# A STRATEGY FOR DEVELOPING CARBON ABATEMENT TECHNOLOGIES FOR FOSSIL FUEL USE

CARBON ABATEMENT TECHNOLOGIES PROGRAMME

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# Foreword

Energy is central to most aspects of modern life. It provides heat and light for homes and offices, fuels for transport and communications, and energy for manufacturing processes. Fossil fuels are expected to continue to dominate energy supply for decades to come. Developing countries in particular need more energy to support their industrial and social development. However, using fossil fuels will add to the problem of global warming unless their emissions can be abated. Carbon Abatement Technologies (CATs) have the potential to help reduce the threat to our climate from fossil fuel use. Achieving this potential is the purpose of this Strategy.

The Energy White Paper recognised the need for urgent global action to combat climate change, with the UK showing global leadership by putting itself on a path to a 60% reduction in carbon dioxide emissions by 2050. We are reinforcing this aim during our Presidency of the G8 by making climate change one of two main areas for action.

There is no one solution to this challenge. Measures to meet our domestic goals have so far concentrated on encouraging energy efficiency, transport measures and the development of renewable energy technologies - but more is needed.

CATs are a group of innovative technologies that complement other abatement actions. They provide an option for using fossil fuels during the transition to a low carbon energy system. CATs, working with fossil fuel technologies, can take advantage of existing facilities and committed investments, which is particularly important for developing countries that are likely to make large investments in fossil fuel plant and other industrial installations over the next 20 years.

CATs offer carbon dioxide reductions from 5 to 30% by making existing technologies more efficient and through mixing nominally carbon-neutral biomass with fossil fuels. More radically, there is a longer-term potential to reduce emissions by around 85% with Carbon Capture and Storage (CCS) technologies, which separate the carbon dioxide produced in large combustion plant and store it in geological formations. Some of these CCS technologies also have the potential to produce hydrogen for use in transport systems.

We see CATs complementing renewables technologies in a family of sustainable energy technologies for tackling climate change in a safe and environmentally sound fashion that takes full account of the UK's obligations under international treaties, including those to protect the marine environment. Development and implementation of CATs will require the involvement of many business sectors including power engineering, electricity generation, process engineering, fossil fuel supply, offshore engineering, petroleum engineering, geological services and project developers. The UK has a strong presence in all of these sectors, and also has the natural resources for long-term storage of carbon dioxide in its offshore oil and gas fields and in deep saline aquifers. We are therefore well placed to contribute to their development and deployment both in the UK and worldwide.

This Strategy provides a much-needed focus on the development of CATs for use with fossil fuels, which have the potential to help people in many countries to enjoy the benefits of fossil energy supplies without endangering the future.

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# Contents

# 1. Introduction and Executive Summary

## 1.1 Introduction

Fossil fuels presently underpin most aspects of modern life. While this dependency may fall through greater efficiency in energy use and the deployment of alternative energy sources, most projections have fossil fuels continuing to dominate energy supply well into the century. Indeed, the consumption of fossil fuels seems set to rise as developing countries require more energy to support their industrial and social development. However, the combustion of fossil fuels produces carbon dioxide ($CO_2$), the main gas causing climate change, a phenomenon that is generally acknowledged to pose a major threat to the social and economic well being of both developed and developing countries.

Reconciling the imperatives of supporting the convergence of world economies, maintaining the quality of life in developed countries and mitigating climate change is a major challenge for which there is no one solution. A portfolio of measures will be needed; encompassing a greater drive for energy conservation, use of renewable energy and other low-to-zero $CO_2$ energy sources. Fossil-fuel based carbon abatement technologies (CATs) are a group of innovative technologies that enable fossil fuels to be used with substantially reduced $CO_2$ emissions, and therefore can be part of the solution to climate change.

The DTI's Cleaner Fossil Fuels Programme[1] formerly the Cleaner Coal Technology (CCT) Programme has supported collaborative work covering R&D on cleaner coal technologies together with technology transfer and export promotion. A review of $CO_2$ capture and storage[2] (CCS) recommended that this Programme should be complemented or replaced by a broader programme aimed at the development and implementation of CATs. Accordingly, this report presents the UK's Strategy for supporting the technical development and commercial deployment of CATs both in the UK and global markets. The Strategy has benefited from a public consultation and workshop, the responses to which have been summarised in an accompanying report[3].

The report considers the key strategic issues affecting CATs:

- the policy context and need for a UK CAT Strategy
- the future prospects for fossil fuels in the UK and worldwide
- the current status and deployment prospects for CATs
- the status of CAT-related industries in the UK
- opportunities and constraints for CAT development and deployment.

The reports goes on to present:

- the rationale and objectives for a CAT Strategy
- a plan for delivering the Strategy.

The remainder of this chapter gives an executive summary of the Strategy.

## 1.2 Executive summary

### *Why do we need a UK CAT Strategy?*

The level of $CO_2$ in the atmosphere has risen by more than a third since the industrial revolution, and is currently increasing faster than ever before. The Intergovernmental Panel on Climate Change (IPCC)[4] has estimated that, with the current growth in demand for fossil fuels, atmospheric concentrations of $CO_2$ could be more than three times pre-industrial levels in 2100 resulting in increases in the global mean temperature of up to 5.8°C. Such increases in global temperature imply major changes in climatic terms. For the UK this will mean a greater likelihood of heat waves, greater risk of flooding and more water stress in the South and East. However, it is developing countries, particularly the poorest countries that are particularly at risk. Their infrastructures are most

1 www.dti.gov.uk/energy/coal/cfft/cct
2 *Review of the feasibility of carbon dioxide capture and storage in the UK*, DTI Report URN 03/1261, September 2003.
3 *An analysis of the responses to the consultation on carbon abatement technologies* (DTI/Pub URN 05/602) March 2005.
4 *Climate Change 2001: The Scientific Basis*, IPCC Third Assessment Report, 2001.

vulnerable to extreme events, and there is wide expectation that climate change will worsen their food security, water availability and health, as well as accelerating biodiversity losses.

There is no international consensus over what is an acceptable increase in greenhouse gas concentrations and hence in climate change. For $CO_2$ a level of 550ppm, double the pre-industrial level, has been discussed. The European Union (EU) has reaffirmed its view that the global average mean surface temperature increase should not exceed 2°C, and that stabilisation well below 550ppm $CO_2$ equivalent is likely to be needed to achieve this[5]. A wide range of potential emissions trajectories could be followed to achieve stabilisation. The IPCC has examined a range of global trajectories for stabilisation of fossil fuel $CO_2$ emissions (Figure 2.1). This has shown that stabilisation at 550ppm requires emissions to be reduced below 1990 levels by about 2100, and to continue to decrease steadily thereafter[6]. The Royal Commission on Environmental Pollution (RCEP) concluded that for the UK, stabilisation implied cuts of 60% from current levels by 2050 and 80% by 2100[7]. Emissions abatement must accommodate the needs of developing countries whose demand for energy is growing faster as their economies expand and their populations look to enjoy a better quality of life.

The Energy White Paper (EWP) - *Our Energy Future - Creating a Low Carbon Economy*[8], addressed climate change as one of its main objectives, and set out to place the UK on a path to cut $CO_2$ emission by 60% by 2050. The intent was not simply to secure the UK's contribution to greenhouse gas abatement, but also to give a lead for action worldwide, which is necessary for effective abatement since the UK only accounts for only about 2% of global greenhouse gas emissions. This leadership role is being taken forward through the UK's presidency of the G8 group of countries in 2005, during which climate change and concerted actions for the reduction of emissions from fossil fuel combustion are one of two main themes.

The first steps for achieving the UK's 60% abatement target place an emphasis on the development and deployment of renewable technologies as well as improvements in energy efficiency. The EWP also recognised that fossil fuels have a role to play in a low-carbon economy, but that they (particularly coal) need to reduce their $CO_2$ emissions significantly compared with the present. It saw this being achieved through the development and deployment of CATs.

***Is it so difficult to reduce fossil fuel consumption in the UK and worldwide?***

The recently published International Energy Agency (IEA) World Energy Outlook 2004[9] shows that total world primary energy demand in 2002 exceeded 10,000 Mtoe[10] of which 80% was met by fossil fuels. Demand is expected to increase by about 60% up to 2030 with fossil fuels continuing to meet more than 80% of demand (ie 22% coal, 35% oil and 25% natural gas). The implication of this trend is for energy-related $CO_2$ emissions to increase by 62% from 23.6Gt per year to 38.2Gt per year.

Two thirds of the growth in demand is expected to come from developing countries, and consequently by 2030 their share of world demand will have increased from 37% to 48%. China and India notably, will account for nearly half of developing country demand. Demand for electricity is expected to grow faster than total energy demand, roughly doubling by 2030.

The growth in demand for electricity will require a massive deployment of new generation capacity. The IEA data shows that at least 800GW of additional capacity will be needed by 2010 and a further 1300GW by 2020. Much of this capacity will be fossil-fuelled and a large proportion of it will be built in developing countries. New plant

5 Council of the European Union, December 2004.
6 *Climate Change 2001: IPCC Third Assessment Report – Summary for Policy Makers*, IPCC, 2001.
7 *Energy - the Changing Climate*, 22nd Report of the Royal Commission on Environmental Pollution, June 2000.
8 *Our energy future - creating a low carbon economy*, Cm 5761, (DTI/Pub URN 03/660), February 2003.
9 *World Energy Outlook 2004*, International Energy Agency, Paris, October 2004
10 Million tonnes of oil equivalent (Mtoe).

being built now will probably operate for 40-60 years and therefore will have a major influence on future $CO_2$ emissions.

For the UK, DTI energy projections[11] see total final energy consumption increasing by about 13% between 2000 and 2020 with electricity generation increasing about 10%. By 2020 the UK is projected to be still very dependent on fossil fuels for the bulk of its electricity generation. About 75% of our electricity will come from fossil fuel generation compared with 70% in 2000. The forecasts indicate, however, that we will be more dependent on natural gas rather than coal by then with around 58% of electricity being generated from gas and about 16% from coal.

Beyond 2020, MARKAL modelling studies supporting the EWP[12] indicated that with no additional policies to reduce $CO_2$ emissions, fossil fuels would continue to supply up to 96% of UK primary energy demand to 2050. This was mainly natural gas (64%) for space heating and power generation, and oil products (30%) used principally for road transport. Coal would cease to be used for power generation between 2020 and 2030 as existing stations were retired and similarly nuclear power generation would end by 2030. Recent MARKAL studies undertaken in support of this CAT Strategy concurred with the earlier work in showing fossil fuels continuing to dominate UK energy supplies[13]. This new assessment includes a revised database for fossil power generation technologies, including advanced coal plant. Results showed that with these lower cost and higher efficiency plant coal could continue to be used for power generation.

Though large gains in energy efficiency are undoubtedly possible, and more renewables will certainly be deployed, the trend to fossil fuels is very unlikely to reverse in the period to 2050, particularly in developing countries. This implies that the large reductions in $CO_2$ emissions needed by 2050 will require a major deployment of CATs on a world scale.

### *What are CATs and what are their deployment prospects?*

CATs cover a range of generic options for reducing the $CO_2$ emissions from fossil fuel combustion. These include:

- **Higher efficiency conversion processes** - the amount of fuel consumed, and the associated emission of $CO_2$, is reduced when conversion processes (eg power generation, oil refining) are made more efficient. This can contribute emissions reductions of 10-30% depending on the performance of the old and replacement plant.
- **Fuel switching to lower carbon alternatives** - the main example for the UK is the replacement of coal-fired power generation with natural gas, which reduces emissions by about 50% per unit of output[14]. However, as far as this strategy is concerned the main option is co-firing with 5-10% of $CO_2$-neutral biomass, which can deliver emissions reductions of 5-10%.
- **$CO_2$ capture and storage (CCS)** - in which the carbon in fossil fuels is captured (as $CO_2$) either before or after combustion and committed to long-term storage in geological formations. This approach can reduce emissions by up to 85% depending on the type of non-capture plant displaced.[15] Even higher levels can be attained by combining CCS with co-firing with biomass.

CCS is the most radical of the CAT options. It involves the deployment of a chain of technologies for $CO_2$ capture, transportation and storage, rather than developments focused on combustion plant alone. CCS is the least commercially developed of the CAT options because at present there are no policy measures in place to achieve the high levels of $CO_2$ abatement that can be delivered by these

11 *Updated Emissions Projections (final Projections to inform the National Allocation Plan)*, DTI, November 2004, www.dti.gov.uk/energy/sepn/uep2004.pdf and www.dti.gov.uk/energy/sepn/uep_addendum.pdf.
12 *Options for a low carbon future*, DTI Economics Paper Number 4, June 2003.
13 *The role of fossil fuel carbon abatement technologies (CATs) in a low carbon energy system*, Future Energy Solutions, to be published.
14 Part of this reduction is attributable to the higher efficiency of new gas turbine combined cycle (GTCC) plant.
15 *Review of the feasibility of carbon dioxide capture and storage in the UK*, (DTI/Pub URN 03/1261), September 2003.

technologies, only aspirational targets, and hence no market to pull through to commercial deployment. Nonetheless, most of the technologies needed to implement CCS are currently available through other applications. The first requirement is to combine and optimise their operation for $CO_2$ capture.

An interim step towards CCS would be to build capture-ready plant. Capture-ready plant is power plant, probably coal or natural gas fired, that is designed and constructed to make later retrofitting of $CO_2$ capture equipment more straightforward and less expensive. There are increasing levels of capture-readiness, but basic designs can simply be a matter of configuration and should not add significantly to the capital or operating costs of plant.

There are several options for the long-term storage of $CO_2$ in geological formations including injection into depleted oil reservoirs, depleted natural gas fields, deep saline aquifers and unmineable coal seams. Together these are estimated to have a global storage capacity of 1000-10,000Gt $CO_2$, therefore with current world $CO_2$ emissions of about 25Gt per year there is sufficient storage capacity for CCS to play a major role in emissions abatement.

Geological storage of $CO_2$ is well established for normal engineering timescales, but the key challenge is to establish the integrity of storage over the longer timeframes needed to abate climate change. Work has been underway for several years to develop the geological models to describe the transportation and geochemical reactions of $CO_2$ after injection, and to develop the monitoring methods to test and validate these models. Major international collaborative projects are continuing to monitor existing $CO_2$ injection sites, notably at Sleipner, Norway and Weyburn, Canada, and similar work is planned for In Salah, Algeria and Gorgon, Australia.

MARKAL modelling analysis has shown that CATs could play an important role in delivering the UK's $CO_2$ abatement targets. It was found that the size of the deployment depended on future patterns of economic and social development, primary energy prices and the deployment of other abatement options such as end-use energy efficiency. Improvements in generation efficiency were implemented when old power plant needed to be replaced, and, in the case of existing pulverised coal plant, by retrofitting advanced boilers and steam turbines. Co-firing with energy crops was deployed up to the maximum allowed of 10% in all pulverised coal plant.

CCS was needed to abate $CO_2$ emissions from both power generation and hydrogen production (for transport) with deployment commencing between 2010 and 2020, but in high demand scenarios this advanced to around 2010. The level of $CO_2$ capture was typically 10-25Mt/yr in 2010-2020 increasing to 100-150Mt/yr in 2040-2050, although more than 150Mt/yr was captured in the high growth scenarios by 2040. Significantly, the model found it to be cost effective to retrofit capture technology to plant built earlier, underlining the value of the capture-ready approach. It was also found that CCS complements the deployment of renewable energy by providing cost effective back-up to intermittent sources such as wind power. The model did not examine CCS on other types of large combustion plant.

A global energy analysis undertaken by the IEA[16] has shown that CATs have the potential to deliver considerable reductions in world $CO_2$ emissions. CCS offers the greatest reduction of up to 8Gt per year by 2030, rising to more than twice this by 2050, or almost 30% of projected energy-related emissions. Some CCS technologies have been deployed in niche opportunities and their wider deployment awaits policy measures on $CO_2$ abatement that will stimulate "market pull".

16 *The prospects for $CO_2$ capture and storage*, International Energy Agency, Paris, December 2004.

### *How else could CATs contribute to the Energy White Paper's objectives?*

CATs will be deployed as part of the transition to a low $CO_2$ energy system and therefore other benefits stemming from their deployment should be considered in the context of such a system. With regard to energy security CATs will allow a higher level of fossil fuel use for any given level of $CO_2$ emission. Thus by enabling the retention of more fossil fuel in the energy mix, CATs could contribute to the diversity of supply. Furthermore, since several of the renewable resources available to the UK are intermittent (eg onshore wind, offshore wind, wave energy, tidal power) the deployment CATs would also contribute to security and firmness of supply, particularly for electricity. Finally, by maintaining the option of using fossil fuels in a low carbon economy, CATs help provide a wider range of supply options, which should give greater price competition.

### *Does UK business have the capabilities to commercialise CATs?*

Development and implementation of CATs will require the involvement of a large number of business sectors including power engineering, electricity generation, process engineering, fossil fuel supply, offshore engineering, petroleum engineering, geological services and project developers. The UK has a strong presence in all of these sectors through UK-based multinational oil companies such as BP and Shell, leading engineering companies such as BOC and Rolls-Royce, international equipment manufacturers such as Mitsui Babcock and ALSTOM Power and as an international centre for process engineering consultants and contractors, financial services and project management expertise. The UK is also endowed with the natural resources for the long-term storage of $CO_2$ in its offshore oil and gas fields and in deep saline aquifers.

CATs offer several lines for innovation, which will produce opportunities to establish new specialist products, including those based on membrane technology, specialist chemicals, catalysts and advanced materials. The lead being shown by the UK for $CO_2$ abatement should be used to establish market opportunities for the deployment of CATs. This will provide the springboard to tackle the much larger markets that will emerge overseas, particularly in developing countries, as the drive to reduce $CO_2$ emissions gathers pace, recognising of course that overseas markets will want to manufacture as much as possible of CATs domestically.

A particular area in which a British company is taking a world lead is the $CO_2$ Capture Project (CCP). BP is a leading partner in this international project, which is also funded by other companies such as Shell, Statoil and Chevron-Texaco, as well as the European Commission (EC) and the US Department of Energy. This project, consisting of a series of engineering and assessment studies is now entering its second phase. It addresses the issue of reducing emissions in a manner that will contribute to an environmentally acceptable and competitively priced continuous energy supply for the world[17].

### *What are the opportunities and constraints affecting the development of CATs in the UK?*

The UK is in a strong position to lead in the development of CATs and to gain large commercial and social benefits from their deployment. The reasons include the following:

- The UK Government's commitment to give a world lead on $CO_2$ abatement should create an early domestic market for CATs.
- A strong industrial base to develop and manufacture CATs.
- A near-term market opportunity from the approaching need to replace a large part of the UK's coal and nuclear power generation capacity.
- Geological formations for long-term storage of $CO_2$, making the UK an ideal location to demonstrate CCS.

17 See www.co2captureproject.org/overview/overview.htm for more information.

- Strong capabilities in offshore engineering, oil and gas extraction and the geological sciences needed to appraise, operate and monitor $CO_2$ storage sites.
- An existing infrastructure to support offshore $CO_2$ storage operations, stemming from North Sea oil and gas extraction.
- The potential to use $CO_2$ for enhanced oil recovery, which would give some financial return to partially offset the cost of CCS.
- UK industry is well established as a supplier to key markets such as China where fossil fuel demand is growing and CATs will be needed to reduce $CO_2$ emissions.

The deployment of CATs, and in particular CCS, is affected by a range of financial and regulatory factors including:

Financial:

- Uncertainties over the implementation and value of market-based instruments, including the European Union - Emissions Trading Scheme (EU-ETS).
- New commercial relationships between producers, shippers and those who commit the $CO_2$ to long-term storage.

Regulation:

- Legal and regulatory regimes.
- Monitoring and verification of $CO_2$ storage.
- Long-term ownership of stored $CO_2$.
- Planning and authorisation.

### *What is the rationale for Government support for CAT development?*

The preceding sections have demonstrated that CATs could make a substantial contribution both to the EWP $CO_2$ reduction targets and to potential actions on global $CO_2$ abatement to be taken through the G8. There are additional arguments in favour of UK Government support for CAT innovation.

Like other governments around the world the UK Government provides support for technology innovation where private organisations may under-invest in R&D because of market or system failures[18] such as in the case of CATs:

- The failure of the market to fully value the abatement of $CO_2$ emissions.
- The spillover of benefits to international competitors.
- Barriers to effective collaboration across industrial sectors.
- Regulatory uncertainty.

#### *Market failure*

Market-based measures to reward the abatement of $CO_2$ emissions are currently in their infancy with the EU-ETS having started on 1 January 2005. Initially, under this scheme, permits are likely to trade at a price that does not fully reflect the social cost of climate change. UK measures such as the Renewables Obligation for electricity supply and the Climate Change Levy (CCL) exemption for good quality CHP do not extend to CATs. Consequently there is no mechanism fully to reward the benefits to be gained from CATs and this is a disincentive to investment in their development. Strengthening the market instruments will take time and will require international agreement. Therefore, in the meantime, more targeted support for CATs is needed.

#### *Spillover of benefits*

Energy industries are international and most CAT developments will have international markets. In these circumstances some of the knowledge gained through R&D in one organisation will inevitably spill over, such that other organisations gain part of the benefits. In these circumstances firms will be reluctant to risk their resources on R&D.

18 *Competing in the Global Economy: the Innovation Challenge*, DTI, December 2003 (www.dti.gov.uk/innovationreport).

*Barriers to effective co-ordination*

Capturing the full benefit of CATs will require collaboration and co-ordination between a broad range of commercial organisations including power engineering, process engineering, power generation, oil and gas production, petroleum engineering, materials and specialist chemicals manufacture, chemical engineering and others. These organisations will range from large international companies to small and medium-size enterprises (SMEs). Government support may be required to foster the establishment of joint programmes among such organisations.

*Regulatory uncertainty*

Many CAT opportunities are currently regarded as high risk by commercial organisations. This is partly due to the market failure described above, but is also linked to a range of regulatory, legal, political and social uncertainties. The greatest uncertainty applies to the longer-term CCS technologies. It is linked to a number of factors including:

- Lack of agreed regulations and standards for the licensing of $CO_2$ storage sites.
- Treatment of long-term ownership and liabilities for $CO_2$ storage.
- Legality of $CO_2$ storage under national and international laws governing waste management.
- The need to win political support and social acceptance for CCS.
- The outcome of political decisions on alternative technologies such as nuclear power.

The UK is already taking a leading role in resolving many of these issues; for example by promoting discussions within the London and OSPAR Treaty organisations on their treatment of $CO_2$ storage beneath the sea bed, with the EC on the verification and monitoring of CCS within the EU-ETS, and with the IPCC to develop greenhouse gas inventory methodologies. However, these processes are necessarily detailed and will take time. The conditions under which CCS is currently permitted under the London and Ospar Conventions are discussed below.

***What is the objective of the CAT Strategy and the actions to be undertaken?***

The objective of the CAT Strategy is:

> *To ensure the UK takes a leading role in the development and commercialisation of Carbon Abatement Technologies that can make a significant and affordable reduction in $CO_2$ emissions from fossil fuel use.*

The Strategy has defined ten areas for action:

- Support for research, development and demonstration of CATs.
- Support for the demonstration of $CO_2$ capture-ready plant.
- Support for the demonstration of $CO_2$ storage.
- Facilitation of international collaboration in UK-based CAT development and demonstration projects.
- Facilitation of and support for UK collaboration in CAT development and demonstration projects based in other countries.
- Within the Climate Change Programme Review (CCPR), examine possible measures to encourage the initial commercial deployment of CCS technologies in the UK.
- Facilitation of the acquisition and transfer of knowledge about CATs and know-how stemming from their innovation both in the UK and abroad to businesses and other organisations involved with their commercialisation.
- Leading the preparation of the national and international regulatory frameworks and market mechanisms needed to support CATs.
- Increasing public awareness and stimulating an informed debate on the role of CATs in mitigating climate change.

- Development and maintenance of a route map for the development of CATs in the UK.

The CAT Strategy differs from the previous CCT Programme by including support for demonstration projects. This is because both capture and storage technologies have reached a stage of maturity where demonstrations are essential to further their technical development and to address some of the non-technical factors that could be barriers to commercialisation. Furthermore, these demonstrations will show leadership in tackling greenhouse gas abatement and climate change. A second difference from the CCT Programme is that the CAT Strategy will cover all fossil fuels. This is intended to accommodate the role of natural gas in the UK energy system whilst encouraging the development of technologies for the UK's export markets, some of which (eg China, India) are expected to use coal for most of their power generation.

If capture-ready designs were adopted widely for the new and replacement fossil generation capacity planned worldwide over the next 10-15 years (and which could operate for 40-60 years) this would facilitate later capture of $CO_2$ from these plant. The demonstration of capture-ready technology is an action area under the Strategy both to encourage a worldwide trend, and also because many of the key components of a $CO_2$ capture plant can be demonstrated on a capture-ready facility (eg advanced steam or gas turbines, advanced boilers, air separation, gasification, etc). A demonstration is considered to be the most cost effective option for advancing CCS at this stage, and one that can be implemented rapidly, in the next 3-4 years.

At present it is not clear what type of capture-ready demonstration should be supported. This will be informed by the detailed project assessments currently being supported by the DTI through the final Call of the Cleaner Fossil Fuels Programme. It will also depend on an industry view of which technology offers the greatest potential market both in the UK and internationally.

The Strategy also aims to support a demonstration of $CO_2$ storage. This is important for developing UK experience and know-how in the design, authorisation, regulation and monitoring of a storage facility. It will also provide an additional facility for proving the long-term integrity of a geological store and will help build public confidence in the reliability of CCS as a $CO_2$ abatement option. This could be undertaken in combination with the demonstration of capture-ready plant, for example by undertaking capture on a fraction of the $CO_2$ output from the demonstration, or as a separate project should a lower cost source of $CO_2$ be available. An important consideration will be that this demonstration delivers technical benefits that are additional to ongoing projects and demonstrations elsewhere in the world.

The examination of measures to encourage commercialisation of CCS has been included because such a "pull through" of technology is essential to maintain the commitment of UK business and momentum in the development and commercialisation of CCS. It should also strengthen the position of UK business as a leader in both the implementation and management of this chain of technologies. Furthermore, a commercial-scale project could avoid about 0.5-2Mt $CO_2$/yr, which would in itself be a significant contribution to the UK's abatement target. It is intended that measures should be examined that would encourage deployment of combustion plant fitted with $CO_2$ capture technology and associated transport and storage by about 2010-2012. This will be undertaken in the Climate Change Programme Review.

This is not a go-it-alone Strategy for the UK to develop CATs. The UK does not have the resources to do this, nor would it deliver the benefits required since CATs developed from a purely UK perspective may not meet global needs. International collaboration is an important element of the Strategy, and actions are included to encourage and assist this process.

### *How will we deliver the CAT Strategy?*

#### *General Management*

The CAT Programme will undertake the key actions listed above. The Programme will run for at least ten years commencing in April 2005 with a full review after five years. There will be a specific assessment in Year 2 of the Programme to consider the options for demonstration projects covering capture-ready plant and $CO_2$ storage.

The CAT Programme is intended to be industry-led, and therefore not prescriptive about the work it will support. The Strategy defines broad areas for work and looks to industry and the research community to come forward with innovative projects.

Support for R&D will come from DTI's Technology Programme[19] under the direction of the Technology Strategy Board (TSB). Calls for collaborative R&D under the Technology Programme are made twice a year. The DTI's Technology Programme embraces all technologies, those to be included in specific Calls being determined by the TSB. The projects supported under the final Call of the CCT Programme focus on CATs and are seen as a bridge to the new CAT Programme. Other activities within the CAT Programme will be managed by the Carbon Abatement Technologies Unit under the guidance of the Advisory Committee on Carbon Abatement Technologies (ACCAT).

#### *Advisory Committee on Carbon Abatement Technologies (ACCAT)*

ACCAT currently provides strategic advice on the activities of the CCT Programme and has assessed and made recommendations on Government support for R&D projects under the CCT Programme. ACCAT is constituted in accordance with the Nolan guidelines on public appointments. Membership is selected on the basis of its members' experience and knowledge of the energy sector and in particular on technical knowledge and ability to assess project proposals. Membership is drawn from the energy sector, covering equipment manufacturers, power generators, energy consultants and academia. Officials from the relevant areas of government also attend.

The new central arrangements in the DTI for managing R&D projects under the Technology Programme mean that ACCAT will no longer be required to assess R&D proposals. ACCAT will therefore have purely an oversight role for R&D while providing more detailed advice and guidance to the DTI on the development of the CAT Strategy and on the other actions in the CAT Programme. ACCAT's role as an advisory body will be reviewed during 2005 with the objective of recruiting a membership appropriate to its new role. As part of this review it is thought that membership should be drawn from a wider population of stakeholders than in the past, (eg a wider range of industry and academia, representation from the NGOs).

#### *Funding*

Under the 2004 Spending Round the Cleaner Fossil Fuels Programme was allocated £20M in total for the period 2005/06 to 2007/08. This funds industry-led R&D under the Technology Programme, together with policy development on issues around sustainable fossil fuel energy technologies. It is considered from past experience that at this stage this budget should be sufficient to support laboratory-based R&D. This budget is also intended to assist UK collaboration in international R&D Programmes including the Memoranda of Understanding with the USA and China.

The budget includes an element to fund work on policy issues affecting CATs. It also covers DTI's ongoing contribution to the British Coal Utilisation Research Association's (BCURA's) research programme, and membership contributions to the IEA's Implementing Agreement on Cleaner Coal.

19 See www.dti.gov.uk/technologyprogramme/ for more information.

The Strategy recognises that we are reaching a point where demonstrations up to full-scale may be necessary. There are a number of areas of potential demonstration that extend beyond low to zero $CO_2$ emission technologies to the related areas of hydrogen production and fuel cells.Therefore the Government will provide a funding package of £40M over four years commencing in 2006/07 for demonstrations across CATs, hydrogen and fuel cells. Of the total around £25M is expected to be dedicated to CATs with the balance split approximately 50:50 between hydrogen and fuel cells. Projects that combine technologies, for example CATs and hydrogen, will be able to seek funding from both elements. This funding will be made available in the form of Capital Grants, and will be subject to State Aid rules and approval.

*Collaborative R, D&D*

There will be considerable benefits from collaborating with other countries in the development of CATs. The Strategy identifies those activities where the UK should seek to collaborate with other countries or international groupings. The second phase of the FENCO (Fossil ENergy COalition) project, in which the UK is a leading partner, is soon to commence under the EC's Framework Programme. This project is aimed at developing an European Research Area Network (ERA-Net) for CATs, and will provide a good opportunity to identify partners within the EU. Areas for mutual collaboration have already been established with the USA where two projects are already underway, with a third area for collaborative research currently being studied. It is expected that a collaborative arrangement will also be established with China.

## 1.3 Conclusions and the way forward

This Strategy presents the case for supporting the development of CATs for fossil fuel power generation and other large-scale combustion plant.

Three areas of technology appear to offer opportunities for reducing $CO_2$ emissions from fossil fuel use: improved efficiency, co-firing with biomass and, for more radical reductions, CCS. These technologies are not mutually exclusive but could (and should) work together for an overall reduction in emissions. CCS could have an increasingly significant role in reducing emissions from about 2010 onwards, while other CATs could be deployed earlier.

While cost reduction and technology development are the key concerns for improved efficiency, co-firing and $CO_2$ capture, there is a different set of issues to be tackled for $CO_2$ storage. The key factors are linked to the design of an appropriate regulatory regime for safe and reliable storage, demonstrating that the $CO_2$ will not leak back to the atmosphere, and undertaking outreach to assure the public that CCS is not a major risk to the environment.

CATs should be looked at, not in isolation but as part of a portfolio, working with renewable and end-use energy efficiency technologies to reduce $CO_2$ emissions. CATs should be regarded as bridging technologies for giving short to medium-term reductions in $CO_2$ emissions, thus providing a breathing space for the development of truly sustainable energy technologies.

This Strategy identifies a number of actions ranging from R&D, through demonstration projects, facilitation of international collaboration, and a review of measures to encourage commercial deployment of CCS, to taking forward the social, economic, legal and regulatory issues around the introduction of these technologies. This action plan will advance the development of CATs with the aim of achieving the objective of this Strategy.

# 2. The need for a UK Carbon Abatement Technologies Strategy

Fossil fuels presently underpin many aspects of modern life; they support commercial activities, provide mobility for people and goods, and the comforts that a developed society takes for granted. While this dependency may be reduced through greater efficiency in energy use and the deployment of alternative energy sources most projections foresee fossil fuels continuing to dominate energy supply well into the century. Currently, the consumption of fossil fuels in absolute terms seems set to rise as developing countries require more energy to support their industrial and social development. However, fossil fuel combustion produces $CO_2$, the main gas causing climate change, which is generally acknowledged to pose a major threat to the social and economic wellbeing of all countries.

Reconciling the need to encourage economic development, reduce the gap between richer and poorer countries, and mitigate climate change is a major challenge for which there is no single solution. A portfolio of measures including energy conservation, more renewable energy and other low-to-zero $CO_2$ energy sources will be needed. Fossil fuel-based CATs are a group of innovative technologies that enable fossil fuels to be used with substantially reduced $CO_2$ emissions, and can be part of the solution to climate change. This chapter examines the policy context for CATs and the justification for the UK taking a lead in their development and implementation.

## 2.1 The policy context for a CAT Strategy

The EWP[20], has set the framework for future UK energy policy. This identified four main objectives:

- Tackling climate change and greenhouse gas emissions and putting the UK on a path to cut $CO_2$ emissions by 60% by 2050.
- Maintaining the reliability of energy supplies.
- Promoting competitive markets.
- Ensuring every home is adequately and affordably heated.

The first objective has probably received most attention since it is linked to the Government's acceptance of the RCEP's recommendations on stabilisation and implies major changes to how energy is supplied and used in the UK. The policy driver behind this objective was not simply to secure the UK's contribution to greenhouse gas abatement and the mitigation of climate change, it was also intended to give a lead for action worldwide. Since the UK accounts for only about 2% of global greenhouse gas emissions this latter aim is critical. This is being taken forward through the UK's 2005 presidency of the G8, during which climate change and concerted actions for the reduction of emissions from fossil fuel combustion will be one of two main themes.

The first steps for achieving the UK's 60% abatement target place an emphasis on the development and deployment of renewables technologies, such as wind power, as well as improvements in energy efficiency. As part of this Strategy it is planned to produce 10% of our electricity from renewable sources by 2010 and 15% by 2015. These measures will deliver the UK's Kyoto target of reducing greenhouse gas emissions by 12.5% and aim to move towards the domestic goal of reducing $CO_2$ emissions by 20% below the 1990 level by 2010. The EWP also recognised that fossil fuels have a role to play in a low-carbon economy, but that they (particularly coal) need to significantly reduce their $CO_2$ emissions compared with the present. It saw this being achieved through the deployment of CATs; including technologies with higher conversion efficiencies, co-firing with biomass, and ultimately through CCS technologies. For example, simply ensuring best available technologies are deployed in preference to less advanced options could give $CO_2$ emissions savings of 15-20%. Linked to this, the EWP saw opportunities for UK industry to promote cleaner coal technologies in countries

20 *Our energy future - creating a low carbon economy*, Cm 5761, (DTI/Pub URN 03/660), February 2003.

such as China and India where there is massive growth in new coal-fired power plant. China alone is expected to construct 400GW of capacity (about five times total UK capacity) by 2020[21].

On other objectives set by the EWP, CATs will be deployed as part of the transition to a low $CO_2$ energy system and therefore their contribution to energy security should be considered in the context of such a system. In this circumstance the main contribution of CATs will be to allow a higher level of fossil fuel use for any given level of $CO_2$ emission. Therefore, by enabling the retention of more fossil fuel in the energy mix, CATs could contribute to the diversity of supply. Furthermore, since several of the renewable resources available to the UK are intermittent (eg onshore wind, offshore wind, wave energy, tidal power) the deployment CATs would also contribute to security and firmness of supply, particularly for electricity. Finally, by maintaining the option of using fossil fuels in a low carbon economy, CATs help provide a wider range of supply options, which should give greater price competition.

This leaves the question of the security of the fossil fuel sources to be used with CATs. The UK's own resources of natural gas will be increasingly depleted in the next 15 years or so leading to greater reliance on imports, particularly from Norway and Russia. However, there will be strong demand on these sources as other European countries move to gas, and it is likely that other supplies will be needed. There are already plans to expand UK supplies through liquefied natural gas. Security can be enhanced by a sufficient spread of supplies, including the retention of coal in our fuel mix. The UK still possesses substantial reserves of coal, and also as an internationally traded fuel it will reduce any risks of disruption to supply or large price variations. It is also possible to store relatively large reserves of coal at power stations and other stocking sites. Consequently, if CATs enable the retention of some coal in the UK's fuel mix they will further contribute to our security of supply.

21 *World Energy Outlook 2004*, IEA, Paris, November 2004.
22 Proceedings of the international symposium on *"Avoiding Dangerous Climate Change"*, Hadley Centre, Exeter, February 2005 (www.stabilisation2005.com).

## 2.2 Climate Change – the imperative for action

The world is facing climate change and one of the major causes of this is the increase of anthropogenic greenhouse gases in the atmosphere. The concentration of $CO_2$, the main anthropogenic greenhouse gas, has risen by more than a third since the industrial revolution, from a pre-industrial level of around 280ppm to approaching 380ppm today. The rate of build up is increasing and is currently about 2ppm per year. Without effective mitigation action atmospheric concentrations of $CO_2$ could be more than three times pre-industrial levels in 2100, with resulting increases in the global mean temperature of up to 5.8°C. Recent work[22] suggests that climate sensitivity to increased $CO_2$ could be greater than previously anticipated.

Such increases in global temperature imply major climatic changes. For the UK this will mean a greater likelihood of heat waves, greater risk of flooding and more water stress in the South and East. At some places on the east coast extreme sea levels, currently with a 2% chance of occurring in any year, could be 10 to 20 times more likely by the 2080s. However, it is developing countries, particularly the poorest countries that are most at risk. Their infra-structures are more vulnerable to extreme events, and there is wide expectation that climate change will worsen their food security, water availability and health, and that biodiversity losses will accelerate. Moreover, the greater the climate change, the higher the risk of wholesale shifts in the climate system such as changes in the pattern of ocean circulation, increased loss of forest cover and destabilisation of the Greenland and West Antarctic ice sheets.

There is no international consensus over what is an acceptable increase in greenhouse gas concentrations and hence in climate change. For $CO_2$ a level of 550ppm, double the pre-industrial level, has been discussed. The EU has reaffirmed

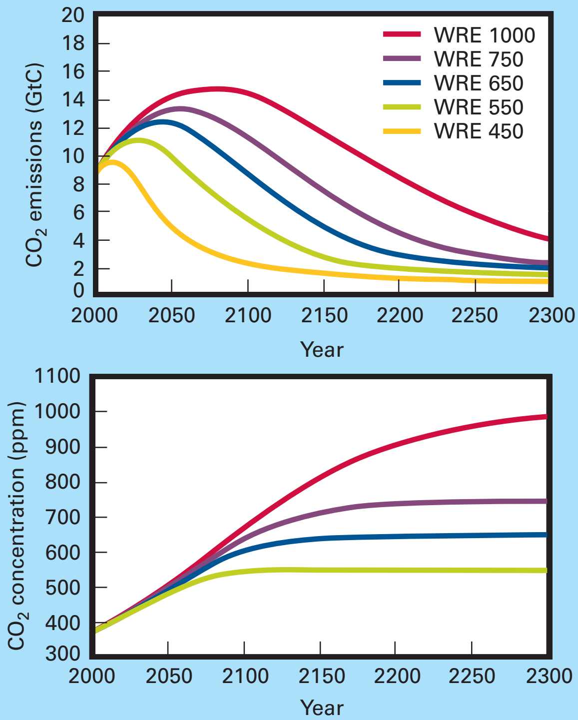
**Climate change will mean a greater likelihood of heat waves, greater risk of flooding and more water stress for the UK (courtesy of Ian Britton).**

its view that the global average mean surface temperature increase should not exceed 2°C, and that stabilisation well below 550ppm $CO_2$ equivalent is likely to be needed to achieve this[23].

A wide range of potential emissions trajectories could be followed to achieve stabilisation. The IPCC has examined a range of global trajectories for stabilisation of fossil fuel $CO_2$ emissions (Figure 2.1). This has shown that stabilisation at 550ppm requires emissions to be reduced below 1990 levels by about 2100, and to continue to decrease steadily thereafter[24]. The RCEP concluded that for the UK, stabilisation implied cuts of 60% from current levels by 2050 and 80% by 2100[25].

The IPCC stabilisation trajectories reflect the need for developed and developing countries to make massive $CO_2$ reductions in aggregate, taking account of the need for increasing energy services in developing countries as their economies expand and their populations look to enjoy a better quality of life. Developing countries such as China and India are currently making massive investments in capital plant such as power stations, which will operate for many decades to come. Therefore it is vital to the success of the global response to climate change that this investment goes for the best available technology, not only with a high conversion efficiency but with the capability to accommodate the retrofit of $CO_2$ capture at a later date.

**Figure 2.1 Alternative stabilisation scenarios for global $CO_2$ emissions (courtesy of Intergovernmental Panel on Climate Change).[24]**



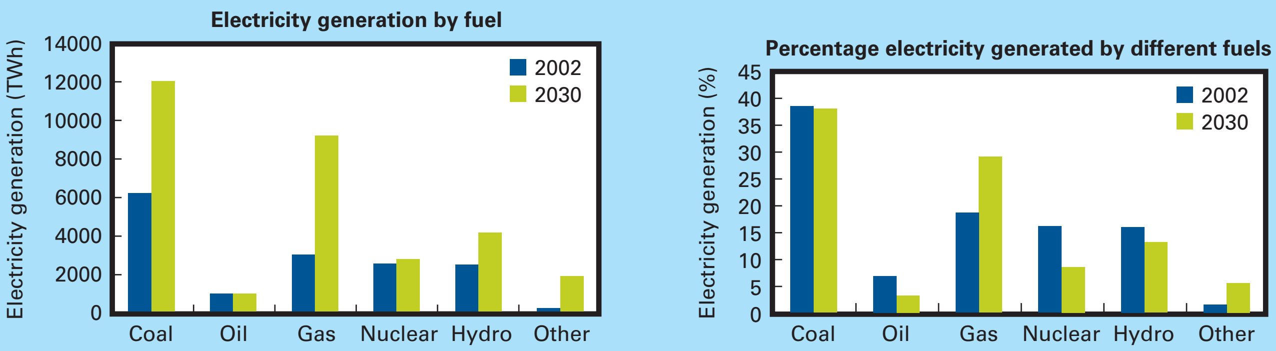

The UK's target to reduce $CO_2$ emissions by 60% by 2050, while extremely challenging, is a small contribution to abatement in absolute terms since we only account for about 2% of global emissions. However, this effort can have much greater significance by fostering the development of abatement technologies such as CATs that can be deployed worldwide.

## 2.3 Global trends in fossil fuel consumption

The recently published International Energy Agency (IEA) World Energy Outlook 2004[26] shows that total world primary energy demand in 2002 exceeded 10,000Mtoe of which 80% was met by fossil fuels. Demand is expected to

23 Council of the European Union, December 2004.
24 *Climate Change 2001:* IPCC Third Assessment Report - Summary for Policy Makers, IPCC, 2001. WRE: data from Wigley, Richels and Edmonds, Nature **379**, 240-243, 1996.
25 *Energy - the Changing climate*, 22nd Report of the Royal Commission on Environmental Pollution, June, 2000.
26 *World Energy Outlook 2004*, IEA, Paris, November 2004.

**Figure 2.2 Electricity generation by fuel type in 2002 and projected for 2030 (IEA 2004).**




increase by about 60% up to 2030 with fossil fuels continuing to meet more than 80% of demand (ie 22% coal, 35% oil and 25% natural gas). The implication of this trend is for energy-related $CO_2$ emissions to increase by 62% from 23.6Gt per year to 38.2Gt per year.

Within the present fossil fuel mix a large proportion of coal (69%) and natural gas (36%) is used in centralised heat and power plant. As shown in Figure 2.2 this trend is expected to increase as demand for electricity is expected to grow faster than total energy demand, roughly doubling by 2030. By 2030 coal is expected to remain the largest source of electricity (38%), with natural gas increasing its share (29.5%) to make up for the low growth in oil and nuclear output.

There are important variations within the overall global trend in energy. Two thirds of the growth in demand is expected to come from developing countries, and as a result by 2030 their share of world demand will have increased from 37% to 48%. China and India are notable for accounting for nearly half of developing country demand (Figure 2.3).

There are significant regional variations in the mix of energy sources expected to be used for electricity generation by 2030 (Figure 2.4) with Europe expanding natural gas based generation (32%) while North America retains coal as the main source (40%). Coal is also by far the preferred fuel for power generation in developing countries, supplying 47% of demand. The predominance of coal for electricity generation is expected to be even greater in the key

**Figure 2.3 Projected shares of world primary energy demand in 2030 (IEA 2004).**

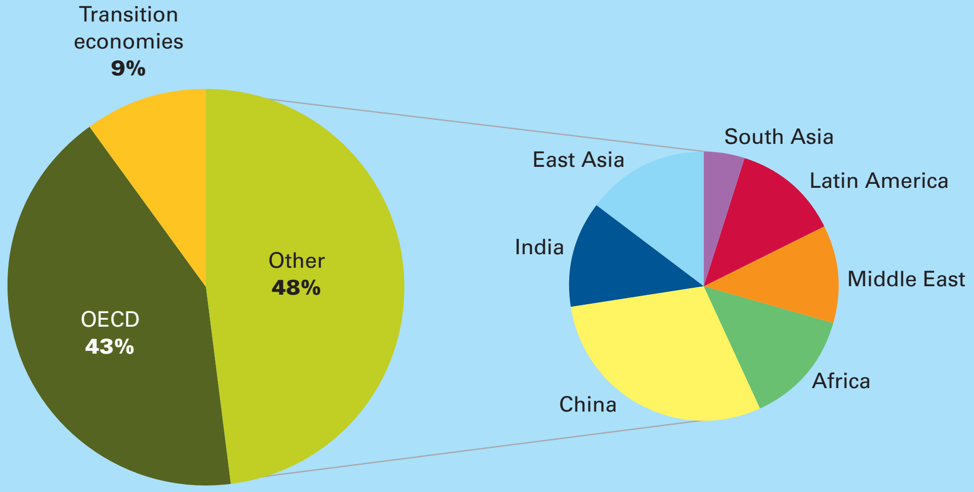
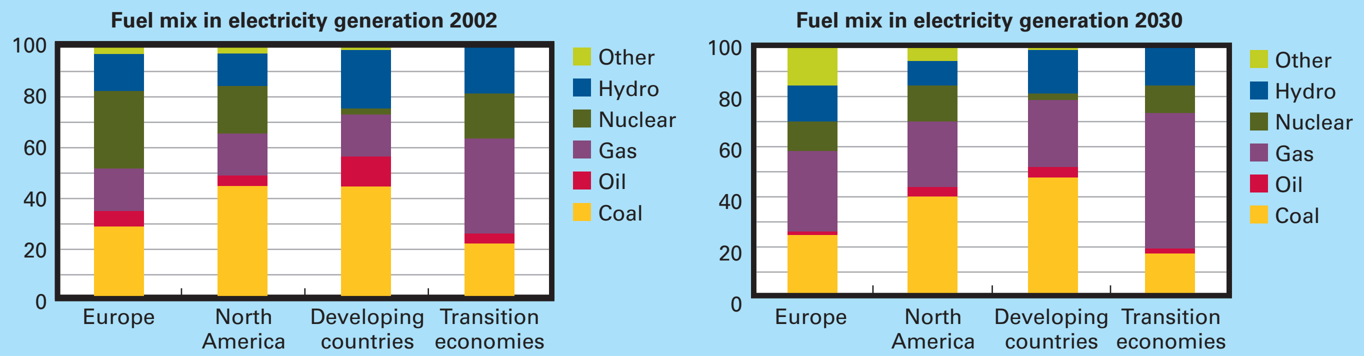


**Figure 2.4 Fuel mix used in electricity generation in 2002 and 2030 (IEA 2004).**




developing countries, China and India, where respectively 72% and 64% of electricity will come from coal in 2030.

The growth in demand for electricity will require a massive deployment of new generating capacity. The IEA data shows that at least 800GW of additional capacity will be needed by 2010 and a further 1300GW by 2020. Table 2.1 shows that much of this capacity will be fossil-fuelled plant and a large proportion of it will be built in developing countries. Plant being built now will probably operate for 40-60 years having a major influence on future $CO_2$ emissions, and so investment decisions being made now are critical.

**Table 2.1 Additional coal and gas fired power generation capacity (GW) required over each of the next three decades.**[27]

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| World | 520 | 967 | 1205 |
| OECD | 160 | 309 | 363 |
| Developing Countries | 343 | 587 | 750 |
| Transition Economies | 16 | 72 | 90 |
| European Union (25) | 39 | 105 | 132 |
| North America | 83 | 141 | 171 |
| China | 162 | 210 | 260 |
| India | 24 | 66 | 97 |
| Russia | 5 | 27 | 34 |

Note the values are for each decade (ie they are not cumulative)

27 Derived from the IEA World Energy Outlook 2004 Reference Scenario.
28 *DTI - Updated Emissions Projections (Final projections to inform the National Allocation Plan)*, November 2004, www.dti.gov.uk/energy/sepn/uep2004.pdf and www.dti.gov.uk/energy/sepn/uep_addendum.pdf.

**The Loy Yang opencast mine and power station in the Latrobe Valley, Victoria, Australia - fossil fuels are expected to continue to meet most of the world's energy requirements at least to 2050.**

## 2.4 DTI projections for UK energy supply and demand to 2020

DTI energy projections[28] see total final energy consumption in the UK increasing by about 13% between 2000 and 2020 with electricity generation increasing at a slightly lower rate (~10%) to 381TWh in 2020 compared with 346.3TWh in 2000. As a result of the Renewables Obligation and other Government incentives, it is likely that by 2010 the UK will have around 10% of its electricity generated from renewable sources, increasing towards 20% by 2020. By 2020 there will at most be three operational nuclear plants meeting about 7% of demand. This latter result assumes that there will be no new nuclear plant coming on line during this period, although the EWP has left this option open for future consideration.

What is significant in the projections is that by 2020 the UK will still be very dependent on fossil fuels (natural gas and coal, and to a lesser extent oil) for the bulk of its electricity generation. In fact they indicate that about 75% of our electricity will come from fossil fuel generation compared with 70% in 2000 (Figure 2.5). The forecasts indicate that we will be more dependent on natural gas than coal with around 58% of electricity being generated from gas and about 16% coming from coal.

In addition to electricity generation, natural gas is expected to be widely used for domestic and commercial space and water heating and in a range of industrial applications. As a result the direct use of natural gas is expected to account for 34% of final energy consumption by 2020. The other major source of energy is oil, accounting for 47% of demand in 2020, mainly for transport applications. With these trends, and the decline of nuclear power, fossil fuels are expected to account for a larger share of UK energy demand than at present, exceeding 90% by 2020.

With this move to fossil fuels, albeit to lower carbon intensity natural gas, the downward trend in $CO_2$ emissions could be reversed after 2010 (Table 2.2). By 2020 the Government projections indicate that $CO_2$ emissions from power generation (from all sources) could be about 17% lower than in 2000 and 34% lower than in 1990, much of this latter decrease being a result of the dash for gas in the 1990s.

Looking beyond 2020, studies in support of the EWP indicated, that with no additional policies to reduce $CO_2$ emissions, fossil fuels would continue to supply up to 96% of UK primary energy demand up to at least 2050. This was mainly natural gas for space heating and power generation and oil products used principally for road transport. Coal ceased to be used for power generation after 2020-2030 as existing stations were retired and similarly nuclear power generation ended by 2030. Most of this retired capacity was replaced by natural gas that accounted for nearly 80% of generation by 2050.

Additional MARKAL studies have been undertaken in support of this Strategy to investigate the deployment prospects for CATs. This is reported more fully in the next chapter, but it is important to note that the baseline assessment, with no additional policies to reduce $CO_2$ emissions, concurred with the earlier work in showing fossil fuels continuing to dominate UK energy supplies. The new assessment includes a revised database for fossil power generation technologies, including advanced coal plant. Results showed that with these lower cost and higher efficiency plant coal could continue to be used for power generation (Figure 2.6)[29].

**Figure 2.5 Fuel mix for UK electricity generation in 2000 and 2020.**

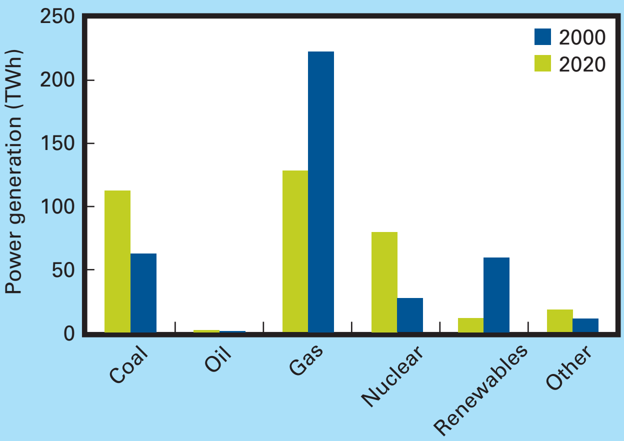
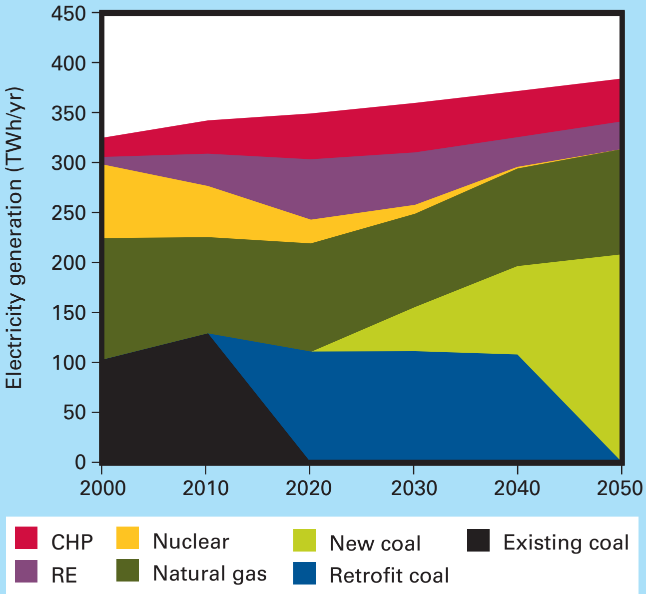



**Table 2.2 Emissions projections for UK economic sectors (MtC/year).**

| | 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| Power stations | 54.1 | 43.1 | 37.4 | 35.9 |
| Refineries | 4.8 | 4.4 | 5.5 | 5.5 |
| Residential | 21.5 | 23.0 | 20.5 | 21.8 |
| Services | 8.5 | 8.1 | 7.5 | 7.9 |
| Industry | 35.5 | 33.8 | 31.6 | 30.1 |
| Transport | 34.7 | 36.0 | 38.5 | 42.4 |
| **Total** | **159.1** | **148.4** | **141.0** | **143.6** |

29 *The role of fossil fuel carbon abatement technologies (CATs) in a low carbon energy system*, Future Energy Solutions, to be published.

**Figure 2.6 Electricity generation by fuel type under the MARKAL Baseline scenario without constraints on $CO_2$ emissions.**




## 2.5 $CO_2$ emissions from other stationary sources

Although the origin of this Strategy has been about reducing $CO_2$ emissions from fossil fuel power generation, Table 2.2 above indicates that other industrial sources will also be significant. This raises the question of whether a CAT Strategy should include in its scope all stationary industrial sources of $CO_2$. In addition to power generation, iron and steel manufacturing, cement making and oil refineries could also be included in any future programme of work.

Since the technologies for $CO_2$ separation will be similar for such plant and the systems for transport and storage of the $CO_2$ will be identical it has been concluded that the new Programme could include such sources without losing the focus of the Programme. However, as an industry-led Programme it will be for these industries to bring forward innovative proposals that are applicable both in the UK and internationally as well as having commercial advantages for the industrial sectors concerned.

## 2.6 CATs – the way forward

Drawing together the above it is clear that fossil fuels are going to dominate world energy supplies for many decades to come and that this runs contrary to the imperative of taking action to mitigate greenhouse gas emissions and climate change. CATs offer an option for retaining fossil fuels whilst reducing greenhouse gas emissions, thus giving a longer period to move to truly sustainable energy sources and to facilitate the achievement of sustainable national $CO_2$ emission intensities whilst ensuring equitable energy services for all.

It seems likely that a large international market will emerge in CATs. Therefore we should seek to position UK industry to take full advantage of the future market for this technology.

Although some, though not all, of the industries involved in CATs are well established the risks and uncertainties are considerable. Therefore the level of Government funding for CAT innovation needs to be adequate to stimulate investment by industry, and to support academic research, in future development and deployment.

Later chapters of this Strategy examine in more detail the Government support needed and how this should be channelled to gain maximum advantage both in the UK market and internationally.

## SUMMARY

- Projections show global energy demand increasing by about 60% by 2030 with the largest proportion of this growth occurring in developing countries.
- Fossil fuels will continue to provide 80% of total world energy requirements, which will result in $CO_2$ emissions being 62% higher by 2030.
- Coal and natural gas are the main fuels used worldwide for electricity generation and are expected to provide 38% and 30% respectively in 2030. The dominance of coal for power generation is greatest in the major developing countries of China and India whose demand is expected to more than double by 2030, with coal providing 72% and 64% respectively.
- A large amount of new power generation capacity will be built over the next decade (over 160GW in China alone). Since this will operate for 40-60 years the choice of plant will have a major influence on future ability to reduce $CO_2$ emissions.
- UK demand for electricity is expected to grow by a more modest 10% by 2020, but here again most of this will be generated from fossil fuels (75%), of which the largest proportion will be from natural gas (58%).
- Encouraged by new lower cost and higher efficiency technology, combined with an increasing price advantage over natural gas, coal could show significant expansion in UK power generation after 2020.
- These trends are in conflict with the need for radical reductions in $CO_2$ emissions the bulk of which come from fossil fuel combustion.
- To stabilise the atmospheric $CO_2$ concentration even at 550ppm, roughly double the pre-industrial level, requires global emissions to be reduced below 1990 levels by about 2100, and to continue to decrease steadily thereafter.
- The UK is showing leadership by putting our economy on a path to a 60% reduction in $CO_2$ emissions by 2050. However, with the UK accounting for only 2% of world emissions this needs to stimulate global action to be effective.
- CATs offer a means to retain the option of using fossil fuels whilst considerably reducing $CO_2$ emissions, thus giving a longer period to move to more sustainable energy systems. The deployment of CATs would also contribute to energy security and competitive energy markets, by retaining fossil fuels in a low carbon energy system.

# 3. The current status and prospects for Carbon Abatement Technologies

The previous chapter has shown that, although fossil fuel consumption is the major source of $CO_2$ emissions, energy projections currently anticipate an expansion in their use, at least to 2050[30]. This shows how fossil energy underpins all aspects of modern life (eg provision of warmth, light, motive power, mobility, communications, etc.), and the difficulty of developing economic, effective and socially accepted alternatives over only a few decades. CATs provide an option for continuing to enjoy the benefits of fossil energy whilst moving towards a low carbon energy system. They work with the grain of existing fossil fuel production, conversion and distribution systems to take maximum advantage of this in place investment. Ultimately of course fossil fuels are a finite resource, therefore CATs should be regarded as transitional technologies that can give a longer period for the transition to an economy that is based on truly sustainable energy sources.

## 3.1 What are the Carbon Abatement Technology options?

CATs cover a range of generic options for reducing the $CO_2$ emissions from fossil fuel combustion. These include:

- **Higher efficiency conversion processes** - the amount of fuel consumed, and the associated emission of $CO_2$, is reduced when conversion processes (eg power generation, oil refining) are made more efficient. This can contribute emissions reductions of 10-30% depending on the performance of the old and replacement plant. For example, increasing the efficiency of coal-fired power generation plant from 36% to 45% reduces emissions by 20%.
- **Fuel switching to lower carbon alternatives** - the main example for the UK is the replacement of coal-fired power generation with natural gas, which reduces emissions by about 50% per unit of output[31]. However, there are other options such as co-firing with 5-10% $CO_2$-neutral biomass, which can deliver emissions reductions of 5-10%.
- **$CO_2$ Capture and Storage (CCS)** - in which the carbon in fossil fuels is captured (as $CO_2$) either pre-combustion or post-combustion and committed to long-term storage in geological formations. This approach can reduce emissions by up to 85% depending on the type of non-capture plant displaced[32]. (NB even higher levels can be attained by combining CCS with co-firing with biomass.) (See Annex II for a fuller description of $CO_2$ capture technologies.)

The $CO_2$ reductions given by these options are additive, and often complementary, in improving both technical performance and cost of implementation. For example the technical advances that contribute to higher conversion efficiencies will in many cases also benefit plant converted to co-firing with lower carbon fuels, and also CCS by compensating for the energy penalty associated with capturing $CO_2$. Similarly co-firing benefits other bio-energy technologies by providing a relatively convenient and low cost option that can stimulate the establishment of an infrastructure for the production and delivery (eg planting/harvesting) of energy crops. Other technologies can be categorised as CATs when linked with CCS. For example, $CO_2$ from underground coal gasification could be used to enhance the production of coal bed methane in an integrated, low-emission energy project.

The timescale over which the above CAT options will be needed in the transition to a low carbon economy will depend on the pace of the transition. Against the background of current UK policy objectives higher efficiency conversion processes and fuel switching could have a role up to 2010 when the aim is to have reduced $CO_2$ emissions by 20% relative to 1990 levels. Going beyond this, CCS technologies would also contribute to the UK's aim for a 60% reduction in $CO_2$ emissions by 2050 (see Section 3.2). CCS is essential if fossil fuels are still to be used

30 *World Energy Outlook 2004*, IEA Paris; *EU-15 Energy and Transport Outlook to 2030*, European Commission, Brussels, 2003; *International Energy Outlook 2003*, US Energy Information Administration, 2003.
31 Part of this reduction is attributable to the higher efficiency of new GTCC plant.
32 *Review of the feasibility of carbon dioxide capture and storage in the UK*, (DTI/Pub URN 03/1261), September 2003.

while delivering the global reductions in emissions (See Section 3.2) that are needed in the longer term to stabilise the atmospheric concentration of $CO_2$.

### Development status

#### *Higher efficiency conversion processes*

Combustion technologies have improved continuously since the first steam engines of the industrial revolution. The main pathways to increased efficiency currently include:

- advanced boilers to produce steam at higher pressures and temperatures
- improved steam turbines to handle higher temperatures and pressures and to convert thermal energy into motive power with greater efficiency
- gas turbines for higher temperature gas combustion, and hence improved efficiencies
- improved gasifiers for converting coal and heavy oils into synthesis gas.

Such improvements require advances in enabling technologies and systems such as high temperature materials, modelling and simulation to optimise combustion processes, process heat integration, novel sensors and advanced control systems. While much has been achieved in this area there is still substantial potential for further improvement. For example with coal-fired power generation current best available technologies have conversion efficiencies of around 44-46% but there is potential for this to increase to 60%. Similarly with power generation from natural gas efficiencies could increase from the present 56% to 70-75%[33].

In the past these developments have been driven by the economic benefits of lower fuel consumption, but there is now the additional need to reduce $CO_2$ emissions. Consequently there is a need to encourage an increased pace of development bringing forward options that may not be justified by fuel economy alone.

#### *Fuel switching to lower carbon alternatives*

Apart from switching from coal to natural gas the main option for reducing net $CO_2$ emissions is the co-firing of fossil fuel with biomass such as energy crops, food processing residues or forestry waste. Co-firing is already underway at a number of UK pulverised fuel plant and there is much interest in its wider application. The low energy density of biomass often limits co-firing to about 5% of fuel input, although direct firing may allow higher levels. In general it is only economic to collect biomass fuel from sources lying within a 30-50km radius of the plant. Possible exceptions are coastal plant where larger quantities can be delivered by boat, or plant situated close to sizeable sources of energy crops and biomass waste. Development projects have been mainly concerned with blending and injection of coal/biomass fuels, and with their ash production and slagging characteristics. The Cleaner Fossil Fuels Programme has supported work in these areas and there may be a need for additional R&D in the future.

#### *$CO_2$ capture and storage (CCS)*

CCS is the most radical of the CAT options. It involves the deployment of a chain of technologies for $CO_2$ capture, transportation and storage, rather than developments focused on combustion plant alone. CCS is the least commercially developed of the CAT options because at present there are no policy measures in place to require or reward the high levels of $CO_2$ abatement it can deliver. There are only aspirational targets, and hence there is no market to encourage commercial deployment. Nonetheless, many of the technologies needed to implement CCS are currently available through other applications.

For example, for post-combustion capture, amine scrubbing has been used for over 60 years for the removal of hydrogen sulphide and $CO_2$ from

33 *A Vision for Cleaner Fossil Power Generation*, Recommendations for a UK carbon abatement programme for fossil power generation 2004, a report from the UK Advanced Power Generation Technology Forum, May 2004.

hydrocarbon gas streams. However, most of this experience is with reducing gas streams (eg taking $CO_2$ out of natural gas) rather than oxygen containing flue gases, and at a smaller scale than for power plant. Similarly most of the technology for the alternative pre-combustion capture has been proven in ammonia production. Also it is operating at utility-scale in the USA at the Great Plains Synfuels Plant[34] where the captured $CO_2$ can be sold across the Canadian border for use in EOR. There is less experience with post-combustion capture based on Oxy-firing (see Annex II for technology descriptions), and consequently more operational questions to be addressed relating to:

- uncertainties over boiler performance
- minimising air ingress to the boiler
- the degree of flue gas clean-up needed before $CO_2$ compression, transport and storage
- corrosion and safety issues with modified boiler operation
- milling and fuel feeding systems that may require changes.

Designs for $CO_2$ capture plant based on current technologies involve substantial capital investment and a significant energy penalty associated with operating the plant and compressing the $CO_2$ for transport and storage. However, many international studies have identified major opportunities for reducing cost and energy consumption both by better integration of existing technologies and through the development of advanced methods.

Novel processes are being developed to avoid the need for an energy intensive air separation unit, which is a main component in current designs of $CO_2$ capture plant based on pre-combustion or Oxy-firing. One example is chemical looping which uses a metal oxidation reaction to separate oxygen, with subsequent reduction of the metal oxide providing the oxygen needed to burn the fossil fuel. Another potential development for low

34 *Carbon dioxide capture and storage*, Report of DTI International Technology Service mission to the USA and Canada, DTI/APGTF, February 2003.

**A post-combustion amine scrubbing plant in Bellingham, Massachusets, USA that can capture 360t $CO_2$/day from a gas turbine exhaust - many of the technologies needed to implement CCS are currently available through other applications (courtesy of Fluor Enterprises Inc).**

energy air separation is ion transport membranes. Similarly, large gains in conversion efficiency could be attained through the incorporation of fuel cells in "triple cycle" systems integrating fuel cells, gas turbines and steam turbines for power generation. With post-combustion capture there is potential to develop advanced amines that could increase solvent efficiency (thus reducing the size of scrubbing plant), reduce degradation and minimise the energy needed for regeneration. Also the energy penalty could be reduced through optimal integration of the capture plant within power station steam systems and by increasing the overall efficiency of the plant with advanced boilers and stream turbines.

The transport of $CO_2$ either by pipeline or by ship is well-established technology but gas storage, particularly over the long timeframes needed to avoid adding to atmospheric greenhouse gas concentrations, is less familiar. Several options for the long-term storage of $CO_2$ in geological formations have been proposed including injection into:

- depleted oil reservoirs (125Gt)
- depleted natural gas fields (800Gt)
- deep saline aquifers (400 to 10,000Gt)
- unmineable coal seams (148Gt).

The values in brackets are estimates of the global storage capacities for each medium that have been made by the IEA Greenhouse Gas R&D Programme[35]. With current world $CO_2$ emissions of about 25Gt per year there is sufficient storage capacity for CCS to play a major role in emissions abatement.

An additional storage option is to inject liquid or solid $CO_2$ into the ocean deeps, but this is not considered an option in this Strategy because of the uncertain environmental impact.

A comparison of the costs of $CO_2$ abatement in electricity supply with CCS compared with other technologies that offer substantial cuts in emissions is given in Table 3.1. The results are derived from the MARKAL technology database for 2010, use a 15% discount rate, and for CCS include the transport and injection of $CO_2$. Results are sensitive to the benchmark power plant assumed to be displaced by the abatement technology, and to the cost of the fuel used for generation. For example, the abatement gained per unit of electricity generated by displacing natural gas technology is less than when coal is displaced, but if the price of coal is low compared with natural gas, then it may be cheaper to replace gas. Consequently, abatement costs are presented for the displacement of both conventional coal and natural gas power plant.

These results should only be considered to be illustrative because they are sensitive to assumptions on operational parameters such as the availability and load factor of the plant and on

**Table 3.1 Comparison of $CO_2$ abatement costs for a range of renewables, fossil fuel and nuclear generation technologies in 2010.[36]**

| Technology | Abatement cost relative to coal (£/tC) | | Abatement cost relative to natural gas (£/tC) | |
|---|---|---|---|---|
| | Low | High | Low | High |
| Onshore wind | (-36) | 72 | (-35) | 167 |
| Offshore wind | 64 | 165 | 152 | 340 |
| Energy crops | 62 | 115 | 138 | 257 |
| Nuclear | 25 | 46 | 51 | 94 |
| Wave | 159 | 343 | 329 | 671 |
| CCS retrofit on CCGT | 14 | 26 | 58 | 108 |
| CCS on new CCGT | 31 | 58 | 87 | 162 |
| CCS retrofit on coal | 38 | 70 | 112 | 208 |
| CCS on new coal | 53 | 127 | 140 | 325 |

its ability to load follow. A full review of the costs of different technologies and carbon abatement policies is being undertaken for the Climate Change Programme Review (CCPR). The indicative results in Table 3.1 suggest that CCS is cost competitive with most renewables technology options (ie offshore wind, energy crops, wave energy). CCS also has costs comparable with nuclear power, particularly when displacing conventional coal-fired plant.

### *Status of CCS technologies*

CCS technologies merit further consideration because these offer the potential for substantial reductions (up to 85%) in the $CO_2$ emissions from fossil fuels. These technologies are generally regarded as medium-term (ie 2020-2030) options because at present policy measures have not been introduced to reward the high level of $CO_2$ reduction they can deliver. However, as discussed above, all of the key components are developed and deployed in other applications and could be brought together within five years if a market demand existed. This is confirmed by the significant niche applications already using CCS technologies.

For capture, the largest established application is the Great Plains Synfuels Plant in North Dakota, USA, which is currently separating 2Mt/yr of $CO_2$

35 IEA Greenhouse Gas R&D Programme Reports - Number PH3/22, February 2000; SR3, June 1994 and PH3/3, August 1998.
36 The low and high values reflect the uncertainties affecting the cost and performance of the technologies and hence their abatement costs.

## Box 1 CAT TRAJECTORIES FOR FOSSIL FUEL POWER PLANT

The UK Advanced Power Generation Technology Forum (APGTF) in its strategic vision for the development of near to zero emission fossil fuel power plant identified two themes or trajectories for a strategic R,D&D Programme for CATs[38]:

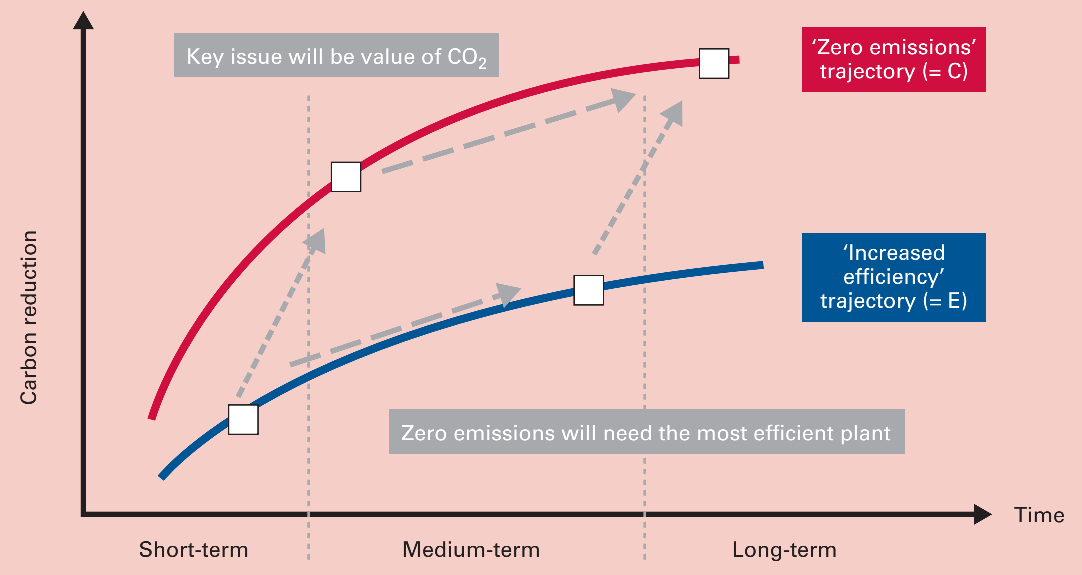
- increasing plant efficiencies
- near-to-zero emission power generation with $CO_2$ capture.

The efficiency part uses efficiency improvements, which reduce emissions themselves, and also offset the impact of $CO_2$ capture on the overall efficiency of the system. The future value of $CO_2$ abatement determines when the switch is made from one trajectory to the other, as shown schematically in the figure below.

**The plant efficiencies trajectory (E)** is a continuation of the existing programmes with which the UK is involved. In the short (2005+) to medium (2010+) terms this trajectory would involve the development and demonstration activities aimed at increasing plant efficiency and the establishment of capture ready designs (those that would facilitate easy and optimal retrofitting of $CO_2$ capture when needed).

**The $CO_2$ capture trajectory (C)** involves the development and demonstration of CCS technologies, involving R&D on optimum capture methods, and demonstration as opportunities arise that placed a significant value on the $CO_2$ captured, such as enhanced oil recovery. Otherwise trajectory C would move to demonstration and commercialisation when the demand for $CO_2$ abatement became sufficiently strong. When this time came the trajectory would draw in the efficiency improvements gained through trajectory E.

This twin trajectory approach for power plant focuses first on the development of capture-ready plant, which delivers benefits over commercial timeframes and is important even where CCS is not adopted.




using pre-combustion methods. This is a commercial operation with the gas being transported through a 330km pipeline to be used for enhanced oil recovery (EOR) in Canada's Weyburn oil field[37]. Also in the USA the Department of Energy has established the FutureGen programme to design and construct a zero emissions coal-fired power and hydrogen plant. The US Government plans to provide 80% of the $1bn estimated cost and the construction stage is expected to start in 2008-2010.

Many natural gas reservoirs produce gas containing significant amounts of $CO_2$, which must be separated in order make the gas marketable. This is carried out by either amine

37 *Carbon dioxide capture and storage*, Report of DTI International Technology Service mission to the USA and Canada, DTI/APGTF, February 2003.
38 *A Vision for Cleaner Fossil Power Generation*, Recommendations for a UK carbon abatement programme for fossil fuel power generation 2004, a report from the UK Advanced Power Generation Technology Forum, May, 2004.

scrubbing or pressure swing adsorption methods with annual throughput for individual plant of about 1Mt $CO_2$/yr. Much of this gas is vented to atmosphere but in recent years some projects have chosen to reinject it for storage. A notable example is the Sleipner Project on the Norwegian continental shelf where 1Mt of $CO_2$ has been injected annually since 1996 into an overlying saline aquifer. The Norwegians are also considering a second project of about the same size for their Snohvit gas field in the northern North Sea. Both of these projects have been encouraged by Norway's carbon emission tax of 315NOK/t $CO_2$. Another recently initiated example is the BP-led In Salah Gas Joint Venture natural gas project in Algeria, where 1.2Mt/yr of $CO_2$ is separated and injected back into the gas-bearing strata[39]. Planning is also underway to separate up to 5Mt of $CO_2$/yr from Australia's Gorgon gas field, which again will be injected for geological storage[40].

Geological storage of $CO_2$ is also well established for normal engineering timescales through the projects mentioned above, and others in the USA where $CO_2$ is used for EOR. In west Texas for example, around 22Mt of $CO_2$ is transported and injected annually into oil fields in the Permian Basin. The key remaining challenge is to establish the integrity of storage over the longer timeframes relevant to climate change. Work has been underway for several years to develop the geological models to describe the transportation and geochemical reactions of $CO_2$ after injection, and to develop the monitoring methods to test and validate these models. Major international collaborative projects are continuing to monitor Sleipner and Weyburn, and similar work is planned for In Salah and Gorgon. Additionally, smaller-scale experimental projects to develop and test geological models are underway or planned in several countries, including Japan, Australia, Germany and The Netherlands. A further line of investigation is the study of natural analogues, naturally occurring geological concentrations of $CO_2$, which can give valuable insights into how the gas can be isolated for thousands of years[41].

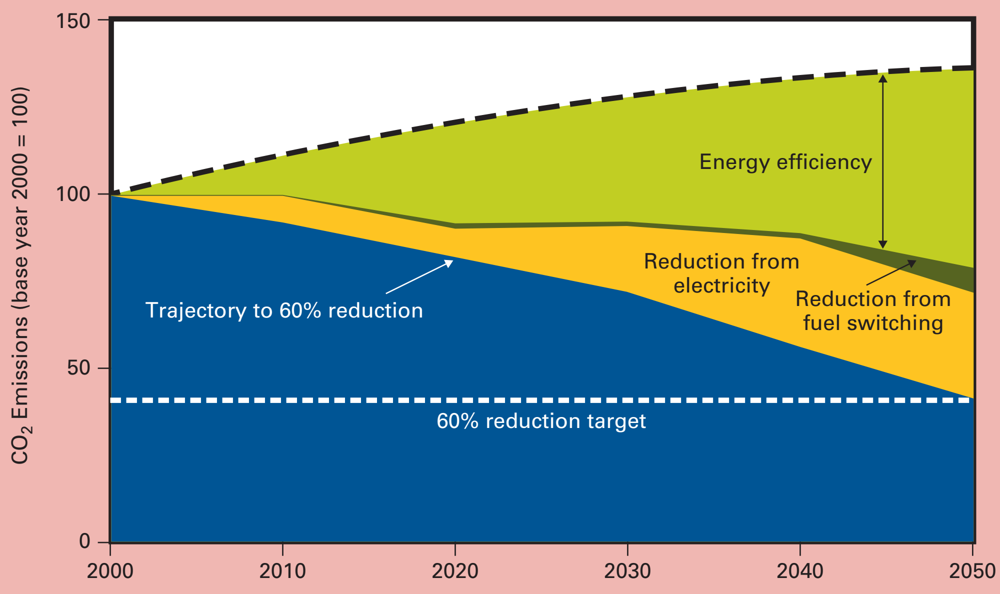
## 3.2 What are the deployment prospects for CATs?

The potential importance of CATs in delivering a lower carbon energy system is illustrated by results from an analysis of the UK's energy system undertaken to advise this Strategy (Figure 3.1)[42]. This shows the increase in $CO_2$ emissions that would occur if the UK economy grows at an average rate of 2.25% per year and the energy intensity of the economy (ie final energy consumption divided by GDP) improves at an annual rate of 1.6%, the rate it achieved between 1990 and 2000. The lower lines in Figure 3.1 show the reductions in $CO_2$ emissions that can be delivered by improvements in end use energy efficiency, fuel switching (excluding the power generation sector) and action to reduce emissions from power generation. The rate of improvement in energy efficiency corresponds to a reduction in energy intensity (ie final energy consumption divided by GDP) averaging about 2.7% per year. This exceeds the 1.6%% per annum improvement achieved between 1990 and 2000, and the 2.1% attained between 1970 and 2000, which was historically high because of the rundown of some energy intensive industries. The main impact from fuel switching in the demand sectors comes after 2040 when hydrogen, produced from natural gas with CCS, begins to be used in substantial quantities for road transport.

The results illustrate the importance of electricity generation and energy efficiency in the attainment of the emissions target. Without a major reduction of emissions from electricity generation the target will be difficult to achieve. Likewise, if the rate of improvement in energy efficiency is less than indicated more will have to be done, and sooner, to reduce emissions from electricity generation or by switching to less carbon-intensive fuels (eg hydrogen in transport,

39 F. Riddiford, I. Wright, C. Bishop, A. Espie and A. Tourqui, *Monitoring Geological Storage - The In Salah Gas $CO_2$ Storage Project,* GHT7, Vancouver, September 2004.
40 *Carbon dioxide capture and storage in Australia - a carbon management technology option,* Report of DTI Global Watch mission to Australia, DTI/APGTF, June 2004.
41 The Nascent Project - Natural analogues for the storage of $CO_2$ in the geological environment: www.bgs.ac.uk/nascent/home.html
42 *The role of fossil fuel carbon abatement technologies (CATs) in a low carbon energy system,* Future Energy Solutions, to be published.

**Figure 3.1 Potential contribution of different energy areas to the attainment of the UK's 60% reduction in $CO_2$ emissions by 2050.**




electricity for space heating). Clearly CATs can contribute to the progressive decarbonisation of electricity generation and are a favoured option for the production of alternative low to zero carbon fuels such as hydrogen.

### *UK deployment*

The supporting analysis for the EWP included an energy systems analysis using the MARKAL model to investigate the technical options for delivering a low carbon energy system[43]. As part of the development of this Strategy MARKAL has been revised with a more detailed representation of CATs for electricity generation and hydrogen production to examine their potential role in reducing UK $CO_2$ emissions[44]. In addition to the existing capital stock the new technologies included:

- Co-firing at existing and new coal plant with up to 10% energy crops.
- Retrofitting pulverised coal plant with advanced boilers and steam turbines.
- New advanced pulverised coal plant.
- Retrofitting coal gasification to an existing gas turbine combined cycle (GTCC).
- New advanced integrated coal gasification combined cycle (IGCC) plant.
- IGCC with combined electricity and hydrogen production.
- Advanced natural gas GTCC plant.
- Hydrogen production from coal and natural gas.

Additionally, the model included the option to fit or retrofit $CO_2$ capture to these technologies and to transport the $CO_2$ by pipeline for storage offshore in depleted oil and natural gas reservoirs and in deep saline aquifers. Options for fitting CCS to other large point sources of $CO_2$ such as steel plant and cement works were not examined in this study, although the technology could be applicable to such plant (Section 2.5).

The modelling study extended to 2050 to examine options for attaining the EWP aim of reducing $CO_2$ emissions by 60% by this time. Clearly there are considerable uncertainties in making such projections, such as the future pattern of UK economic development and the related demand for energy services (eg space

43 *Options for a low carbon future,* DTI Economics Paper No.4, June 2003.
44 *The role of fossil fuel carbon abatement technologies (CATs) in a low carbon energy system,* Future Energy Solutions, to be published.

**Table 3.2 Fuel price assumptions used in the MARKAL model.**

| | | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| **Baseline** | | | | | | | |
| Natural Gas | (p/therm) | 23.0 | 23.0 | 25.5 | 29.7 | 33.0 | 33.0 |
| Coal | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |
| **World Markets** | | | | | | | |
| Natural Gas | (p/therm) | 23.0 | 27.2 | 31.3 | 38.0 | 38.0 | 38.0 |
| Coal | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |
| **Global Sustainability** | | | | | | | |
| Natural Gas | (p/therm) | 23.0 | 24.7 | 28.0 | 33.0 | 34.7 | 36.3 |
| Coal | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |

heating, entertainment, business activity, mobility, etc), social trends and preferences and the trend in the prices of primary energy sources. Consequently, the study used a scenario-based approach to examine a range of possible futures. More detail on these scenario assumptions is given in Annex III, but briefly three sets of scenarios were investigated:

Baseline (BL) - in which the current values of society remain unchanged and policy intervention in support of environmental objectives is pursued in a similar way to now (GDP growth 2.25% per year).

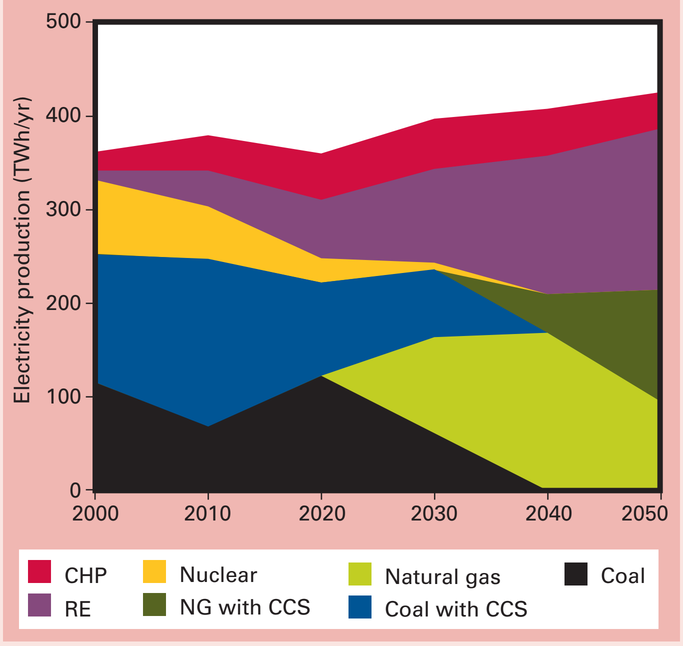
World Markets (WM) - based on individual consumerist values, a high degree of globalisation and scant regard for the global environment (GDP growth 3% per year).

Global Sustainability (GS) - based on the predominance of social and ecological values, strong collective environmental action and globalisation of governance systems (GDP growth 2.25% per year).

Within these scenarios the prices of coal and natural gas delivered to large combustion plant is important in determining the choice of CAT technology. The prices used in the scenarios are listed in Table 3.2. The coal price was assumed to be constant between scenarios and over time reflecting the high level of reserves, the wide range of suppliers and the likelihood that international competition would stabilise long run prices. Natural gas prices were anticipated to increase as global demand continues to expand in all scenarios. Natural gas prices were higher for the Global Sustainability (GS) Scenario compared to the Baseline Scenario (BL) because the greater environmental concern in GS was expected to place a premium on gas.

Results from this study are typified by those shown in Figure 3.2 for one of the BL scenarios, which aimed for a 60% reduction in $CO_2$ emissions by 2050 assuming no additional construction of nuclear power plant. This shows fossil fuels holding roughly 50% of electricity

**Figure 3.2 Results from the MARKAL Model for the Baseline scenario with no new nuclear build showing the mix of fuels used for electricity generation.**



supply up to 2050, with CCS being deployed from 2020, and being applied to all fossil generation by 2040. CCS was also applied to the production of hydrogen from both natural gas and coal, with hydrogen totally replacing petrol and diesel for car and bus transport from 2040. Notably, the other CATs also played an important part in delivering the 60% reduction in $CO_2$:

- Co-firing with energy crops was deployed up to the maximum allowed of 10% in all pulverised coal plant.
- By 2020 15GW of existing pulverised coal plant was retrofitted with advanced $CO_2$ capture-ready boilers, and later these were retrofitted with amine scrubbers to capture $CO_2$.
- IGCC with combined electricity and hydrogen production was deployed after 2020.

Overall, the timing and size of deployment of CATs was sensitive to assumptions on the rate of improvement in energy efficiency in the economy, the rate of economic growth and the availability of new nuclear build. The timing of deployment was also sensitive to rate of reduction of $CO_2$ emissions, which in this study was fixed at 10% in 2010, 20% in 2020, 35% in 2030 and 60% in 2050, all relative to 2000. If a steeper rate of reduction had been adopted, then the deployment of CATs, and particularly CCS, would have been earlier. To investigate these factors a set of scenario combinations (below) was examined:

The deployment of CCS across these scenarios for both electricity generation and hydrogen production is summarised in Figure 3.3. Generally, CCS was first deployed between 2010 and 2020, but for the high energy demand WM scenario deployment was needed by 2010. The level of deployment increased over time and in most scenarios exceeded 100Mt $CO_2$/yr by 2040. Co-firing with energy crops was also deployed in pulverised coal plant, to the maximum of 10% of fuel burn, in all scenarios.

The deployment of CCS was less if new nuclear build occurs, but it was still deployed for electricity generation, and all hydrogen production was still from fossil fuels with $CO_2$ capture. Significantly, the cost of $CO_2$ abatement was only slightly higher without nuclear power (eg 11% in the BL scenario in 2050). This is because the cost of power generation from CCS technologies and nuclear power are similar (see also Table 3.1), and indeed the difference is probably less than the uncertainty applying to the long-term cost and performance estimates input to MARKAL. The load factor of fossil fuel technologies with CCS also differed depending on the deployment of nuclear power. When nuclear build took place the CCS technologies had load factors of 50-60% and the nuclear plant operated on base load. In contrast when there was no new nuclear plant some of the fossil plant operated at base load. It seems that with nuclear power

| | |
|---|---|
| BL-60 | Baseline Scenario – 60% reduction in $CO_2$ by 2050 |
| BL-60NN | Baseline Scenario – 60% reduction in $CO_2$ by 2050, no new nuclear build |
| BL-60EN | Baseline Scenario – 60% reduction in $CO_2$ by 2050, no new nuclear build, limit on improvement in energy efficiency |
| BL-60E | Baseline Scenario – 60% reduction in $CO_2$ by 2050, limit on improvement in energy efficiency[45] |
| GS-60 | Global Sustainability Scenario – 60% reduction in $CO_2$ by 2050 |
| GS-60NN | Global Sustainability Scenario – 60% reduction in $CO_2$ by 2050, no new nuclear build |
| GS-60EN | Global Sustainability Scenario – 60% reduction in $CO_2$ by 2050, no new nuclear build, limit on improvement in energy efficiency |
| WM-60 | World Markets Scenario – 60% reduction in $CO_2$ by 2050 |
| WM-60NN | World Markets Scenario – 60% reduction in $CO_2$ by 2050, no nuclear build |
| WM-60EN | World Markets Scenario – 60% reduction in $CO_2$ by 2050, no new nuclear build, limit on improvement in energy efficiency |

45 In these scenarios the rate of improvement in energy intensity (ie total energy consumption divided by GDP) was limited to the average achieved by the UK between 1990 and 2000, which was 1.6% per year.

CCS technologies are used to back up renewable energy generation, much of which was onshore or offshore wind, and in this sense the two complement each other.

CCS was applied to both coal and natural gas in all scenarios although the balance between these fuels varied depending on relative fuel prices. CCS on natural gas was implemented by retrofitting to capture-ready plant, while with coal this involved a combination of pulverised fuel and IGCC. The pulverised fuel plant were existing facilities that were also refurbished with advanced boilers and steam turbines, while the IGCC was always deployed in cogeneration mode to produce both electricity and hydrogen. Totally new pulverised coal plant were not constructed due to a slightly higher cost compared with IGCC. As for the case of nuclear power this cost difference was small compared with the uncertainty over long-term costs, and certainly does not support choosing winners between pulverised coal and IGCC technologies.

### *International perspective*

The potential significance of CATs as a worldwide option for reducing $CO_2$ emissions can be estimated by considering four options, namely:

- Retrofitting best available technology (eg boilers, steam turbines) to existing plant to bring their efficiency up to modern standards.
- All new build uses best available technology (BAT) with the highest attainable conversion efficiency.
- Biomass co-firing (assumed to be 10%).
- $CO_2$ capture and storage (CCS).

**Figure 3.3 Summary of the scenario results showing the total amount of $CO_2$ capture undertaken between 2000 and 2050.**

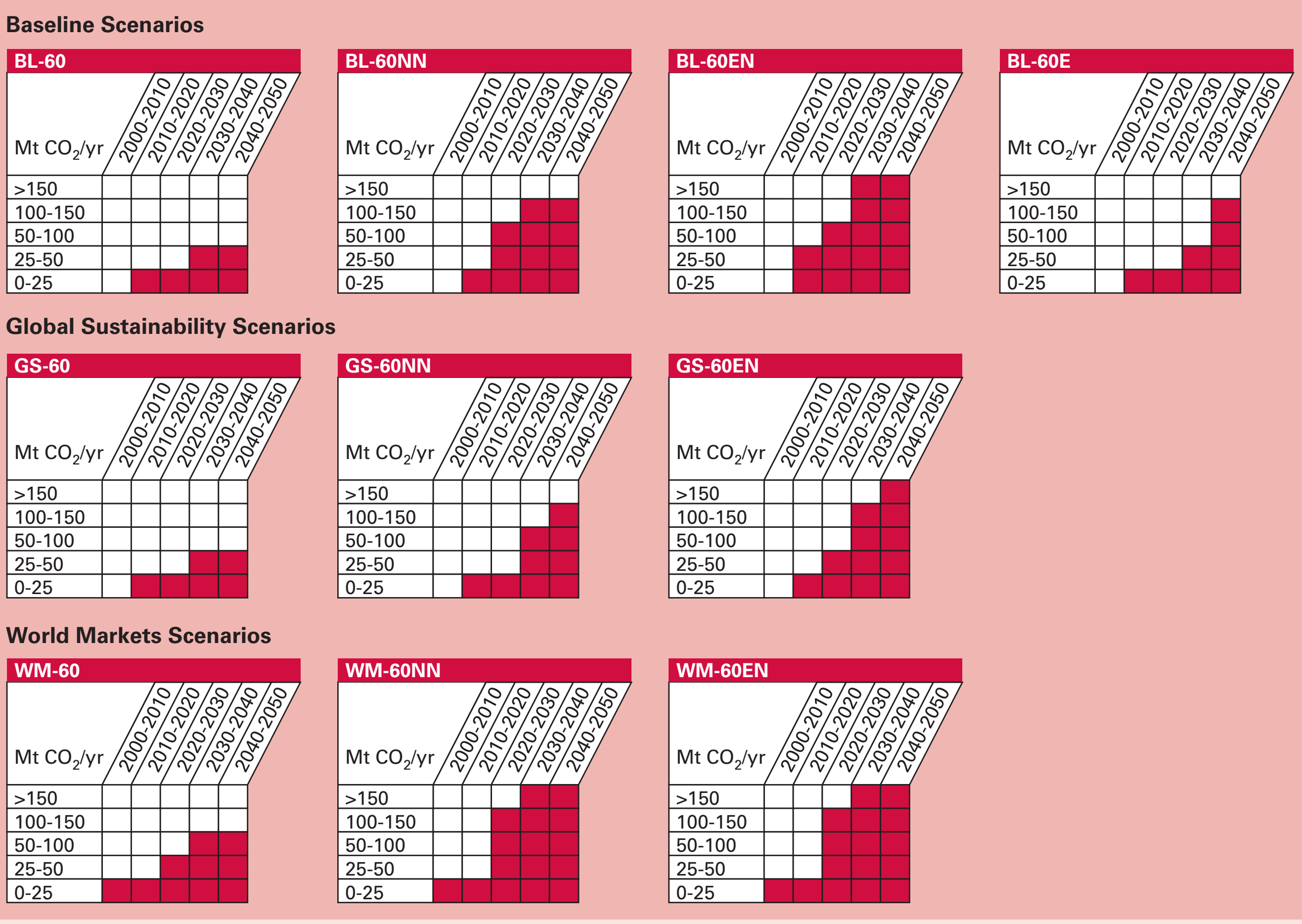


**Table 3.3 Potential reductions in $CO_2$ from different CATs applied to coal-fired power plant in 2020 (Mt $CO_2$/yr).**

| Country/Region | Retrofit[46] | BAT[47] | Co-firing | CCS[48] |
|---|---|---|---|---|
| World | 1176 | 798 | 973 | 6341 |
| OECD | 325 | 274 | 419 | 2948 |
| Developing Countries | 666 | 445 | 490 | 3087 |
| Transition Economies | 184 | 79 | 63 | 306 |
| China | 424 | 316 | 305 | 1877 |
| India | 127 | 86 | 85 | 515 |
| Russia | 120 | 47 | 39 | 176 |

Table 3.3 lists estimates of the potential reductions in $CO_2$ emissions that could be attained by 2020 if these measures were applied to all coal-fired power plant in different world regions and countries. The estimates are based on the projections in the IEA's World Energy Outlook 2004, and give a snapshot picture of what is technically possible.

This simple assessment shows that individual CATs applied to coal alone have the technical potential to reduce $CO_2$ emissions by between approximately 800 and over 6000 Mt $CO_2$/yr by 2020. The greatest reductions come from CCS and represent almost 20% of total projected, energy-related emissions. This is likely to be an overestimate because not all coal power plant may be able to accommodate CCS technology and with others CCS may not be cost effective compared with other abatement options, such as additional end-use energy efficiency or renewable energy. On the other hand, the analysis only considers coal power generation while CATs could also contribute to the abatement of gas- and oil-fired generation, and transport emissions through the production of hydrogen with CCS. In summary, CATs represent a major technical option for $CO_2$ abatement that is applicable worldwide.

International studies of the size and timing for the deployment of CATs have focused on the role of CCS options in a global drive to abate greenhouse gas emissions[49]. In general, these studies have concluded that CCS has a large potential to contribute to abatement with cumulative storage of up to 400Gt $CO_2$ by 2050. However, estimates of when commercial deployment will commence range from as early as 2005 to 2035. This wide range reflects different assumptions on such factors as the growth in energy demand, fossil fuel prices, the progress of other technologies and measures and the targeted reduction in emissions.

The most detailed study so far on CCS technologies and their prospects for deployment has been made by the IEA using its Energy Technology Perspectives (ETP) model. This is an energy systems model similar to the MARKAL model used in the UK. The IEA has used this model to investigate the global deployment of a range of CCS technologies (covering capture, transportation and storage) with the World divided into 15 regions. The basic results were obtained with a Baseline scenario which envisages a future where current trends are continued resulting in a doubling of primary energy demand by 2050. The role of CCS was assessed by imposing a $CO_2$ emission charge on the Baseline scenario. This charge was set for OECD and the Transition Economies at \$10/t $CO_2$ in 2005 increasing to \$50/t $CO_2$ by 2015. The same charges were applied to developing countries from 2015. This charge roughly stabilised $CO_2$ emissions at current levels (ie 23-28Gt $CO_2$/yr) up to 2050, which was about half what the emissions would have been in 2050 without the emission charge. Clearly this is a substantial reduction in potential emissions, but it is not as challenging as the UK's aim of reducing emissions by 60% below the current level, also by 2050.

46 It was assumed that retrofitting would increase the generation efficiency of existing plant to 42.5% from the current national or regional average for these plant. For example, with OECD the current average efficiency is about 36%, therefore an increase to 42.5% would reduce fuel consumption and emissions by about 15%.
47 BAT coal generation plant were assumed to have an efficiency of 45.5%.
48 The energy used for $CO_2$ capture and compression was assumed to reduce generation efficiency by seven percentage points in 2020. No account was taken of any additional energy needed for $CO_2$ injection and storage because this is small compared with the energy used in capture and compression.
49 For example the papers by (1) McFarland J.R.; Herzog H.J. and Reilly (2) Dooley J.J and Wise M.A and (3) Riahi K.; Rubin E.S and Schrattenholzer L. in the proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto, Japan, 2002.

## Box 2 PROSPECTS FOR $CO_2$ CAPTURE AND STORAGE

The IEA was established in 1974 to implement an international energy programme to improve systems for coping with the oil supply disruptions that were being experienced. The Agency aims to promote rational energy and related environmental policies around the world. It achieves this by publishing statistics on energy use along with information and advice on alternative energy sources, energy efficiency and the environmental impacts of energy supply and use.

In December 2004, the IEA published a report on the prospects for CCS[50]. It draws on results from the IEA's newly-developed Energy Technology Perspectives (ETP) model, reported here in Section 3.2. The ETP model belongs to the MARKAL family of bottom-up models, as does the model used by the DTI to analyse future energy scenarios for the UK, also discussed in Section 3.2.

The IEA report reaches a number of important conclusions:

- CCS is a promising emission reduction option with potentially important environmental, economic and energy supply security benefits. It should be considered as an essential "transition technology" to a sustainable energy system over the next 50 to 100 years.
- Large-scale CCS is probably 10 years off, with real potential as an emission mitigation tool from 2030 in developed countries, followed by roll out in developing countries.
- The total cost of CCS could range from 50 US$ to 100 US$ per tonne of $CO_2$, but this could halve by 2030.
- A scenario where global $CO_2$ emissions are stabilised by 2050 would require a cost penalty of 50 US$ per tonne of $CO_2$, with half the total reduction coming from CCS technologies. Capture from coal-fired processes would represent 65% of the total $CO_2$ captured. Without CCS, the cost penalty would need to be doubled to achieve the same emission reduction.
- CCS technologies can co-exist with renewables and nuclear as part of a cost-effective portfolio of options for reducing $CO_2$ emissions.
- RD&D investment into CCS must be accelerated to fully realise its potential and allow it to have a significant impact on emissions in the coming decades. A fivefold increase in current CCS RD&D budgets is needed - implying a 30% increase in the current global RD&D budget for fossil fuels and power technologies. Such investment could be a good "insurance policy" for the future.
- It is not yet possible to pick a "winning" capture technology and more commercial-scale storage pilot projects are needed to better understand and validate the permanence of underground storage.
- The present shortage of sizeable RD&D projects needs to be addressed by governments - by 2015, at least 10 major power plants fitted with capture technology need to be operating.
- Effective emission reduction incentives for CCS, alongside other climate change mitigation technologies, will be needed to achieve market deployment from 2015 onwards.

The United Nations Framework Convention on Climate Change (UNFCCC), at its Seventh Conference of the Parties (COP7) expressed its interest in carbon capture and storage by inviting the IPCC to prepare a Technical Paper on geological carbon storage technologies. Following a workshop on the subject in November 2002 at Regina, Canada, the Panel decided to prepare a Special Report on $CO_2$ Capture and Storage[51] and approved the outline in February 2003. The report is being prepared by IPCC Working Group III and should be completed in the second half of 2005. The Special Report, that will include a summary for policymakers and a technical summary, represents an important step in terms of providing a consensus view of CCS technology and its prospects.

50 *Prospects for $CO_2$ Capture and Storage*, Paris: Organisation for Economic Co-operation and Development/International Energy Agency; ISBN 92-64-108-831; December 2004.
51 See http://arch.rivm.nl/env/int/ipcc/ for more information.

**Figure 3.4 Projected global fuel mix for electricity production with a $CO_2$ emission charge of \$50/t $CO_2$ (©OECD/IEA, 2004[52]).**

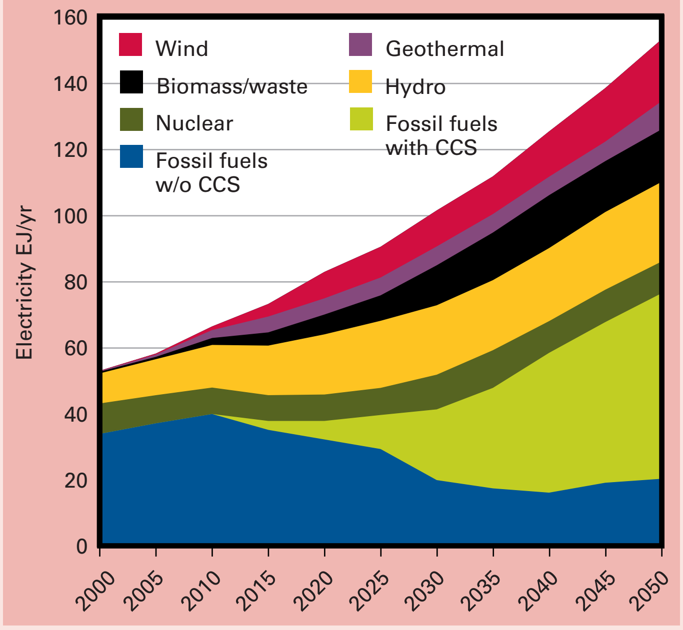



**Figure 3.5 Deployment of CCS technologies by process area (©OECD/IEA, 2004[53]).**

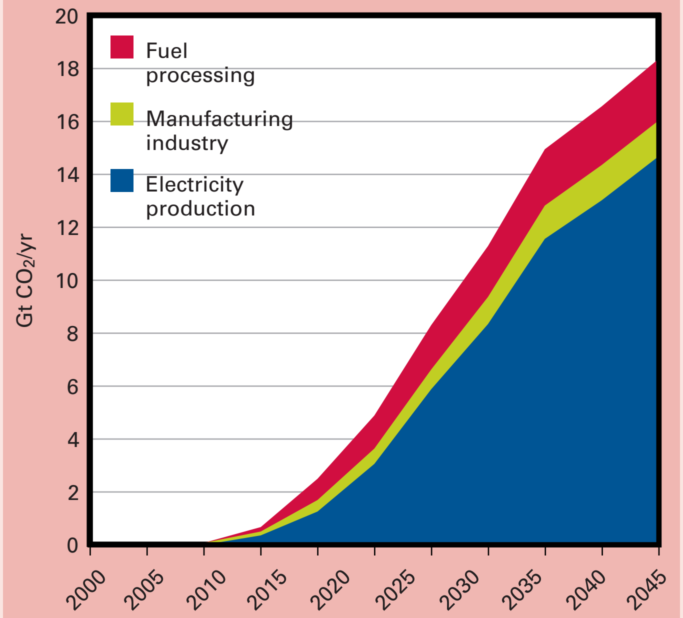



Figure 3.4 shows the breakdown of electricity production by fuel type with the emissions charge. Total demand for electricity was 153EJ (1EJ=$10^{18}$J) in 2050 compared with 148EJ without the emission charge. This is because some demand sectors switched to electricity as a cost effective way of reducing their $CO_2$ emissions. The fossil fuels share of generation fell from 64% in 2000 to 54% in 2050 with renewable sources increasing from 19% to 40%. Around 70% of the electricity generated from fossil fuel came from CCS plant with deployment starting in 2010-2015.

Figure 3.5 shows the overall deployment of CCS. This was predominantly for electricity generation although significant $CO_2$ capture was also undertaken in the manufacturing and fuel processing sectors. The IEA examined the CCS technologies deployed and found that IGCC was the favoured option, particularly when this was used in a dual role for electricity and synthetic fuels production.

The IEA study also found that innovation was important to the successful implementation of these technologies. For example it was found that CCS deployment was reduced by 20% if the more speculative capture options incorporating advanced membranes and fuel cells were excluded from the model.

## 3.3 The $CO_2$ capture-ready option

There is growing interest in developing and building power generation plant that are designed to facilitate later retrofitting of $CO_2$ capture equipment; the capture-ready option. This concept is motivated by the recognition that large investments in new power plant are currently being made and are likely to continue over the next decade, but that at present there are no market or regulatory measures to encourage $CO_2$ capture on these plant. Consequently, decisions could be made that could make the retrofitting of capture plant more costly or even impracticable.

With capture-ready plant decisions would be made to ensure that the later retrofitting of capture technology was relatively easy and entailed minimum cost. These decisions could cover:

- Where possible locating the plant close to suitable sites for the geological storage of $CO_2$.

52 *Prospects for $CO_2$ Capture and Storage (CCS)*, IEA, Paris, December, 2004.
53 $CO_2$ capture with electricity production includes co-production of hydrogen.

- Having enough land within the power plant site to accommodate the capture plant.
- Providing sufficient space within the plant to accommodate the additional pipe-work, valves, etc needed to retrofit capture equipment.
- With post-combustion capture designing the steam cycle for optimal integration of the amine scrubber thus minimising the energy penalty of operating the capture equipment.
- For pre-combustion capture selecting coal gasification technology that integrates with the water-gas shift and $CO_2$ separation plant to minimise efficiency losses.

These measures should involve little additional capital cost if implemented at the design stage.

A further measure with pulverised coal plant would be to add best available flue gas clean-up technology, although this may not be necessary to meet current environmental standards. This would have the benefit of avoiding the later retrofit of such plant, which is needed to prevent degradation of the amine absorbers used for $CO_2$ capture, and which occurs through chemical reaction of the amines with $SO_x$ and $NO_x$ in the flue gases. This measure would be more costly amounting to about £10-15M for a 500MW unit.

## SUMMARY

- CATs provide an option for continuing to enjoy the benefits of fossil energy whilst moving towards a low carbon energy system. CATs should be regarded as transitional technologies that can give a longer period for the transition to an economy based on truly sustainable energy sources.
- CATs cover a range of generic options for reducing the $CO_2$ emissions from fossil fuel combustion. They include:
  - Higher efficiency conversion processes contributing reductions in $CO_2$ emissions of 10-30%.
  - Fuel switching to lower carbon alternatives delivering $CO_2$ emissions reductions of up to 50% when moving from coal to natural gas and 5-10% when substituting biomass for fossil fuel.
  - CCS yielding $CO_2$ emission reductions of up to 85%.
- CCS is the least commercially developed of the CATs because at present there are no policy measures in place that encourage or require the high levels of $CO_2$ abatement that can be delivered by these technologies, and in the absence of such measures, CCS is largely uneconomic. Nonetheless, many of the technologies needed are currently available through other applications.
- There is sufficient geological storage capacity for CCS to make a major contribution to $CO_2$ abatement at the global level.
- $CO_2$ capture from fossil fuels has been implemented at a commercial scale in the USA and further demonstrations are planned. There are also several large-scale, commercial storage projects underway, which are being used as test beds to give assurance of long-term storage integrity.
- CATs can play an important role in delivering the UK's $CO_2$ abatement targets. Studies show their deployment is robust to uncertainties regarding future developments in the UK energy system, although the level of deployment is sensitive to future patterns of economic and social development, primary energy prices and the deployment of other abatement options such as end-use energy efficiency.
- CCS is cost competitive for $CO_2$ abatement with offshore wind, energy crops and wave energy and comparable to nuclear power.
- In most scenarios CCS was needed to abate $CO_2$ emissions from both power generation and hydrogen production with deployment commencing between 2010 and 2020, but in high demand scenarios this advanced to around 2010.
- CCS complements the deployment of renewable energy by providing cost effective back up to intermittent sources such as wind power.
- CATs have the potential to deliver considerable global reductions in $CO_2$ emissions. CCS offers the greatest reduction of up to 6 Gt $CO_2$/yr from coal-fired power generation alone, or almost 20% of all energy-related emissions by 2020.
- The development and deployment of capture-ready designs would ensure that plant being built now would be amenable to the retrofitting of CCS when this was needed. Most features of capture-ready plant would add little to the capital cost of the plant.

# 4. The status of CAT-related industries in the UK

This chapter identifies the UK's industries that would need to be involved in the production and/or operation of CATs, and their capability to contribute and gain benefit from such developments.

## 4.1 The linkage between CATs and UK industries

Although some developments for increased conversion efficiency and co-firing could benefit relatively small-scale plant it is likely that most CAT developments will be focused on large facilities for fossil energy consumption or conversion. This points to power generation and power engineering as being key sectors for the development of CATs, which is undoubtedly true, although the nature of CATs means that other sectors should also have a strong interest in their development. For example, with co-firing the producers and suppliers of energy crops, while with coal gasification most current experience lies with the process engineering and petroleum refining industries. Moreover, CCS will demand an even broader range of capabilities, both for the manufacture of $CO_2$ separation plant and in the selection and operation of geological storage facilities.

Table 4.1 gives a broad, but not necessarily complete, listing of the industry sectors that most need to be engaged in the development and commercialisation of CATs, and how they could be involved.

Also a large range of industries supply key components or services to these broad areas. Examples included advanced materials, pumps and valves, sensors, catalysts, fuel handling equipment, flue gas treatment, specialist chemicals, membranes, etc.

However, the development and commercialisation of CATs will do more then extend the number of industrial sectors involved in the production and operation of large energy plant; it is highly likely that it will stimulate new linkages and working arrangements between these groups. For example, the established practice in the power generation industry has been for a major supplier to contract to design, build and commission a power station, which is then handed over to the generation company. This lead contractor could build all of the plant or subcontract the supply of some parts (eg boilers, steam turbine, fuel handling) to specialist manufacturers. This practice could change if the

**Table 4.1 Industry sectors that need to be involved in the development of CATs.**

| Indstry | Involvement |
|---|---|
| Power plant operators and operators of other large combustion plant (eg iron and steel, refineries, cement works) | Involvement in the development of the technologies to be informed buyers and ultimately through the purchase and operation of CAT plant. |
| Power engineering companies | Development of the technologies and the delivery of plant either through turn key contracts or the supply of major components (eg boilers, gas turbines, steam turbines). |
| Process engineering companies | Design and turn key delivery of power and industrial process plant incorporating CATs. |
| Fossil fuel supply companies | Providing know-how and operating facilities for the utilisation and/or storage of $CO_2$. |
| Offshore engineering and service companies | Design, construction and operation of facilities for the injection of $CO_2$. |
| Electricity and gas shippers | Development and operation of the integrated systems needed to implement CCS. |
| Project developers | Putting together CAT projects including planning, due diligence, finance and project management. |

power generators chose to switch to certain CATs such as coal gasification plant or $CO_2$ capture through flue gas scrubbing or Oxy-firing, all of which incorporate chemical processes that are unfamiliar to the power generation industry. In these circumstances the power generator may look to link up with other organisations that are familiar with the new technologies and arrange to buy in the service. For example, a chemical process or petroleum refinery company could own and operate a coal gasifier linked to an existing GTCC plant with the power generator buying in fuel gas over the fence. Similarly an air separation unit (ASU) providing oxygen to an Oxy-firing power station could be owned and operated by a company specialising in gas separation. This is precisely the model followed by the UK steel industry when switching to Oxy-steel production, which bought in oxygen from ASU plant built at the steel works, but owned and operated by specialist gas suppliers.

## 4.2 Presence of CAT industries in the UK

The UK currently has about 55GW of fossil-fuelled power generation capacity supplying roughly 70% of our electricity. Consequently there is a strong capability in the design and operation of fossil power plant among our generation companies. Furthermore, some of these companies (eg Scottish Power, International Power) have foreign operations, which enable them to be involved in other national R&D programmes as well as having an interest in the development of technology for locations outside the UK. Several of these organisations maintain R&D capabilities in the UK, with links to the equipment suppliers, and are already involved in the development of CATs through DTI's current CCT Programme.

The UK also has several large oil refineries operated by multi-national companies including BP, Shell and Conoco, as well as other large combustion facilities such as iron and steel plant and cement works, all of which could benefit from CATs. The oil companies in particular have recognised that CATs may offer future business development opportunities and are actively involved with their assessment and development. A notable example is the BP-led $CO_2$ Capture Project (CCP), a multi-company and multi-national programme evaluating and developing options for both $CO_2$ capture and storage[54]. This programme has received funding from the EC, US DOE and the Norwegian Government.

**Mitsui Babcock's clean combustion test rig which has been used for development work on Oxy-firing of pulverised coal (courtesy of Mitsui Babcock Energy).**

The UK has long been involved in the development and manufacture of power generation plant, and has a sizeable industry. This includes major suppliers such as ALSTOM Power (turnkey plant, steam turbines, gas turbines) and Mitsui Babcock (an international supplier of boilers), and companies specialising in particular components such as fans, compressors, coal and ash handling equipment, pumps and valves, industrial gas turbines, and many other smaller items. A survey for the DTI[55] identified over 600 companies involved with power engineering and employing around 150,000 staff. As well as

54 See www.co2captureproject.org/overview/overview.htm for more information.
55 *Supply Chain in the UK Fossil Fuel Power Generating Sector*, S Harrison and M Holmes, Mott MacDonald, internal presentation to the DTI, 2002.

supplying the home market these industries have a strong presence in those export markets crucial to CATs, most importantly China and India.

Some CATs lie outside the specialist area of power engineering and incorporate other processes such as gasification, catalytic conversion, hydrogen production, chemical separation and physical separation. This is the province of process engineering specialists that bring expertise in mass and energy integration to optimise plant performance. These organisations undertake the detailed design of process plant and then manage their construction and commissioning, buying in component plant on an international basis from recognised suppliers. The UK has become a world centre for process engineering consultants hosting UK companies and major offices of international firms such as Foster Wheeler, Jacobs, Kellogg Brown and Root, Fluor, Amec and others. Additionally we have strength in air separation technology, which is a key element of several CATs (eg coal gasification, Oxy-firing) through BOC and Air Products.

Fossil fuel suppliers clearly have a strong interest in CATs as an option for retaining fossil fuels in a low carbon economy, at least for a transition period to more sustainable energy resources. However, they also have skills important to the deployment of CATs. Oil and gas producers are major centres of expertise in the geo-physical and geo-chemical techniques needed to identify and operate $CO_2$ storage facilities, and also have experience in the transportation of large volumes of gas. Some oil companies are already engaged with the geological storage of $CO_2$. The longest running example is Statoil's Sleipner Project that injects 1Mt $CO_2$/yr separated from natural gas into a saline aquifer overlying the gas reservoir. More recently the BP-led In Salah Gas Joint Venture has commissioned a similar project based on its In Salah gas field in Algeria. Through the exploitation of North Sea oil and gas the UK is a major centre of operations for many oil and gas companies including BP and Shell. Fuel suppliers are also potential developers/investors in the energy crops and supply chains needed for co-firing.

Oil and gas suppliers are served by a range of companies that provide specialist services in areas such as drilling, reservoir characterisation, petroleum engineering, design and construction of offshore facilities, and supply of specialist chemicals. These companies could fulfil a similar role for the storage of $CO_2$. The UK enjoys a strong presence with these organisations through their involvement in North Sea oil and gas exploration and production.

Companies specialising in the shipping of gas, which in the UK is covered by National Grid Transco, may have a role in establishing and operating the network of pipelines needed to collect and transfer $CO_2$ to the storage site. This is key since the shipping stage will provide an important function in managing and balancing the operation of CCS facilities. Energy shipping companies may also be key players in the development of a hydrogen supply infrastructure.

Finally, the success of CAT projects will depend on the ability to put together projects that meet the objectives of both investors and operators. The UK is particularly strong in all aspects of project brokerage and finance and could take a leading role in setting up CAT projects both in the UK and internationally.

## 4.3 Status of UK CAT industries

The previous section has shown that the UK has a strong presence in all of the main industry sectors that need to be involved in the development and deployment of CATs. This offers a definite opportunity to take a lead in the implementation of these technologies not merely in the UK but in key export markets. Nonetheless, there are two factors affecting these industry sectors that need to be recognised and accommodated by the CAT Strategy:

- Many of the companies are subsidiaries, or are directly controlled by foreign corporations.
- An increasing proportion of manufacturing is being carried out under licence overseas.

***Ownership of UK CAT industries***

Power generation and power engineering has seen substantial changes over the last decade leading to the consolidation of companies and globalisation of their operations. As a result some major UK power generators are now owned by foreign companies, while other UK owned generators have bought into overseas markets. Similarly with power engineering, there are now only two European based turnkey suppliers of power plant, ALSTOM Power and Siemens. These groups have absorbed most European design and manufacturing capacity and operate from facilities located in several countries including the UK where they manufacture and refurbish steam turbines, gas turbines and control equipment. In contrast Rolls-Royce has moved its aeroderivative-industrial gas turbine activities to Canada. Mitsui Babcock, the UK's main boilermaker, is under Japanese ownership. These changes to some extent mirror the oil and gas industry, which is already highly consolidated, and process engineering, which as described above, is led by a number of international consultancies.

In these circumstances it is reasonable to question how the UK will capture the benefits from public funding of R&D into CATs apart from the direct one of fostering appropriate measures to assist in the global stabilisation of greenhouse gas concentrations. The concern is that the international structure and ownership of some key players will mean these benefits accrue to overseas parts of the companies. Of course, there is also the possibility that benefits could flow in the opposite direction.

There is no absolute way of ensuring against benefit leakage, but current experience shows this is not the way these companies operate. For example, ALSTOM Power has doubled the size of its main technology centre at Whetstone over the last five years, employing over 350 scientists and engineers, and maintains a full power plant design capability in Cheshire. Similarly, Mitsui Babcock operates as a fully autonomous subsidiary of Mitsui Engineering and Shipbuilding of Japan with R&D facilities in Renfrew and design offices in Crawley. The wellbeing of these companies depends on the innovation achieved by these technology centres. This trend parallels the established approach of the major oil companies such as BP and Shell that operate research centres in the UK.

***Location of manufacturing activities***

The consolidation of the power engineering sector has led to some rationalisation of manufacturing facilities. For example, the ALSTOM Power and Siemens facilities in the UK are focused on steam turbines, smaller-scale gas turbines and ancillary equipment. The large gas turbines used in GTCC plant are not manufactured in the UK nor are the large gasifiers needed for IGCC plant. This raises the issue of whether the UK should focus on those elements of CATs for which we have established manufacturing capacity.

A second trend in manufacturing, and one that is more significant to the UK's CAT Strategy, is the trend in export markets for the host country to want to maximise local production. This is particularly true in the UK's two main target markets of China and India, where the amount of capacity needed over the next 20-30 years could approach 1000GW and where they are looking to build up their own manufacturing capacity. As a result an increasing proportion of UK exports to these countries comprises technology licensing and support. For example

**The In Salah gas field in Algeria where about 1Mt $CO_2$/yr is separated and reinjected – large-scale storage projects are needed to develop monitoring and verification methods and establish the long-term integrity of $CO_2$ storage (courtesy of In Salah Gas Joint Venture).**

Mitsui Babcock has licensed 14GW of boiler capacity to China over the last 12 months but only 1GW of this will be manufactured in the UK.

This trend will almost certainly continue with CATs. In fact it is only following the pattern now established in process engineering where the main contractor (usually the designer of the plant) buys in the plant components from suppliers in an international market. What this shows is that the UK should aim to gain value from its R&D as much from IPR as from physical manufacture. UK industry will need to concentrate on high added value products, such as innovative designs, specialist components, monitoring and control equipment, software and speciality materials - in short, to build a knowledge-based economy.

Overall, these trends suggest that it is unrealistic for the CAT Strategy to concentrate on trying to establish new products for manufacture in the UK. The dynamics of the power engineering and process engineering sectors is moving towards a global supply base with keen price competition. Value and wealth creation will come from the know-how to develop, design and implement superior CAT systems that match the needs of both the UK and export markets.

## 4.4 Opportunities for new businesses

So far this chapter has concentrated on the established industries that could be involved in CATs. However, there is also the possibility of new production and service companies being established based on the know-how developed in the R&D Programme, particularly for the longer-term deployment of CCS technologies where there is considerable potential for innovation. For example there are requirements for new membranes, chemical absorbers and catalysts to reduce the cost and increase the efficiency of capture plant. Similarly, there is a need for more accurate and lower cost methods for monitoring the performance of geological storage sites for $CO_2$.

The UK is particularly strong in the provision of a broad range of support services and CATs will present another major market for these. In additional to the financial services needed for their implementation CATs will require auditing and verification systems to confirm the delivered reductions in $CO_2$ emissions and to register and trade these reductions in the growing emissions trading market. There will also be a demand for know-how to evaluate and minimise the non-greenhouse gas environmental impacts of CATs, and on how to frame and implement regulatory regimes to control their operation.

The UK has a strong research base in universities in fossil fuel combustion, membranes and catalysis, although at present not much of this work is directed at CATs. Also, the British Geological Survey is an international leader in the study of geological storage of $CO_2$. By working with the Research Councils' Towards a Sustainable Energy Economy (TSEC) Programme. the UK Energy Research Centre (UKERC) and the British Coal Utilisation Research Association (BCURA), the CAT Programme can encourage developments that could form the basis of new spin-off companies. Furthermore, the demonstration projects proposed in this Strategy will give business opportunities to acquire practical experience, both of the technologies and of the service functions needed in their implementation and operation.

## 4.5 What does this mean for a CAT Strategy?

The UK has most, if not all, of the industrial and commercial expertise needed to implement CATs as well as vital physical resources such as the geological capacity to store large quantities of $CO_2$. Moreover, the fact that a significant part of the industry is under overseas ownership should not prevent the UK from gaining full benefit from its publicly funded R&D. Both the power engineering and process engineering industries operate internationally, and the consolidation that has taken place over the last decade has created companies that are increasingly multinational in their outlook.

An important trend is that the main export markets for UK technology are looking to increase the proportion of plant constructed locally through licensing agreements. This trend is likely to extend to CATs and shows that the UK will need to gain benefits from its R&D investments through a combination of licensing and consultancy work combined with the provision of specialist components and services.

This shows that the emphasis in the CAT Programme should be on knowledge acquisition and the development of high value-added components and services. These activities should include participation in bilateral or international collaborative programmes, but only where the aims and targets of the work match UK interests and expertise.

Demonstration in the UK would be directed at those technologies and processes that the UK can exploit. Alternatively, the UK could seek to host an internationally funded demonstration where, again, the UK funds those elements of the project that fit with its own interests and expertise.

## SUMMARY

- The development and implementation of CATs will require the involvement of a large number of business sectors including power engineering, electricity generation, process engineering, fossil fuel supply, offshore engineering, petroleum engineering, geological services and project developers.
- The UK has a strong presence in all of these sectors through UK based multinational oil companies such as BP and Shell, leading engineering companies such as BOC and Rolls-Royce, international equipment manufacturers such as Mitsui Babcock and ALSTOM Power and as a centre for process engineering consultants and financial services.
- The UK is also endowed with the natural resources for the long-term storage of $CO_2$ in our offshore oil and gas fields and in deep saline aquifers.
- There is a strong opportunity for innovation which could establish new products based on membrane technology, specialist chemicals, catalysts, advanced materials and other specialist technologies.
- The lead being shown by the UK for $CO_2$ abatement should be used to establish market opportunities for the deployment of CATs. This will provide the springboard to tackle the much larger markets that will emerge overseas, and particularly in developing countries, as the drive to reduce $CO_2$ emissions gathers pace.
- Some overseas markets will want to manufacture CATs domestically, wherever possible. Therefore, UK industry needs to gain added value from its investment by focusing on consultancy and licensing together with the production of specialist components.

# 5. Opportunities and constraints

So far the Strategy has shown how fossil fuels are set to remain the main source of world energy supplies, at least to 2050 and quite probably beyond, and therefore CATs will be needed if effective global action is to be taken to reduce greenhouse gas emissions. It has also been shown that the UK has a strong industrial base for the development and commercialisation of CATs. However, experience shows that having a large prospective market and the industries to exploit that market may not be sufficient to ensure success; there have to be other factors to encourage the new technology. This chapter examines the opportunities available to the UK to take an active worldwide lead in the development of CATs. It also addresses the non-technical factors that could constrain the deployment of CATs both in the UK and internationally.

## 5.1 Opportunities for the UK

The EWP aim of reducing UK $CO_2$ emissions by 60% by 2050 is designed to give a worldwide lead on climate change, and is the cornerstone for encouraging UK business interest in CATs. It could be argued that the UK should stand back from the development of CATs, and simply buy these in as and when they are needed. However, this would lose the first developer/user advantages, which could give UK industry a strong position in the market for these technologies. Moreover, it would also waste a number of business and resource advantages that the UK holds on CATs. In particular the UK has:

- A strong business capability with CATs, not only in their manufacture, but also in the areas of design/development and project development/finance relevant to the knowledge economy.
- Considerable capital stock of coal and nuclear power plant that will need to be refurbished or replaced over the coming decade. This represents an opportunity to invest in CATs.
- Geological formations well suited for long-term storage of $CO_2$ making the UK an ideal location to demonstrate the complete chain of CCS technologies.
- Strong capabilities in the offshore engineering, oil and gas extraction and geological sciences needed to appraise, operate and monitor $CO_2$ storage sites.
- An existing infrastructure to support offshore $CO_2$ storage operations stemming from North Sea oil and gas extraction.
- The potential to use $CO_2$ for enhanced oil recovery on maturing oil fields in the North Sea, which would give some financial return to partially offset the cost of capture and transportation, and the $CO_2$ would be retained in storage.
- UK industry is well established as a supplier to key markets such as China where fossil fuel demand is growing and CATs will be needed to reduce $CO_2$ emissions.

Together, these attributes give the UK the opportunity to lead from innovative development to full-scale deployment of CATs. Specifically the combination of capabilities in combustion plant, oil and gas recovery and geological storage, combined with access to offshore storage sites places the UK in a strong position to host a full-scale demonstration of CCS. This

**Co-firing operations at E.ON UK's Kingsnorth power station (courtesy of E.ON UK).**

could be used to showcase the best of UK technology, attract developers of leading-edge technologies to the UK and give UK service businesses first hand experience of implementing and managing CCS technologies.

## 5.2 Enhanced oil recovery (EOR)

The use of $CO_2$ for EOR in the North Sea has attracted special interest as a storage option for $CO_2$ in the UK and merits further discussion. The advantages of $CO_2$-based EOR are:

- It offers some financial return from the additional oil recovered that will partially offset the cost of $CO_2$ capture and transportation.
- Injection of $CO_2$ for EOR is not prohibited under the London and OSPAR treaties which govern the dumping of matter into the sea or the underlying seabed.
- In contrast, the injection of $CO_2$ under the seabed for pure storage is more restricted under the London and OSPAR treaties, which preclude the use of existing oil and gas production platforms as well as vessels for this purpose.
- There is a limited time before North Sea oil fields are decommissioned, which gives greater urgency for the implementation of EOR.

Oil producers were consulted in autumn 2003 on the feasibility and merits of implementing a demonstration project of $CO_2$ EOR, in response to an action in the EWP. This showed that EOR was not commercially viable at the test oil prices applied by producers. Furthermore, it was found that the likely value placed on $CO_2$ storage through the EU-ETS, the only mechanism that could be available to CCS to reward $CO_2$ abatement, would not be sufficient to bridge the financial gap. It is understood that these relatively low test oil prices have not changed significantly although market oil prices have increased substantially in the last 12 months. This is because the companies need to take a long-term view, and also a comparatively low test price is reasonable for appraising competing investment opportunities when capital is limited.

The outcome of the EOR implementation study prompted suggestions that $CO_2$ EOR should be encouraged through adjustments to the tax system applied to North Sea oil production. This view was repeated by several respondents to the CAT Consultation and justified for two reasons:

- It would increase the extraction of oil from UK continental shelf resources yielding more revenue, securing jobs and increasing the UK's security of oil supplies.
- It would be a convenient measure to stimulate full-scale deployment of CCS.

Changes to the North Sea tax regime go beyond a CAT Strategy and would need to be considered against the broader background of all possible approaches for extracting additional oil and the technical and commercial barriers affecting their deployment. The PILOT[56] initiative has set up a brown fields think tank, to address barriers to further development of mature oilfields, and this is a more appropriate forum for government-industry dialogue on this issue.

The CAT Strategy does, however, take note of the need to consider other, more direct mechanisms for encouraging the deployment of CCS technologies, which clearly will include EOR.

## 5.3 Constraints

There is a range of constraints that currently affect the deployment of CATs and which need to be addressed by a CAT Strategy. These can be roughly divided into financial constraints and regulatory constraints.

### *Financial constraints*

Three key factors have been identified that could act as barriers to investment in CATs:

- Lack of experience with the EU-ETS.
- Uncertainties over the implementation of market-based instruments.

56 PILOT is a joint government/industry initiative for the exchange of data and experience in oil and gas operations on the UK continental shelf with the aim of reducing costs and improving the availability of North Sea facilities.

- New commercial relationships between producers, shippers and those who commit the $CO_2$ to long-term storage.

*Lack of experience with the EU-ETS*

The EU-ETS is the main market based instrument aimed at facilitating greenhouse gas abatement across the EU, and therefore will have growing significance in rewarding investment in CATs. However, although CCS is not ruled out for the present phase of the scheme, no protocols for its inclusion are agreed (see monitoring and verification below), and potential investors have no experience of the scheme, and are uncertain on how it will be introduced in other EU member states and how its implementation will be monitored and verified. Consequently they are likely to hold back from capital intensive investments such as CATs until they have more confidence in the scheme.

*Uncertainties over the implementation of market-based instruments*

This is linked to uncertainty over the treatment of CATs within the market based instruments being introduced to encourage $CO_2$ abatement. Presently this applies mainly to the EU-ETS but could also apply to the other Flexible Mechanisms under the Kyoto Protocol.

Under the EU-ETS the initial allocation of permits for the emission of greenhouse gases is done through a system in which combustion plants receive an allocation based on their previous emissions. This allocation is nearing completion for the first, three-year period of the ETS. There is uncertainty concerning allocations for subsequent, five-year periods after investments have been made. For example, if a power generator invests in retrofitting a more efficient supercritical boiler, thus reducing $CO_2$ emissions, will the plant's permit allocation be reduced in the next phase of the ETS? On one hand it could be argued that this is a normal business decision, with no additionality in $CO_2$ abatement since the investment would have been made in any case, and therefore should not be rewarded through the ETS. Yet again, the continued allocation of more permits to a plant that is not retrofitted could be considered to be a disincentive to investment in CATs and hence in $CO_2$ abatement.

This same question of permit allocation will affect other CATs such as co-firing and CCS and needs to be resolved.

*New commercial relationships*

This constraint mainly affects CCS for which deployment of the chain of technologies for capture, transportation and storage will involve new contractual and working relationships between the operators of large combustion and process plant, gas transporters and offshore operators. This will involve arrangements for sharing operating and financial risks between organisations that may not be familiar with working together.

***Regulatory constraints***

Regulatory constraints mainly affect CCS and are typical of any technological paradigm shift:

- Legal and regulatory regimes.
- Monitoring and verification.
- Long-term ownership of stored $CO_2$.
- Planning and authorisation.

*Legal and regulatory regimes*

Most of the UK's resources for storing $CO_2$ in geological formations are located offshore. Injection into such repositories is governed by three treaties designed to protect the marine environment from the dumping of matter. These are the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters 1972 (the London Convention), the 1996 Protocol to that convention, and the Convention for the Protection of the Marine Environment of the North East Atlantic 1992 (the OSPAR Convention). The 1996 Protocol will supersede the London Convention between those Parties that ratify the Protocol, but it is not yet in force.

However, the UK has ratified the Protocol, and UK policy is to apply its requirements. In order to meet its international obligations the UK would seek to adhere to whichever of these treaties was the most stringent.

Over the last year the UK has taken a lead in considering the position of $CO_2$ storage under these treaties, and the generally accepted view that has emerged is that:

- It is arguable that geological storage of $CO_2$ is not affected by the original 1972 London Convention on the grounds that it only addresses the water column.
- $CO_2$ storage through EOR is allowed under OSPAR and the 1996 Protocol since both permit "placement of matter for a purpose other than mere disposal".
- Injection of $CO_2$ into the sea bed from offshore oil and gas installations purely for storage would be regarded as disposal and therefore in general would not be permitted under OSPAR or the 1996 Protocol[57].
- OSPAR does not prohibit injection of $CO_2$ from platforms that have been purpose built to take gas from a pipeline emanating from land and apply a pressure boost before injection.
- The 1996 Protocol does not prohibit storage in a seabed repository accessible only from land, which would appear to leave open the option of direct injection through a pipeline.

While this provides options for $CO_2$ injection to go ahead it does restrict operations in ways that may not be of benefit to the environment as a whole. Indeed it is quite clear that the treaties were not designed with $CO_2$ emissions and the potential need for $CO_2$ injection in mind. For example the treaties do not cover the harmful effects on the marine environment of increased atmospheric concentrations of $CO_2$ through ocean acidification. Consequently it is important to achieve agreement amongst the contracting parties to the OSPAR and London treaties both to consider amendments to cover $CO_2$ storage and to develop common regimes for the authorisation and regulation of CCS activities. The UK government has already begun this process.

It will be necessary to assess the full energy and environmental costs and benefits associated with the options to be explored to ensure negative consequences are identified and adequately mitigated.

### *Monitoring and verification*

Market-based instruments such as the EU-ETS require monitoring and verification procedures to ensure that contracting parties give accurate declarations of their emissions in relation to their holding of emissions permits. For combustion plant standard procedures have been established for this that are based either on the quantity of fuel burned or direct monitoring of the flue gases. These arrangements conform with the needs of CATs with the exception of CCS where additional measures are needed to cover accounting for potential leakage of $CO_2$ during transport and injection and also any seepage during storage.

The UK has taken forward the development of such monitoring and verification procedures through its chairmanship of an ad hoc group of EU Member States that has been established in collaboration with the EC to develop draft guidelines. A study report on key issues with suggestions on how these should be managed has been published recently[58] and further work is underway to draft a monitoring and verification protocol. The UK is also closely involved in the development of emissions inventory guidelines that will enable the CCS installations to be included in national greenhouse gas inventories. These should be agreed in 2006.

57 The injection of $CO_2$ undertaken in Norway's Sleipner project is not prohibited under OSPAR or the 1996 Protocol because it is undertaken as part of a hydrocarbon extraction processes and therefore is "placement of matter other than for mere disposal".

58 *Developing monitoring reporting andverification guidelines for $CO_2$ capture and storage under the EU-ETS*, (DTI Report URN 05/583), January 2005. (www.dti.gov.uk/energy/coal/cfft).

### *Long-term ownership of stored $CO_2$*

$CO_2$ injected into geological formations will be at pressures of around 60-100 bar[60], and although it will be gradually dissolved in groundwater and ultimately be immobilised by mineralisation reactions, the potential for leakage will persist for several centuries. This raises the question of the long-term ownership of the storage site and the organisation responsible for taking remedial measures should leakage occur.

It has been proposed that ownership should be transferred from the operating company to the state after an agreed period. One such option is for the transfer to take place when the site has been filled and sealed and is being left for long term monitoring. It is argued that this is necessary because commercial organisations have finite lives, and in any case there is a need to define the duration of commercial responsibility. In principle this could be an acceptable way forward, provided the transfer of ownership did not distort the market for other $CO_2$ abatement options. Any such arrangement would need to take account of arrangements managing other long-term liabilities.

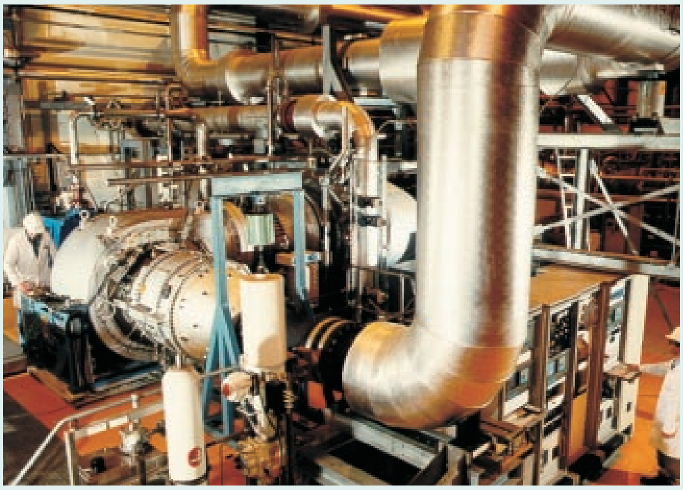
### *Planning and authorisation*

The processes for gaining planning permission and authorisation to operate industrial plant both onshore and offshore in the UK are well established, and are full and complete for most CATs. However, CCS raises new issues in relation to the authorisation of storage sites. As indicated above such a system will be needed to satisfy OSPAR and London Convention requirements as well as the UK's domestic concerns. In particular, standards will be needed to guide the selection of suitable geological storage formations and locations to minimise the risk of leakage. Also standards will be needed to

59 The bar is a unit of pressure equal to 105pascals, standard atmospheric pressure is about 1.01bar.

60 *Gap Analysis for Regulations Relevant to Carbon Dioxide Capture and Storage in the UK*, T Dixon (DTI) and M Anderson (Environment Agency), DTI internal document to CSLF Task Force on Legal, Regulatory and Finance, June 2004, and *Considerations of Regulatory Issues for Carbon Capture and Storage projects*, CSLF LRF Task Force Report to CSLF Ministerial Meeting, Melbourne, September 2004.

**ALSTOM Power's gas turbine aerodynamics test rig located at the Whittle Test Centre, Whetstone, UK (courtesy of ALSTOM Power Ltd).**



regulate the operation of a storage site, for example to ensure that it is operated and sealed in a way that does not reduce its integrity.

The UK has initiated work in this area through a gap analysis of existing regulatory systems[60]. This is to be followed up with the establishment of a working group of regulatory agencies, led by the DTI, to examine how to develop any additional systems.

### ***Public perception***

Public perception is included here to acknowledge that the future CAT Strategy needs to include actions to raise public awareness of the issues and why CATs are important. There is a role for Government in bringing together technology developers and users with external stakeholders including local government, the regulatory authorities, national and regional media and non-governmental organisations (NGOs). Dialogue with stakeholders should include exchange of information on progress with the technologies, the increasing knowledge base on the benefits and impacts of CATs and views on the location and options for their deployment.

## 5.4 Capture-ready plant

The constraints discussed above mean that CCS will only be deployed in the near term through niche opportunities. However, it has been shown in Chapter 2 that a large amount of new capacity for power generation and other energy conversion processes will be ordered and built over the next 10 years. For example in India and China alone new generation capacity approaching 200GW is expected to be commissioned by 2010. This new plant will have operating lifetimes of 40-60 years and will have major implications for future actions to reduce $CO_2$ emissions.

While it is unrealistic under current market conditions to expect most plant being built in the next 5-10 years to be fitted with $CO_2$ capture equipment it is important to have the option of retrofitting this technology. This has stimulated the proposal for capture-ready designs that would ensure the optimal performance of retrofitted capture technology (Section 3.3).

The demonstration of this capture-ready concept in the UK would deliver two benefits:

- It would help the UK to demonstrate the benefits to other countries, and in particular those developing countries planning large expansions in fossil power generation capacity, and thereby persuade them to order plant designed to be capture-ready.
- It would strengthen the position of UK industry to offer capture-ready designs to both its UK and export customers.

## SUMMARY

- The UK has a number of advantages that put it in a strong position to lead in the development of CATs and to gain large commercial and social benefits from their deployment. These advantages include:
  - the UK Government's commitment to give a world lead on $CO_2$ abatement should create an early domestic market for CATs
  - a strong industrial base to develop and manufacture CATs
  - a near-term market opportunity from the approaching need to replace or refurbish a large part of the UK's coal and nuclear power generation capacity
  - geological formations for long-term storage of $CO_2$ making the UK an ideal location to demonstrate CCS
  - strong capabilities in the offshore engineering, oil and gas extraction and geological sciences needed to appraise, operate and monitor $CO_2$ storage sites
  - an existing infrastructure to support offshore $CO_2$ storage operations stemming from North Sea oil and gas extraction
  - the potential to use $CO_2$ for EOR, which would give some financial return to partially offset the cost of CCS
  - UK industry is well established as a supplier to key markets such as China where fossil fuel demand is growing and CATs will be needed to reduce $CO_2$ emissions.
- The deployment of CATs, and in particular CCS, is affected by a range of financial and regulatory factors including:

Financial:

  - lack of experience with the EU Emissions Trading Scheme
  - uncertainties over the implementation of market based instruments
  - new commercial relationships between producers, shippers and those who commit the $CO_2$ to long-term storage.

Regulation:

  - legal and regulatory regimes
  - monitoring and verification
  - long-term ownership of stored $CO_2$
  - planning and authorisation.

- The future CAT Strategy needs to include actions to raise public awareness of the issues and why CATs are important.
- Capture-ready designs are mainly about configuration and should add only a small additional cost to new plant whilst significantly reducing the cost of retrofitting $CO_2$ capture equipment. The UK should support a demonstration of this concept to encourage its adoption worldwide and to help UK manufacturers offer such plant to both UK and export markets.

# 6. Rationale and objectives for a CAT Strategy

This chapter considers the rationale for Government support for the development of CATs, the objectives of the Strategy and the actions and scope of the support needed to deliver an effective CAT Programme.

## 6.1 Rationale for DTI support for CATs

Preceding sections have shown how CATs could make a substantial contribution both to the EWP $CO_2$ reduction targets and to potential actions on global $CO_2$ abatement to be taken through the G8. However, this alone need not justify UK Government support for CAT innovation. Like other governments around the world the UK Government provides support for technology innovation where private organisations may under-invest in R&D because of market or system failures[61]. There are a number of such factors that motivate and justify such support for CATs[62]:

- The failure of the market to fully value the abatement of $CO_2$ emissions.
- The spillover of benefits to international competitors.
- Barriers to effective collaboration across industrial sectors.
- Regulatory uncertainty.

### *Market failure*

Market-based measures to reward the abatement of $CO_2$ emissions are currently in their infancy with the EU-ETS having started on 1 January 2005. Initially, under this scheme permits are likely to trade at a price that does not fully reflect the social cost of climate change. UK measures such as the Renewables Obligation for electricity supply and the Climate Change Levy (CCL) exemption for good quality CHP do not extend to CATs. Consequently, there is no mechanism fully to reward the benefits to be gained from CATs and this is a disincentive to investment in their development.

61 *Competing in the Global Economy: the Innovation Challenge*, DTI, December 2003 (www.dti.gov.uk/innovationreport).

62 *The Green Book, Appraisal and Evaluation in Central Government*, Annex I, pp. 51-52, HM Treasury.

Strengthening the market instruments will take time and will require international agreement. Therefore, in the meantime, more targeted support for CATs is needed.

### *Spillover of benefits*

The energy industries are international in nature and most CAT developments will have international markets. In these circumstances some of the knowledge gained through R&D in one organisation will inevitably spillover such that other organisations gain part of the benefits. Indeed with developing countries being a key target for CATs such spillover should be desirable. Spillover is a particular issue because of the likely long-term nature of the CAT market, particularly where CCS is an option. In these circumstances firms will be reluctant to risk their own financial resources on R&D.

### *Barriers to effective co-ordination*

Capturing the full benefit of CATs will require collaboration and co-ordination between a broad range of commercial organisations including power engineering, process engineering, power generation, oil and gas production, petroleum engineering, materials and specialist chemicals manufacture, chemical engineering and others. These organisations will range from large international companies to SMEs formed by spin-offs from research organisations and universities. Government support may be required to foster the establishment of joint programmes among such organisations.

### *Regulatory uncertainty*

Many CAT opportunities are currently regarded as high risk by commercial organisations. This is due in part to the market failure described above, but is also linked to a range of regulatory, legal, political and social uncertainties. One near-term example is the uncertainty over the treatment of co-firing options within the Renewables Obligation from 2015. Another is the treatment of retrofit options to improve power generation efficiency within the EU-ETS.

However, it is with the longer term CCS technologies that the greatest uncertainty exists. This is linked to a number of factors including:

- The lack of agreed regulations and standards for the licensing of $CO_2$ storage sites.
- The treatment of long-term ownership and liabilities for $CO_2$ storage.
- The legality of $CO_2$ storage under national and international laws governing waste management.
- The need to win political support and social acceptance for CCS.
- Political decisions on alternative technologies such as nuclear power.

The UK is already taking a leading role to resolve many of these issues, for example by promoting discussions within the London and OSPAR Treaty organisations on their treatment of $CO_2$ storage beneath the sea bed and with the EC on the verification and monitoring of CCS within the EU-ETS and with IPCC to develop relevant emission inventory methodologies. However, these processes are necessarily detailed and will take time.

## 6.2 Objectives of the Strategy

The key messages to be drawn from the preceding chapters that justify a CAT innovation programme and direct its broad approach are:

- There is agreement amongst forecasts that fossil fuels will continue to meet most of the world's energy requirement at least to 2050 (eg IEA[63] estimates over 80% in 2030).
- With such a dependence on fossil fuels large-scale deployment of CATs is needed to reduce $CO_2$ emissions. In particular CCS will be needed to deliver the large cuts in emissions required to stabilise atmospheric greenhouse gas concentrations and thereby limit climate change.
- Natural gas and coal will be the main fuels used in the large combustion plants to which CATs can most readily be applied, with coal the first choice in North American and key developing countries (eg China and India) and gas the first choice in Europe and some transition economies. Therefore CATs need to be available for both gas and coal combustion. Fortunately many of the options for innovation can benefit both fuels.
- By helping to retain coal in the energy mix, CCS strengthens the security and diversity of energy supplies.
- There is strong synergy in the development of CATs. For example near-term development of capture-ready designs incorporating advanced high efficiency technology is an essential step towards the longer-term deployment of CCS through both retrofit and new build. Beyond this, biomass co-firing can further reduce $CO_2$ emissions from existing and new plant.
- The UK has a strong base in the technical know-how, business capabilities and natural resources needed to lead in the development of CCS.
- Taking a lead in the development of CATs is consistent with the EWP's aim for the UK to show international leadership on climate change mitigation measures, and this is reinforced by the UK giving priority to climate change during its presidency of the G8.
- Leading on the development of CATs offers substantial advantages in the commercialisation of these technologies both in the UK and export markets.
- CATs have been recognised internationally to have the potential to make a major contribution to the abatement of energy related $CO_2$ emissions, therefore UK initiatives should seek international involvement while the UK should seek to be involved in leading overseas activities.
- The market mechanisms needed to reward $CO_2$ abatement are only just developing and at present do not return the full economic and social value of the abatement achieved.

63 *World Energy Outlook 2004*, IEA, Paris, November 2004.

- There is a range of financial and regulatory uncertainties needing resolution that currently make some CATs, and particularly CCS, a high-risk investment.
- The environmental impact of CATs needs to be examined to avoid or mitigate potential negative impacts.
- There is a need to raise public awareness of the potential role of CCS in tackling climate change and to address any concerns this may raise.

Guided by the above factors it has been concluded that the overall objective of the CAT Strategy should be:

> ***To ensure the UK takes a leading role in the development and commercialisation of carbon abatement technologies that can make a significant and affordable reduction in $CO_2$ emissions from fossil fuel use.***

## 6.3 Actions

To deliver the above objective a portfolio of Government-supported actions is needed that should include:

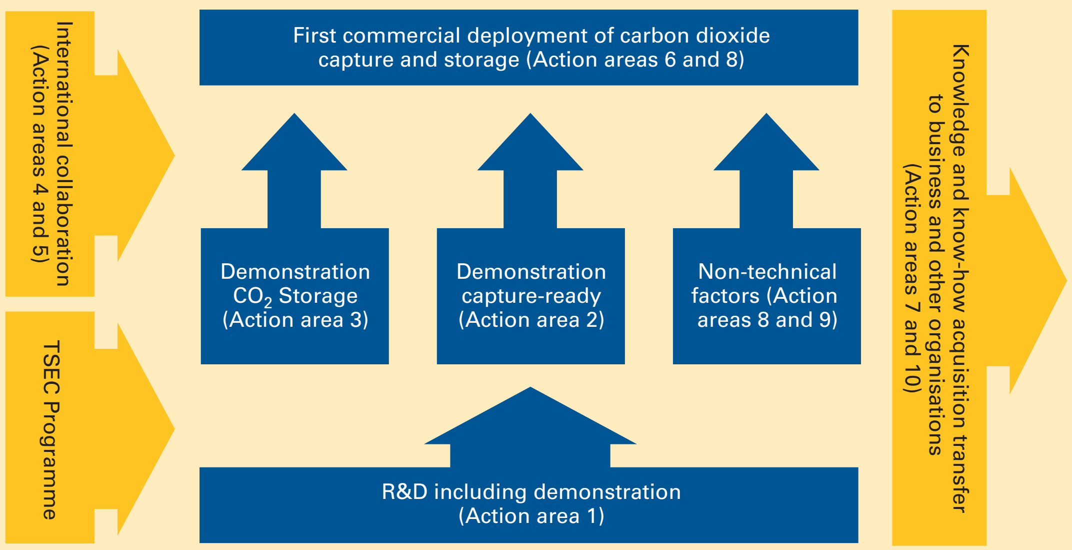
| Action | Purpose |
|---|---|
| 1. Support research, development and demonstration of CATs. | To develop and demonstrate advanced CAT designs and equipment with reduced costs and improved performance. |
| 2. Support the demonstration of $CO_2$ capture-ready plant. | To showcase these technologies and plant concepts thereby encouraging their commercial deployment worldwide and establishing UK industry as a leading supplier of know-how and specialist capture equipment. |
| 3. Support the demonstration of $CO_2$ storage. | To establish the frameworks for authorising and licensing storage sites, to demonstrate their long-term integrity and to build public confidence in CCS as a $CO_2$ abatement option. |
| 4. Facilitate international collaboration in UK-based CAT development and demonstration projects. | To cost share in the demonstration of CATs and to attract developers of leading-edge technologies to the UK. |
| 5. Facilitate and support UK collaboration in CAT development and demonstration projects based in other countries. | To enable UK business to gain from involvement in the best and most relevant overseas developments. |
| 6. Within the Climate Change Programme Review examine possible measures to encourage the initial commercial deployment of CCS technologies in the UK. | To examine the cost and market implications of alternative measures to encourage full-scale commercial deployment of CCS. |
| 7. Facilitate the acquisition and transfer of knowledge and know-how stemming from CAT innovation both in the UK and abroad to businesses and other organisations involved with their commercialisation. | To help push forward the boundaries of knowledge about CATs and assist UK business to gain maximum benefit from the provision of equipment and services that allow significant $CO_2$ emission reductions to be made, particularly in developing countries. |
| 8. Lead in preparing the national and international regulatory frameworks and market mechanisms needed to support CATs. | To ensure that the commercial deployment of CATs is not impeded by legal uncertainty or inappropriate systems. |
| 9. Increase public awareness and stimulate an informed debate on the role of CATs in mitigating climate change. | To give decision makers and the general public the information they needed to assess CATs against other greenhouse gas abatement options. |
| 10. Develop and maintain a route map for the development of CATs in the UK. | To give a more detailed framework to guide the day to day implementation of the UK's CAT Programme and measure progress. |

The relationship and linkages between these actions is illustrated in Figure 6.1. This shows the action areas building towards the ultimate goal of the commercial deployment of CCS. However, as discussed in Chapter 3, the other aspects of CATs, increased efficiency and co-firing, are complementary to this goal, and R&D in these areas will deliver useful benefits along the way. For example, a key theme for R&D will be improved efficiency in fossil fuel combustion and conversion (eg to electricity), and the demonstration of capture-ready plant (Action 2) will need to be based on an advanced high efficiency design. Improvements in efficiency will themselves deliver useful reductions in $CO_2$ emissions and will enable UK equipment suppliers to offer the best available technology to key growth markets such as China and India. Similarly, co-firing of biomass in advanced combustion plant offers an immediate reduction in $CO_2$ emissions, and when used with CCS will give even higher net reductions in $CO_2$ emissions than when CCS is applied to plant fuelled only with fossil fuels.

Like the previous CCT Programme the CAT Programme is intended to be industry-led, with commercial organisations being invited to bid for Government support to undertake projects, possibly in collaboration with universities and other R&D organisations. Therefore implementation of the above actions will depend on the willingness of industry to commit resources to the necessary work. Calls for proposals will be broadly specified to enable industry to propose work that takes maximum advantage of its technical and commercial strengths. However, as discussed above, the purpose of the Programme is to address market and systems failures affecting CATs, and therefore proposals will be expected to cover work that is additional to that which companies would be reasonably expected to undertake as part of their normal business development.

The CAT Strategy differs from the previous CCT Programme by including support for demonstration projects including, in association with R&D (Action 1), capture-ready technology (Action 2) and $CO_2$ storage (Action 3) together with an examination of possible measures to encourage first commercial deployment of CCS technologies (Action 6). This is because both capture and storage technologies have reached a stage of maturity where such demonstrations are essential to further their technical

**Figure 6.1 Illustration of the linkages between the Action Areas forming the CAT innovation programme.**



development and to address some of the non-technical factors that could be barriers to commercialisation (Section 6.1). Furthermore, these demonstrations will add to the leadership role the UK is taking in tackling greenhouse gas abatement and climate change.

There is a need to complement this technological development with studies to push forward the boundaries of knowledge in CATs. This work is already being undertaken by the IEA's Implementing Agreements covering the Clean Coal Centre and the Greenhouse Gas R&D Programme. The DTI supports both of these and gains benefit from the desk research and knowledge development both these organisations provide. Besides having access to the results of the studies we also need to undertake our own investigations into areas which are specific to UK circumstances, or into areas in which other IEA members do not have an interest. In addition to this, there is a need to disseminate the knowledge and know-how which is gained so that it can be used effectively in developing new technologies for reducing $CO_2$ emissions. Action 7, therefore, is identified so that this knowledge-based activity can be developed, co-ordinated and disseminated to assist with the objective of increasing our understanding and knowledge of CATs.

Action 2 is directed at the demonstration of capture ready technology (Sections 3.3 and 5.4) because this is considered to be the most cost effective option for advancing CCS at this stage, and one that can be implemented at low cost in the next 3-4 years.

The demonstration of capture ready plant is a crucial part of a global Strategy for attaining major reductions in $CO_2$ emissions because large investments in new fossil fuel power generation plant without CCS technology will be made over the next 10-15 years. It is unlikely that this plant, with operating lifetimes of 40-60 years, will be scrapped prematurely, particularly in capital constrained developing economies, therefore it is important to be able to fit CCS to this capacity at a reasonable cost and without a substantial loss of performance. The sort of measures required to make coal and natural gas plant capture-ready need not involve substantial additional capital investment (Section 3.3), but the market signals to build capture-ready plant do not exist in the UK and most other markets at present.

It is not clear what type of capture-ready demonstration should be supported (ie post combustion, pre-combustion or Oxy-firing). This decision will be informed by the detailed project assessments currently being supported by DTI through the final Call of the Cleaner Fossil Fuels Programme. It will also depend on industries' views of which technology offers the greatest potential market both in the UK and internationally.

It is also proposed to support a demonstration of $CO_2$ storage (Action 3). This is important for developing UK experience and know-how in the design, authorisation, regulation and monitoring of a storage facility. It will also provide an additional facility for proving the long-term integrity of a geological store and will help build confidence with the UK public in the reliability of CCS as a $CO_2$ abatement option. It is not clear at this stage what form such a demonstration should take. It could be undertaken in combination with the demonstration of capture ready plant, or as a separate project should a lower cost source of $CO_2$ be available. It could be a full-size (ie 0.5-2Mt $CO_2$/yr) project or a smaller-scale project possibly located onshore. An important consideration will be that this demonstration delivers benefits that are additional to ongoing projects and demonstrations elsewhere in the world, for example by using different geological strata, additional monitoring methods or more instrumentation to test mathematic model predictions on $CO_2$ movement.

The examination of measures to encourage first commercialisation of CCS (Action 6) is essential to maintain the commitment of UK business and momentum in the innovation process. It should also strengthen the position of UK business as a leader in both the implementation and management of this chain of technologies. It is intended that measures should be examined that would encourage the commercial-scale deployment of power generation capacity fitted with $CO_2$ capture technology and associated transport and storage by about 2010-2012. Full-scale demonstration of $CO_2$ capture would require significant support, both for the capture plant and the pipeline infrastructure needed to transport the $CO_2$ to the storage site, but the project itself could make a useful contribution to UK $CO_2$ abatement of the order of 0.5-2.0Mt $CO_2$/yr. This work will be an input to the Climate Change Programme Review. The study would also examine what additional measures if any were needed to ensure that the legal and regulatory requirements for $CO_2$ storage would be met (Section 5.3).

CATs are presently attracting considerable international interest and it will be important to maintain an up to date vision of how UK activities fit into the broader international scene. To do this Action 10 will develop and maintain a route map for the CAT Programme to give a clear and transparent framework to guide both programme participants and the DTI. As part of this action an annual report will be produced on the status of the technologies and progress of the Strategy.

## 6.4 Scope

The CAT Strategy will cover all fossil fuels. This is intended to accommodate the role of natural gas in the UK energy systems whilst also encouraging the development of technologies for the UK's export markets, some of which (eg China, India) are expected to use coal for most of their power generation. Although this Strategy focuses on emissions from power generation, there are also considerable emissions from other industrial point sources such as iron and steel manufacture, cement production etc. CCS technologies, particularly those based on post-combustion capture, will be just as relevant for these applications as for power generation. Therefore the Strategy will also be receptive to innovation in the development of CATs for large combustion plant and processes other than power generation.

The focus of the Strategy is on $CO_2$ abatement. It is not intended to support work aimed specifically at the abatement of other emissions (eg $NO_x$, $SO_x$, particulate material, mercury, etc) associated with fossil fuel combustion because these are near-term problems for which development work is being encouraged by current and future emissions standards and regulations (eg the EC Large Combustion Plants Directive). However, some $CO_2$ capture technologies need other emissions to be reduced below current regulatory requirements to work efficiently (eg amine scrubbing requires $SO_x$ to be reduced to ppm levels). Therefore work on advanced flue gas desulphurisation, as part of a broader development of CATs, would be in the scope of the Strategy.

Overall the actions making up the CAT Strategy are only defined in broad terms without being prescriptive about their precise targeting. For example detailed themes for RD&D (Action 1) are not defined nor is any choice made on the types of demonstration projects to be favoured. This is partly because the CAT Programme is intended to be industry led, and also because the final choice needs to be guided by on-going design studies of certain of these options that are being supported by the final Call of the previous Cleaner Fossil Fuels Programme. However, bids for funding will be judged against a set of criteria which are likely to include:

- The capability of UK industry to develop and exploit the technology.
- UK and international market potential.
- Linkages and positioning relative to other foreign and international developments and demonstrations.
- Affordability.

Chapter 3 has shown that the development of technologies for the transportation, storage and use of hydrogen are closely related to CATs because fossil fuels offer a technically and economically attractive method for hydrogen production. Fuel cell development also links to CATs because fuel cells could be incorporated in long-term high efficiency power generation plant (eg triple cycle concepts incorporating fuel cells, gas turbines and steam turbines). Hydrogen and fuel cells are already covered by separate DTI initiatives, and their development will not be included in the CAT Programme. However, projects that involve these in the development of CATs will be within the scope of the CAT Programme; for example, studies on the incorporation of fuel cells in advanced power generation cycles or joint production of electricity and hydrogen in gasification plant.

## 6.5 Underground coal gasification

The Cleaner Fossil Fuels Programme included an assessment of underground coal gasification (UCG). This showed that the technology had advanced so that it could be economically comparable with conventional mining, at least onshore, but that it would need to be deployed in combination with CCS to make a significant contribution to $CO_2$ abatement. In this respect, the potential to inject $CO_2$ into adjacent coal seams offers the attraction of enhanced coalbed methane (ECBM) production alongside $CO_2$ storage. Work by BGS has identified substantial onshore coal reserves (about 17 billion tonnes) suitable for UCG and the likelihood of immense offshore reserves (eg southern North Sea). This Strategy does not consider UCG as a specific CAT option to be pursued, but notes that UCG stands to benefit, along with other fossil fuel gasification technologies (eg IGCC), from the development of CATs in general. Additionally, the CAT Programme will continue to maintain a watching brief on the development of key enabling technologies such as directional drilling and ECBM. Initially, this will focus on the on-going UCG feasibility study in the Firth of Forth area being undertaken by Heriot-Watt University, which is part-funded by the DTI.

## 6.6 Linkage to Research Council programmes

The TSEC Programme is funded by the Natural Environment Research Council (NERC), the Engineering and Physical Sciences Research Council (EPSRC) and the Economic and Social Research Council (ESRC) to promote R&D into sustainable energy technologies, including renewable technologies as well as conventional energy technologies. More recently the UK Energy Research Centre (UKERC) has been created within TSEC to co-ordinate the research being supported by the Research Councils in order to pursue a whole-systems approach to R&D and to bring coherence to a diverse range of research activities through the establishment of a National Energy Research Network. The TSEC Programme has a £28M budget of which £12M is being used to fund the UKERC with the remainder to support work being undertaken by the Research Councils, which is complementary to that undertaken by UKERC. Carbon management is one of the broad themes being addressed by TSEC, with CCS being one of the technologies identified.

The mission of UKERC is *to promote an understanding of the means for achieving an energy system which is environmentally sustainable, socially acceptable and meets energy needs securely and affordably*. The main focus will be desk studies to address the energy system as a whole, looking at demand, supply and infrastructure and the interactions between these elements. This is likely to include further analysis of how CCS and fossil fuels in general fit into the UK energy economy in the medium to long term.

A consortium of universities has presented a programme to TSEC for a UK Carbon Capture and Storage Centre (UKCCSC). The mission of the UKCCSC is *to promote an understanding of how options for decoupling fossil fuel use from carbon emissions through the use of carbon capture and storage could be used to assist the UK in achieving an energy system which is environmentally sustainable, socially acceptable* *and meets energy needs securely and affordably*. Once again this is likely, at least in its early years, to be focused on desk studies of issues affecting deployment including public acceptance, mapping potential storage sites, economic analysis of storage with EOR and limited fundamental work on capture technology.

The EPSRC also individually supports energy innovation to encourage the development of new, longer-term options R&D. Those areas relevant to this Strategy include (with the total value of the grants given):

- conventional electricity generation (£2.5M)
- combustion, including the clean and efficient use of carbon fuels (£12M)
- coal technology (£0.2M)
- oil and gas extraction (£2.8M).

Research Council support is aimed at universities and hence at basic research activities whereas a Programme of R&D under a CAT Strategy would be aimed at supporting industrial activity. Clearly there will be technology interfaces and overlaps between the two and it is important that there is close co-ordination between both areas.

## 6.7 Other funding bodies

Other UK organisations that could potentially be involved with supporting innovation in CATs, and in particular CCS, include the regional development agencies (RDAs), the devolved administrations, agencies such as the Scottish Intermediary Technology Institute for energy and the British Coal Utilisation Research Association. It is important to engage these organisations in the full spectrum of activities needed to develop and commercialise CATs. This will be a key part of the work in several of the actions in this Strategy.

## 6.8 European Union support for CATs

UK R&D and business organisations also have access to EU mechanisms to support research and development. Innovation on CATs in the EU has been funded by the Directorate-General for Research through the Framework Programmes (FP). This has mainly been concerned with work on CCS. Under FP5 the EU contributed EUR16 million to nine projects worth over EUR30 million, including two projects on $CO_2$ capture, six projects on storage and monitoring and one Thematic Network. Many of the projects involve UK organisations and the network (CO2Net) is lead by a UK SME.

The current FP6 has placed emphasis on the assembly of a critical mass of resources in key areas by pulling together and integrating Member State efforts. One of these areas has been CCS with resources concentrated on a limited number of priority areas:

- Post-combustion $CO_2$ capture
- Pre-combustion $CO_2$ capture
- Geological storage of $CO_2$
- Chemical mineral sequestration of $CO_2$.

To date, five projects have been funded by the EU in this area with a contribution of up to EUR35 million. A further Call for proposals in this area closed at the end of 2004 and covered the following topics:

- $CO_2$ capture and hydrogen production from gaseous fuels
- The monitoring and verification of $CO_2$ geological storage
- Preparing for large scale $H_2$ production from decarbonised fossil fuels including $CO_2$ geological storage
- Advanced $CO_2$ separation techniques
- Mapping geological $CO_2$ storage potential, matching sources and sinks
- European coordination and networking activities in $CO_2$ capture and storage.

Additionally the EC has announced the quick-start hydrogen programme known as HypoGen. From December 2004, demonstration projects can be proposed for hydrogen production from fossil fuels with CCS. A budget of EUR1.3 billion is foreseen for HypoGen with roughly half the funds coming from the Framework Programmes. HypoGen is aimed at demonstrating the economic viability of co-production of hydrogen and electricity from de-carbonised fossil fuels and at testing the regulatory frameworks needed for safe and reliable geological storage of $CO_2$.

Looking to the future, the EC continues to place strong emphasis on strengthening European research and ensuring critical mass programmes and teams to match those in North America and Japan. This is to be achieved by a combination of increased research budgets and better and more effective coordination and collaboration between Member State programmes. In the area of CATs the EC has funded the specific supporting action, FENCO, to develop mechanisms and actions for greater collaboration on fossil fuel R&D. This project is aimed at government-level collaboration and was led by Germany's Ministry of Labour and Economics and the DTI. It is expected that a second phase of FENCO will soon commence, which will be a Concerted Action involving 14 Member States led by Germany, The Netherlands and the UK. This will take the collaboration forward with the ultimate aim of establishing collaborative programmes and projects through a European Research Area Network (ERA-NET). Initially FENCO will concentrate on establishing a strong understanding across the group on the policy priorities that will drive R&D on CATs.

In parallel with the governmental initiatives, European industry (including companies from the UK) together with other stakeholders is developing the formation of a European Technology Platform in the technology area of CATs and clean power. This will result in the definition of a European Strategic Research Agenda and a complementary Deployment Strategy Document, both of which will have a significant linkage with the next EU Framework Programme (FP7) due to start in 2006.

## 6.9 International collaboration

This is not a go-it-alone Strategy for the UK to develop CATs. The UK does not have the resources to do this, nor would it deliver the benefits required since CATs developed from a purely UK perspective may not meet global needs. International collaboration is an important element of the Strategy.

A number of countries have initiated or are planning development programmes for CATs and in particular CCS. In addition some international groups have been established to facilitate the development of CCS including the Carbon Sequestration Leadership Forum (CSLF), IEA Greenhouse Gas R&D Programme and the $CO_2$ Capture Project (CCP). It is important that the UK contributes to these activities and has the mechanisms in place to make full use of the delivered results, and this is recognised by having two action areas (Actions 4 and 5) dedicated to facilitating such collaboration.

The actions making up the Strategy have been classified in Figure 6.2 according to whether they are:

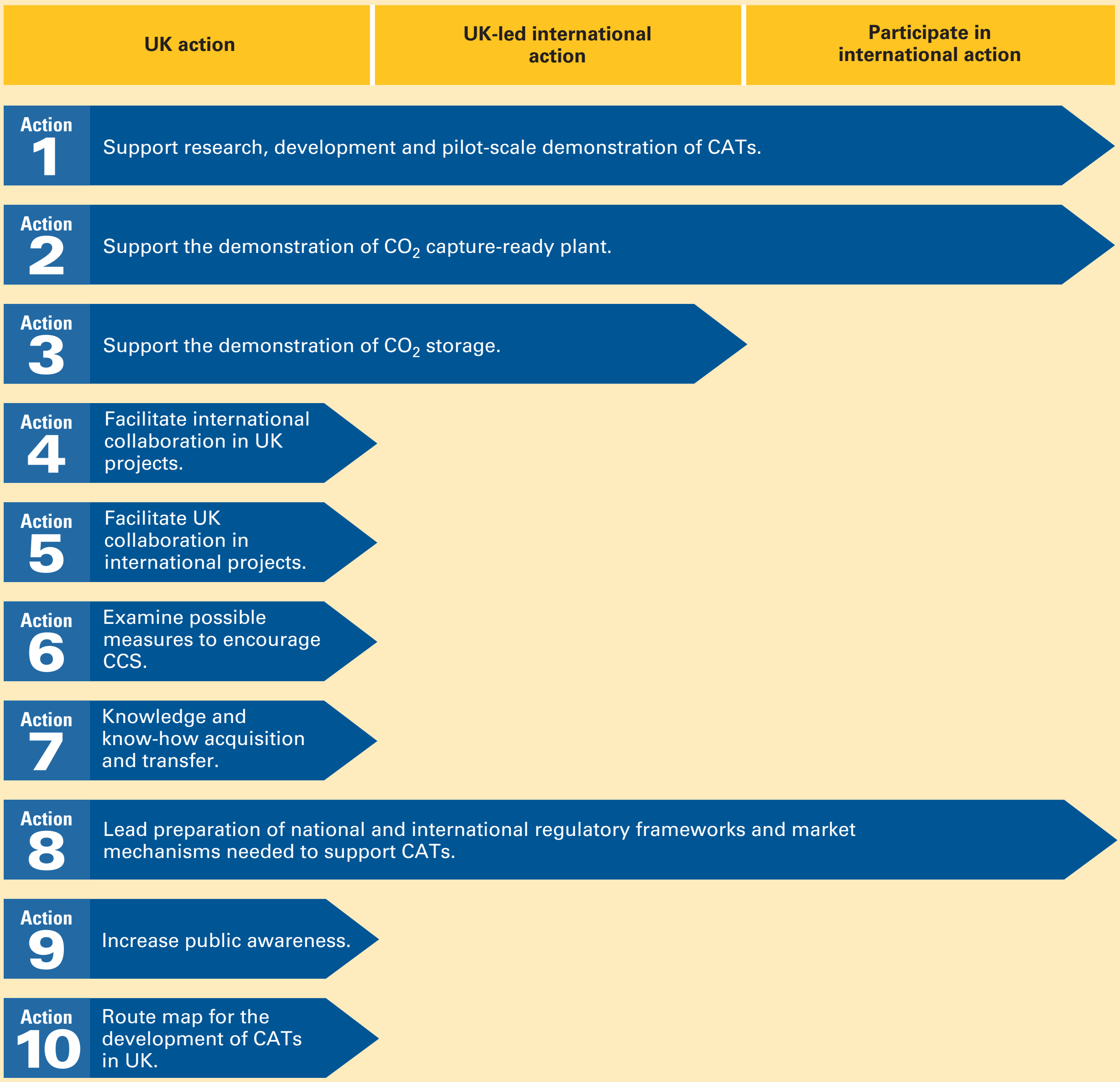
- central to the UK's needs and/or the UK has the necessary capability and would benefit from working independently (UK Action)
- central to the UK's needs and also of international importance (UK led international action)
- would be beneficial, but the UK does not have the capability to lead (participate in international action).

Action 1 on RD&D cuts across all three categories because it is probable that some work will best be undertaken exclusively for the UK (eg design studies for UK-based CCS), while other work may be of international interest and would benefit from involvement in a larger effort. Similarly it is not clear until the options for a capture-ready demonstration (Action 2) have been defined more precisely whether this action should be undertaken exclusively by the UK or through some form of international collaboration.

Action 3 to demonstrate $CO_2$ storage is important for gaining direct UK experience with this process and for building UK public confidence in CCS. Therefore the demonstration must be located in the UK, although international participation could be beneficial.

Actions 4-7 and 9-10 are concerned with the implementation of the CAT Strategy and are centred on work to be undertaken by the UK. However, Action 8, is concerned with international legal and regulatory frameworks and market systems, and therefore must be pursued internationally. The UK will play its part in these activities, taking the lead when it has the appropriate skills and know-how.

**Figure 6.2 Illustration of the level of international collaboration to be sought for each of the ten action areas in the CAT Programme.**



## SUMMARY

- Government support is needed to encourage investment in CATs because the market systems needed to reward $CO_2$ abatement are only just developing and at present do not return the full economic and social value of the abatement achieved. Moreover, there is a range of systems failures and uncertainties needing to be resolved that currently make many of the CATs a high risk investment.
- The rationale for the CAT Strategy is based on the following observations:
  - Fossil fuels will continue to meet most of the world's energy requirement at least to 2050.
  - Consequently, large-scale deployment of CATs, and in particular CCS, will be needed to reduce $CO_2$ emissions to the levels necessary to stabilise the concentration of $CO_2$ in the atmosphere.
  - Natural gas and coal will be the main fuels used for electricity generation and in other large combustion plant, therefore CATs need to be applicable to both gas and coal combustion if they are to have maximum global impact.
  - By helping to retain coal in the energy mix CCS also strengthens the security and diversity of energy supplies in the UK.
  - The UK has a strong base in the technical know-how, business capabilities and natural resources needed to lead in the development of CCS.
  - Leading the development of CATs is consistent with the EWP's aim for the UK to show international leadership on climate change mitigation.
  - Leading on the development of CATs offers substantial first user advantages.
  - Government support is needed to encourage investment in CATs because the market mechanisms needed to reward $CO_2$ abatement are not yet fully developed.
  - There is a need to resolve financial and regulatory uncertainties that currently make CATs a high risk investment.
  - There is a need to raise public awareness of the potential role of CCS in tackling climate change.
- The objective of the CAT Strategy is:

To ensure the UK takes a leading role in the development and commercialisation of CATs that can make a significant and affordable reduction in $CO_2$ emissions from fossil fuel use.

- The key action areas for the Strategy are:
  - Support research, development and demonstration of CATs.
  - Support the demonstration of $CO_2$ capture technologies and capture-ready plant.
  - Support the demonstration of $CO_2$ storage.
  - Facilitate international collaboration in the development and demonstration of CATs.
  - Within the Climate Change Programme Review examine possible measures to encourage the initial commercial deployment of CCS technologies in the UK.
  - Facilitate the acquisition and transfer of knowledge and know-how stemming from CAT innovation both in the UK and abroad to business.
  - Lead in preparing the national and international regulatory frameworks and market mechanisms needed to support CATs.
  - Increase public awareness and stimulate an informed debate on the role of CATs in mitigating climate change
  - Developing and maintaining a route map for the development of CATs in the UK.
- The CAT Programme will be coordinated with other work on CATs supported by the Research Councils and with the activities of the devolved administrations and regional development agencies.
- The CAT Strategy has identified action areas that will benefit from international collaboration and others where work should be centred on the UK. Where appropriate international collaboration will be encouraged and supported within the CAT Programme.

# 7. Delivering the Strategy

Chapter 6 considered the rationale for Government support for the development of CATs as well as the objective, scope, timing, and activities of the new Strategy. This chapter considers how the new Strategy should be delivered covering its management, monitoring, organisation and resourcing. It also considers how it should interlock with other Government activities supporting the development of CATs.

## 7.1 Organisation and management of the CAT Programme

### *General Management*

The CAT Programme will run for at least ten years commencing in April 2005 with a full review after five years. There will be a specific assessment in Year 2 of the Programme to consider the options for demonstration projects covering capture-ready plant and $CO_2$ storage.

Support for R&D will come from the DTI's Technology Programme[64] under the direction of the TSB. Calls for collaborative R&D under the Technology Programme are made twice a year. The DTI's Technology Programme embraces all technologies, those to be included in specific Calls being determined by the TSB. The projects supported under the final Call of the Cleaner Fossil Fuels Programme focus on CATs and are seen as a bridge to the new CAT Programme. Other activities within the CAT Programme will be managed by the Carbon Abatement Technologies Unit under the guidance of the ACCAT.

It is important to note that the Programme is intended to be industry-led and therefore will not be prescriptive about the work supported. Rather, the Strategy defines broad areas for work and looks to industry and the research community to come forward with innovative projects. However, in general terms it is expected that proposals will cover one or more of the key action areas identified in the CAT Strategy.

The Carbon Abatement Technologies Unit, which is part of DTI's Emerging Technologies team (EET), will have specific responsibility for managing the CAT Programme on a day-to-day basis. Among other activities a key task will be to help establish projects between the disparate partners involved in CCS (eg fuel suppliers, combustion plant operators, equipment suppliers, geologists, project financiers, etc) who are unfamiliar with working together.

### *The Advisory Committee on Carbon Abatement Technologies and the Carbon Abatement Technologies Unit*

ACCAT currently provides strategic advice on the activities in the Cleaner Fossil Fuels Programme and has assessed and made recommendations on Government support for R&D projects under the Cleaner Fossil Fuels Programme. ACCAT is an Advisory Committee constituted in accordance with the Nolan guidelines on public appointments. Members are selected on the basis of their experience and knowledge of the energy sector and in particular on their technical knowledge and

**The Strategy will also consider the development of CCS for other large sources of $CO_2$ emissions such as iron and steel plant, cement works and oil refineries (courtesy of Corus).**

64 See www.dti.gov.uk/technologyprogramme/ for more information.

ability to assess project proposals. As can be seen from the list at Annex V, membership is drawn from the energy sector, covering equipment manufacturers, power generators, energy consultants and academia. Officials from the relevant areas of government also attend.

The new central arrangements in the DTI for managing R&D projects under the Technology Programme mean that ACCAT will no longer be required to assess R&D proposals. ACCAT will therefore have purely an oversight role for R&D whilst providing more detailed advice and guidance to the DTI on the development of the CAT Strategy and on the other actions in the CAT Programme. ACCAT's role as an advisory body will be reviewed during 2005 with the objective of recruiting a membership appropriate to its new role. As part of this review it is thought that membership should be drawn from a wider population of stakeholders than in the past, (eg a wider range of industry and academia, representation from the NGOs).

### *Coordination with other programmes*

It is clear that there are a number of CAT support activities across government. Besides the industry-based work supported by the Carbon Abatement Technologies Unit, the Research Council's TSEC Programme also sponsors R&D into these technologies both directly and through the UK Energy Research Centre (UKERC). The Research Councils are also supporting work relevant to CATs outside of TSEC. However, support for industrial and academic research is fragmented and needs to be better co-ordinated. While restructuring the ACCAT will improve this position it is thought that some co-ordinating function to provide a broad overview of all R&D activity would be beneficial for future strategic planning by ensuring there is consistency across Government in supporting the development of these new CAT technologies. Furthermore, the EC also supports R, D&D activities through its Framework Programmes, and there is a requirement to co-ordinate UK involvement and thereby take maximum advantage of these multi-partner projects.

To decide how best to achieve this DTI's Carbon Abatement Technologies Unit will work with the Office of Science and Technology to identify a function for overseeing R&D activity. From the CAT Programme viewpoint this will form part of the work to prepare a technology route map (Action 10).

## 7.2 Strategy planning and funding

### *Timescales*

The Programme will run for at least ten years commencing in April 2005 with a full review after five years. There will be a specific assessment in Year 2 of the Programme to consider the options for demonstration projects covering capture-ready plant and $CO_2$ storage. Further work may be required to determine the costs and benefits of different options and this will be included as part of Action 1. Some of the projects supported in the final Call of the Cleaner Fossil Fuels Programme should provide valuable input to this.

The recommended timescales for the activities identified in Chapter 6 are shown in Figure 7.1. The plan in Figure 7.1 runs only for the first five years of the Programme because of the need to initiate the activities underpinning the Strategy and the greater uncertainties associated with its early stages. An annual review of the technological status of CATs will be undertaken and published as part of Actions 7 and 10.

### *Funding*

Under the 2004 Spending Round the Cleaner Fossil Fuels Programme was allocated £20M in total for the period 2005/06 to 2007/08. This funds industry-led R&D under the Technology Programme, together with policy development on issues around sustainable fossil fuel energy technologies. It is considered from past experience that at this stage this budget should be sufficient to support laboratory-based R&D. This budget is also intended to assist UK collaboration in international R&D Programmes including the Memoranda of Understanding with the USA and China.

**Figure 7.1 Timescale and duration of the actions to be undertaken as part of the CAT Programme.**

| | Action | Management | 2005/06 | 2006/07 | 2007/08 | 2008/09 | 2009/10 | Years 5-10 |
|---|---|---|---|---|---|---|---|---|
| 1. | Support research, development and pilot-scale demonstration of CATs. | **Technology Strategy Board** | | | | | | |
| | | | | | | | **Review** | |
| 2. | Support the demonstration of $CO_2$ capture-ready plant. | **Carbon Abatement Technologies Unit** | | **Review of options** | | | | |
| 3. | Support the demonstration of $CO_2$ storage. | | | **Review of options** | | | | |
| 4. | Facilitate international collaboration in UK-based CAT development and demonstration projects. | | | | | | | |
| 5. | Facilitate and support UK collaboration in CAT development and demonstration projects based in other countries. | | | | | | | |
| 6. | Examine possible measures to encourage the initial commercial deployment of CCS. | | | | | | | |
| 7. | Facilitate the acquisition and transfer of knowledge and know-how. | | | | | | | |
| 8. | Lead in preparing the national and international regulatory frameworks and market systems. | | | | | | | |
| 9. | Increase public awareness and stimulate an informed debate on the role of CATs. | | | | | | | |
| 10. | To develop and maintain a route map for the development of CATs in the UK. | | | | | | | |

The budget includes an element to fund work on policy issues affecting CATs. It also covers DTI's ongoing contribution to the BCURA's research programme, and membership contributions to the IEA's Implementing Agreement on Cleaner Coal.

The Strategy recognises that we are reaching a point where demonstrations up to full-scale may be necessary. There are a number of areas of potential demonstration that extend beyond low to zero $CO_2$ emission technologies to the related areas of hydrogen production and fuel cells.Therefore the Government will provide a funding package of £40M over four years commencing in 2006/07 for demonstrations across CATs, hydrogen and fuel cells. Of the total around £25M is expected to be dedicated to CATs with the balance split approximately 50:50 between hydrogen and fuel cells. Projects that combine technologies, for example CATs and hydrogen, will be able to seek funding from both elements. This funding will be made available in the form of Capital Grants, and will be subject to State Aid rules and approval.

## 7.3 Collaborative R, D&D

There are considerable benefits to be gained through collaborating with other countries in the development of CATs and particularly CCS. The Strategy identifies those activities where the UK should seek to collaborate with other countries or international groupings. Work during the first two years of the Strategy will aim to seek out these partnerships. The work about to commence under the FENCO Specific Supporting Action will provide a good opportunity to identify such partners within the EU. Areas for mutual collaboration have already been established with the USA where two projects are already underway, with a third area for collaborative research currently being studied. It is also expected that a collaborative arrangement will be established with China during 2005.

**The Puertollano IGCC power plant - international collaboration will be important for the demonstration and implementation of CATs (courtesy of Uhde GmbH).**

## SUMMARY

- The ten actions identified in Chapter 6 will form the basis for delivering the Strategy. They will stretch over at least a ten-year Programme of work which should be reviewed after five years.
- There will be a specific assessment in Year 2 of the Programme to consider the options for demonstration projects covering capture-ready plant and $CO_2$ storage.
- R&D activity will come under the DTI's Technology Programme while all other actions will be managed by the Carbon Abatement Technologies Unit.
- An Advisory Committee constituted in accordance with the Nolan guidelines on public appointments will be needed to provide strategic and technical advice to the DTI on the development of the Strategy. This will follow the model of the Cleaner Fossil Fuels Programme's ACCAT, but its composition and role will be reviewed during 2005.
- There should be greater co-ordination on CAT R&D between the Carbon Abatement Technologies Unit and the Research Councils, and with EC R&D support through the Framework Programmes. A co-ordination function should be defined to cover this.
- It will be important to collaborate with other countries in developing some of the CATs and partners will be identified over the next two years.
- Recognising that we are reaching a point where demonstrations up to full-scale may be necessary, the Government will provide a funding package of £40M over four years commencing in 2006/07 for demonstrations across CATs, hydrogen and fuel cells, with £25M of this earmarked for CATs.

# 8. Conclusion and way forward

This Strategy has set out a framework for supporting the development of CATs for fossil fuel power generation and other large-scale combustion plant. It is clear that fossil fuels, whether coal or natural gas will have a major role to play in power generation and other energy-related activities for decades to come. In fact it is highly likely that in the longer term as natural gas reserves diminish reliance on coal will once again increase. Fossil fuels are also a potential low cost method for producing hydrogen for use in a low carbon road transport system. On the other hand the use of fossil fuels are contributing to global warming, and to reconcile their continued use they will have to be used much more cleanly than they are now. The Government has set a target of reducing $CO_2$ emissions by some 60% by 2050, this means than even if natural gas replaced all coal in the UK's mix of energy supplies it still would not be sufficient to reach this target.

Three areas of technology appear to offer opportunities for reducing carbon dioxide emissions from fossil fuel use: improved efficiency, co-firing with biomass and for more radical reductions, CCS. These technologies are not mutually exclusive but could work together for an overall reduction in emissions: carbon capture brings with it cost implications as well as having an impact on the efficiency of plant, consequently it will be important to increase plant efficiency to compensate. Also CCS with biomass co-firing will give bigger emissions reductions. It will be for industry to lead in identifying the particular technologies within these areas which will be the most cost-effective. The modelling undertaken in support of the CAT Strategy suggests that CCS will have a positive role to play in reducing emissions from about 2010-2020 onwards, whereas the others could be deployed earlier.

While cost reduction and technology development are the key concerns for improved efficiency, co-firing and $CO_2$ capture, for $CO_2$ storage there is a different set of issues to be tackled. Here the issue is not so much about the development of plant and devices, but about designing a regulatory regime for safe and reliable storage, demonstrating that the carbon dioxide will not leak back to the atmosphere and undertaking outreach to assure the public that we are not taking further risks with the environment.

The ten action areas identified for delivering the Strategy are designed to address the above issues. Not only do they include RD&D, but also possible demonstration, and developing the right regulatory infrastructure.

It is important that CATs should not be looked at in isolation but as part of a portfolio, working with renewable and end-use energy efficiency technologies to reduce $CO_2$ emissions. CATs should be regarded as bridging technologies for giving short to medium term reductions in $CO_2$ emissions thus providing a breathing space for the development of truly sustainable energy technologies. This Strategy proposes how and why we should pursue CATs as a part of the overall EWP plan to meet the RCEP targets.

The main measures and actions to take the CAT Strategy forward are:

1. The DTI's present Cleaner Fossil Fuels Programme will be replaced by a CAT Programme aimed at reducing the $CO_2$ emissions of large fossil fuel combustion plant.
2. The new CAT Programme will cover three areas for innovation and implementation, namely increased conversion efficiency, co-firing with carbon neutral biomass and carbon dioxide capture and storage (including geological storage), with the ultimate objective of developing near to zero emission technology.
3. The CAT Programme will focus on the development of technology suitable for both the UK market and important developing markets such as China and India.
4. The CAT Programme will run for at least ten years with a review after five years to test the continuing validity of its rationale, objectives, operation and achievements.

5. The Programme will develop a road map for the development and implementation of CATs in a UK context. An annual report will be produced on the status of the technologies and the progress of the Strategy.
6. Support for the R&D part of the Programme will come from DTI's Technology Programme under the direction of the TSB. This does not include support for near to full-scale demonstration projects (see Actions 2 and 3).
7. The Programme will be extended beyond power generation to other industries that operate large point source emissions of $CO_2$ such as iron and steel and cement manufacture. It will also encompass coal, oil and gas fuels.
8. In addition to supporting R&D the CAT Programme needs to extend to demonstrations of $CO_2$ capture-ready plant and $CO_2$ storage. The Government will provide a funding package of £40M over four years commencing in 2006/07 for demonstrations across CATs and the related areas of hydrogen and fuel cells. Of the total around £25M is expected to be dedicated to CATs.
9. Until the market delivers the full value of $CO_2$ abatement other measures will be needed to encourage the first commercial deployment of CCS. The CAT Programme will work with other areas of Government, within the Climate Change Programme Review, to assess possible measures to encourage the full-scale deployment of CCS. These studies will also address the full range of potential environmental impacts.
10. The R&D and demonstration elements of the CAT Programme will be industry-led and therefore the Strategy is not prescriptive beyond defining the generic areas, and requiring additionality to normal industrial RD&D.
11. The CAT Programme will to take forward a range of policy and enabling actions that are important for paving the way to commercialisation of CATs and in particular CCS. The actions include:
    - Facilitation of international collaboration in UK-based CAT development and demonstration projects.
    - Facilitation of UK collaboration in CAT development and demonstration projects based in other countries.
    - Facilitation of the acquisition and transfer of knowledge and know-how.
    - Leading the preparation of national and international regulatory frameworks and market systems, including emissions trading and the status of CCS under the London and OSPAR treaties.
    - Helping to increase public awareness and stimulate an informed debate on the role of CATs.
    - Developing and maintaining a route map for the development of CATs in the UK.
12. An Advisory Committee will continue to provide strategic and technical advice to the DTI on the development of the Strategy. However, its composition and role will be reviewed during 2005.
13. The Carbon Abatement Technologies Unit will continue with the day-to-day management of the Strategy.
14. There will be greater co-ordination on CAT R&D between the Carbon Abatement Technologies Unit and the Research Councils. It is also important to coordinate work with, and take advantage of, R&D support through the EU's Framework Programmes.

# Annex I – The Cleaner Coal Technology Programme

The Cleaner Coal Technology Programme (later the Cleaner Fossil Fuels Programme) was defined in Energy Paper 67 (EP67)[65] and published in 1999. This not only provided Government support for the research and development of cleaner coal technologies (CCTs) it also provided a basis for technology transfer activities through publications and international collaboration and support for promoting UK CCTs to countries such as China and India. Two of its key aims were:

- To assist industry meet the technology targets determined by the Foresight Energy Panel Task Force for advanced power generation.
- To encourage the development of an internationally competitive cleaner coal component industry and promote UK expertise and know-how in the main export markets.

In all, 45 R&D projects on power generation with a total value of £30M received some £12.5M of Government support. Other R&D plus technology transfer and export promotion (TT&EP) activities, which have been undertaken between 1999 and 2004, received government support of some £11M towards a portfolio of work with a total value substantially in excess of £19M. Note the total value of work is difficult to quantify because some projects were part of much large programmes supported by the EC.

The Programme provided support for research into a range of technologies, treatments for coal as well as generation systems to reduce a variety of emissions from its combustion; besides $CO_2$ these included sulphur dioxide, oxides of nitrogen, particulate matter and trace elements such as mercury. However, much of the work has focused on technologies to improved boiler efficiency, coal gasification and $NO_x$ controls.

### *Programme Evaluation*

In 2004 the CCT Programme was evaluated by NERA[66]; in their report they concluded that the Programme had been generally successful. Key points from their report are given below:

### *CCT R&D Programme*

- The projects had been of a high standards and had enabled the UK to stay close to the frontier of knowledge on CCTs, although the limited funding across a wide range of technology areas made it doubtful that this could be the case across the board.
- The Programme had been valuable in that it had stimulated R&D projects which would not have gone ahead without Government support.
- It had been effective in that about half of the participants in the Programme would use the outputs of R&D projects other than their own, thus enabling a degree of dissemination of the results supporting the case for Government-funded research.

### *CCT Technology Transfer and Export Promotion Programme*

- The projects supported had been generally of high technical quality.
- The Programme provided support for activities which were closer to market commercialisation and hence were more likely to displace or fund activities which companies would have funded themselves, however many activities were found to have provided good value for money.
- The Programme was generally considered to have had a positive impact on exports of UK CCT technologies.

However, since the CCT Programme started some five years ago, there have been a number of developments particularly in terms of the increased emphasis on reductions in $CO_2$ emissions together with advances in understanding the potential of new technologies. Key changes have been:

65 DTI Energy Paper 67 - *Cleaner Coal Technologies - Future plans for research and development, technology transfer and export promotion,* 1999.
66 *Evaluation of the Cleaner Coal Technologies Programme - A report for the Department of Trade and Industry.* NERA Economic Consulting July 2004.

- The RCEP's report and the subsequent EWP moved the focus towards the control of greenhouse gas emissions and the need to reduce these significantly over the next 50 years. Further, mechanisms to price $CO_2$ emissions, firstly through the UK's pilot scheme and then through the EU-ETS, due to come into effect in 2005, mean that $CO_2$ emissions will cost those industries which emit.
- It has been recognised that longer-term cleaner fossil fuel technologies, such as CCS, have the potential to significantly reduce if not eliminate $CO_2$ emissions from fossil fuel use.
- Technologies for managing acid gases, such as $SO_x$ and $NO_x$, and most particulates from coal use, have to, all intents and purposes, been developed to a point where they are being commercially deployed. They have reached the point therefore where the key criteria for government support, to address market failure, has been met. It is not considered appropriate therefore for Government to support further development of these technologies. This leaves the management of $CO_2$ emissions as a priority area.
- Not only is there greater concern about the impact of greenhouse gases, such as $CO_2$, on the world's climate but also the fuel mix in the UK has changed and is predicted to undergo further significant change over the next 15 years. Specifically, since 1993 the use of natural gas for power generation has been increasing to the point that in 2003 it accounted for 38% of electricity generated, compared to coal at 35%.

It was concluded therefore that a new Strategy was needed to replace EP67, which reflected the new policy emphasis set out in the EWP and the changing circumstances in which coal and natural gas are used today.

EP67 included two additional objectives:

- To encourage fundamental coal science research in universities in support of the Foresight recommendations and in collaboration with BCURA.
- To examine the potential for developing the UK coal bed methane resource and underground coal gasification technology.

The BCURA arrangements in which the DTI co-funds R&D through BCURA was reviewed as part of the NERA review as well as through a separate independent review commissioned by the DTI. Both reviews concluded that these arrangements should continue for a further three years and be reviewed again in 2007.

# Annex II – Options for carbon dioxide capture

There are three generic process routes for capturing $CO_2$ from fossil fuel combustion plant:

- Post-combustion capture.
- Pre-combustion capture.
- Oxy-fuel combustion.

Each of these processes involves the separation of $CO_2$ from a gas stream. There are five main technologies available for doing this, with the choice depending on the state (ie concentration, pressure, volume) of the $CO_2$ to be captured:

- Chemical solvent scrubbing.
- Physical solvent scrubbing.
- Adsorption/desorption.
- Membrane separation.
- Cryogenic separation.

**Post-combustion capture** (Figure A1) involves the separation of $CO_2$ from flue gas. The preferred technique at present is to scrub the flue gas with a chemical solvent (usually an amine), which reacts to form a compound with the $CO_2$. The solvent is then heated to break down the compound and release the solvent and high purity $CO_2$. The flue gas needs to be cooled and, for coal- and oil-fired plant, treated to remove reactive impurities (eg sulphur and nitrogen oxides, particulate material) before scrubbing, otherwise these impurities will react preferentially with the solvent causing unacceptable rates of solvent consumption and corrosion of the plant. With current processes a significant amount of energy is needed to regenerate the solvent and to compress the $CO_2$ for transport, which reduces the net electricity output of the plant. One advantage of the post-combustion route is that it can continue to generate electricity if there is a problem with the $CO_2$ amine unit. This is in contrast to the pre-combustion (IGCC) plant which has the separation upsteam of the rotating power generation equipment so any problems in the upstream "chemical plant" will result in a loss of electrical output.

**Pre-combustion capture** (Figure A2) involves reacting fuel with oxygen or air, and in some cases steam, to produce a gas consisting mainly of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in a catalytic shift converter to produce more hydrogen and $CO_2$. The $CO_2$ is then separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process can be applied to natural gas, oil or coal, but with the latter two fuels additional equipment is needed to remove impurities such as sulphur compounds and particulates.

Compared with post-combustion, pre-combustion separation produces a smaller volume of gas for treatment, which is richer in $CO_2$ and at a higher pressure. This reduces the size of the gas separation plant, resulting in some reduction in capital cost of this part of the overall process. Also, the higher concentration of $CO_2$ enables less selective gas separation techniques to be used (eg physical solvents, adsorption/desorption) that require less energy

**Figure A1 Schematic diagram of the post-combustion capture process.**

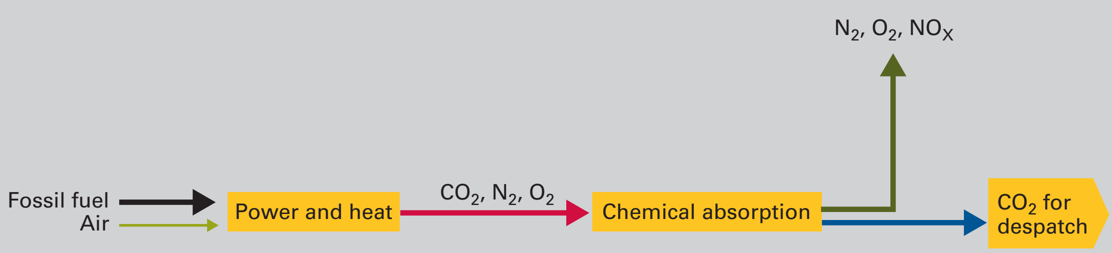
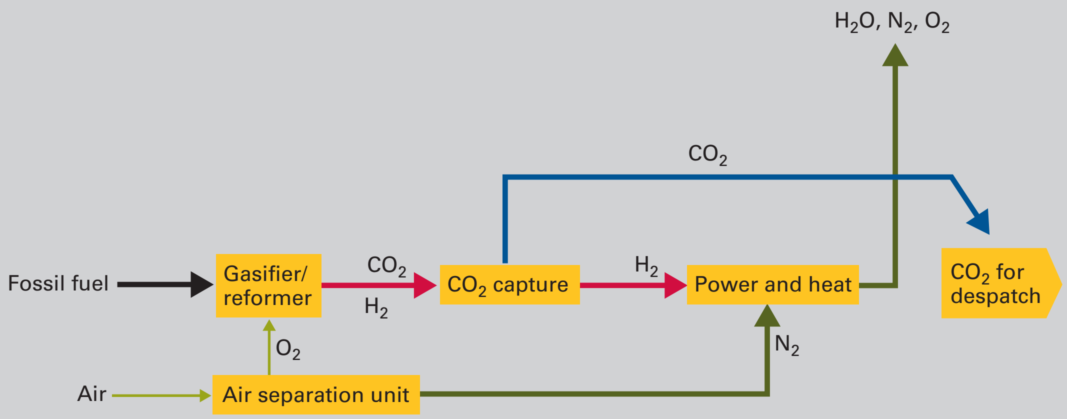


**Figure A2 Schematic diagram of the pre-combustion capture process.**



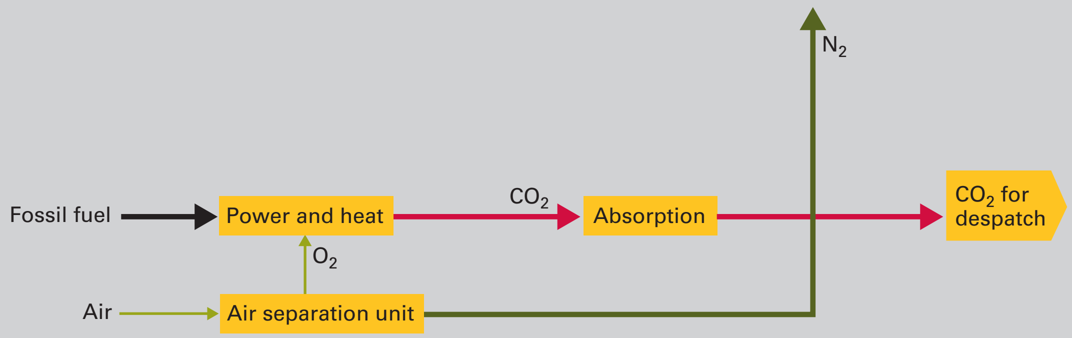

to operate. However, the process requires an air separation unit, which uses a significant amount of energy and adds to capital costs.

One advantage of pre-combustion technology is that it may also be used to supply hydrogen, either separately or in combination with electricity, which many studies have shown to be the leading option for reducing $CO_2$ emissions from road transport.

**Oxy-fuel combustion** (Figure A3) involves burning fuel in an oxygen/$CO_2$ mixture rather than air to produce a $CO_2$-rich flue gas. Generally the oxygen is derived from an air separation unit, and the oxygen/$CO_2$ mixture is produced by recirculating some flue gas to the combustor. The oxygen/$CO_2$ mixture is needed to control flame temperature, which would be too high if combustion took place in pure oxygen. Some novel processes seek to avoid the need for an air separation unit, which has a high energy demand. For example, chemical looping uses a metal oxidation reaction to separate oxygen, with subsequent reduction of the metal oxide to provide the oxygen needed to burn the fossil fuel. Oxy-fuel combustion can be applied to boilers and gas turbines, although a different design of gas turbine would be needed to work with highly concentrated $CO_2$, which rules out retrofit to existing GTCC stations.

Oxy-fuel combustion produces a highly $CO_2$-enriched flue gas that in principle enables simple and low-cost $CO_2$ purification methods to be used. Also, because combustion occurs in a low nitrogen environment, the formation of nitrogen oxides ($NO_x$) is greatly reduced. However, it has

**Figure A3 Schematic diagram of the Oxy-fuel combustion capture process.**



the disadvantage of requiring an air separation plant, which is expensive and requires a considerable amount of energy to operate.

All three of the above approaches could be applied to new plant or retrofitted to some existing facilities. New build has the advantage of allowing maximum integration of the capture facilities into the power generation plant, which will benefit overall generation efficiency. It also avoids any space limitations associated with fitting new equipment to an existing facility, and could permit the plant to be located closer to the $CO_2$ storage facility thus reducing transport costs. Retrofit is likely to have lower capital cost, although this advantage is reduced if appreciable refurbishment is needed to extend the operating life of the plant. Also retrofitting to coal-fired plant could include additional investment in flue gas desulphurisation and nitrogen oxides control technologies.

# Annex III – MARKAL scenario development

The future demand for energy services and the costs of primary energy supplies are uncertain, particularly over long timeframes like the 50-year period covered by this MARKAL study. Consequently, the study followed the general practice and explored a range of possible futures through scenarios that conceptualise alternative development paths. This supports debate on future options as well as assessing how robust individual technologies are to price and market uncertainties. In this study three scenarios were developed, namely Baseline, World Markets and Global Sustainability. The latter two following the themes and general trends developed by the Energy Futures Task Force of DTI's Technology Foresight Programme. These scenarios can be briefly characterised as follows.

- Baseline (BL) - in which the current values of society remain unchanged and policy intervention in support of environmental objectives is pursued in a similar way to now (GDP growth 2.25% per year).
- World Markets (WM) - based on individual consumerist values, a high degree of globalisation and scant regard for the global environment (GDP growth 3% per year).
- Global Sustainability (GS) - based on the predominance of social and ecological values, strong collective environmental action and globalisation of governance systems (GDP growth 2.25% per year).

None of the scenarios considered security of supply as an issue for the choice of fuels or technologies.

### *Demand for energy services*

The demand for energy services or useful energy demand is a measure of the utility of a service for which energy is consumed. Useful energy demands can be met by a variety of competing fuels, burned in different devices with different efficiency. For example, useful energy demand for space heating reflects the desired level of comfort and the area to be heated. This demand could be met by electric heating, gas boilers or solar heating or it could be ameliorated by insulation measures designed to reduce the heat supply required.

The method adopted to estimate useful energy demands over the period to 2050 is as follows.

1. Estimate the level of useful energy demand for the relevant end use in 2000, $U_{2000}$.
2. Select a proxy measure (P) for growth of useful energy demand.
3. Calculate for the proxy measures an escalation factor $E_n$, for each year in the future $E_n=P_n/P_{2000}$.
4. Derive useful energy in the year n, $U_n = E_n \times U_{2000}$.

The escalation factors En for each sector under the three scenarios are shown below. A more detailed account of the development of these, with greater disaggregation of the demands is given in DTI Economics Paper No. 4 - *Options for a Low Carbon Future*, June 2003.

**Table A1 Index of useful energy demands for each scenario.[67]**

**Baseline scenario**

| | Domestic | Industry | Service | Transport |
|---|---|---|---|---|
| 2000 | 100 | 100 | 100 | 100 |
| 2010 | 118 | 103 | 116 | 118 |
| 2020 | 133 | 107 | 127 | 135 |
| 2030 | 145 | 110 | 135 | 148 |
| 2040 | 151 | 114 | 142 | 158 |
| 2050 | 154 | 117 | 149 | 165 |

**World Markets scenario**

| | Domestic | Industry | Service | Transport |
|---|---|---|---|---|
| 2000 | 100 | 100 | 100 | 100 |
| 2010 | 128 | 104 | 119 | 122 |
| 2020 | 150 | 108 | 132 | 145 |
| 2030 | 168 | 111 | 142 | 165 |
| 2040 | 180 | 115 | 154 | 183 |
| 2050 | 184 | 119 | 166 | 198 |

67 Scenario demands for useful energy in transport were constructed assuming annual road transport growth rates would diminish due to road capacity constraints and saturation effects in car ownership. As such they most closely parallel the IAG demand scenarios that also assumed such constraints.

**Table A1 Index of useful energy demands for each scenario (cont.)**

| Global Sustainability scenario | | | | |
|---|---|---|---|---|
| | Domestic | Industry | Service | Transport |
| 2000 | 100 | 100 | 100 | 100 |
| 2010 | 117 | 104 | 114 | 112 |
| 2020 | 131 | 108 | 120 | 122 |
| 2030 | 140 | 112 | 127 | 127 |
| 2040 | 145 | 116 | 133 | 130 |
| 2050 | 145 | 120 | 138 | 129 |

In line with the underlying concepts of the scenarios WM involves a greater increase in demand than BL across all sectors. In contrast GS, despite having the same overall GDP growth rate as BL, has a slower increase in demand for energy services. This reflects a greater readiness to adopt sustainable patterns of behaviour by commercial organisations, government and private individuals. Population growth and the increase in number of households are other key drivers for useful energy demands. All three scenarios assume modest growth in population (~7-10%) but a greater expansion in the number of households (~17-35%) by 2050. This is reflected in some slowing of transport and domestic demand growth.

Overall energy savings and hence reductions in $CO_2$ emissions come from a combination of energy efficiency improvements by suppliers and end users combined with structural changes (eg reductions in energy-intensive industry, change in the utilisation of transport modes, increased share of service sector activities in total GDP). Such structural change has been included in the scenario assumptions.

## *Energy prices*

The main energy prices required for the model were the primary prices for oil, natural gas and coal. These were developed in consultation with the DTI, taking account of the long run supply position and demand variations between scenarios. It was assumed that the world would be following the same scenario development pathway as the UK when considering the strength of demand. Consistent with this, the demand for oil, and hence price, was assumed to be strongest in the World Markets scenario and weakest in the Global Sustainability scenario, with the Baseline scenario lying roughly midway between these. Demand for gas was also expected to be strongest in the World Markets scenario, but in this case demand in the Global Sustainability scenario was expected to be stronger than in the Baseline scenario. This is because natural gas was expected to command a premium price, as a relatively "clean" fuel in the environmentally driven future. Demand for internationally traded coal was expected to be weak in all scenarios because of the environmental and technical advantages of other fuels. Consequently the coal price was set at a constant value, which was close to current prices. The end user prices derived through this approach are listed in Table A2.

**Table A2 End user energy prices used in MARKAL.**

| Baseline scenario | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| Jet Kerosene | (p/litre) | 16.49 | 12.57 | 12.57 | 15.31 | 15.31 | 15.31 |
| DERV | (p/litre) | 80.80 | 75.78 | 75.78 | 78.72 | 78.72 | 78.72 |
| Unleaded petrol | (p/litre) | 80.09 | 74.95 | 74.95 | 77.96 | 77.96 | 77.96 |
| Fuel Oil (industrial) | (p/litre) | 12.38 | 10.22 | 10.22 | 11.81 | 11.81 | 11.81 |
| Fuel oil (ESI) | (p/therm) | 34.7 | 28.3 | 28.3 | 32.3 | 32.3 | 32.3 |
| Petroleum (services) | (p/litre) | 15.5 | 13.1 | 13.1 | 15.2 | 15.2 | 15.2 |
| Petroleum (domestic) | (p/litre) | 16.3 | 13.8 | 13.8 | 16.0 | 16.0 | 16.0 |
| Gas oil (ESI) | (p/therm) | 46.1 | 39.7 | 39.7 | 43.7 | 43.7 | 43.7 |
| Gas (industrial) | (p/therm) | 21.5 | 21.5 | 24.0 | 28.2 | 31.5 | 31.5 |
| Gas (domestic) | (p/therm) | 50.0 | 50.0 | 52.5 | 56.7 | 60.0 | 60.0 |
| Gas (services) | (p/therm) | 27.5 | 27.5 | 30.0 | 34.2 | 37.5 | 37.5 |
| Gas (ESI) | (p/therm) | 23.0 | 23.0 | 25.5 | 29.7 | 33.0 | 33.0 |
| Coal (Industrial) | (p/therm) | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 |
| Coal (domestic) | (p/therm) | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 |
| Coal (services) | (p/therm) | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 |
| Coal (ESI) | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |

| World Markets scenario | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** |
| Jet Kerosene | (p/litre) | 16.49 | 14.75 | 16.14 | 20.74 | 20.74 | 20.74 |
| DERV | (p/litre) | 80.80 | 78.11 | 80.45 | 84.53 | 84.53 | 84.53 |
| Unleaded petrol | (p/litre) | 80.09 | 77.35 | 79.75 | 83.93 | 83.93 | 83.93 |
| Fuel Oil (industrial) | (p/litre) | 12.38 | 11.49 | 12.76 | 14.96 | 14.96 | 14.96 |
| Fuel Oil (ESI) | (p/therm) | 34.7 | 31.5 | 34.7 | 40.3 | 40.3 | 40.3 |
| Petroleum (services) | (p/litre) | 15.5 | 14.7 | 16.4 | 19.3 | 19.3 | 19.3 |
| Petroleum (domestic) | (p/litre) | 16.3 | 15.5 | 17.4 | 20.4 | 20.4 | 20.4 |
| Gas oil (ESI) | (p/therm) | 46.1 | 42.9 | 46.1 | 51.7 | 51.7 | 51.7 |
| Gas (industrial) | (p/therm) | 21.5 | 25.7 | 29.8 | 36.5 | 36.5 | 36.5 |
| Gas (domestic) | (p/therm) | 50.0 | 54.2 | 58.3 | 65.0 | 65.0 | 65.0 |
| Gas (services) | (p/therm) | 27.5 | 31.7 | 35.8 | 42.5 | 42.5 | 42.5 |
| Gas (ESI) | (p/therm) | 23.0 | 27.2 | 31.3 | 38.0 | 38.0 | 38.0 |
| Coal (Industrial) | (p/therm) | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 |
| Coal (domestic) | (p/therm) | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 |
| Coal (services) | (p/therm) | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 |
| Coal (ESI) | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |

**Global Sustainability scenario**

| | | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Jet Kerosene | (p/litre) | 16.49 | 9.83 | 9.83 | 9.83 | 9.83 | 9.83 |
| DERV | (p/litre) | 80.80 | 72.84 | 72.84 | 72.84 | 72.84 | 72.84 |
| Unleaded petrol | (p/litre) | 80.09 | 71.93 | 71.93 | 71.93 | 71.93 | 71.93 |
| Fuel Oil (industrial) | (p/litre) | 12.38 | 8.85 | 8.85 | 8.85 | 8.85 | 8.85 |
| Fuel Oil (ESI) | (p/therm) | 34.7 | 24.3 | 24.3 | 24.3 | 24.3 | 24.3 |
| Petroleum (services) | (p/litre) | 15.5 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| Petroleum (domestic) | (p/litre) | 16.3 | 11.5 | 11.5 | 11.5 | 11.5 | 11.5 |
| Gas oil (ESI) | (p/therm) | 46.1 | 35.7 | 35.7 | 35.7 | 35.7 | 35.7 |
| Gas (industrial) | (p/therm) | 21.5 | 23.2 | 26.5 | 31.5 | 33.2 | 34.8 |
| Gas (domestic) | (p/therm) | 50.0 | 51.7 | 55.0 | 60.0 | 61.7 | 63.3 |
| Gas (services) | (p/therm) | 27.5 | 29.2 | 32.5 | 37.5 | 39.2 | 40.8 |
| Gas (ESI) | (p/therm) | 23.0 | 24.7 | 28.0 | 33.0 | 34.7 | 36.3 |
| Coal (Industrial) | (p/therm) | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 | 14.4 |
| Coal (domestic) | (p/therm) | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 | 57.2 |
| Coal (services) | (p/therm) | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 | 19.5 |
| Coal (ESI) | £/tonne | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 | 30.5 |

Because the scope of the modelling study did not include oil refining, or the transmission and distribution costs of refined liquid fuels and natural gas, these prices were estimated off-model. This was done by the DTI, based on the assumption that the present absolute price differential between primary and delivered energy prices was maintained throughout the modelling period.

Another factor affecting delivered energy prices is taxation and duty. Here it was assumed that the current rates would apply throughout the modelling period. One important exception was alternative road transport fuels, where it was assumed that they would be duty free (as at present) until they exceeded 3% of the market. Further production above the 3% level attracted the same duties as gasoline and diesel (ie on a unit of energy basis) on the assumption that tax revenues would need to be broadly maintained.

# Annex IV – Glossary of Terms

| | |
|---|---|
| ACCAT | Advisory Committee on Carbon Abatement Technologies |
| APGTF | Advanced Power Generation Technology Forum |
| BCURA | British Coal Utilisation Research Association |
| BGS | British Geological Survey |
| CATs | Carbon abatement technologies |
| Capture-ready plant | Capture-ready plant is power plant designed and constructed to make later retrofitting of $CO_2$ capture equipment more straightforward and less expensive |
| CCL | Climate Change Levy |
| CCS | $CO_2$ capture and storage |
| CCT Programme | Cleaner Coal Technology Programme, now the Cleaner Fossil Fuels Programme |
| CSLF | Carbon Sequestion Leadership Forum |
| DTI/EITU | The DTI Energy Industries and Technologies Unit |
| ECBM | Enhanced Coalbed Methane [recovery] |
| EOR | Enhanced Oil Recovery |
| EPSRC | Engineering and Physical Sciences Research Council |
| ESRC | Economic and Social Research Council |
| EU-ETS | European Union - Emissions Trading Scheme |
| GTCC | Gas turbine combined cycle |
| IGCC | Integrated gasification combined cycle |
| IPCC | Inter Governmental Panel on Climate Change |
| NERC | Natural Environment Research Council |
| RCEP | Royal Commission on Environmental Pollution |
| RDA | Regional Development Agency |
| SME | Small and Medium-size Enterprise |
| TSB | The DTI Technology Strategy Board |
| TSEC | Towards a Sustainable Energy Economy - a Research Councils' Programme |
| UCG | Underground Coal Gasification |
| UKERC | United Kingdom Energy Research Centre |
| UN FCCC | United Nations Framework Convention on Climate Change (the Kyoto Agreement) |

# Annex V – Membership of the Advisory Committee on Carbon Abatement Technologies (ACCAT)

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| | |
|---|---|
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*Members*

| | |
|---|---|
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| Mr John Griffiths | Jacobs Engineering |
| Professor John McMullan | University of Ulster |
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| Dr Paul Freund | independent |
| Dr Roy Banks | Costain |
| Miss Celia Greaves | Synnogy |
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