where each household or community generates its own electricity and shares any extra with its neighbours?

And of course there is the question of demand. The fastest way to reduce CO_2 emissions is to use less electricity. This means finding ways to improve the efficiency of electricity use and intelligent methods to manage demand.

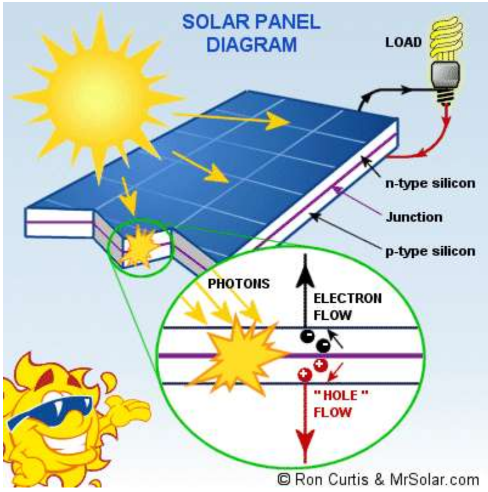
There will be no single solution to reducing CO_2 emissions, and large scale fossil fuel based power stations are here to stay for some time yet. That means we need to do something about their emissions, and this is why carbon capture and storage (CCS) is important. But CCS incorporates a number of technology options, and we need to consider the pros and cons of each to match the best CCS technology to the different types of fossil fuel power station (coal, oil, gas, …).

Alternative centralised low carbon energy generation: SOLAR



Photovoltaics

There are two flavours of solar electricity. The most common are photovoltaics. These are the typical solar panels you see on house roofs, but for centralised electricity generation they are arranged into large arrays called solar farms. They convert solar radiation to electricity by the photovoltaic effect. A p-n junction semiconductor (e.g. silicon or cadmium telluride) is attached between two electrodes. When photons strike the semiconductor electrons become excited and flow between the electrodes.

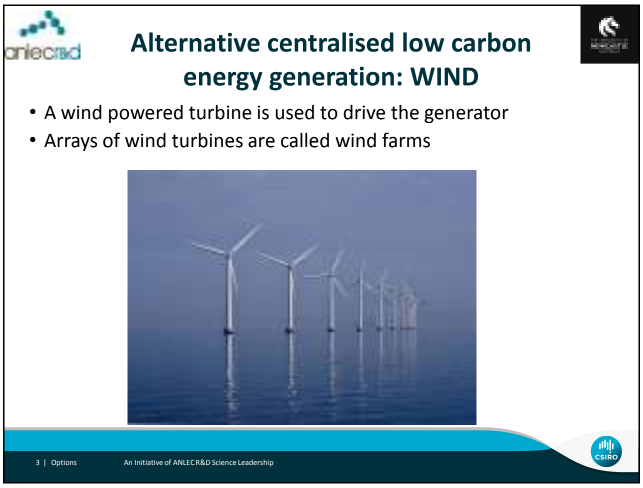


Solar thermal

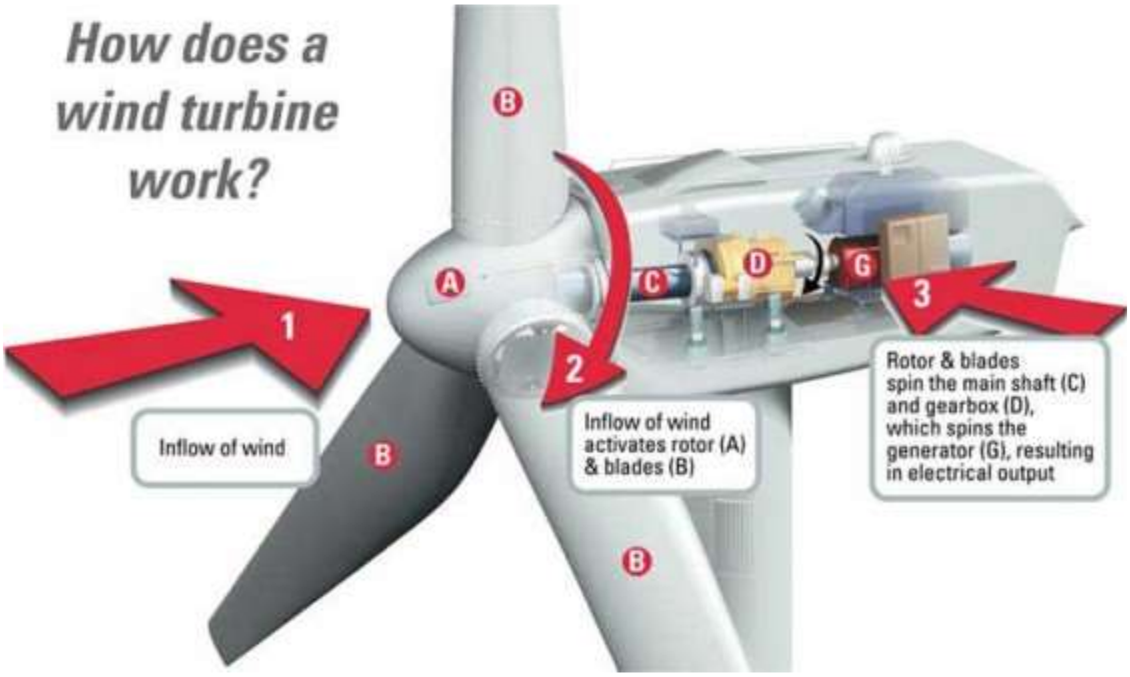
Solar thermal is more straightforward. Mirrors are used to focus and concentrate solar radiation to produce heat. That heat is used either to produce steam and drive a turbine, or produce hot gas to drive a turbine. The heat might also be used in a chemical process to convert water or methane into hydrogen, which can then be combusted in a turbine.

The PS20 20 MW solar thermal power ststaion in Spain.

Alternative centralised low carbon energy generation: WIND

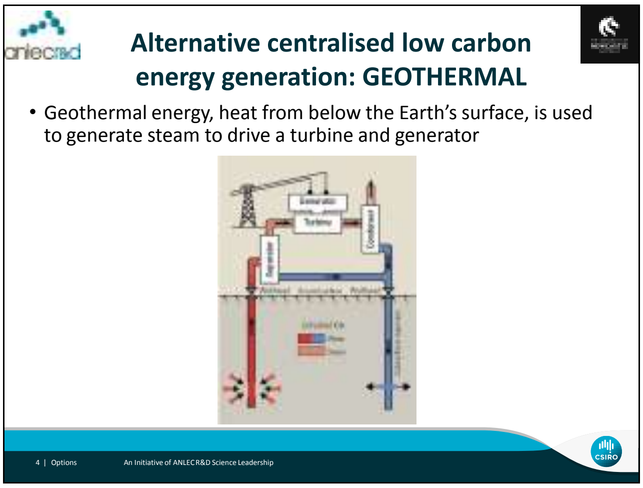


The use of wind to turn a turbine dates back centuries in the form of windmills. Originally the rotation was used to mill grain. In modern wind turbines the rotation turns the axle of a generator to produce electricity. Centralised electricity generation using wind turbines is achieved by having many turbines arranged in a wind farm.



Currently (as of 2012) the largest wind farm in the world, the Alta Wind Energy Centre, is in California. It has an installed capacity of 1020 MW from 390 turbines. But it is Denmark that generates the largest proportion of its electricity using wind – 26% in 2011.

Alternative centralised low carbon energy generation: GEOTHERMAL

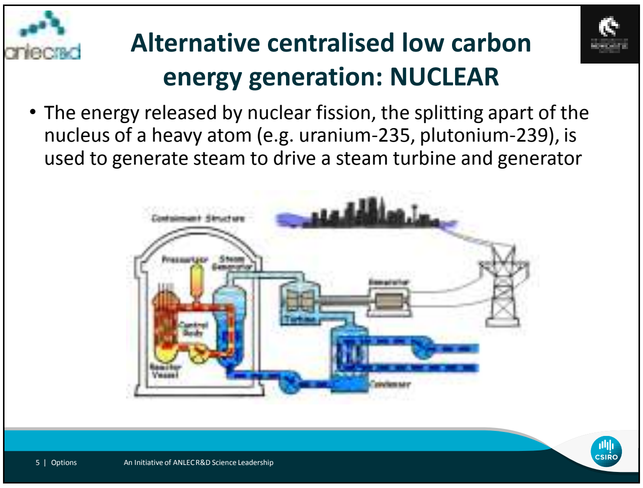


Geothermal electricity generation relies on "hot rocks" under the earth's surface. Radioactive decay occurring in the earth's core produces heat and this heat moves to the earth's surface. At depths of several kilometres or more temperatures are high enough to generate steam for electricity generation. In some places with particular types of geology such as Iceland, there is geothermal activity close to the surface. These locations are the most attractive for geothermal power as bores need only be drilled to shallow depths.

The Nesjavellir Geothermal Power Station near Reykjavik in Iceland.

Steam is produced either by drilling bores in locations where water is already present, or by pumping water down into the hot subsurface to produce steam. The steam is returned to the surface to drive a steam turbine, condensed, and then pumped back underground.

Alternative centralised low carbon energy generation: NUCLEAR



Recently nuclear power has fallen out of favour due to heighten safety concerns from recent accidents and issues around waste disposal. But it is still a low CO_2 emission source of power that is used extensively, providing about 15% of electricity globally.

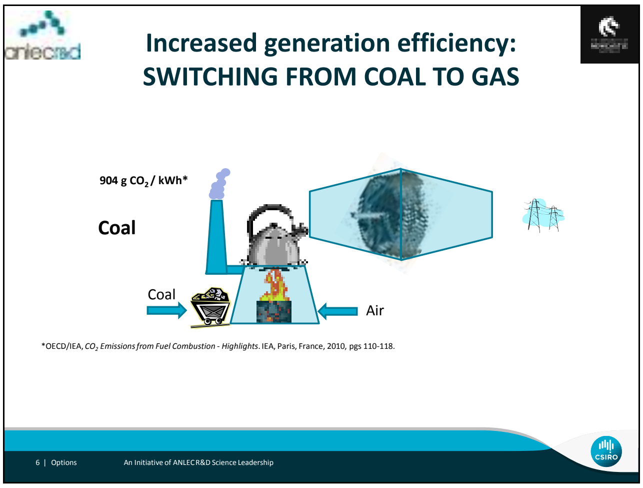
In a nuclear power station steam from heating water is used to drive a turbine in the same way as a typical fossil fuel power station. The difference is the heat is produced by nuclear reactions rather than combustion. When some atoms are hit by a neutron ($^{1}_{0}n$) they split or undergo fission and large amounts of energy are released. Typically the isotopes uranium-235 ($^{235}_{92}U$) and plutonium-239 are used as the fuel for nuclear power reactors. A neutron source such as californium-252 is also required to start the nuclear reaction.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{142}_{58}Ba + ^{91}_{38}Kr + 3^{1}_{0}n + energy$$

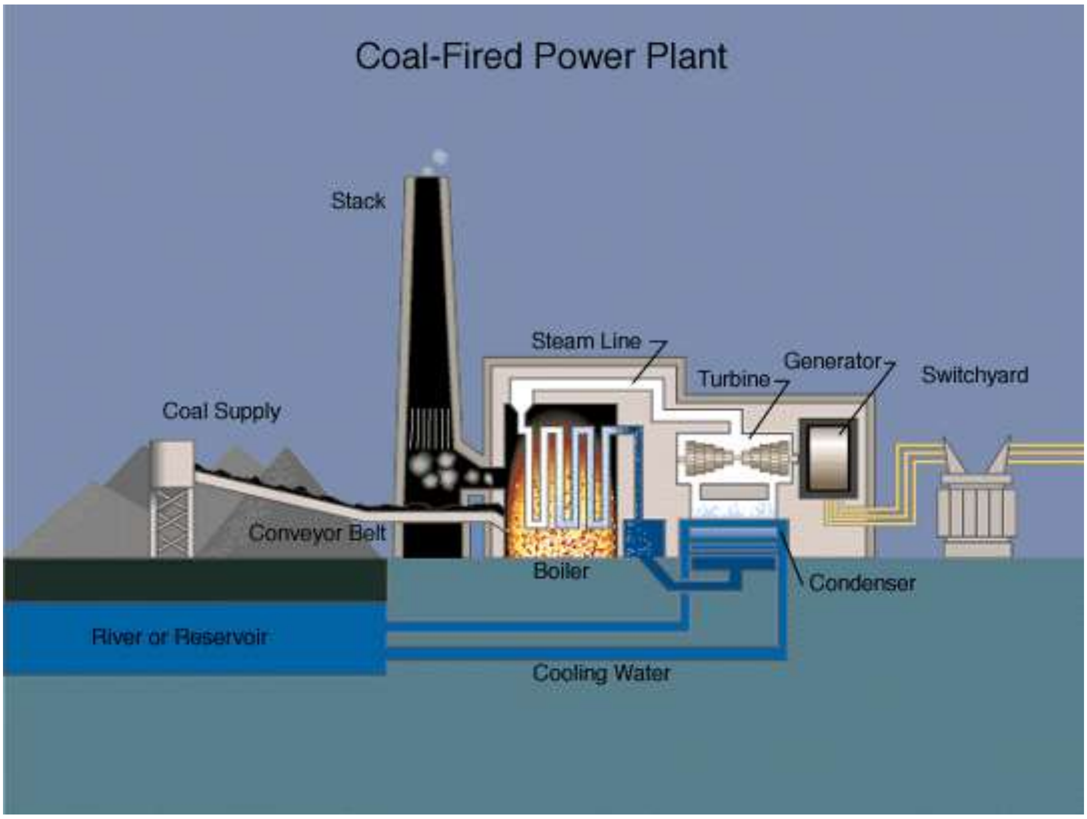
In the above reaction fission also produces more neutrons which in turn results in more fission. This is a nuclear chain reaction, which occurs when a critical mass of nuclear fuel is present. Because of this chain reaction some of the neutrons produced must be absorbed or slowed down to avoid a runaway reaction, otherwise known as a nuclear bomb!

The atoms resulting from fission are still radioactive, which is why disposal of used nuclear fuel is a challenge.

Increased generation efficiency: SWITCHING FROM COAL TO GAS

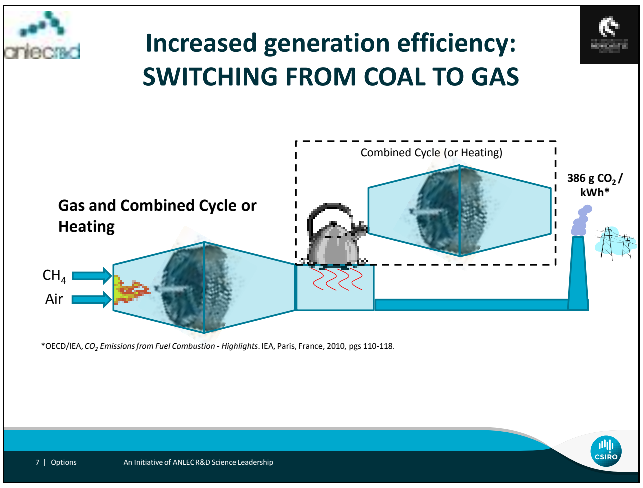


A typical black coal fired power station emits 904 g of CO_2 per kWh of electricity produced. This is because considerable energy is wasted via the process of heating water to produce steam followed by condensation of the vapour after it has passed through the turbines. The coal combustion is only indirectly driving the turbine.



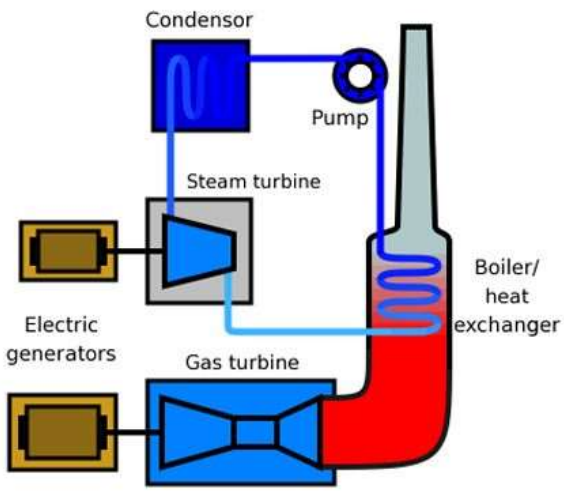
A coal fired power station.

Increased generation efficiency: SWITCHING FROM COAL TO GAS



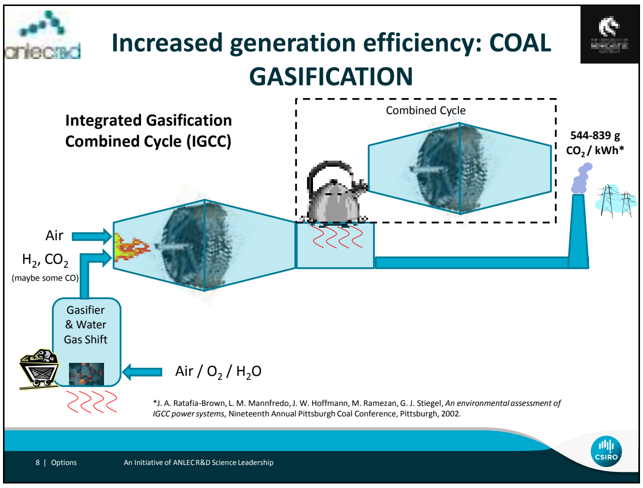
Alternatively using a gas turbine fuelled by methane results in emissions of 386 g CO_2 per kWh of electricity. The major reasons are the combustion gases can directly drive a turbine and the turbine exhaust gases are hot enough to produce steam. This steam can then be used to produce electricity using a steam turbine or for other heating, such as peoples' homes. It is this direct use of the combustion gases use of the waste heat from the gas turbine that makes the process more efficient. If a gas turbine is combined with a steam turbine it is called a combined cycle power station. If a gas turbine is combined with heating it is called a combined heat and power station.

Gas turbines have other advantages too. They can be more easily turned up or down to match production of electricity with demand.



A combined cycle gas power station.

Increased generation efficiency: SWITCHING FROM COAL TO GAS

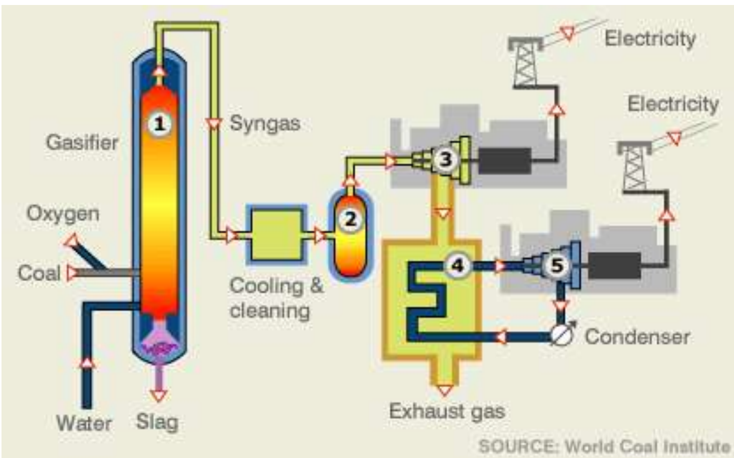


As we saw already electricity can be generated more energy efficiently using a gas turbine. But what if you want to use coal with a gas turbine? This is possible via the process of coal gasification. If coal is heated in the presence of steam and a restricted oxygen supply the coal is oxidised and hydrogen is formed:

$$3C\ (coal) + O_2 + H_2O \xrightarrow{heat} H_2 + 3CO$$

Syngas, the mixture of H_2 and CO, can be used as a fuel directly. Alternatively the H_2 content of syngas can be increased using the water gas shift reaction:

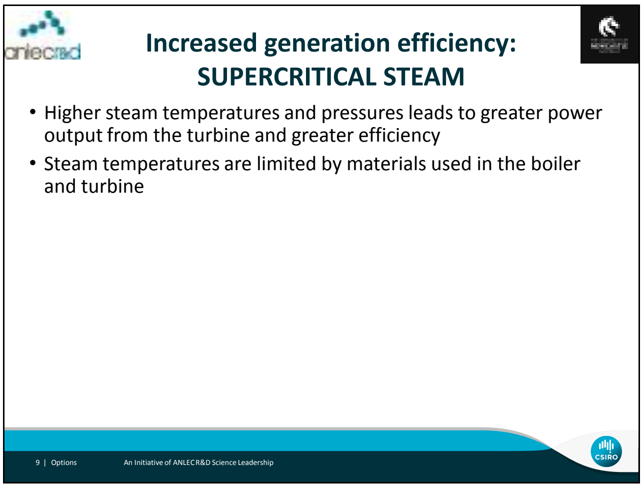
$$CO + H_2O \xrightarrow{heat} H_2 + CO_2$$



An integrated gasification combined cycle (IGCC) power station.

Gas turbines using syngas are commercially available, but turbines able to use pure H_2 are still being developed. Once the gasification process is complete the electricity and heat generation process is the same as that seen previously for a gas turbine.

Increased generation efficiency: SUPERCRITICAL STEAM

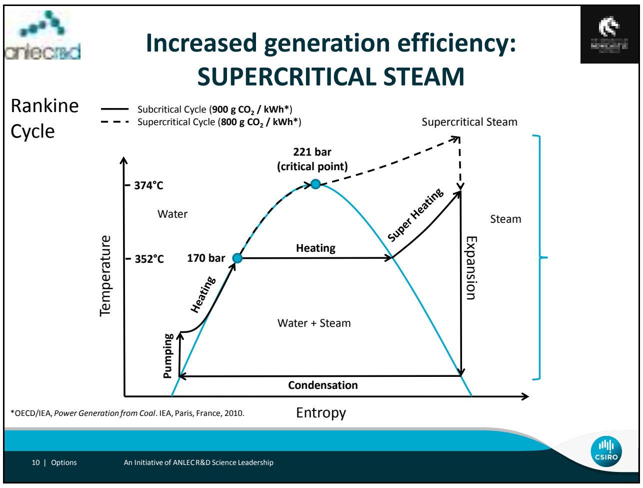


The efficiency of a coal fired power station can be increased by increasing the temperature of the steam used to drive the turbines. The higher the steam temperature, the greater the amount of energy that can be extracted from it during expansion.

The steam temperature in a power station is limited by the materials used in the boiler and turbine. In the past it was necessary to keep the steam temperature and pressure below the critical point. This is called a subcritical steam power station. Above the critical point the steam becomes super critical and is an excellent solvent.

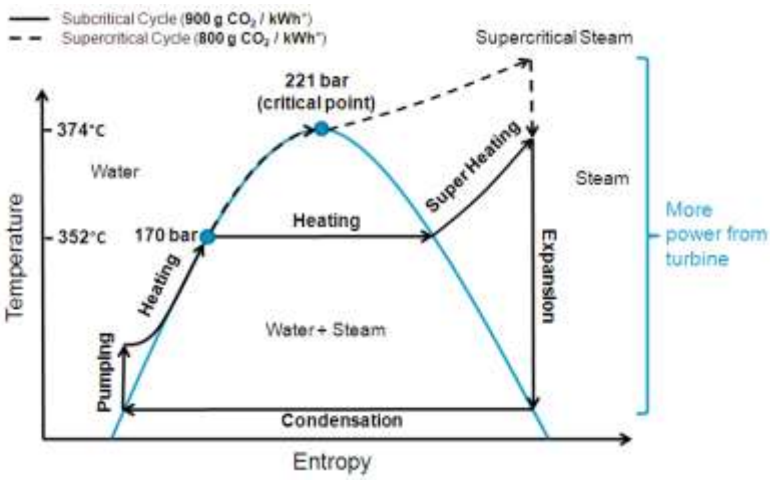
Modern materials mean it is now possible to operate at supercritical steam temperature and pressure. These are supercritical steam power stations and they are about 11% more efficient in terms of CO_2 emissions per kWh of electricity.

Increased generation efficiency: SUPERCRITICAL STEAM



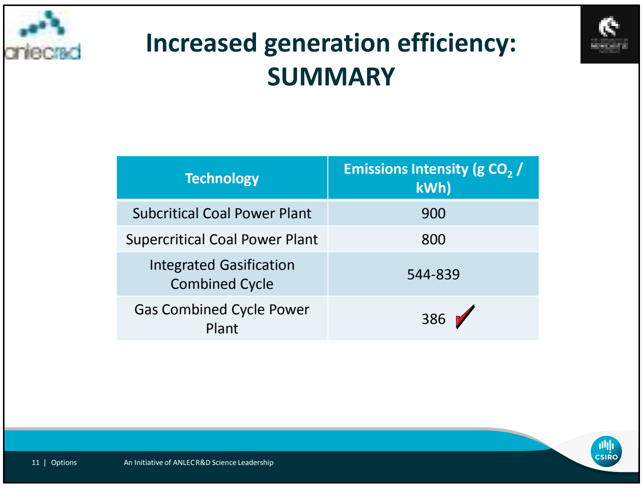
This temperature-entropy diagram shows the subcritical and supercritical steam cycles. The area under the blue curve is where both water and steam are present, to the left is water only and to the right steam. Above the critical point only the single supercritical phase is present.

Following the arrows for the subcritical cycle and starting at the bottom left: 1) water is heated by pumping; 2) further heating is then done in the boiler to 352°C and 170 bar; 3) heating is continued from this point at constant temperature (the heat energy goes into vaporisation); 4) the steam produced leaves the boiler and is superheated to ensure there are no water droplets; 5) the steam is expanded through the turbine, condensed and returned to 1.



The only difference for the supercritical cycle is that the heating in the boiler with increasing temperature and pressure is continued to the critical point.

Increased generation efficiency: SUMMARY

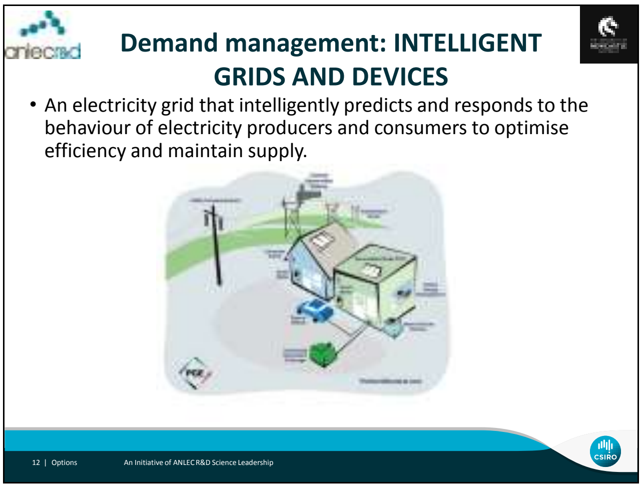


In terms of the CO_2 emissions intensity of fossil fuel electricity generation the clear winner is a combined cycle gas power station at 386 g CO_2 per kWh of electricity. Next is a combined cycle coal gasification plant followed by supercritical and subcritical steam coal fired power stations.

You might be wondering why oil doesn't feature here? Oil is not really used for large scale electricity generation. It is typically only used to generate electricity in isolated areas that are not grid connected. Furthermore, areas that are not grid connected are becoming less common meaning oil will disappear as a fuel for electricity generation in the near future.

Technology	Emissions Intensity (g CO_2 / kWh)
Subcritical Coal Power Plant	900
Supercritical Coal Power Plant	800
Integrated Gasification Combined Cycle	544-839
Gas Combined Cycle Power Plant	386 ✓

Demand management/reduction: INTELLIGENT GRIDS AND DEVICES

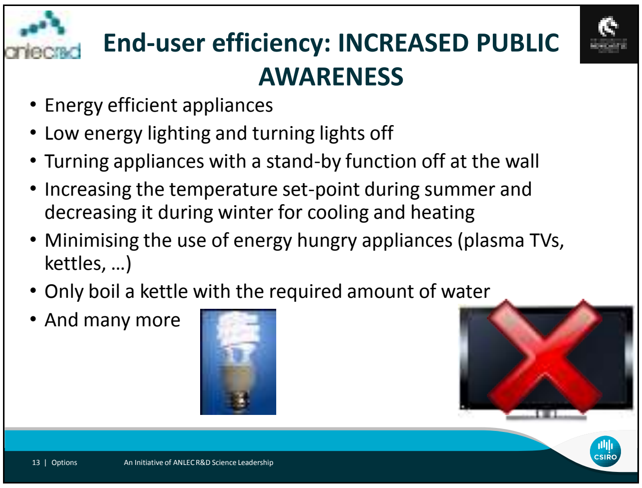


Electricity demand goes through peaks and troughs during the day and night and depending on the weather conditions. Power stations attempt to match their electricity production to demand, but this is difficult particularly for coal fired power stations which are slow to respond. Because of this there is often an excess of electricity produced to ensure enough is available for the next peak. Also as renewable electricity generation is introduced electricity supply is likely to fluctuate from location to location depending upon how sunny/windy it is.

This is where an intelligent electricity grid and intelligent devices come in. To reduce the peaks and troughs the devices in the grid measure supply and demand, and communicate with appliances such as air conditioners and refrigerators. These devices turn on/off in response to supply and demand to maintain a balanced electricity load across the grid. Sophisticated algorithms are used to control the devices in such a way that consumers don't see any significant loss in performance.

Price of electricity and electricity demand profiles for NSW during a week in April 2012.

End-user efficiency: INCREASED PUBLIC AWARENESS



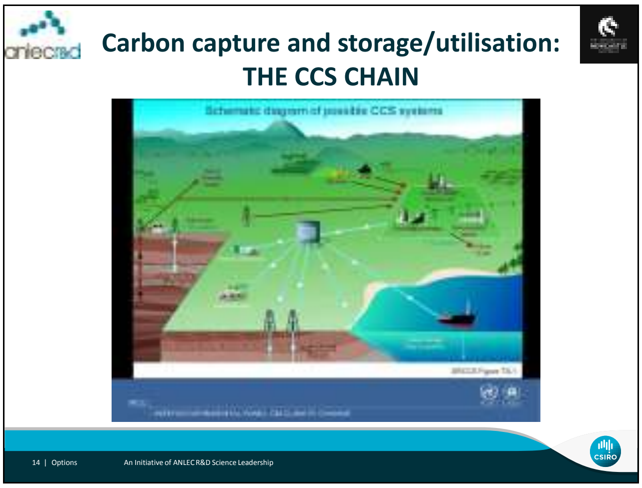
An important and conceptually easy way to reduce electricity demand is to educate the general public about how to use electrical devices efficiently. This sounds easy but any social scientist will tell you that changing habitual behaviour is difficult.

In terms of buying devices energy rating stickers allow users to see how energy efficient they are. A lot of people don't realise for example that plasma TV's consume more electricity than old CRT technology.

In terms of behaviour there are a lot of habits people can get into that can significantly reduce electricity demand:

- Turn off lights when you leave a room
- Turn appliances off at the wall when not in use
- Only cool/heat rooms you are using
- Get used to being a little cooler/warmer and set the temperature accordingly (a degree or two makes a big difference in energy consumption)
- Only wash with a full load of clothes
- Only boil enough water in the kettle for what you are using
- And many more …

Carbon capture and storage/utilisation: THE CCS CHAIN



CAPTURE → TRANSPORT → STORAGE/UTILISATION

Capture

The first step in carbon capture and storage (CCS) is capture. This step involves separating CO_2 from other gases to produce captured pure CO_2. Typically this is done at an emissions point source (e.g. a power station), because as we have seen, it is more efficient to capture CO_2 when it is concentrated. But, CO_2 capture from air is also an option.

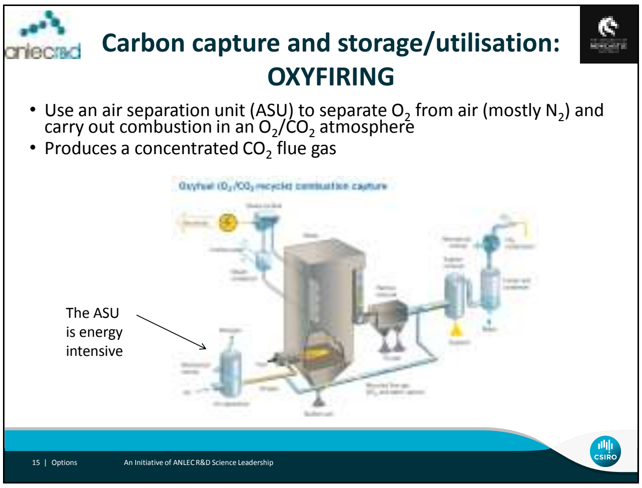
Transport

Once CO_2 has been captured we need to get it to the place where it will be stored or used. This is often some distance away. To transport CO_2 it is compressed until it becomes a liquid or supercritical gas (~130-150 bar). Once compressed is has the density of a liquid (the volume is reduced about ~400x) and it can be easily pumped through pipelines. In the US there are thousands of kilometres of CO_2 pipelines that have been used for enhanced oil recovery (pumping CO_2 into oil reservoirs to force more oil out) for decades.

Storage/Utilisation

The majority of CO_2 captured using CCS will end up stored by pumping into either deep saline aquifers of depleted gas reservoirs. Deep saline aquifers are at depths of 800 m or greater and are regions of porous rock impregnated with saline water. Suitable aquifers have an impermeable cap rock, and when pumped into the aquifer CO_2 dissolves forming a dense liquid that migrates downward.

Carbon capture and storage/utilisation: OXYFIRING



Oxyfiring is also called denitrogenation. It is where in a step prior to combustion, oxygen is separated from air. This is done in an air separation unit which typically uses cryogenic distillation to separate O_2 from air. The O_2 is then combined with CO_2 and combustion is carried out in an O_2/CO_2 atmosphere. This results in a flue gas that is mostly CO_2 eliminating the post combustion separation step.

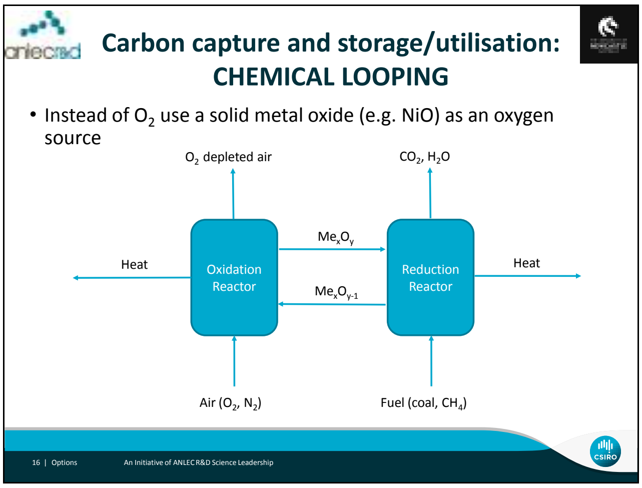
While the CO_2 separation step is eliminated, the air separation unit requires a large amount of energy. It relies on cooling air to below its boiling point and then raising the temperature to distil off O_2. Also post combustion gas clean-up is still required to remove any SO_x, particulates, water and other contaminants prior to CO_2 compression and transport.

The Callide A power station in Queensland.

In Queensland this oxyfiring process is being demonstrated at the Callide A power station: http://www.callideoxyfuel.com/

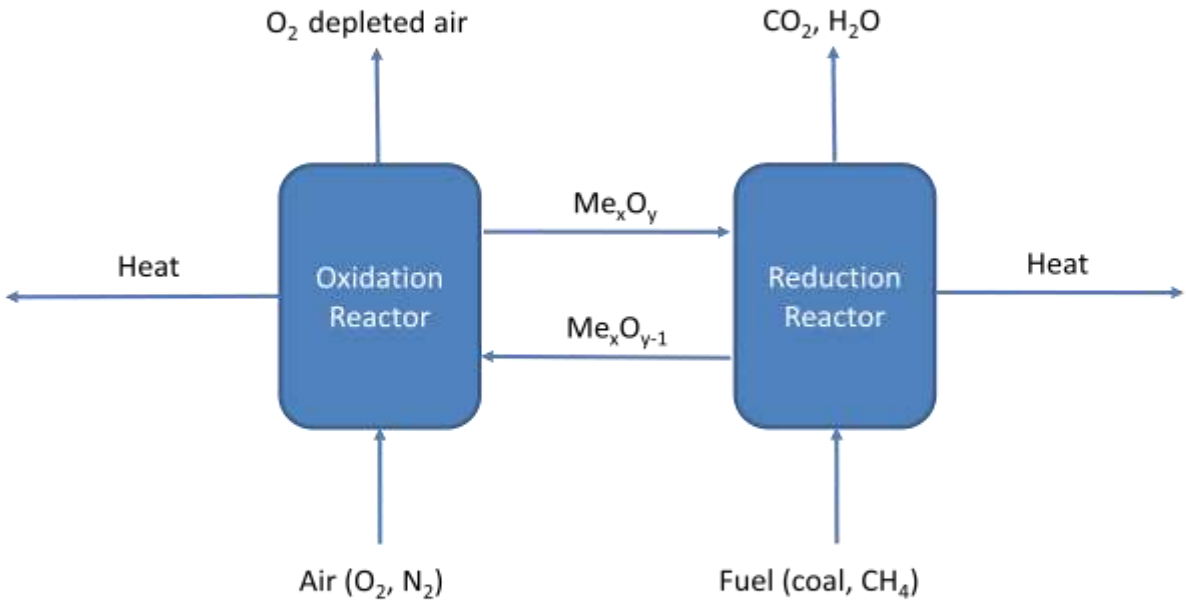
This is a 30 megawatt demonstration and includes CO_2 compression, transport and storage.

Carbon capture and storage/utilisation: CHEMICAL LOOPING



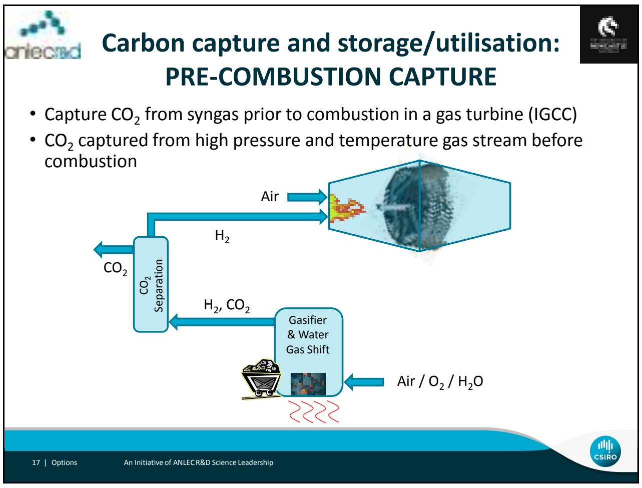
Chemical looping is a combustion process where an oxidant other than O_2 is used for the combustion process. Typically the oxidant is a metal oxide such as NiO. In a reduction reactor the solid metal oxide is contacted with a fuel such as coal or methane. The combustion process produces heat which is used for electricity generation. The flue gas consists only of CO_2 and water. The water can be easily separated and the CO_2 compressed for transport and storage. The reduced metal oxide then goes to an oxidation reactor where, upon exposure to O_2 it is oxidised ready for reuse. Oxidation also produces useful heat.

This technology is still at the research stage. With a number of challenges around the kinetics, and degradation of metal oxide still being addressed.



The chemical looping process.

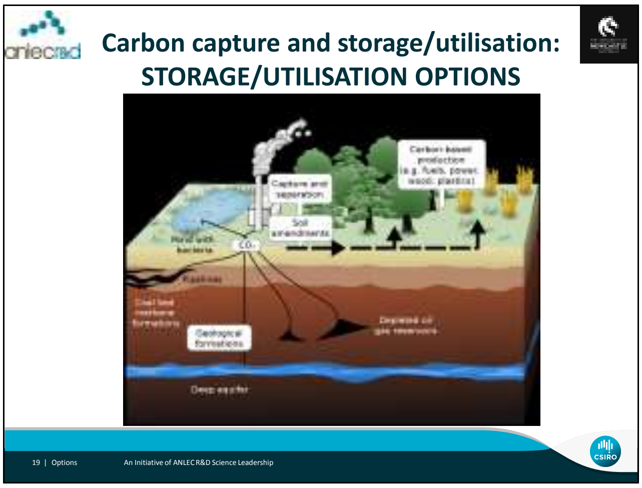
Carbon capture and storage/utilisation: PRE-COMBUSTION CAPTURE



We have already seen how the coal gasification works. By heating coal at high pressure in the presence of O_2 and applying the water gas shift reaction syngas is produced. Syngas is a mixture of H_2 and CO_2 and possibly some CO. This can be combusted in a turbine as is. An alternative to reduce CO_2 emissions is to carry out CO_2 capture to remove the CO_2 from the syngas prior to combustion.

Syngas is at high pressure and this, combined with the fact that CO_2 is being separated from H_2, makes it a relatively easy separation task. Separation can be done using reactive chemical absorption, but physical adsorption using solids (e.g. solid carbonates) or liquids (e.g. glycol) is also an option due to the high pressure of the gas.

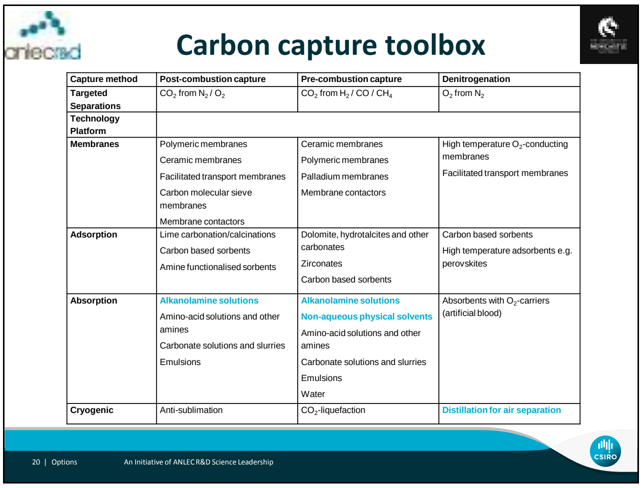
Carbon capture and storage/utilisation: STORAGE/UTILISATION OPTIONS



Once captured CO_2 is compressed into a liquid state. The question then remains about what should be done with it. CO_2 utilisation is an attractive option as it is putting a waste product to use. CO_2 can be used as a reagent in the synthesis of many carbon based materials such as plastics. It can also be used to synthesise liquid fuels such as methanol. However, for this type of utilisation to be viable it is critical that the synthesis process does not itself result in the production of more CO_2 than is used. Creating such low energy demand processes is an area of ongoing research. Another option is using CO_2 as a feedstock for the growth of algae. The algae can then be used to make biofuels.

Unfortunately utilisation will never be able to consume all the CO_2 captured if capture technology is rolled out at large scale. Storage will still be required. The bulk of CO_2 storage will occur by pumping captured CO_2 into depleted oil and gas reservoirs. This already occurs to some extent in storage studies and where CO_2 is used to force extra oil out of oil reservoirs. Another option is storage in deep saline aquifers. These are areas of porous rocks which contain mineral laden water, typically at depths of more than 1 km. Liquid CO_2 is pumped into these aquifers where it eventually dissolves in the water.

Carbon capture toolbox



This is a table that lists the different electricity generation processes to which CO_2 capture could be applied as the columns. The rows are the capture technology options. The technologies that are most promising for each electricity generation process are highlighted in blue.

Capture method	Post-combustion capture	Pre-combustion capture	Denitrogenation
Targeted Separations	CO_2 from N_2 / O_2	CO_2 from H_2 / CO / CH_4	O_2 from N_2
Technology Platform			
Membranes	Polymeric membranes Ceramic membranes Facilitated transport membranes Carbon molecular sieve membranes Membrane contactors	Ceramic membranes Polymeric membranes Palladium membranes Membrane contactors	High temperature O_2-conducting membranes Facilitated transport membranes
Adsorption	Lime carbonation/calcinations Carbon based sorbents Amine functionalised sorbents	Dolomite, hydrotalcites and other carbonates Zirconates Carbon based sorbents	Carbon based sorbents High temperature adsorbents e.g. perovskites
Absorption	Alkanolamine solutions Amino-acid solutions and other amines Carbonate solutions and slurries Emulsions	Alkanolamine solutions Non-aqueous physical solvents Amino-acid solutions and other amines Carbonate solutions and slurries Emulsions Water	Absorbents with O_2-carriers (artificial blood)
Cryogenic	Anti-sublimation	CO_2-liquefaction	Distillation for air separation