COAL MEETING THE CLIMATE CHALLENGE

TECHNOLOGY TO REDUCE GREENHOUSE GAS EMISSIONS

WORLD COAL INSTITUTE
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Climate change is a global challenge and requires a concerted global response.
A sustainable energy future is one where society’s energy needs are met using resources available to us over the short, medium and long term. At the same time, it means producing and utilising all these energy sources in a way that minimises adverse impacts on the environment and maximises economic and social benefits.

This is a significant challenge – particularly because of surging energy demand, concerns about energy security, and the environmental impacts of energy production and consumption. We have to take steps to reconcile economic and social objectives with environmental imperatives – specifically those posed by climate change. Over the last ten years, world primary energy demand has risen by over 20% and this upward trend is set to continue. Fossil fuels will continue to dominate energy consumption; still meeting around 80% of energy needs in 2030. Coal will meet over 25% of global energy demand.

Coal is abundantly available, affordable, reliable, geographically well-distributed and easy and safe to transport. Coal markets are well-functioning and responsive to changes in supply and demand. The major challenges facing coal are concerned with its environmental impacts. Viable, highly effective technologies have been developed to tackle the release of pollutants – such as oxides of sulphur (SOx) and nitrogen (NOx) – and particulate and trace elements, such as mercury. More recently, greenhouse gas (GHG) emissions, including carbon dioxide (CO2) and methane (CH4) have become a concern because of their link to climate change.

Climate change is a global challenge and requires a concerted global response. CO2 makes up 80% of anthropogenic (human induced) GHG emissions. Over the last century, the amount of CO2 in the atmosphere has risen, in large part driven by fossil fuel use but also because of other factors, such as land-use change and deforestation.

Technology is Key
There is growing recognition that technology developments have to be part of the solution to climate change. This is particularly true for coal because its use is growing in so many large economies, including the largest and fastest growing countries such as China and India. There are two primary ways of reducing CO2 emissions from coal use.

- The greatest potential is offered by carbon capture and storage (CCS) which can reduce CO2 emissions to the atmosphere by 80-90%.

- Improving efficiencies at coal-fired power stations – meaning lower emissions per unit of energy output.
CCS technologies enable emissions of CO₂ to be stripped out of the exhaust stream from coal combustion or gasification and stored in geological formations so that they do not enter the atmosphere. CCS offers the potential of moving towards near-zero emissions to the atmosphere from coal-fired and gas-fired power stations. Geological features being considered for CO₂ storage fall into three categories:

- Deep saline formations
- Depleted oil and gasfields
- Unmineable coal seams.

Storing CO₂ in geological formations is a secure option. The Intergovernmental Panel on Climate Change (IPCC) 2005 Special Report on Carbon Dioxide Capture and Storage found that the risk of leakage from geological storage was very likely to be less than 1% over 100 years and likely to be less than 1% over 1000 years.

The cost of CCS is project specific, depending on the technology of the plant producing the CO₂ and on the proximity of the plant to adequate storage resources. For power generation, the cost of CCS today is estimated at between USD40 and USD90 per tonne of CO₂ avoided. Subject to access to suitable storage sites, capture and compression costs dominate the overall cost of CCS for power generation – reducing these costs is therefore a priority. Over the next decade, the cost of capture could be reduced by 20-30% and more should be achievable by new technologies that are still in the research or demonstration phase. Economies of scale will also help to bring down costs.

Efficiency improvements include the most cost-effective and shortest lead time actions for reducing emissions from coal-fired power generation. This is particularly the case in developing and transition countries where existing plant efficiencies are generally lower and coal use in electricity generation is increasing. Not only do higher efficiency coal-fired power plants emit less CO₂ per megawatt, they are also more suited to retrofitting with CO₂ capture systems.

Improving the efficiency of pulverised coal-fired power plants has been the focus of considerable efforts by the coal industry. There is huge scope for achieving significant efficiency improvements as the existing fleet of power plants are replaced over the next 10-20 years with new, higher efficiency supercritical and ultra-supercritical plants.

A one percentage point improvement in the efficiency of a conventional pulverised coal combustion plant results in a 2-3% reduction in CO₂ emissions.

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i. Very likely is defined by the IPCC as a probability between 90-99%.
ii. Likely is defined by the IPCC as a probability between 66-90%.
iii. The quantity of CO₂ emissions avoided is less than the quantity captured, because the energy consumed during capture results in additional CO₂ production. The cost per tonne of CO₂ captured would therefore be lower than the cost per tonne of emissions avoided.
An alternative to achieving efficiency improvements in conventional pulverised coal-fired power stations is through the use of gasification technology. Integrated Gasification Combined Cycle (IGCC) plants use a gasifier to convert coal to syngas, which drives a combined cycle turbine. IGCC efficiencies typically reach the mid-40s, although plant designs offering around 50% are achievable. Gasification may also be one of the best ways to produce clean-burning hydrogen (H₂) for tomorrow’s cars and power-generating fuel cells.

**Achieving the Vision**
The coal industry recognises that climate change is a significant challenge facing the world today. Coal is one of the biggest sources of anthropogenic CO₂ emissions to the atmosphere and therefore has to be fully involved in meeting the climate change challenge through international research, development and deployment of advanced coal technologies. Success in achieving a sustainable energy future will require:

**Policy Certainty** – governments need to provide supportive policy frameworks that recognise the continuing role of coal and the need to work with industry in accelerating the development and adoption of low emissions coal technologies.

**Collaboration** – the public/private partnership route is going to be critical to a sustainable energy future. It is clear that neither industry nor government alone can deliver the technologies required to achieve the emissions reduction trajectory discussed by the IPCC.

**Large-scale Integrated Projects** – there is a pressing need for significantly more large-scale, integrated coal-based CCS demonstration projects if commercial readiness is to be achieved by 2020.

**Regulatory & Legal Frameworks** – a commitment to CCS needs to be complemented by regulatory and legal frameworks for CO₂ storage that provide policy certainty for project proponents and address the technical issues and uncertainties associated with projects.

**Financing the Future** – actions are needed by governments, industry and financial institutions to create a suitable investment framework.

The coal industry is contributing to a sustainable energy future. In addition to supporting specific demonstration projects, it is actively involved in international initiatives aimed at pushing technologies forward.

EXECUTIVE SUMMARY END
Genesee 3 (450MWe) is Canada’s first ever coal-fired supercritical unit.

Photo courtesy of EPCOR
A sustainable energy future would mean society’s energy needs are met using resources that are available to us over the short, medium and long term. At the same time it would mean producing and utilising all these energy sources in a way that minimises adverse impacts on the environment and maximises economic and social benefits.

Creating a sustainable energy future is a significant challenge, particularly because of:

- Surging energy demand – driven by population growth and economic development.
- Concerns about security of supplies of some sources of energy.
- Environmental impacts of energy production and consumption – particularly those associated with GHG emissions, such as CO₂.

Social and economic development and poverty alleviation depend on the availability of abundant, affordable, and reliable energy sources. Achieving full access to electricity is a vital factor in alleviating global poverty. While access to energy has been improving, particularly in China, 1.6 billion people worldwide are still without access to modern energy systems and there is clearly a long way to go.

Cleaner Energy Revolution

The challenge is to reconcile economic and social objectives with environmental imperatives – particularly those posed by climate change. Creating a sustainable energy future will necessitate a transformation in the way we produce and use energy.

- Technology is the key to achieving deep cuts in CO₂ emissions from energy use and to the role of coal in a sustainable energy future.
- Achieving near-zero emissions to the atmosphere from fossil fuel-based power production will be vital. Carbon Capture and Geological Storage (CCS) will be essential to reaching the goal of near-zero emissions of CO₂ to the atmosphere. Major programmes are under way to accelerate the development of CCS, with the aim of achieving commercial readiness of near-zero emissions coal-fired power plants by 2020.
- Improving efficiency levels at power plants will be essential to cutting GHG emissions, as well as increasing the number of energy efficient buildings and improving the fuel efficiency of vehicles.
A portfolio approach to energy sources is needed, including cleaner fossil fuels, safe and affordable nuclear, and more reliable and affordable renewable energy. The portfolio will differ between countries according to national circumstances but improvements in all these areas will lead to a global cleaner energy revolution.

Reducing demand for energy, through energy efficiency improvements and behavioural change will be important.

Moving towards low carbon transportation networks will be required – this should include the increasing uptake of electric vehicles.

The transition to near-zero emissions to the atmosphere from power generation is going to require a significant increase in investment by both the public and private sectors. To date, investments in the development of low emissions technologies by governments and industry sectors alike have been insufficient when compared to the challenge. The reductions in global emissions needed to avoid climate change are unlikely to be achieved without major improvements in the performance and cost of low emissions energy technologies. Substantially increased Research, Development and Demonstration (RD&D) investment is required to produce the effective and affordable technologies that are a prerequisite to achieving deep cuts in emissions.

It is also essential that there is a global policy and regulatory framework to enable power producers to participate and invest in the necessary RD&D of advanced technologies. Whether systems are in place in 2050 – and the sustainability of the global energy system – will largely depend on investments and policy decisions made from today through to 2020.

The coal industry contributes substantially to global energy security, is a powerful force in alleviating poverty and has demonstrated a capacity for technological innovation in previous environmental challenges (see Annex). The industry wants to ensure that the world can benefit from the responsible and sustainable use of coal in the future. In Coal Meeting the Climate Challenge: Technology to Reduce GHG Emissions, the World Coal Institute:

Highlights the pivotal role that coal plays in a sustainable energy future.

Sets out the technological options which will substantially reduce GHG emissions to the atmosphere from coal use.

Reviews what is needed to push forward with technological innovation, development, deployment and commercialisation.

States the coal industry’s commitment to a sustainable energy future and to being part of the solution to climate change.
World Coal Institute & Climate Change

1. The World Coal Institute recognises that climate change is a significant global issue, which requires concerted global action.

2. Climate change must be dealt with across all sectors and cannot be considered in isolation to other challenges. WCI supports policies that meet the issue of climate change with the need for secure, reliable and affordable energy supplies.

3. The World Coal Institute acknowledges that emissions reductions resulting from the use of coal are required and are achievable over time within a sustainable energy future.

4. Technology solutions will require large-scale investments which, in turn, need international energy and climate change policies to provide certainty for long-term investments to be made.

5. Carbon capture and storage needs to be a cornerstone of any effective post-2012 climate change regime. The world has to make fossil fuel use climate compatible if it is to meet its climate change objectives.
Schwarze Pumpe lignite-fired power plant in Germany. New supercritical and ultra-supercritical power plants operate at higher temperatures and pressures and achieve higher efficiencies than conventional pulverised coal-fired units.

Photo courtesy of Vattenfall
Coal is affordable, reliable, abundantly available, geographically well-distributed in politically stable regions, and easy and safe to transport. In most circumstances coal is cheaper per energy unit than other fuels (see Figure 1). Coal markets are well-functioning and responsive to changes in supply and demand.

The major challenges facing coal are concerned with its environmental impacts. These include the release of pollutants, such as oxides of sulphur and nitrogen (SOx and NOx), and particulate and trace elements, such as mercury. Viable, highly effective technologies have been developed and deployed to minimise these impacts – such as successfully meeting the challenge of ‘acid rain’ associated with SOx emissions from power plants. Ensuring that best available technology is more widely deployed remains a key goal for the coal industry.

More recently GHG emissions, including CO₂ and methane, have become a global concern. The release of GHG emissions into the atmosphere from human activities is linked to climate change – this includes emissions from the use of fossil fuels, land-use, deforestation and agriculture.

See Annex for more detailed descriptions of other environmental challenges facing coal and the technological response.
All fossil fuel use contributes to CO₂ emissions to varying degrees and mitigation measures are needed in all areas (see Figure 4). This report focuses on coal and specifically its use in power generation – over two-thirds of the almost 6.3 billion tonnes of coal produced annually is used for this purpose, with coal fuelling around 40% of global electricity production [IEA 2007a & b].

Climate Change
Climate change is a global challenge and requires a concerted global response. The IPCC has emphasised that there is enough evidence to show that the world is warming and that action needs to be taken. According to the IPCC’s 4th Assessment Report, most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations [IPCC 2007].

Even the minimum predicted shifts in climate for the 21st century have the potential to be significant and disruptive. Estimates of surface temperature increases by the end of this century range from 1.1°C-6.4°C. The potential effects of this warming include increased air and ocean temperatures, widespread melting of snow and ice, and rising average sea levels [IPCC 2007].

Carbon dioxide makes up almost 80% of anthropogenic GHG emissions. Over the last century, the amount of CO₂ in the atmosphere has risen, in large part driven by fossil fuel use but also because of other factors such
as land-use change and deforestation. Atmospheric concentrations of CO\textsubscript{2} have increased 35% above the pre-industrial level, from about 280 parts per million (ppm) to 379 ppm in 2005 [IPCC 2007].

The atmospheric concentration of methane – 23 times as potent as an equivalent amount of CO\textsubscript{2} over a 100-year time horizon – has significantly increased from the pre-industrial level of 715 parts per billion (ppb) to 1774 ppb in 2005. The IPCC has stated that it is very likely that the observed increase in methane concentrations is due to human activities, mainly agriculture and fossil fuel use.

**Energy Demand**

Over the last ten years, world primary energy demand has risen by over 20% and this upward trend is set to continue [BP 2007].

Population growth will continue, with the global population expected to reach over 8 billion by 2030 from its current level of 6.4 billion [IEA 2006a].

In the absence of new policies, global energy demand and CO\textsubscript{2} emissions are forecast to more than double by 2050. More than two-thirds of this increase will come from developing countries [IEA 2006a].

Fossil fuels will continue to dominate energy consumption; still meeting around 80% of energy needs in 2030. Coal will meet over 25% of global energy demand in 2030 [IEA 2006a].

Coal fuels almost 40% of the world’s electricity and in many countries this figure is much higher – Australia, China, India and South Africa, for example, use their large indigenous supplies of coal to generate most of their electricity (see Table 1). With 1.6 billion people – or 25% of the population worldwide – lacking access to electricity, it is essential that steps are taken to increase access to affordable energy supplies, while minimising environmental impacts.

| Table 1: Coal in Electricity Generation (2006) |
|------------------|------------------|------------------|------------------|
| Poland           | 93%              | Israel           | 71%*             | Czech Republic   | 59%              |
| South Africa     | 93%*             | Kazakhstan       | 70%*             | Greece           | 58%              |
| Australia        | 80%              | India            | 69%*             | USA              | 50%              |
| PR China         | 78%*             | Morocco          | 69%*             | Germany          | 47%              |

Source: IEA 2007a
* Only 2005 data available for these countries

| Table 2: Coal-fired Generation Capacity in China & India |
|------------------|------------------|------------------|
| PR China         | GW | % of Total Capacity | GW | % of Total Capacity |
| 2004             | 307 | 69                   | 72  | 55                   |
| 2015             | 688 | 72                   | 128 | 56                   |
| 2030             | 1041| 70                   | 251 | 58                   |

Source: IEA 2006a
For many countries, particularly those with large indigenous reserves such as China and India, this will mean continuing to use coal for power generation (see Table 2). Over the past 20 years, China has connected some 700 million people to the electricity system – the country is now 99% electrified, with around 80% of China’s electricity fuelled by coal. China is currently constructing the equivalent of two, 500MW coal-fired power plants each week [MIT 2007]. By 2030, India and China are predicted to account for more than 50% of installed coal power capacity globally [IEA 2006a].

Response

Coal is expected to remain the most important fuel for power generation across both developed and developing economies. A successful response to the challenge of climate change therefore has to incorporate minimising environmental impacts at coal-fired power stations. This can be achieved through:

» Developing technologies and supporting knowledge base to enable near-zero emissions to atmosphere through CCS;

» Examining the feasibility of applying ('retrofitting') these techniques to existing and new power stations being installed in the next 15-20 years;

» Improving efficiency levels through the utilisation of supercritical and ultra-supercritical technologies – and through integrated gasification combined cycle (IGCC) systems.

» Hydrogen may be a future clean energy carrier, alongside a greater reliance on distributed (modular/onsite) and integrated (combined heat and power) energy systems.

Meeting these challenges is going to require skilful long-term planning and implementation. Clearly there is no single solution to the global challenges we face. It is therefore important that we effectively mitigate climate change while also creating sustainable energy systems. Any response to climate change has to recognise the existence of different starting points, perspectives, priorities and solutions – and provide a long-term vision of the future.
**Coal Meeting the Climate Challenge**

**Carbon Capture & Storage**

CCS enables emissions of CO₂ to be captured and stored indefinitely in geological formations so that the CO₂ is not released to the atmosphere. CCS is most cost-effective when applied to large, stationary sources of CO₂ – such as power stations and steelworks. The IPCC has stated that power plants with CCS could reduce CO₂ emissions by 80-90% net and that the majority of CCS technologies are either economically feasible under specific conditions or part of a mature market now.

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### Figure 4: Global Greenhouse Gas Emissions – Sources & Activities

*Sources: UNFCCC & WRI*

<table>
<thead>
<tr>
<th>GHG by Sector</th>
<th>GHG by Gas</th>
<th>CO₂ &amp; CH₄ by End-Use / Activity</th>
<th>GHG from Fossil Fuels &amp; Other Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial &amp; Waste 7%</td>
<td>CH₄ 14%</td>
<td>Coal 9%</td>
<td>Oil &amp; Gas 37%</td>
</tr>
<tr>
<td>Land Use &amp; Agriculture 32%</td>
<td>CO₂ 77%</td>
<td>Argon 36%</td>
<td>Coal 25%</td>
</tr>
<tr>
<td>Energy Production &amp; Consumption 61%</td>
<td>Other 9%</td>
<td>Waste 23%</td>
<td>Oil &amp; Gas 18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Land Use Change 24%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas 15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oil 30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coal 31%</td>
<td></td>
</tr>
</tbody>
</table>

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**GHG by Gas**

- **CH₄**: 14%
- **CO₂**: 77%
- **CH₄**: 14%
- **Argon**: 36%
- **Waste**: 23%
- **Land Use Change**: 24%
- **Gas**: 15%
- **Oil**: 30%
- **Coal**: 31%
- **Rest**: 38%
- **Coal**: 9%
- **Oil & Gas**: 18%
- **Waste**: 23%
- **Agriculture**: 50%
- **Land Use Change**: 24%
- **Gas**: 15%
- **Oil**: 30%
- **Coal**: 31%
- **Rest**: 38%
- **Coal**: 9%
- **Oil & Gas**: 37%
- **Agriculture**: 50%
- **Land Use Change**: 24%
- **Gas**: 15%
- **Oil**: 30%
- **Coal**: 31%
- **Rest**: 38%
The Sleipner West field project in which around 1Mt of CO₂ per annum is stripped from natural gas recovered from beneath the North Sea and re-injected into a nearby deep saline formation.

Photo courtesy of Statoil
This is particularly true for coal because its use is growing in so many large economies, including the largest and fastest growing countries, such as China and India. There are two primary ways of reducing CO₂ emissions from coal use. The greatest potential is offered by CCS which can reduce CO₂ emissions to the atmosphere by 80-90%. Improving efficiencies at coal-fired power stations – meaning lower emissions per unit of energy output – also reduces CO₂ emissions and can be achieved immediately (see Figure 5).

**Carbon Capture & Storage**
CCS offers the potential for moving towards near-zero emissions to the atmosphere from coal-fired and gas-fired power stations. The scale of the potential has been outlined by the IPCC, which has stated: “in most scenarios for stabilisation of atmospheric greenhouse gas concentrations between 450 and 750ppmv CO₂ and in a least-cost portfolio of mitigation options, the economic potential of CCS would amount to 220-2200 Gigatonnes (Gt) CO₂ cumulatively, which would mean that CCS contributes 15-55% to the cumulative mitigation effort worldwide until 2100” [IPCC 2005].

While all the elements of CCS have been separately proven and deployed in various fields of commercial activity, a key aim is the successful demonstration of fully integrated large-scale CCS systems and optimisation of the various processes. Such large-scale demonstrations would help to lower costs and provide a critical mass of scientific data for proving that operations, monitoring, verification, and mitigation can be carried out in a manner acceptable to regulators and the public. Supporting policy and regulatory environments also have to be developed for these RD&D activities.
Post-combustion systems separate CO₂ from the flue gases produced by the combustion of coal in air. Post-combustion CO₂ capture technology, based on chemical absorption processes, is already proven and commercially available in the oil and gas industry. It is the closest to large-scale commercial deployment for power generation but not yet at the scale required.

Technical and commercial challenges lie in treating the very large quantities of exhaust gases required to achieve a high rate of CO₂ removal. Post-combustion capture is best suited to new build, high efficiency plant, although it can be retrofitted to existing high efficiency power plants.

Oxyfuel combustion involves combustion of coal in pure oxygen, rather than air, to fuel a conventional steam generator. By avoiding the introduction of nitrogen into the combustion cycle, the amount of CO₂ in the power station exhaust stream is greatly concentrated, making it easier to capture and compress. Oxyfuel combustion could be applied to otherwise conventional coal combustion plant with little modification; however some technical challenges have to be resolved and it is still at the small-scale demonstration phase (see Table 3).

Each of these options has its particular benefits. Post-combustion capture and oxyfuel have the potential to be retrofitted to existing coal-fired power stations and new plants constructed over the next 10-20 years. Pre-combustion capture utilising IGCC is potentially more flexible, opening up a wider range of possibilities for coal, including a major role in a future hydrogen economy.

CO₂ Capture
While CO₂ capture technologies are new to the power industry they have been deployed for the past sixty years by the oil, gas and chemical industries. They are an integral component of natural gas processing and of many coal gasification processes used for the production of syngas, chemicals and liquid fuels.

There are three main CO₂ capture processes under development for power generation.

Pre-combustion capture systems take the syngas produced from coal gasification (see page 30) and convert it via a steam-based chemical reaction into separate streams of CO₂ and hydrogen. This facilitates the collection and compression of the CO₂ into a supercritical (fluid-like) form suitable for transportation and geological storage. The hydrogen can be used to generate power in an advanced gas turbine and steam cycle or in fuel cells, or a combination of both. The gasification process also opens the way to the production of chemicals and synthetic transport fuels.
Table 3: Oxyfuel Demonstration Projects

<table>
<thead>
<tr>
<th>Demonstration Project</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS Energy (Australia/Japan Consortium) – Callide</td>
<td>Australia</td>
<td>30MWe pulverised coal plant, retrofit to Callide A Unit No. 4</td>
</tr>
<tr>
<td>Total – Lacq</td>
<td>France</td>
<td>30MW new build gas-fired oxyfuel boiler producing 150,000tpa supercritical CO₂ to be piped for storage in a depleted oil and gas reservoir</td>
</tr>
<tr>
<td>Vattenfall – Cottbus</td>
<td>Germany</td>
<td>30MWth lignite-fired new build plant</td>
</tr>
<tr>
<td>Jupiter Oxygen Corporation – Orrville</td>
<td>USA</td>
<td>25MWe pulverised coal retrofit of Orrville pressurised boiler</td>
</tr>
</tbody>
</table>

All of the technologies, however, require substantial investment in RD&D to prove their practicality and reduce costs. Significant scaling-up of existing capture systems is required (20-50 times) to handle the quantity of gas produced by a commercial power plant and to reduce the energy penalty\(^4\).

**CO₂ Transportation**

CO₂ is largely inert and easily handled and is already transported in high pressure pipelines. The technology for CO₂ transportation and its environmental safety are therefore well-established – it is no different from that used in the gas industry. There are already 3100km of pipelines for CO₂ worldwide, most of which are in North America transporting CO₂ for enhanced oil recovery (EOR) operations [IEAGHG 2006]. The means of transport depends on the quantity of the CO₂ to be transported, the terrain and the distance between the capture plant and the storage site. In general, pipelines are used for large volumes over shorter distances. In some situations or locations, transport of CO₂ by ship may be more economic, particularly when the CO₂ has to be moved over large distances or overseas.

To ensure the safety of transported CO₂, safety valves that stop a continuous outflow of CO₂ in the case of a pipeline rupture can be utilised. Careful monitoring is also essential.

**CO₂ Storage**

While there are a number of CO₂ storage options, geological storage offers the most significant potential\(^5\). As CO₂ is pumped deep underground, it is compressed by the higher pressures and becomes essentially a liquid, which then becomes trapped in the pore spaces between the grains of rock. There are a number of different types of geological trapping mechanisms (depending on the physical and chemical characteristics of the rocks and fluids) which can be utilised for CO₂ storage (see Table 4). The longer the CO₂ remains underground, the more securely it is stored (see Figure 8).

**Geological Storage**

Geological features being considered for CO₂ storage fall into three categories:

- deep saline formations
- depleted oil and gasfields
- unmineable coal seams

\(^4\) Energy Penalty – capturing CO₂ from power stations requires energy and therefore decreases efficiency levels.

\(^5\) While ocean storage has a larger storage capacity than geological formations, it is not considered an acceptable storage option.
Deep Saline Formations are underground formations of permeable reservoir rock, such as sandstones, that are saturated with very salty water (which would never be used as drinking water) and covered by a layer of impermeable cap rock (e.g. shale or clay) which acts as a seal. In the case of gas and oilfields, it was this cap rock that trapped the oil and gas underground for millions of years. CO₂ injected into the formation is contained beneath the cap rock. In time this dissolves into the saline water in the reservoir. CO₂ storage in deep saline formations is expected to take place at depths below 800m.

Saline formations have the largest storage potential globally but are the least well-explored and researched of the geological options. However, a number of storage projects are now using saline formations and have proven their viability and potential.

Depleted Oil and Gasfields are well-explored and geologically well-defined and have a proven ability to store hydrocarbons over geological time spans of millions of years. They usually have good reservoir characteristics that minimise CO₂ injection costs. CO₂ is already widely used in the oil industry for EOR from mature oilfields. When CO₂ is injected into an oilfield it can mix with the crude oil causing it to swell and thereby reducing its viscosity, helping to maintain or increase the pressure in the reservoir. The combination of these processes allows more of the crude oil to flow to the production wells (see Figure 9). In other situations, the CO₂ is not soluble in the oil\(^6\). Here, injection of CO₂ raises the pressure in the reservoir, helping to sweep the oil towards the production well. In EOR, the CO₂ can therefore have a positive commercial value.

The Weyburn-Beulah project, which combines CO₂ injection for EOR with CO₂ captured from coal gasification, is a good example of a large-scale operating system incorporating the key components of CCS. The good record of safety and containment associated with this large-scale subsurface injection activity, as well as with the associated surface transport of CO₂, provides confidence that these proven technologies can be widely applied in CCS.

\(^6\) It is dependent on the specific gravity of the oil – miscible flooding is when the oil is soluble and immiscible is when it is not.
### Table 4: Geological Trapping Mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>When the CO₂ is pumped deep underground, it is initially more buoyant than water and will rise up through the porous rocks until it reaches the top of the formation where it can become trapped by an impermeable layer of cap rock, such as shale. The wells that were drilled to place the CO₂ in storage can be sealed with plugs made of steel and cement.</td>
</tr>
<tr>
<td>Residual</td>
<td>Reservoir rocks acts like a tight, rigid sponge. When CO₂ is pumped into a rock formation, much of it becomes stuck within the pore spaces of the rock and does not move.</td>
</tr>
<tr>
<td>Dissolution</td>
<td>CO₂ dissolves in salty water, just like sugar dissolves in a hot drink. The water with CO₂ dissolved in it is then heavier than the water around it (without CO₂) and so sinks to the bottom of the rock formation.</td>
</tr>
<tr>
<td>Mineral</td>
<td>CO₂ dissolved in salt water is weakly acidic and can react with the minerals in the surrounding rocks, forming new minerals as a coating on the rock. This process can be rapid or very slow, depending on the chemistry of the rocks and water, and effectively binds the CO₂ to the rocks.</td>
</tr>
</tbody>
</table>

Source: IEAGHG/WCI 2007a

---

**Coal Seam** storage involves another form of trapping in which the injected CO₂ is adsorbed onto (accumulates on) the surface of the in situ coal in preference to other gases (such as methane) which are displaced. The effectiveness of the technique depends on the permeability of the coal seam. It is generally accepted that coal seam storage is most likely to be feasible when undertaken in conjunction with enhanced coalbed methane recovery (ECBM) in which the commercial production of coal seam methane is assisted by the displacement effect of the CO₂. One such pilot project conducted by Burlington Resources in the San Juan Basin, USA, involved the injection of approximately 277,000t of CO₂ from 1995-2001. It demonstrated that increased methane production can be achieved by CO₂ injection, and the fact that no CO₂ was found in the produced gas indicated that the injected CO₂ had been stored as predicted [IEAGHG 2007b].

---

**Figure 8: Trapping Mechanisms**

Source: IPCC 2005
The capture and utilisation of coal mine methane (CMM) provides a valuable fuel source as well as improving mine safety and reducing GHG emissions. CMM is recovered using gas drainage drill-hole systems, which were originally developed for safety reasons, but which are now also used to reduce the amount of methane released to the atmosphere during mining.

Currently only part of the global CMM resource is recovered in a suitable form to be used for heat or power production. However, utilisation is increasing rapidly, driven by growing demand for gas as well as by the need to mitigate GHG emissions. CMM is usually either sold into the pipeline market or used to generate power in mine-site power stations.

CMM is a significant source of energy in Australia and the USA and is of growing importance in a number of other countries, including China, Germany, Kazakhstan, Poland, Russia, Ukraine and the UK [USEPA 2006].

Methane accounts for around 14% of all global GHG emissions. Over 60% of total methane emissions are from human-related activities, including agriculture, rice cultivation, coal mining, landfills, and oil and natural gas systems. Methane emissions from coal mining account for around 9% of global anthropogenic methane emissions [WRI 2007].

Some coal types contain significant amounts of methane, the main component of natural gas, which can be a safety hazard in underground mines and contributes to climate change if released to the atmosphere.

CASE STUDY: COAL MINE METHANE

Xstrata Oaky Creek power station in Queensland, Australia, was commissioned in 2006 and is expected to save 341,000t CO₂e per annum. The gas-fired station uses methane extracted from the coal mine to generate electricity for supply to the national grid.

Photo courtesy of Xstrata
Mapping & Monitoring

The IPCC has stated that developing an improved picture of major CO₂ sources relative to suitable storage sites would facilitate decision-making about large-scale deployment of CCS. Projects are under way to improve knowledge of CO₂ geological storage potential, such as EU GeoCapacity and the Geological Storage of CO₂ from Fossil Fuel Combustion (GESTCO) projects in Europe and MIDCARB in the USA. These projects will help to decrease uncertainty around CO₂ storage and better understand risks and prospectivity. They will also allow more accurate estimates of storage capacity at the global, regional and local levels to be developed.

Storing CO₂ in geological formations is a secure option. According to the IPCC, the risk of leakage from geological storage was very likely7 to be less than 1% over 100 years and likely8 to be less than 1% over 1000 years. Industry has a large body of experience in this field with analogous technologies, such as natural gas storage, acid gas injection, and EOR.

A diverse portfolio of tools is available for monitoring CO₂ storage sites. Many of these are well-established and proven in other geological applications; some have been proven as viable in CO₂ demonstration projects; while other potentially useful techniques require further research and development. Monitoring techniques utilised include advanced seismic technology, soil and air gas measurements, gravimetry and airborne monitoring for potential CO₂ leaks.

Table 5: CO₂ Storage Potential

<table>
<thead>
<tr>
<th>Reservoir type</th>
<th>Estimate of Storage Capacity (Gt CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower limit</td>
</tr>
<tr>
<td>Deep saline formations</td>
<td>1000</td>
</tr>
<tr>
<td>Oil &amp; gasfields</td>
<td>675</td>
</tr>
<tr>
<td>Unmineable coal seams</td>
<td>3-15</td>
</tr>
</tbody>
</table>

Source: IPCC 2005

Figure 9: Schematic Diagram of CO₂-EOR

At the Sleipner project, advanced seismic technology is being used to monitor the behaviour of injected CO₂ in the Utsira Formation. Time-lapse seismic monitoring is showing that there is no observable CO₂ leakage, which strongly indicates that the cap rocks are sealing as expected. Simulations also suggest that the CO₂ ‘mega-bubble’ may reach its ultimate size after a few hundred years, thereafter shrinking and finally disappearing within a few thousand years.

7 Very likely is defined by the IPPC as a probability between 90-99%
8 Likely is defined by the IPCC as a probability between 66-90%
Time-lapse seismic monitoring is showing that there is no observable CO2 leakage, which strongly indicates that the cap rocks are sealing as expected.

**Figure 10: Geological Storage Options for CO2**

- Ultra clean fuels
- Clean electricity
- Enhanced Oil Recovery
- Unmineable Coal Seams
- Enhanced Coalbed Methane
- Deep Saline Formations
- Coal
- CCS Costs

The cost of CCS is project specific, depending on the technology of the plant producing the CO2 and on the proximity of that plant to adequate storage resources.

Natural gas processing, hydrogen and ammonia production, and some forms of coal gasification already produce a concentrated CO2 by-product and therefore incur no material additional capture cost. However, power generation, which currently produces relatively dilute CO2, incurs a substantial additional cost for capture.

Large-capacity, high-permeability storage reservoirs can store large volumes of CO2 with just a few injection wells and a minimum of compression, reducing storage costs. Low permeability reservoirs increase the number of required injection wells and the compression requirements, substantially increasing costs.

For power generation, the cost of CCS is estimated at between US$40 and US$90 per tonne of CO2 avoided, depending on the power plant fuel and technology used. For the most cost-effective technologies and storage sites:

- Capture costs are US$20-40 per tonne
- Transport and injection costs are about US$10 per tonne.

Subject to access to suitable storage sites, capture and compression costs dominate the overall cost of CCS for power generation, reducing these costs is therefore a priority. Over the next decade, the cost of capture could be reduced by 20-30% and more should be achievable by new technologies that are still in the research or demonstration phase [IPCC 2005].

For plants located close to oil and gas production, revenues from using CO2 for EOR could be substantial. EOR can provide a useful economic catalyst for the early deployment of CCS, even though it does not have the longer-term potential to absorb a significant proportion of forecast power generation CO2 emissions.

As with any technology, the cost of CCS will reduce over time as experience builds, economies of scale and standardisation take effect, and advances in the technology are achieved.

---

9 The quantity of CO2 emissions avoided is less than the quantity captured, because the energy consumed during capture results in additional CO2 production. The cost per tonne of CO2 captured would therefore be lower than the cost per tonne of emissions avoided.
### Table 6: Cost Ranges for Components of CCS System*

<table>
<thead>
<tr>
<th>CCS System Components</th>
<th>Cost Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture from coal- or gas-fired power plant</td>
<td>US$15–75 t/CO₂ net captured</td>
<td>Net costs of captured CO₂ compared to the same plant without capture</td>
</tr>
<tr>
<td>Capture from hydrogen &amp; ammonia production or gas processing</td>
<td>US$5–55 t/CO₂ net captured</td>
<td>Applies to high-purity sources requiring simple drying and compression</td>
</tr>
<tr>
<td>Transport</td>
<td>US$1–8 t/CO₂ transported</td>
<td>Per 250km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO₂/yr</td>
</tr>
<tr>
<td>Geological storage</td>
<td>US$0.5–8 t/CO₂ net injected</td>
<td>Excluding potential revenues from EOR or ECBM</td>
</tr>
<tr>
<td>Geological storage: monitoring &amp; verification</td>
<td>US$0.1–0.3 t/CO₂ injected</td>
<td>This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements</td>
</tr>
</tbody>
</table>

*Applied to a given type of power plant or industrial source

Source: IPCC 2007

### Table 7: Cost of Electricity for Different Power Plants with CCS

<table>
<thead>
<tr>
<th>Power Plant</th>
<th>Natural Gas Combined Cycle</th>
<th>Integrated Gasification Combined Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>COE without CCS (US$/MWh⁻¹)</td>
<td>43 – 52</td>
<td>31 – 50</td>
</tr>
<tr>
<td>COE with CCS (US$/MWh⁻¹)</td>
<td>63 – 99</td>
<td>43 – 77</td>
</tr>
<tr>
<td>[ % increase ]</td>
<td>[43 – 91]</td>
<td>[37 – 85]</td>
</tr>
<tr>
<td>CCS mitigation cost (US$/tCO₂ avoided)</td>
<td>30 – 71</td>
<td>38 – 91</td>
</tr>
<tr>
<td>COE with CCS &amp; EOR (US$/MWh⁻¹) [ % increase ]</td>
<td>49 – 81</td>
<td>37 – 70</td>
</tr>
<tr>
<td>[12 – 57]</td>
<td>[19 – 63]</td>
<td>[40 – 75]</td>
</tr>
<tr>
<td>CCS &amp; EOR Mitigation cost (US$/tCO₂ avoided)</td>
<td>9 – 44</td>
<td>19 – 68</td>
</tr>
<tr>
<td></td>
<td>(-7) – 31</td>
<td>(-7) – 31</td>
</tr>
</tbody>
</table>

COE = Cost of Electricity

Source: IPCC 2005
CCS Legal & Regulatory Framework

CO₂ injection for EOR is generally permitted under existing petroleum legislation, but there is no comparable regulatory regime in place for CCS. A whole new regime of enabling legislation, regulations and guidelines is therefore required. This would define resource access rights and obligations, govern post-storage operations and monitoring, and ensure that impacts on other resources and rights are appropriately managed. Guidelines and standards will also be required for the accreditation of CCS mitigation for the purposes of carbon pricing arrangements, such as emissions trading. Work has been under way in some jurisdictions for several years on the development of legal and regulatory regimes for CCS – most notably in Australia, the USA and in Europe.

Changes have been made to a number of international treaties to ensure they do not unnecessarily impede the development of CCS. The London Protocol has been amended to allow storage of CO₂ under the seabed from February 2007. The Protocol takes a precautionary approach and prohibits the dumping of wastes at sea, except for certain substances, listed in Annex 1 to the Protocol. ‘CO₂ streams from CO₂ capture processes for sequestration’ have been added to this list.

The OSPAR Convention has also been altered and now permits CCS in the North-East Atlantic. The decision allows the storage of CO₂ in sub-seabed geological formations and enters into force in January 2008.

The International Energy Agency (IEA) has also been undertaking work in this area, as part of its G8 Gleneagles Programme.

In October 2006, the IEA and the Carbon Sequestration Leadership Forum (CSLF) convened a workshop with legal experts, to discuss the range of legal issues associated with expanded use of CCS. The IEA has now released a report providing policymakers with a detailed summary of the main legal issues surrounding the CCS debate and recommendations to facilitate deployment.¹⁰

### Table 8: Coal-fired CCS Power Projects

A number of commercial scale integrated coal-fired CCS projects have been proposed.

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>MW</th>
<th>Expected Start-up</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZeroGen</td>
<td>Australia</td>
<td>50</td>
<td>2010</td>
<td>ZeroGen will involve IGCC power plant technology with CCS, with storage in a saline formation.</td>
</tr>
<tr>
<td>Hydrogen Energy -</td>
<td>Australia</td>
<td>500</td>
<td>Investment decision could be in 2011, with project in operation after three year construction period</td>
<td>Located in Kwinana, the power station will be a hydrogen-fuelled power project, enabling the capture and transportation of around 4Mt/CO₂ each year in a geological formation beneath the seabed of the Perth basin.</td>
</tr>
<tr>
<td>BP &amp; Rio Tinto</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GreenGen</td>
<td>China</td>
<td>250</td>
<td>2018</td>
<td>GreenGen will commission a 250MW IGCC plant by 2009, with scale-up in 2012 and full integration with CCS by 2018.</td>
</tr>
<tr>
<td>Dynamis - Hypogen</td>
<td>Europe</td>
<td>250</td>
<td>2012</td>
<td>The project is co-funded by the European Commission under the sixth Framework Programme (FP6) and consists of large-scale power generation using advanced power cycles with hydrogen-fuelled gas turbines. The project will investigate routes to large-scale co-production schemes for hydrogen and electricity with full integrated CO₂ management.</td>
</tr>
<tr>
<td>RWE</td>
<td>Germany</td>
<td>400–450</td>
<td>2014</td>
<td>The first of the RWE proposals will use IGCC technology and will be able to separate hydrogen after gas treatment and cleaning to use directly as an energy source or in synthetic fuel production. CO₂ will be stored in a depleted gas reservoir or saline formation.</td>
</tr>
<tr>
<td>Vattenfall</td>
<td>Germany</td>
<td>250</td>
<td>2020</td>
<td>Vattenfall are due to finish its 30MW CCS pilot plant in 2008. This pilot plant will provide a platform for the R&amp;D that is required to build a larger commercial scale plant (1000MW) by 2020.</td>
</tr>
</tbody>
</table>

Table continues on page 28
### Table 8: Coal-fired CCS Power Projects (continued)

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>MW</th>
<th>Expected Start-up</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progressive Energy</td>
<td>UK</td>
<td>800</td>
<td>2011</td>
<td>The Progressive Energy project will use IGCC and capture 5Mt/CO₂ per year to be used for EOR in the Central North Sea. The project will be able to operate on coal or petroleum coke with the possibility of including biomass.</td>
</tr>
<tr>
<td>Powerfuel</td>
<td>UK</td>
<td>900</td>
<td>Post-2012</td>
<td>The Powerfuel IGCC CCS project is to be located at the Hatfield Colliery, which re-opened in 2007.</td>
</tr>
<tr>
<td>E.On</td>
<td>UK</td>
<td>450</td>
<td>Post-2012</td>
<td>The E.On IGCC project will be co-located with its existing gas-fired power plant in Killingholme. The first phase of the project would be the construction of the power plant with CCS being added in the second phase.</td>
</tr>
<tr>
<td>E.On</td>
<td>UK</td>
<td>2x800</td>
<td>2015</td>
<td>E.On UK will build two new 800MW supercritical units at its Kingsnorth power station, once the current 4 x 485MW units have ceased operation by the end of 2015.</td>
</tr>
<tr>
<td>RWE nPower</td>
<td>UK</td>
<td>1000</td>
<td>2016</td>
<td>The second of the RWE proposals will investigate supercritical technology combined with post-combustion CCS at Tilbury. This is the largest of all the proposed CCS projects to date.</td>
</tr>
<tr>
<td>Carson Project</td>
<td>USA</td>
<td>500</td>
<td>2011</td>
<td>Hydrogen Energy, along with partner Edison Mission Energy, intends to use a gasifier to convert petroleum coke to H₂ and CO₂, and then use the H₂ as a fuel for a 500MW power station and store up to 5Mt/CO₂ per year underground.</td>
</tr>
<tr>
<td>FutureGen</td>
<td>USA</td>
<td>275</td>
<td>2012</td>
<td>FutureGen will use IGCC to produce electricity and H₂ as well as utilising CCS. The project is a partnership between the US Department of Energy and industry.</td>
</tr>
</tbody>
</table>
Efficiency Improvements

Increases in the efficiency of electricity generation are essential in tackling climate change. Not only do higher efficiency coal-fired power plants emit less CO₂ per megawatt, they are also more suited to retrofiting with CO₂ capture systems.

Efficiency improvements include the most cost-effective and shortest lead time actions for reducing emissions from coal-fired electricity. This is particularly the case in developing and transition countries where existing plant efficiencies are generally lower and coal use in electricity generation is increasing.

Improving the efficiency of pulverised coal-fired (PCF) plants has been the focus of considerable efforts by the coal industry. Significant efficiency improvements and CO₂ reductions can be achieved as the existing fleet of power plants are replaced over the next 10-20 years with new, higher efficiency supercritical (SC) and ultra-supercritical (USC) plants (see Table 9 and Figure 5). A one percentage point improvement in the efficiency of a conventional pulverised coal combustion plant results in a 2-3% reduction in CO₂ emissions, depending on the level of efficiency prior to the change.

Supercritical & Ultra-supercritical Technology

New pulverised coal combustion systems – utilising supercritical and ultra-supercritical technology – operate at increasingly higher temperatures and pressures and consequently achieve higher efficiencies than conventional PCF units and significant CO₂ reductions.

Supercritical steam cycle technology has been used for decades and is becoming the system of choice for new commercial coal-fired plants in many countries. Recent plant built in Europe and Asia use supercritical boiler-turbine technology and China has made this standard on all new plant 600MWe and upwards.

>> In China, more than 60GW of SC units were ordered over 2004-2005. By the end of 2006, the total number of large SC units was 26, with China currently constructing around two units a week [IEA CCC 2007]. The first of four 1000MWe ultra-supercritical units using Siemens technology is now under construction at Yuhuan [IEA 2006b].

>> In India, the first of three 660MWe SC units are under construction by Doosan at Sipat. Another SC project is under way – the Bahr Super Thermal Power Plant in Bihar, which is again three 660MW units. Several other pithead SC projects are also under consideration. India has announced plans for a series of ~4000MW ‘ultra-mega’ power projects and at the end of 2006 the first two projects (in Gujarat and Madhya Pradesh) were awarded to successful bidders [WCI 2006].

>> There are currently over 20 new SC projects proposed or in the pipeline in the USA. Many are due to come on line 2009-2011.

### Table 9: Average Efficiency Levels at Pulverised Coal-fired Power Plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Low Efficiency</th>
<th>Higher Efficiency</th>
<th>Supercritical</th>
<th>Ultra-supercritical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Efficiency Levels:</td>
<td>29%</td>
<td>39%</td>
<td>Up to 46%</td>
<td>50-55%</td>
</tr>
</tbody>
</table>

Source: Doosan Babcock
Other countries currently using or proposing to adopt SC/USC include Canada, Czech Republic, Denmark, Germany, Italy, Japan, Mexico, Poland, Russia, South Africa, South Korea, Chinese Taipei and the UK [IEA 2006b].

Research and development is under way for ultra-supercritical units operating at even higher efficiencies, potentially up to around 50%. The introduction of ultra-supercritical technology has been driven over recent years in countries such as Denmark, Germany and Japan, in order to achieve improved plant efficiencies and reduce fuel costs. Research is focusing on the development of new steels for boiler tubes and on high alloy steels that minimise corrosion. These developments are expected to result in a dramatic increase in the number of SC plants and USC units installed over coming years.

Integrated Gasification Combined Cycle

An alternative to achieving efficiency improvements in conventional pulverised coal-fired power stations is through the use of gasification technology. IGCC plants use a gasifier to convert coal (or other carbon-based materials) to syngas, which drives a combined cycle turbine (see Figure 11).

Coal is combined with oxygen and steam in the gasifier to produce the syngas, which is mainly H₂ and carbon monoxide (CO). The gas is then cleaned to remove impurities, such as sulphur, and the syngas is used in a gas turbine to produce electricity. Waste heat from the gas turbine is recovered to create steam which drives a steam turbine, producing more electricity – hence a combined cycle system.
Gasification offers a further potential option for coal through the utilisation of underground coal gasification (UCG). UCG is a method of injecting air or oxygen into a coal seam to support an in-situ gasification process. This process converts the un-mined coal into a combustible gas, which can be brought to the surface to be used for industrial heating or power generation. Current UCG projects are relatively small-scale, but if the process can be developed as a reliable, large-scale source of coal syngas, it could also potentially be used to feed capital intensive plants producing hydrogen, synthetic natural gas or diesel fuel. UCG in combination with CCS is also recognised as a potential route to carbon abatement from coal. A number of issues remain to be fully resolved before wider deployment can be achieved.

By adding a ‘shift’ reaction additional hydrogen can be produced and the CO can be converted to CO₂ which can then be captured and stored. IGCC efficiencies typically reach the mid-40s, although plant designs offering around 50% efficiencies are achievable. There are currently four commercial-scale, coal-based IGCC demonstration plants worldwide (Table 9) and a number of other IGCC projects have been proposed (see Table 8). IGCC plants also operate at Schwarze Pumpe in Germany and Vresova in the Czech Republic.

Gasification may be one of the best ways to produce clean-burning hydrogen for tomorrow’s cars and power-generating fuel cells. Hydrogen and other coal gases can be used to fuel power-generating turbines, or as the chemical building blocks for a wide range of commercial products, including diesel and other transport fuels.

Reliability and availability have been challenges facing IGCC development and commercialisation. Cost has also been an issue for the wider uptake of IGCC as they have been significantly more expensive than conventional coal-fired plant. It has been suggested that the first large-scale commercial IGCC plants have a 20-25% premium over pulverised coal plant. However, as IGCC is deployed, that premium is expected to be reduced to 10% or less [GE2007].

---

11 Introducing steam between the cooler and the gas clean-up.
Major technological change is needed to reconcile future energy needs with deep, lasting cuts in GHG emissions.
The coal industry recognises that climate change is a significant challenge facing the world today.

Coal is currently one of the biggest sources of anthropogenic CO₂ emissions to the atmosphere. It therefore has to be fully involved in meeting the climate change challenge through international RD&D of advanced coal technologies. An effective and sustainable response to climate change has to take account of the following factors:

- Fossil fuels will continue to dominate energy supplies for the conceivable future. Within this context, coal use will continue to grow solidly, remaining the leading fuel for power generation and an essential input for steelmaking and other industrial uses.

- A sustainable energy future will involve a more, not less, diverse range of options encompassing low emissions fossil fuel technologies, nuclear power and renewables, alongside widespread improvements in energy efficiency.

- Major technological change is needed to reconcile future energy needs with deep, lasting cuts in GHG emissions.

- Near-zero emissions to atmosphere through CCS will play a vital role.

- Improving the efficiency of existing coal-fired power stations and investing in best available technology for new plants is essential, particularly in developing countries.

- Substantial investment in coal production and use is already needed over the next two decades to ensure global energy security and help alleviate energy poverty. The additional investments associated with the development and up-take of near-zero emissions to atmosphere coal use will require carefully targeted policy support and close international cooperation.

- The transition to sustainable energy use will also require visionary planning. Short term, purely market driven reactions are an inadequate response to a problem of the scale and duration of climate change. Lasting global solutions are needed.

The coal industry has become more proactive in its response to climate change and is taking significant steps to ensure it is part of the solution. The industry is working with researchers, technology providers, energy generators and governments around the world as part of its response to climate change and to push forward the deployment of near zero emissions technologies (see Table 11). Success in achieving a sustainable energy future will include:

- Continued reductions in the emissions intensity of conventional coal-fired power. This can be achieved through the application of best available commercial standards to new generating capacity in developed and developing countries.
Preparing for commercial near-zero emission to atmosphere coal technologies by incorporating the potential for subsequent retrofit of CCS into the planning of new coal-fired plant; where feasible, new plant should be designed and situated to be ‘CCS-ready’.

The mapping and exploration of the world’s CO2 storage resources has barely begun and must be dramatically stepped up to provide a platform for the large-scale investments required for CCS demonstration and subsequent commercial plants.

Increased cooperation between different stakeholders in order to optimise resources, avoid duplication and maximise synergies.

Policy Certainty
For their part, governments need to provide a supportive policy framework that recognises the continuing role of coal and the need to work with industry in accelerating the development and adoption of near-zero emissions to atmosphere coal technologies. This includes establishing a high degree of long-term policy certainty to facilitate the large, risky investments needed in new and innovative energy systems over the typical 30 year investment periods.

Collaboration
The public/private partnership route is going to be critical to a sustainable energy future. It is clear that neither industry nor government alone can deliver the technologies required to achieve the emissions reduction trajectory assessed by the IPCC. The first power plants equipped with CCS are going to be the most costly, but will provide essential operational experience from which much will be learnt to enable cost reductions in the plants that follow. Government support will be required to enable the private sector to invest in this technology until it comes down the cost curve and is able to operate commercially under the prevailing market conditions (see Figure 12).

Large-scale Integrated Projects
There is a pressing need for significantly more large-scale, integrated coal-based CCS demonstration projects if commercial readiness is to be achieved by 2020. Governments and industry must together address the present shortage of sizeable RD&D projects in order to advance technological understanding, increase efficiency and drive costs down.

RD&D for CCS would represent a five-fold increase in the current global government CCS budget – not insurmountable given the scale of past energy R&D budgets. It would represent a 30% increase in the current total R&D budget for fossil fuels, power and storage technologies. Leveraging funds in private/public partnerships will be essential [IEA 2006b].
### Table 11: Examples of Research Programmes/Initiatives Supported by the Coal Industry

<table>
<thead>
<tr>
<th>Research Programmes/Initiatives</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asia-Pacific Partnership on Clean Development and Climate (AP6)</strong></td>
<td>AP6 consists of representatives from Australia, China, India, Japan, South Korea and the USA who are working together to develop cleaner, more efficient technologies that will meet climate concerns without negatively affecting economic growth. AP6’s Cleaner Fossil Fuels Taskforce aims to accelerate the development and deployment of technologies through collaborative research and on-going demonstration in order to reduce costs and facilitate the availability of a range of accessible and affordable low-emission technologies.</td>
</tr>
<tr>
<td><strong>Carbon Sequestration Leadership Forum (CSLF)</strong></td>
<td>CSLF is an international climate change initiative that is focused on the development of cost-effective technologies for CCS. CSLF aims to make these technologies broadly available internationally and to identify and address wider issues relating to CCS. CSLF is currently comprised of 22 members, including 21 countries and the European Commission.</td>
</tr>
<tr>
<td><strong>COAL21 Fund</strong></td>
<td>The Australian coal industry launched the COAL21 Fund in March 2006 to support the financing of near-zero emission coal demonstration projects and associated R&amp;D. The Fund is being raised by an A$0.20 per tonne voluntary levy on coal producers that is expected to raise up to A$1 billion over the next ten years. Through the COAL21 Fund, the Australian coal industry will work with governments, electricity generators and researchers to advance knowledge and commercial-readiness of low emissions energy technology.</td>
</tr>
<tr>
<td><strong>Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)</strong></td>
<td>CO2CRC is a collaborative research organisation – involving industry, research parties, international collaborators, and government organisations – focused on the development and application of technologies to more effectively capture and geologically store CO2.</td>
</tr>
<tr>
<td><strong>EPRI 66 CoalFleet for Tomorrow</strong></td>
<td>The EPRI 66 CoalFleet for Tomorrow programme is tackling the technical and economic/institutional challenges to making advanced, near-zero emission coal power plants a good investment option. This industry-led programme provides a vehicle for collaborative RD&amp;D on deployment-related issues for near-term plants.</td>
</tr>
<tr>
<td><strong>European Technology Platform on Zero Emission Fossil Fuel Power Plants (ETP ZEP)</strong></td>
<td>The European Commission, European energy industry, research community and NGOs have established a European Technology Platform on Zero Emission Fossil Fuel Power Plants (ETP ZEP). The Platform aims to develop and deploy new competitive options for near-zero emission fossil power plants within the next 15 years.</td>
</tr>
<tr>
<td><strong>IEA G8 Gleneagles Programme</strong>*</td>
<td>Under the G8 Gleneagles Plan of Action, the IEA is working with partners around the globe to focus on climate change, clean energy and sustainable development. The IEA’s G8 Gleneagles Programme is promoting energy-sector innovation, better practice and use of enhanced technology. This includes programmes focusing on cleaner fossil fuels and CCS.</td>
</tr>
</tbody>
</table>

* The IEA Clean Coal Centre (IEA CCC) and IEA Greenhouse Gas R&D Programme (IEA GHG) are also active in this area. IEA CCC provides information on the sustainable use of coal worldwide, including reports and online databases of coal information. IEA CCC also provides direct advice, facilitation of RD&D and networks. IEA GHG is an international collaborative research programme which focuses on studying technologies to reduce GHG emissions.
Regulatory & Legal Frameworks

A commitment to CCS needs to be complemented by regulatory and legal frameworks for CO₂ storage that provide policy certainty for project proponents and address the technical issues and uncertainties associated with projects. These frameworks also need to be based on public understanding and acceptance of the role of CCS in a global GHG response. They need to provide public assurance that the safety and environmental integrity of geological storage activities will be adequately managed. Important steps have been taken in these areas, such as the changes to the London Protocol and OSPAR Convention, which have created a basis in international environmental law to regulate storage of CO₂ in sub-seabed geological formations.

Financing the Future

Actions are needed by governments, industry and financial institutions to create a suitable investment framework for a sustainable energy future. Some governments have elected to take part in emissions trading schemes as a means of meeting the challenge. A fundamental consideration must be to ensure that whatever mechanisms are chosen, they lead to a sustainable energy future and not simply to short-term solutions. A number of institutions are taking positive steps in this area.

- The World Bank is working on an Investment Framework for Clean Energy and Development. This framework will catalyse investments from public and private sources to increase access to energy in developing countries, while using cleaner technologies that protect the environment.

- The United Nations Development Programme Global Environment Facility (UNDP GEF) is providing a grant of US$45.4 million to co-finance coal-fired power generation rehabilitation projects in India. The project will improve efficiency levels at coal-fired power stations, while ensuring that demand for energy is met. The loan will leverage an additional US$299.7 million from the World Bank and the Indian government, taking the total to US$345 million.
In China, many companies have undertaken bilateral efforts to facilitate access to clean coal technologies. Multilateral institutions, such as development banks and the Global Environment Facility have also been active in this field [IEA 2005]. China is also emerging as a significant investor in overseas energy projects – the China Development Bank, for example, has assets bigger than the World Bank and Asian Development Bank combined [FT 2007].

The European Commission’s new energy policy was launched at the beginning of 2007 and includes a number of commitments on cleaner fossil fuels. The Commission has stated that by 2020 all new coal-fired power plants should be fitted with CCS and existing plants should then progressively follow the same approach. To help support this commitment, the energy programme under 7th Framework Programme for Research and Technological Development (FP7) will target CCS and clean coal technologies.

It is also vital that the Kyoto Protocol’s ‘Flexibility Mechanisms’ – the Clean Development Mechanism (CDM), Joint Implementation (JI) and Emissions Trading – are adapted so that they can be used to accommodate large-scale CO₂ mitigation projects, such as CCS. An important step has been the recent approval by the CDM Executive Board (CDM EB) of a “Consolidated Methodology for New Grid Connected Fossil Fuel-Fired Power Plants Using a Less GHG Intensive Technology”. The new methodology allows Certified Emissions Reduction (CERs) credits to be issued for the CO₂ emissions saved as a result of using efficient combustion technologies on new power plants relative to the standard technology deployed in that geographical region.

Cap and trade systems can be a helpful but not sufficient condition for promoting the wide-scale development of a balanced sustainable energy system, including the utilisation of CCS. However, significant government assistance to promote CCS as a public good is also required in the near-term.

**Realising the Vision**

The coal industry is contributing to a sustainable energy future. In addition to supporting specific demonstration projects, it is actively involved in international initiatives aimed at pushing technologies forward (Table 11). It also believes that with CCS, near-zero CO₂ emissions to the atmosphere from coal-fired power stations are achievable and can play a major role in meeting the global challenge of climate change.
The nature of the impact is dependent on the specific generation technology used and may include concerns over land and water resource use, pollutant emissions, waste generation and public health and safety concerns. The use of coal for power generation is not exempt from these impacts and has been associated with a number of environmental challenges, primarily associated with air emissions. Coal has demonstrated the ability to meet such challenges in the past and the expectation is that it will successfully meet future environmental challenges.

Reducing Pollution
Technologies are now available to improve the environmental performance of coal-fired power stations for a range of pollutants. In many cases a number of technologies are available to mitigate any given environmental impact (see Table 12). Which technology option is eventually selected for a power plant will vary depending on its specific characteristics such as location, age, and fuel source. The maturity of environmental technologies varies substantially, with some being widely deployed and available ‘off the shelf’ to new innovative technologies which are still in the demonstration phase.

A key strategy in the mitigation of coal’s environmental impacts is to improve the energy efficiency of power plants. Efficient plants burn less coal per unit of energy produced and consequently have lower associated environmental impacts. Efficiency improvements, particularly those related to combustion technologies, are an active area of research and an important component of a climate change mitigation strategy (these technologies are covered in more detail in Section 2).

Mined coal is of variable quality and is frequently associated with mineral and chemical material including clay, sand, sulphur and trace elements. Coal cleaning by washing and beneficiation removes this associated material, prepares the coal to customer specifications and is an important step in reducing emissions from coal use.

Coal cleaning reduces the ash content of coal by over 50% resulting in less waste, lower sulphur dioxide (SO₂) emissions and improved thermal efficiencies, leading to lower CO₂ emissions. While coal preparation is standard practice in many countries, greater uptake in developing countries is needed as a low-cost way to improve the environmental performance of coal. Only around 11% of thermal coal in China, for example, is currently washed. If a greater proportion of this coal were cleaned, there is the potential for thermal efficiency improvements of at least 2-3% and possibly up to 4-5% [IEACCC 2003a].

ANNEX

OTHER ENVIRONMENTAL CHALLENGES

The deployment of all energy generating technologies invariably leads to some degree of environmental impact.
Particulates

Particulate emissions are finely divided solid and liquid (other than water) substances that are emitted from power stations. Particulates can affect people’s respiratory systems, impact local visibility and cause dust problems. A number of technologies have been developed to control particulate emissions and are widely deployed in both developed and developing countries, including:

- electrostatic precipitators
- fabric filters or baghouses
- wet particulate scrubbers
- hot gas filtration systems.

Electrostatic precipitators (ESP) are the most widely used particulate control technology and use an electrical field to create a charge on particles in the flue gas in order to attract them to collecting plates.

Fabric filters collect particulates from the flue gas as it passes through the tightly woven fabric of the bag. Both ESP and fabric filters are highly efficient, removing over 99.5% of particulate emissions. Wet scrubbers are used to capture both particulates and sulphur dioxide by injecting water droplets into the flue gas to form a wet by-product. The addition of lime to the water helps to increase SO₂ removal.

Hot gas filtration systems operate at higher temperatures (260-900°C) and pressures (1-3 MPa) than conventional particulate removal technologies, eliminating the need for cooling of the gas, making them suitable for modern combined-cycle power plants such as IGCC. A range of hot gas filtration technologies have been under development for a number of years but further research is needed to enable widespread commercial deployment.

Acid Rain

During the late 20th century, rising global concerns over the effects of acid rain led to the development and utilisation of technologies to reduce emissions of sulphur dioxide and nitrogen oxides (NOₓ). The formation of SO₂ occurs during the combustion of coals containing sulphur and can lead to acid rain and acidic aerosols (extremely fine air-borne particles). A number of technologies, collectively known as flue gas desulphurisation (FGD), have been developed to reduce SO₂ emissions (see Figure 12). These typically utilise a chemical sorbent, usually lime or limestone, to remove sulphur dioxide from the flue gas. FGD technologies have been installed in many countries and have led to enormous reductions in emissions (see Sulphur Dioxide case study on page 42).

The combustion of coal in the presence of nitrogen, from either the fuel or air, leads to the formation of nitrogen oxides. The release of NOₓ to the atmosphere can contribute to smog, ground level ozone, acid rain and GHG emissions. Technologies to reduce NOₓ emissions are referred to as either primary abatement and control methods or as flue gas treatment.
Primary measures include the use of low NOx burners and burner optimisation techniques to minimise the formation of NOx during combustion. These primary control measures are routinely included in newly built power stations and may also be retrofitted when reductions in NOx emissions are required. Alternatively technologies such as Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) lower NOx emissions by treating the NOx post-combustion in the flue gas. SCR technology has been used commercially for almost 30 years and is now deployed throughout the world, removing between 80-90% of NOx emissions at a given plant.

Research is under way to develop combined SO2/NOx removal technologies. Such technologies are technically challenging and expensive but new advances hold the promise of overcoming these issues. This would allow the deployment of these combined technologies to be realised at a lower cost than separate SO2 and NOx removal equipment. Combined SO2/NOx units have been developed and are already used in a number of countries for low and medium-sulphur coal-fired power plants.

Trace Elements
Coal is a chemically complex substance, naturally containing many trace elements including mercury, selenium and arsenic. The combustion of coal can result in trace elements being released from power stations with potentially harmful impacts to both human health and the environment.

A number of technologies are used to limit the release of trace elements including coal washing, particulate control devices, fluidised bed combustion, activated carbon injection and FGDs. The choice of mitigation technology will be dependent on the trace elements present and local air quality standard objectives. Research is ongoing to develop better sorbents and reagents that will improve the performance of FGD with respect to trace element removal.

Waste
The combustion of coal generates waste consisting primarily of non-combustible mineral matter along with a small amount of unreacted carbon. The production of this waste can be minimised by coal cleaning prior to combustion. This represents a cost-effective method of providing high quality coal, while helping to reduce power station waste and increasing thermal efficiencies. Waste can be further minimised through the use of high efficiency coal combustion technologies.

There is increasing awareness of the opportunities to reprocess power station waste into valuable materials for use primarily in the construction and civil engineering industry. A wide variety of uses have been developed for coal waste including boiler slag for road surfacing, fluidised bed combustion waste as an agricultural lime and the addition of fly ash to cement.
<table>
<thead>
<tr>
<th>Environmental Challenges</th>
<th>Technological Response</th>
<th>Maximum Reduction Achievable</th>
<th>Deployment Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particulates</strong></td>
<td>Hot gas filtration</td>
<td>98%</td>
<td>Conventional technologies widely deployed in both developed and developing countries.</td>
</tr>
<tr>
<td>Impact: Human health; dust; visibility</td>
<td>Wet particulate scrubbers</td>
<td>99.9%</td>
<td>New technologies under development for use with advanced combustion technologies, such as combined cycle.</td>
</tr>
<tr>
<td></td>
<td>Electrostatic precipitators</td>
<td>99.99%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fabric filters</td>
<td>&gt;99.9999%</td>
<td></td>
</tr>
<tr>
<td><strong>Sulphur Dioxide</strong></td>
<td>Sorbent injection process</td>
<td>90%</td>
<td>Technologies mature and widely deployed in developed countries, greater deployment in developing countries needed.</td>
</tr>
<tr>
<td>Impact: Acid deposition; human health</td>
<td>Regenerable systems</td>
<td>&gt;95%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spray dry scrubbers</td>
<td>&gt;95%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry scrubbers</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combined SO₂/NOₓ removal</td>
<td>&gt;98%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wet scrubbers</td>
<td>99%</td>
<td></td>
</tr>
<tr>
<td><strong>Nitrogen Oxides</strong></td>
<td>Flue gas recirculation</td>
<td>&lt;20%</td>
<td>Technologies widely deployed in developed countries, greater deployment in developing countries needed.</td>
</tr>
<tr>
<td>Impact: Acid deposition; greenhouse gas; smog; ground level ozone</td>
<td>Burner optimisation</td>
<td>39%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selective Non Catalytic Reduction</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air staging</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel staging</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low NOₓ burners</td>
<td>70%</td>
<td>Current reductions are offset by increasing fuel use</td>
</tr>
<tr>
<td></td>
<td>Combined SO₂/NOₓ removal</td>
<td>80%</td>
<td>necessitating new improved technologies to enable further reductions.</td>
</tr>
<tr>
<td></td>
<td>Selective Catalytic Reduction</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td><strong>Mercury</strong></td>
<td>Wet scrubbers</td>
<td>26%</td>
<td>Abatement technologies for other pollutants, such as particulates, reduce mercury emissions.</td>
</tr>
<tr>
<td>Impact: bio-accumulates in environment; toxic</td>
<td>Electrostatic precipitators</td>
<td>42%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coal washing</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Baghouses</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modified ESP + sorbents</td>
<td>&gt;90%</td>
<td>Research to develop specific mercury control technologies in response to regulations on mercury emissions is being undertaken.</td>
</tr>
<tr>
<td></td>
<td>and/or flue gas cooling</td>
<td>&gt;90%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry scrubbers + sorbents</td>
<td>&gt;90%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wet scrubbers</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td><strong>Fly Ash</strong></td>
<td>Utilisation as construction and civil engineering materials</td>
<td>100%</td>
<td>Fly ash can be used for a wide variety of purposes. The proportion used in countries is typically dependent on environmental regulations regarding waste disposal.</td>
</tr>
</tbody>
</table>

Source: IEA CCC
Over the last century there has been a huge increase in the use of fossil fuels, notably coal, for power generation as populations have grown and economies developed – and energy demand has risen. This led to large increases in the quantities of SO$_2$ being released into the atmosphere as a result of human activities. Coal use contributed over half of the human induced SO$_2$ emissions. At the beginning of the 20th century it was estimated that human activities resulted in the release of 20Mt SO$_2$ annually; by 1950 this had risen to 58Mt and to 140Mt by 1985.

The environmental impacts of SO$_2$ emissions have led many countries to implement legislation to reduce emissions. The measures deployed vary according to national circumstances and preferences and include internationally agreed emissions ceilings, plant emissions standards and market-based incentives, such as emissions trading and SO$_2$ taxes.

The development and deployment of SO$_2$ emission reduction technologies has succeeded in breaking the link between coal use and SO$_2$ emissions. In the US, for example, the use of coal for electricity generation has risen by over 77% since 1980 but during this same period SO$_2$ emissions have declined by over 40% (Figure 13). This success has been mirrored at the global level, with SO$_2$ emissions in 2000 20% lower than 1990 emissions. To date the reductions have been driven by significant improvements in developed regions which has offset rising emissions in some developing countries (Table 13). Clearly the widespread transfer of SO$_2$ mitigation technology to developing countries is needed to enable further emissions reductions to be achieved.
Table 13: Estimated World Anthropogenic
SO₂ Emissions (Mt) for Selected Years*

<table>
<thead>
<tr>
<th>Region</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Saharan Africa</td>
<td>4.8</td>
<td>4.9</td>
<td>5.4</td>
</tr>
<tr>
<td>Centrally Planned Asia and China</td>
<td>22.0</td>
<td>25.4</td>
<td>28.4</td>
</tr>
<tr>
<td>Central and Eastern Europe</td>
<td>11.1</td>
<td>8.1</td>
<td>5.9</td>
</tr>
<tr>
<td>Latin America and Caribbean</td>
<td>6.7</td>
<td>7.8</td>
<td>6.2</td>
</tr>
<tr>
<td>Middle East and North Africa</td>
<td>3.1</td>
<td>4.2</td>
<td>5.0</td>
</tr>
<tr>
<td>North America</td>
<td>24.4</td>
<td>20.3</td>
<td>18.5</td>
</tr>
<tr>
<td>Newly Independent States</td>
<td>19.5</td>
<td>12.2</td>
<td>11.1</td>
</tr>
<tr>
<td>Pacific OECD</td>
<td>2.7</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Other Pacific Asia</td>
<td>5.1</td>
<td>5.0</td>
<td>4.3</td>
</tr>
<tr>
<td>South Asia</td>
<td>4.8</td>
<td>6.4</td>
<td>7.6</td>
</tr>
<tr>
<td>Western Europe</td>
<td>17.9</td>
<td>11.7</td>
<td>7.9</td>
</tr>
<tr>
<td>World Total</td>
<td>122.1</td>
<td>108.5</td>
<td>102.9</td>
</tr>
</tbody>
</table>

* Emissions from biomass burning, international shipping and aircraft are not included
Source: IEA CCC 2006a
REFERENCES


>> Doosan Babcock, Information supplied directly to World Coal Institute from Doosan Babcock


>> IEA 2006a, World Energy Outlook, OECD/IEA, Paris

>> IEA 2006b, Energy Technology Perspectives 2006: Scenarios & Strategies to 2050, OECD/IEA, Paris


>> IEA 2007a, Coal Information 2007, OECD/IEA, Paris

>> IEA 2007b, Electricity Information 2007, OECD/IEA, Paris

>> IEA CCC 2003a, Improving Efficiencies of Coal-fired Power Plants in Developing Countries, IEA Clean Coal Centre, London

>> IEA CCC 2003b, Trace Elements – Occurrence, Emissions & Control, IEA Clean Coal Centre, London

>> IEA CCC 2005, Utilisation of Ashes, Slags & Residues, IEA Clean Coal Centre, London

>> IEA CCC 2006a, Trends in SO2 emissions, IEA Clean Coal Centre, London

>> IEA CCC 2006b, NOx Emissions & Control, IEA Clean Coal Centre, London

>> IEA CCC 2007, Information supplied directly to World Coal Institute by IEA Clean Coal Centre

IEAGHG/WCI 2007a, Storing CO₂ Underground, IEA Greenhouse Gas R&D Programme & World Coal Institute, Cheltenham/London


MIT 2007, The Future of Coal, Massachusetts Institute of Technology, Cambridge, USA

NMA 2005, Clean Coal Technology, Current Progress, Future Promise, National Mining Association, Washington DC

UNFCCC http://unfccc.int

USEPA 2006, CMM Global Overview, prepared by the US Environmental Protection Agency Coalbed Methane Outreach Program in Support of The Methane to Markets Partnership, Washington DC

WCI 2006, “Clean Coal Technologies in India”, prepared by IEA Clean Coal Centre, Ecoal, July 2006, Volume 58, World Coal Institute, London

WRI 2007, World Resources Institute, www.wri.org
FURTHER READING

>> Asia Pacific Partnership on Clean Development & Climate
   www.asiapacificpartnership.org

>> BP
   www.bp.com

>> Carbon Capture & Storage Association
   www.ccsassociation.org.uk

>> Carbon Sequestration Leadership Forum
   www.csilforum.org

>> COAL21

>> Cooperative Research Centre for GHG Technologies
   www.co2crc.com.au

>> CS Energy
   www.csenergy.com.au

>> Doosan Babcock
   www.doosanbabcock.com

>> Dynamis Hypogen
   www.dynamis-hypogen.com

>> E.On
   www.eon.com

>> EPCOR
   www.epcor.com

>> EPRI
   www.epri.com

>> European Technology Platform on Zero Emission Fossil Fuel Power Plants
   www.zero-emissionplatform.eu

>> FutureGen
   www.futuregenalliance.org

>> Hydrogen Energy
   www.hydrogenenergy.com

>> IEA Clean Coal Centre
   www.iea-coal.org.uk

>> IEA G8 Gleneagles Programme
   www.iea.org/G8/index.asp

>> IEA Greenhouse Gas R&D Programme
   www.ieagreen.org.uk

>> International Maritime Organization
   www.imo.org

>> IPCC
   www.ipcc.ch

>> Jupiter Oxygen Corporation
   www.jupiteroxygen.com

>> Monash Energy
   www.monashenergy.com.au
>> Powerfuel  
www.powerfuel.plc.uk

>> Progressive Energy  
www.progressive-energy.com

>> RWE  
www.rwe.com

>> Snøhvit Project  
www.snohvit.com

>> Statoil  
www.statoil.com

>> Total  
www.total.com

>> Tyndall Centre, “Investment for Innovation, a Briefing Document for Policymakers”, Tyndall Briefing Note No. 13, April 2005, Tyndall Centre for Climate Change Research

>> UCG Partnership  
www.ucgpartnership.com

>> UN, “Confronting Climate Change: Avoiding the Unmanageable & Managing the Unavoidable”, UN Foundation, Washington DC, 2007

>> UNFCCC  
http://unfccc.int

>> US Department of Energy  
www.energy.gov/energysources/coal.htm

>> Vattenfall  
www.vattenfall.com

>> World Bank  
www.worldbank.org

>> World Business Council for Sustainable Development  
www.wbcsd.org

>> World Resources Institute  
www.wri.org

>> ZeroGen  
www.zerogen.com.au
World Coal Institute

The World Coal Institute is the only organisation working on a global basis on behalf of the coal industry.

The World Coal Institute promotes:

» Coal as a strategic resource, essential for a modern quality of life, a key contributor to sustainable development and an essential element in enhanced energy security.

» A progressive industry, committed to technological innovation and improved environmental outcomes within the context of a balanced and responsible energy mix.

The objectives of the World Coal Institute are to:

» Provide a voice for coal in international policy discussions on energy and the environment;

» Promote the role of clean coal technologies in improving the environmental performance of coal;

» Highlight the valuable role affordable and abundant coal resources play in a world ever more concerned with energy security;

» Improve understanding of the importance of coal as the single largest source of fuel for electricity generation, and its vital role in other industries – including steel production, cement manufacturing, chemicals and liquid fuels;

» Form strategic partnerships and alliances to coordinate actions and maximise resources to improve the perception of coal worldwide;

» Ensure decision-makers and opinion formers are fully informed of the contribution of coal to social and economic development;

» Address misconceptions about coal through the production and dissemination of information resources.

The World Coal Institute has strong contacts and relationships with important international agencies, including the International Energy Agency and the World Bank, and has accredited consultative status with the United Nations.

Membership is open to coal enterprises worldwide, including coal associations, with members represented at Chief Executive level.