UKERC

**UKERC ENERGY RESEARCH LANDSCAPE: COAL COMBUSTION**



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## 1. Overview

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### Characterisation of the field

The scope of the coal combustion research topic covers science and engineering activities focused on the development of cleaner and more efficient coal utilisation techniques and systems, including comparison to alternatives within the context of sustainable energy supply and economic development.

For basic and applied strategic research, the range of disciplinary inputs includes chemistry, physics, metallurgy and materials science, environmental sciences, mechanical, combustion and chemical engineering, and the built environment. Increasingly, a range of disciplines from the social sciences and economics are providing some input into coal related issues. These include assessments of public awareness and attitudes to the use of coal within a sustainable energy mix and the growing use of economic drivers to ensure ever better environmental compliance by coal end users.

Coal combustion research addresses a broad range of challenges including coal characterisation, coal utilisation efficiency and environmental performance, components development and systems integration. The more basic research covers characterisation studies, including the development of innovative analytical techniques and modelling approaches. The applied research programmes are usually designed to provide practical solutions for improvement of the energy efficiency, environmental and economic performance of coal utilisation technologies and techniques. Such applied research will often incorporate some basic studies but as means to an end not an end in itself.

### Research Challenges

Globally, there is a growing concern about fuel diversity and security of supply, particularly with regard to oil and natural gas. For the UK, supplies are very dependent on imports, prices are uncertain, while some suppliers show a willingness to use their oil and gas to influence political decisions. At the same time, global demand for oil has been increasing significantly due to the economic development of China and India while oil exploration has failed to keep up with production. Consequently, the use of coal, which is available from a much wider range of sources and has greater price stability than oil and gas, is increasingly attractive. On a global basis, coal use is increasing rapidly, and by 2030 may well reach a level of more than 4,500 Mtoe, corresponding to close to a doubling of current levels. The main market will be in the developing countries, especially China and India, while OECD use will decline. At the same time, tightening regulations will require better solutions for achieving environmental compliance, for which coal has a number of key issues to address.

Most of the coal used for combustion applications will be in the power generation sector, while in developing economies there is also likely to be significant use for cement production. The key research challenges are to develop and deploy methods by which coal can be used cleanly, efficiently, and in a sustainable way. These include improvements to existing coal utilisation technologies, particularly to improve fuel and operational flexibility together with high availability, while reducing energy use through higher efficiencies, which for power plants will include the introduction of more advanced steam cycles and improved systems integration. There is an increasing need to ensure improved emissions control, with the emphasis on achieving ever-lower emissions of particulates, $SO_2$ and NOx while also introducing control of trace species, particularly mercury.

Alongside this, a key challenge is the integration of techniques that can capture $CO_2$ and store it in secure geological formations, thereby resulting in near zero emissions of $CO_2$ (the development of which is covered elsewhere in this research atlas). From a coal combustion perspective, the need is to achieve such integration while minimising any adverse impact on power plant efficiency, performance of existing emissions control systems, operational flexibility and availability.

With regard to both the UK home market and the major global opportunities for new and replacement coal fired power plant, the main technologies of industrial interest are Advanced Supercritical Pulverised Coal (PC) Boiler /Steam Turbine systems in the 600-1000 MWe range and Integrated Gasification Combined Cycle (IGCC) systems at a scale of about 500 MWe. The continuing advancement of these existing clean coal technology (CCT) variants is required together with an associated and major effort to ensure that the related near-zero emission techniques 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, which have wider applications than just coal-fired plant. Thus the former will be needed both for use in natural gas fired combined cycle plant and advanced coal based IGCC systems, with particular reference to the future use of coal as a transitional fuel for the establishment of hydrogen as an energy vector. Similarly, advanced steam turbines will be required both for combustion and gasification power plant applications.

At a smaller scale, there is growing interest in coal bed methane production and utilisation. The methane can be recovered from both operational and abandoned mines and the requirement is to burn such gas effectively, which is often of low calorific value. There is also potential to extract methane from coal seams where mining has yet (or is unlikely ever) to take place for which issues are covered elsewhere in this atlas. This includes enhanced recovery methods, where $CO_2$ or $N_2$ is injected into the coal, which provides a possible link to $CO_2$ storage provided that the coal seam in which $CO_2$ might be injected will never be mined. While economic quantities of methane can be produced, there is a need to improve utilisation options, for example, via energy recovery from small scale power generation schemes through better utilization of the waste heat. At the same time, the need to establish water disposal options, which are environmentally acceptable and yet economically feasible, is a key requirement.

This overall approach to coal combustion research and development 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 techniques can subsequently be established on a cost effective and credible basis.

## 2. Capabilities Assessment

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Within the UK, coal use is primarily for power generation, with most of the remainder used in the steel industry and to a lesser extent in the cement production sector. Over the past two decades, there has been a significant reduction of coal use within the power sector. Within what is becoming a more diversified UK energy mix, the indications are that its future use will at best be at current levels, provided that lower cost, higher efficiency, coal fired plant with good environmental performance and near zero $CO_2$ emissions can be established.

Traditionally, the UK has been recognised as a global leader in coal research and development. While that position has fallen away to an extent in recent years, there remains a strong research capability in coal combustion. There is a select group of UK universities that continues to offer high quality research expertise and this readily complements the capabilities within the UK power generating companies, the power sector equipment manufacturers, together with industrial non-power equipment suppliers and end users. These UK organisations continue to play a significant role in collaborative R&D initiatives, both within the European context, as noted in Section 8, and with the USA.

From a market perspective, although it is very competitive, the global clean coal power generation opportunities are very significant. This covers the provision of individual components through to major engineering and procurement contracts. In many cases such opportunities are developed through collaborative ventures, in which universities can have a significant role to play. As such, the UK can play a major part in the global introduction of clean coal power generation technology and, in due course, near zero emissions coal based technology.

Although small compared to large scale coal based power generation, there is an increasing focus on coal bed methane (CBM) utilisation, which is the extraction of methane that is still locked into the vast reserves of coal and coal measures strata that remain un-worked in Great Britain. This involves directly drilling into the strata to release the methane, without detrimentally affecting the physical properties of the coal. To date, there has been very limited commercial production of CBM in the UK and the output is used to generate electricity for local use rather than being fed into the national gas distribution network. However, the use of directional drilling techniques to give greater process control may mean that CBM exploitation could become an economically viable prospect. A number of new developments have been initiated and, as of September 2010, the Coal Authority had granted permission at 13 sites in Great Britain for companies to extract methane from un-mined coal seams. While these were all for pilot drilling projects, there is considerable scope to increase the scale of operations and several of the licensees have declared plans to expand operations in due course.

From a global perspective, there is considerable interest in CBM, including many countries in Asia, and several UK companies are able to offer technology and consulting expertise.

**Table 2.1 UK Capabilities**

| UK Capability | Area | Market potential | Timescale |
|---|---|---|---|
| **High** | • Gas and steam turbines<br>• Pulverised coal combustion burners<br>• Power sector boilers and heat exchangers<br>• Associated technical services and consultancy | • Continuing global potential<br>• Continuing global potential<br>• Continuing global potential<br>• Continuing global potential | • Now<br>• Now<br>• Now<br>• Now |
| **Medium** | • IGCC components<br>• CBM expertise (utilisation technology & consultancy) | • Possible global market input<br>• Possible global market input | • 5+ years<br>• Underway with full commercial opportunities within 5+ years |

## 3. Basic and applied strategic research

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Within the UK, almost all the basic research is undertaken directly at Universities as there are no significant independent research institutes remaining. Some of this is supported by the EPSRC through its 'responsive mode' programme while some is supported through organisations such as the Biomass and Fossil Fuel Research Alliance (BF2RA). All UK universities that are involved in coal related research enjoy good links with UK industry and, as such, most can be involved in R&D collaborative activities with such companies. This is generally through the provision of basic and/or more fundamental research to support an applied, industrially focussed activity.

University-based coal combustion research falls into several different clusters ranging from coal characterisation studies, investigation of emissions from coal, supporting studies for component development, together with, at present, a limited input on social studies of public perceptions to coal-based energy technologies (especially on carbon capture and storage).

The universities can be grouped as follows, according to speciality:

- Traditional, practical based research groups working on all aspects of the understanding of combustion processes and associated environmental performance, including small scale test-work and associated modelling
- Environmental sciences groups concerned primarily with the monitoring and evaluation of emissions from coal fired plant
- Research groups that are more concerned with techno-economic aspects of coal utilisation
- Groups that are now applying social science assessment techniques to various UK situations for coal fired power plant, with and without CCS

The UK industrial partners are primarily involved in applied research and development, which is focused around large-scale trials on pilot plants, to provide results that can be scaled up with some confidence to demonstration and commercial scale activities. Certain industrial partners also support basic R&D via their membership of BF2RA and, in principle, via the EPSRC (see table below) for whom selected UK industrial supporters provide comment on proposals received, and, in the case of BF2RA, also monitor progress of the projects that are undertaken.

**Table 3.1: Research Funding**

| Funding Stream | Funding Agency | Description | Committed Funds | Period | Representative Annual Spend |
|---|---|---|---|---|---|
| The Biomass and Fossil Fuel Research Alliance | BF2RA | BF2RA was established in September 2009 as a private not for profit company, with a membership that includes representatives from the ESI, major equipment suppliers, major fuel users and the research sector. Its 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. Through its Industrial Members, it provides part-funding primarily for EngDs and PhDs. Since 2010, it has established a portfolio of 12 projects, with a gross value of ~£1.8m. The reduction of carbon emissions from fossil fuel based systems is a key requirement, for which priority themes include the utilisation of fossil fuel and biomass; materials development; advanced cycles for fossil fuel/biomass utilisation and issues relating to performance; and control of emissions and products arising. | ~£300k to date | Indefinite | ~£150k |

| | | | | | |
|---|---|---|---|---|---|
| Conventional generation and combustion | EPSRC | The EPSRC supports long term research and postgraduate training in order to support UK economic competitiveness and quality of life. This includes providing funding to university partners in projects supported by the Technology Strategy Board. While its energy portfolio includes research on conventional power generation and combustion, the EPSRC had decided to constrain financial support in this area to allow greater support for the less developed, low carbon technologies, such as CCS, which will have a key role to play in the UK's low carbon future. Thus, in recent years, besides some generic materials development projects, there is only one new project (covering supercritical coal fired power plant dynamic responses and control for grid code compliance) that is not directly CCS related within the coal power sector. However, in mid 2012, there was a non-CCS call to establish a research consortium to address the key challenges in conventional power. Key topics included the need for improved plant efficiency, flexibility, fuel flexibility, and sustainability. | Not known, competitive tendering against other topics within the energy sector | Indefinite | Not applicable. |

**Table 3.2: Key Research Providers**

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| Cranfield University: Centre of Energy and Resource Technology; Dept of Offshore, Process and Energy Engineering; Dept of Power and Propulsion | Main interests include the combustion and gasification of solid. Liquid and gaseous fuels and their use in energy systems | • Combustion processes, pulverised fuel, fluidised bed, fixed beds using coal, alone and co-fired with biomass and waste-derived fuels<br>• Pyrolysis and gasification systems – fluidised beds and fixed beds<br>• Boilers , heat transfer and heat exchangers<br>• Gas and steam turbines<br>• Materials and coatings for aggressive environments<br>• Component life prediction<br>• Gas cleaning and upgrading, including $NO_x/NH_3$ reduction, $SO_x/H_2S$ removal, particulates, $CO_2$ separation etc<br>• Process modelling and engineering scale-up<br>• Risk and reliability studies<br>• Emissions and environmental impact assessments<br>• Techno-economic studies | >100 academic and research staff | Chemical Engineering, Energy Engineering, Mechanical, Aeronautical and Manufacturing Engineering, Metallurgy and Materials |
| Glasgow Caledonian University, School of Engineering and Built Environment | The School is interested in coal (and ash) handling and conveying for all applications. | • Coal Flow Property Determination<br>• Pneumatic conveying<br>• Coal segregation | 14 full time academic staff | Mechanical, Aeronautical and Manufacturing Engineering |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| Imperial College, Department of Chemical Engineering and Chemical Technology | This Department is interested in all aspects of coal characterisation and reaction for various coal processing routes. | • Carbon Capture and Storage:<br>  ○ Carbonate looping Chemical looping<br>  ○ Integration of CCS with industrial processes (e.g. cement and iron and steel)<br>• Coal pyrolysis<br>• Coal devolatilisation<br>• Characterisation of coal products distribution<br>• Coal combustion characterisation<br>• Analytical techniques development | 42 full time academic staff, 49 research staff | Chemical Engineering |
| Imperial College, Department of Materials | Interests include the physical/chemical properties of coal and chars, combustion residues, characterisation and the development of analytical methods. | • Coal microstructure<br>• Mineral distributions and properties<br>• Deposition/fouling/slagging mechanisms under various process conditions | 34 Full time academic staff 76 research staff | Metallurgy and Materials |
| Imperial College, Department of Mechanical Engineering | The Department is particularly interested in all aspects of clean coal power generation, with emphasis on all technical and non-technical issues associated with near zero emissions power generation. | • Carbon capture ready systems for coal fired power plant<br>• CCS options for power generation systems<br>• Techno-economic studies<br>• Policy development for near zero emissions power production<br>• Co-firing characterisation<br>• Hydrogen production from fossil fuels<br>• Influence of coal behaviour on combustion and gasification plant performance | 45 full time academic staff 58 research staff | Mechanical, Aeronautical and Manufacturing Engineering |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| University of Bath, Department of Chemical Engineering | Main interests are basic studies of coal under various processing schemes | • Basic reactions of combustion and gasification processes<br>• Physical/chemical properties of coals and coal chars structures<br>• Characterisation and analyses | 18 full time academic staff | Chemical Engineering; Metallurgy and Materials |
| University of Birmingham, School of Chemical Engineering | Focus is on gas cleaning research | • Filter media development and testing<br>• Modelling/characterisation of cyclones, ceramic filters and granular bed filters<br>• Materials development and process modelling for carbon capture options | 25 full time academic staff 18 research staff | Chemical Engineering |
| University of Bristol, Department of Mechanical Engineering | Fluidised beds fundamental research. | • Fundamental understanding of bubbling characteristics<br>• Characterisation of particle properties and surface flow properties<br>• Validation of numerical models of particle flows | 23 full time academic staff 19 research staff | Mechanical, Aeronautical and Manufacturing Engineering |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| University of Cambridge, Department of Chemical Engineering and Biotechnology | Main interests are fluidised bed combustion with emphasis on gaseous pollutant formation and removal, novel schemes for the capture of $CO_2$ and gasification. Also fluidised bed fundamentals, e.g. particle mixing, gas-solids mixing etc. | • FBC performance<br>• Environment<br>• Gas cleaning<br>• Basic reactions<br>• Pyrolysis<br>• Oxygen carriers<br>• Chemical looping combustion<br>• Chemical looping for hydrogen production<br>• Carbonate looping for pre and post-combustion $CO_2$ capture.<br>• Fundamental modelling of fluidised bed reactors<br>• LCA and thermodynamic analysis of novel schemes for $CO_2$ capture. | | Chemical Engineering |
| University of Cardiff, School of Engineering, Institute of Energy | The School of Engineering has interests in all aspects of coal utilisation, with some emphasis on fundamental studies of pulverised fuel combustion | • Combustion, gasification, environment, gas cleaning, process modelling, laser diagnostics | 15 full time academic staff 11 research staff | Mechanical, Aeronautical and Manufacturing Engineering ; Metallurgy and Materials |
| University of Cardiff, Centre for Research in Energy, Waste and the Environment | This centre carries out research on a wide range of problems relating to energy, electricity generation, solid, liquid and gaseous pollutants. A key area of its research portfolio is in the field of sustainable and integrated waste management, particularly that of Municipal Solid Waste. As a Welsh Development Agency Centre of Excellence, the centre seeks to stimulate and | • Industrial scale burning of solid, liquid or gaseous fuels<br>• Renewable energy<br>• The use of advanced diagnostic equipment in energy conversion systems<br>• Large scale combustion modelling using CFD and experimental validation<br>• Flame propagation, single and two-phase<br>• Phenomenological modelling of various combustion processes.<br>• Characterising and modelling of | 6 academic staff | Mechanical, Aeronautical and Manufacturing Engineering; Chemical Engineering; Chemistry |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| | support industry through technology transfer, research, advice and technical support. | nozzles, injectors and spray systems<br>• Investigation and characterisation of fine particulate emissions<br>• Reclamation of mineral wastes and spoil heaps<br>• Novel treatment, containment and alternatives to waste treatment<br>• Biological processing of solid wastes<br>• Occurrence and treatment of acid and metal rich waters<br>• Health and safety monitoring in the occupational and urban environment | | |
| The University of Edinburgh, School of Engineering, Institute for Materials and Processes | Main interests are two-phase flow, including application to combustion processes | • Air-particle flows<br>• Flow in heat exchangers | | Mechanical, Aeronautical and Manufacturing Engineering |
| The University of Edinburgh, School of Engineering, Institute for Infrastructure and Environment | Main interests in coal are handlability and its rapid assessment, blending processes and prediction of blended coals handlability | • Solids handling<br>• Optimum utilisation of all coal grades<br>• Functional and structural design of storage containers | | Granular solids mechanics, Geotechnical and Structural Engineering |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| University of Greenwich, The Wolfson Centre | Main interest is handleability (i.e. transportation, storage and discharge). Additional expertise in maintaining bulk particulate properties ( ie. blend homogeneity) and minimisation of particle attrition or agglomeration in storage. | • Characterisation of particle properties<br>• Design of bulk storage and reclaim equipment<br>• Pneumatic conveying<br>• Coal/biomass segregation<br>• Quantiifcation of bio-activity effects on handleability<br>• Quantification / control of generation of fugitive particles through handling operations | | Mechanical, Aeronautical and Manufacturing Engineering |
| University of Glamorgan, Department of Engineering, Faculty of Advanced Technology | Main interest focuses on various aspects of fluidised bed combustion systems | • Modelling<br>• Coal behaviour<br>• Co-firing<br>• System design | | Chemical Engineering; Mechanical, Aeronautical and Manufacturing Engineering |
| University of Kent, School of Engineering | Main interests include sensors and instrumentation for the optimisation of coal fired combustion processes | • Mass flow metering of pulverised coal and biomass<br>• On-line particle sizing<br>• Flame imaging<br>• Flame stability monitoring<br>• On-line fuel tracking<br>• $CO_2$ flow metering<br>• $CO_2$ leakage detection | 14 full time academic staff 25 research staff | Electrical and Electronic Engineering |
| University of Leeds Energy Technology and Innovation Initiative *and* Energy Research Institute | This institute is interested in coal combustion and gasification for power generation, particularly covering environmental performance issues | • CFD combustion modeling, combustion of coal with air, oxy-coal combustion,<br>• Mercury and $SO_x$ modeling<br>• Oxycoal combustion radiation models and application to pf plants<br>• Modelling oxycoal integrated plant with ASU and amine plant<br>• Modelling cofiring of biomass and coal | 16 full time academic staff | Chemistry; Chemical Engineering; Mechanical, Aeronautical and Manufacturing Engineering |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| | | • Modelling cofiring-influence of irregular shaped biomass particles<br>• Experimental studies of Oxy Coal Combustion for various fuel mixtures | | |
| University of Manchester, School of Materials | High temperature corrosion-erosion-wear in coal fired systems | • Materials degradation<br>• Alloys/refractories performance in coal derived environments | | Metallurgy and Materials |
| University of Newcastle upon Tyne, School of Natural Sciences | Main interests are fundamental studies of coal utilisation, with emphasis on pollutants formation and release | • Combustion<br>• Gasification<br>• Environment<br>• Physical/chemical properties<br>• Release of nitrogen. sulphur and chlorine species<br>• $NO_x$ and $SO_2$ formation and release | 36 full time staff<br>12 research staff | Chemistry; Chemical Engineering |
| University of Nottingham, School of Chemical, Environmental and Mining Engineering | The University undertakes R&D on all aspects of coal utilisation, including characterisation, handling, preparation, combustion. | • Combustion, gasification, liquefaction, pyrolysis for coal and coal/biomass mixtures<br>• Fluidised bed systems<br>• Ash characterisation techniques<br>• Demineralisation,<br>• Fate of sulphur and nitrogen pollutants<br>• Pollutant removal techniques<br>• Fuel performance modelling<br>• Co-utilisation<br>• Modelling<br>• Trace elements emissions and control | 25 full time academic staff<br><br>22 research staff | Chemistry; Chemical Engineering |
| University of Sheffield, | Interests include | • Combustion | 22 full time | Chemical |

| Name | Description | Sub-topics covered | No of staff | Field |
|---|---|---|---|---|
| Department of Chemical and Biological Engineering | development of fluidised bed concepts and novel cycles for power generation | • Environment<br>• Gas cleaning<br>• Process modelling<br>• CFD modelling<br>• Co-gasification of coal with waste<br>• Co-firing waste and biomass material | academic staff<br>18 research staff | Engineering |
| University of Sheffield, Department of Engineering Materials | Interests include modelling and computation | • Thermodynamic modelling<br>• Gaseous/particulate pollutants<br>• Trace elements mobilisation<br>• Gas turbines<br>• Coal fired industrial boilers | 38 full time staff<br>65 research staff | Mechanical, Aeronautical and Manufacturing Engineering ; Metallurgy and Materials |
| University of Strathclyde, Carbon Materials and Energy Group | Main interests are structural issues for coal utilisation processes | • Coal structures<br>• Coal utilisation | | Chemical Engineering; |
| University of Teesside, Department of Process Manufacturing and Design | Determination of mechanical properties of coals. | • Process modelling<br>• Coal storage and handling<br>• Physical/chemical properties of coal<br>• Coal preparation and processing<br>• Coal utilisation<br>• Process design and development. | 17 full time academic staff | Mechanical, Aeronautical and Manufacturing Engineering |

## 4. Applied Research and Development

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There is a limited number of organisations that actively undertake applied coal combustion research and development in the UK (as opposed to CCS). These comprise one of the power generation companies that arose from the privatisation of the electricity supply industry and several power sector equipment developers. There are also some non-power sector companies that undertake some R&D that is focussed exclusively on the continued operation of their own equipment within the UK.

The utility, E.ON UK, undertakes applied research to remain an informed end user within the international marketplace, which can assist it both to remain competitive in its existing activities and to aid any assessments on new activities worldwide. This includes the need to address issues for existing plant as well as those associated with the introduction of improved variants and alternative coal fired technologies. As such, its prime interests cover the need:

- To increase plant availability and flexibility rather than efficiency of existing coal fired plants, while using certain non-standard fuels. This particularly includes the possible use of biomass and certain organic wastes, which attract a subsidy when fired with coal, plus imported fuels, such as natural gas, coal and petroleum coke.
- To meet the requirement to operate existing boilers at lower minimum loads.
- To ensure compliance of the existing coal fired fleet within the tightening framework of environmental legislation, with continued pressure on emissions reduction. Specifically this includes the introduction of the 50mg/$m^3$ particulates limit from large power plant. Alongside this is the need to identify improvement strategies for Nitrogen Oxides ($NO_x$) and Sulphur Oxides ($SO_x$) control, arising from recent EC directives. These are the Large Combustion Plant Directive (LCPD) from 2008 and the Integrated Pollution Prevention and Control (IPPC) Directive from 2006. In addition, the European Union (EU) Emissions Trading Scheme (ETS) from 2005, impacts on activities.
- To address the need for new and replacement plant both within and outside of the UK. This will most likely be by the introduction of advanced higher efficiency combustion systems.

In accordance with UK Government policy, new plant will need to demonstrate the full CCS chain at commercial scale, with wider scale deployment of CCS expected to be possible from 2020 and plants with demonstrations expected to retrofit CCS to full capacity by 2025. Consequently, any new plant must meet this CCS requirement while ensuring that the overall adverse impact on cycle efficiency can be minimised and that the conventional environmental performance can be maintained. Several concepts have been shortlisted within the DECC UK full chain CCS demonstration competition. These include:

- Captain Clean Energy Project: A proposal for a new 570MWe, fully abated coal Integrated Gasification Combined Cycle (pre-combustion) project in Grangemouth, Scotland;
- Peterhead: A 340MWe post-combustion capture retrofitted to part of an existing 1180MWe Combined Cycle Gas Turbine power station at Peterhead, Scotland.
- Teesside Low Carbon Project: A pre-combustion coal gasification project, linked to a 330MWe net power generating capacity fuelled by syngas; and
- White Rose Project: An Oxyfuel capture project at a proposed new 304MWe fully abated supercritical coal-fired power station on the Drax site in North Yorkshire.

For the longer term, should underground coal gasification be proven, which is discussed in the Coal Conversion Landscape, it could result in a clean fuel source, which if used to fuel a gasification based power generation/large industrial process then CCS would need to be included. Similarly, it is possible that if

CBM is established, at large enough scale, then it could provide a significant fuel source for power generation applications.

The equipment developers and manufacturers include Alstom Power (AP) and Doosan Babcock (DB). Both are part of international companies, Alstom and Doosan Power Systems respectively, whose interests span all aspects of the coal fired power generation market. From a UK perspective, AP is mostly focussed on the maintenance, refurbishment and operation of many of the country's existing coal and gas power plants, while its service business includes steam turbine retrofits, and boiler retrofitting, including biomass co-firing, NOx reduction, performance improvement and fuel flexibility. The DB core business is the design, supply and construction of advanced steam generation technology for the power industry, from turnkey steam power-plant projects to boilers and, via a sister company, steam turbines. In both cases, their specific interests are in ensuring that they have CCT and CCS products available to meet current and future market needs on a competitive basis. Consequently, their R&D portfolios include the need to achieve efficiency and operational flexibility improvements for their technologies in the short and medium term followed by the adaptation of those technologies and/or the development of alternative technologies for use with $CO_2$ capture systems in the medium to longer term. Thus, within such a framework, technologies are needed for new power plant, for replacement power plant and for retrofitting of existing plant, and they must be available for both base load and load-following operation, while meeting all environmental standards, and being proven for the full range of coal types and co-firing applications appropriate to the global market prospects.

For the short to medium term (5-10 years), both companies are working on various aspects of the international drive to achieve very high efficiency with advanced ultra-supercritical steam cycles for pulverised coal fired plant, while ensuring that novel components using new materials of construction can achieve acceptable reliability at economic cost. This covers all aspects of the combustion process, and the development of high performance steam turbines for such advanced combustion power plants.

For the medium to longer term, they are involved in the development and integration of carbon capture technologies to existing clean coal technologies. DB needs to ensure that their combustion based technologies can maintain full performance if post-combustion $CO_2$ scrubbing systems are introduced on pulverised coal fired plant. At the same time they are a lead organisation in the development of the oxy-fuel technologies as an alternative approach for combustion plant $CO_2$ capture. AP is developing an ammonia based $CO_2$ capture process and also has a strong corporate interest in oxy-fuel combustion while they are also extensively involved in the establishment of improved efficiency and reliability for gas turbines. This includes the design and materials for higher temperature gas turbines, ensuring gas composition flexibility and in particular including the need for hydrogen adaptation should IGCC and/or natural gas reforming be introduced in due course.

Outside of the power sector, the use of coal combustion for other industrial processes includes the cement sector, the raising of process steam and some smaller applications such as drying of agricultural products for subsequent processing. Of these, cement manufacture is a significant coal consuming activity in the UK. This process releases large quantities of $CO_2$, both from the burning of coal and from the calcination of limestone. Since about one tonne of coal is used for each 3.5 tonnes of cement produced, the partial replacement of coal with alternative fuels such as various waste materials has been actively pursued. The cement companies tend to address their own R,D&D needs individually, which include maximising combustion efficiency, reducing emissions, and understanding how the use of coal-coal and coal /waste blends will impact on process performance.

**Table 4.1: Research Funding**
The UK funding providers for applied research and development on coal combustion (rather than CCS) are, at present, limited to the Technology Strategy Board, with support via DECC.

| Programme | Funding Agency | Description | Committed Funds | Period | Representative Annual Spend |
|---|---|---|---|---|---|
| The Carbon Abatement Technology (CAT) Programme | Technology Strategy Board | The Technology Strategy Board (TSB) stimulates technology enabled innovation in the areas which offer the greatest scope for boosting UK growth and productivity. Energy generation and supply is a high priority and for coal the TSB 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 some measures to improve combustion performance and overall power cycle efficiency. | | | |

**Table 4.2: Key Research Providers**

| Name | Description | Sub-topics covered | Scale of Operation | Sector |
|---|---|---|---|---|
| Alstom | As part of its Clean Power strategy, Alstom has allocated substantial R&D efforts to drive innovation to improve efficiency, a key factor in cutting thermal power plant emissions and maximising power transmission performance, and flexibility to ensure the optimal integration of renewable energy into the grid. Alstom is also the world leader in air quality control systems and a pioneer in $CO_2$-capture technologies, key to meeting the world's emissions targets. | • Coal utilisation for power generation<br>• Power transmission and power electronics<br>• Air quality control<br>• Materials development<br>• Analytical methods development<br>• Carbon capture performance assessment<br>• Fuel flexible gas turbines. | >5500 staff in the UK including power, grid and transport activities | Manufacturing |
| British Sugar | Their interest is for the use of coal in furnaces to dry sugar beet | • Process performance<br>• FBC | | Manufacturing |
| Doosan Babcock | This company supplies utility scale pulverised coal burners and boiler island equipment. It is interested in all aspects of the combustion performance of such equipment together with emissions and emissions control. There is an increasing interest in the development and assessment of options for carbon dioxide capture for coal fired plants, with an associated emphasis on determining the impact of the | • Pulverised coal burners<br>• In-furnace and post combustion emissions control<br>• Heat transfer<br>• Systems design | | Manufacturing |

| | | | | |
|---|---|---|---|---|
| | integration of such equipment on existing components | | | |
| Environmental Scientifics Group (ESG) Ltd | Provision of testing, inspection and compliance services.<br>ESG is also responsible for the maintenance of what was previously the BCURA Coal Bank | • Geotechnical Services<br>• Laboratories and Analytical Services<br>• Environmental Safety Compliance<br>• Materials Testing | | Consulting Engineers |
| E.ON UK | This major power generator has an interest in all aspects of coal/biomass combustion for advanced power generation, together with emissions and emissions control technologies. There is active work ongoing in the assessment of carbon dioxide capture processes together with their integration on advanced coal fired units. | • Coal/biomass combustion<br>• Coal/biomass gasification<br>• Environmental issues<br>• Process modelling<br>• Fuel utilisation economics<br>• Power generation<br>• Carbon capture & storage. | 400 (at E.ON Engineering, Ratcliffe) | Electricity and Gas |
| Gastec at CRE<br><br>A Trading Division of Kiwa Ltd | This company is involved in all aspects of coal combustion relevant to the domestic / commercial / industrial sectors | • Handling<br>• Combustion<br>• Promotion of solid fuel use | 35 staff | Consulting Engineers |
| Lodge Cottrell (formerly Lodge Sturtevant Limited) | Their interests include all aspects of particulate and gaseous emissions removal from coal fired plant | • Hot gas clean-up<br>• Systems engineering | | Manufacturing |
| Mott MacDonald Limited | These power industry consultants have a wide ranging interest in | • Efficiency improvements | | Consulting Engineers |

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| | aspects of coal fired power generation | • Gasification<br>• Co-firing<br>• $CO_2$ capture | | |
| Ricardo-AEA | Ricardo-AEA provides consultancy to public and private sector organisations across the world to find answers to the growing challenges of sustainable energy, climate change and related environmental issues. This includes some input on coal related issues. | • Energy and carbon management<br>• Technology assessment<br>• Policy and strategy consultancy<br>• Environmental and economic performance | 6 staff working on coal related consultancy | Consulting engineers |
| Wardell Armstrong llp | Their business interests include assessment of components performance for coal fired power plants | • Coal gasification for power generation<br>• Physical/chemical properties of coal ash/slag from gasification processes | | Consulting Engineers |

## 5. Demonstration Funding

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Currently, there are no active clean coal technology-combustion related-demonstration programmes in the UK. DECC is continuing to support its competition to establish a demonstration of near zero emissions coal fired power generation. Although the first stage of this competition did not proceed beyond the FEED studies, DECC has indicated that opportunities remain for three alternative CCS demonstrations. For coal bed methane utilisation, while demonstration funding sources are not currently available, the UK Coal Authority has given permission for several industrial scale pilot projects, as set out below, which will include utilisation of the methane so produced.

| Licensee |
|---|
| Coastal Oil and Gas Ltd |
| Composite Energy (East England) |
| Composite Energy (Forth Valley) Ltd |
| Composite Energy (West England) Ltd |
| Greenpark Energy Ltd |
| Nexen Exploration UK Ltd |
| UK Gas Ltd |

## 6. Research Facilities and Other Assets

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In recognition of the previous decline of the coal sector in the UK, there are no major independent R&D/testing/certification facilities remaining. The facilities that are available are owned by several of the end users and equipment developers referred to in the previous sections, as set out in the table.

**Table 6.1: Research Facilities and Assets**

| Name | Description | Type of asset | Number of Supporting Staff | Annual Operating Budget |
|---|---|---|---|---|
| E.ON UK | 1 MWth combustion test facility with residence time scaled to reflect full scale time/temperature history<br>Coal analysis and analytical chemistry laboratories<br>Stack emissions testing team<br>Mobile ambient air quality monitoring laboratory<br>Coal quality impact model (VISTA) | Industrial scale test facility with ability to fire different fuels/blends (coal/oil/biomass). Capable of air or oxyfuel firing. Side-stream suitable for assessment of mercury capture from flue gas. | | |
| Doosan Babcock | Pulverised coal utility scale furnace with full-scale burner, capable of both air and oxy-combustion<br>Emissions control furnace and post-combustion gas cleaning facility | Industrial scale test facility with supporting pilot scale test units and diagnostics | | |

## 7. Networks

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There are three networking arrangements relevant to coal combustion R&D in the UK. The Coal Research Forum acts to promote informal networking with the benefit of developing collaborative relationships between members having similar interests. The British Flame Research Committee is a professional association providing a bridge between industry and academia in the field of industrial combustion. The Energy Generation and Supply Knowledge Transfer Network (EG&S KTN) comprises business, technology, academic and policy stakeholders for strategic and effective knowledge exchange to advance the UK EG&S sector.

**Table 7.1 Networks**

| Network | Date Established | Description | Membership Profile | Activities |
|---|---|---|---|---|
| The Coal Research Forum | The Coal Research Forum (CRF) was formed in 1989 to bring together those organisations in UK with interests in coal research, with the aim of promoting and integrating their interests. | The objectives of the CRF are to:<br>• Contribute to and encourage development of a national policy on UK coal research.<br>• Promote coal and energy research with funding bodies.<br>• Encourage and promote submission of proposals on coal research.<br>• Record successful funding applications for UK coal research.<br>• Encourage dissemination and exchange of information on coal research.<br>• Further develop the co-ordination of coal research activities between universities, industry and others.<br>• To publicise the | The members comprise those organisations and individuals with an interest in coal research. The activities are co-ordinated by an Executive Committee with members from industry and universities.<br><br>The CRF has six research divisions: Combustion, Advanced Power Generation, Coal Conversion,Coal Characterisation, Environment and Coal Preparation. | The Divisions each hold meetings, seminars and talks to update members on current coal research issues and to establish where further R&D is needed.<br><br>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.<br>The Forum also provides information such as:<br>• A register of UK Coal Researchers.<br>• A report on Coal R&D Successes in the UK.<br>• A Handbook on British, European and American Coal Sample Banks.<br>• A report on Coal Research and Engineering Needs in the UK.<br>• A four monthly newsletter, which contains information on research events, current |

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| | | achievements and successes of coal research in the UK. | | research contracts, and other topical news. |
| British Flame Research Committee | The BFRC was formed in 1956. | It is a professional association providing a bridge between industry and academia to apply and exploit a range of developments in industrial combustion and environment engineering. The organisation covers specific themes such as power generation, metals, petrochemicals, cement, equipment suppliers and fuel services. | This includes UK industry research organisations and universities | These include Flame Days and specific topic orientated seminars. The Committee is a founder member of the International Flame Research Foundation. The latter, supported by its members, undertakes R&D on cleaner, more efficient combustion processes, provides technical information and implements specific dedicated training services. |
| Energy Generation and Supply Knowledge Transfer Network | The Energy Generation & Supply KTN was formally launched by the Technology Strategy Board on 13th October 2009. | The aim is to create a network of stakeholders delivering strategic and effective knowledge exchange to advance the UK EG&S sector. There are four priority areas, namely Carbon Abatement Technologies (CATs), Fuel Cells, Oil & Gas and Renewables (wind and marine). The Advanced Power Generation Technology Forum is the delivery body for CATs. | Membership is open to business, technology, academic and policy stakeholders. | Promotion of collaboration and knowledge sharing. For CATs, this includes higher efficiency coal utilization processes leading to emissions reductions and cofiring as well as CCS. |

## 8. UK Participation in EU Activities

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UK industry and universities are involved in various clean coal technology R&D activities with financial support from the EU Seventh Framework Programme (FP7) and the Research Programme of the Research Fund for Coal and Steel (RFCS). The FP7 Programme on clean coal technologies covers two areas:

- The reduction of the traditional pollutants emitted by coal combustion, such as $SO_x$, $NO_x$ and particulates. The related technology has been developed but there is scope to improve the cleaning efficiency and to address other pollutants such as mercury.
- The improvement of 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 for ultra supercritical pulverised coal plant (AD 700), but also integrated gasification combined cycle plant (IGCC) and other combustion options, such as fluidised bed.

Alongside FP7, the complementary research programme under the RFCS provides funds for research projects on coal combustion, which can include research and demonstration projects, accompanying measures, as well as support and preparatory actions related to coal and steel. The number of new projects supported each year varies and depends on the total budget available as well as on the budget claimed by each individual project. Thus if a high cost project is rated highly and is funded, its inclusion means that the level of funding for additional projects is reduced.

Projects that involve UK organisations and either remain active or will commence in early 2013 are listed below, with those supported by FP7 being listed before those funded by the RFCS. In each case, contracts have been signed with the Commission to implement the R&D programme and information is in the public domain. These include some generic materials development projects that will have application for advanced coal power plants.

**Table 8.1: UK Participation in EU Activities**

| Project | Objectives | Action Line | Type of Action | UK Participants | Co-ordinator and partners | Total Funding | EU Funding | Duration | Annual spend |
|---|---|---|---|---|---|---|---|---|---|
| **OXIGEN** Oxide Dispersion Strengthened Materials for the Additive Manufacture of High Temperature Components in Power Generation | To produce an integrated, world-leading capability to directly manufacture from powder various part custom-designed, best-in-class high temperature alloys for power generation components | FP7-NMP 310279 | Project | TWI Ltd. Heriot-Watt University, The University of Liverpool | TWI Ltd., UK<br><br>11 partners | €5.68m | €4.0m | February 2013-January 2017 | €1.42m |

| Project | Objectives | Action Line | Type of Action | UK Participants | Co-ordinator and partners | Total Funding | EU Funding | Duration | Annual spend |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| **POEMA**<br><br>Production of Coatings for New Efficient and Clean Coal Power Plant Materials | To develop new coatings for supercritical steam power plants for efficient and clean coal utilization, with a significant reduction of emissions to be expected by increasing cycle efficiencies to ~50% | FP7-NMP 310436 | Project | Sheffield Hallam University | Universidad Complutense de Madrid, Spain<br><br>15 partners | €4.65m | €3.40m | January 2013-December 2016 | €1.16m |
| **GHG2E**<br><br>Greenhouse gas recovery from coal mines and un-mineable coal beds and conversion to energy | To contribute to global GHG emissions reductions by addressing the key challenges facing the CBM and CMM industries and emerging economies which also are major coal mining counties worldwide | FP7-Energy 268194 | Project | Imperial College of Science, Technology & Medicine, Trolex Ltd. Formac Electronics Ltd. | Imperial College of Science, Technology & Medicine<br><br>12 partners | €2.45m | €1.64m | October 2011-March 2015 | €0.70m |
| **MACPLUS**<br>Component Performance-driven Solutions for Long-Term Efficiency Increase in Ultra Supercritical Power Plants | To increase the net efficiency of coal-fired power plants by increasing the performance and reliability of some critical component**s** | FP7-Energy 249809 | Project | Doosan Power Systems, Alstom, Goodwin Steel Castings, E.ON New Build & Technology, Loughborough University, NPL Management, Imperial College of Science, Technology & | Centro Sviluppo Materials, Italy<br><br>24 partners | €18.20m | €10.70m | January 2011-June 2015 | €4.04m |

| Project | Objectives | Action Line | Type of Action | UK Participants | Co-ordinator and partners | Total Funding | EU Funding | Duration | Annual spend |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Medicine | | | | | |
| **NEXTGENPOWER** Meeting the Materials and Manufacturing Challenge for Ultra High Efficiency PF Power Plants with CCS | To demonstrate new alloys and coatings in boiler, turbine and the interconnecting pipework, for integration in existing and new power plants. | FP7-Energy 249745 | Project | Doosan Babcock, MonitorCoatings, Goodwin Steel Castings, Cranfield University, Alstom Power | KEMA, The Nederlands<br><br>12 partners | €10.26m | €6.0m | May 2010-April 2014 | €2.57m |
| **$H_2$IGCC** Low Emission Gas Turbine Technology for Hydrogen-rich Syngas | To provide and demonstrate technical solutions that will allow the use of state-of-the-art highly efficient, reliable gas turbines in the next generation of IGCC plants, firing hydrogen-rich syngas with emissions and process parameters similar to current state-of-the-art natural gas turbine engines. | FP7-Energy 239349 | Project | E.ON Engineering, Cranfield University, Cardiff University, University of Sheffield, University of Sussex | European Turbine Network, Belgium<br><br>24 partners | €17.19m | €11.28m | May 2009-October 2013 | €4.30m |
| **DCFC** Efficient conversion of coal to electricity-direct coal fuel cells | To apply Direct Carbon Fuel Cell technologies to achieve higher efficiency coal to electricity systems, while increasing scale, improving cell design, seeking new active and conductive structure and surface promoted catalysts, addressing durability, investigating coal source and optimising coal processing | RFCR-CT-2011-0004 | Project | The University Court of the University of St. Andrews | The University Court of the University of St. Andrews<br>4 partners | €2.03m | €1.22m | July 2011-June 2014 | €0.68m |

| Project | Objectives | Action Line | Type of Action | UK Participants | Co-ordinator and partners | Total Funding | EU Funding | Duration | Annual spend |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| **FLOX-COAL 11** Development of scale-up methodology and simulation tools for the demonstration of PC-FLOX burner technology in full scale utility boilers | To develop a scale-up methodology and simulation tools for the implementation of Pulverised-Coal Flameless Oxidation (PC-FLOX) burners in utility plants, through pilot scale investigation to support the development and validation of scale-up methodology and CFD sub-models, followed by a CFD study and techno-economic analysis of utility plants operated with PC-FLOX burners. | RFCR-CT-2011-00005 | Project | Doosan Power Systems | University of Stuttgart, Germany<br><br>8 partners | €2.69m | €1.61m | July 2011-June 2014 | €0.90m |

## 9. International Initiatives

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The UK participates in three IEA Implementing Agreements broadly linked to coal combustion and conversion, and a fourth that focuses on greenhouse gas issues, in which coal is a significant factor.

**Table 9.1: International Activities**

| Name | Type | Description | UK Contact Point |
|---|---|---|---|
| Clean Coal Centre | IEA Implementing Agreement | The IEA Clean Coal Centre provides a source of unbiased information on sustainable use of coal worldwide. This includes technical assessments, economic reports and market studies on specific topics throughout the coal chain. It also provides data bases on coal characterisation, coal fired power plants and emissions standards. Services are delivered to governments and industry through direct advice, review reports, facilitation of R & D and provision of networks. | The managing director is Dr John Topper.<br><br>The UK is represented by Mr Tom Wintle of DECC tom.wintle@decc.gsi.gov.uk |
| Clean Coal Science | IEA Implementing Agreement | The focus is the basic science of coal combustion. The specific objectives are to encourage, support and promote research and development that will lead to improved understanding and characterisation of conventional combustion processes; develop techniques that control and reduce solid, liquid and gaseous emissions associated with combustion processes; improve operating efficiency, and identify methods for the effective utilisation of combustion by-products. The Agreement embraces a wide range of activities associated with coal combustion, including work related to advanced power generation technologies. | The UK is represented by Mr Tom Wintle of DECC tom.wintle@decc.gsi.gov.uk |

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| Fluidised Bed Conversion | IEA Implementing Agreement | The aim is to bring together experts wishing to work on common problems. The main activity is technical exchanges during meetings and workshops. Participants are carrying out research on operational issues in support of local commercial fluidised bed conversion activities and sharing the results. | The UK is represented by Dr Marcos Millan<br>m.millan@ic.ac.uk<br>Dept. of Chemical Engineering and Chemical Technology,<br>Imperial College,<br>Prince Consort Road,<br>London SW7 2BY |
| Greenhouse Gas R&D Programme | IEA Implementing Agreement | The IEA Greenhouse Gas R&D Programme (IEA GHG) is an international collaborative research programme. IEA GHG focuses its efforts on studying technologies to reduce greenhouse gas emissions. IEA GHG was established in 1991 and aims to provide its members with informed information on the role that technology can play in reducing greenhouse gas emissions. The Programme has three main activities which are:<br><br>• Evaluation of technologies aimed at reducing greenhouse gas emissions,<br>• Promotion and dissemination of results and data from its evaluation studies,<br>• Facilitating practical research, development and demonstration activities (R,D&D) | The managing director is Dr John Topper.<br><br>The UK is represented by Ms Louise Barr of DECC<br>louise.barr@decc.gsi.gov.uk |