COAL RESEARCH FORUM

COAL RESEARCH AND ENGINEERING NEEDS IN THE UK

5th edition

A report of the Coal Research Forum, compiled by Dr Andrew Minchener

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Edited by Dr David J.A. McCaffrey

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EXECUTIVE SUMMARY

The aim of Coal Research and Engineering Needs in the UK is to consider the technology development pathways and the specific areas of research, development and demonstration (R,D&D) where further work is needed to meet both short-term and longer-term coal utilisation objectives from a UK perspective. It is intended to assist policy makers to reach decisions that will help to ensure that coal can continue to play a significant and sustainable role within the UK and the world energy scene.

On a business as usual scenario, global coal use is predicted to rise by up to 50% over the period to 2030, to reach 7200 Mt coal equivalent, with the majority of the increase expected in non-OECD countries such as China and India. This is considered unsustainable due to man-made climate change concerns, with annual CO_2 emissions rising from 28.8 Gt in 2007 to 40.2 Gt in 2030. However, as yet, there is no global agreement on the appropriate way forward to best reduce such emissions. Many of the industrializing nations are limiting their initiatives to reducing carbon intensity as a function of GDP through increased efficiency of coal utilization. In contrast, Europe is pushing hard to increase the significant use of renewables and, to some degree, nuclear energy. It is also at the forefront of establishing a legal and regulatory framework such that fossil fuel power plants and other large industrial processes will have to significantly cut CO_2 emissions, with the expectation that an enabling environment will be established such that carbon capture and storage (CCS) will be commercially deployable from 2020.

Coal use in the UK has declined steadily since the early 1990s to a 2009 level of 50Mt, of which some 80% was consumed by power stations with most of the remainder used in the coking industry. The UK coal fired power plants are coming to the end of their useful lives, and so the future for coal will be linked to decisions made by the Electricity Supply Industry (ESI). The UK Government has stated that it is appropriate to continue to use coal, taking advantage of indigenous sources where possible, while also ensuring its environmental acceptability for low carbon electricity. In this regard, the UK is at the forefront in establishing frameworks to support the deployment of CCS. The Government policy, backed up by regulations, is that no new clean coal fired power plants will be approved without CCS. The regulatory measures include:

- All new power plants must be carbon capture ready.
- Applications for new plant will have to include plans to capture CO_2 from at least 300MWe net of capacity.
- Developers must provide evidence of technically feasible CCS plans (including offshore storage), environmental consents and permits for the full CCS chain.
- The Environment Agency will have new powers to monitor the performance of CCS demonstrations.
- New coal fired plants with part CCS will be expected to retrofit to their full capacity by 2025.

From the UK perspective, coal utilisation R&D will need to be focussed on the twin track approach to CO_2 abatement, i.e. establishing efficiency and environmental improvements in the short to medium term, with the introduction of CCS in the longer term. Looking at both the UK home market and the major global opportunities for new and replacement coal fired power plant, the technology of prime industrial interest is the advanced supercritical pulverised coal boiler /steam turbine system in the 400-1000 MWe range. Thus the continuing advancement of this existing clean coal technology (CCT) is required together with an associated and major effort to ensure that the related near-zero emission technologies can be developed and established on an attractive economic basis. Alongside this is the need to further improve the efficiency performance of large gas and steam turbines. The former will be needed both for use in gas fired combined cycle plant but also for use in advanced coal based gasification systems, should the latter be developed sufficiently to meet power sector requirements. This approach offers the vision of maintaining coal-based technologies for which there will be the benefit of efficiency and environmental improvements plus lower costs compared with the existing technology options. At the same time, it will provide the framework on which the related near-zero emissions technologies can be established in a cost effective, credible manner.

The R&D will include improving the efficiency of coal fired power generation with effective removal of conventional pollutants such as SOx, NOx particulates and trace metals. This will include work to improve the use of more advanced steam cycles, for which the need to improve performance through materials selection is important. There will also be a need to ensure improved plant integration, together with enhanced fuel and operational flexibility. At the same time, there is a growing need to establish near zero emissions systems such that CO_2 can be prevented from being released to atmosphere, with any adverse technical impacts on such efficiency and environmental performance being minimised in as cost effective manner as possible. The needs include improvements to first generation CO_2 capture systems and the development of second generation systems that will overcome some of the inherent disadvantages of the first. The first generation technologies of interest are post-combustion capture using amine based scrubbing and oxyfuel. There is also interest in pre-combustion capture techniques for gasification applications, particularly with regard to ensuring gas turbine combustors can fire very hydrogen rich fuels. Second generation techniques of interest include post-combustion carbonate looping and membranes for less energy intensive CO_2 separation and for O_2:N_2 separation respectively. Alongside the capture related activities, there is a critical need to improve assessment and modelling of CO_2 storage capacity in various geological formations, together with the development of improved monitoring and verification techniques. At the same time, better understanding of the properties of CO_2 and the provision of robust transport systems will become increasingly important.

The engineering challenges include the need to offer designs for both new and retrofit plant that are cost effective and fully compatible with the future market needs. These will include both high performance coal power plants and their near zero emissions variants that incorporate integrated CCS. Such CCTs will be required to operate in a mixed generation portfolio alongside nuclear, gas and renewable power plants. Therefore they must be available for both base load and load-following operation, while proving capable of using a range of coal types appropriate to the market prospects. With regard to the latter point, it is essential to look beyond the UK power generation market needs and to recognise the extensive global markets for these technologies and the related environmental and business benefits through exports from the UK.

The UK Government has also made a commitment to provide financial support to establish CCS on four large industrial scale fossil fuel CO_2 emission sources. The first option, for which a competition is close to conclusion, will enable post-combustion CO_2 capture with storage in a North Sea geological formation to be demonstrated on a coal fired power plant. For the other three projects, although the detailed approach has yet to be finalised, the expectation is that they may use any combination of fuel and capture types, i.e. either coal or gas using pre-combustion, post-combustion or oxyfuel capture. Overall, this will allow the UK to gain an understanding of different capture technologies and to build experience in the transport and injection of CO_2. The storage sites, including depleted oil/gas fields with or without enhanced oil recovery (EOR) and saline aquifers, will also act as test cases for licensing and, later, for monitoring and verification, while also exploring the potential of North Sea (and possibly Irish Sea) storage for future projects. That said, the timescales are very tight if advanced, environmentally acceptable coal (and gas) power plants are to be established on a commercial basis by 2020.

Consideration needs to be given to the possible uptake of underground coal gasification (UCG) and coal bed methane (CBM) as contributors to UK energy production. These are new extraction processes that are starting to be demonstrated and deployed, and there are linking factors that need to be addressed as they will introduce lower carbon intensive energy sources, which could be suitable for both power and non-power applications, including transport fuel applications. Outside of the power sector, there is a much smaller but still significant use of coal in the iron and steel industry, which is a sector that has continued to experience difficult market conditions. Here the environmental challenges remain very significant and addressing these together with ensuring sustainable costs reduction are the major aims of the industry.

This UK R,D&D programme must continue to be industry-led. At the same time, such an industrial initiative will benefit from support by added value scientific/fundamental research at universities and research organisations. This will not only aid the technology developments but will also continue to establish scientific/technical capabilities, including the provision of suitably qualified scientists and engineers in the relevant disciplines. The latter point is very important as it is essential that the UK can have available skilled and experienced engineers and scientists for such R,D&D activities. Consequently, a key aspect is the development of science and technology competencies and capabilities to meet these needs, which in itself represents a major challenge as the traditional sources of such personnel from universities moving to industry has become constrained due to the lack of opportunities in recent years, leading to a turn down in appropriate coal research related postgraduates.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 The Coal Research Forum

The Coal Research Forum (CRF) was formed in 1989 to bring together those organisations in the United Kingdom (UK) with interests in coal research, in order to integrate and promote their interests. The aims of the CRF are:

- To provide a forum for the exchange of information between technology providers and key stakeholders.
- To support the utilisation of coal in the UK as a secure primary source of energy.
- To promote UK research and expertise on coal to a worldwide audience.

The key activities to achieve these aims include:

- Contributing to and encouraging the development of a national policy for research on coal in the UK.
- Promoting coal and energy research with the various funding bodies.
- Encouraging and promoting the submission of proposals on coal research.
- Recording successful applications for funds for UK coal research.
- Encouraging the dissemination and exchange of information on coal research.
- Further developing the co-ordination of coal research activities through interchange between coal research groups and others.
- Publicising the achievements and successes of coal research in the United Kingdom.

The activities are co-ordinated by an Executive Committee with members from industry and universities. The CRF has six research divisions: Advanced Power Generation, Coal Characterisation, Coal Conversion, Coal Preparation, Combustion, and Environment. These Divisions hold meetings, seminars and talks to update members on current coal research issues and to establish where further research and development (R&D) is needed. There are two meetings each year, in the Spring and Autumn, of the whole Forum, which bring together wider audiences on topics of more general interest to members.

The Forum also provides information such as:

- A register of UK Coal Researchers.
- A report on Coal R&D Successes in the UK.
- A Handbook on British, European and American Coal Sample Banks.
- This report on Coal Research and Engineering Needs in the UK.

These documents are updated at regular intervals. A four monthly newsletter is also produced, which contains information on research events, current research contracts, and other topical news. The CRF also promotes informal networking with the benefit of developing collaborative relationships between members having similar interests. Further information on the activities of the CRF may be obtained from:

The Secretary,
Coal Research Forum,
P.O.Box154,
Cheltenham,
Glos. GL52 5YL
Tel: 01242 236973

E-mail: info@coalresearchforum.org

Website: www.coalresearchforum.org

1.2 Purpose of this document

The aim of Coal Research and Engineering Needs in the UK is to consider the technology development pathways and the specific areas of research, development and demonstration (R,D&D) where further work is needed to meet both short-term and longer-term coal utilisation objectives from a UK perspective. It is intended to assist policy makers to reach decisions that will help to ensure that coal can continue to play a significant and sustainable role within the UK and world energy scene.

The projected global role of coal is described, with particular reference to security of energy supply and environmental considerations, which is followed with an overview of the current and likely future UK situation. There is then a description of the various funding sources available to support clean coal utilisation R,D&D in the UK. The clean coal utilisation R,D&D needs are next presented, which comprises a description of the key technology options for each market sector together with the proposed R,D&D priorities, covering both new technology developments as well as improvements to existing coal utilisation systems. This is followed by an assessment of the engineering challenges associated with establishing the priority technologies. The greater emphasis is on coal fired power generation although consideration is given to other significant coal fired industrial processes. Finally, the key conclusions from this review are presented.

2. AN OVERVIEW OF COAL USE AND FUTURE PROJECTIONS

2.1 Global issues

The International Energy Agency (IEA) publishes an annual projection of global energy use, which comprises a reference (business as usual) scenario together with alternatives dependent on the application of various polices and market instruments. The Energy Information Administration (EIA) of the United States of America (USA) publishes a similar assessment. In 2009, the IEA noted that although there had been a significant reduction in energy use due to the global financial crisis, this would be short-lived, with global energy use moving upwards from 2010. In overall terms, energy use would rise from 12,000 Mtoe in 2010 to close to 18,000 Mtoe by 2030 (IEA 2009a). Coal showed by far the biggest increase, followed by gas then oil (Figure 1).

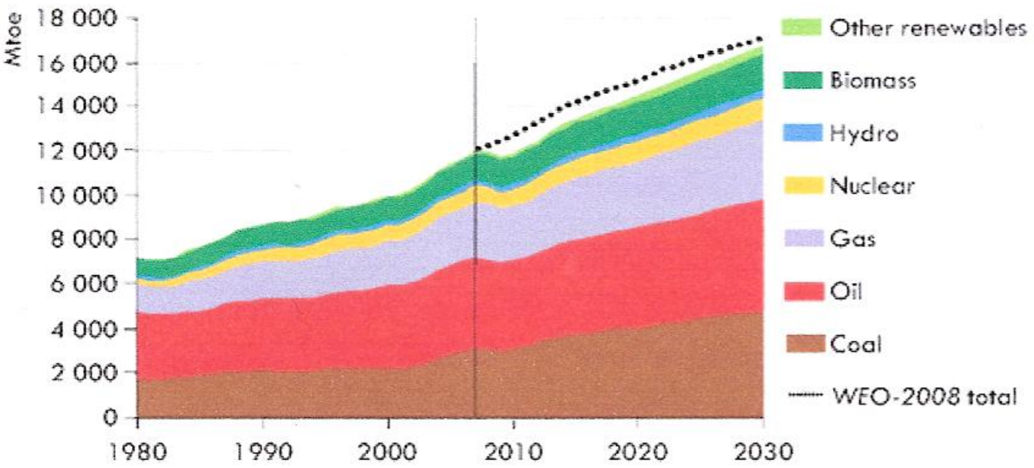

Figure 1 Cumulative primary energy demand-IEA reference scenario (IEA 2009a)

The main drive for increased coal and gas use is in power generation, with coal use in that sector rising by three percentage points to 44% in 2030. However, the increase in energy demand and coal use is not uniform around the world. China and India represent over 53% of incremental primary energy demand to 2030 (IEA 2009a). For coal, over 80%.of the growth will be in non-OECD countries, especially China, Figure 2 (EIA 2010).

At the same time, the IEA has stressed that such an energy pathway has significant adverse implications for environmental protection, energy security and economic development. It is considered unsustainable due to man-made climate change concerns, with the IEA reference scenario showing annual CO_2 emissions rising from 28.8 Gt in 2007 to 34.5 Gt in 2020 and 40.2 Gt in 2030. Consequently, the IEA produced an alternative low-carbon energy future scenario, which would result in any global temperature rise being limited to 2^{o}C where the greenhouse gas concentration would be stabilised at around 450 ppm CO_2-equivalent. The effect of this 450 scenario on the global energy demand is shown in Figure 3 (IEA 2009a).

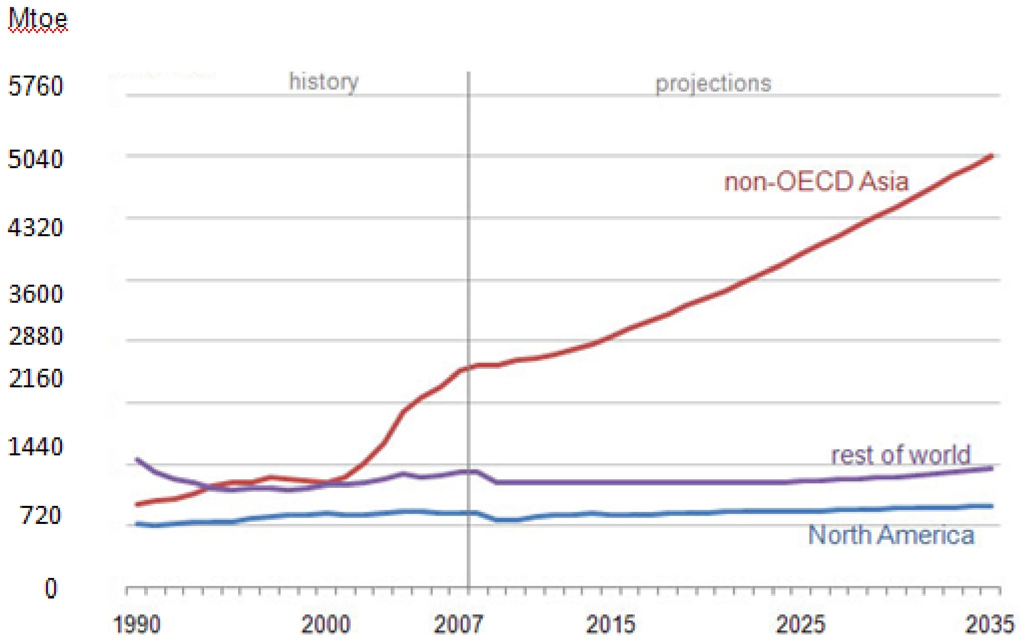

Figure 2 Coal use by region (based on EIA 2010)

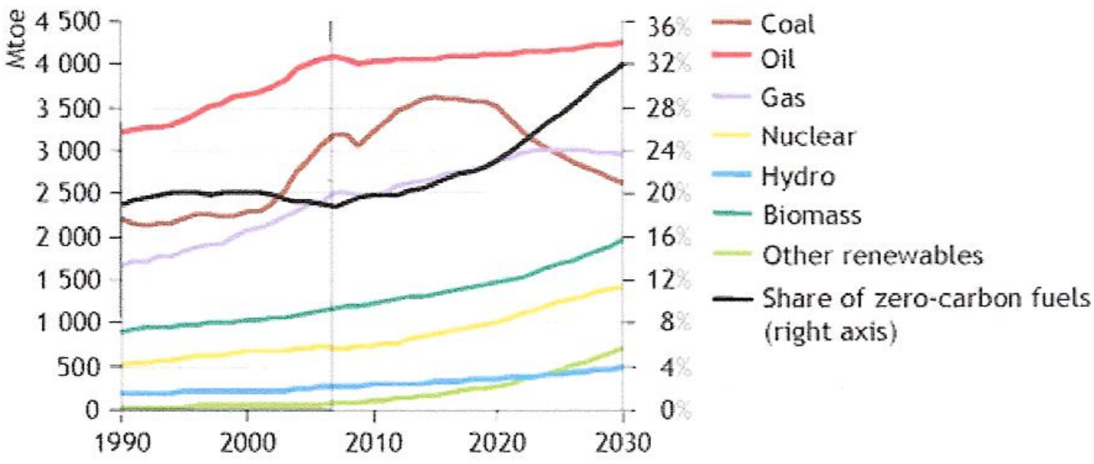

Figure 3 Primary energy demand for each source-IEA 450 scenario (IEA 2009a)

In this scenario, primary energy demand growth corresponds to an average annual rate of 0.8%, compared with 1.5% in the Reference Scenario. The share of non-fossil fuels in the overall primary energy mix increases from 19% in 2007 to 32% in 2030, while CO_2 emissions per unit of GDP are less than half their 2007 level. Yet, fossil fuels remain the dominant energy sources in 2030 and, with the exception of coal, demand for all fuels is higher in 2030 than in 2007. It is stressed that this is but a result of a modelling exercise and that this very challenging option would require a radical global change in global policy approach, comprising a combination of cap-and-trade systems, sectoral agreements and national measures, with countries subject to common but differentiated responsibilities (IEA 2009a). The aim would be to massively improve end-use efficiency, ensure early retirement of old, inefficient coal plants and their replacement by more efficient units, many of which would be fitted with carbon capture and storage (CCS), increased deployment of renewables, plus nuclear power. The potential impacts of the various actions are shown in Figure 4 (IEA 2009b). The IEA has suggested that to achieve the 450 Scenario would require an additional global investment of US$ 10.5 trillion in the period 2010-2030, relative to the Reference Scenario, although it is suggested that some US$ 6.2 trillion would be offset by fuel cost savings.

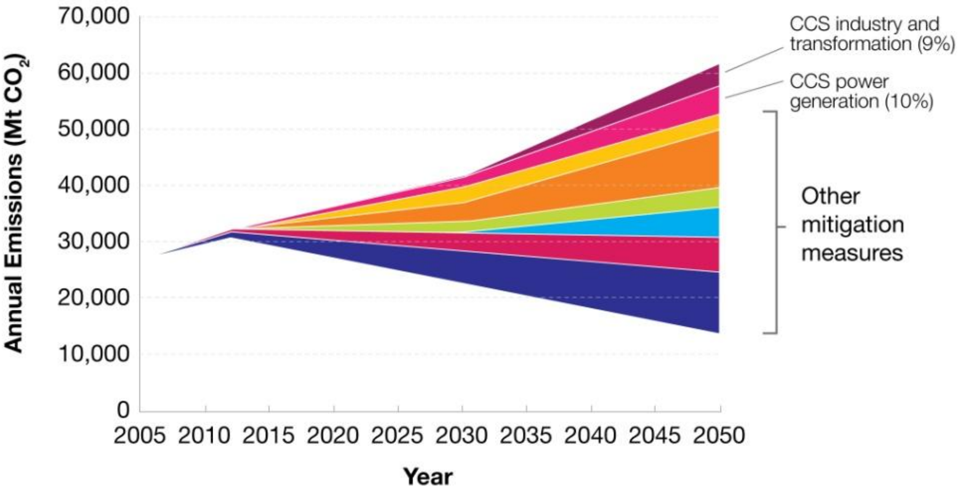

Figure 4 Potential CO_2 emissions reduction from CCS for the IEA 450 scenario (adapted from IEA 2009b)

Future coal demand through to 2030 is consequently likely to lie somewhere between these two IEA projections since, as yet, there is no global agreement on the appropriate way forward. Many of the industrializing nations are limiting their initiatives to reducing carbon intensity as a function of GDP through increased efficiency of coal utilization and the introduction of low and zero carbon energy resources. In contrast, Europe is pushing hard to increase the significant use of renewables and, to some degree, nuclear energy. It is also at the forefront of establishing a legal and regulatory framework such that fossil fuel power plants and other large industrial processes will have to significantly cut CO_2 emissions, with the expectation that an enabling environment will be established for CCS to be commercially deployable from 2020 (UCL 2009a).

2.2 UK perspective

Coal use in the UK has declined steadily since the early 1990s, as shown in Figure 5 (DECC 2010a). At the same time, domestic supplies have been replaced by imports and the latter now account for over two thirds of the coal used. The proportion of coal consumed by power stations has increased steadily since the 1970s to reach 86% in 2006 before falling back to 83% in 2008. However, in absolute terms, coal for power generation in 2009 was some 40 Mt, the lowest level on record. Most of the remainder of the coal was used in the coking industry.

Within the UK, it is evident that the future use for coal will predominantly be for power generation and, as the UK coal fired power plants are coming to the end of their useful lives, the future for coal will be linked to decisions made by the Electricity Supply Industry (ESI), which will be dependent on Government policies. In this regard, there has been considerable uncertainty in recent years, to the extent that numerous industrial bodies have been warning that, unless decisions are made very soon, the capacity of the power generation sector will fall below critical levels such that power outages could occur from around 2016 onwards. The lack of investment is due in part to questions regarding the impact of stricter environmental limits, including for CO_2 emissions.

The capacity concern has eased a little with a compromise that resulted in the EU Industrial Emissions Directive (IED), which was approved in July 2010 (Power-Gen Worldwide 2010). This recast seven existing directives related to industrial emissions, including the Large Combustion Plant Directive and the Integrated Pollution Prevention and Control (IPPC) Directive, into a single legislative instrument (Herbert Smith 2010). The IED will apply strict limits on air pollution and lays down rules on the integrated prevention and control of pollution resulting from industrial activities. It also sets rules designed either to prevent or, where that is not practicable, to reduce emissions to air, water and land and to prevent the generation of waste. In particular, it sets stricter limits on pollutants such as nitrogen oxides, sulphur dioxide and dust.

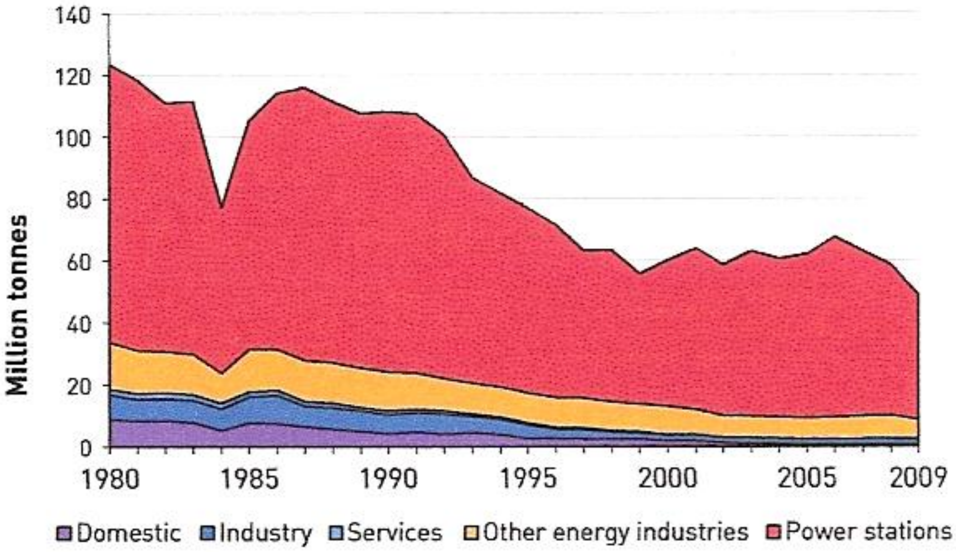

Figure 5 UK coal consumption 1980-2009 (DECC 2010a)

It applies to numerous sectors, including the combustion of fuels in installations with a total thermal input of 50 MW or more; the refining of mineral oil and gas; the production of coke, and the gasification or liquefaction of coal or other fuels in installations with a total thermal input of 20 MW or more. While, as a general rule, installations will have until 2016 to comply with the stricter limits, operators of combustion plants can opt out, providing the number of operating hours is limited to 17,500 hours between 1 January 2016 and 31 December 2023, after which, or sooner, the plant will cease to operate. This is particularly important to the UK since, given the age of the UK's coal fired fleet, the generating companies intend to close a significant number of plants rather than make significant investment in gas clean-up systems. The loss of this capacity by end of 2015, prior to the extension allowed within the IED, and the lack of investment in new plant had raised the likelihood of subsequent power outages, not least as the ageing nuclear power plants would also be closing during the same time period. Consequently, this offers a breathing space to the UK (Power-Gen Worldwide 2010).

With regard to the significant reduction of CO_2 emissions, the UK is at the forefront in establishing frameworks to support deployment of CCS, with the expectation that the technology will be available on a commercial basis by 2020 (UCL 2009b). The Government policy, backed up by regulations, is that no new clean coal fired power plants will be approved without CCS (Carbon Capture 2010). The regulatory measures include:

- All new power plants must be carbon capture ready.
- Applications for new plant will have to include plans to capture CO_2 from at least 300MWe net of capacity.
- Developers must provide evidence of technically feasible CCS plans (including offshore storage), environmental permits and consents for the full CCS chain.
- The Environment Agency will have new powers to monitor the performance of CCS demonstrations.
- New coal fired plants with part CCS will be expected to retrofit to their full capacity by 2025.

The Government has also made a commitment to provide financial support to establish CCS on four industrial scale fossil fuel fired industrial processes, which is described in Section 3.1.

3. FUNDING ROUTES FOR UK COAL RESEARCH, DEVELOPMENT AND DEMONSTRATION

There have been considerable changes in both funding availability and focus for coal utilisation R,D&D in recent years. While some activities are financially supported by associations that have specific interests in coal technology, the larger financial sources are available from organisations where the overall driver is to establish sustainable energy systems, of which clean coal utlisation is one part. Consequently, competition for such funds reflects the national and international priorities within which the emphasis is towards newer technologies that in due course may replace coal as a primary energy source. It is possible to investigate the various funding routes via a web-based Energy Funding Landscape Navigator (Technology Strategy Board 2011). An overview is provided below of the more relevant sources of grant funding for coal utilisation R,D&D that can support both fundamental and pre-competitive, applied research as well as demonstration activities. The UK based sources are presented first, followed by those available via the European Commission.

3.1 DECC CCS Demonstration Programme

The starting point for the UK Department of Energy and Climate Change (DECC) activities is the Carbon Abatement Technology (CAT) Programme, which was established in 2005, and covers all fossil fuels, power generation and all large non-power combustion based industrial processes (UKDTI 2005). It is an industry led programme, with possible supporting input from universities and other research organisations, with an indicative funding level of £25 million over ten years. Its recent initiatives have been undertaken in conjunction with the Technology Strategy Board (Technology Strategy Board 2009). In broad terms the objectives include:

- To support R,D&D of CATs.
- To support the demonstration of CO2 capture ready plant.
- To support the demonstration of CO2 storage.
- To facilitate international collaboration in UK based CAT development and demonstration projects.
- To facilitate and support UK collaboration in CAT development and demonstration projects based in other countries.

In addition, DECC is managing the UK competition to establish a demonstration of post-combustion capture of at least 100MWe capacity on a new coal fired plant by 2014 (DECC 2010b). There remains one proposed project under consideration, namely Scottish Power's Longannet power plant. A Front End Engineering and Design study is being undertaken and, if the results are found to be satisfactory, this project will be set to receive total funding of up to £1 billion, with contract signature during 2011. This will form part of DECC's commitment to establish CCS on four industrial scale fossil fuel fired industrial processes across the UK.

The basis of the competition for the other three demonstration projects will be finalized in 2011 (DECC 2010c). However, the terms of reference indicate that the demonstration of commercial-scale CCS can be either on 3 power generation stations that are connected to the GB grid and / or dedicated to serving large scale industrial processes. Unlike the first project, these may:

- Utilise any combination of fuel and capture types i.e. coal or gas using pre-combustion, post-combustion or oxyfuel capture.
- Be scaled to around 300-400MWe (net).
- Have the prospect of operating for at least a 10 – 15 year demonstration period and preferably longer.
- Be carried out on new build, refurbished or on existing generation plant.

The DECC funding mechanism is expected to include a level of commercial return necessary to attract private sector investment. Any funding awarded to projects under the Programme will be contingent on securing state aid approval from the European Commission (see below).

3.2 Technology Strategy Board initiatives

The Technology Strategy Board stimulates technology enabled innovation in the areas which offer the greatest scope for boosting UK growth and productivity (Technology Strategy Board 2010). Energy generation and supply is a high priority and for coal it has supported industry led R&D, with supporting basic research input from universities and other research organisations. To date, jointly with DECC and the Northern Way, the focus has been on carbon abatement technologies, which has included measures to improve combustion performance and overall power cycle efficiency as well as a CCS industrial pilot project (Technology Strategy Board 2009).

3.3 Energy Technologies Institute

The Energy Technology Institute supports a CCS programme, which specifically addresses the UK's needs to develop a technology base within the UK (Energy Technologies Institute 2011). The aims are to:

- Accelerate implementation of CCS technology on fossil-fuel fired power stations and other major stationary CO_2 sources in the UK, by demonstrating innovative technology which reduces the capital costs of capture and storage plants and reduces the energy needed by the capture and storage processes.
- Reduce risks and costs of storage projects by advancing knowledge of UK storage assets, improving monitoring and efficiency of use.
- Improve the reliability, flexibility and operability of a fully developed chain of CCS assets.

Work to date includes support for UK CO_2 storage appraisal, benchmarking of next generation CO_2 capture technologies, and an assessment of measurement, monitoring & verification technologies and field experience.

3.4 Environmental Transformation Fund

This is a financial commitment by Government to help the UK and developing countries address the challenge of climate change (DECC 2010d). It is split into a UK and an international fund. The UK part supports the development and deployment of low carbon energy technology, including technology for the efficient use of energy. The international part supports development and poverty reduction through environmental protection, and helps developing countries respond to climate change. The Environmental Transformation Fund began operation in April 2008, and aims to accelerate the commercialisation of low carbon energy and energy efficiency technologies in the UK, with a specific focus on the demonstration and deployment phases of bringing low carbon technologies to market (DECC 2010d). The intention is to work closely with other organisations funding earlier stage research and development including the Energy Technologies Institute, the Technology Strategy Board, and the Research Councils' Energy Programme.

3.5 Engineering and Physical Sciences Research Council

The EPSRC is the UK's main agency for funding research and related postgraduate training in engineering and the physical sciences. It leads the Research Councils' UK Energy Programme, the aim of which is to position the country to meet its energy and environmental targets and policy goals through world-class research and training (Riches 2009). This includes funding centres for doctoral training to provide a supportive environment for students to carry out a challenging PhD-level research project together with taught coursework. It also funds university partners in projects supported by the Technology Strategy Board. A priority topic is research to pioneer a low carbon future, and for coal there is some emphasis on combustion-related conventional power generation, to improve the combustion process and to make conventional power generation more efficient with reduced environmental impact, including CCS. The current energy budget is £567 million, via all councils, of which 15% is allocated to conventional power generation with conventional plant improvements, combustion and CCS receiving 2%, 3% and 6% respectively (Riches 2009). Calls are advertised on the EPSRC website (EPSRC 2010).

Recent activities in CCS include supporting four consortia proposals in carbon capture and transport, supporting projects that include collaboration with China, networking to take forward the work of the university based UKCCS Consortium, establishing consortia to examine ecosystems impacts both of geological carbon storage and CCS whole systems.

The EPSRC supports the SUPERGEN initiative, which is concerned with the sustainable and efficient generation of electrical power from low carbon, zero-carbon or carbon neutral generation systems. It aims to promote a significant step change rather than incremental progress and involves multidisciplinary partnerships working in major programmes of work rather than individual research groups working in isolation. Some £25 million of funding has been allocated for a five-year programme. There are fourteen themes, including one on power plant life extension. Discussions are taking place as to the scope of the next SUPERGEN programme.

The EPSRC with the Carbon Trust are also running an initiative called Carbon Vision to bring together the needs of business with the capabilities of university R&D departments to deliver on low carbon technologies in the UK (Carbon Trust 2010). Under the scheme, identified demands from business for low carbon technologies and solutions will be matched against those university R&D departments best able to research ways to address these demands and overcome barriers. It is possible that this could include coal related activities.

3.6 British Coal Utilisation Research Association

BCURA is an independent charity that funds fundamental research on the production, distribution and utilisation of coal (BCURA 2010). In 1991, the common interest between BCURA and the Department of Trade and Industry (DTI) Coal R&D programme was recognised and a jointly funded programme, meeting the objectives of both parties, was established. The Agreement for this jointly funded programme has been renewed at periodic intervals, now with the Department of Energy and Climate Change, (DECC), with the latest renewal being in April 2008 for the funding for their lifetime of the current projects, which concludes in March 2011. In 2001, BCURA formed an Industrial Panel of subscribing members who each contribute to an Industrial Fund, which forms part of the charity's financial resource. The funding typically supports either postgraduate or post-doctoral research projects. In 2009, BCURA made the decision not to fund any new applications for research grants. It is the current intention of the BCURA Council to continue with the organisation of the annual BCURA Coal Science Lecture.

3.7 Biomass and Fossil Fuels Research Alliance

The Biomass and Fossil Fuels Research Alliance (BF2RA) was established in September 2009 as a private not for profit company, with a membership that includes representatives from the ESI, major equipment manufacturers, major fuel users and the research sector. Its prime objectives are to promote research and other scientific studies into key aspects of the production, distribution and use of biomass and fossil fuel and their derivatives. The intention is to fund appropriate research with support from the industrial members. BF2RA let its first three research grants during the autumn of 2010 and will launch an open call for research proposals in early 2011 for projects that will start in the autumn of 2011.

3.8 Scottish Power Academic Alliance

Scottish Power has announced that it will invest close to £5 million over the next five years to support research into the capture and offshore storage of CO_2, the policy and regulatory aspects of CCS, and the enabling steps to exploit the commercial opportunities that the technology offers. However, funding will be limited to supporting researchers working at the University of Edinburgh and Imperial College, London (Scottish Power 2010).

3.9 European Commission's New Entrant Reserve (NER) 300 Scheme

This is a European Union led funding programme to support CCS and innovative renewables projects (DECC 2010c). The NER will make funding available for commercial-scale CCS projects, with the funds generated through the sale of 300 million EU Emissions Trading Scheme (EU ETS) allowances from the New Entrant Reserve of Phase 3 of the EU ETS DECC 2010). The Commission intends to publish two calls for proposals, the first of which was launched in November 2010. Proposers for UK located CCS demonstration projects that meet the NER eligibility criteria may apply for funds under the scheme, as well as for funding delivered through Phase 2 of the DECC competition.

3.10 EU Framework Programmes

The Seventh Framework Programme (FP7) includes several specific components (European Commission 2010) as set out below:

- Cooperation, through fostering collaboration between industry and academia to gain leadership in key technology areas.
- Ideas, by supporting basic research at the scientific frontiers (implemented by the European Research Council).
- People, through supporting mobility and career development for researchers both within and outside Europe.
- Capacities, by helping develop the capacities that Europe needs to be a thriving knowledge-based economy.

For energy, the objective is to aid the creation and establishment of the technologies necessary to adapt to a more sustainable, competitive and secure energy system. This includes less dependence on imported fuels and the use of a diverse mix of energy sources, in particular renewables, energy carriers and non polluting sources. The EU Member States and the European Parliament have earmarked a total of € 2.35 billion for funding this theme over the duration of FP7, with emphasis on the following activities (European Commission 2009):

- Hydrogen and fuel cells.
- Renewable electricity generation.
- Renewable fuel production.
- Renewables for heating and cooling.
- CCS technologies for zero emission power generation.
- Clean Coal Technologies.
- Smart energy networks.
- Energy efficiency and savings.
- Knowledge for energy policy making.

The common aim of the two partly complementary activities ENERGY.5 (CCS) and ENERGY.6 (clean coal) is to enable an integrated technological solution for zero emission power generation from fossil fuels. In accordance with the strategic priorities of the European Commission, this requires large scale demonstration in place by 2015 if integrated solutions for zero emission fossil fuel based power are to be available by 2020 (European Commission 2010).

For CCS, the requirement is to significantly reduce the adverse environmental impact of fossil fuel use with highly efficient and cost effective power and/or steam generation plants with near zero emissions. The programme includes work to take forward the first generation CO_2 capture technologies (post-combustion, pre-combustion) towards demonstration at very large scale integrated with a coal fired power plant, to push forward the development of oxyfuel combustion through large scale activities, as well as to rapidly scale up the more promising second generation technologies (such as post combustion carbonate looping), together with improving the understanding and establishing better techniques for underground storage of CO_2 in geological formations.

For clean coal technologies, the need is to substantially improve the efficiency, reliability and cost of coal (and other solid hydrocarbons) fired power plants. This can also include the production of secondary energy carriers (including hydrogen) and liquid or gaseous fuels. As such, in this context, clean coal means a sustainable solid hydrocarbon value chain with a focus on efficient and clean coal utilization that can be successfully be integrated with CCS. The work programme includes the reduction of the traditional pollutants emitted by coal combustion, such as SOx, NOx and particulates, through improvement of the cleaning efficiency, while also addressing other pollutants such as mercury. Alongside this, the need is to improve the conversion efficiency of coal into electricity to above 50% through further R&D and better integration of components. This covers not only the mainstream combustion techniques (the ultra supercritical AD 700 pulverised coal plant) but also integrated gasification combined cycle plant (IGCC) and other combustion options, such as fluidised bed and oxyfuel.

3.11 Research Fund for Coal and Steel

The Research Programme of the Research Fund for Coal and Steel (RFCS), which succeeded the European Coal and Steel Community Programme, is managed by EC DG Research, with its own budget outside of the Framework Programme. In broad terms, one aim is to improve the competitive position of EU coal, through efficient protection of the environment, and improvement in the use of coal as a clean energy source. It comprises research, pilot and demonstration projects together with accompanying measures related to the promotion of the use of the knowledge gained (Cordis 2010). The activities cover coal mining, coal conversion and coal combustion. The annual budget for coal R,D&D is about €16 million, with some €3.5 million allocated to coal conversion and €6.9 million to coal combustion.

In the coal utilisation programme, while there is R&D on CO_2 capture, much of the work has been and continues to be focussed towards improving the efficiency, environmental performance and amenity value of coal fired power plant, and aiding the development of advanced combustion and gasification processes, including their integration to facilitate CO_2 capture from both power and other industrial applications. The latter include coking and, more recently, coal liquefaction and underground coal gasification.

4. CLEAN COAL UTILISATION R,D&D NEEDS

4.1 Rationale

The 2005 edition of Coal Research and Engineering Needs in the UK, issued by the Coal Research Forum, considered the technology development pathways and the specific R,D&D areas where further work would be needed to meet both short-term and longer-term coal utilisation objectives from a UK perspective. It noted that the UK faced significant challenges to establish a sustainable energy use and management policy while meeting environmental standards and ensuring security of supply. Within the various scenarios being considered, the expectation was that coal would have to provide a significant part of the overall energy mix.

The report concluded that it is essential that 'the key enabling steps are established and financed so that advanced clean coal technologies (CCTs) and near zero emissions power plants with CCS, including its link to hydrogen production, can be taken forward'. At the same time, since many of the necessary developments were still at the pre-competitive R&D stage and the market drivers were not clearly defined, it further stressed that 'UK industry, in partnership with various UK research institutes and universities, needs support to take forward these initiatives, via various national and international R,D & D programmes. This would allow UK stakeholders to address both the near term market issues and the medium to longer-term strategic technology developments'.

While these overreaching policy and strategic drivers remain sound, the position has evolved significantly. It is publically recognised by the UK Government that it remains appropriate to continue to use coal, taking advantage of indigenous sources where possible, while also ensuring its environmental acceptability for low carbon electricity. Thus coal will remain attractive to stakeholders providing that it can be used efficiently and with reduced environmental impact, with polices and tightening regulations being applied to ensure appropriate compliance.

Consequently, coal utilisation R&D will need to be focussed on improving the efficiency of coal fired power generation with effective removal of conventional pollutants such as SOx, NOx, particulates and trace metals. At the same time, there is a growing need to establish near zero emissions systems such that CO_2 can be prevented from being released to atmosphere, with any adverse technical impacts on such efficiency and environmental performance being minimised in as cost effective manner as possible. This is the twin track R&D approach, as shown in Figure 6 (Farley 2008).

This will include work to improve existing plant through retrofit, including fuel and operational flexibility, for which the need to improve performance through materials selection is important. All new plant will need to be capture ready and there will need to be credible plans to include CO_2 capture from plants of at least 300MWe net of capacity. With regard to CCS itself, the needs include improvements to first generation CO_2 capture systems and the development of second generation systems that will overcome some of the inherent disadvantages of the first. Alongside this, the need to improve assessment and modelling of CO_2 storage capacity becomes increasingly important.

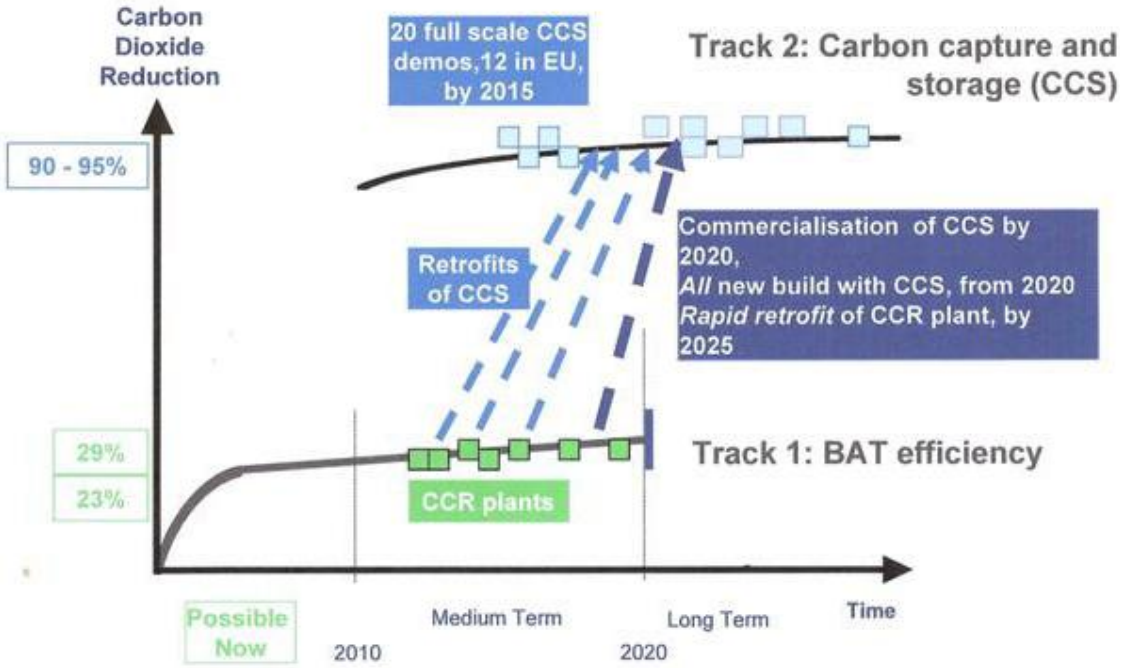

Figure 6 Twin track R&D approach to near zero emissions power plant (based on Farley 2008)

Outside of the power sector, there is a much smaller but still significant use of coal in the iron and steel industry, which is a sector that has continued to experience difficult market conditions. Here the environmental challenges are greater than ever and addressing these together with ensuring sustainable costs reduction are the major aims of the industry. In due course, the possible introduction of CCS will need to be considered.

Finally, consideration needs to be given to the possible uptake of underground coal gasification (UCG) and coal bed methane (CBM) as contributors to UK energy production. These are new extraction processes that are starting to be demonstrated and deployed, and there are linking factors that need to be addressed as they will introduce lower carbon intensive energy sources.

Therefore the R&D needs break down into three parts:

- The development and deployment of clean coal technologies, for power generation, including CCS.
- The improvement in efficiency and environmental performance of non-power coal utilisation technologies.
- The issues associated with the utilisation of gas arising from novel coal extractive technologies.

In each case, any R&D requirements must be compatible in scope and timescale with national targets, as is indicated below.

4.2 Clean coal and CCS for power generation

In recent years, there has been considerable development of strategies, building on the Government's original CATs Strategy with the 2020 target for CCS commercialisation (Carbon Capture 2010) and the commitment to meeting the 2050 target to reduce national greenhouse gas emissions by 80% relative to 1990 levels (DECC 2010e). There has been considerable advice from organisations such as the Advanced Power Generation Technology Forum, which has helped to develop an overall technology vision, including R&D suggestions (APGTF 2009).

4.2.1 Coal combustion based power plant

Both globally and in the UK, pulverized coal (PC) fired power plants are the coal based technology of choice, with considerable advances having been made in recent years to establish supercritical and ultra-supercritical designs. The state of the art efficiency in Europe is >45% (net, LHV basis), for a plant operating with supercritical steam temperatures of about 600oC, with plants having been installed in Denmark, Italy and Germany. Also, techniques have been established to control particulate emissions and acid gas pollutants such as NOx and SO_2. Globally, the major market is in China where over 400 GWe of supercritical and ultra-supercritical power plants are either operational, under construction or at the design stage (Minchener 2010). Unit sizes are operational up to 1000 MWe while designs are underway for 1320 MWe units (Mao 2010). In contrast, while PC boilers have been the traditional technology of choice in the UK, the units now in operation are relatively old and with modest efficiencies compared to the state of the art units. However, UK manufacturing companies such as Alstom Power and Doosan Babcock are active in licensing, building and supplying both the advanced units and their individual components and have a significant international presence. As such, it is a technology option that continues to be of considerable interest to UK industry.

There is scope to further improve the competitiveness of PC technology for application within international markets. The ongoing need is to reduce costs, increase efficiency and environmental performance while improving flexibility of operation and maintaining high availability, including the ability to utilize alternative fuels in combination with coal. It is important to stress that such advances are also needed to provide the best possible basis to offset the power losses associated with CCS while any integration of CO_2 capture systems must be achieved with minimal adverse impact on the overall performance of the basic power plant.

For completeness, the alternative combustion based process, circulating fluidised bed combustion (CFBC), is noted. However, this is not a technology that has been applied in the UK since it is best suited to low and variable grade feedstocks, which are not used in UK applications. Consequently the R&D needs are focused on PC plants and priority activities include:

- Optimisation of cycles, including better utilization of waste heat, to focus primarily on engineering design considerations (see Section 5) that will feed through to demonstration activities.
- Development, selection and fabrication of materials to ensure progressive increases in steam temperature and pressure towards 700^{o}C and 35 MPa, while ensuring that novel components using new materials of construction can achieve acceptable reliability and economic cost. This would include appropriate inspection, monitoring and life assessment technologies. This requires materials and structure development for maximum process parameters, through the development and use of high-temperature corrosion resistant materials, verification of strength characteristics, weld joints for nickel base materials and mixed joints. This must be industrially led but there is considerable scope for UK research organisations and universities to continue to play a major role in materials testing, characterisation and certain modelling activities (Oakey 2000). Industry will use the outcomes from the research work to develop improved component and systems designs, leading ultimately to full-scale demonstration of a coal fired advanced ultra-supercritical steam power plant.
- Improved multi-pollutant control, ensuring adequate interaction of individual components, leading to optimum combination of technologies that ensure compliance with present and future emission regulations. This would include characterisation of the release of trace pollutants for the full range of fuel types, determining the influence of trace metal emissions on the removal of traditional pollutants (NOx, SOx and particulates), together with the demonstration of a trace species capture system that can significantly improve on the costs and accuracy of current designs, including the means to accurately monitor the individual metal species. Linked to this is the need for industry to determine the impact of any new pollutant control systems on the usability and marketability of the various by-products arising from the power plant. UK companies have been active in various European initiatives at the forefront of this technology development, both in the materials and plant component areas, while universities and other research organizations are well placed to undertake extensive fuel characterization.
- Improvement in flexibility of operation and control , with the need to establish the optimum compromise between efficiency and operability, through dynamic modelling, control and

instrumentation development, as well as assessment of the impact of rate of change on the integrity of materials and welds. This will need to be industry led but there is scope for universities to provide a valuable supporting role.

- Improvement in the capability to cofire coal with either biomass or other organic wastes, up to 20% or more by heat input, while minimizing adverse impacts due to furnace corrosion, slagging and fouling and impact on NOx reduction catalysts for the full range of coals and alternative feedstock combinations. This should include all aspects of the biomass/wastes chain, such as efficient preparation and processing of sustainable feedstocks, understanding of materials issues, as well as ensuring that any impacts on post-combustion CO_2 capture processes are understood and addressed at the integration stage. This will require industrial fuel testing on pilot and full-scale plant backed up by extensive fuel characterisation, of which the latter can best be provided by universities and other research organisations. This is an area where such supporting research (e.g. burn-out, conversion reactions, transportation, deposition and interaction mechanisms) will be particularly beneficial. UK industry can then take forward the appropriate options for modifications to design and operational procedures.

4.2.2 Coal gasification based power plant

IGCC is a technology that offers the prospect of very low conventional emissions from coal based power plant while also achieving higher cycle efficiencies through ongoing improvements to gas turbine technology. However, to date, this potential has not been realised due to major concerns with higher capital costs and lower levels of reliability and availability, compared to advanced PC plant. For the medium- to longer-term, IGCC is well placed technically for CO_2 capture capability as it offers an attractive and comparatively lower cost removal solution prior to the fuel gas combustion process. In addition, this offers the possibility for integrated CO_2 separation in combination with supplying gaseous feed-stocks for use in the chemical and petrochemical industries. Even so, market penetration will depend on whether the overall cost for coal based IGCC power generation with CO_2 capture will be significantly lower than for advanced PC systems with post-combustion CO2 capture installed. To put that in context, there are only a few coal based IGCC demonstration plants operational at modest efficiencies of 41-43%. It is not a technology that is offered by the major UK equipment manufacturers although all are in a position to supply certain key components and supporting services.

However, there are plans for new demonstrations in China and various early stage plans for projects in the USA. In the UK, Powerfuel, the owner of the Hatfield Colliery, had obtained a licence and announced plans to establish a commercial scale IGCC unit in the UK. The company received some financial support from the EU available from the stimulus programme (Hatfield IGCC 2010). However, late in 2010, Powerfuel brought in administrators as it failed to raise both the funding needed for the IGCC/CCS project and for loan repayments to enable work at the colliery to be undertaken. Consequently, future prospects for this technology demonstration are dependent on finding a new owner capable of raising the significant level of funding necessary to take the CCS project forward (The Telegraph 2010).

In terms of the overall development needs for the technology, the primary aim is to establish adequate performance and availability such that generating companies can have confidence that it is a commercially viable technology. The subsequent aim is to reduce costs, increase efficiency and improve flexibility of operation, including the ability to utilize alternative fuels in combination with coal, while ensuring integration of pre-combustion capture systems. The work would include:

- Optimisation of cycles through utilisation of waste heat and with as much integration as possible of the various components to ensure a lower system capital cost without adversely affecting availability. With regard to the components themselves, for entrained flow gasification systems the issues include materials to ensure greater reliability, especially refractories, improved dry feeding, particularly for mixed feed-stocks, improved fire-tube cooler designs to minimise deposition and corrosion. UK industry has been involved in numerous technological development programmes and can offer significant input and expertise. Alongside this, there is a strong university based capability on many IGCC aspects that can provide added value support in materials testing, characterisation and certain modelling activities.

- Establishment of hot gas cleaning improvements for pollutant removal at elevated temperatures. This will include the development of more robust systems, with integrated higher efficiency syngas cooling, capable of removing all pollutants. This is an area where considerable supporting research is required, which can be provided by UK universities and research organisations. UK industry can use the results to establish improved designs that can then be tested, initially probably on side streams of existing plants and then ultimately as part of full-scale demonstration of an improved IGCC system.
- Inclusion of advanced gas turbines into the cycle, to fire the fuel gases that will arise from different gasification units, particularly hydrogen, which will be the prime fuel produced when CO_2 capture is undertaken. This will require materials development and selection, development of fabrication techniques and blade cooling technologies (see Section 4.2.3). UK industry is well placed to undertake and lead such developments but there is scope for universities to provide support through materials testing and modelling activities.
- Improved fuel flexibility to allow for co-use of alternative fuels, such as biomass and waste, in applications where the economics are favourable. This includes the development of improved feeding and handling systems capable of use for all viable feedstock combinations. There is significant scope for universities and other research organisations to carry out fuel characterisation studies, which will also need to include consideration of the mechanisms for release of trace metals, carbonyls and other pollutants. Industry will need to consider how best to scale up the results from such studies, given the limited number of large-scale units available.
- Development of a more cost effective air separation process. This must be driven by industry but there is considerable scope for supporting research into alternative concepts (e.g. membranes).

4.2.3 Advanced power generation enabling technologies

Alongside the technology variants under development, there are continuing R,D&D needs for turbo-machinery and enabling technologies. Thus for the future of clean coal technologies and CCS, the key enabling technology will be turbo-machinery. Gas and steam turbines, with the generator, are critical system elements and have the potential to further increase overall process efficiency. In each case, the UK has a strong market presence together with a sound R&D base and is well equipped to meet the challenge. The key needs, which are priority activities, are as follows:

- Development of high performance steam turbines for advanced combustion power plants. The performance of steam turbines is closely linked to the higher steam temperature and pressure, combustion based cycles considered above, where efficiency improvements remain one of the most important developments. This includes improving component integrity for the proposed increased steam parameters, introduction of higher performance blading for higher efficiencies, and establishment of improved operation, especially at part load conditions. This is very much an area where industry will take the lead with the need to establish improved designs that will minimise internal losses. However, there is scope for supporting research, in areas such as materials testing.
- Establishment of improved efficiency and reliability for gas turbines. Gas turbines will be the key prime movers for all power systems based on natural gas and for coal gasification-based technologies where the fuel may be either syngas or hydrogen. As natural gas becomes more expensive, fuel flexibility, i.e. the ability to handle alternative fuels such as poorer quality natural gas, industrial process gas, and gasification products of coal and bio-fuel, will become increasingly important. Targets have been set for the development of gas-turbine technologies to meet this challenge. These include materials development to raise metal and surface temperatures, improvement of near wall cooling technologies; manufacturing techniques and validation, development of modelling and simulation techniques, improvements in combustion kinetics and acoustics development to allow the use of low calorific value gases and of hydrogen, and improvements in wet compression, sealing technologies and robust performance. As with steam turbines, much of this work will best be undertaken by industry but there will be scope for some supporting research in areas such as materials testing and characterisation.

4.2.4 First generation CO_2 capture options

The purpose is to remove CO_2 from the gas stream of a fossil fuel fired industrial process in order to produce a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site. The cost of capturing CO_2 will be lower if this is done in large plants, in gas streams having a high concentration of CO_2 and which are at elevated pressure. The need is to minimise emissions of CO_2 while maintaining very low levels of other pollutants. Depending on the type of plant, there is a choice of three main approaches to capturing the CO_2, all of which either need to be optimised and/or have some major technical issues to be resolved. The EU CO_2 capture projects, under the Sixth and Seventh Framework Programmes are large and will contribute significantly to maintaining a high European R&D profile within the field of CCS. The UK is strongly involved in these projects, which offer a significant springboard for the future. Scottish Power has a small (1MW) post combustion test unit, operating on a side-stream of Longannet coal fired power plant (Scottish Power 2009), while Scottish and Southern Electricity, with Doosan Babcock, are in the process of building a larger (14MW) unit on a side-stream of the Ferrybridge Power Plant (Farley 2010). The R&D needs are significant; however, there is also a need to take the more promising developments forward through large-scale demonstrations and deployment in order to meet the 2020 deadline.

Post-combustion capture systems separate CO_2 from the flue gases produced by the combustion of the fuel in air; the proportion of CO_2 is low (typically up to 15% by volume) with the main constituent of the flue gas stream being nitrogen. Separation is typically by use of a liquid solvent such as monoethanolamine (MEA); such processes have been used with coal- and gas-fired power plants although, to date, there have been no full-size applications of CO^2 capture at large (e.g. 500 MWe) power plants (NZEC 2009).

MEA provides a reference against which performance can be measured; however, if this solvent should be used in a first generation capture system, it would result in a significant loss of power plant cycle efficiency and high levels of solvent degradation, both leading to high capture costs. Thus, for first generation CO_2 post-combustion capture technologies, the focus should be on reducing the cost and reducing the efficiency penalty that incurs when such systems are integrated on power plants. The work, which is of high priority, should include:

- CO_2 capture demonstrations for amine scrubbing. These will need to be undertaken by industry. As noted previously, in the UK the various PC plants are elderly with relatively modest steam conditions. It is possible that industry will consider a retrofit of such a plant with advanced steam conditions together with a CO_2 capture stage. However, it is also important to consider alternative opportunities to participate in demonstrations in other countries as these might provide a better technology assessment. This would also give UK companies the opportunity to showcase their expertise as part of an international technology promotion.

- Process optimization, with improved heat integration, including utilisation of the waste heat. This includes better integration of the combustion process with the CO_2 capture stage in order to minimise efficiency losses and potential plant flexibility/availability problems for the power plant. This may well include improved amine process systems, with use of improved materials of construction. Universities and research organisations can best carry out the under-pinning R&D, under the direction of UK industry. Industry will need to use the results to establish improved designs that can then be tested, possibly as a side stream of an existing plant prior to any larger scale demonstration.

- Development and characterization of new and less energy intensive solvents (e.g. amines, carbonates, ammonia) while also avoiding solvent degradation, provided that robust techno-economic studies suggest that the estimated benefits can justify the development costs. UK industry has built up considerable understanding of solvent behaviour. It has also explored options to optimise the process, much of which has been undertaken within EC funded Framework projects. Further work is needed and UK universities can provide valuable support, with laboratory based solvent characterization, plus testing at small scale, which can provide a cost effective means to characterize a reasonable number of solvents in order to select the better candidates for industrial scale trials prior to any demonstration of an improved technology.

- Obtain the environmental and safety related data necessary to obtain permits for the process and equipment on large power plants. This needs industry input.

Pre-combustion capture systems process the primary fuel in a reactor with steam and air or oxygen to produce a synthesis gas, consisting mainly of carbon monoxide and hydrogen. The carbon monoxide is converted into CO_2 by reacting it with steam in a second reactor (a 'shift reactor'). The resulting mixture of hydrogen and CO_2 can then be split into separate streams with the hydrogen being used as fuel by the plant. High concentrations of CO_2 are produced by the shift reactor; high pressure can be produced in such plant, which is more favourable for CO_2 separation. Pre-combustion capture would be used at coal-power plants based on IGCC technology. The techniques that would be used for pre-combustion capture are already in use for the large-scale production of hydrogen for ammonia and fertilizer manufacture, in petroleum refineries and coal-to-liquids plants. It is evident that a major technology development, demonstration and deployment programme will be required to establish IGCC but, if high efficiency units can be established with integral CO_2 capture and storage, they would represent a major step towards introducing hydrogen into the UK energy system and elsewhere. However, the underlying need is for IGCC to become established, which will be difficult under current market conditions.

For first generation CO_2 pre-combustion capture technologies, the focus should be to limit the efficiency penalty in order to achieve costs reduction for the overall combined cycle process. The work should include:

- Better integration of the gasifier, gas cleaning system and shift converter to ensure improved availability.
- Improved reliability of the gas cleaning system.
- Better gas conditioning, both for optimisation of the shift conversion and associated CO_2 capture processes, and for the H_2 fuel gas stream to the gas turbines.
- Optimisation of the H_2 premix burners for the gas turbine combustor.
- Enhancement of the ASU through process optimisation, with improved absorbents for contaminant removal, and high-efficiency packings for distilling.
- Technical and economic assessment of the poly-generation option to determine the viability of developing gasification-based processes with several possible products.
- Development of gas separation membranes, as an alternative to cryogenic O_2/N_2 separation and H_2/CO_2 separation, with lower costs and energy penalties. This would need to include the development, manufacture and pilot demonstration of candidate materials together with detailed integration into the full scale gasification plant cycle.

All such work must be industry led but there is scope in each case for university input through characterisation studies, modelling and instrumentation development, together with labscale testing as a precursor to larger scale trials.

Oxyfuel combustion systems would use oxygen instead of air for combustion of the primary fuel, with gas recycle to control the flame temperature, to produce a flue gas that is mainly CO_2 and water vapour. The latter would then be removed by cooling and compressing the gas stream. Further treatment of the flue gas would be needed to remove pollutants and non-condensable gases before the CO_2 would be sent to storage. This need for additional gas treatment to remove pollutants limits the fraction of CO_2 captured.

This technology is currently at the pilot scale development stage. Work underway in the UK includes Doosan Babcock operating a full scale (40MWth) individual burner unit at their Renfrew site while E.ON has a 1MWth combustion test unit capable of running under oxy-combustion conditions, which is located at the Ratcliffe Technology Centre. Alongside this, in Germany, Vattenfall have established a 30MWth complete integrated pilot unit while, in Italy, ENEL are developing an extensive R,D&D programme. There remain a lot of questions to be answered regarding likely plant integrity due to the extreme conditions within the recycle loop, and the overall environmental impact should back end gas cleanup devices not be used. The key needs are:

- Establish process optimisation, including start-up/shut-down/flexibility.
- Improve understanding of combustion chemistry and kinetics, heat transfer prediction and flame characteristics.

- Assessment and determination of adequate materials of construction for components within the oxy-fuel environment, in order to address corrosion and ash related issues.
- Determination of ash properties, including the impact on mineralogy and implications for deposition and ash sales.
- Development and pilot demonstration of technologies for the cost-effective clean-up of oxy-fuel product gas, including integration and interaction with conventional flue gas cleaning equipment.
- Assessment of safety options to minimise the likelihood and mitigate the effects of recycled CO_2 leakage.
- Development of alternative concepts for gas separation, such as membranes, including manufacture and pilot demonstration of materials capable of reducing the energy penalty of O_2/N_2 development, to be followed by integration into a full oxy-fuel plant design.

This must all be taken forward by industry, using pilot-scale testing where appropriate, to develop the overall process optimisation and heat management schemes. There is scope for universities to provide supporting type research that covers materials testing, modelling of slagging and fouling processes. Ultimately industrial demonstration of the process will then be required, at a scale such that a meaningful assessment of the combustion process integrated with the CO_2 capture stage can be achieved. The timescale for such an activity is difficult to ascertain at present due to the comparative immaturity of the technology.

4.2.5 Advanced and novel CO_2 capture technologies

There are a number of promising CO_2 capture concepts (post combustion carbonate looping, chemical looping combustion, membrane based systems) being tested in several small laboratory prototype installations. In order to maintain momentum to improve the CO_2 capture processes, it is important that these second generation concepts are robustly assessed and that the more promising options are taken forward. The European Commission has already noted that rapid scaling up, involving testing in substantially larger pilots, is required, in order to accelerate the development of one or more of these concepts (European Commission 2009).

It is arguable that the more promising technique is the post-combustion carbonate looping cycle. There is still a need to complete the collation of basic chemical thermodynamic data but the key issue is to establish pilot plant facilities, with appropriate data gathering and data analysis facilities, in order that the technique can be comprehensively assessed.

Chemical looping combustion is another technique that has shown some early promise although there are issues with particle degradation, emissions of potentially toxic fine particulates and concerns with overall process complexity. This suggests a need to develop degradation-resistant solids with appropriate O_2 supply and capture conditions together with a fluidised bed combustion system appropriate for large solids circulation conditions. Consequently, following further research, there may be merit in larger scale operation so that the potential of this process can be finally assessed under meaningful and robust conditions.

With regard to membranes, these could provide a key means to improve both O_2 separation processes (for use in IGCC and oxyfuel) and for CO_2 removal. There is a need to continue to gather basic chemical thermodynamic data, from which the more promising options need to be tested in large pilot plant facilities with appropriate data gathering and data analysis facilities.

4.2.6 CO_2 transport

The UK will store captured CO_2 offshore, with capture and compression onshore at source, followed by transport to the storage sites. The UK has a promising situation for CCS deployment, with a number of groupings of large CO_2 emission sources that, after the CO_2 has been captured, in principle could be clustered so that economies of scale could be implemented for CO_2 transport and offshore storage, Figure 7, (Hazeldine 2010). Transport of CO_2 is routinely undertaken using road, rail and ship tankers as well as pipelines. Road tankers are most suitable for small quantities (i.e. tens to hundreds of tonnes per day), whilst rail and ship tankers and pipelines can handle progressively larger amounts. For the scale of operation envisaged with capture of CO_2 from large coal fired power plants in an UK onshore location, pipelines are the appropriate method of transport with the CO_2 compressed to a pressure of 10 to 15 MPa.

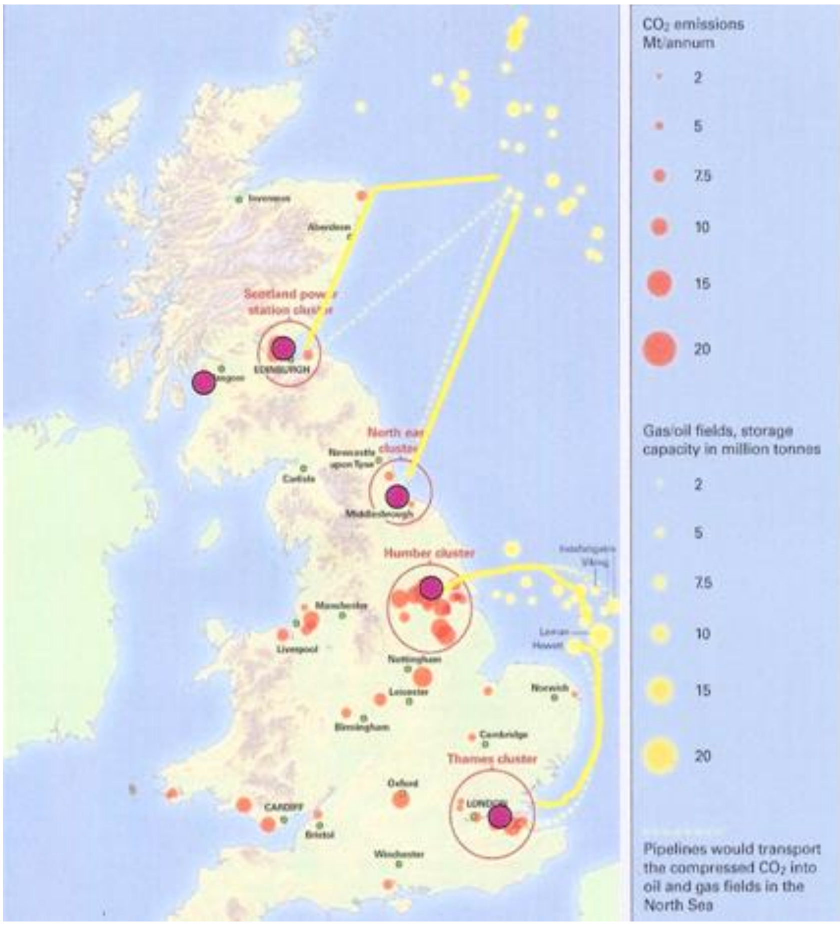

Figure 7 UK emission sources and potential CO_2 clusters (Adapted from Hazeldine 2010)

With regard to R&D needs, there are some areas where work should be undertaken:

- Assessment of the health and safety issues related to pipeline transport including design, integrity assessment, leakage and dispersion modelling. For economic reasons, CO_2 captured from flue gas streams is likely to be transported in a supercritical or dense phase state. A major area for investigation is to comprehensively understand the characteristics of dense/supercritical CO_2 and the potential impact on health and on component integrity. This is likely to include the development and validation of a consequence model for high pressure and dense phase carbon dioxide, for both pipelines and bulk vessels.
- Determination of the corrosion behaviour of pipelines as a function of material, temperature, and impurity content of the CO_2 stream. Linked to this is the selection of materials, joining technologies, and sealing technologies in order to ensure that pipeline integrity meets all regulations and guidelines.

The focus on logistics and any transport network would be a task for an industry specialist. However, most of the R&D needs could best be undertaken by universities with guidance from the industrial stakeholders.

4.2.7 CO_2 storage options

Various geological formations may be used for storing CO_2, which involves injecting CO_2 into rock formations, to trap it underground. Suitable rock types are found in oil and gas fields, saline aquifers and possibly coal seams. Opportunities for CO_2 storage will typically be at depths below 800m, where the CO_2 will be in the dense (liquid) phase. Various mechanisms will trap the CO_2. The reservoir rocks need to be porous, so as to store large volumes of CO_2, and permeable enough to allow the easy flow of fluids but be capped by impermeable rock above to prevent escape of CO_2 (NZEC 2009). The main options are:

- The injection of CO_2 into mature oil fields to improve the recovery of oil through Enhanced Oil Recovery (EOR) and, during this process, some of the injected CO_2 would be stored underground, even though the primary purpose is to produce more oil. The economics of this process can be quite variable as they depend on the price of oil, the cost of CO_2, and the location of the reservoir in relation to the CO_2 source. There is much experience with large-scale EOR, especially in the USA.
- The injection of CO_2 into depleted oil and gas reservoirs, for which there is reasonable confidence that reservoirs that have previously held hydrocarbons for millions of years have potential for storage of CO_2. Provided the reservoir's ability to retain these fluids (especially the seal on the formation) has not been impaired by the production of oil or gas, it should then be capable of holding CO_2 for a long time. However, this will depend on the exact nature of the reservoirs, and how the hydrocarbons were extracted as the existence of a large number of wells, for example, might involve extensive remedial work to ensure the long-term containment of CO_2.
- The injection of CO_2 into saline aquifers, which are likely to have the greatest potential for storage of CO_2 globally. Such aquifers are filled with salt water and typically have no commercial use at present. However, as yet, there is limited information available on their characteristics although this is being gained via large scale projects in several countries (e.g. the project to monitor the injection of up to 1 Mt of CO_2 per year into a saline aquifer on the Statoil-operated Sleipner field in the North Sea).

In order to assess basins for possible storage of CO_2, three main characteristics of a geological formation are normally considered: the capacity to hold CO_2; whether it can retain the CO_2 safely and securely; and how easy it would be to inject CO_2 into the formation. Estimating the potential capacity for CO_2 storage as part of an EOR operation is aided by the availability of geological information in the public domain. In contrast, the assessment of storage in saline aquifers is constrained by the limited amount of detailed information available since, until now, there has been little use for them so they have mostly not been surveyed. For this reason, estimates of storage capacity of aquifers must at present often be based on gross assumptions extrapolated across large areas rather than more detailed, site-specific assessments.

Assessment of possible CCS projects needs to consider the geographic relationship between the sources of emissions and the possible storage sites. The scale of potential capture opportunities also needs to be tested against available storage capacity. This will affect the transportation distances, infrastructure requirements and costs.

A related issue is the need to ensure that storage of CO_2 will be safe on a long-term basis, because of the potential risks to people and the environment associated with release of CO_2. Although the collective experience of the oil and gas industry suggests that CO_2 can be contained for very long periods underground, when selecting appropriate CO_2 storage sites, it will be essential to address health and safety issues as part of an overall risk assessment process. This will require a rigorous approach to site selection and assessment together with robust monitoring and verification, for which several techniques are being established.

Most potentially viable storage capacity in the UK, suitable for the scale of CO_2 emissions created by a modern power plant, is believed to lie offshore (APGTF 2009). The British Geological Survey (BGS) has made an initial estimate of the theoretical gross capacity of 292 sinks in UK waters as 24.7 Gt CO_2 (BERR 2007b). The UK annual CO_2 emissions from power plants are some 170 Mt CO_2. With the exception of depleted gas fields where no aquifer influx has occurred, these capacity numbers are largely theoretical and represent a likely upper limit. Over 60% of this theoretical storage potential lies within saline formations. Some part of this resource will be required to meet the UK's storage requirements; substantial storage may also be available to store CO_2 arising in other EU Member States. However significant technical investigations are needed to better understand the realistic capacity.

In terms of priority R&D needs, these include:

- Detailed scientific, technological and engineering assessments of CO_2 EOR opportunities.

- Depleted oil- and gas-field storage assessment and subsequent large scale testing, which would cover capacity, availability and risk, as well as facilities, integrity and re-use.
- Development of improved methods of aquifer site appraisal, beyond the theoretical approach used so far, which would include the development of methods to assess aquifer injectivity, aquifer seal performance, improved estimation of storage ability, better understanding of CO_2 physical properties as a function of different groundwater salinities.
- Improved understanding of the injection and storage process. This would include site stability studies with the development of remote sensing of geo-mechanical stability during re-pressurisation, improved validated software for reservoir and region with the development of measuring, high-resolution monitoring, modelling and verification techniques.
- Better site performance assessment to reduce the impact of subsurface uncertainty on performance prediction and risk. This would include calculation of local pressures, temperature and forces down the well and in the injection region of the storage rock for various combinations of reservoir and injection conditions.
- Better understanding of the geochemical impact. There is a need to ascertain the major reactions of minor contaminants in the CO_2 stream and a validated database of equilibrium and kinetic data for modelling should be established.
- Improved understanding of CO_2 storage in unmineable coal beds. This would include a determination of CO_2 absorption capacity of coal as a function of depth and permeability.
- Improved understanding of the environmental issues. While the risk of leakage is believed to be small, there is a need to better understand such risks and their consequences. This should include modelling of the dispersion of CO_2 following possible leakages in various storage formations, an assessment of the impact of leaks on ecosystem, including the impacts of seepage on shallow marine systems.

Much of this R&D can readily be undertaken by UK universities and research institutions such as BGS, who already have gained valuable expertise and experience from participating in various national and international collaborative initiatives.

4.2.8 Social issues

In addition, to the technical challenges, there is a need to consider the associated social issues. Good risk communication with the public is a key challenge, as public understanding and acceptance of clean coal technologies and CCS will be crucial to successful planning and development. Early projects in the UK will affect public attitudes, with knock-on effects on the government and industry's ability to develop and deploy CCS at the scale required to meet emissions reductions targets. It is essential that everyone involved in CCS provides clear and consistent messages about both the risk and risk management. A robust safety regime can underpin public confidence in industrial processes like CCS.

The IEA's CCS Roadmap makes clear that community residents will have legitimate concerns about possible risks and impacts of CCS projects (IEA 2009b). This suggests that governments need to prioritise public engagement and outreach efforts to address these concerns. It is envisaged that this would include offering readily accessible information about planned projects to local communities. This information should convey the role of CCS within the larger set of GHG mitigation options, in order to build support for CCS at a national level. The IEA also notes that, as the level of information and lessons learned from CCS public engagement and education efforts increases, these emerging best practices should be collected together into a common platform that guides future CCS projects. This approach should be used as early as possible during the design stage, in order to avoid late-stage stakeholder protests.

To date, while some public perception studies have been undertaken in the UK and elsewhere, there is a need to further define the issues and to undertake additional studies in order to establish a coherent message to allay public concerns.

4.3 Maintaining operation of existing UK coal-fired power plant

If existing coal fired power plant is to be maintained, there is a need to improve overall cost effectiveness, through improvements in availability and flexibility while meeting the ever tightening environmental legislation. Many aspects of this can be viewed as part of the process for establishing advanced PC plant, as defined above. As such, it may be possible to gain support from the various funding programmes, particularly the RFCS, as set out in Section 3. However, it seems likely that much of this work will have to be taken forward primarily by UK industry itself. That said, there should be scope for industry to use UK universities to provide some input by, for example, the B2FRA funding route. Areas of interest include:

- Improving overall boiler performance through improving grind quality from mills, individual burner characterisation, improving PC /airflow distribution & measurement/control, prediction and minimisation of the impact of blends of new coals/alternative fuels on combustion/ NOx/ slagging/ fouling/ corrosion/ particulates/ trace pollutants, and optimisation of combustion-based NOx control technologies.
- Characterisation of co-firing fuels such as biomass, petroleum coke and waste products on emissions and by-products
- Improving environmental impact by improving electrostatic precipitator performance, measuring PM concentration and size distribution, optimising carbon in ash beneficiation, enhancing ash precipitability, determining impact of the IED on NOx emissions, characterising and removing mercury/trace elements and trace organics such as dioxins and poly-aromatic hydrocarbons, introducing continuous monitoring techniques, establishing multi-pollutant control options and establishing techniques for using/ disposing of wastes/ by-products.

4.4 Metallurgical uses of coal

The R&D needs in the metallurgical industry mirror to a degree those in the power generation sector. Thus there is a need to improve the overall performance and cost effectiveness of existing units while also seeking ways to advance the technology to ensure future environmental compliance, including minimising CO_2 emissions. Short to medium term areas of importance include:

- Improved characterisation of coals of different rank and of imported coals since coal sources change and it is important to know the effect of these changes on process performance. This requires the development of tests that simulate the conditions of coal use in practice, to determine the impact of coal blending together with the effects of long storage or transit times.
- Increasing the life span and plant efficiency of coke ovens are of paramount importance to the coking industry and a significant factor in this is a sound understanding of the behaviour of individual blend components and their constituents during the plastic temperature range in order to assist blend formulation for carbonisation. Consequently, a sound understanding of thermoplasticity, gas pressures in coking and plastic layer rheology is required.
- Greater understanding is needed of the plastic/fluid phase of carbonisation if any significant improvements are to be made in the manufacture of metallurgical coke using non-coking material in order to reduce costs. In this respect, modern methods need to be utilised to gain better measurement and hence better understanding of the plasticity developed and how to control and use this plastic phase to achieve the coke structure required for the optimum coke properties.
- In order to improve the cost effectiveness of coke oven operations, investigations are needed of ways and means for maximising the yield of coke in the size range specified to meet the requirements of particular operations.
- There is a need to improve the cost effectiveness of blast furnace operations and reduce coke usage. Investigations are needed to identify the factors contributing to coal and char gasification behaviour in order to maximise the rate of coal injection to meet the requirements of efficient and stable operation.

- From an environmental perspective, increasingly stringent environmental legislation may require reductions in the current levels of poly-aromatic hydrocarbons and benzo(a)pyrene. Further research is needed to develop techniques and equipment to facilitate reductions.

- Some coals cause operational problems in coal preparation, transport and storage systems. Techniques and equipment, which can identify and reduce potential problems, will be important to optimise coal usage and reduce coal processing costs.

- With regard to global CO_2 issues, there is an international initiative to reduce emissions in the coking sector, which has been undertaken for several years, and discussions are ongoing as to how best to develop further phases of such work.

All such work must be industry led but there is scope in each case for university input through characterisation studies, modelling, techniques and monitoring equipment development, together with labscale testing as a precursor to larger scale trials.

4.5 Other non-power uses of coal

For other non-power coal using processes, the R,D&D needs include maximising combustion efficiency, reducing emissions, and understanding how the use of coal-coal and coal-biomass/waste blends will impact on plant performance. In addition, of importance to all such users, is the issue of coal handling. Thus appliance suppliers will need to continue to be active in developing improved systems that give greater amenity in use. At the same time, coal suppliers must continue to meet the needs of the fiercely competitive fuel market by delivering good quality, consistent and competitive products.

4.6 Fundamental science considerations

As noted above, under the various market sector considerations, while the major technology development programmes will need to be industrially driven, there remains a significant role for research institutes and universities to provide added value underpinning support, including fundamental research that will be of benefit regardless of the technology concept. Key areas include:

- Basic coal science will remain important to the understanding of all coal utilisation processes. Means of readily evaluating coals and of predicting the behaviour and characteristics of coals and coal blends in advanced clean coal technologies continue to be needed. For example, in advanced PC plants, particularly those with, say, oxy-fuel firing, plant manufacturers will need simple (low cost) tests to help in plant designs. Standard tests will need to be defined for simulated process conditions, e.g. true volatile matter measured at realistic heating rates and temperatures, tests to predict NOx emissions, improved techniques for collection of in-flame data, development of reliable cost effective techniques to measure corrosion and deposition rates.

- Equipment and systems for on-line monitoring of various species and conditions in coal-fired plants will need to be developed. Examples include non- intrusive techniques for the temperature monitoring of coals and flames. There is also a need for suitable fast response techniques for the monitoring of various gaseous species and carbon-in-ash levels. However, the needs now extend much further to encompass the CO_2 injection and storage issues in order to understand what is happening in these deep geological formations. In addition, while underground coal gasification is making rapid development progress, the need for robust monitoring techniques to understand and control the reactions in deep coal seams is of great significance if this technique is to be deployed.

- The development of computational fluid dynamics (CFD), other software tools and powerful computers means that modelling techniques can increasingly be of value. For example, there is a need for mathematical modelling (static, dynamic) of components and their integration into full plant. CFD modelling needs to be improved to reflect the latest findings of coal science such as the development of particle structure, pore diffusion and reaction within particles.

- The development of advanced materials is critical to achieving significant improvements in power plant efficiency with reduced emissions (UKDTI 2002). Such research can take decades to progress from the conceptual stage to commercial exploitation. A DTI sponsored review recommended that an integrated long-term materials R&D core programme would be needed for power generation. With regard to the coal based power generation technologies set out above, for advanced PC systems, there is a clear need for the development of acceptable materials of construction for critical heat transfer components while further development of enabling technologies such as steam and gas turbines depend in part on appropriate advanced materials becoming available. Materials studies needed for IGCC components include refractories, and alloys for syngas coolers. Alongside this, it will be important to consider any cross-technology issues associated with the chemical/petrochemical industry for cost-effective use of syngas. It is also evident that the need for advanced materials of construction will be very important to establishing certain CO_2 removal techniques. One such example is the development of cost-effective gas separation systems, e.g. via membrane techniques for the systems O_2/N_2; CO_2/N_2; $_{CO2}/H_2$.

- Emissions of trace elements and volatile organic species are of increasing concern. There is merit in being able to predict trace element mobilisation in combustion and gasification systems from the composition of the coal mineral content as well as being able to predict their removal capability in various plant components.

- Techno-economic studies are needed in areas such as control and cycle performance for new power cycles such as advanced PC systems with and without CO_2 removal systems. Issues to be explored include improving plant operability, plant costs and integration. In addition, scoping studies are needed on extending IGCC to embrace technologies such as fuel cells, co-production of chemicals or hydrogen and co-gasification. From a broader viewpoint, life cycle analyses are needed of alternative power station concepts (including fuel availability, operational constraints, load requirements). Similarly there is a need for an assessment of retrofit considerations, covering component issues, site-specific issues and overall economics.

4.7 Underground coal gasification

Underground coal gasification (UCG) is the in-situ gasification of coal in the seam, which is achieved by injecting oxidants, gasifying the coal and removing the product gas through boreholes drilled from the surface. The gas can be used either for power generation, industrial heating or the manufacture of hydrogen, liquid products, synthetic natural gas and other chemicals. The gas can be processed to remove CO_2 before it is passed on to end users, thereby providing a source of clean energy with minimal GHG emissions. Thus the potential for UCG includes maintaining an acceptable level of security and diversity of energy supply while also reducing emissions of environmental concern. There have been several studies to consider the possible role of UCG as part of a carbon abatement technology strategy. The idea would be to use UCG in combination with CCS since there is scope to inject CO_2 into adjacent coal seams, which offers the prospect of enhanced CBM production alongside CO_2 storage. There is also the option of storing large volumes of dense-phase CO_2 in the voids that would be created by gasifying coal at depths in excess of 800 metres.

There have been several major international large-scale trials undertaken, from which the basic feasibility of UCG has been proven (UKDTI 2004). Further detailed studies are required to prove the technology of precision drilling process control and to fully evaluate any possible environmental impact on underground aquifers and adjacent strata. Such work is now getting underway, with considerable emphasis in the UK, reflecting both the need for diversification of the UK energy mix and the fact that this approach could offer an alternative way to obtain the energy from coal without mining. It could also provide access to the large-scale UK coal resources inaccessible by conventional mining, including the substantial resources under the southern North Sea. Accordingly, the UK Coal Authority has issued 14 conditional licenses to UK industrial companies to explore and characterise offshore and estuary sites for UCG (Coal Authority 2010a). The areas include Swansea Bay, the Humber Estuary and the Firth of Forth. There are major global market opportunities for UCG demonstration and deployment in many coal producing countries, including Australia, China, India and Eastern Europe, with the UK being able to offer technology and consulting expertise. Several UK companies are active internationally in developing UCG projects for Australia and China. Several universities have built up expertise relevant to UCG and opportunities to utilise their skills are increasing, in part through funding being available via the European Commission.

That said, while large scale trials are getting underway, there remain several technical issues where further coal related R&D is required, including:

- A robust, objective assessment of the costs and the subsequent viability of the process under likely UK economic conditions, to include various options for utilization of the gas produced, particularly gas based power generation.
- Process engineering studies for large scale applications.
- Improved understanding for geological subsurface characterization, geo-mechanics, and development of subsurface process monitoring and control techniques.
- Risks and hazards assessments, including environmental issues.
- Development and costing of potential schemes where CO_2 capture and storage might be integrated with UCG. The key requirement would be to identify potential synergies that could enhance economics and site performance compared with other options.
- Development of standards and regulations for siting and operation of UCG facilities. Prior to any commercial deployment, it would be necessary establish the technical basis to determine acceptable sites and encourage sound investments.
- Development of combustion-process models to address the issues associated with the utilization of low CV coal-derived gases of varying quality, which often contain quite high concentrations of hydrogen. This will need to address the impacts on the performance of gas burners and gas turbines.

4.8 Coal bed methane

Coal bed methane is the generic term for gases, which are either adsorbed onto the coal or dispersed into pore spaces around the coal seam. These gases, which are a significant energy resource, are recovered by drilling wells into the coal seam, after which the seam is dewatered, and the methane extracted from the seam, compressed and piped to market. This approach decreases the water pressure by pumping water from the well, which then allows methane to desorb from the coal and flow as a gas up the well to the surface. Gas content generally increases with coal rank, with depth of the coal seam, and with reservoir pressure. While economic quantities of methane can be produced, water disposal options that are environmentally acceptable and yet economically feasible, are a concern.

This methane can be recovered under various conditions. These include:

- Draining, prior to it entering the mine air stream (known as coal mine methane).
- Collection from abandoned mines (abandoned mine methane).
- Extraction from coal seams where mining has yet (or is unlikely ever) to take place (virgin CBM). This also includes enhanced recovery methods, where CO_2 or N_2 is injected into the coal (enhanced CBM). Thus there is a potential link to CO_2 storage provided that the coal seam in which CO_2 might be injected will never be mined.

Europe, and the UK in particular, leads the world in abandoned mine methane collection. Small scale projects producing methane from coal mines have been running in the UK since 1990. Of the 33 UK projects operating in 2008, over half were in abandoned mines and the rest at active underground mines. At the same time, a number of new developments have been initiated and, as of September 2010, there were 13 active Coal Authority licences to extract methane from unmined coal seams although these were all for pilot drilling projects (Coal Authority 2010b). To date there are no large-scale projects although several of the licensees have declared plans to expand operations in due course. Likely use for the methane is as boiler fuel, for small scale power generation, and for injection into the national gas transmission system. There are some technical issues with the latter approach as the methane quality produced from CBM operations is variable and in many cases may not meet the gas pipeline standards required. Purification of the gas to raise its calorific value can be expensive, but where circumstances permit, blending or ‘co-mingling’ with pipeline gas may be one solution. Where pipeline transmission is uneconomic due to distances or production volumes, local utilisation to generate electricity will be the preferred option. Electricity produced from CBM is already being fed into the national grid at one site.

There are some R&D challenges, which require input from both industry and research organizations such as universities, as set out below:

- Improvement with in-seam drilling technology in order to reduce surface drilling location constraints.
- Better estimation of abandoned mine methane opportunities, through a better understanding of the characteristics of abandoned mine gas reservoirs coupled with the development of methods for enhancing gas production.
- The feasibility of developing biotechnological methods for enhancing CBM extraction rates.
- Improving energy recovery from small scale power generation schemes through better utilization of the waste heat.

4.9 International collaborative R&D

The overwhelming focus of coal utilisation R,D&D will be to address issues associated with energy efficiency and carbon abatement, recognising the need to minimise the global environmental impact of coal use within the power generation sector. Consequently, in many instances, there are significant benefits to be gained through collaborating with other countries in the development of CATs and particularly CCS. For example, areas of mutual cooperation have already been established with the United States of America (USA) on two project areas while DECC has strongly supported capacity building activities in China to support the China-EU Memorandum of Understanding that is designed to establish CCS demonstrations within Europe and China by 2015 (NZEC 2009). It is also evident that, in many cases, the organisations that support coal utilisation R,D&D have structured their programme requirements to ensure such cooperation. For example, both the EU Framework Programme and the RFCS will only fund projects that are proposed by consortia that are drawn from more than one EU nation state and associated countries. In addition, the EPSRC has supported joint R&D initiatives with countries like China on globally related issues that include CATs and CCS.

4.10 Technology transfer promotion

In support of various industrial technology transfer initiatives, there continues to be merit in market reviews, particularly in countries like China and India where opportunities are increasing rapidly. This can often link with collaborative R&D activities between appropriate R&D organisations and, in some cases, universities within the UK and these countries.

4.11 Availability of UK skills and experience base

Clean coal and CCS technology requirements in the power sector should be extensive, with a need to both establish demonstrations of integrated options while also developing improved solutions as second generation systems. This will require industry to have available skilled and experienced engineers and scientists to implement and assess the first generation demonstrations, while universities will need to have high grade scientists that can work closely with industry. For CO_2 capture technologies in particular, this will require a breadth of technical expertise in technological areas not currently widely applied in the power sector. Consequently, a key aspect of any UK RD&D programme is the development of science and technology competencies and capabilities to meet these needs, as the first tranche of plants is built and, subsequently as they are commissioned and subsequent designs developed (APGTF 2009). Such competencies are needed to support deployment and also underpin the training of a new generation of engineers and scientists that will be needed in a growing CCS industry. In the UK this need comes at a time when a significant proportion of the existing power generation fleet needs to be replaced so that the workforce needed to drive the expansion of CCS will be in addition to that required to replace the current generation of plant. At the same time, the traditional sources of such personnel from universities moving to industry is constrained due to the lack of opportunities in recent years leading to a turn down in appropriate coal related postgraduates.

5. UK CCT ENGINEERING CHALLENGES

5.1 Introduction

This section considers the key challenges facing UK industry in taking the R&D results forward in order to ensure that the resulting technology designs will be economically viable within the appropriate market context.

This needs to focus on coal fired power plant and be undertaken in a timescale consistent with Government policy if appropriate technologies with CCS are to be available on a commercial basis by 2020. There has been considerable discussion within the UK coal R&D community from which the APGTF, the CRF and others have made suggestions that include the following, each of which needs action from Government and industry:

- There is a need for a series of demonstrations of CCS technologies by UK companies, including several full scale demonstrations of the complete CCS train in the UK by 2014. DECC has indicated that it will provide financial support for four such demonstrations. The timescale to achieve this is extremely tight.
- The demonstration of CO_2 storage is needed as part of the overall CCS chain but there is also a need for a more detailed characterisation of cost-effective storage options relevant to UK.
- On the basis that CCS is to become established in the UK coal power sector, there will be a need for large scale deployment of CO_2 transport infrastructure.
- The government, for its part, will need to establish viable financial incentives for CCS to supplement the incentive of the carbon price, until this provides sufficient incentive itself. It will also need to establish long- term, stable regulatory and financial frameworks to enable the UK deployment of CCS, which will best be done by working to achieve a consistent international basis.

5.2 Advanced combustion plant

Supercritical and ultra-supercritical coal fired power plants have been established in Europe and have shown significant increases in efficiency compared to sub-critical units, although the impact is best shown in China where some 90% of the current global market for such units has been established. However, Europe is at the leading edge for the next step, with plans to establish a 500MWe unit with a cycle efficiency of at least 50% (net, LHV) through very high steam conditions of 35 MPa/700°C/720°C (using advanced new materials). This technology is at the component development and testing stage, which has included the AD700 project within the EU Framework Programme, the follow-up E-max and Cooretec activities, and the component test project COMTES within the RFCS Programme (European Commission 2004c). These are supported by various materials development projects under the European Cooperation on Scientific and Technical Research Programme (COST), again with significant input from UK organisations (Oakey 2000). The challenge is to establish an overall engineering design that can achieve the required efficiency while maintaining fuel and operational flexibility in a cost competitive manner. In order to meet the arduous steam conditions, such a design requires the use of advanced materials of construction, including:

- Nickel based alloys, which are used in final super-heaters, re-heaters including headers, reheat steam lines, turbine valves, inlet section of turbine casing and rotors.
- The development of advanced austenitic steels for superheaters and reheater sections in the temperature range 600-650OC.
- The development of martensitic steels for headers and interconnecting steam lines in the temperature range 600-6500C.

Such materials are very expensive compared to conventional boiler materials. As such, this advanced technology option is vulnerable to these additional high costs. Therefore, in order for the technology to be competitive, it is essential that the higher materials costs can be offset by establishing a compact design of boiler to minimise the need for the very expensive heat transfer materials (Bugge 2005). This requires a change of design for furnace walls, the re-location of the heat transfer surfaces, a change to the overall plant concept including the location of the turbine headers closer to the steam turbine. It is stressed that the designers must ensure that the overall cost/benefit analyses are commercially attractive. This requires significant innovation, both in the design of individual components and in the integration of the complete power plant concept.

E.ON had initiated plans to establish a demonstration of this technology at Wilhelmshaven in Germany. However, currently that project is suspended in order that further research can be undertaken to better define the materials required for the key components described above.

Irrespective of the steam conditions to be achieved, any advanced PC plant to be built in the UK will need to be designed for CCS (see below). In addition, all power plants must meet the appropriate transmission grid requirements. In the UK, for coal fired plant, this includes the capability to increase output by 10% in 10 seconds and maintain it for 30 minutes. For subcritical plants, this could be achieved by throttling the steam cycle to obtain 5% while adjustments to the steam cycle could provide the remainder. For an advanced ultra-supercritical plant this will be very challenging.

As well as operational flexibility, fuel flexibility will be required and there are indications that up to 25% energy input by biomass might be effective compared to the lower levels (~5%) currently utilised. Consequently, the introduction of a dedicated milling and injection system might be needed and it will be necessary to ensure high mill efficiencies and effective transportation for the processed biomass to the burners. It would probably be sensible to prove this on an alternative unit

With regard to environmental performance, better NOx control will become critical although ultimately selective catalytic reduction (SCR) will probably be the way forward. However, integrated emissions control is a key requirement. For example, mercury can deactivate the SCR catalyst so its control would be important while not impacting adversely on other pollutant removal systems.

As noted previously, it would appear that a significant proportion of existing UK coal fired plant, albeit currently with modest steam conditions but good operational flexibility, will remain operational after 2016. If this proves to be the case, there will be a need to ensure that such plant can continue to be utilised. Here the engineering challenge will be to introduce the necessary improvements to various subsystems within the existing power station building. These could include the need to:

- Establish a supercritical boiler design with a parallel modification of the steam turbine within the existing support steelwork.
- Design in fuel flexibility for biogenic material co-firing at higher levels than currently practiced.
- Introduce innovative feed-water preheating.

Such modifications will need to be integrated wherever possible to minimise operational risks and to ensure overall unit competitiveness (Spalding 2005).

5.3 Advanced combustion plant with CO_2 capture

Government policy requires the introduction of CCS technology onto new coal fired plant and in due course on retrofitted units. In both cases, the need is to minimise the efficiency and possible availability losses associated with the CO_2 capture stage. For PC plant, the current choice will be to incorporate a post-combustion absorption-based amine scrubber. The engineering challenges include the need to design the steam cycle for optimal integration of the amine scrubber, and to minimise the energy penalty of operating this capture equipment. There will also be a need to consider the likely need for enhanced flue gas clean-up of conventional pollutants (dust, SO2, NOx) and trace metals as some of these can degrade the amine absorbers. With regard to the amine scrubber system itself, the recovery of the CO_2 from the amine stream from the absorber is highly energy intensive. Again, careful integrated design is needed to minimise the very significant export power loss.

The alternative approach to capture CO_2 from combustion based plant is to use oxyfuel firing. This technology is still very much at the pilot scale development phase and has a significant number of challenges to overcome. Should it be shown to be an attractive option for conditioning the flue gas stream, then scale-up designs of the concept for power plant application will be needed. The same design principles will apply, although the issues may well be different. For example, there will be the need to design a boiler furnace that can prove resistant to the CO_2 impacts on boiler corrosion, fouling and slagging. The appropriate way forward will be to establish a demonstration plant.

5.4 IGCC

IGCC remains a technology with unfulfilled potential. Various studies have shown that it could achieve much higher efficiencies than those of the demonstration plants by implementing fairly simple design changes based on conventional and available technology (European Commission 2004). However, the reality is that the technology needs to show acceptable component reliability and cycle availability. Engineering design issues will include the need to establish IGCC power plants with improved feeding systems, particularly for mixed feedstocks, improved firetube cooler designs with regard to minimising deposition and corrosion, selection of materials to ensure greater reliability, especially refractories, dry units for dust removal, sulphur removal and alkali/trace metals control, together with lower cost ASUs.

5.5 IGCC with CO_2 capture

There is interest in the option of IGCC as a source of syngas for chemicals production. This offers the prospect of using coal as a raw material to produce hydrogen, which may provide a major impetus to establish the technology, provided that the use of hydrogen as a transport fuel can be established. This opens up the prospect of multi-product IGCC systems, producing electricity and hydrogen, fired on coal in conjunction with other opportunity fuels as circumstances permit. At the same time, when hydrogen is produced via IGCC the resulting by-product is a gas stream highly concentrated in CO_2, which can then be readily processed for transport to a storage site.

This introduces a further engineering challenge, which is to integrate the water gas shift reactor into the gasification process, introduce a high pressure scrubbing CO_2 removal process and ensure that the hydrogen rich gas can be adequately combusted in the gas turbine. While the scrubbing process has been demonstrated at reasonable scale, the major challenge is to demonstrate a high-efficiency gas turbine working on a very high H_2 content fuel . Such changes to the basic IGCC system must be accommodated without adverse impact on process flexibility and availability.

In view of the future vision for gasification technology, as a process to generate both power and syngas, there should be a demonstration of a multi-product IGCC system. The demonstration should use coal, maybe in combination with other low-cost and readily available fuels. It should be designed to produce electricity, heat and synthesis gas. The plant should be located near an industry that could use the synthesis gas to produce high value chemical by-products, such as hydrogen, ammonia and methanol. The project should also demonstrate that the capture and utilisation or storage of the carbon dioxide is practicable. Such a project is being planned and implemented in China and cooperation on such a venture may be appropriate.

5.6 CO_2 transport and storage

When considering CO_2 geological storage as a means for carbon abatement, the challenge is to establish and ensure the integrity of the storage option over the very long timescales compatible with the policy to counter climate change. The two key engineering challenges are to develop an onshore transport network that can be linked to several CO_2 capture sites, and to establish demonstrations of CO_2 storage including EOR, if appropriate, together with depleted gas and oil fields and saline aquifers.

6. THE WAY FORWARD

The UK continues to face significant challenges to establish a diverse, secure, environmentally acceptable energy supply. Although coal use has declined in recent years, it can remain a significant part of the overall energy mix provided that it can be used in an increasingly efficient and environmentally acceptable way. For power generation, which dominates coal use in the UK, future plant must include advanced CCTs either with or capable of subsequently including CCS technologies so that ever-tighter regulatory emissions limits can be met. At the same time, the UK power plant manufacturing and supply industry needs to remain competitive so that it can take advantage of the major global opportunities for new and replacement power plant. In the near to medium term this will be for advanced, higher efficiency plant while over the longer term this well probably include the need for near-zero emission technologies. Looking at both the UK home market and the major global opportunities for new and replacement coal fired power plant, the technology of prime industrial interest is the advanced supercritical pulverised coal boiler /steam turbine system in the 400-1000 MWe range. There is also a need for the continuing advancement of large gas turbines, these being needed both for use in gas fired combined cycle plant but also for use in advanced coal based gasification systems, should the latter be developed sufficiently to meet power sector requirements. Such developments must proceed together with an associated and major effort to ensure that the related near-zero emission technologies can be developed and established in a cost effective, credible manner.

The key R,D&D challenges include:

- Improve the efficiency of coal fired power generation with effective removal of conventional pollutants such as SOx, NOx particulates and trace metals.
- Improve the use of more advanced steam cycles, for which the need to improve performance through materials selection is critically important.
- Improve plant integration, together with enhanced fuel and operational flexibility.
- Establish near zero emissions systems such that CO_2 can be prevented from being released to atmosphere, with any adverse technical impacts on such efficiency and environmental performance being minimised in as cost effective manner as possible. This will require large scale demonstrations of the first generation CO_2 capture systems and offshore CO_2 storage within a complete CCS chain.
- Improve effectiveness and costs of the first generation CO_2 capture systems and the development of second generation systems that will overcome some of the inherent disadvantages of the first.
- Gain a better understanding of the properties of CO_2 to ensure the provision of robust transport systems.
- Improve assessment and modelling of CO_2 storage capacity in various geological formations, together with the development of improved monitoring and verification techniques.

Consideration needs to be given to the possible uptake of underground coal gasification (UCG) and coal bed methane (CBM) as contributors to UK energy production. These are new extraction processes that are starting to be demonstrated and deployed, and there are linking factors that need to be addressed as they will introduce lower carbon intensive energy sources, which could be suitable for both power and non-power applications, including transport fuel applications. Outside of the power sector, there is a much smaller but still significant use of coal in the iron and steel industry, which is a sector that has continued to experience difficult market conditions. Here the environmental challenges remain very significant and addressing these together with ensuring sustainable costs reduction are the major aims of the industry.

This UK R,D&D programme must continue to be industry-led. At the same time, such an industrial initiative will benefit from support by added value scientific/fundamental research at universities and research organisations. In this way, the UK can benefit hugely from the scope to address the near term market issues while also addressing the medium to longer-term strategic technology developments.

Such an approach will not only aid the technology developments but will also continue to establish scientific/technical capabilities, including the provision of suitably qualified scientists and engineers in the relevant disciplines. The latter point is very important as it is essential that the UK can have available skilled and experienced engineers and scientists for such R,D&D activities. Consequently, a key aspect is the development of science and technology competencies and capabilities to meet these needs. This represents a major challenge as the traditional sources of such personnel from universities moving to industry has become constrained due to the lack of opportunities in recent years.

7. REFERENCES

APGTF (2009) Cleaner Fossil Power Generation in the 21st Century. Available from: http://www.apgtf-uk.com/index.php?option=com_docman&Itemid=81 Advanced Power Generation Technology Forum (2009)

BCURA (2010) Welcome to the British Coal Utilisation Research Association. Available from: http://www.bcura.org/ (2010)

BERR (2007a) Meeting the energy challenge: a white paper on energy. Available from: www.berr.gov.uk/energy/whitepaper/page39534.html (23 May 2007)

BERR (2007b) *Report to the North Sea Basin Task Force, Development of a CO_2 Transport and Storage Network in the North Sea* (December 2007).

BF2RA (2010) An introduction to the Biomass and Fossil Fuel Research Alliance. Available from: http://bf2ra.org/ (2010)

Bugge, J. et al (2005) *Review of the AD700 Technology*. Presented at 2nd International Conference on CCTs for our Future, Sardinia, Italy, May 2005

Carbon Capture (2010) Carbon Capture for Coal Power: Key Element of a Clean Energy Policy. Available from: http://www.carboncapturejournal.com/displaynews.php?NewsID=543 (17 March 2010)

Carbon Trust (2010) Welcome to the Carbon Trust. Available from: http://www.carbontrust.co.uk/Pages/Default.aspx (2010)

Coal Authority (2010a) Underground coal gasification in the UK. Available from: http://www.coal.gov.uk/publications/miningtechnology/ucgoverview.cfm (2010)

Coal Authority (2010b) Methane associated with coal seams. Available from: http://www.coal.gov.uk/publications/miningtechnology/coalmineandbedmethane.cfm (2010)

Cordis (2010) The Research Fund for Coal and Steel. Available from: http://cordis.europa.eu/coal-steel-rtd/ (2010)

DECC (2010a) UK energy statistics in brief. Available from: http://www.decc.gov.uk/assets/decc/Statistics/publications/brief/190-uk-energy-in-brief-2010.pdf (29 July 2010)

DECC (2010b) CCS demonstration competition. Available from: http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/ccs/demo_comp/demo_comp.aspx UK Department of Energy & Climate Change (2010)

DECC (2010c) *UK Carbon Capture and Storage (CCS) Commercial Scale Demonstration Programme Delivering Projects 2-4 (Further Information).* Office of Carbon Capture and Storage (December 2010)

DECC (2010d) The Environmental Transformation Fund. Available from: http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/lc_business/lc_economy/env_trans_fund/env_trans_fund.aspx (2010)

DECC (2010e) Carbon Emissions Reduction Target (CERT). Available from: http://www.decc.gov.uk/en/content/cms/what_we_do/consumers/saving_energy/cert/cert.aspx UK Department of Energy & Climate Change (30 July 2010)

EIA (2010) International Energy Outlook 2010. Available from: http://www.eia.doe.gov/oiaf/ieo/ Energy Information Administration, US Department of Energy, USA (27 July 2010)

Energy Technologies Institute (2011) Carbon Capture and Storage (CCS) Programme. Available from: http://www.energytechnologies.co.uk/Home/Technology-Programmes/carbon-capture.aspx (January 2011)

EPSRC (2010) Pioneering research and skills. Available from: http://www.epsrc.ac.uk/Pages/default.aspx (2010)

European Commission (2004) *World Energy, Technology and Climate Policy Outlook*. Published by the European Commission, Brussels, Belgium (2004)

European Commission (2009) EU Framework Programme for energy. Available from: http://cordis.europa.eu/fp7/energy/home_en.html (2009)

European Commission (2010) EU FP7 overview. Available from: http://ec.europa.eu/research/fp7/pdf/fp7-brochure_en.pdf (2010)

Farley M (2008) A clean future for coal fired power. Available from: http://www.bcura.org/csl08.pdf BCURA Coal Science Lecture (13 October 2010)

Farley M (2010) *Clean coal and CCS roadmaps to 2020.* Presented at All Energy 2010: Industrialising new energy technologies. Available from: www.all-energy.co.uk (2010)

Hatfield IGCC (2010) Clean Power projects. Available from: http://powerassetmodelling.co.uk/html/hatfield_igcc_.html (2010)

Hazeldine S (2010) *CCS: What is, and should, the UK be doing?* Presented at: APGTF meeting, London, UK (16 March 2010)

Herbert Smith (2010) The EU Industrial Emissions Directive. Available from: http://www.herbertsmith.com/NR/rdonlyres/F35EEC82-9F8C-47EF-998A-CD204305BE8D/0/IED190710.html (19 July 2010)

IEA (2009a) World Energy Outlook 2009. Available from: http://www.worldenergyoutlook.org/docs/weo2009/WEO2009_es_english.pdf International Energy Agency, Paris, France (November 2009)

IEA (2009b) Technology Roadmap: Carbon Capture and Storage. Available from: www.iea.org/papers/2009/CCS_Roadmap.pdf (2009)

Mao J (2010) *Personal communication*, Tsinghua University, China (September 2010)

Minchener A (2010) *Developments in China's coal-fired power sector*, IEA Clean Coal Centre Report CCC/163. ISBN 978-92-9029-483-2 (January 2010)

NZEC (2009) China-UK Near Zero Emissions from Coal Programme: Summary Report. Available from: www.nzec.info (October 2009)

Oakey, J.E. et al (2000) *Power Generation in the 21st century-The new European COST Action*, Parsons 2000, Cambridge, UK, July 3-7, 2000

Power-Gen Worldwide (2010) EU compromise gives power plants until 2020 to meet LCPD emissions rules. Available from: http://www.powergenworldwide.com/index/display/articledisplay/6937568263/articles/powergenworldwide/emissions-and-environment/regulation/2010/07/eu-compromise_gives.html (July 2010)

Riches S (2009) Research Councils' UK Energy Programme. Available from: www.newton.ac.uk/programmes/SCS/seminars/052709451.ppt (2009)

Scottish Power (2009) UK First At Longannet As Scottish Power Brings Clean Coal Technology One Step Closer To Reality. Available from: http://www.scottishpower.com/PressReleases_1876.htm (29 May 2009)

Scottish Power (2010) Scottish Power Academic Alliance. Available from: http://www.scottishpower.com/carbon_capture_storage/docs/press_release_9September10.pdf (9 September 2010)

Spalding, D. (2005) *Future Priority Options for Carbon Abatement of Advanced Supercritical Coal-Fired Power Plants* Presented at 2nd International Conference on CCTs for our Future, Sardinia, Italy May 2005

Technology Strategy Board (2009) Carbon Abatement Technologies Competition for Funding. Available from: http://www.thenorthernway.co.uk/downloaddoc.asp?id=631 (June 2009)

Technology Strategy Board (2010) Driving innovation. Available from: http://www.innovateuk.org/deliveringinnovation/collaborativeresearchanddevelopment.ashx (2010)

Technology Strategy Board (2011) Energy Funding Landscape Navigator. Available from: https://ktn.innovateuk.org/web/energy-funding-landscape-navigator (January 2011)

The Telegraph (2010) Hatfield Colliery owner Powerfuel enters administration. Available from: http://www.telegraph.co.uk/finance/newsbysector/industry/mining/8192474/Hatfield-Colliery-owner-Powerfuel-enters-administration.html (10 December 2010)

UCL (2009a) Dedicated CCS Legislation: Directive 2009/31/EC. Available from: https://www.ucl.ac.uk/cclp/ccsdedlegstorage.php. University College Legal Department (2009)

UCL (2009b) Dedicated national CCS legislation: United Kingdom. Available from: https://www.ucl.ac.uk/cclp/ccsdedlegnatoverview.php. University College Legal Department (2009)

UKDTI (2002) Advanced Materials for Power Generation, DTI Technology Status Report 018. (2002)

UKDTI (2004) *Review of the Feasibility of Underground Coal Gasification in the UK*, DTI/Pub URN 04/1643 (October 2004)

UKDTI (2005) *A strategy for developing carbon abatement technologies for fossil fuel use*, DTI/Pub URN 05/844 (June 2005)

ANNEX A
GLOSSARY OF TERMS

APGTF	Advanced Power Generation Technology Forum
ASU	Air separation unit
BCURA	British Coal Utilisation Research Association
BF2RA	Biomass and Fossil Fuels Research Alliance
BGS	British Geological Survey
CAT	Carbon Abatement Technology
CBM	Coal bed methane
CCGT	Combined cycle gas turbine
CCS	CO2 capture and storage
CCT	Clean coal technology
CFBC	Circulating fluidised bed combustion
CFD	Computational fluid dynamics
CO2	Carbon dioxide
COST	Cooperation on Scientific and Technical Research
CRF	Coal Research Forum
CV	Calorific value
^{o}C	Degree Celsius
DECC	Department of Energy & Climate Change
DTI	Department of Trade and Industry
€	Euro
EIA	Energy Information Administration
EOR	Enhanced oil recovery
EC	European Commission
EPSRC	Engineering and Physical Research Council
ESI	Electricity Supply Industry
ETS	Emissions trading scheme
EU	European Union
FGD	Flue gas desulphurisation
FP7	Seventh Framework Programme
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonnes

GWe	Gigawatts electric
IEA	International Energy Agency
IED	Industrial Emissions Directive
IGCC	Integrated gasification combined cycle
£	Pound sterling
LHV	Lower heating value
MEA	Monoethanolamine
MPa	MegaPascal
Mt	Million tonnes
Mtoe	Million tonnes oil equivalent
MW	Megawatt
MWe	Megawatt electric
MWth	Megawatt thermal
NOx	Nitrogen oxides
OECD	Organisation for Economic Cooperation and Development
%	Percentage
PC	Pulverised coal
R&D	Research and development
R,D&D	Research, development and demonstration
RFCS	Research Fund for Coal and Steel
SCR	Selective Catalytic Reduction
SO_2	Sulphur dioxide
SOx	Sulphur oxides
UCG	Underground coal gasification
UK	United Kingdom
USA	United States of America
US$	United States dollar