A Vision for Clean Fossil Power Generation

Recommendations for a UK Carbon Abatement Programme for Fossil Fuel Power Generation 2004

UK Advanced Power Generation Technology Forum
An Associate Programme of UK Foresight

APG TF

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May 2004

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Executive summary

In its Energy White Paper, the Government recognised that the scale of the issues presented by global warming and security of energy supply needed 'a new direction for energy policy'. This policy recognises that fossil fuels will continue to play a significant role for decades to come, both in the UK and abroad.

An economics study carried out in conjunction with the White Paper suggests that coal fired generation may disappear by 2030, unless economic ways are found to reduce emissions, that gas fired generation will increase significantly, and that existing nuclear generation will be mostly decommissioned by 2030. It also suggests that use of renewables will increase, but that their intermittency will limit their growth.

The reason for the dominance of gas after 2030 is that the economics study was based on meeting the CO_2 constraints at least cost, and gas is projected to be cheaper than new coal power plants. However, more recent studies, referred to in the economics study, indicate that retrofitting of new boilers to existing coal plant can be cost competitive with new gas plant as a means of increasing UK generation efficiencies. These studies also indicate that for the latest designs of new coal plant, coal can be competitive with gas in a high gas price scenario. A further study carried out for the EC (WETO), suggests that new coal-fired plant will become cheaper than gas by 2025, and that with a positive RD&D programme, this date could be brought forward to 2015.

The White Paper study also acknowledges that the most cost effective means of reducing CO_2 emissions from fossil fuels is by increasing generation efficiencies. However, the projected increases in gas fired generation efficiencies are insufficient to achieve the target reductions in CO_2, hence significant installation of 'zero emission' carbon capture and storage (CCS) systems is required from about 2030 onwards.

It should be noted that the efficiency targets of 50% and 60% for coal (HHV) as proposed in the RD&D programme, represent CO_2 emissions reductions of 30% and 42% respectively, compared to currently installed coal-fired plant. This is a major contribution toward meeting national CO_2 emissions reductions aspirations. It also provides a firm technology platform from which to develop carbon dioxide capture and storage activities.

Other analyses indicate that global energy needs over the coming decades will not be met without calling upon all energy sources and fuels, and particularly, coal. Between now and 2030, the global demand for new generating plant is expected to be over 5000GW, with a value of $4000 billion. The IEA estimates that 1400GW of this will be new-build coal plant, which is worth approximately $1400 billion at today's prices. For gas, the estimated new-build is 2000GW, with a value of $1200 billion. The UK share of the global market for new power plant in the last decade was in the region of 11-12.5%. If the UK could retain a 10% share of the clean coal and GT markets over the next 15 years, this would be worth £51 billion.

The Government has also acknowledged the significance of near-zero-emissions technologies (ZEPG) for fossil fuel-based power generation, and it recognises that UK industry must be well placed to take advantage of the very large demand for these in global markets. However, other countries have initiated advanced RD&D programmes in this area. So, if the UK power engineering industry is to retain and grow its world market, it too needs to be at the forefront in the development of these technologies.

There are significant risks and costs to industry in developing new technologies and in seeking to establish a 'first of kind' scheme at a commercial scale. Government assistance is essential, not only to encourage initial research and development, but also to help bring the resultant technologies to the market. This all points to the urgent need for a strong and focused programme for RD&D and commercialisation of clean new-build and retrofit fossil technologies suitable for world markets to ensure that UK companies can offer state of the art technology. The programme needs to consider gas, coal and biomass for the short, medium and long terms.

The programme must be consistent with Government policy, and its aims should be:

- to provide commercially available large scale near-to-zero-emissions power plant
- to provide UK industry with global power market opportunities out to 2030
- to contribute significantly to UK wealth creation

If this strategy and the proposed R,D&D programme are fully implemented, they will provide key technologies to help the Government to achieve its goals for significant reductions in carbon dioxide emissions (CO_2), whilst maintaining security of supply.

The programme proposed by the APGTF is based on the successful six-year Clean Coal Technology programme (1999-2005) with enhancements to focus on carbon management and carbon capture technologies for fossil fuels. This should include increasing efficiencies as well as CO_2 separation and capture. It would also be appropriate to include hydrogen production from fossil fuels or biomass.

The programme has six main R,D&D themes: *Basic Research, Components and Technologies, Virtual Demonstration, Physical Demonstration, Systems Analysis,* and *Social Research.* Each of these themes should be pursued in conjunction with prioritised power plant and carbon capture technologies. The proposed RD&D themes should be implemented in joint programmes between industry and the relevant Government agencies.

The first element of a joint programme should be an **Industry-led R,D&D programme** in which APGTF strategy is used to inform planning, and programme management follows the Cleaner Coal R&D model. The emphasis of the programme should be in *Components and Technologies, Virtual Demonstration and Physical Demonstration;* the scope should also include cost-effective demonstrations, techno-economic studies; studies to identify R&D needs, and participation in international programmes as well as R&D.

In the **Technology Transfer and Export Promotion programme**, the Government should provide a ‘catalyst role’, acting as a focus for international collaborations, and promoting technology transfer and exports.

The Industry led RD&D programme and the Technology Transfer and Export Promotion programme should, together, form the basis of a joint DTI/Industry **Carbon Abatement Technology programme.**

The **Academic Research programme** should have strong industrial input and be coordinated by the new Energy Research Centre. It should also relate to the work of the Carbon Trust and the Scottish Energy ITI. In particular, the *Basic Research programme* should be promoted with the new Energy Research Centre, and build upon already established industry/research relationships, such as the British Coal Utilisation Research Association.

There should be **Measures to Encourage Closer Industry/Academe Cooperation** which ensure industry participation in University programmes, ensure academic research is linked to business objectives, seeks more added value from long term research, and encourages the development of new technologies and skills.

The *Social Research* and *Systems Analysis* programmes should be supported by the appropriate parts of Government, with industry providing a full supporting role.

The total DTI funding required for the UK RD&D 4 year programme is:

£10m for the first year
£20mpa for each of the following 3 years.

It must be remembered that the strategy being proposed goes out to 2020 and beyond and so there is a requirement for longevity in the technology programmes that needs to be reflected in financing of future phases.

The **collaborative elements** of the UK programme (including involvement with the IEA Greenhouse Gas R&D Programme) will all provide access to large **international and EU** programmes which will ensure that the funding is highly geared. The activities in this area to date should therefore be built upon and so **ensure that UK industry is in a position to take maximum advantage whilst fostering UK capability and skills. Such an approach relies on a strong focussed national activity on carbon abatement encompassing fossil fuels.**

Finally, it is recommended that the **APGTF builds upon its success to date and takes a more pro-active role in implementing strategy through its work with Government.**

1 Introduction

1.1 Purpose of this document

This document has been prepared by the Advanced Power Generation Technology Forum (APGTF)[1] and aims to provide advice to the Government on its R,D&D policy for power generation technologies from fossil and biomass fuels. It also proposes a strategy for carbon abatement with such fuels through the establishment of a collaborative R,D&D programme linking industry, academia and involving different funding sources. It therefore builds upon the recommendations of the Government's White Paper of 2003 (1).

The report focuses on two of the priority themes of the White Paper (global warming and security of supply) and recognises that these issues are both national and global in nature. It also recognises that for UK industry, any R,D&D programme must allow for the development of future national and global markets.

The rationale and the need for the proposed programme are presented, with a description of the collaborative work plan for industry, the universities and the funding agencies.

The strategy for the programme considers R,D&D for whole plant and component technologies as well as the underpinning research that is needed. The document also describes the technical targets that it is believed the programme must achieve, with defined timescales. It also addresses how these technologies can be used on a wider basis, for example in additional industrial sectors.

International collaboration is seen as a fundamental part of the programme and a strategy for enhancing such collaboration is presented.

In developing the strategy and R.D&D programme, the APGTF has recognised that:

- The government has announced that it will maintain a programme for cleaner fossil fuel research and development and will seek to support demonstration of a retrofit of advanced supercritical boiler/turbine technology.
- It has committed to developing a plan to demonstrate carbon dioxide capture and storage.
- Additional funding has been committed to R&D to be coordinated via a new Energy Research Centre.
- The Carbon Trust is funding R,D&D in technologies which will reduce carbon emissions, and in Scotland a new Energy ITI[2] has been announced to stimulate energy R&D and the associated business development.

In developing the strategy and R,D&D programme, the APGTF has consulted extensively with UK industry, academia and Government. The strategy sets out a path of progressive reductions to near-to-zero emissions for fossil fuel power generation technology with the following aims:

- to provide affordable, acceptable and commercially available, low emissions power plant
- to provide UK industry with global power market opportunities out to 2030
- to contribute significantly to UK wealth creation

If the strategy and the proposed R,D&D programme are fully implemented, they will provide key technologies to help the Government to achieve its goals for significant reductions in carbon dioxide emissions (CO_2), whilst maintaining security of supply – thus allowing fossil fuel technologies to contribute to the establishment of a future sustainable energy supply.

[1]APGTF is a Foresight Associate Programme that provides the focus for the UK Power Generation Sector on power generation technologies for fossil fuels, biomass and associated technologies. It represents a broad range of interests, mainly through the key Trade Associations involving the power generators and users, equipment manufacturers and fuel suppliers (namely Association of Electricity Producers, Combined Heat and Power Association, BEAMA/Power Generation Contractors Association, Industrial Power Association and Confederation of UK Coal Producers) together with representatives from the Research Community, Government (DTI, DTI-OST and DTI-SEPU) and the Funding Agencies (EPSRC).

[2] ITI – Intermediary Technology Institute

1.2 Background

"Near-to-Zero Emission Power Generation" from fossil fuels (coal, gas and oil), including biomass, refers to a range of technologies (ZEPG) that are capable of producing electricity with greatly reduced emissions to the environment, taking account of their full fuel cycles. These technologies are strategically important because:

- they provide the opportunity to supply electricity with near-to-zero carbon dioxide emissions using the fuels that will be globally dominant for power generation in the near to medium term (see Section 2.1).
- they lead to negligible emissions of sulphur and nitrogen oxides, and particulates.
- they also contribute to diversity and security of power supply.

As the global dependence on fossil fuels continues, the development of ZEPG plant technologies is crucial for achieving major reductions in greenhouse gas (GHG) emissions. It is widely believed that such reductions are needed beyond 2020 if climate change is to be contained within tolerable limits (2, 3).

The main fossil fuel power generation technologies currently in use, and their present status, are shown in Table 1.

Table 1

Current status of plant types

Technology	Status	Capital Costs £/kWe ($/kWe)	Performance	Issues
Pulverised Coal with fgd	Commercial, strong position, supercritical	600-670 (900-1000)	up to ~45% eff Needs fgd	Leading, proven technology
IGCC	High efficiency plant at commercial demo stage	730-800 (1100-1200)	Depends a lot on GT 41-45%	Perceived as clean. Complex
Fluidised Bed Combustion	Commercial, niche market for poor fuels and expanding market position	690-800 (1000-1200)	up to 40% eff.	Competitive for low grade fuels
Fuel Cells	Some are commercial. Small types at commercial demo	>1700 (>2500)	40 - 60% eff, depending on type	Still developing, costs falling. Could be significant for DG
GTs	Commercial, strong position	330-470 (500-700) for >1MW_e	Small ~ 33% Mid ~ 42% CCGT ~ 60%	Mid-size and micros currently niche. Included in CHP
ICEs	Commercial, strong position for DG	270-400 (400-600)	up to 50% for large ICEs	Leading, proven technology for up to ~20MW
Hydrogen fuelled	Pilot scale demos	N/a	Unknown (zero CO_2 from plant)	Could need new infrastructure
Novel cycles	Demo	N/a	Targeting 50-70%	eg Kalina, CO_2 recycling, recuperation, condensing cycles

N/a – denotes no commercial plant
ICE – Internal Combustion Engine
IGCC – Integrated Gasification Combined Cycle
FB – Fluidised Beds
DG – Distributed Generation
fgd – Flue gas desulphurisation

In the UK, three approaches are currently being used to reduce CO_2 emissions from fossil fuel-based power generation:

- Switching to lower carbon content fuels such as natural gas
- Increasing efficiency of conversion from fuel to energy
- Reducing demand through energy efficiency and demand-side management

The push for increasing efficiency is also raising the profile of Combined Heat and Power (CHP) both at small and large scales. There is concern, however, that external factors such as the structure of the market are currently restricting the growth of the CHP sector.

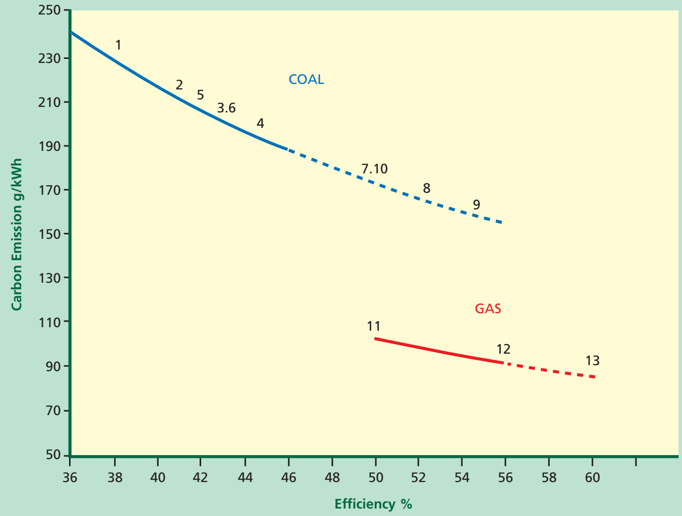
Opportunities for efficiency improvements also arise where waste heat can be used in absorption chilling to deliver cooling in industry, commerce and the public sector.

Previous Department of Trade and Industry (DTI) fossil fuel R&D programmes have promoted the development of many of the technologies in Table 1. These technologies have led to the availability of much more efficient plant (eg 45% instead of 35%) and this, in turn, has led to reductions of around 25% in emissions of CO_2 per MW of electricity produced.

The achievements of current R&D programmes and the medium term developments to which they are contributing are shown in Figure 1.

Figure 1

Efficiency improvements and impact on CO_2 emissions



Plant type	Efficiency with Cooling Tower %	Source
1 Subcritical pf with FGD	38	typical
2 Subcritical pf with FGD	41	best available
3 Supercritical pf with FGD	43	typical
4 Supercritical pf with FGD	45	best available
5 PFBC	42	demonstration
6 IGCC	43	demonstration
7 PFBC (2010)	50	•
8 IGCC (2010)	53	•
9 Supercritical pf (2010)	55	•
10 ABGC (2010)	50	••
11 CCGT (early)	50	typical
12 CCGT (current)	56	typical
13 CCGT (2005)	60	•••

• Energy World, March 1997
•• Private Communication
••• Power Generation, 1997

Electricity production from biomass uses similar technologies to fossil fuel power generation. However, plant sizes are dictated by the local availability and price of the fuel, together with the economics of the overall system. Because power generation from biomass is regarded as carbon neutral, this is seeing increased implementation both in the UK and globally.

A potentially important route for overcoming these difficulties and achieving economies of scale is to co-fire biomass with fossil fuels. This is now being adopted as an alternative means of reducing CO_2 emissions and using fossil fuels effectively.

In 2002-3, the Government recognised that the scale of the issues presented by global warming and security of supply needed, according to the Prime Minister (1), 'a new direction for energy policy'. This policy recognises that fossil fuels will continue to play a significant role for many decades to come both in the UK and abroad.

Looking out to 2020, the White Paper predicts that gas will form a large part of the energy mix. Coal has advantages for security of supply, but, if it is to play a significant role in the UK energy mix beyond 2015, generators will need to find economic ways of reducing or dealing with the consequential CO_2 emissions.

One option is CO_2 capture and storage (CCS) and this is seen as 'offering a promising way forward' (1). This is part of the ZEPG power generation technology referred to above. It also has the advantage that if the CO_2 is captured as part of a gasification cycle, one of the products produced is hydrogen. Such an approach therefore could provide a link between fossil fuels and the hydrogen economy increasingly being examined.

The Government has also acknowledged the significance of ZEPG technology in global markets, and it recognises that UK industry should be well placed to take advantage of these large global markets.

However, this has also been recognised in other countries with strong power engineering sectors, and has led to the initiation of RD&D programmes such as the USA's Vision 21 and FutureGen programmes, Canada's CO_2 capture and storage programme, Japan's New Sunshine Programme, and Germany's COORETEC programme. If the UK power engineering industry is to retain and grow its world market, it too needs to be at the forefront in the development of these technologies.

This all points to the urgent need for a strategy and R,D&D programme for the progressive development of Cleaner Fossil Fuel and Near-to-Zero Emission power generation technologies in the UK. This would be an integral part of a carbon abatement strategy addressing fossil fuels.

2 Future energy scene

2.1 Global Power Generation

The IEA, in its World Energy Outlook 2002 (6), projects that global electricity demand will grow by 2.4% per annum from 2000 to 2030. This projection means that nearly 5000 GW of new generating capacity will need to be installed, worldwide, over this period. Total installed capacity will rise from 3397GW in 1999 to 7157GW. About a third of new capacity will be in developing Asia. In the EU average growth out to 2020 is predicted at 2% per annum (5). Figure 2 illustrates the expected contributions of the different fuels (6).

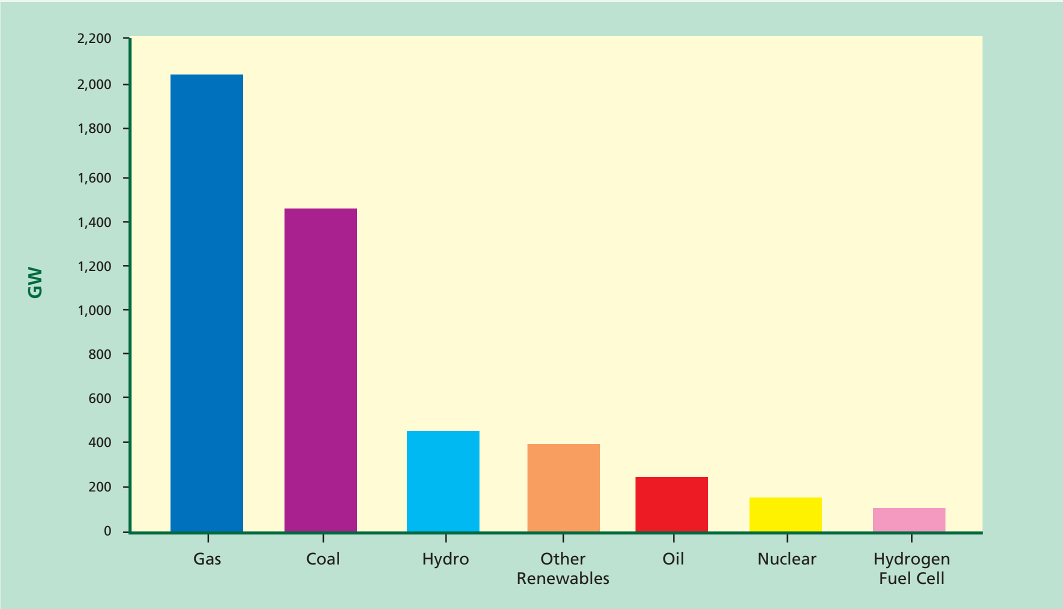
Over the next three decades, fossil fuels will continue to dominate in global power generation but with a shift in favour of natural gas. The IEA global predictions are (6):

- Coal based generation will dominate, and coal based production will more than triple, in developing countries. Nonetheless, the share of coal fired generation in the global mix will decline by more than two percentage points to 37% because this increase in developing countries is more than offset by a decline in the OECD.
- Gas fired generation is projected to increase significantly from 17% in 2000 to 31% in 2030. Gas turbine based plant will remain the preferred option for new generation with fuel cells in distributed generation applications expected to start contributing from around 2020.
- Oil accounts for about 8% of electricity generation globally, and its use in power generation has fallen steadily since the first oil shock. Its share is projected to continue falling to about 4% by 2030.
- Non-hydro renewable energy will account for a small but rapidly growing percentage of global electricity. In 2000, it was about 1.6% and it is projected to rise to about 4.4% by 2030. However, in OECD countries the growth in non-hydro renewables is expected to be more rapid, reaching 7.1% in 2020. Wind and biomass are projected to dominate this sector.

Figure 2

World Electricity Capacity Additions, 2000-2030

Source: World Energy Outlook (6)



2.2 UK Power Generation

The White Paper puts forward a vision for the UK energy system in the year 2020. It is envisaged that much of our energy will be imported, and that the system will be much more diverse than today, with a greater mix of energy sources, especially in electricity production.

The vision for power generation presented in the White Paper (1) includes:

- The backbone of the system will still be a market-based grid balancing the supply of large power stations. These large stations will include fossil fuel plant, large wind farms and offshore marine plants. The market will need to manage intermittent generation by using back-up capacity when weather conditions affect the output from renewables

- There will be much more local generation from medium to small power plants fuelled by locally grown biomass, from local wind sources or possibly from local wave and tidal generators. These will feed local distributed networks. Plant will also increasingly generate heat for local use
- There will also be much more micro-generation for example from CHP plant, fuel cells in buildings or photovoltaics
- Gas will form a large part of the energy mix
- Coal fired generation will either play a smaller part than today in the energy mix or be linked to CO_2 capture and storage (if that proves to be feasible on technical, environmental and economic grounds)
- The existing fleet of nuclear power stations will almost all have reached the end of their working lives

In an EU study (4), the UK's growth in electricity demand is predicted to average at 2.6% out to 2010 and then drop to 1.5% to 2020 although Energy Paper 68 (5) gave a lower growth figure for the UK (about 1% to 2010, then less than 0.5% to 2020).

An economics study (9) done in conjunction with the White Paper has looked at various energy scenarios for the UK out to 2050, and in particular at the likely fuel types to achieve the Government's target of 60% reduction in CO_2 emissions by 2050. The details vary according to the assumed scenario but all scenarios show that for the range of assumptions used:

- coal fired generation may disappear by 2030, unless economic ways can be found to reduce CO_2 emissions
- existing nuclear generation is mostly decommissioned by 2030
- gas fired generation increases significantly
- renewables increase but if intermittency of renewables is taken in to account this will limit their growth (over this period renewables are dominated by wind and biomass)
- the most cost effective means of reducing CO_2 for fossil fuels is by increasing generation efficiencies but the projected increases in gas fired generation efficiencies are insufficient to achieve the target reductions in CO_2, hence significant installation of 'zero emission' CCS is required from about 2030 onwards

If new nuclear build is allowed, gas fired generation still grows but it can reduce or remove the need for CCS.

The reason for the disappearance of coal fired generation post 2030 is that the economics study was based on meeting the CO_2 constraints at least cost, and, under all scenarios, coal is replaced by gas as the new plant costs are projected to be cheaper for gas. For coal to survive in the UK post 2030, it must compete with gas on p/kWhr for new plant. However, more recent studies, which are referred to in the annexe to the economics study (9) indicate that retrofitting of new boilers to existing coal plant can be cost competitive with new gas plant as a means of increasing UK generation efficiencies. These studies also indicate that for the latest designs of new coal plant, coal can be competitive with gas in a high gas price scenario. A further study (WETO, (10)) carried out for the EC, suggests that coal-fired plant will become cheaper than gas by 2025, and that with a positive R&D programme, this date could be brought forward to 2015.

For transport, hydrogen fuel is projected to be required post 2020 and possibly earlier for the distributed generation market; the economics studies show that the least cost option is by generation from gas, or possibly biomass.

2.3 Carbon Dioxide Emissions

According to the Intergovernmental Panel on Climate Change (7), "Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate". The major contributor is carbon dioxide (CO_2), which arises mainly from the use of fossil fuels. In the UK, for the year 2000 (8) about 190Mt CO_2 from the total energy related emissions of 530Mt CO_2 were produced in energy conversion plant; over 80% of the CO_2 from energy conversion was associated with electricity production.

Globally, IEA projections (6) indicate that CO_2 emissions will increase by 1.8% per year from 2000 to 2030. Electricity generation will be a growing source of total CO_2 emissions resulting from human activities, rising from 40% of total CO_2 emissions to 43% in 2030.

Developing countries will account for almost three-quarters of the incremental CO_2 emissions from power generation. Coal-fired plants in these countries will account for more than half of the global increase in power generation CO_2 emissions in the next three decades.

The projections of CO_2 emissions are based on there being a continued, gradual increase in power generation conversion efficiencies, as shown, for example, in Figure 1. Under current assumed scenarios, CCS technologies are not expected to be deployed globally on a large scale before 2030 (this aligns with the projections for the UK). There are economic, social, legal and technical issues to be overcome with CCS before it can be implemented on a large scale. However, if these can be resolved it would increase the attractiveness of fossil fuels over renewable energy sources and in the words of the IEA (6) when referring to global energy, 'This would revolutionise long term prospects for energy supply'. For fossil-fuel technologies, CO_2 capture is a future possibility. A similar view is expressed by The Royal Commission on Environmental Pollution (3), which comments that if CO_2 removal can be done safely and cost-effectively then a substantial proportion of the UK's electricity could continue to be produced by fossil fuels.

Worldwide, the capacity for geological storage of CO_2 is over 1500Gt, or about 100 times the current world annual energy related CO_2 emissions.

Carbon capture and storage also provides the option for producing hydrogen from fossil fuels with zero or near-to-zero CO_2 emissions. Globally, transport is the second largest producer of man-made greenhouse gas emissions. The auto industry (1) generally expects hydrogen powered fuel cell cars to move towards mass marketing around 2020, and this will require large-scale generation of hydrogen. This is recognised by the White Paper, which is supporting R,D&D programmes for hydrogen in the transport sector. Power generation from fossil fuels with CCS offers a means of producing hydrogen without CO_2 emissions – for example by gasification.

Clearly, power generation technology is critical in meeting the needs of current and future generations. Developments will be required to support the growing energy demand without unacceptable impact on the environment. In particular, the issue of CO_2 emissions from fossil-fuelled power generation plant will have to be addressed.

3 Future markets for power generation plant

3.1 The Global Market
Over the next 30 years, the global business for new generating plant is expected to be in excess of $4000 billion, with over 5000GW of new generating capacity being built worldwide between 2000 and 2030.

For the next 30 years, the large central power station is still seen as being dominant for both existing and new-build power plants (6). Coal and gas will remain as the two major fuel sources. Over this period, coal is expected to remain the largest source of electricity generation but there will be more new-build gas plant than coal plant, see Figure 2.

The International Energy Agency estimates the new build coal plant for the period 2000-2030 to be 1400GW (6), which is worth approximately $1400 billion at today's prices. The dominant technology in the short term is likely to remain as Pulverised Fuel (pf).

For gas, the projected new-build plant for this period is estimated to be 2000GW (6), which is worth approximately $1200 billion. Gas Turbines (GTs) are expected to continue to be the technology of choice. Large GTs will remain dominant, however there will be a growing market for micro, small and mid-size GTs.

The key drivers that will determine which particular power plant technologies will enter the market place in the future have been identified by the APGTF as:

- Cost (e.g. capital, through-life, fuel, infrastructure)
- Regulation (e.g. environmental, government policy, public opinion)
- Resources (e.g. fuel, fuel flexibility, security of supply)
- Business/Market Dynamics (e.g. deregulation, ownership, electricity/emissions trading)

Over the next 20 years some of these drivers are expected to lead to the gradual growth of Distributed Generation (DG), where electricity and possibly heat is produced close to the load centre. This would lead to some displacement of conventional large power plant.

Predictions for global electricity production from distributed generation plant range between 10 and 20% over the next 20 years, and in the EU (4), predictions are for up to 20% by 2020. If fuel cells can be made cost-competitive, they are expected to start making significant contributions in distributed generation applications around 2020, with the projection of 100GW by 2030 (4), almost entirely in OECD countries.

Longer term, these drivers are likely to produce substantial changes in power plant technology mix, particularly if there is continued commitment to reduce greenhouse gases. Post 2020, renewables could start to make a major impact and in the EU, partly because of the decommissioning of existing nuclear plant, predictions show that other technologies may also start to contribute (3). These could include: clean fossil fuels; hydrogen; renewables; fuel cells; new nuclear; wider use of combined heat and power (CHP).

3.2 The UK's Position in the Market
The UK share of the global market for new power plant in the last decade was in the region of 11-12.5%. In 1995 the UK power engineering industry had a turnover of £13.6 billion and employed 150000 staff (11).

Power engineering equipment companies in the fossil sector in the UK include major companies such as ALSTOM (turnkey plant, steam turbo-generators, gas turbines), Mitsui Babcock (boilers and pipework, low NOx systems), Howdens (fans, compressors, air heaters), Clyde Bergemann (sootblowers, coal and ash handling), Weir Group (pumps and valves), Rolls Royce (aeroderivative gas turbines, CHP, fuel cells), Siemens (Industrial gas turbines), Peter Brotherhood (steam turbines, CHP, gas compressors), Wood Group (gas turbine services and turbo machinery services), and Caterpillar (diesel engine power generation systems). In addition to these there are companies such as Jacobs (coal gasification), Fluor (flue gas scrubbing to remove CO_2) and BOC (oxygen production for gasification or oxyfuel firing). All these companies are global technology leaders with technology expertise residing in the UK. This is not an exhaustive list, but is intended to reflect the range of strengths within the industry.

Thus, the UK has technology strengths in areas such as boilers, steam turbines, gas turbines, clean coal technology, flue gas clean-up, materials, combustion science, catalysts and power systems engineering. It is also an acknowledged leader in systems design, environmental assessment and in the overall technical and financial management of power plant design, construction and operation. In recent years, these strengths have moved away from that of heavy manufacturing industry to the specialist or high technology manufacturing and high intellectual property products and services; this has resulted in a greater emphasis on high added value components and technologies.

The companies have developed their business strategies to recognise the globalisation of the industry and the demands of customers to combine the strength of established technologies with the lower costs of local suppliers. The companies have established subsidiaries, partnerships and licence arrangements around the developing world to serve these needs. Furthermore they have built up sustainable long-term after sales services business worldwide taking advantage of their technologies and OEM[3] status. The companies are strong in Europe, Asia, the Pacific Region, and America.

If the UK could retain a 10% share of the clean coal and GT markets over the next 15 years, this would be worth £51billion (11). Achieving such a share is an increasingly tough challenge as a large proportion of the market, in the early years at least, will be in China where customers will seek to maximise local supply. There therefore needs to be a strong and focused programme for research, development and commercialisation of clean fossil technologies suitable for world markets (both New Build and Retrofit opportunities) to ensure that UK companies can offer state of the art technology. Such a programme is needed to allow UK companies to keep pace with their overseas competitors (see below).

3.3 The Nature of the Competition

Governments in other countries are making significant investments in power plant technology development for the longer term, typically 2010 and beyond, to ensure that their industries remain competitive; details are shown in Table 2.

This, combined with the preference of the US, Japan and certain European countries to install locally supplied plant, and the more open nature of the UK power plant market, could put UK industry at a significant relative disadvantage. The UK needs to have, or be part of, a similar strategic R,D&D programme to maintain its position in the future UK and global markets.

An additional factor is the way in which the privatisation of electricity generation has affected both the commercial and R,D&D environment. Instead of having a large monopolistic single generator, the UK now has a number of small generators who are often owned by overseas companies. This is affecting the climate for R,D&D because of the tendency to locate research activities in the home country of the parent company.

This effect is compounded by the current low selling price of electricity, which is reducing the capacity of the generating companies to invest in both plant and R,D&D, and is having a knock-on effect throughout the industry. While this may be a transient phenomenon, it is nevertheless having a major impact at present.

One of the best ways of countering these transient market effects is to have a healthy national R,D&D programme that maintains the momentum of development and ensures that UK technology development and skills are not disadvantaged relative to those in other countries.

3.4 The future UK power plant industry

The future power plant industry for cleaner use of fossil fuels will be adapted to the needs of the global marketplace whilst serving local requirements in the UK. It will combine the current strengths of the UK's companies in this sector with ownership of new technology and the supply of higher value products and services. A variety of routes will be used to secure business including licensing, design contracts, partnerships, consultancy, after-market services, and traditional engineer-procure-construct contracts. Manufacturing will continue to have an important role, albeit smaller than in the past, with a focus on higher value, proprietary components, and new products based on technological developments.

[3] OEM – Original equipment manufacturer

Table 2

Strategic development programmes in the USA, Japan, Germany and Canada

	Programme	Objectives	Value	Status
USA	**DoE Clean Coal Technology Demonstration Programme**	To foster secure, environmentally and economically sustainable energy supply over a broad range of technologies. Emphasis on environmental control devices, advanced electric power generation, coal processing for clean fuels, and industrial applications.	$5.2bn (total)	Almost complete. This programme formed the foundation for future programmes
USA	**Clean Coal Power Initiative**	Ten year programme. Round 1 is aimed at reducing SO_2 emissions to 3 MT/y, NOx to 1.7 MT/y and Hg to 15 t/y over 15 years, and at reducing greenhouse gas emissions through increased efficiency.	$2.0bn (federal)	On-going
USA	**Power Plant Improvement Initiative**	Demonstration of near-term technologies to increase efficiency, lower emissions, and improve economics of coal-fired power plants.	$95m (federal)	On-going
USA	**Fossil Energy Vision 21**	To eliminate environmental concerns associated with the use of coal and other fossil fuels. To provide the basis for flexible commercial plant designs by 2015, with interim benefits from 2005. Targets include: Efficiencies (electricity) > 60% on coal; > 75% on gas Overall thermal efficiency 85%-90% Near zero pollutant emissions Cost effective management of carbon emissions Lower cost of electricity than today.	$220m (2001 budget)	On-going
USA	**Coal Power Programme Roadmap**	To demonstrate power and multi product plants meeting strict criteria, plus target costs for liquid fuels (<US$30/bbl) and hydrogen (US$3–5 /10^6BTU) from coal by 2020. An additional target is 90% CO_2 removal and sequestration at an additional cost of electricity of <10%.	$10.7bn (total proposed)	On-going
USA	**FutureGen**	Development of a 275MWe coal-fuelled IGCC plus hydrogen production plant demonstration with CO_2 separation and geological sequestration.	$1.0bn 80% Federal	Proposed
Japan	**New Sunshine Programme**	Clean coal technology; Gas turbine efficiency > 70% Commercial, cost effective hydrogen technology.	£360m (1999 budget)	On-going
Germany	**COORETEC**	CO_2 reduction; target is an emission free fossil fuel based power plant.	€120m	Start in Q4/2003
Canada	**Clean Coal Power Coalition**	To assess the feasibility of retrofitting a pf coal plant with CO_2 capture systems by 2007, and of building a green field installation by 2010	Phase 1 C$5m Retrofit C$500m Green field C$1bn	On-going

The sector will continue to support a large number of high quality jobs with a large supply chain of small and medium sized enterprises (SMEs). In this sector a high proportion of the jobs are in engineering, from engineering operators to engineering technicians and professional engineers. At the operator level the jobs include machinists, welders, fitters, erectors, all who operate high technology equipment. Technician jobs include welding, electronics, instrumentation, non-destructive testing (NDT), inspection and quality control. A wide range of professional engineering disciplines are involved in power plant design, manufacture and commissioning – including mechanical engineers, chemical engineers, electrical engineers, design engineers and control engineers.

Maintaining a thriving UK power plant industry for cleaner use of fossil fuels will have major benefits:

- High technology, high value products will be available for large power plant, distributed generation and cogeneration/chp applications based on technology vested in the UK. Improved technology performance will reduce harmful emissions while increasing electricity output. This will have environmental benefits in the UK and globally and will contribute directly to achieving the Government's Energy Policy goals.
- The sector will continue to make a major contribution to UK exports with major markets in Europe, Asia and the Americas for both products and services.

It is also recognised that technologies developed for power generation do have a wider application to other industrial sectors and therefore accrue additional benefits to the UK. This is discussed in Section 4 for the existing programmes and in Section 8 for those activities being proposed as part of the carbon abatement approach put forward in this document.

The technological development required will be achieved by building on the partnership between UK companies and the universities, developed through the government Clean Fossil Fuel programmes (past, present and future) and underpinned by longer term R&D already planned in the universities. Benefits are already accruing from the earlier stages of the DTI's programmes (see Section 4) and future benefits will be greater as the global market moves further towards cleaner use of fossil fuels.

4 Benefits from DTI cleaner coal R,D&D programmes

The UK industry's technology strengths have increasingly benefited from the DTI's Clean Coal R&D programmes. These were initiated in the early 90s in response to the privatisation of the electricity supply and coal industries. The focus was initially on completing British Coal's strategic R&D programme, but then moved to encouraging collaboration between industry, universities and overseas organisations. Following a review in 1998, the DTI Energy Paper 67 was published in 1999 (17). This paper set out aims and objectives for a six year (1999-2005) programme, with a review after three years when the possibility of extending the programme to support demonstration projects would be considered. The overall aim was: "To provide a catalyst for UK industry to develop cleaner coal technologies and obtain an appropriate share of the growing world market for the technologies".

The collaboration requirements of the DTI's Clean Coal Programmes have encouraged industry (power plant manufacturers and generators) and universities to combine their efforts, and to seek international partnerships. This has raised the profile of the UK industry in Europe, Asia and the USA and allowed the development of key corporate and individual skills in cleaner coal technology. The expertise gained has allowed UK companies to participate in many collaborative projects with European, American and Chinese partners.

Substantial technological benefits and follow-on business have been gained in eight areas:

- Once through boilers for subcritical (eg. Yaomeng, in China), supercritical, and advanced/ultra-supercritical applications
- Boiler materials including steels and alloys for the 700°C/300 bar ultra-supercritical AD700 project
- Validated Computational Fluid Dynamics (CFD) modelling of coal pulverisers, burners, furnaces, precipitators
- Turbine material and components for advanced steam conditions
- NOx reduction and control technologies: burners, overfire air, reburn, selective autocatalytic reduction
- Biomass co-firing
- Gas turbine combustion technology for a wide range of low to medium calorific fuels
- Measurement of coal, air, flue gas, fuel flow
- Furnace performance monitoring and automated optimisation
- Reducing risk in power plant projects overseas due to improved competence

Some specific examples of products which have benefited directly or indirectly from the programmes are listed in Table 3 overleaf.

Although developed specifically for power generation some of the technologies have had a wider application in such sectors as aerospace, automobile and chemicals. Specific examples include the way in which knowledge developed on low emission combustion systems is now being taken up in aero engine developments where the environmental drivers are similar. [Note: ALSTOM has a small but strategically important UK aero engine activity where it designs, makes and supports engine parts. Most of the large power generation companies world wide are associated with aero engines because of the synergy between the technologies]. Also there is a greater liaison on material and coatings issues where many of the specific technologies are common to both land and air based gas turbines (for instance on heat and corrosion resistant coatings, use of nickel based alloys and life prediction). Coatings technologies are also used by the chemical industries.

Design and analytical modelling (such as aerodynamics, CFD, stress analysis and life assessment) are widely applicable and used across many different sectors, aero, auto and chemical to name but three. Tools that are developed by the power industry therefore add to the general knowledge within the UK and get broad use.

Table 3

Examples of specific benefits from the DTI Cleaner Coal Technology R&D programmes

Programme	Objectives	Companies involved
Ultra-supercritical Power Plant	UK companies are major participants in the THERMIE AD700 project to develop a 300 bar/700ºC ultra-supercritical power plant with 50-55% efficiency and will be well placed to benefit from a follow-on demonstration project.	Alstom, Mitsui Babcock, Corus, Powergen, Innogy, Wyman Gordon, Goodwin
Advanced Supercritical Boiler/Turbine Retrofits	A group of UK companies have developed a retrofit product, taking advantage of state-of-the-art components and materials that have been tested under several projects, and the experience gained in the course of a once-through retrofit at Yaomeng in China.	Mitsui Babcock, Alstom, Scottish Power, Cranfield University
Supercritical Boiler for new build in overseas markets	Collaboration between a boilermaker and a utility has led to a generic design using state-of-the-art commercial materials and a vertical-tube low mass flux positive flow response furnace which is cost competitive in overseas markets including USA and China.	Powergen, Mitsui Babcock and European partners
Low NOx Combustion Systems	Low NOx burners and overfire air have been separately developed and successfully marketed by two UK companies. Burners have been proven for a wide range of coal types including, recently, low volatile Chinese coals, and furnace types (corner fired, wall fired and opposed wall fired). Over 75% of UK coal fired plant has been retrofitted with Low NOx burners sourced from UK companies and the product has been exported around the world. Technologies are available to meet the demands of the Large Combustion Plant Directive.	Mitsui Babcock, Alstom
Gas Reburn and Coal Reburn for NOx reduction	Gas and coal reburn technologies have been developed and, with EU support, demonstrated at full scale in the UK and Italy respectively. These were each the largest demonstration of their type in the world.	Mitsui Babcock, Powergen, ScottishPower, Howden
NOx and Burnout Prediction	Developing the techniques and tools to enable manufacturers and generators to be able to predict the NOx emissions and carbon-in-ash from coal specifications. Projects identified capabilities of modelling and the desirability of combustion rigs	Innogy, Powergen, Scottish Power, Mitsui Babcock, Alstom, TXU, Imperial College, Leeds and Nottingham Universities, Fluent, Computational Dynamics, Cinar
Downshot furnaces for Anthracite	Furnace modelling using CFD techniques developed and validated with the support of the programme was an essential tool for the design of a family of boilers exported to China.	Mitsui Babcock
Coal Bunker Level Monitors development	Development of coal bunker monitors to detect operational problems and therefore reduce safety and business interruption risk	Innogy, British Energy,
Unit optimisation	On-line optimisers for furnace operation, NOx control, unburnt carbon, heat rate, turbine performance, intelligent sootblowing, and ESPs have been developed and tested. The GNOCIS product has been sold widely in the USA.	Powergen and collaborators
Air-heater performance model	Development of an on-line air-heater model to determine when to clean and when to maintain to ensure good plant performance	Innogy, Howdens
Biomass cofiring	Limitations of biomass cofiring are better understood both for current plant and future advanced plant such as AD700, and have been demonstrated at rig and full scale.	Innogy, Powergen, Mitsui Babcock, Vattenfall
Impact of coal blending	Identification of the effect of blending on coal impact on power plant	Innogy, CRE
Impact of Chinese and Indian coal on power plant performance	Production of a database of the characterisation of Indian and Chinese coals	Innogy, Imperial College, Mitsui Babcock, Powergen, Royal Holloway College
Materials for Boiler retrofits	New European and Japanese steels (higher strength, greater creep and fatigue resistance, better corrosion properties) are available for plant retrofits as well as for new build.	Innogy, Powergen, Mitsui Babcock, Corus, Cranfield University

5 Policy framework and objectives

The Government's policy, as described in the White Paper, has set four goals (1)

- To put ourselves on a path to cut the UK's CO_2 emissions by some 60% by 2050
- To maintain the reliability of energy supplies
- To promote competitive markets in the UK and beyond, helping to raise the rate of sustainable growth and to improve our productivity
- To ensure that every home is adequately and affordably heated

Based on the UK policies in existence before the White Paper, UK CO_2 emissions were expected to be 135Mt of carbon (MtC)[4] by 2020. The Government is now proposing cuts of 15-25MtC below that for 2020, which it believes is consistent with their long-term target of 65MtC emissions by 2050 (a 60% reduction compared with 1990).

The White Paper comments that the future for coal must lie in cost-competitive cleaner coal technologies, which can increase the efficiency of coal-fired plant or carbon capture and storage. Electricity generation from coal will become more expensive when the EU's large combustion plant directive (to control emissions of sulphur dioxide, nitrogen oxides and dust) comes into effect. Plant that does not meet the demanding standards is likely to be retired over the period to 2015. EU-wide carbon emissions trading will also make coal less attractive as a source for power. Also, in North America there are concerns regarding mercury which may ultimately result in future controls on the emission of mercury.

If cost-effective ways can be found to reduce carbon dioxide emissions at the same time as meeting other emissions limits, keeping coal fired generation in the fuel mix would offer significant energy security and diversity benefits (1). If coal is to play more than a marginal role in the mix beyond 2015, ways must be found of reducing the consequential CO_2 emissions. As mentioned above, both efficiency improvements and carbon capture and storage have been identified as the promising approaches. For carbon capture, the most promising approach at present would be to lock the gas away in geological structures such as depleted oil and gas fields. The UK North Sea offers a potentially very valuable resource in this respect; it also offers the additional potential of extending the life of the North Sea oil reserves by using captured CO_2 for enhanced oil recovery (EOR).

The White Paper recognises the importance of Carbon Abatement Technologies (CAT) for the UK and in particular it recognises 'the potentially significant strategic role that might be played by CCS in the longer-term' (1). The DTI has commissioned a review of the feasibility of CO_2 capture and storage in the UK and in particular of EOR (8).

This review points out that the UK has access to substantial carbon dioxide storage capacity including about 2600 Mt in depleted oil fields, 4900 Mt for storage in depleted natural gas fields in the North Sea and substantially more than this in deep saline aquifers. About 750Mt of this potential could be stored as part of EOR operations. This can be compared with the emission of approximately 150Mt CO_2 from the power-generation sector in 2000.

The main conclusions of the review are:

- All the factors considered make carbon capture and storage an important greenhouse gas abatement option for the UK. Furthermore, with its strong industrial base in power engineering, the UK could win a substantial share of the much larger global market for carbon capture technology. There is a need for further action to stay at the forefront of CCS technology, which is now moving to the demonstration stage.
- Overall, the results show that EOR is the leading option for demonstrating carbon capture and storage in the UK. This is because it is the lowest cost option and is likely to be permitted under the current London and OSPAR Conventions.

The time at which EOR needs to start varies between fields depending on when they were first brought into production; this means the duration of an EOR scheme can vary from about 10 to 20 years for the North Sea. Previous studies as reported in (8), suggest an annual carbon dioxide demand of about 15Mt CO_2/yr averaged over 20 years, with the demand peaking at about 35Mt/yr in 2020.

[4] In quoting emissions, 12 tonnes of carbon equates to 44 tonnes of CO_2.
Thus, 135MTC is equivalent to 495MTCO_2.

Overall these studies suggest that total demand for CO_2 for EOR in UK North Sea oil fields could be about 10 Mt/yr up to 2010, increasing to about 25 Mt/yr from 2010-2015 and reaching a peak of 35 to 40 Mt/yr between 2015 and 2025.

The White Paper has recognised this limited time window and says, “If EOR is to be of value to the UK it needs to start within 5 years”. This means that the target date is ~2010 for a commercial demonstration of power plant with CO_2 capture linked to EOR.

6 Technology development strategy for zero emissions

6.1 Policy

A UK R,D&D technology development programme for fossil fuelled power generation must be consistent with Government policy. It is the view of the APGTF that the aims of the programme should be:

- to provide affordable, acceptable and commercially available large scale near-to-zero-emissions power plant
- to provide UK industry with global power market opportunities out to 2030
- to contribute significantly to UK wealth creation

Such a R,D&D programme needs to be considered within an overall system for the development, demonstration and commercialisation of near-to-zero-emissions technologies. It also requires longevity (the product life cycle time with such components and plant being up to several years/decades in duration) and be subject to regular review. The essential elements should focus on ensuring that the barriers, both technical and non-technical, are reduced/removed and are as follows:

- research, development and demonstration;
- policies and measures to support a market for the technologies;
- understanding of all market drivers;
- action to win social acceptance.

There are significant risks and costs to industry in developing new technologies and in seeking to establish a 'first of kind' scheme at a commercial scale, especially with the increased levels of liberalisation, privatisation and de-regulation in the market place. Government assistance is essential not only to encourage initial research and development, but also to help bring the resultant technologies to the market.

It will be essential that any UK initiative developed in energy R,D&D should not be pursued in isolation. The next EU RTD Framework Programme (FP7) is under development and it is likely that this will form the basis of future EU Research Framework Programmes post 2006. The UK has a significant opportunity to take a leading role in the formation of large critical mass Integrated Projects and Networks of Excellence in the field of energy. It is therefore important that the UK Government takes an active role in supporting the UK Energy Sector in this respect and in shaping future programmes to ensure benefit to the UK, especially industry. It is also recommended that the Government should support the development of other international collaborations, particularly with North America. For example: a MOU is already in place with the USA, this should be utilised to the full to ensure benefit to the UK. Also active participation should be maintained in the newly USDOE initiated Carbon Sequestration Leadership Forum (CSLF) where 16 nations have signed a Charter to promote ZEPG/CCS technologies for fossil fuels.

The only way that UK industry will be able to compete in the future is by bringing to the global market place new technologies and new ideas that its competitors do not have. For this reason, it is essential that the UK has an active, well supported R,D&D programme that will produce the new technologies and skills for the future.

Taking account of the UK and the world market potential, a UK R,D&D programme needs to consider gas, coal and biomass for the short, medium and long terms.

6.2 The Strategic Programme

It is clear that there should be two themes to a strategic R,D&D programme for fossil and biomass fuels:

- increasing plant efficiencies at commercially competitive costs
- near-to-zero emission power generation with a CO_2 capture goal

The "plant efficiencies" part can be seen as a precursor to that of 'CO_2 capture' for OECD countries but for the markets in the developing world, it may represent the long term solution. Also it should be recognised that there is an interaction between the two parts (the amount depending upon the technology under consideration), with the `$CO_2$ capture` part needing to take advantage of the higher efficient components to offset the detrimental impact of CO_2 capture on the overall efficiency of the system.

A key parameter in this interaction will be the future value of CO_2; at present very uncertain but with the EU Emissions Trading Scheme being introduced in 2005, it could be a firmly established market commodity within the next decade.

The interaction between the two carbon abatement trajectories is shown schematically in Figure 3.

The plant efficiencies programme (E) should carry on from existing programmes with which the UK is involved, and for which medium and long term targets have already been proposed (11).
In addition, there should be a short term target looking at the potential for increasing the efficiencies of existing plant by retrofit upgrades. Hence this programme should have 3 parts:

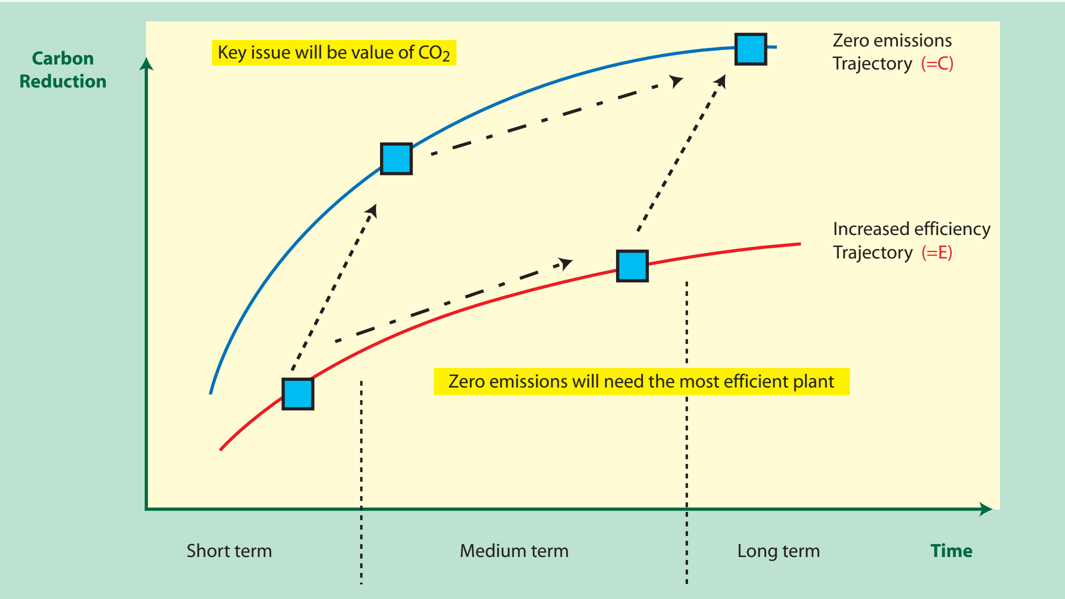
E1)	*Short term*	evaluation of increasing efficiencies of existing plant by using best available technology (BAT)
E2)	*Medium term*	increased efficiencies with higher operating temperatures and advanced steam conditions
E3)	*Long term*	further increase in efficiencies with higher temperatures and advanced technologies

Where:

Short term	=	available for commercial implementation 2005 onwards
Medium term	=	available for commercial implementation 2010 onwards
Long term	=	available for commercial implementation 2020 onwards

Figure 3

Strategy trajectories and their interactions



The corresponding targets are shown in Table 4.

An economics study (9) done in conjunction with the White Paper takes a value of approximately 35% as the average efficiency for the existing fleet of UK coal-fired plants (in 2000). Hence these efficiency targets of 50% and 60% (HHV) for coal represent reductions of CO_2 emissions of better than approximately 30% to 40% respectively, compared to currently installed coal-fired plant.

For gas-fired plant, the study (9) takes efficiency of existing plant as about 40%, so the figures represent between approximately 40% to 50% reductions in CO_2 emissions, compared to currently installed gas-fired plant.

Table 4

Technology targets for fossil fuel plant

	2005+	2010+		2020+
Electrical efficiency using coal	Best available technology	50%	HHV	60%
Electrical efficiency using gas	Best available technology	65%	LHV	70-75%
NOx, SOx, particulate emissions	Best available technology		Near zero	
RAM	Best available technology		Better than current values	
Costs	Cost effective generation		Cost effective generation	

It should be noted that the targets relate closely to those of US DOE in Table 2 and generally regarded as 'stretch targets'. However, they do in effect set the 'standard' which has to be met.

The CO_2 capture programme (C), needs to take account of the timescales for the projected implementation of CCS in the UK as given in Section 5.2, and for the requirements of EOR. For this programme, 3 parts are proposed:

C1)	*Short term*	carbon capture retrofit with best available technology for EOR
C2)	*Medium term*	carbon capture based on development of current technologies
C3)	*Long term*	carbon capture based on advanced technologies.

The targets for this programme are linked to those of Table 4 except there will be an additional target for minimising the generation efficiency penalty associated with carbon capture. These are shown in Table 5.

Table 5

Technology targets for fossil fuel plant with CCS

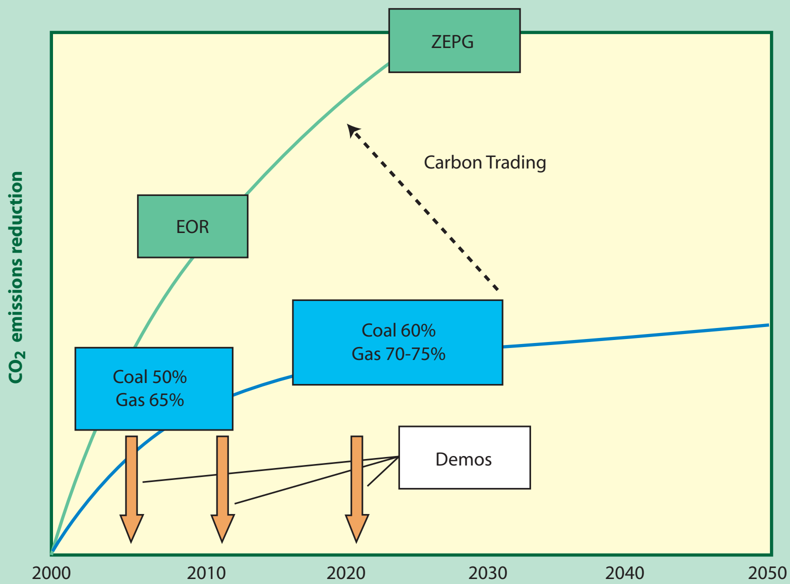
	2005+	2010+	2020+
Electrical efficiency using coal	Best available technology	50%	60%
Electrical efficiency using gas	Best available technology	65%	70 to 75%
Carbon capture penalty	Best available technology	-9%	-6 to 7%
NOx, SOx, particulate emissions	Best available technology	Near zero	
RAM	Best available technology	Better than current values	
Costs	Cost effective generation & EOR	Cost effective generation	

The timescales and priorities for each of these programmes will be driven partly by the speed of technology development but also by the economics, market/policies and social acceptance of carbon capture and storage. For example, the impact of the proposed Carbon Trading agreement could influence the speed at which the development of zero-emission technologies is driven. The time lines for the proposed programmes are shown schematically in Figure 4.

It is doubtful whether the necessary R,D&D investment will be made by industry without policy and market measures being taken to stimulate a potential market for the technologies. However, even if R,D&D is undertaken, and policies, market measures and regulatory systems are put in place, there are significant uncertainties about deployment of the technologies unless it is approached in a way that is socially acceptable.

Figure 4

Technology development time lines



The culmination of each phase will be the commercial demonstration of the power plant. Target dates corresponding to high priority being placed on CO_2 capture, as shown in Figure 4 are:

Advanced high efficiency coal plant	~ 2005+
Low emission power plant	~ 2010+
Zero emission power plant	~ 2020

The 2005+ plant should be a new or retrofit demonstration, including EOR if that is of commercial interest. The 2010+ demonstration should include carbon capture if the market trends support it, otherwise it should be carbon capture ready. The 2020 demonstration should include carbon capture; it could also include large-scale hydrogen production if the market and infrastructure support it.

The key plant technologies and the underpinning R,D&D that are needed to achieve these aims and targets of this strategic programme are presented in the following sections.

7 Future plant technologies

7.1 Power Plant

There are several power plant technologies for fossil fuels and biomass at various stages of research or development that may have the potential to meet the targets and aim points in a cost-effective way within the specified time frame. These technologies were assessed in a previous UK study (11) and for centralised power plant, the following were judged to be the key medium or longer-term technologies for UK R,D&D:

- **pf + fgd** – pulverised coal fired plant equipped with flue gas desulphurisation and operating at sub-critical or supercritical steam temperatures.
- **IGCC** – integrated gasification combined cycle in which coal or biomass is gasified; currently integrated with gas turbines (GTs) but could also be integrated with fuel cells (see Figure 5a). A gasifier could also be linked to an existing CCGT. Hydrogen could be produced as a by-product
- **GTs** – gas turbines; these can be integrated with other plant such as in combined cycle gas turbines (CCGT) (see Figure 5b). More complex cycles, such as wet cycles or inter-cooled recuperative cycles, can also be used
- **Fuel cells** – a strong contender for distributed generation; they could become a key component in any future hydrogen economy (see Figure 5c). These could also be integrated with other technologies such as gas turbines and gasification for centralised power plant.

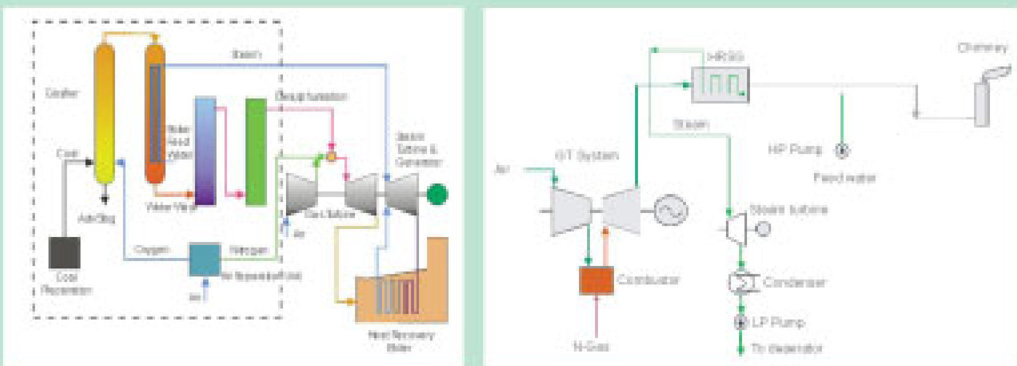
The chosen key power plant technologies have the potential to achieve the aim points and this will result in significant reductions in CO_2 emissions from future fossil fuelled power plant. The gasification technology also has the potential to produce hydrogen for the transport sector and the distributed generation sector with near zero emissions, using coal and CCS or biomass as a feedstock

These technologies are also relevant to power generation from biomass. Using current plant technology and current biomass stock to produce a constant 10MWe with an efficiency of 35%, requires approximately 4000ha of biomass planting. Achieving the aim point of 60% efficiency for solid fuels would result in a reduction of this acreage by approximately 40%; or, would produce approximately 70% more CO_2-neutral power from the same acreage.

Fig 5

Principles of Advanced Power Generation Technologies

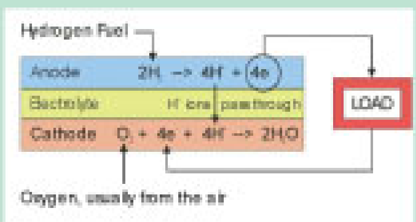
(a) (b)



(a) Integrated gasifier combined cycle

(b) Combined cycle gas turbine

(c) Fuel cell principle (example used is the alkaline fuel cell)



(c)

The plant efficiencies part (E) of the R,D&D strategy requires underpinning research and development and demonstration of the key plant types.

7.2 CO_2 Capture Plant

The CO_2 capture programme (C) will require R,D&D of plant to capture the CO_2 and its integration with generation plant with an ongoing programme to optimise the cost-effectiveness and performance of such plant.

There are three generic approaches for capturing CO_2 from power plant (Appendix 1):

- **Post-combustion capture** – CO_2 is captured from combustion products in the power plant flue gas
- **Pre-combustion capture** – coal is gasified (or natural gas is reformed) to produce synthesis gas (syngas) of carbon monoxide (CO) and hydrogen (H_2); a water/CO shift then takes place to produce H_2 (the fuel) and CO_2 which is separated before combustion of the fuel
- **Oxyfuel combustion** – fuel is burnt in oxygen with recycled CO_2-rich flue gas to increase the CO_2 concentration in the flue gas prior to capture

All three of the above approaches could be applied to new plant or retrofitted to existing facilities. Taking account of the existing generation capacity, the more feasible options for the UK can be grouped as listed in Table 6.

Table 6

Possible carbon capture technologies that could be deployed in the UK

Technology	Status	Type
Integrated gasification combined cycle (IGCC)	New	Pre-combustion capture
Gas turbine combined cycle with catalytic shift	New	Pre-combustion capture
Pulverised fuel (PF) with flue gas scrubbing	Retrofit	Post-combustion capture
PF + oxyfuel combustion + flue gas scrubbing	Retrofit	Oxyfuel combustion
PF + supercritical boiler + flue gas scrubbing	Retrofit or New	Post-combustion capture
PF + supercritical boiler + oxyfuel combustion + flue gas scrubbing	Retrofit or New	Oxyfuel combustion
CCGT with flue gas scrubbing	Retrofit	Post- combustion capture
CCGT with new coal gasifier to effectively produce an IGCC plant	Retrofit	Pre-combustion capture

New-build has the advantage of allowing maximum integration of the capture facilities into the power generation plant, which will benefit overall conversion 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 to reduce 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 oxide control technologies.

An alternative with pulverised coal plant would be to undertake a more comprehensive retrofit involving repowering with supercritical boilers and steam turbines. Although involving more capital investment this would improve the generation efficiency of the plant thus off-setting some of the energy losses associated with capture.

Having captured the CO_2, it needs to be transported to the storage site. For this, because of the large volumes of gas involved, pipeline transport is seen as the only practical option for a commercial operation; this is regarded as an established commercial technology (11).

Various methods have been proposed for storage or management of captured CO_2, including injection into geological formations, deposition on the deep ocean floor and conversion into solid minerals, again for placement in the deep ocean. Previous studies, e.g. within the IEA Greenhouse Gas R&D Programme (13), have looked at each of these options and the associated issues. A more recent study (8) has focused on geological storage because understanding of the processes is more advanced and it can be undertaken within UK or its surrounding territorial waters. There are public acceptability and regulatory issues to be addressed for all of these methods and they are considered in the quoted references. The main outstanding technical issue is to demonstrate that the CO_2 is retained in storage and that the leakage risks are fully understood.

7.3 Economics

The costs for implementing carbon capture and storage (CCS) have been examined for fossil plant in a UK context (8). Costs for the capture, transport and storage phases were estimated for a range of case studies considering large scale implementation (8Mt CO_2 per year) and covering alternative capture technologies (new build and retrofit), alternative locations, and storage through EOR or injection into depleted UK offshore gas fields.

The results given in Table 7 are central values based on generic cost data, and have an uncertainty of about +/- 30% reflecting site and plant specific variations. The ranges given for transport costs reflect different locations for the capture plant.

Table 7

Estimated costs for carbon dioxide capture, transport and storage in the UK North Sea oil and gas fields

	Cost (£/t CO_2)*
Capture	
Coal PF Retrofit of scrubber	19
Coal Pf supercritical with scrubber Retrofit***	21
CCGT Retrofit	14
New IGCC	13-34**
New CCGT	21
Transport	
Pipeline transport for EOR	7-8
Pipeline transport for storage in depleted gas fields	4-6
Injection	
Injection for EOR	7
Injection for gas field storage	1

* Capture costs estimated using a 10% discount rate and a cost factor of 80%. Costs are estimated by subtracting the cost of electricity from the long-run marginal cost plant (assumed to be fas fired CCGT) from the cost at plants with CO_2 capture and attributing this cost difference to CO_2.
** Costs based on two alternative design studies for IGCC plant
*** Costs from Gibbons et al, DTI seminar (not Reference 8)

The results show the overall cost of CCS to be of the order of £28-35/tCO_2 for EOR and £22-27/tCO_2 for storage in depleted gas reservoirs (Note: These costs mean that the higher cost IGCC option is excluded from Table 7). Capture is the most expensive element of CCS although this also holds the greatest potential for innovation and cost reduction in the longer term. This is illustrated by the results for new-build IGCC plant in Table 7 where the lower cost of £13/tCO_2 is claimed for a new design that considerably reduces the energy losses associated with gas separation.

Storage involving EOR is more expensive to implement than injection into a depleted natural gas reservoir because it requires extra investment in injection and production wells and modifications to production platforms. The advantage is that EOR gives a financial return from the additional oil produced. Assuming an oil price of $20/bbl this was estimated to be equivalent to about £24/tCO_2, which reduces the overall cost of CCS through EOR to about £4-10/t CO_2.

Table 8

Comparison of the CO_2 abatement costs for various technologies

Technology	Abatement cost estimates for 2020/25 (£/tCO_2)	
	Low	High
Energy efficiency	-70	10
Renewable energy		
Onshore wind	-10	35
Offshore wind	45	130
Energy crops	40	50
Wave	30	120
Tidal	70	190
PV	600	870
New nuclear	29	50
CO_2 capture and storage		
CCS with EOR	6	50
CCS with storage	34	93

These costs are estimated to add 1.0-2.3p/kWh to the cost of electricity (0.2-1.0p/kWh with EOR), which compares favourably to other large-scale abatement options. A comparison of the forecast carbon dioxide abatement costs for different technologies is presented in (8) and is summarised in Table 8. While the above economic assessment concentrates solely on CO_2 abatement, it must be stressed that CCS also deliver reduced emissions of sulphur and nitrogen oxides and particulate material. Also, for fossil fuel plant, these costs are expected to be reduced appreciably through a focused R,D&D programme.

At present there are no commercial electricity generation plants in the world using CO_2 separation and capture technologies. However, there is a large international interest in the development and demonstration of CCS. The USA and Canada in particular are already fully committed to the development of these technologies (12). With the UK's strong industrial base in power engineering and oil and gas production it could win a substantial share of the potentially much larger global market for carbon capture and storage technology.

8 Themes for R,D&D

In order to meet the technology targets set out in Section 5, the priorities for the key plant technologies can be defined by the matrix of technology options shown in Table 9. Each of these technologies is covered by six main R,D&D themes:

- Basic Research
- Components and Technologies
- Virtual Demonstration
- Physical Demonstration
- Systems Analysis
- Social Research

Table 9

Matrix of options

Short term	Medium term	Long term
Pulverised coal	Pulverised coal (USC*)	Gasification
Gas Turbines (GTs)	GTs	Fuel cells
	GT hybrids (niche**)	GTs/GT hybrids
	Gasification (niche)	Oxy-fuel pulverised coal
	Fuel cells (niche)	CO_2 capture & storage
	Oxy-fuel pulverised coal (niche)	Hydrogen fuelled

* USC - ultra supercritical
** Niche - limited market penetration

8.1 Basic Research

This theme covers a broad range of activities including the study of basic processes and R&D into underpinning technologies that are incorporated into power generation plant and are crucial to its design and performance. Work of this type has traditionally been undertaken in universities and research establishments with input from industry. The APGTF has considered the scientific developments required by the key, longer-term power plant technologies. In doing so it has consulted with UK academia and industry and it has identified the relevant sciences that will need to be supported in the future. These are listed in Table 10.

The main topics to be considered within these underpinning sciences are:

• *Combustion*	modelling, flame stability, pollutant production, cofiring with biomass, diagnostic techniques
• *Materials*	high temperature materials, alloy development, coatings, crack growth, corrosion, fatigue, creep, fatigue materials processing, repair, lifetime prediction & modelling, biomass impacts - a more detailed breakdown of materials research requirements is presented in (14)
• *Electrochemistry*	fuel cells
• *Catalysts*	fuel cells, combustion, pollutant removal, gas separation, fuel processing
• *Membranes*	fuel cells, gas separation
• *Control and instrumentation*	intelligent, 'wireless' for harsh conditions
• *Fuel science*	hydrogen production from fossil fuels, decarbonisation of fossil fuels, gasification, ash properties, biomass
• *Manufacturing methods*	advanced materials, thin films, membranes, low cost processes
• *Mathematical modelling*	fluid flow, heat transfer, interactions with chemistry, dynamic modelling, combustion modelling
• *Component life integrity*	lifing studies, creep, fatigue
• *Electronics*	electrical systems integration
• *Carbon clean-up*	preparation, including reforming, of fuels for fuel cells
• *Aero-dynamics*	turbines, compressors

Table 10

Basic research areas

Technology	Combustion	Materials	Electro-chemistry	Catalysts	Membranes	Control & instrumentation	Fuel science	Manufacturing	Mathematical models	Component Life Integrity	Electronics	Carbon clean-up	Aerodynamics
Gasification		*		*	*	*	*	*	*	*			
Fuel Cells		*	*	*	*	*		*		*	*	*	
GTs	*	*		*		*		*	*	*	*		*
Pf	*	*		*		*	*	*	*	*			
Novel cycles	*	*	*	*	*	*	*	*	*	*			
Carbon Management	*	*		*	*	*	*						

The benefits of basic research are threefold:

- generation of knowledge that diffuses into industry and can be integrated in the evolutionary development of existing systems
- supply of more innovative ideas for devices and processes for development into new products for manufacture
- sustained supply to industry of high quality engineers and scientists.

8.2 Components and Technologies

The power plants of the future are likely to be more complex than those of today, with more integration of different supporting technologies. Some power plants may also be providing hydrogen as a by-product for transport or for distributed generation. This means that R,D&D needs to consider, not only the individual components and technologies, but also their integration. This theme covers innovative design studies of the supporting technologies and their integration, up to and including the manufacture of small-scale prototypes. Work of this type tends to be undertaken through collaboration between universities, research organisations and industry.

The APGTF has looked at the key, medium and longer term power plant technologies and has identified the following supporting technology areas that need further R,D&D:

- *Combustion technology* — for gas turbines and pf plant
- *Low-NOx combustion* — for pf plants
- *Oxy-fuel combustion* — for pf plants
- *Co-fuelling with biomass* — technologies for dealing with biomass together with fossil fuels
- *Mercury capture* — removal of mercury from power plant emissions
- *Fuel flexible gasification* — for gasification with either coal (including low rank coals), biomass or waste fuels. Optimisation & integration
- *Gasification* — durability of refractory, plant availability and cost reduction
- *Air separation units* — development of membranes for O_2 separation at lower cost
- *Hot gas clean-up* — pollutant removal from higher temperature gas streams
- *High temperature heat exchangers*
- *Hybrid or novel cycles* — development of existing technologies that will make up the cycle, systems integration, novel heating (or cooling) cycles for chp(c)
- *Reformers and fuelling* — for fuel cells
- *Electrochemical processes* — for fuel cells
- *Membranes* — for fuel cells and gas separation (O_2/N_2, CO_2/N_2)
- *Component integrity* — for components operating at more extreme conditions
- *Control systems* — for increased performance, reduced emissions, increased safety, etc.
- *Power electronics* — for integration and control of distributed generation
- *Plant manufacture* — for advanced manufacturing methods giving high quality components at lower cost

• *CO_2 Capture*	
– *Post-combustion*	solvent efficiency with amines, solvent degradation and regeneration
– *Plant integration*	with post-combustion capture for reduced costs and higher efficiencies
– *Pre-combustion*	use of product gas in GTs and fuel cells
– *Oxy-fuel capture*	mill and boiler performance, minimising air entrainment, gas-side corrosion
• *CO_2 storage*	assessment of leakage

8.3 Virtual Demonstration

The costs and financial risks associated with building and operating demonstration plant have increased as designs have become more elaborate and equipment pushes further towards technical limits. At the same time, the liberalisation of energy markets has made the power generating industry more risk averse. Therefore, there is a need to develop computer-based systems that go beyond design to virtual demonstration. Such systems should make much more sophisticated and detailed plant simulations and thus reduce the need for, and remove some of the risks from, real demonstration projects.

Clearly, the primary benefit from the development of such systems is reduced costs for demonstration. They also open up the potential to take a broader range of design concepts further towards development before the selection of preferred systems needs to be made.

The APGTF has examined the development required in virtual demonstration and has concluded that a UK initiative is needed to develop a Virtual Plant Demonstration Model (VPDM). This should be designed to provide an integrated software framework that will allow the full potential for whole plant modelling software to be realised. This should be done in two phases:

- *Phase 1 (2004-2007)* should develop a VPDM with integrated components, and utilising the internet; this will be limited to steady state. A demonstration application should be carried out on a selected coal plant technology with carbon capture – see Section 7.4
- *Phase 2 (2007-10)* should extend the VPDM to include dynamics and control analysis. Developments should also be included that will allow integration with design and construction management software.

These developments should be integrated with the Physical Demonstration activity, and the strategic targets described in section 5.2 make it clear that the emphasis should be on plant with carbon capture.

8.4 Physical Demonstration

Ultimately near-to-zero-emission plant will need to be demonstrated at full scale, both to gain operational experience and to reduce the investment risks attaching to new untried designs. Demonstration is expensive, particularly with large fossil plant, and it is unlikely that UK industry would be prepared to carry such costs on its own. Therefore clear strategies are needed for:

- The use of virtual demonstration
- Separate demonstration/validation of key components and systems
- Engineering and commercial studies of whole plant
- Whole plant demonstrations both nationally and abroad

These comments apply not only to the central power plant, but also to the complete fuel cycle including the disposal/storage of CO_2, and hydrogen production if relevant.

Any near-term plans for full scale plant demonstration must focus on the short to medium-term technologies shown in Table 9 with the CCS options shown in Table 6. The ultimate goal for a full-scale demonstration programme must be to showcase UK technology and capability. Also, the upgrading or replacement of the UK's existing fossil fuel plant should be used as an opportunity to demonstrate CCS technology; however, if this proves not to be feasible, a near term retrofit demonstration on an overseas plant would be attractive if there is sufficient commercial-pull to benefit UK plc.

The timescales for demonstration are linked to the strategic target dates defined in Section 5.2. The principle of using retrofits as a lower cost and faster route to full demonstration of new technologies should also be recognised. This has been highlighted in the DTI's Demonstration Review (15), particularly for the case of supercritical components. It also applies to gasification and carbon dioxide capture technologies. In order to meet these timescales, it is essential that a start is made now on planning for full-scale demonstrations.

The technology options to be considered for an **initial demonstration in 2005+**, are the critical short- to medium-term technologies detailed above with the key options being:

• *Advanced supercritical retrofit*	with CO_2 scrubbing
	with oxyfuel firing
	without capture
• *Coal gasification retrofit*	with pre-combustion capture
	without capture
• *CCGT retrofit*	with post-combustion scrubbing
	without capture

The first phase should be to carry out engineering studies to determine price, programme, technical risks, and R,D&D requirements. These studies should be based on actual site options and should be linked to a similar full assessment of EOR applied to a specific oil field. The studies should include:

- Consideration of Capture Demonstration projects for:
  – components and systems
  – complete plants
- Consideration of Storage Demonstration projects
- Review of mechanisms for Government support

In addition to these whole plant retrofits, there is also a need for demonstration of key components and systems, which can also be important for future CO_2 reductions. These should include:

- *GTs and turbine upgrades*
- *Biomass co-firing*
- *Slip-stream demonstration of CO_2 capture technologies*

For the medium term demonstration activity, 2010+, new build plant should be considered with the technologies highlighted as 'new' in Table 6, namely:

- *IGCC*
- *GTCC with catalytic shift*
- *PF+supercritical boiler+flue gas scrubbing*
- *PF+supercritical boiler+oxyfuel combustion+flue gas scrubbing*

8.5 Systems Analysis

Near to zero emissions technologies will need to be deployed into an evolving energy system which must continue to provide a secure supply of electricity. One issue affecting their deployment is the balance between large centralised and smaller distributed power plants. Other issues are the options for backing up and storing the output from intermittent renewable energy sources. The potential role of electricity in reducing carbon emissions from other energy-consuming sectors, such as transport, is also an area that should not be ignored.

Fossil and biomass fuelled power generation has a key role to play in ensuring security of supply. However, because of the wide range of options available (fossil, renewables and nuclear) and their potential impact on both the design and market size for near-to-zero-emission plant, there is a need for systematic assessments. This also needs to examine how systems may evolve with time and how economies of scale and "learning by doing" can affect technology costs and performance both in manufacture and operation.

8.6 Social Research

Experience with the deployment of energy technologies has shown that public acceptance is crucial to their commercial success. However, the public appears to be reluctant to accept the building of many forms of energy plant despite their growing demand for energy related services. This is an important area for social science research in relation to the broad area of sustainable development. Research is needed into markets and into methods and approaches to engage the general public in the energy debate. This will help to identify the technical and perception issues that need to be addressed in order to make near-to-zero-emission plant more acceptable.

8.7 Other Supporting R,D&D

The R,D&D necessary for demonstrating the suitability of CO_2 storage is not covered in this document but it is key to the future potential of CCS. The APGTF supports the recommendations in (8) on this issue, namely:

- Further research is required to support the development of predictive models to give assurance regarding the integrity of long-term storage
- There is also a need for a greater knowledge base to support environmental impact assessments of the consequences of CO_2 releases to the terrestrial and marine environments.

8.8 Applicability to Other Industrial Sectors

As indicated in Section 4, many of the technologies proposed will have applicability to other industrial sectors.

- **Basic Research**
  Many of the disciplines identified have relevance to other areas of application. For instance, modelling methods of a general nature are widely used in automotive, aerospace, chemical and transport sectors. Each has specific applications in combustion, aerodynamics, CFD, materials and life assessment. Active development in these technologies under a power generation programme can only enhance the capability of the UK in what is an increasingly important aspect of design, manufacture and support.

  The chemical industry should benefit from activities in electro-chemistry, membranes and catalysts. Also the topic of control and instrumentation is becoming increasingly adopted widely across many different sectors, especially those concerned with advanced maintenance/diagnostics in the service area.

- **Components and Technologies**
  Component development and validation are becoming increasingly important aspects industry wide. The drive for lower cost and improved reliability demand that components and key technologies are proven before they enter the market, irrespective of the industrial application. The components and technologies identified in this document have other applications than just power generation. For example, low emission combustion technology is important for aero-engines as well as for land based turbines; reformers and membranes are widely used in the oil/gas and chemical industries; control system technology is vital to the processing industry; and hot gas clean up is a key component of many chemical plants, certainly as emissions regulation gets tighter and tighter.

- **Virtual Demonstration**
  Any way in which costs can be reduced is attractive to a wide range of industries that involve complex systems of one form or another (energy, power generation, chemicals, process, oil and gas etc). Traditionally, despite the advances in component simulation and design, industry requires that the complete plant or system is demonstrated to establish confidence in its operation. However in the past much has been done through a series of demonstrations of increasing complexity and cost. There is now a move to reduce this effort by optimising system design through computer modelling and so reduce the number of iterations of physical demonstration required. The work proposed in this document is being done using the basis and standards established by the chemical and processing industry and developments will be widely applicable in this sector.

- **Social Research**
  Public acceptance of new technologies is becoming an increasingly important issue. It is anticipated that the lessons learned from this work will be widely applicable to other areas of energy production (such as from renewable and nuclear sources) and to industrial plant in general.

Overall it is anticipated that the proposed programme will lead to benefits in many other sectors, the most applicable being aerospace, chemical and processing industries.

9 The way forward

9.1 The Basis of an Overall R,D&D programme

The Government White Paper sets out a strategy for energy, which industry welcomes.

However, the Government must continue to provide leadership, in particular, to integrate 'UK plc' resources so that it not only addresses the national energy requirements but also ensures that economic benefit is accrued through export. The following initiatives are suggested for the policymakers:

1) Set long-term policies consistent with export opportunities and emerging legislation
2) Organise funding for pre-competitive R&D in a programme which is market-oriented, coordinated and followed through to demonstration and deployment of new power generation products and services
3) Establish mechanisms to drive forward the implementation of new power generation technologies that meet the long-term objectives of the government.

The role of industry is seen as being:

1) To invest in R,D&D
2) To work together with government and academia to develop and implement the agreed strategy

These issues are general to the energy sector whatever the type of resource used. For fossil fuel, as identified in this document, it is becoming increasingly recognised by the important energy stakeholders that the clean use of such fuels will be a critical transitional issue in the move towards a fully sustainable energy future. It needs therefore to be addressed alongside and complementary to other initiatives on 'new and renewable energy' technologies. The thrust of the approach should be on Carbon Abatement Technologies for Fossil Fuels and involve the short-mid term issues of efficiency improvement right up to the mid-long term issues of (near) zero emission power generation involving CO_2 capture and storage. It is therefore essential that separate activities being undertaken in the UK on Hydrogen and on Fuel Cells are viewed in a complementary manner to those being proposed in this document.

This document identifies six main R,D&D themes that should form the constituent parts of a technology programme targeting the clean use of fossil fuels. These are defined in Section 8 and cover:

- Basic Research
- Components and Technology Validation
- Virtual Demonstration
- Physical Demonstration
- Systems Analysis
- Social Research

Each of these themes should be pursued in conjunction with the power plant and carbon capture technologies as prioritised in Section 7 with the aim points of Section 6 being adopted as targets. The important Power Plant Technologies for the UK cover:

- Pulverised coal fired power plant (pf+fgd)
- Integrated Gasification Combined Cycle (IGCC) plant
- Gas Turbines based systems
- Fuel Cells with the associated link to Hydrogen

From a management perspective, the areas of 'Basic Research' and 'Social Research' are pertinent to the Research Councils, especially that of the Engineering and Physical Sciences (EPSRC) and Economics and Social Science (ESRC) respectively. The other four areas are the province of the DTI and similar governmental funding agencies that are closely linked with industry.

9.2 International Collaboration

International collaboration is considered a critical element in meeting the proposed Carbon Abatement Strategy.

For the longer term it is clear that the development of technology for carbon dioxide capture and storage (CCS) still has some way to go before it is accepted in the market place. It has become an area of intense international activity over the last 5 years with both the USA and Canada being fully committed to the development of these technologies. Significant programmes are also underway in Japan, Australia and several European Countries.

The Carbon Sequestration Leadership Forum (CSLF), with all the above countries among the 16 (including the UK) that have agreed to the Charter, is likely to become a focal organisation for taking forward the technologies, especially at the level of demonstration where the initial project is likely to be the USDOE `Futuregen` Plant (a 1billion US$ project targeting a zero carbon electricity and hydrogen demonstration production facility for 2015). A Technology Route Map is planned that is likely to recommend the development of a limited number of complementary activities worldwide. A parallel initiative involving many of the same countries and instigated by the US in a similar manner is the International Partnership for the Hydrogen Economy (IPHE). It is important that the UK remains involved in both these initiatives and uses them to maximise the benefit towards the UK.

Opportunities for collaboration in North America can be identified relatively easily as a result of the DTI's support over the last two years to establish relationships with other countries. A good example was the recent DTI-APGTF technology mission to USA and Canada on advanced power generation/carbon dioxide capture and storage (11) where a number of opportunities were identified for possible UK collaboration or involvement with both the USA and Canada. Other collaboration opportunities with the USA have been identified under the Energy Research MOU where pilot projects on Materials and Virtual Demonstration are currently about to start. If successful, there is the opportunity for longer term research collaboration on ZEPG.

From an EU perspective the European Commission would like to see a comparable initiative and is actively pursuing ideas within Europe under the EC Framework Research Programmes. It is felt strongly by the industrial sector as a whole that such an initiative should be part of a Carbon Abatement Strategy that embraces the whole range of fossil fuel plant from high efficiency to ultimately zero emissions (an approach very similar to that being proposed here and in the planned German programmes) with the technology being developed in pace and in tune with market demand. This way the finances necessary for such projects could be more forthcoming. It is also consistent with the strategies being developed by the EC Thematic Networks (POWERCLEAN, fossil plant; CAME-GT, gas turbines; and CO_2NET, carbon capture and storage) that are representative of the stakeholders (such as industry, fuel suppliers and technology providers) within the sector across Europe. As a result it is possible that the EC, as part of the continuing FP6 activity, will be willing to support some preparatory work on large projects (termed `lighthouse projects`) that would be used as very visible indicators for the development of the technology.

Also within the EU, the Commission have financed a government initiative (termed FENCO) to see if there is the basis for a critical mass programme to be established in clean fossil power generation with the financing coming from several Member States and the EC, matched by industry. This Specific Supporting Action under the EC Framework 6 RTD Programme is being led by the UK and Germany and is due to report later in 2004. If taken further it may be possible to initiate a complementary EC `Technology Platform to that being proposed for Hydrogen. At the same time the industry (manufacturers, generating companies, fuel suppliers and technology providers) are defining the technical content of such a critical mass programme; this activity is termed POWER21. The same companies are active in the definition of the different Member State programmes, thus ensuring synergy between what is required on a European level with that in the national programmes.

By taking an active part in these EU initiatives, the UK should be able to influence EU technology development strategy, which will put the UK in a favourable position for collaboration in the EU, particularly on full-scale demonstration/lighthouse activities. Also by already having a proactive involvement in such activities, both at a European and world level, the UK has established a good position to benefit subsequently from any resulting initiative. This activity needs to continue to ensure that further development in the UK is planned to take maximum advantage of opportunities from international collaboration, while at the same time fostering a competitive UK capability to design, manufacture, and operate carbon dioxide capture and storage systems.

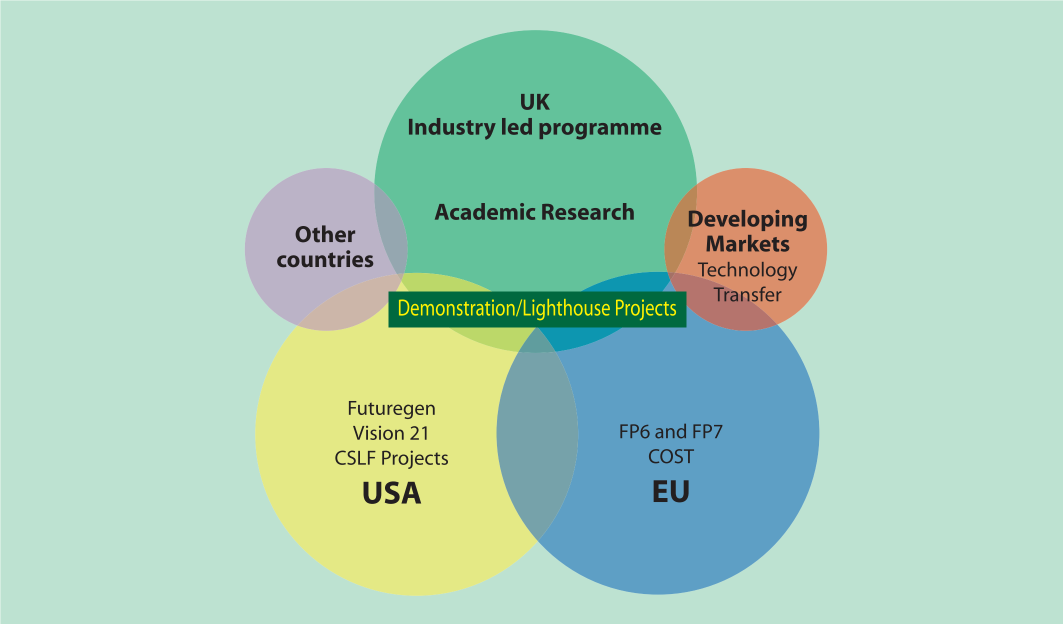
Such an approach relies on a strong well thought through focussed national UK activity on carbon abatement.

It would be necessary to take advantage wherever possible of working with the IEA Greenhouse Gas R&D Programme (IEA GHG) where a considerable expertise and knowledge has been developed over the last decade and more.

The inter-linking of the national programme with international collaborations is illustrated in Figure 6, with further descriptions of the UK programmes given in the next section.

Figure 6

Relationship between National and International

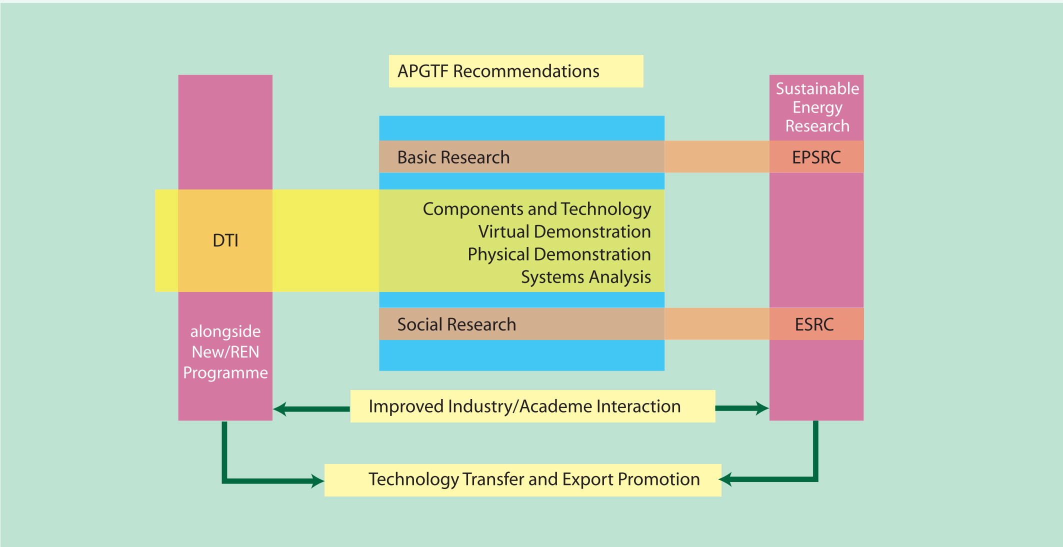


9.3 Implementation

The Government contributions to the proposed RD&D themes would need to be split between the Research Councils and the DTI in the manner shown in Figure 7. However, UK industry would view all the themes as part of a single national RD&D strategy, so effective industry/academe interaction will be essential.

Figure 7

Split of RD&D Programme between Government Departments and Carbon Abatement Technology



The proposed RD&D themes should be implemented in joint programmes between industry and the relevant Government agencies. A high level of co-ordination between the Research Councils and the DTI will be essential.

The six-year DTI Clean Coal Technology programme (1999-2005) should continue with enhancements, with its focus being on carbon management and carbon capture technologies for fossil fuels. This should include the development of increasing efficiencies as well as CO_2 separation and capture, as detailed in this document. It would also be appropriate to include a link to hydrogen production from fossil fuels or biomass.

It is proposed that this programme should be developed jointly with industry and should cover the Components and Technologies, Virtual Demonstration and Physical Demonstration programmes. It should also promote the actions needed to get the technologies into the market place.

This should result in an **Industry-led R,D&D Programme** in which:

- APGTF strategy is used to inform planning
- DTI continues to be represented on APGTF to ensure liaison and review
- The newly formed Advisory Committee on Carbon Abatement Technologies has representation from APGTF
- Management follows that of the DTI Cleaner Coal R&D Programme model
- Scope of programme includes cost-effective demonstration, techno-economic-engineering studies, work to define optimum R&D needs, and participation in international programmes as well as R&D
- Export opportunities are created whether or not full scale CO_2 Capture and Storage goes ahead in the UK

The Government should also provide a ‘catalyst role’ acting as a focus for: international collaborations and establishing partnership activities with other organisations; export promotion and transfer for UK technologies.

This should result in a **Technology Transfer and Export Promotion Programme** in which:

- Programme is designed to engage future customers for new build, retrofit and after-market services
- Focus is on emissions reduction potential as well as export opportunities

The Industry led RD&D programme and the Technology Transfer and Export Promotion programme should, together, form the basis of a joint DTI/Industry **Carbon Abatement Technology Programme.**

Industry should have a strong input into the university programmes to be coordinated by the new Energy Research Centre, and to the work of the Carbon Trust and the Scottish Energy ITI. In particular, the Basic Research programme detailed in this document should be promoted with the new Energy Research Centre, and build upon already established industry/research relationships, such as the British Coal Utilisation Research Association (BCURA).

This should result in an **Academic Research Programme** in which:

- APGTF Strategy is used to inform planning
- EPSRC and others (ITI) are represented on APGTF
- APGTF is represented on key bodies which fund R&D in this technical area, e.g. Carbon Trust, the Scottish Energy ITI, BCURA

Industry and academe need to improve the way they work together and in particular there should be **Measures to Encourage Closer Industry/Academe Cooperation** which:

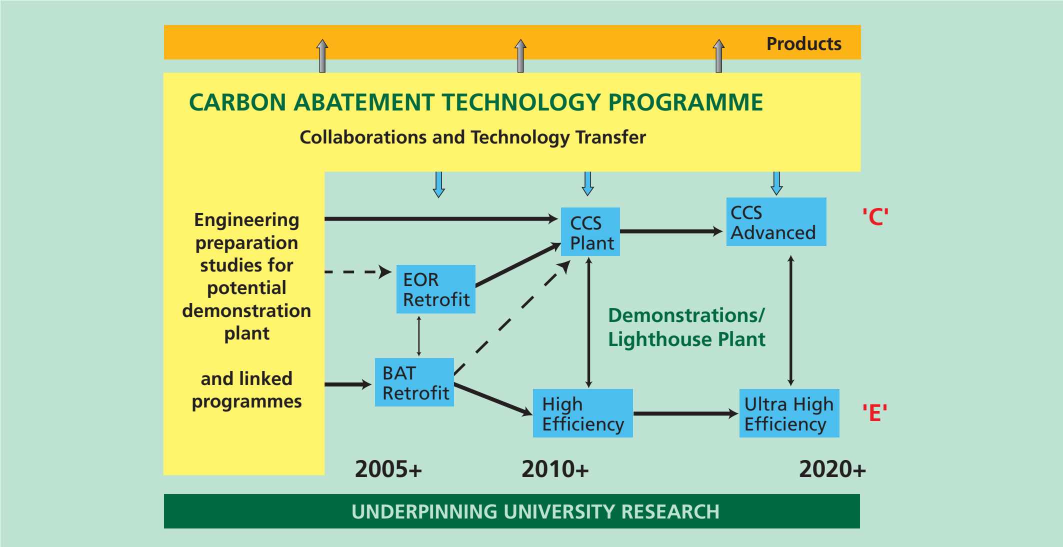
- Ensure industry participation in University programmes
- Ensure academic research is linked to business objectives
- Seek more added value from long term research
- Encourage development of new technologies and skills

The Social Research and Systems Analysis programmes should be supported by the appropriate parts of Government, with industry providing a full supporting role.

Finally, the remit of the **APGTF** should continue but it should be more proactive in implementing strategy. Its remit includes the following objectives:

Fig 8

Interactions of the RD&D Programmes



- To ensure that there is a continuing review of the R,D&D strategy and its implementation
- To promote this R,D&D strategy throughout the sector including industry, the academic/research community, Government, the EU and public funding bodies
- To identify strategic technologies and skills throughout the sector which will be suitable for commercialisation and to promote the actions that will result in direct benefit to the UK
- To assist in the development of national and international collaborations that will bring benefit to the strategic R,D&D programme
- To develop an understanding of the sectors Education and Training needs for future technologies and to work with appropriate bodies to ensure that they will be met.

The interaction of these programmes is illustrated in Figure 8. These interactions should be managed by the APGTF and the DTI working in collaboration.
Finally, within the APGTF there should be Technical Groups for each of the main technology activities, which should follow the lead of the existing, successful Materials and Combustion Groups.

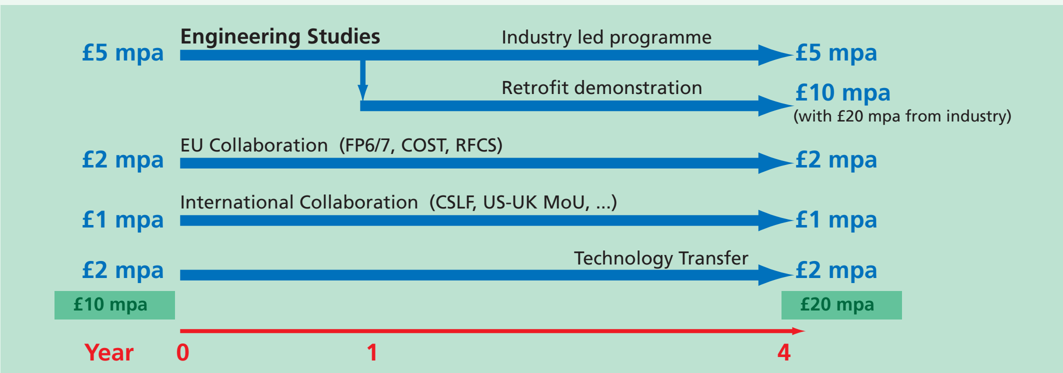
9.4 Financing

The UK, Government and industry, should fund the proposed industry led programme and the academic research programme. The initial demonstration, scheduled for 2005+, should take place in the UK preferably to give maximum benefit to UK industry and the UK environment. This is likely to require full funding from within the UK; if this is not possible an overseas demonstration could be considered if there is sufficient commercial pull to benefit UK plc. The subsequent demonstrations could be done through international collaborations and therefore the UK would only part-fund these activities with funding levels commensurate with the benefits accrued to the UK.

Figure 9 illustrates the DTI funding levels that will be required for a 4 year programme, which will need to start in 2004/5. However, it must be remembered that the developed strategy goes to 2020+ and some of the activities, particularly the international collaborations, will require a commitment extending beyond 4 years.

Fig 9

Financing of RD&D Programme



The Industry-led programme, which is part-funded with industry, needs £5mpa over 4 years. The Engineering Studies will require funding for 1 year, from the start of the programme, and this is included in the industry-led programme funding. These studies are regarded as essential as they will be used to define the way forward. It is anticipated that these will be followed by a retrofit demonstration with a total cost of £100m, with £10mpa for 3 years from the Government and the rest coming from the manufacturers and the generators.

The funding shown as EU collaboration will be needed by UK companies if they are successful in getting EU support for the two major CO_2 projects that are proceeding with EU funding under Framework Programme 6, and additional by funding for the future collaborations that are being planned within the EU.

The International Collaboration funding includes the CSLF/Futuregen collaboration being led by the US, which is still being developed. The UK has indicated its intention to be involved with this and UK funding should be at a level to ensure a 'seat at the table'. This funding will probably not be required before the second year of the UK programme. The funding for the planned US-UK MOU activities is also included here together with that for any future international collaborations

The Technology Transfer and Export Promotion programme will need to run over the 4 years of the programme at a level of £2mpa.

The total DTI funding required for the UK RD&D 4 year programme is:

£10m for the first year
£20mpa for each of the following 3 years.

In addition to this, the University Research programme is to continue over the 4 years of the programme with funding at £4mpa.

The collaborative elements of the UK programme all provide access to large programmes which will ensure that the funding is highly geared, as illustrated in Table 11.

Table 11

Gearing of funding

Programme	Government funding	Programme size
UK Retrofit	£30m	£100m
Futuregen	Part of £4m	$1000m (~£550m)
FP6	£2m	€30m (~£20m)

10 Conclusions and recommendations

10.1 Conclusions

- The APGTF has developed a technology RD&D strategy for clean fossil power generation which follows on from the White Paper and takes account of global issues and global markets
- Clean fossil power generation is crucial in meeting the needs of present and future generations; in particular it is a critical transition issue in moving to a sustainable future. In the longer term it is likely to be a source of hydrogen. It is therefore essential that any carbon abatement strategy tackles clean fossil fuels alongside any other fuel source considered.
- The strategy has been developed to ensure that the new technologies are available when they are needed and so that the UK retains its share of the global market
- The uncertain future demands the need for a broad strategy covering:

  i) increasing plant efficiencies at commercially competitive costs
  ii) near to zero emission power generation with CO_2 capture

  thus covering the options for short, medium and long term. Engineering studies on a range of options are regarded as essential in setting out the future direction.
- There is a large international interest in the development of CO_2 capture and storage; the forecast costs compare favourably with other CO_2 abatement options
- International collaboration will be essential, especially in establishing demonstration ('lighthouse projects') and hence deployment of technology
- The changing face of the power generation industry is resulting in greater emphasis on added value components and technologies; these need a 'shop window'.
- Many of the technologies being developed within the power generation sector have wide applicability to other industries.
- Government assistance is essential not only to encourage initial research and development but also to help bring the resultant technologies to the market. A high level of co-ordination between different governmental departments is regarded as essential to ensure an effective programme overall in the field of energy.
- The engagement of industry is essential and therefore there have to be benefits delivered in the short, medium and long term

10.2 Recommendations

- The proposed strategic programme should be adopted, by both Government and industry, as the UK's RD&D programme for clean power generation from fossil and biomass fuels. This should be an integral part of the Government's drive towards a sustainable energy economy
- The Government and industry should commit to an initial four year Carbon Abatement technology programme for fossil and biomass fuels, with DTI funding of:
  £10m for the first year
  £20m pa for the following three years
- The proposed strategy extends to 2020 and beyond and so there is a requirement for longevity in the technology programmes that needs to be reflected in financing of future phases.
- Future development of the strategy in the UK, particularly for large scale demonstrations, should be planned to take maximum advantage of opportunities for international collaboration, while fostering UK capability and skills
- There should be a 'bridge' from existing programmes to a new Carbon Abatement Technology programme to make best use of the technology under development and so prepare for the future
- The DTI should continue to support joint industry-academe activities in technology transfer and export promotion, especially in regions with major business opportunities
- The APGTF should build on its success to date and take a more proactive role in implementing strategy.

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Appendix 1

Technologies for capturing CO_2 from power plant

Post-combustion capture 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) and then to heat the solvent to release high purity CO_2. The flue gas needs to be cooled and, for coal and oil fired plant, treated to remove reactive impurities (e.g. sulphur and nitrogen oxides, particulates) before scrubbing, otherwise these impurities will react with the solvent causing unacceptable consumption rates and corrosion of the plant. A large amount of energy is needed to regenerate the solvent and to compress the CO_2 for transport, which significantly reduces the net electricity output of the plant.

Alternative methods for separating CO_2 from flue gases are physical solvent scrubbing, adsorption/desorption, membranes and cryogenics. However, at present these methods are most effective with high CO_2 concentration gas streams at elevated pressures and therefore are more suited to pre-combustion and oxyfuel methods.

Amine scrubbing has been used for over 60 years for the removal of hydrogen sulphide and carbon dioxide from hydrocarbon gas streams. However most of this experience is with reducing gas streams rather than with oxygen-containing flue gases, and at a smaller scale than is needed for power plant. The largest operating unit, at Trona, California captures 800 tCO_2 per day; less than 10% of the capacity needed for a 500MW coal fired power station.

Pre-combustion capture 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 carbon dioxide. The carbon dioxide 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.

The advantage of pre-combustion separation relative to post-combustion is that it produces for treatment a smaller volume of gas, which is richer in CO_2. This reduces the size of the gas separation plant thus reducing capital costs. Also the higher concentration of CO_2 enables less selective gas separation techniques to be used (e.g. physical solvents, adsorption/desorption). These require less energy to operate.

Most of the technology for pre-combustion capture is well proven in ammonia plant. One of the novel aspects is that the fuel gas feed to the gas turbine will be hydrogen, which is diluted with nitrogen or steam prior to combustion to reduce emissions of nitrogen oxides.

Oxyfuel capture involves burning fuel in an oxygen/CO_2 mixture rather than air to produce a CO_2 rich flue gas. 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. The technique 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.

The advantage of oxyfuel combustion is that it produces a highly enriched CO_2 flue gas that enables simple and low cost CO_2 purification methods to be used. However, it has the disadvantage of requiring an air separation plant, which is expensive and requires a considerable amount of energy to operate.

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