Coping with carbon: a near-term strategy to limit carbon dioxide emissions from power stations

BY PAUL BREEZE *

62 Elm Park Court, Pinner HA5 3LL, UK

Burning coal to generate electricity is one of the key sources of atmospheric carbon dioxide emissions; so, targeting coal-fired power plants offers one of the easiest ways of reducing global carbon emissions. Given that the world’s largest economies all rely heavily on coal for electricity production, eliminating coal combustion is not an option. Indeed, coal consumption is likely to increase over the next 20–30 years. However, the introduction of more efficient steam cycles will improve the emission performance of these plants over the short term. To achieve a reduction in carbon emissions from coal-fired plant, however, it will be necessary to develop and introduce carbon capture and sequestration technologies. Given adequate investment, these technologies should be capable of commercial development by ca 2020.

Keywords: power stations; sequestration; supercritical plant; oxy-fuel combustion; nuclear power

1. Introduction

One of the key sources of atmospheric carbon dioxide emissions is the generation of electric power from fossil fuels. The use of oil, gas and coal for electricity generation accounts for roughly 25 per cent of annual global carbon dioxide emissions (Science Daily 2007). Targeting the emissions from these concentrated sources of carbon dioxide represents, therefore, one of the best ways of reducing global carbon emissions.

Of the three fossil fuels, coal is by some margin the largest source of atmospheric carbon dioxide from power stations. According to the US Energy Information Administration (2007), coal accounted for 43 per cent of electricity production in 2004, close to twice the next most important source, natural gas. On top of this, coal produces more carbon dioxide per unit of electricity than natural gas, thereby amplifying its significance further. So, any reduction in emissions from coal-fired plants can have a significant impact globally. (It is worth bearing in mind, however, that much of the emission-reduction technology applicable to coal plants can be applied to gas-fired plants too.)

*paul.breeze@btinternet.com

One contribution of 12 to a Theme Issue ‘Geoscale engineering to avert dangerous climate change’.
The economics of coal-fired power generation make it most cost effective to build large power stations. Individual plants are often capable of generating 1000 MW or more of power and these power plants are major sources of carbon dioxide. Some of them are among the largest single sources of greenhouse gas emissions on Earth. Equally, reducing or eliminating the emissions from a single power plant of this size would provide a large environmental benefit.

From an environmental perspective, it would be preferable to abandon completely the burning of fossil fuels, and especially of coal, as a means to generate electricity. Unfortunately, that is not an option for either the short or the medium term. The world’s great economies are driven by coal combustion and none of them is going to abandon its use easily. Table 1 lists the proportion of electricity derived from coal combustion for a range of the world’s major economies. The USA derives 51 per cent of its electricity from coal, India relies on the fuel for 82 per cent of its electrical power, China for 82 per cent and South Africa for 93 per cent. All these countries have massive coal reserves; but even South Korea and Japan, which have negligible coal reserves of their own, burn large amounts of imported coal to generate electricity.

Indeed, rather than a reduction in its use, the consumption of coal for power generation is expected to increase substantially over the next 20 years. Coal’s contribution to total world energy consumption, covering all uses including power generation, is expected to rise from 26 per cent in 2004 to 28 per cent in 2030 (US Energy Information Administration 2007). Approximately 65 per cent of all coal shipped is used to generate electricity and coal’s share of power generation is expected to increase from 43 per cent in 2004 to 45 per cent by 2030. This must be taken against a background of increasing power generation to meet rising demand. Again, according to figures from the US Energy Information Administration, generation output is expected to increase by 2.4 per cent each year from 2004 to 2030. The result, as table 2 shows, is that total output rises from 16 424 million MW h in 2004 to 30 364 million MW h in 2030.

The message from these figures is that coal consumption is likely to rise substantially over the medium term. Coal is a cheap source of electricity and it is available in large quantities in many parts of the world. The Western world has

Table 1. Coal use for power generation (Breeze 2007b).

<table>
<thead>
<tr>
<th>countries</th>
<th>proportion of total electrical power from coal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Africa</td>
<td>93</td>
</tr>
<tr>
<td>China</td>
<td>82</td>
</tr>
<tr>
<td>Australia</td>
<td>80</td>
</tr>
<tr>
<td>India</td>
<td>75</td>
</tr>
<tr>
<td>USA</td>
<td>51</td>
</tr>
<tr>
<td>Africa</td>
<td>46</td>
</tr>
<tr>
<td>South Korea</td>
<td>36</td>
</tr>
<tr>
<td>Europe</td>
<td>30</td>
</tr>
<tr>
<td>Russia</td>
<td>30</td>
</tr>
<tr>
<td>Japan</td>
<td>22</td>
</tr>
</tbody>
</table>
built much of its prosperity on coal and now the developing world is intent on doing the same. If greenhouse gas emissions are to be reduced then this must, at least for the next 20–30 years, take place against a background of increased coal use for power generation.

### 2. Alternatives to coal combustion

One of the reasons why coal use will not fall is that no viable alternative exists today. The only other comparable source in terms of size and technology is nuclear power; but nuclear power is unlikely to be able to replace even a small part of current coal capacity. A nuclear power station is both cost effective and produces much lower greenhouse gas emissions than any fossil fuel power plant. There are some major environmental objections to increased nuclear generation but perhaps the largest hindrance to a massive growth in nuclear capacity is the availability of uranium to fuel the plants. While the nuclear fuel industry would almost certainly argue otherwise, it is not clear today that it can support anything more than a modest growth in global capacity (IEA 2006; Breeze 2007a). So, while existing nuclear plants may be replaced in, for example, the USA and the UK, additional plants are unlikely to be built. Elsewhere capacity may grow, but never sufficiently to reduce coal use.

Renewable technologies offer the other major alternative to fossil fuel combustion. Today, however, these technologies are simply not in a position to meet the growing demand for new capacity across the globe. Growth in wind power capacity, perhaps the best option for the medium term, is already showing signs of being constrained by global manufacturing capacity. Solar power is almost certainly the earth’s long-term solution to electricity supply but it will probably be another generation before it can begin to provide the sort of capacity the world needs. Hydropower might be able to provide significantly more output, particularly in Africa where the infrastructure associated with increased hydro capacity can have other major benefits. Biomass, marine technologies, tidal power: all these will have a role to play but none can match coal for cheapness, reliability and gross capacity.

The other important way of constraining growth in coal consumption is by introducing energy efficiency measures. There are simple measures that can lead to major savings but these will mostly take place in the developed world. The growth in the use of coal will mostly take place in the developing world. Inevitably, therefore, coal use will increase.

---

Table 2. Predicted global power generation. (Source: US Energy Information Administration.)

<table>
<thead>
<tr>
<th>Year</th>
<th>Global Output (million MW h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>16,424</td>
</tr>
<tr>
<td>2010</td>
<td>19,554</td>
</tr>
<tr>
<td>2015</td>
<td>22,289</td>
</tr>
<tr>
<td>2020</td>
<td>24,959</td>
</tr>
<tr>
<td>2025</td>
<td>27,537</td>
</tr>
<tr>
<td>2030</td>
<td>30,364</td>
</tr>
</tbody>
</table>

---

*Phil. Trans. R. Soc. A* (2008)
3. Facing up to coal

The politics of coal have already been alluded to briefly but it is worth emphasizing its significance once again. Coal is a cheap, widely available, high energy-density fuel. Since the industrial revolution, it has provided the energy that has driven industry in the West. Indeed, coal is arguably the fount of Western prosperity. Today it continues to provide both energy and energy security in many Western countries and particularly the USA where, as noted, it accounts for over 50 per cent of electricity generation.

The recognition of greenhouse warming and the identification of carbon dioxide emissions as a primary cause have led to a reappraisal of fossil fuel use. As a result international efforts are taking place, under the auspices of the United Nations, to reach a comprehensive agreement to control and eventually reduce greenhouse gas emissions. Unfortunately, this comes at a time when the economies of two major developing nations, India and China, are growing rapidly. And, like the Western nations before them, they are growing on the back of coal. It is unrealistic to expect either of these nations, or any of the other developing nations that currently rely on coal, to sacrifice their prosperity for the sake of the planet. Any international agreement will therefore have to take this into account. In practice, this means that while Europe (and one hopes, eventually, the USA) will aim for drastic cuts in its greenhouse gas emissions, coal use will continue to increase. If, therefore, overall emissions are to be limited, then technological solutions based around coal use will have to be implemented. Fortunately these already exist. Applied pragmatically, they can do a lot to ameliorate the problems associated with coal combustion.

(a) Conventional solutions

The traditional coal-burning power plant in use today was developed over the course of the twentieth century. In such a plant coal is burnt in air to generate heat that is used to raise steam in a boiler and the steam is used to drive a steam turbine generator, producing electricity. The most highly developed of this type of plant, and the one that is of most interest here, is the pulverized coal-fired power plant. This plant burns coal that has first been reduced in grinders to a fine powder, which can be injected pneumatically into the boiler combustion chamber where it is burnt under carefully controlled conditions in order to minimize the production of nitrogen oxides. Such plants probably account for 90 per cent of current coal-fired generating capacity.

The temperature in the combustion zone of a pulverized coal-fired power plant may reach 1500–1700°C. Under these conditions, nitrogen oxides are easily produced from the nitrogen in air, so the amount of air (and hence oxygen) is restricted in order to maintain reducing conditions in this hottest region. Further air is added in a cooler part of the furnace to complete the combustion reaction.

The heat released during combustion is both radiant and convective. Radiant heat is captured by passing water through piping within the walls of the furnace while convective heat is captured higher up with bundles of water-containing tubes placed in the path of the exhaust gases. The product from the combustion of coal in air is, bar some traces of impurities, carbon dioxide. This may amount
to 15 per cent by volume of the exhaust gases from the plant. The production of this carbon dioxide cannot be avoided in a plant of this type but the environmental performance of the plant may be improved significantly by improving its overall energy-to-electricity conversion efficiency. A steam turbine cycle approximates to that of a Carnot cycle engine. The key to higher efficiency in such engines is to increase the operating temperature and pressure.

The steam system of most conventional coal-fired plant includes a drum located part way through the system where water is converted to steam. Steam beyond this stage is superheated before being pumped to the steam turbine from which it is eventually condensed and returned as water to the boiler. A typical plant of this type might operate with a steam temperature of 540°C and a steam pressure of 17.5 bar. The resultant efficiency is approximately 38 per cent. Plants based on this type of steam cycle are known as subcritical plants.

Some of the most modern plants operate with steam under conditions that are above the critical point of water. In these plants, there is no need for a steam drum within the steam cycle since the phases of water can coexist. Plants that operate under these conditions are referred to as ‘supercritical plants’. Two types of supercritical plant are in use today. The first, called simply a supercritical plant, will typically operate at a steam temperature of 580°C, a steam pressure of 29 bar and an overall energy conversion efficiency of 41 per cent, three percentage points higher than the subcritical plant. The second type, the ultra-supercritical plant, uses yet more extreme conditions. Steam temperature may be as high as 720°C, steam pressure at 37–38 bar that allows an operating efficiency of over 44 per cent, seven percentage points more than the best subcritical station.

These efficiency gains are extremely important when it comes to environmental performance. Many old coal-fired plants commonly found in developing countries operate at an efficiency of only 30 per cent. Even in a technically advanced country such as the USA, the average efficiency of the coal-fired fleet is only 33 per cent (Science Daily 2007). Increasing the efficiency of a coal-fired plant from 33 to 45 per cent would reduce the amount of carbon dioxide produced for each unit of electricity by 27 per cent. The extreme operating conditions in supercritical and ultra-supercritical coal-fired plants require technically advanced materials. As these are developed further, even higher performance can be expected. The European Commission-funded AD700 programme aims to achieve an efficiency of 50–55 per cent for an advanced coal-fired plant by 2015. Meanwhile, it is encouraging to note that supercritical plants are already being built in both China and India, with more than one hundred on order in the former and where the first supercritical plants have already entered service. This appears to put the USA in the shade: of approximately 160 proposed new coal-fired plants that are currently under consideration there, only 14 are supercritical and 4 ultra-supercritical.

Converting the world’s coal-burning fleet to high efficiency plant offers one effective short-term strategy for limiting carbon dioxide emissions (albeit modestly). This is a measure that can begin to be implemented immediately. And while it will not reduce overall emissions it will slow their increase. Emission reduction from coal plants will require another set of technologies: carbon capture and sequestration.
(b) Advanced power cycles

The aim of carbon capture and sequestration technologies is to create a (near) zero-emissions coal-fired power plant. If higher efficiency in existing plants represents a short-term strategy to limit power plant carbon dioxide emissions then the zero-emissions plant is the medium-term solution. If we accept the arguments presented here that coal burning will continue well into the middle of this century, it is important that these technologies are brought into service as quickly as possible.

In practice, that time scale is likely to be another decade at least. To date there has been no coal plant scale demonstration of either capture or sequestration of carbon dioxide. Significant problems remain to be solved before either capture or storage can be implemented widely. Nevertheless, the basic technologies are in place and with sufficient investment there is no reason why they cannot be perfected over this time scale.

Three different carbon-capture strategies are being developed in parallel today. These are termed post-combustion capture, pre-combustion capture and oxy-fuel combustion. It is likely that each will have a part to play in the future of coal combustion and all three will be considered briefly here.

‘Post-combustion’, as its name suggests, involves capturing carbon dioxide from the flue gases of a power plant after combustion has taken place. The carbon dioxide, approximately 15 per cent by volume of the exhaust gases, is mixed primarily with nitrogen, so post-combustion capture involves the separation of these two gases. Separation can be achieved today most easily using a chemical absorption technique involving an aqueous solution of the solvent monoethanolamine (MEA). This is carried out in a plant similar to that used for sulphur dioxide scrubbing. The flue gases from the power plant are passed up a tall tower from the sides of which a solution of MEA is sprayed into its path. With currently available technology, this can result in the capture of 80–95 per cent of the carbon dioxide within the exhaust gases. The scrubbed flue gases are released into the atmosphere. Meanwhile, the MEA–carbon dioxide-containing solution is collected at the bottom of the tower, pumped to a second reactor and heated to release the carbon dioxide and regenerate the solvent. This is an energy intensive process that is likely to reduce the overall plant conversion efficiency by 15 per cent. The released carbon dioxide must also be compressed prior to being pumped away for sequestration and this adds to the total energy burden, making an overall efficiency reduction with the two processes of approximately 25 per cent (Breeze 2006).

The major advantage of post-combustion technology is that it can, in principle, be retrofitted to existing power plants. The effectiveness of this will depend both on the existing efficiency of the plant and the availability of space for the capture plant. Modern supercritical and ultra-supercritical plants would make good candidates for future post-combustion capture owing to their already high efficiencies.

Pre-combustion capture, the second of the capture strategies envisaged for coal combustion plants, takes a different approach. In this case, the idea is to avoid entirely the need to capture carbon dioxide after combustion by removing all the carbon from the fuel before combustion takes place, using a process of coal gasification. This process involves reacting coal at high temperature with...
a limited proportion of either air or oxygen and steam. The gasification reaction, which takes place under reducing conditions, produces a mixture of carbon monoxide and hydrogen, a mixture called synthesis gas, syngas for short.

The syngas still contains carbon in the form of carbon monoxide; this is converted in a second process called a shift reaction in which it is reacted again at high temperature with steam. The result of the reaction is a mixture of carbon dioxide and hydrogen. The separation of carbon dioxide from hydrogen can be carried out relatively simply using current pressure swing absorption technology that selectively removes the carbon dioxide, leaving almost pure hydrogen.

Hydrogen produced from coal in this way can be burned in a supercritical boiler of the type described above; it can be burned in a gas turbine-based power plant or in an integrated gasification-combined cycle (IGCC) power plant that couples closely with the gasification and power generation processes. The latter is the configuration that the US Department of Energy (DOE) chose in 2003 as its FutureGen project, aimed at demonstrating a zero-emissions coal-fired power plant by 2012. (In 2008 the FutureGen project was modified, with the DOE proposing to sponsor carbon dioxide capture and sequestration rather than the whole plant.)

Oxy-fuel combustion is, in reality, another form of post-combustion capture of carbon dioxide, but it takes a radical approach in order to eliminate the problems associated with separating carbon dioxide from nitrogen. In an oxy-fuel plant, combustion of the coal takes place in pure oxygen. When the combustion of carbon takes place in oxygen, the only combustion product is carbon dioxide, so there is no separation problem. (In practice, the combustion of coal produces some water vapour too, but this is easily separated from carbon dioxide by condensation.) However, such a plant requires an oxygen separation plant to provide a source of pure oxygen. The combustion of coal in oxygen can reach temperatures of 3500°C, far too high for the best of modern materials. In order to reduce the temperature, part of the carbon dioxide from the exhaust is recycled, cooling the combustion zone. The technology required to implement oxy-fuel combustion is still in the early stages of development and has yet to be demonstrated in a large-scale plant. However, it could potentially be retrofitted to existing and future supercritical power plants.

Which of these different approaches to carbon capture results in the most efficient power plant? Table 3 compares the efficiencies of the main types. These figures suggest that an ultra-supercritical pulverized coal power plant with carbon capture represents the most efficient plant type. This reflects the higher efficiency of this type of plant compared with the supercritical and subcritical plants and makes these plants excellent candidates for future retrofitting. The figure for oxy-fuel combustion should be treated with some caution as this technique has yet to be tested fully. It may yet offer higher efficiency when coupled with an ultra-supercritical boiler.

(c) Carbon sequestration

If carbon capture is to provide a successful strategy for removing carbon dioxide from coal-burning power plants then a means of storing the resultant gas must be found. The amount of carbon dioxide produced by power plants
across the globe is approximately 10 billion tonnes each year (Science Daily 2007). The USA alone produces 1.4 billion tonnes, equivalent to approximately one-third of the natural gas piped around the USA annually (Science Daily 2007). As with carbon capture, the technology to transport and store carbon dioxide is already available and has been tested in three pilot scale projects. These include injection of carbon dioxide from a coal gasification plant in the USA into an oil field at Weyburn, Canada where it is used to force additional oil from the field (enhanced oil recovery), injection into a sandstone reservoir in the Saharan region of Algeria and sequestration of carbon dioxide separated from natural gas from the Norwegian Sleipner gas field into a brine aquifer under the north sea. This latter was a response to Norway’s carbon tax. None of these projects stores the quantity of carbon dioxide that would be produced by a base load coal-fired power plant and the technology has yet to be proved at this scale.

If a significant proportion of the carbon dioxide from coal combustion is to be sequestered, then very large stores will have to be identified. The most promising and cheapest of these available today are exhausted oil and gas wells. Such sites will provide cheap and convenient places to test the viability of carbon dioxide sequestration but they cannot, alone, provide anything like the capacity needed if sequestration is to have a major impact on global emissions (Ansolabehere et al. 2007). Fortunately, there are many other types of geological formation and these, between them, should be able to accommodate all the carbon dioxide that is likely to be sequestered over the next 50 years.

Sequestration, however, is only part of the problem. The sequestered carbon dioxide must remain isolated indefinitely if the capture and storage strategy is to be effective. This means that all sequestration sites will have to be monitored for decades, probably longer. While these sites will almost certainly be operated initially by private sector companies, the responsibility for their security is likely, eventually, to fall to national governments. It is important that this should be understood from the outset if the strategy is to be effective.

\( (d) \) Costs

While the efficiency gains with supercritical and ultra-supercritical coal-fired plants tend to balance the increased cost of the high technology boiler systems, the introduction of capture and sequestration will have a significant effect on the cost of electricity generated from coal. The loss of efficiency, even without the costs associated with running a capture plant and the transportation and storage of carbon dioxide, will push prices up by approximately 25 per cent.
The capital cost of a new subcritical coal-fired plant without carbon capture is $1323 per kW, according to a study carried out jointly by the US New Energy Technology Laboratory and Parsons (Ciferno et al. 2006). The same plant with carbon capture would cost $2358 per kW. Meanwhile, a new supercritical coal plant without capture would cost $1355 per kW and with capture, $2.365 per kW. The same study found a new IGCC plant without capture would cost $1557 per kW and with capture, $1950 per kW. Meanwhile, MIT reported the cost of a new ultra-supercritical coal-fired plant to be $1360 per kW, rising to $2090 per kW with capture (Ansolabehere et al. 2007). The same study put the cost of an oxy-fuel plant to be $1900 per kW.

Table 4 presents estimates of Ansolabehere et al. (2007) for the cost of electricity from these various power plant configurations. Figures from a further study by NETL-Parsons, while not quoted here, are broadly consistent with them for the configurations studied. For the plants without capture, the cost of electricity for the conventional coal-burning plants varies from $0.0478 to $0.0496 per kW h or just under 4 per cent, which is probably insignificant. The IGCC plant with an estimated generating cost of $0.0513 per kW h is higher. When carbon capture is added, however, the IGCC plant becomes the cheapest generator with a cost of $0.0652 per kW h, an increase of 27 per cent over the cost without capture. Oxy-fuel combustion also looks competitive on this estimate, at $0.0698 per kW h, while of the conventional coal-burning plants with carbon capture the ultra-supercritical plant offers the most cost-effective means of generation, producing electricity for $0.0734 per kW h, 48 per cent higher than the cost without capture. The most expensive configuration with capture is the subcritical plant with a cost of $0.0816 per kW h, 69 per cent more than the same plant without capture.

The cost of transportation and storage must be added to the costs in Table 4. This will depend on the type of storage and the distance of the storage site from the power plant. Typical estimates put the cost at between $1 and $8 per tCO₂ (Breeze 2006).

When evaluating these figures with a view to forming future strategy, there are two further points to bear in mind. First, while the IGCC plant appears to offer the cheapest source of electricity with carbon capture, this type of plant is still relatively new and so far its reliability has proved lower than that of the more conventional boiler-based plants (Ansolabehere et al. 2007). Second, supercritical and ultra-supercritical plants built today will be able to be...
retrofitted with carbon capture technologies at a later date. This makes less sense for an IGCC plant as a result of the tight integration between the different plant components necessary at the time of construction and could make the economics of the ultra-supercritical plant the most favourable.

These figures can be placed in perspective by comparing the estimated cost of power from that of various other technologies. The cost of electricity from a new nuclear power plant is likely to be between $0.030 and $0.067 per kWh. A new large hydropower plant can generate for $0.040–0.080 per kWh and an onshore wind plant might be expected to produce power for between $0.060 and $0.090 per kWh (Breeze 2007b).

All these figures suggest that alternatives to coal-fired power generation with carbon capture might be more cost effective. But, as has already been stressed, these alternatives cannot replace coal-fired generation in the short or medium term. So, while a shift to coal-fired generation with carbon capture may well offer future economic opportunities for a range of other technologies, this shift is still necessary in the interests of the planet.

There is one final question: how is this shift to be achieved? Two things are required. The first is investment, primarily from Western governments, to develop the technologies for carbon capture and storage to a state where they can be deployed economically on a wide scale. The second is the introduction of global carbon emission limits, with cost penalties for emitting carbon that are sufficiently stringent to persuade generators across the globe to build plants based on these technologies. Both are within grasp, but, as the arguments at the UN conference in Bali in December 2007 showed, there are some hard bargains to be struck if consensus is to be reached. If, indeed, such a consensus can be achieved then there is no reason why carbon emissions from coal combustion should not fall significantly by 2050 even while the amount of coal burnt continues to rise. That may not be the solution sought by many environmentalists but it does provide a realistic route towards a carbon-free energy economy. If that can prevent catastrophic global warming, then there is no obvious reason why it should not be pursued.

References


