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An Integrated Assessment of Carbon Dioxide Capture and Storage in the UK

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Carbon Dioxide Capture and Storage in the UK: an Integrated Assessment

Abstract

Geological carbon dioxide storage (CCS) has the potential to make a significant contribution to the decarbonisation of the UK. Amid concerns over maintaining security, and hence diversity, of supply, CCS could allow the continued use of coal, oil and gas whilst avoiding the CO_2 emissions currently associated with fossil fuel use. This project has explored some of the geological, environmental, technical, economic and social implications of this technology. The UK is well placed to exploit CCS with a large offshore storage capacity, both in disused oil and gas fields and saline aquifers. This should be sufficient to store CO_2 from the power sector (at current levels) for a least one century. The costs of CCS in our model for UK power stations in the East Midlands and Yorkshire to reservoirs in the North Sea are between £25 and £60 per tonne of CO_2 captured, transported and stored. In addition to the technical and economic requirements of the CCS technology, it should also be socially and environmentally acceptable. Our research has shown that, given an acceptance of the severity and urgency of addressing climate change, CCS is viewed favourably by members of the public, provided it is adopted within a portfolio of other measures. Although there remain uncertainties to be resolved through research and demonstration projects, our assessment demonstrates that CCS holds great potential for significant cuts in CO_2 emissions as we develop long term alternatives to fossil fuel use.

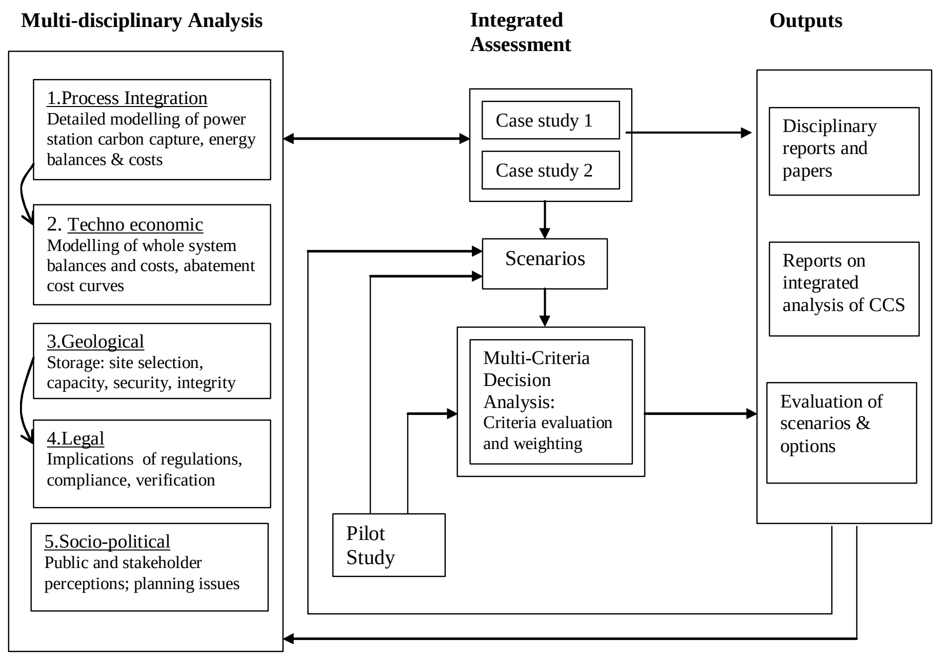
Objectives

The objectives of the project can be summarised as follows:

1) To address major uncertainties associated with specific aspects of CCS technologies, such as:
   - the potential capacity for geological CO_2 storage in the UK;
   - costs of CCS including retrofit or new design of power plants, refineries and other large point sources, pipelines and taking account of benefits of Enhanced Oil Recovery;
   - the opinions, perceptions and more formal evaluations of stakeholders and the public with respect to future potential use of CCS in the UK.
2) To evaluate the short to medium term conditions for, and implications of, deploying the technologies in the UK. This enables us to identify which sources and sinks have the greatest potential in the near and medium timescales, given considerations of cost, capital plant and infrastructure, legal aspects, environmental impacts, geological integrity and public perceptions.
3) To develop integrating frameworks to enable us to address broader implications of implementing CCS, such as the concept of storage as a 'bridging' option towards renewable and new energy technologies or whether the two approaches imply fundamentally different pathways.

Methodological Approach

A schematic of the methodology is illustrated in Figure 1. Multi-disciplinary analysis has brought specific expertise to in-depth analyses of the main components of an assessment of CCS. Two case studies have been chosen to elaborate the key parameters associated with CCS in the UK in the near and medium term. Case study 1 explored the possibilities for using CO_2 from NW England and in the East Irish Sea. Case study 2 analysed options for storing CO_2 from major point sources across the midlands and eastern England at a number of sites in the southern North Sea. Through these case studies, we have extended scenarios and a multi-criteria assessment developed in a pilot study (Tyndall IT1.22, Gough and Shackley, 2002), providing a framework from which to extrapolate specific results from the case studies to a more generally applicable level.



Results

The integrated results for this study are presented here as summary statements relating to techno-economics, geology and regulation and citizen and stakeholder perceptions of geological CCS.

Techno-economics

The costs of CCS in our model for UK power stations in the East Midlands and Yorkshire to reservoirs in the North Sea are between £25 and £60 per tonne of CO_2 captured, transported and stored. This is between about 2 and 4 times the current traded price of a tonne of CO_2 in the EU Emissions Trading Scheme.

With the majority of its large coal fired power stations due to be retired during the next 15 to 20 years, the UK is at a natural decision point with respect to the future of power generation from coal; the existence of both national reserves and the infrastructure for receiving imported coal makes clean coal technology a realistic option. The notion of CCS as a ‘bridging’ or ‘stop-gap’ technology (i.e. whilst we develop ‘genuinely’ sustainable renewable energy technologies) needs to be examined somewhat critically, especially given the scale of global coal reserves. If CCS plant is built, then it is likely that technological innovation will bring down the costs of CO_2 capture, such that it could become increasingly attractive. As with any capital-intensive option, there is a danger of becoming ‘locked-in’ to a CCS system. China, India and the USA all use large amounts of coal, and are likely to use increasing amounts in the future. From a climate change perspective, there is an urgent need to design new coal power plants in all coal-using countries such that they can be modified to capture CO_2 in future (capture-ready).

Geology and Regulation

The UK has sufficient storage capacity to store CO_2 from the power sector (at current levels) for a least one century; this estimate is based on the use of well understood depleted hydrocarbon fields and contained parts of aquifers which are likely to be the lowest risk sites. It is very difficult to produce reliable estimates of the (potentially much larger) storage capacity of the less well understood geological reservoirs, such as non-confined parts of aquifers, without more detailed surveys of those reservoirs. The greatest uncertainty with respect to CCS is whether the CO_2 will leak from the reservoirs. It is not possible to make general statements concerning storage security; assessments must be site specific. The impacts of any potential leakage upon global climate change and marine ecosystems are also somewhat uncertain but should be balanced against the deleterious effects of increased acidification in the oceans due to uptake of elevated atmospheric CO_2 that have already been observed. Provided adequate long term monitoring can be ensured, any leakage of CO_2 from a storage site is likely to have minimal localised impacts as long as leaks are rapidly repaired. A regulatory framework for CCS will need to include risk assessment of potential environmental and health and safety impacts, accounting and monitoring and liability for the long term. In the long-term, it is likely that once a storage site has closed (following agreement between the operator and the regulator) liability for monitoring and managing the site will need to transfer from the operator to the state. A review of the relevant marine and climate change laws reveals that the current legal framework is often ambiguous as to whether certain CCS projects could be prevented or restricted from taking place; primarily because these laws were not drafted with CCS in mind. CCS can contribute to reducing emissions of CO_2 into the atmosphere in the near term (i.e. peak-shaving the future atmospheric concentration of CO_2), with the potential to continue to deliver significant CO_2 reductions over the long term. The value of this will increase if climate change and its impacts are at the higher end of estimates or if unpleasant climate surprises arise.

Citizen and stakeholder perspectives

Our research has shown that, given an acceptance of the severity and urgency of addressing climate change, CCS is viewed favourably by members of the public, provided it is adopted within a portfolio of other measures and is likely to be a more acceptable decarbonisation option to the public than nuclear fission. For many stakeholders one of the benefits of CCS compared to distributed generation is that it fits readily into the existing infrastructure of power plants and the electricity grid.

Potential for further work

The process of Integrated Assessment of CCS in the UK continues under the UK CCS Consortium, funded by NERC under the 'Towards a Sustainable Energy Economy' (TSEC) programme. Several members of the Tyndall project team are members of this consortium and will extend the methods and analysis developed here to enhance understanding of the economic, technical, geological and social processes governing CCS.

Communication highlights

Publications

Bentham, M. (2005), *An assessment of carbon sequestration potential in the UK – Southern North Sea case study* Tyndall Working Paper (submitted)

Gibbins, S. and Shackley, S. (2004), 'Carbon Capture and Storage as an Alternative to Nuclear Expansion', *Climate Change Management*, June 2004, p.12.
Gough, C. and Shackley, S. (2006), 'Towards a multi-criteria methodology for assessment of geological carbon storage options', *Climatic Change (in press)*
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Macrory R., Purdy R. (2004), 'Geological carbon sequestration: critical legal issues', *Tyndall Centre Working Paper* 45
Shackley, S., Cockerill, T. and Holloway, S. (2003), 'Carbon Capture and Storage: Panacea or Long-term Problem?', *Climate Change Management*, **6**, September 2003, p.11.
Shackley, S., McLachlan, C. and Gough, C. (2005), 'The Public Perception of Carbon Capture and Storage in the UK: Results from Focus Groups and A Survey', *Climate Policy*, **4** pp.377-398

Presentations and other communication

Results emanating from this study have been used directly in discussions at the highest level of government in formulating policy on public support mechanisms for CCS.

March 2003: Clair Gough presented a talk entitled 'Social Acceptability of underground CO_2 storage" at the Geological Society meeting "Coping with Climate Change', London 25-27 March, 2003
December 2002: Simon Shackley made a presentation to the TCUK Ad Hoc Group at the DTI on the Tyndall Centre work on carbon sequestration
February 2004: Simon Shackley made a presentation to the DTI, IEA and BP conference on Risk Assessment of Carbon Storage, London.
July 2004: participation at the Carbon Sequestration Leadership Forum (CSLF) meeting on stakeholders London,
September 2004: Michelle Bentham presented and was a member of the panel discussion on public perception of carbon capture and storage to the Green House Gas Technologies Conference (GHGT-7) in Vancouver.
April 2005: Simon Shackley presented on public perceptions of CCS to the EU High-Level Meeting on CO_2 Capture and Storage, Brussels
September 2005: Clair Gough presented the results of the project to 'Decarbonising the UK' Tyndall Centre launch of Theme 2 research, London

Table of Contents

Chapter 1

Introduction - Carbon Dioxide Capture and Storage in the UK

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1.1. The Climate Change Problem and Possible Solutions

It is now widely recognised that large scale reductions in carbon dioxide (CO_2) emissions are required during this century in order to limit the extent of climate change modification. The UK Government, in its Energy White Paper (2003), set itself a target of a 60% reduction in CO_2 emissions by 2050, based upon a global target of stabilising atmospheric CO_2 concentration at 550 ppmv (parts per million unit volume). More recent scientific research suggests that 550 ppmv may well be too high a value and that 450 ppmv is perhaps a more appropriate target (DEFRA, 2004). In that case, emission reductions of at least 80% might be required by 2050 from countries such as the UK.

The most widely known approaches and technologies for CO_2 emissions reduction are reducing energy demand (e.g. through energy efficiency or behavioural changes), renewable energy technologies and nuclear power. In a global context demand for energy, which was formerly increasing in proportion to population growth, is now accelerating faster than population growth. This is partially because of rapid industrialization in some of the largest developing countries, notably China and India. At whatever level of energy use, the ultimate goal must be to establish a sustainable carbon-free energy supply that is sufficient to satisfy the energy demands of the World's industries, agriculture, transport and domestic usage, though constraining growth in *per capita* energy consumption will assist in meeting this goal. Currently, carbon-free energy technologies are far from being developed sufficiently to meet global demands, nor is there a reasonable prospect that they can match current or future demands in the foreseeable future (Deffeyes, 2005). Thus continued use of fossil fuels and associated emissions of CO_2 remain an inevitable part of the foreseeable future. Thus it has become urgent that supply side approaches to reducing these emissions are developed along side measures to reduce demand.

During the 1990s, a new technology has emerged which offers an additional route to large-scale CO_2 emission reduction. This is through the capture of CO_2 from large point-sources such as power stations, oil refineries and chemical works and the storage of that CO_2 in suitable geological reservoirs, a technique known as Carbon dioxide Capture and Storage (CCS) (Holloway, 1997; DTI, 2003). Decarbonised energy carriers, such as electricity and hydrogen, can therefore be made from fossil fuels with 80-90% of the CO_2 captured. Such energy carriers could eventually be used for transportation as well as for a myriad of other energy supply applications. If CO_2 is captured from the combustion of biomass, a net reduction of CO_2 from the atmosphere is possible, as biomass crops take up atmospheric CO_2. This could be offset against the use of carbon-based liquid fuels in premium applications such as aviation to avoid increased concentration of atmospheric CO_2 (Read & Lermit, in press, Rhodes and Keith, in press).

Particularly in the UK, potential geological storage reservoirs may be located offshore, below the sea bed, and this has in the past led to geological CCS becoming confused with direct ocean storage. In this latter approach, CO_2 is transferred directly into the deep oceans rather than being stored in geological rock formations. Ultimately (on millennial time-scales) ~80-85% of anthropogenic carbon dioxide emitted to the atmosphere will be taken up by the oceans. Takahashi (2004) estimates that nearly half the anthropogenic carbon emitted since 1800 has entered the oceans already. The deep ocean has an enormous potential capacity of ~38,000Gt and the basis for the concept of direct ocean storage is to short-cut the natural processes whereby carbon dioxide is transferred into the deep ocean. Ocean pH has already declined by 0.1 pH units and Caldeira and Wickett (2003) have estimated that if all fossil fuels were to be burnt ocean pH would eventually drop by ~0.7 units. There is evidence that carbon dioxide emissions are already radically altering the oceans' calcium carbonate system and hence are beginning to have a serious impact on the biota (Feely *et al.* 2004; Sabine *et al*. 2004). The oceans turn over on millennial scales so if the deep ocean carbon dioxide content is increased more the deep upwelling water will vent more carbon dioxide back into the atmosphere. Direct ocean storage is a highly controversial approach because of the high degree of uncertainty in our knowledge of the fate of CO_2 so stored over hundreds and thousands of years and it has not been demonstrated at a pilot scale; it has not been included for further consideration in this volume. This decision was clear in the UK context because of the ready availability of suitable geological storage sites within the continental shelf making any higher-risk strategy of direct ocean storage unnecessary. The project team also took the decision to concentrate on off-shore storage in geological formations, and not to consider on-shore storage sites. The reason for this decision is that, whilst there are suitable on-shore geological formations in the UK, the risks involved in utilising such storage options are likely to be greater than off-shore storage: in particular, the risks to human health and safety should leakage occur, or intrusion of CO_2 into potable water supplies. Our early work on public perceptions (Gough *et al.*, 2002) also indicated that the public would view on-shore storage much less favourably where there are plentiful sub-sea bed off-shore storage opportunities, as is the case in the UK. For these reasons, on-shore storage was not considered in this research.

In contrast to direct ocean storage, geological CO_2 storage is now becoming established as a mainstream contender in the portfolio of climate change mitigation measures available. Internationally, it has been the topic of a Special Report from the Intergovernmental Panel on Climate Change (IPCC, 2005) which presents a comprehensive description of the key technologies associated with capture, transport and storage of CO_2 and the implications of the inclusion of CCS within the UNFCC (United Nations Framework Convention on Climate Change). We have made every attempt not to duplicate the content of the IPCC report here by focusing on the UK context in more detail. In the UK, the Government has made various statements in support of pursuing CCS further; in March 2005 the Chancellor, Gordon Brown, announced that he would be looking into providing further incentives for CCS during 2005, followed by the announcement of the a Carbon Abatement Technologies Strategy from the DTI which committed £25million to CCS projects (DTI, 2005). Our work is, in essence, an attempt to translate the principles and ideas set out in the IPCC report into practice in the specific context of a national energy system, taking account of the particularities of energy plant and infrastructure, legal and regulatory frameworks, environmental impacts and assessment, stakeholder and public perceptions and priorities and government policy.

1.2. An Integrated Assessment of CCS in the UK

Geological carbon storage has the potential to make a significant contribution to the decarbonisation of the UK. Amid concerns over maintaining security, and hence diversity, of supply, carbon storage could allow the continued use of coal, oil and gas whilst avoiding the CO_2 emissions currently associated with fossil fuel use. However, as a new technology there remain many uncertainties relating to its viability, effectiveness and acceptability. We have adopted an Integrated Assessment

(IA) approach to addressing these concerns. Integrated Assessment is a process which aims to develop insights beyond those derived from single disciplinary studies (Parson 1995; Risbey *et al.*, 1996; Gough *et al.*, 1998). It is not a substitute for rigorous scientific analysis but an addition to the knowledge gathering process within a complex topic. IA is an appropriate approach for CCS which presents complex interactions between many diverse realms of expertise. The IA process described in this report has enabled us to explore some of the uncertainties associated with the application of the CCS concept from a range of perspectives and through a variety of academic approaches to enable a more comprehensive evaluation of carbon storage options in the UK. In addition, we have developed and used integrating tools such as scenario generation and multi-criteria evaluation, which allows a new synthesis of disciplinary insights and knowledge. The IA therefore allows us to address questions not answerable by a single disciplinary approach. Carbon storage is only one amongst a range of climate change mitigation options and its assessment must be carried out in a manner that will enable it to be evaluated within this broader context. Although we do not attempt such a direct comparison here, the findings from the project have fed into a holistic assessment of carbon mitigation options for the UK, undertaken by the Tyndall Centre (Anderson *et al.*, 2005).

The results presented here are based on a three year programme of collaborative research organised around the framework illustrated in Figure 1.1. This evolved from a smaller pilot study (Tyndall project IT1.22) which mapped out a preliminary assessment of carbon sequestration options in the UK (Shackley *et al.*, 2002; Gough and Shackley, 2006). The aim of the study presented here has been to extend this analysis and undertake a more comprehensive evaluation of the potential role of geological Carbon dioxide Capture and Storage (CCS) in the UK's climate change mitigation policy. Specific objectives can be summarised as follows:

1) To address major uncertainties associated with specific aspects of carbon storage technologies, such as:
    - the potential capacity for geological CO_2 storage in the UK;
    - costs of carbon sequestration through retrofit or new design of power plants, refineries and other large point sources, including pipelines, and taking account of benefits of EOR;
    - the opinions, perceptions and more formal evaluations of key decision-makers, stakeholders and the public with respect to future potential use of CCS in the UK.
2) To extend the assessment to evaluate the short to medium term conditions for, and implications of, deploying the technologies in the UK. This has enabled us to identify which sources and sinks of carbon have the greatest potential in the near and medium timescales, given considerations of cost, capital plant & infrastructure, legal aspects, environmental impacts, geological integrity and public perceptions.
3) To develop integrating frameworks to enable us to address broader implications of implementing CCS. This includes the validity of the concept of storage as a 'bridging' option towards renewable and new energy technologies or whether the two groups of technologies imply fundamentally different pathways.

A schematic of the methodology is illustrated in Figure 1.1. Multi-disciplinary analysis brings specific expertise to in-depth analyses of the main components of an assessment of carbon dioxide storage. Two case studies were chosen to elaborate the key parameters associated with CCS in the UK in the near and medium term. Case study 1 explores the possibilities for using CO_2 from NW England with storage in the East Irish Sea. Case study 2 analyses options for storing CO_2 from major point sources across the East Midlands and Yorkshire and Humber regions with storage at a number of sites in the southern North Sea. Through these case studies, we have extended the scenarios and the multi-criteria assessment developed in the pilot study, providing a framework from which to extrapolate specific results from the case studies to a more generally applicable level.

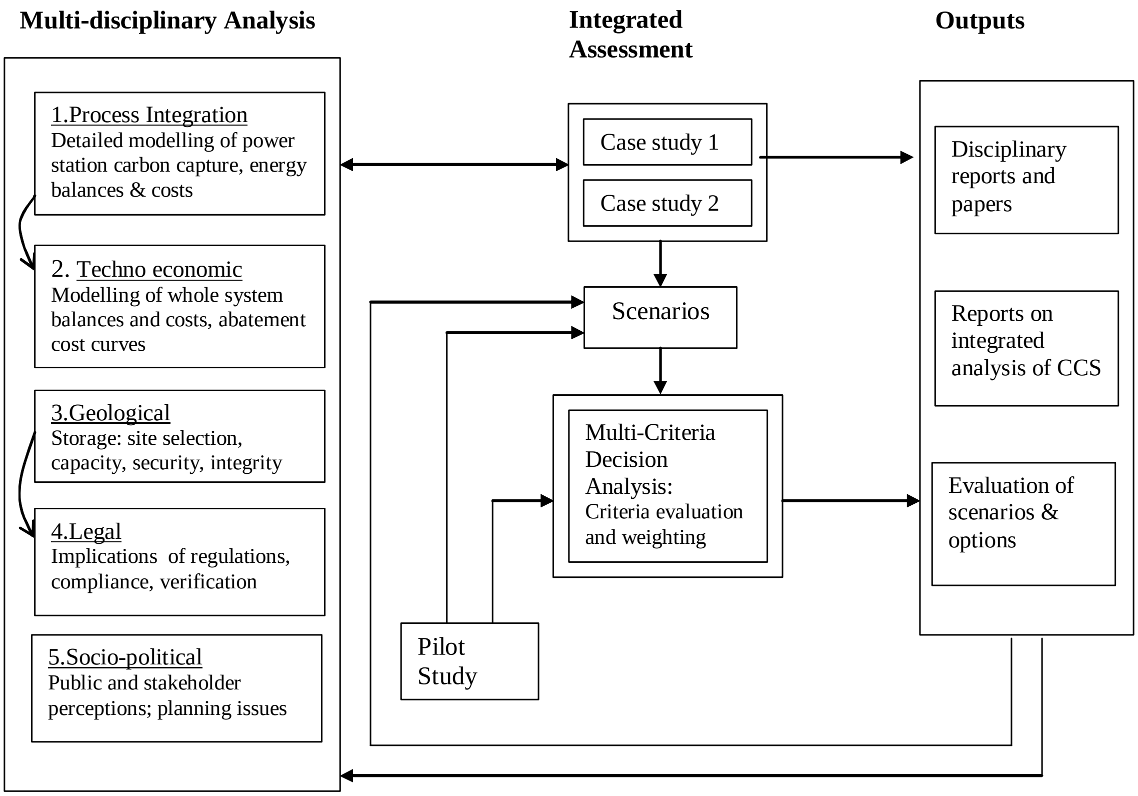

Figure 1.1 The Methodological Framework

1.3. Structure of the report

The structure of this report broadly follows the schematic shown in Figure 1.1. Members of the project team have taken responsibility for individual chapters, with contributions from across the team where appropriate. In Chapter 2, Bentham *et al.* begin with an introduction to the concept of geological storage covering issues such as storage site identification, characterisation and selection, storage capacity, long term monitoring and verification of storage, storage safety and security, integrity of wells in the UK context.

Chapter 3, by Klemeš and Bulatov, reviews the costs and effectiveness of capture and recovery of CO_2 for a range of known technologies (such as physical and chemical absorption and adsorption, gas separation/membrane technology, flue gas recycling /oxyfuel boilers) derived from analysis of current literature and a modelling approach based on thermodynamics (Ahmad *et al.*, 1990) and examination of alternative configurations for process and emissions reduction optimisation. In addition, this chapter presents some more novel routes to CO_2 capture and utilisation that are less well developed.

Chapter 4 by Cockerill explores the CCS in the UK from a techno-economic perspective by extending the analysis of carbon capture and recovery described in Chapter 3 to encompass infrastructure and transport costs such as pipelines, disposal and Enhanced Oil Recovery, etc. This presents an update and extension of a numerical cost and design model of the entire CCS process, based on engineering principles and expert defined data originally developed 10 years ago (Holloway 1996) to study how the costs of CO_2 disposal vary within engineering design parameters. The model has been validated and used to compare the economic and engineering viability of implementing CO_2 capture and disposal schemes at a limited number of existing UK power stations and possible disposal sites.

In Chapter 5, Purdy and Macrory examine existing legal regimes at international, European Community and national level, identifying problem areas and areas for proposed change (these include the Kyoto Protocol; International Convention on the Law of the Sea 1982; London Dumping Convention 1972; OSPAR Convention; ESPOO Convention, Habitats Directive, Integrated Pollution Prevention and Control Directive; UK climate change levy and pilot carbon trading scheme). Issues addressed include where and when these various Conventions apply, the legality of carbon sequestration as an option, requirements for permits or licences, liability, *inter alia*.

Shackley *et al.* assess public perceptions associated with the options for CCS in the UK in Chapter 6. This assessment is based on both Citizen Panels and a larger scale survey. Two Citizens Panels met five times each and called on expert witnesses to present information and opinion relevant to the discussion. Experts included scientists, NGOs, industry spokespersons, etc. On a larger scale, a follow up survey of opinion was designed on the basis of discussions in the panels in order to generalise the findings to a broader context.

Chapters 7 (Shackley *et al*.) and 8 (Gough *et al*.) present the results from the two case study regions. The Case studies incorporate a geological review of the suitability and potential of possible storage reservoirs in the region, a set of scenarios exploring alternative power generation pathways for each region and a Stakeholder Multi-Criteria Assessment (MCA) of these scenarios. The MCA provides an integrating framework bringing together material from the disciplinary research. The methodology has been used in a heuristic role, similar to the Multi Criteria Mapping approach adopted by Stirling and Mayer (2001) and employed a basic MCA methodology and software tool developed during the pilot study to illuminate the key issues and trade-offs associated with CCS.

There are four technical annexes at the end of this report:

Annex 1 accompanies Chapter 3 and presents the detailed modelling of cost functions used in the ICEM model;

Annex 2 provides an overview of the techno-economic model used in Chapter 4;

Annex 3 provides supporting information used in the stakeholder MCA described in Chapter 7;

Annex 4 presents the energy scenarios, methodology and data associated with the Case Study presented in Chapter 8.

1.4. References

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Chapter 2

The Concept of Geological Storage of Carbon Dioxide[1,2]

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2.1 Geological Storage of Carbon Dioxide

Carbon dioxide (CO_2) is a greenhouse gas. Man-made CO_2 emissions resulting from the burning of fossil fuels such as oil, gas and coal are largely responsible for the increased levels of CO_2 in the atmosphere that have arisen since the industrial revolution, and thus for the global warming that this has induced. The UK generated approximately 564 Mt (Million tonnes) of CO_2 in 2002, of which 256 Mt was generated at large industrial plant such as oil refineries, chemical factories and power stations. The biggest category of such large industrial point sources of CO_2 is fossil fuel fired power plants, which produced approximately 174 Mt of CO_2 in 2002 (Figure 2.1).

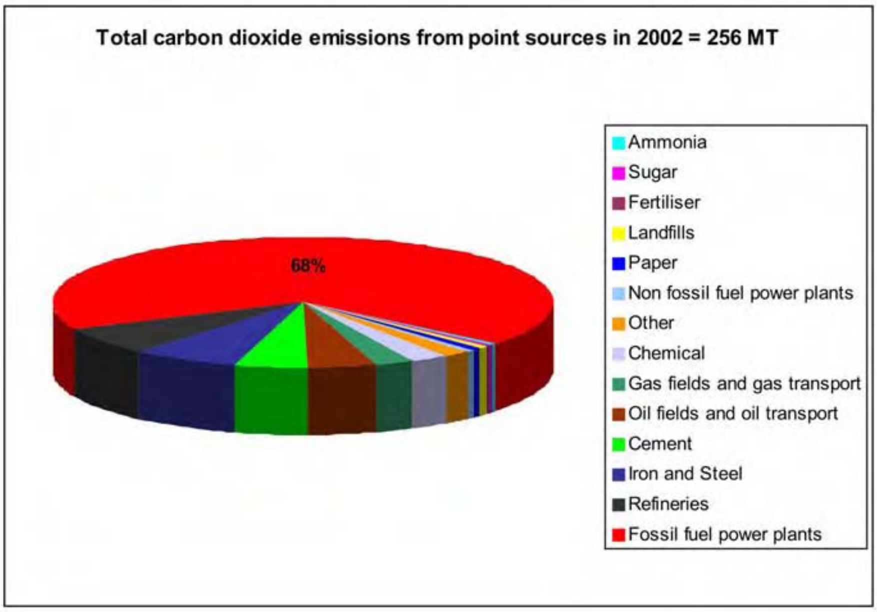

Figure 2.1 Distribution of CO_2 emissions from point sources in the UK (Figure Environment Agency 2002 data)

[1] The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office. Ordnance Survey licence number GD 272191/1999

[2] This Chapter is also available as BGS Internal Report Cr/05/161

It is possible to capture CO_2 at, for example, fossil fuel-burning power plants, inject it down wells and store it deep under the ground in geological formations. This prevents it entering the atmosphere where it acts as a greenhouse gas. This report provides a basic overview of this process, known as Carbon dioxide Capture and geological Storage (CCS).

2.1.1 How long does CO_2 need to be stored for?

If geological storage of CO_2 is to make a contribution to reducing CO_2 levels in the atmosphere, any CO_2 stored underground would have to be retained until well past the end of the fossil fuel era. After the end of the fossil fuel era, atmospheric CO_2 levels might begin a slow decline as ocean/atmosphere CO_2 levels re-equilibrate. Clearly it would not be desirable for stored CO_2 to be released until there had been a significant decline in atmospheric CO_2 levels. Thus the most desirable time frame for storage might be at least thousands of years. Nevertheless, short term storage of a few hundred years could be valuable in shaving the expected peak levels of CO_2 in the atmosphere that might occur towards the end of the fossil fuel era.

2.1.2 What makes a good geological Storage site?

The aim of the geological storage of CO_2 is to prevent CO_2 reaching the atmosphere by locking it away deep underground. The CO_2 gas can be captured at the power station after or before the fuel is burnt (pre or post combustion capture); further explanation of these processes can be found in Chapter 3. After the CO_2 is captured it can be compressed and transported by pipelines to a suitable geological storage site, either on- or off-shore where it is then pumped via a well or wells deep underground (Figure 2.6).

As the storage site may be required to store the CO_2 for tens or hundreds of thousands of years they need to be chosen very carefully on the basis of their geological characteristics. For safe storage in oil or gas fields and aquifers, the storage site must have the geological requirements summarised below.

Reservoir rock, porosity and permeability. A reservoir rock is a layer of rock that is capable of storing fluids, e.g. compressed CO_2, within its structure. Nearly all reservoir rocks are sedimentary rocks, and they are commonly composed of individual grains of sand or carbonate (the main building blocks of limestones) cemented together at their edges. A reservoir rock has gaps between the individual grains of rock called pore spaces. These pore spaces need to be connected by pore throats, so that fluid can flow into and out of the rock creating permeability. This is a measure of how efficiently fluids can flow through the rock and depends on the size of the pore throats and how well the pore spaces are connected via the pore throats and it is essential for the injection of fluids. Under natural conditions, the pore spaces of reservoir rocks are filled with fluids (sometimes described as native pore fluids), except where they are above the water table in onshore areas. The commonest pore fluids are water (which may be fresh or saline) and then oil and gas. When CO_2 is pumped (injected) into the rock it enters the pore spaces (Figure 2.2), partially or completely pushing out (displacing) the fluids that were originally present. There is usually a small amount of the native pore fluid left in the pore spaces, held in place by capillary forces, or adsorbed onto the rock grains. This is known as the residual saturation.

If the native pore fluid is fresh water, the aquifers are often exploited for drinking water; these freshwater aquifers are not considered for geological storage. In many cases the water is salty and has no current use; reservoir rocks containing saline water are referred to as saline aquifers. The measurement of the amount of pore space is referred to as porosity. Porosity is calculated as the percentage of pore space in the total volume of rock. Generally the higher the porosity the better the rock would be for CO_2 storage.

A high permeability means there are good connections between the pore spaces, this allows liquids and gases to pass between the pore spaces. Oil fields, gas fields and saline aquifers have the potential to store CO_2, dependent on the site matching all the other criteria discussed here.

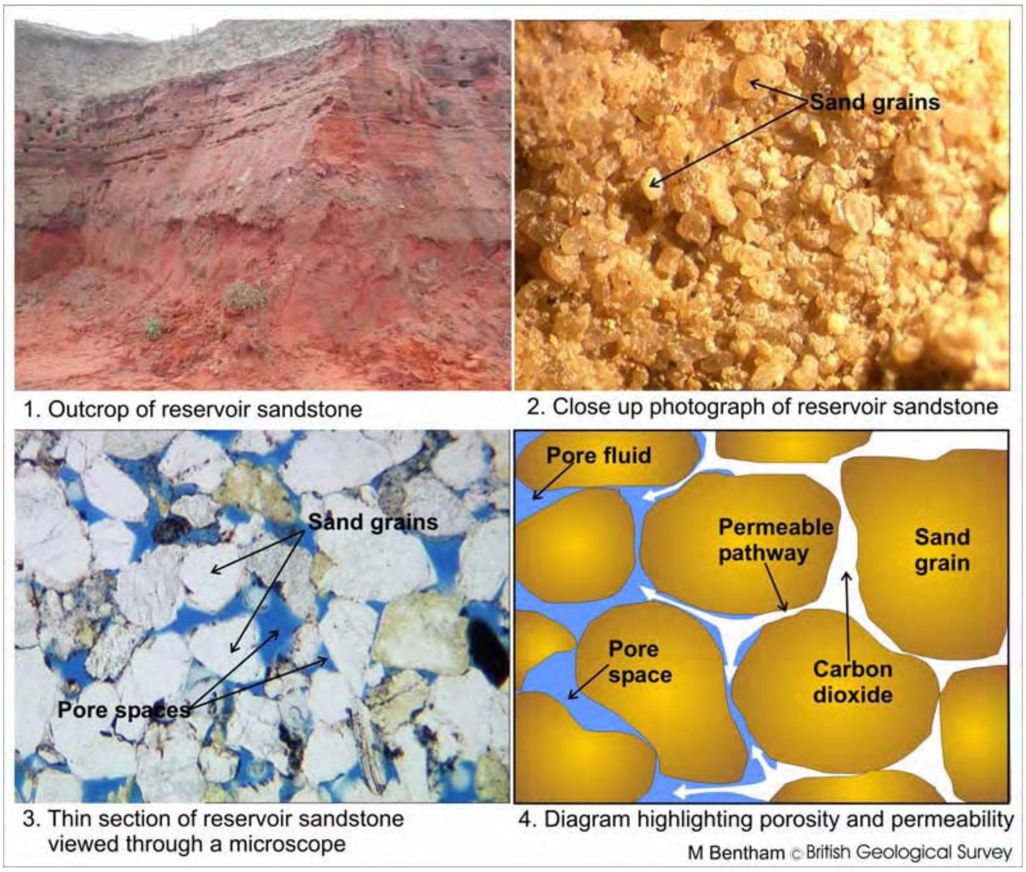

Figure 2.2 Diagram showing porosity and permeability in a sandstone reservoir rock.

Cap rock or seal. This is a rock layer above the reservoir that will form a barrier between the reservoir rock containing CO_2 in its pore spaces, and the surface, preventing the CO_2 moving out of the storage site (Figure 2.3). Cap rocks/seals need to have a low to zero permeability, so liquids and gases cannot pass through them and escape. Cap rocks can be divided into two categories; essentially impermeable strata such as thick rock salt layers (known as aquicludes) and those with low permeability such as shales and mudstones, known as aquitards, through which fluids can migrate, albeit extremely slowly.

Conditions Underground. Pressure and temperature underground increases with depth. The average temperature in many sedimentary basins increases by about 25-30 °C km^{-1} (this is know as a geothermal gradient) below the ground surface or sea bed as a result of heat flow from the inside to the outside of the Earth. However there is considerable variation in such geothermal conditions, both locally within basins and between basins worldwide.
Pressure in the pore spaces of sedimentary rocks is commonly close to hydrostatic pressure, that is the pressure generated by a column of water of equal height to the depth of the pore space. This is because the pore space is mostly filled with water and is connected, albeit tortuously, to the ground surface. However, under conditions where the pore space is either not connected to the surface, or not equilibrated to the surface, pressure may be greater than hydrostatic. Under pressure may also

exist, either naturally, or as the result of abstraction of fluids such as oil and gas from a reservoir rock.

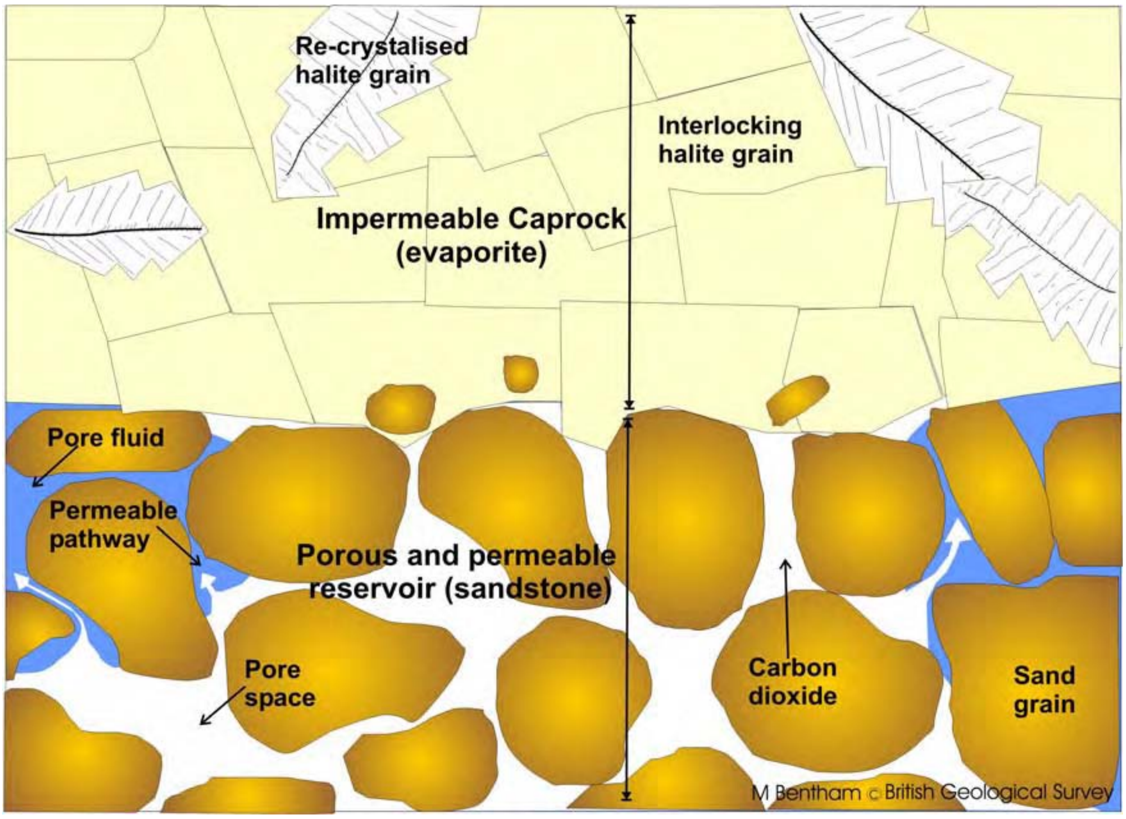

Figure 2.3 Diagram showing the interaction between CO_2 in the reservoir and the cap rock

Pressure and temperature affect how injected CO_2 behaves underground. CO_2 as a gas at the surface occupies a huge volume. But when gas is put under pressure it compresses and the volume decreases. The deeper underground you go the higher the pressure. So when CO_2 is injected deep under ground the surrounding rock exerts sufficient pressure to compress it so that it occupies a smaller volume. The depth at which this process works most effectively is approximately 800m (dependant of pressure and temperature) below ground level as the CO_2 is injected there is a very sharp increase in density associated with a phase change from a gas to a liquid, the CO_2 exists in a very dense phase and occupies a much smaller space. Consequently, CO_2 occupies much less space in the subsurface than at the surface. One tonne of CO_2 at a density of 700 kg/m^3 occupies 1.43 m^3, or less than 6 m^3 of rock with 30% porosity if 80% of the water in the pore space could be displaced. At 0°C and 1 atmosphere one tonne of CO_2 occupies 509 m^3.

This means that the size of storage site required is much smaller than would be required for the same amount of gas at the surface. Therefore storage of large masses of CO_2 in shallow reservoir rocks is not so practical, because the physical conditions at shallow depths underground mean that relatively small masses of CO_2 would occupy relatively large volumes of pore space. Also, shallow reservoir rocks commonly have a more important use – groundwater supply.

Migration or leakage pathways to the surface. Ideally the storage site should have no cracks / faults cutting through the cap rock and reservoir which reach to the surface. It is important to choose a geological storage site where the cap rock is not breached by faults or wells which have a high risk of leakage. Faults may act as pathways, allowing the CO_2 to escape from the reservoir rock at the storage site and migrate to another geological layer / formation, or leak at the surface.

Manmade holes in the cap rock from oil, gas or water extraction wells may also provide a route for CO_2 to migrate out of the storage site, if they have not been properly sealed when they were abandoned (Figure 2.4).

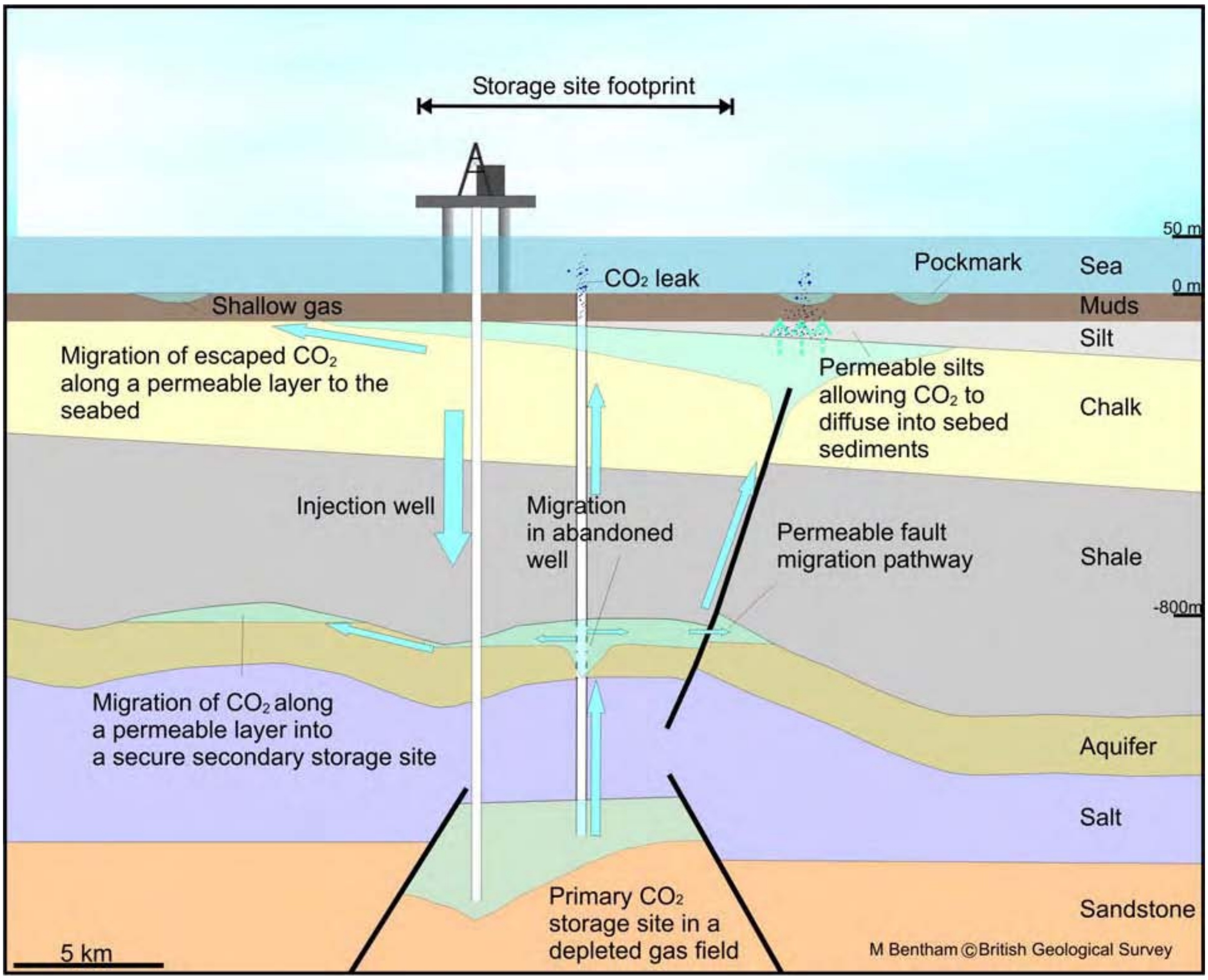

Figure 2.4 Leakage of CO_2 from a storage site

Geological trap. The best situation for CO_2 storage is to be in a geological trap, although this is not essential. A geological trap is an arrangement of the reservoir and seal into a formation that causes the CO_2 to become restricted within a small area of the reservoir, known as a closure or trap. For example, a geological trap is formed when the rock layers are folded and form domes known as anticlines. Storage sites where the CO_2 is injected into a trap are known as ‘confined’, and this type of situation can found in aquifers and oil and gas fields. In some cases it is not necessary to inject CO_2 into a trap providing the reservoir is big enough e.g. Sleipner section 3.1 where the CO_2 has been injected into an ‘unconfined’ aquifer. The difference between these two types of storage is shown on Figure 2.5. When CO_2 is injected into a confined reservoir trap the CO_2 rises to the top of the trap under buoyant flow and, is locked under the caprock. This prevents the CO_2 from spreading out into all of the reservoir rock, it remains restricted to the small area within the trap. When CO_2 is injected into a relatively flat-lying subsurface reservoir (unconfined) and rises to its top, it will be trapped in any small domes or other closed structures that occur on the underside of the cap rock. Once one of these structures becomes full, the CO_2 will spill from it and migrate to the next such structure along the migration path and fill that. As the CO_2 migrates within the reservoir, it may become divided into many small pools in many small closures.

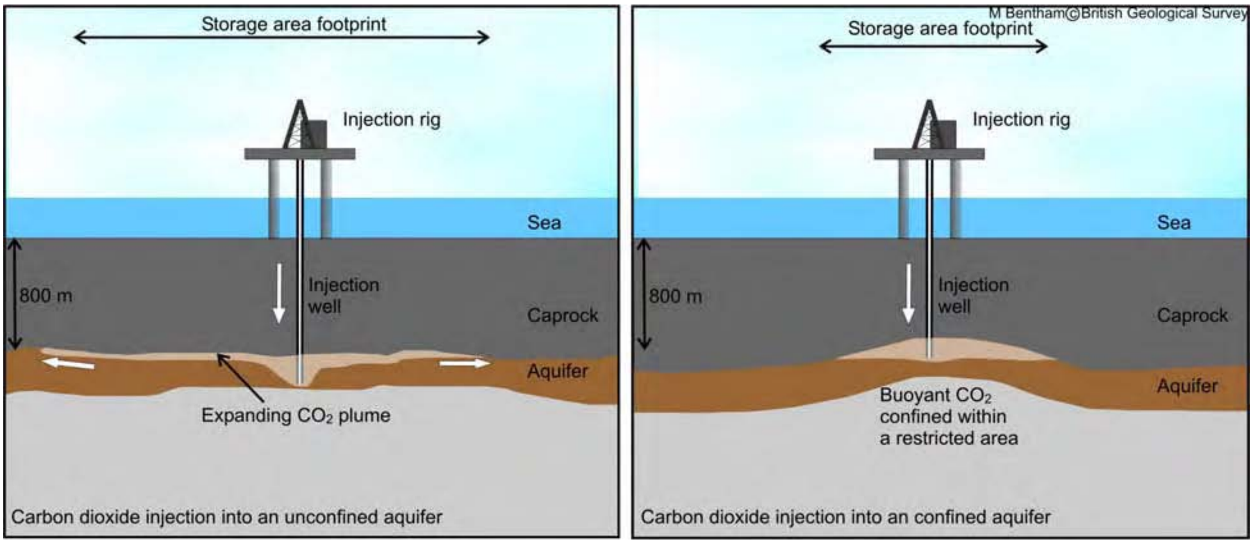

Figure 2.5 unconfined and confined CO_2 storage sites

Geologically stable area. It is essential that the storage site is located in a geologically stable area. For example, this should be an area without earthquakes. Earthquakes may cause faults to open up and allow the CO_2 to escape.

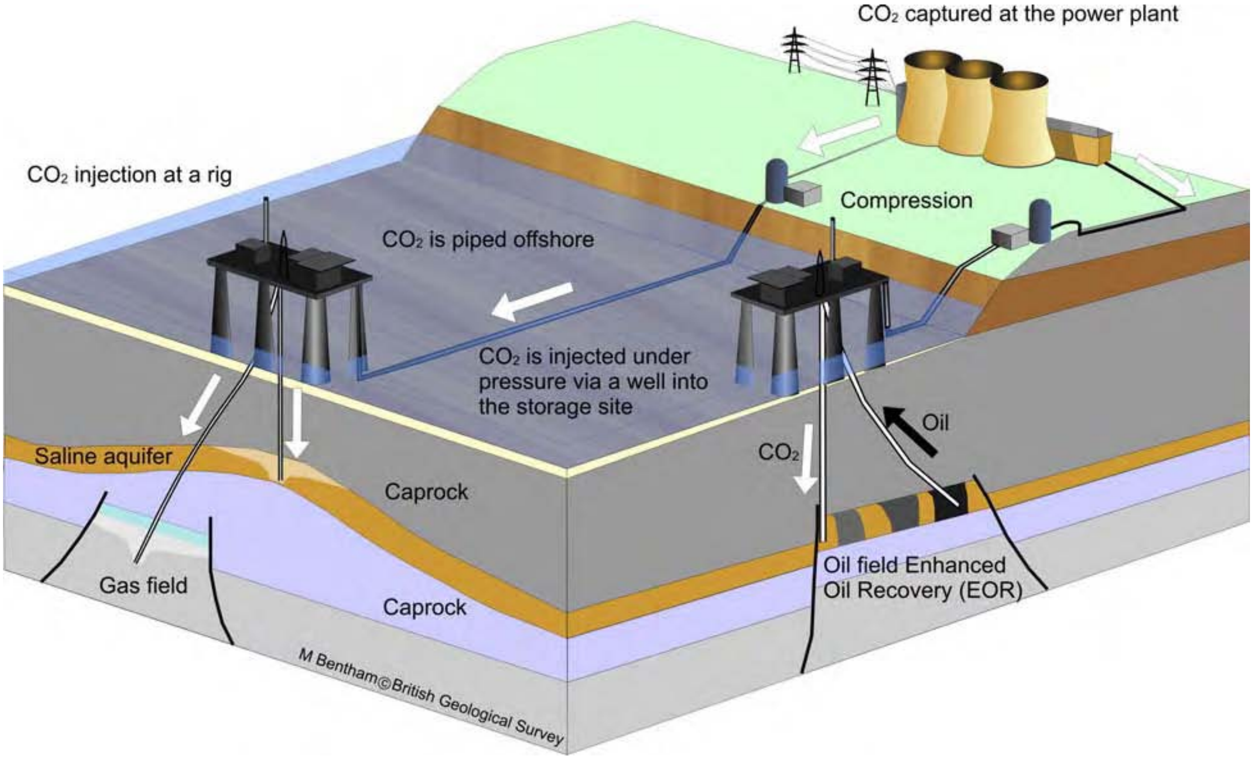

Figure 2.6 Diagram showing how a CO_2 storage scheme might work, in an oil and gas field and a saline aquifer

2.1.3 Types of CO_2 storage sites.

CO_2 could be stored in a range of different geological settings. These include:

Oil and Gas fields. CO_2 can be stored in depleted or nearly depleted oil and gas fields. Oil and gas fields are natural underground traps for buoyant fluids - these sites have been proven to store and retain oil and gas over geological timescales. In many cases there is geological evidence that the oil or gas has been trapped in them for hundreds of thousands or millions of years. In such cases, they will not leak in the geologically short term (a few hundred to a few thousand years) providing their exploitation by man has not damaged the trap and the cap rock is not adversely affected by the injection of CO_2, e.g. through wells. In oil fields, CO_2 can be used near the end of the field lifetime to push out more oil, which otherwise would have been left behind. This is known as enhanced oil recovery (EOR). CO_2 is widely used for enhancing oil recovery in depleted oil fields so it should be possible to store CO_2 in such fields and increase oil production at the same time The production of additional oil would offset the cost of CO_2 storage. Approximately 2.5 to 3.3 barrels of oil can be produced per tonne of CO_2 injected into a suitable oilfield.

Some of the CO_2 used in existing EOR projects is anthropogenic (from fossil fuel combustion), e.g. at Encana's Weyburn field in Saskatchewan, anthropogenic CO_2 from a coal gasification plant in North Dakota is used. The progress of this CO_2 flood will be monitored from a CO_2 storage perspective. It is expected to permanently store about 18 million tonnes of CO_2 over the lifetime of the project. The Rangely EOR project in Colorado has also been monitored to determine whether CO_2 is leaking from the reservoir to the ground surface. Further opportunities for EOR abound, especially if recent increases in the price of oil are maintained. There is undoubtedly significant potential in many of the world's major onshore oil provinces, for example the Middle East, and there may be potential in offshore areas such as the North Sea. The small amounts of CO_2 stored in such projects indicate that EOR would have to take place on a massive scale to have a significant impact on global CO_2 emissions to the atmosphere.

When natural gas is produced from a gas field, the production wells are opened and the pressure is simply allowed to deplete, usually without any fluid being injected to maintain the pressure. Thus, depending on the rate of water inflow into the porosity that comprises the gas reservoir, a large volume of pressure-depleted pore space may be available for CO_2 storage. In many cases there is little or no water flow into a gas reservoir. Therefore it may be possible to store underground a volume of CO_2 equal to the underground volume of the gas produced. Furthermore, there is a possibility that CO_2 injection could enhance natural gas production towards the end of field life.

Saline Aquifers. Saline aquifers are porous rocks in which the pore spaces are filled with saline pore fluid. Porous and permeable sedimentary rocks (known as reservoir rocks) commonly occur in major accumulations known as sedimentary basins that may be up to a few kilometres thick and may cover thousands of square kilometres. However, although very common, sedimentary basins do not occur in every country in the world. Nor are all sedimentary basins suitable for CO_2 storage. In some areas, saline aquifers exhibit all of the necessary criteria for CO_2 storage. Sedimentary basins in the UK are discussed in section 2. Saline aquifers also have the advantage of not being used for any other purpose such as water extraction.

Coal Seams. Coal beds (otherwise known as coal seams) can be reservoirs for gases. Coal contains a natural system fractures within the coal beds known as the cleat. The cleat imparts some permeability to the coal. Coal does not have relatively large pore spaces like a reservoir rock but does have micropores in which natural gas known as coal bed methane (CBM) can, occur. Coal seams in some cases could be used for CO_2 storage. CO_2 injected in the permeability of the coal will displace the methane. This is because the CO_2 has a greater attraction to the coal molecules than the methane and is therefore absorbed on the surface of the coal more readily. The displaced methane could be economically produced in some areas offsetting the cost of CO_2 storage. This is not considered a viable option in the UK so is not considered further. However only a minority of coalfields are suitable for commercial CBM recovery using present technology, because economic production is only possible from coal beds with exceptional permeability. This could be a barrier to the coal seam CO_2 storage option especially in the UK where the coals have a very low permeability.

Natural and man-made caverns. Storage in caverns is not seen as a good way of storing CO_2. Mines for example are not generally leak-proof and most abandoned mines are gradually filling up with water that would force any stored CO_2 out. Leak-proof mines such as salt caverns have other uses. For example mines in Cheshire are used for long-term storage of hazardous waste and documents. Salt is also ductile (flows very slowly) and over long periods of time will creep, which may form cracks and damage the leak-proof nature of the cavern. The storage capacity of man-made caverns is also very small in comparison to other options. For the reasons above caverns have not been further included in this report.

2.1.4 What happens to the CO_2 underground?

As described above, when CO_2 is injected into the pore spaces of a reservoir rock it will permeate through the rock, pushing out some of the pore fluid originally in the pore spaces. For the injected CO_2 to be able to displace the original pore fluid it has to be injected into the reservoir rock at a greater pressure than the existing pore fluid pressure.
Barriers preventing fluid flow such as faults or low permeability may cause an increase in pressure within the reservoir rock pore space during injection. This may limit the amount and rate at which CO_2 can be injected into that particular site. Once the CO_2 has been injected into the reservoir, several process then take place (Figure 2.7).

1) **Trapping**. CO_2 is less dense than the surrounding pore fluid so once it is injected the majority of the CO_2 will move buoyantly upwards through the most permeable pathways toward the top of the reservoir until it reaches the cap rock. Once the CO_2 reaches the cap rock it remains trapped.
2) **Migration Trapping**. As the CO_2 moves through the reservoir, a fraction of the CO_2 may get caught behind permeability barriers within the reservoir, such as shale layers. The CO_2 will may remain retained behind these barriers and permanently trapped within the reservoir.
3) **Dissolution Trapping**. CO_2 is slightly soluble in water, the solubility depends on the temperature, pressure and salinity of the pore fluid. As it comes into contact with the pore water some of the CO_2 will become dissolved in it and remain trapped as a solution in the pore water. There is the potential for large volumes of CO_2 to become trapped in this way but it is dependent on the solubility of the CO_2 in the pore water and the amount of mixing within the reservoir between the pore water and the CO_2. As a result for the maximum amount of CO_2 to become dissolved in the pore water this can take thousands of years.
4) **Residual Trapping**. As the CO_2 moves through the reservoir some of the CO_2 remains behind in the pathway along which the CO_2 has travelled. This is due to capillary forces which cause the CO_2 to remain attached to the surface of the grains of rock within the reservoir. As a result a small amount remains trapped coating the grains (in the order of 5 –30% of the injected CO_2) and this is know as residual trapping. With time the CO_2 trapped in this way may dissolve into the pore water.
5) **Chemical Trapping.** Some of the CO_2 may also become trapped by chemical reaction with either the pore water or the reservoir rock (the latter will take place only over long time scales, i.e. Perhaps 10s – 10000's of years), the amount depending on the pore water chemistry, rock mineralogy and the length of the migration path.

6) **Hydrodynamic Trapping.** Once the CO_2 is outside the influence of the injection well the CO_2 will migrate in the same direction as the natural flow within the reservoir. If it is a free gas within the reservoir, it will migrate faster than the brine (the native pore fluid) because it is less viscous. If the CO_2 has dissolved with the pore fluid it will migrate at the rate of the fluid flow within the reservoir. Fluid flow within reservoir rock is usually very slow. If the migration of the CO_2 is very slow and the proposed injection point is a very large distance from the edge of the reservoir, the CO_2 may not reach the edge of the reservoir for millions of years.

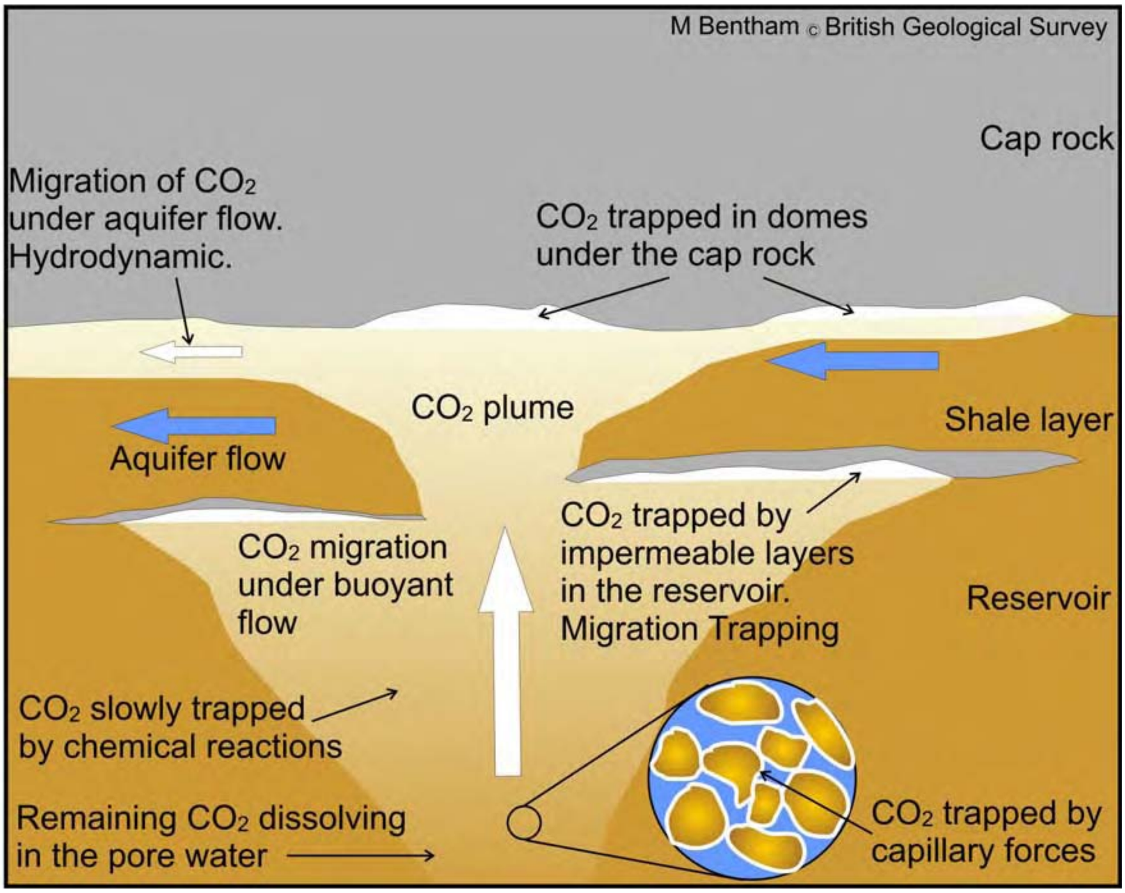

Figure 2.7 Trapping mechanisms

In the long term, the interaction of these mechanisms and, if the seal is not perfect, migration out of the geological storage reservoir, will determine the fate of the CO_2. Escape of CO_2 from the storage reservoir may not necessarily be important, providing there is no adverse impact on man, the natural environment, or other resources such as groundwater, and the required storage period is exceeded.

The amount of CO_2 that can be injected during a particular project or into a particular reservoir is limited by the undesirable effects that could occur. Some of these might be important in the short term, others may occur in much longer timescales, as the result of migration of the injected CO_2. They include: an unacceptable rise in reservoir pressure, conflicts of use of the subsurface (e.g. unintentional interaction with coal mining, or the exploitation of oil and gas), pollution of potable water by displacement of the saline/fresh groundwater interface, pollution of potable water by CO_2 or substances entrained by CO_2 (e.g. hydrocarbons), escape of CO_2 to the outcrop of a reservoir rock and escape of CO_2 via an unidentified migration pathway through the cap rock.

2.1.5 *Monitoring of CO_2 underground.*

Monitoring of the CO_2 underground is essential to verify it is behaving as predicted and not migrating out of the storage site. This is important for the safety, public assurance and permitting / regulation of storage sites. There is a wide range of tools available for monitoring CO_2 storage sites both offshore and onshore storage sites. The most important part of a monitoring scheme is a baseline survey. The chosen set of monitoring tools should be used at the site before CO_2 is injected, as this will enable changes to be detected after the CO_2 has been injected. After injection has started, a long term monitoring plan will likely include repeat surveys over the storage area during and after injection. Once injection ends, it is considered likely that monitoring would continue for a significant period, until the operator and regulator are satisfied that the site is performing, and will continue to perform, as predicted. Site closure would then follow. The frequency of monitoring is likely to decrease as confidence in the site increases.

Onshore and offshore monitoring can be categorised into deep and shallow monitoring. Deep monitoring systems monitor the amounts and movement of the CO_2 within the storage reservoir and migration into the immediate surroundings. Deep monitoring systems will also give warning should CO_2 migrate to shallower depths. Deep monitoring systems can be run from the surface e.g. seismic or gravity or in wells. Shallow monitoring systems, e.g. soil gas surveys, are designed to monitor CO_2 that has migrated to the soil or seabed or leaked to the atmosphere or into seawater (Pearce *et al.,* 2005).

Techniques used for monitoring deep storage sites at present include seismic reflection surveys, seismic attribute studies and gravity surveys and shallow monitoring techniques include infra-red CO_2 detection equipment and data and samples acquired from wells. Monitoring data should be history-matched to predictions from models to check whether the site is performing as predicted. If significant discrepancies are found, more geological data should be acquired and/or the models adjusted as necessary.

2.1.6 *Safety of Storage.*

The most important issue for the underground storage of CO_2 is whether safe and stable storage can be assured - this is likely to have a high impact on public acceptability and regulation.

Stringent risk assessment procedures would be required to assure safe and stable containment of injected CO_2. The first step would be to carry out detailed geological characterisation of the selected site and its surrounding area. This would enable geological models of the site to be built, which would help to assess the risks more accurately by providing information on potential migration paths (gas escape routes). One risk assessment approach is then to identify and assess all the Features, Events and Processes (FEPs) likely to affect the storage site. The geological model of the site should then be converted into a numerical reservoir model so that computer simulations of CO_2 injection can be carried out These can demonstrate the likelihood, size, timing and location of potential CO_2 migration out of a storage site to the ground surface or seabed and help with analysis of the important FEPs. This kind of analysis should provide the basis for a monitoring plan, and a remediation plan should any potential hazards be identified.

There are many uncertainties regarding long-term geological storage of CO_2. The required storage period is greater than the likely lifetime of any corporation. This raises issues of ownership, monitoring and liability for leaks or man-made breaches of the storage integrity in the distant future. Because of the longevity of storage, it seems inevitable that ownership and liability would, at some stage, be transferred to the State.

Leakage of repositories. Carbon dioxide has been used extensively for EOR (Enhanced Oil Recovery) for more than two decades (74 active projects are recorded by Gale & Davison, 2004).

There are three major demonstration projects currently operating at industrial scale, the Weyburn Project a landbased programme close to the Canadian/USA border, the In Salah gas fields project in the Sahara desert in Algeria, and the Sleipner Field project in which the storage is beneath the North Sea. None of these projects has given rise to serious concerns. The impacts of leakage will vary according to location (on land or sub-sea), volume, release rate, and dispersion. Leakage on land will result in the carbon dioxide reaching the atmosphere but it may also contaminate ground water supplies (the popularity of carbonated drinks shows this does not render the water unpotable but it does, by lowering the pH, make it more corrosive). Small leaks in well-ventilated areas are unlikely to be hazardous, but can result in the build up of lethal conditions where the ventilation is poor.

In high concentrations CO_2 is toxic, causing asphyxiation at high concentrations and acidosis at lower concentrations. As CO_2 is colourless and odourless, people (and animals) can be totally unaware of entering areas where the concentrations are dangerously high, and may collapse before being able to make their escape. CO_2 is heavier than air, so it accumulates in depressions and in poorly ventilated enclosed spaces such as cellars and basements. Concentrations of 100,000 ppm (i.e. 10%) are directly toxic (Vendrig *et al.*, 2003). The gas is an asphyxiant, a cerebral vasodilator rapidly causing circulatory failure, coma and then death. The symptoms resulting from acidosis (lowering of the pH of the blood) include headache, nausea, visual disturbance and laboured breathing (dyspnoea). These are normally experienced at concentrations of >15,000 ppm (1.5% CO_2). A few minutes exposure at concentrations of 7-10% is sufficient to cause loss of consciousness and less than a minute's exposure to concentrations of 15-30% can be fatal. West *et al.* (2005) provide an overview natural elevated concentrations and fluxes of CO_2 and the effects of CO_2 exposure on selected organisms.

However, the numerous carbon dioxide springs in Italy illustrate how leakage at rates of 150 tonnes per day can be of little consequence even in regions of high population density. Experience shows that the engineering and routing requirements to optimise the safety of the operation of carbon dioxide pipelines are not going to impose insuperable problems and are likely to be less problematical than the current networks of pipelines transmitting natural gases and hazardous liquids over long distances. Leakage out of the repositories themselves will mimic natural venting of carbon dioxide.

Submarine leakage is of far less concern to mankind. Much of the carbon dioxide released will dissolve in the seawater where the high bicarbonate content will buffer any pH changes. Carbon dioxide is vented from seeps in the seabed, both in shallow water and in deep water with very little apparent influence on marine life. 'Bubbles' of liquid carbon dioxide have been filmed by ROV (Remotely Operated Vehicles) issuing from hydrothermal vents at depths of 900m off the Marianas. Whereas bubbles of gaseous CO_2 appear to have little effect on plankton, *in situ* experiments on the emplacement of liquid carbon dioxide on the seabed at depth have shown that liquid CO_2 is extremely toxic to plankton that ventures into its immediate vicinity. Submarine leakage is likely to have a localised environmental impact, which in the dynamic marine environment will be extremely difficult to detect. Turley *et al.* 2004 have produced an extensive review of the literature relating to the potential environmental impacts of CO_2 to the marine environment. The overlying seawater will shield personnel on platforms at the sea surface. It has to be concluded that submarine disposal will be less risky to humankind, since small leaks will not lead to localised accumulations.

2.1.7 Natural CO_2 Analogues

There are several naturally occurring accumulations of carbon dioxide that can be seen as analogues to stored CO_2 and provide useful insights to the likely impacts of potential leakages from CO_2 storage. An EU-funded project, NASCENT, has carried out an extensive analysis of these analogues in order to enhance understanding of the processes affecting stored CO_2 (NASCENT, 2005). Here we provide a brief overview of three such analogues.

Lake Nyos, Cameroon. In the late evening of 21st August 1986, Lake Nyos, a volcanic lake which lies in a flat floored crater some 200 m deep in the Oku volcanic field in Cameroon at an altitude of 3011m, suddenly vented a large cloud of carbon dioxide. A lethal concentration of the gas reached a height of 120m above the lake surface. Initially it was confined by the surrounding crater walls and, being heavier than air, hugged the ground and flowed over the lake spillway, down into the surrounding valleys for up to 25km suffocating 1700 people and their stock, and injuring over 800 others (Wagner *et al.* 1988). The subsequent scientific investigation showed that CO_2 leaks into the bottom of the lake dissolves into the lake water and progressively builds up in solution in the lower part of the lake (Evans *et al.* 1994). The CO_2-saturated water is denser than the fresh water and results in density stratification of the lake waters. Also, the solubility of CO_2 increases with depth in the lake because the pressure is higher. Once the dense layer becomes saturated with CO_2, any significant disturbance can cause the dense water to rise, which reduces the solubility of CO2 and causes it to start to emit bubbles of CO_2. The rising of these bubbles towards the lake surface would drag up more of the deep CO_2-saturated lake water and escalate the process. It is thought that the 1986 event can be explained by such a scenario rapidly escalating into a major, violent degassing event that caused the complete overturn and degassing of the lake waters. CO_2 is continuing to leak into Lake Nyos and in 2001 a pipe was installed to vent the CO_2 to the atmosphere using a gas-lift process; however, recently concerns have been raised that this may be insufficient to prevent further fatalities should a large CO_2 release occur again (Kling *et al.*, 2005). A similar event occurred earlier in 1984 at Lake Monoun when 37 people were killed. These events illustrate the potential dangers associated with sudden major releases of carbon dioxide from storage within lakes. However, most lakes in temperate regions overturn at least seasonally, so there is less chance of high masses of CO_2 building up in them. Any lakes above or near a CO_2 storage site could be monitored for CO_2 build-up and remediated in the same way as lake Nyos if CO_2 was found to be leaking into them.

Mammoth Mountain discharges. In 1989 there was high seismic activity in the Long Valley caldera (a 15x30km depression, to the south of Mono Lake) in California, which breached a natural reservoir of CO_2. In the vicinity of Horseshoe Lake, in an area of >75 acres (~30 hectares), carbon dioxide (up to 25g CO_2 m^{-2} d^{-1}) began to seep from the soil (i.e. ~50-150 tonnes/day for the whole area). In the soils around the seeps the interstitial gases contain 20-90% carbon dioxide, causing in an extensive area of tree kill (Farrar *et al.*, 2002). As a result of this build-up of CO_2, a ranger sheltering in a snow covered refuge survived by escaping to open air after experiencing a feeling of suffocation, weak legs and a racing pulse and a cross-country skier found in a snow drift in the vicinity was thought to have died through CO_2 asphyxiation (Hill, 2000).

Carbon dioxide vented by fumaroles. Carbon dioxide is a common constituent of the gases vented by fumaroles. Throughout the East African Rift valley there are many fumaroles that are almost continuously venting nearly pure CO_2. Many of these vents lie at the bottom of depressions, which during windless conditions in the early morning can become filled with carbon dioxide. These hollows are death traps for game that accidentally ventures into them, then the smell of the decaying corpses attracts in scavengers that also succumb. These are described locally as ‘elephant graveyards’. In the Virunga volcanic range on the borders of Congo and Rwanda, vents from fumaroles have recently suffocated several people in the vicinity the refugee camp at Goma. There is also a fear that a build up of CO_2 in the deep waters of Lake Kivu may lead to a repeat of the Lake Nyos disaster.

In Southern Italy there are over 150 vents, or carbon dioxide springs, which release ~150 tonnes CO_2 per day. Mount Etna itself is reported to vent 35,000 tons CO_2/day. In total these Italian vents are estimated to release ~5-10% of the estimated magmatic CO_2 discharged globally to the atmosphere by active volcanoes (Cardellini *et al.*, 2000). Responses of the vegetation around these springs have been extensively studied, using the carbon dioxide springs as natural experimental analogues for global rises in atmospheric CO_2 concentrations (Raschi, *et al.*, 1997, Scholefield *et al.*, 2004, Rapparini *et al.*, 2004). A survey of two vents in Tuscany showed an accumulation of dead animals (bats, mice, rabbits, rats, cats and birds, even a 2cm thick crust of flies); only at one was there any sign of living animals – a spider which had woven webs across the vent holes (Bridges *et al*., 2000). Some species of plant flourish in the vicinity of the springs, and show enhanced productivity. One positive effect of the heightened CO_2 concentrations is the inhibition of the release of chloroplast-derived isoprenoids (Rosentiel *et al*., 2003; Scholefield *et al.,* 2004), which otherwise would increase local ozone concentrations. It is worth noting that local human activity is almost totally unaffected by the presence of these CO_2 vents; hence small leaks of carbon dioxide from pipelines need not necessarily cause serious disruption to human activity.

2.2 Suitable Geology for Storing CO_2 in the UK

The majority of the rocks in the UK that are suitable for storing CO_2 are sandstones. Sandstone is a sedimentary rock that is commonly found within the UK's sedimentary basins. Locations of the most suitable UK sedimentary basins for CO_2 storage are shown on Figure 2.8. These areas are also where most of the UK's oil and gas fields are located (Figure 2.9).

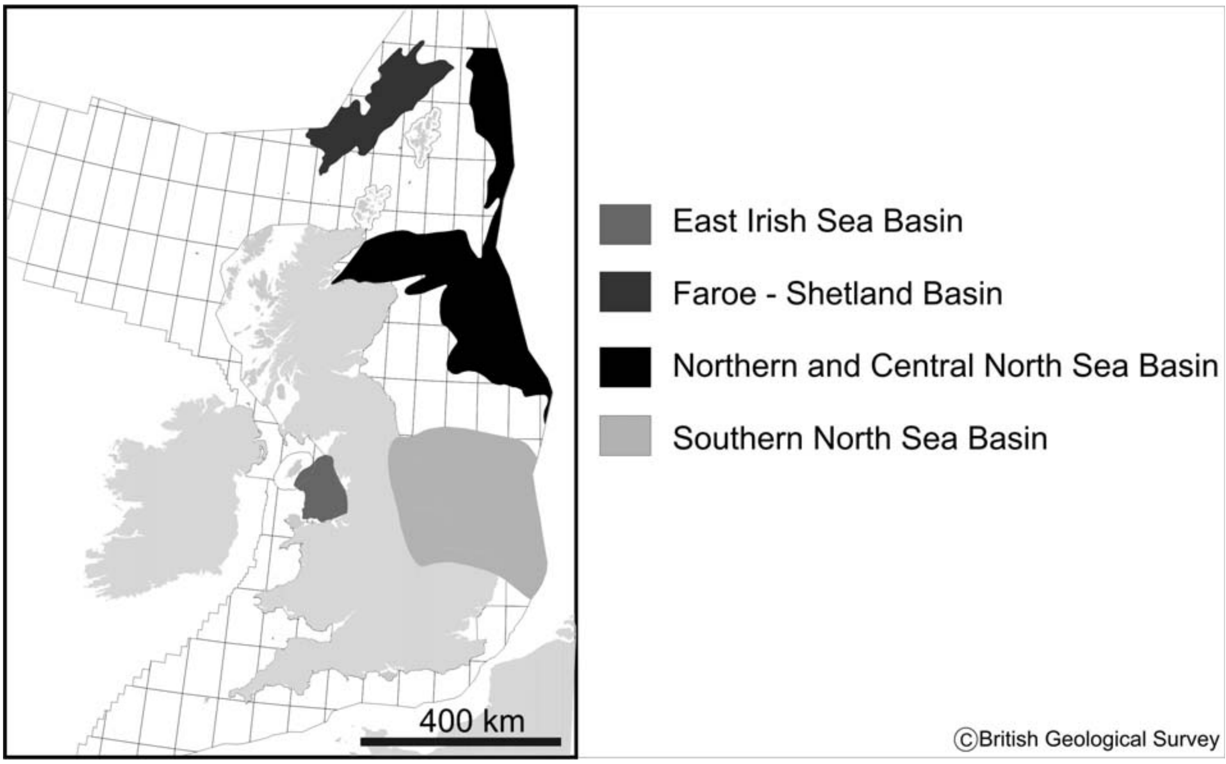

Figure 2.8 Location of the major UK sedimentary basins

The CO_2 storage potential of these basins, with the exception of the saline aquifer potential of the Northern and Central North Sea Basin which hasn't been fully investigated for its storage capacity potential is shown in Table 2.1.

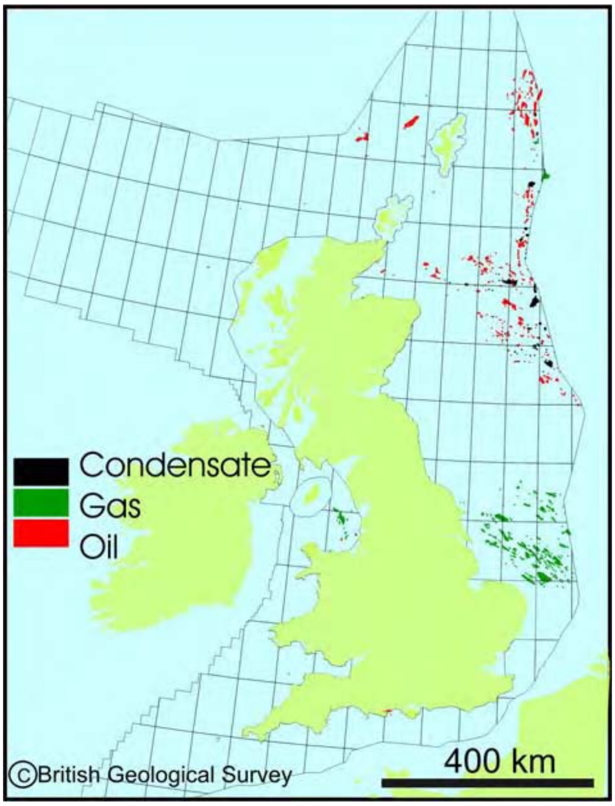

Figure 2.9 Oil and gas fields in the UK sector

Table 2.1 Estimated UK CO_2 storage capacities (Holloway *et al*., 2005)

	Estimated CO_2 storage capacity (Gt)	
Gas fields of the Southern North Sea Basin	0.43 3.3 0.15	(Bunter Sandstone) (Leman Sandstone) (Carboniferous)
Oil fields of the Northern and Central North Sea Basin	6.5	
Gas fields of the East Irish Sea Basin	1.05	
Bunter Sandstone saline aquifer (Southern North Sea Basin)	14.25	
Bunter Sandstone saline aquifer (East Irish Sea Basin)	0.63	
Leman Sandstone saline aquifer (Southern North Sea Basin)	3.13	
Palaeocene Sandstone saline aquifer (Northern and Central North Sea Basin)	≥ 2	

The estimates suggest that the CO_2 storage capacity of the UK may be 25 Gt or more – enough to store more than 100 years of CO_2 emissions from UK power stations (at current emission levels). Regional or basin-wide estimates of storage capacity have a huge amount of uncertainty associated with them. The most accurate are likely to be storage capacities in oil and gas fields.

Due to the large amount of geological data associated with their exploration and production history. As a result reasonably accurate calculations of storage capacity can be made by estimating the amount of CO_2 that could occupy the pore space evacuated by the extracted gas or oil. Estimates of storage capacity in aquifers are much more uncertain. Aquifers have not stored gas or liquids previously so it is generally uncertain as to whether they would store CO_2 because there is always the possibility that they might leak. There is not the same amount of geological data available for aquifers as there is for oil and gas fields. When making regional estimates of storage capacity for aquifers there is large uncertainty about each individual closure and its ability to store CO_2. Uncertainties include the injectivity of the reservoir, porosity or the sealing capacity of the cap rock. It is therefore advised that estimates of storage capacity should be made on a site-by-site basis

2.3 Case Study – CO_2 Storage at the Sleipner West Gas Field

CO_2 storage in a saline aquifer called the Utsira Sand has been carried out at the Sleipner West gas field since 1996. It is the first industrial-scale CO_2 injection project designed specifically to reduce greenhouse gases. The field is located in the middle of the North Sea 200 km from land (Figure 2.10).

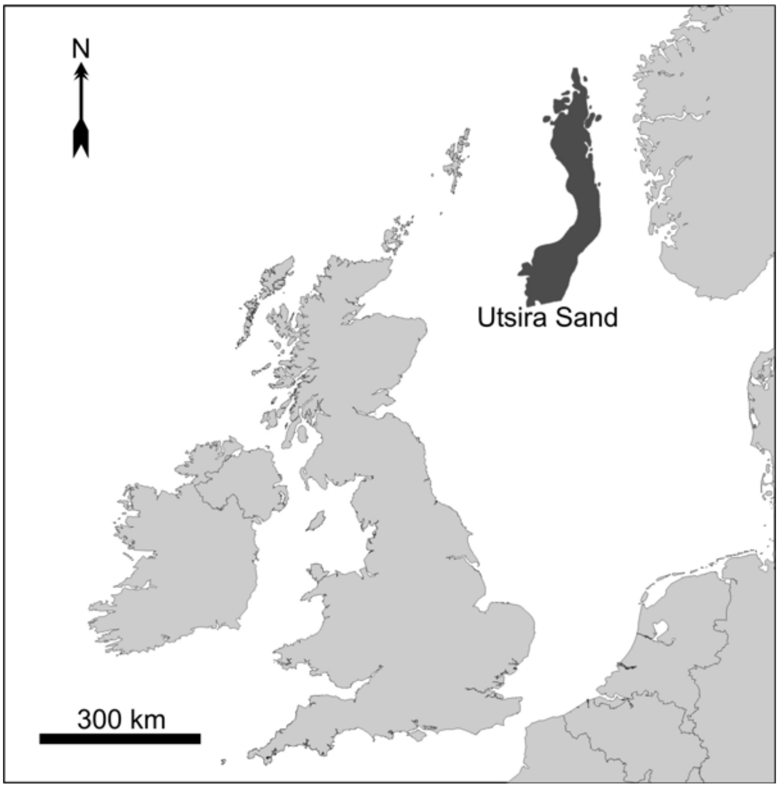

Figure 2.10 Location of the Utsira Sand

Natural gas from the Sleipner West produced is via 18 production wells drilled from a wellhead platform (Sleipner B) and transported to a process and treatment platform (Sleipner T) connected by a bridge to the main Sleipner A platform (Figure 2.11). The natural gas produced at the Sleipner West field has a high concentration of CO_2 - between 4% and 9.5%. For the gas to reach sales quality the amount of CO_2 mixed with the natural gas has to be reduced to 2.5% or less. This process is carried out offshore on the gas platform at the Sleipner West field.

About 1 x 10^6 tonnes of CO_2 is separated from the natural gas annually. This amounts to 3% of Norway's CO_2 emissions. In normal gas production process the CO_2 would be vented to

the atmosphere. In the Sleipner case Statoil, and partners decided to store the CO_2 underground in the Utsira Sand. A reservoir sandstone 150 – 200m thick which lies at a depth of between 800 – 1000 m. The cap rock at the storage site is made up of 100 m of shale directly overlying the reservoir which is named the 'Shale Drape'. The rocks above the Shale Drape are a succession of mudstones. The accumulation of these strata form an effective seal and prevent the CO_2 migrating out of the storage site and to the atmosphere.
CO_2 injection started in August 1996 and will continue for the life of the field (estimate to be 20 years). Additional costs of the operation are about US$15/tonne of CO_2 avoided. A demonstration project, acronym SACS (Korbul and Kaddour, 1995), jointly funded by the EU, industry and national governments, and its successor, acronym CO2STORE, is currently evaluating the geological aspects of the Sleipner subsurface disposal operation. The projects are assessing the capacity, storage properties and performance of the Utsira reservoir, modelling CO_2 migration within the reservoir, and monitoring the subsurface dispersal of the CO_2 using time-lapse seismic techniques.

The time-lapse seismic data is particularly effective at monitoring the distribution of CO_2 within the reservoir. It has reached the base of the cap rock and is migrating horizontally beneath it. Seismic and reservoir modelling is now being carried out to further quantify and constrain the CO_2 subsurface distribution and predict its future behaviour. The Utsira Formation appears to be an excellent repository for CO_2.

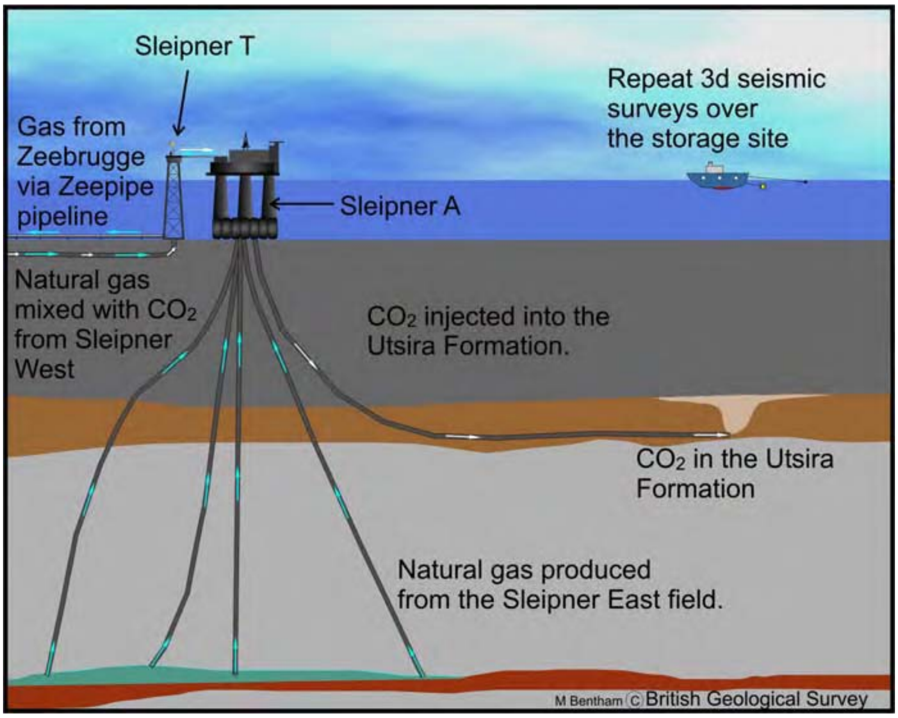

Figure 2.11 The Sleipner storage site (Adapted from a diagram Courtesy of Statoil)

2.4 Summary

Storage of CO_2 in geological reservoirs has the potential to make a large reduction in the CO_2 emissions from power plants in the UK. The UK is well placed with huge amounts of storage potential in the offshore basins of the North Sea, which offer storage potential in saline aquifers and hydrocarbon fields. To make an impact into CO_2 emissions CO_2 would need to remain stored in the storage site for 100 – 10000's of years. As a result site will need to be chosen very carefully based on the geological criteria discussed. This should be done on a site by site basis.

Each site should be subject to a rigorous site investigation which would include a period of data collection, geological characterisation, modelling and finally testing. If the sites are chosen carefully it should reduce the risk of CO_2 leakage at a later date. The site would be monitored over a period of time after injection to ensure the CO_2 is behaving as predicted. There is a large range of monitoring tools available for this including 3D time-lapse seismic data. Demonstration projects such as the Sleipner project and studying natural analogues have given us valuable incites into how CO_2 behaves underground. This technology could be potentially deployed on a large scale in the UK.

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Chapter Three

Engineering Feasibility

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3.1 Introduction

This chapter provides a review and assessment of the major technological options that are available for the capture of CO_2 for emissions from power plants and other process industries. The aim is to provide a critical state-of-the-art review, which is at the same time readily accessible and provides the reader with sufficient information to understand the basic technologies and their possible future evolution. In the first half of this chapter we present a review of established techniques for capturing CO_2 from large industrial sources, followed by modelled results estimating the cost of CO_2 capture. In the second half of this chapter (Section 3.7) we present a review of some of the novel approaches that have been proposed for capturing and storing or sequestering CO_2.

Power generation, being one of the major sources of CO_2 emissions, is based on several processes, some of which are widely used, the others regarded as future technological options. Coal fired power generation using pulverised fuel and flue gas desulphurisation represents the most commonly available technology. Natural gas fired combined cycle (GTCC) is also currently available technology. Integrated Gasification Combined Cycle (IGCC) is an emerging technology likely to be more widely used in the mid term. An oxygen blown gasifier of the entrained flow type with a wet feed of slurried coal is one of the most established variants of this technology. Power generation based on a scheme of burning pulverised coal in oxygen using recycled CO_2 to moderate the combustion temperature (CO_2 recycle). This processing route concentrates CO_2 in the exhaust gas to the extent that further processing is governed by CO_2 purity requirements rather than CO_2 recovery. The technology has not been extensively demonstrated and is therefore regarded as a long term option. Energy-intensive industry, petroleum refining, petrochemicals, iron and steel, cement, lime, soda ash production and natural gas production sectors, is another major source of CO_2 emissions.

3.2 Technical review of existing CO_2 capture processes

Absorption processes are currently the most developed CO_2 removal technology. Absorption systems are continuous scrubbing systems used to remove CO_2 from a gaseous stream. Three main absorption processes available are chemical, physical and hybrid.

CO_2 capture from a power plant is a commercial process nowadays. More than a dozen capture plants operate worldwide. So far, all commercial CO_2 capture plants use processes based on chemical absorption with a monoethanolamine (MEA) solvent. Active research is being carried out on new processes and approaches. Technologies such as cryogenic fractionation, membrane separation, and adsorption using molecular sieves to capture the CO_2 from the flue gas of a power plant have been considered but they are even less energy efficient and more expensive than chemical absorption (Herzog, 2001).

3.2.1 Chemical scrubbing process

Most conventional coal-burning power plants produce electricity using steam turbines, while most natural gas plants use gas turbines (the excess heat being applied to a second, steam-driven turbine). Flue gas streams generated by those plants are characterised with low to moderate concentrations of CO_2. For such streams, the current most effective way to capture CO_2 is absorption using a chemical solvent such as monoethanol amine (MEA) or diethanolamine (DEA), ammonia and hot potassium carbonate (Chinn *et al.*, 2004). Recent research shows that amino-acid salt solutions can be an alternative to amine based solutions (Feron *et al*., 2004).

CO_2 reacting with an MEA solvent forms an intermediate compound with weak bonds. By applying heat, this intermediate compound can be broken down, thus regenerating the original solvent and producing CO_2. These processes can run at low CO_2 partial pressures, but the precondition is that the flue gas should be free of contaminants such as SO_2, O_2, hydrocarbons and particulates since they may cause operating problems in the absorber. At present, this process (Figure 3.1) is regarded as one of the most applicable for CO_2 capture from power plants, these techniques have been used for decades to recover by-product CO_2 or directly manufacture CO_2 from fossil fuel combustion. The food and beverage industry also widely apply chemical absorption to recover CO_2 released during fermentation processes (Anderson and Newell, 2003).

As an energy consuming process, postcombustion chemical absorption has an energy penalty of about 15% to 30% for natural gas plants and about 30% to 60% for coal plants (Herzog *et al.*, 1997; Turkenburg and Hendriks, 1999; David and Herzog, 2000). Research aimed at improving the absorption process performance shows that better integration of capture technologies and applying new solvent technologies (e.g., membranes to facilitate contact between flue gases and chemical solvents) can reduce energy penalties to about 20% for coal and about 10% for natural gas (Herzog *et al.*, 1997; David and Herzog, 2000). The downside however is that the absorption process reduces thermal efficiencies while capital costs of the electricity production increase by about 80% for coal and by 50% for natural gas (Turkenburg and Hendriks, 1999). With current chemical absorption technologies, the cost of CCS for new conventional coal and gas plants is about \$225/tC to \$230/tC, but projected improvements in the technology (i.e., to 2012 technology) can reduce the costs to about \$160/tC to \$190/tC (David and Herzog, 2000). The retrofit of an existing coal plant introducing chemical absorption process would cost about \$190/tC (with additional transport and storage costs of about \$37/tC) (Simbeck, 2001).

Post combustion amine scrubbing is quite a mature technology. However, it still has potential for development, with opportunities for much better performance through energy and process integration (Roberts *et al*., 2004) and operation optimisation (Gibbins *et al*., 2004).

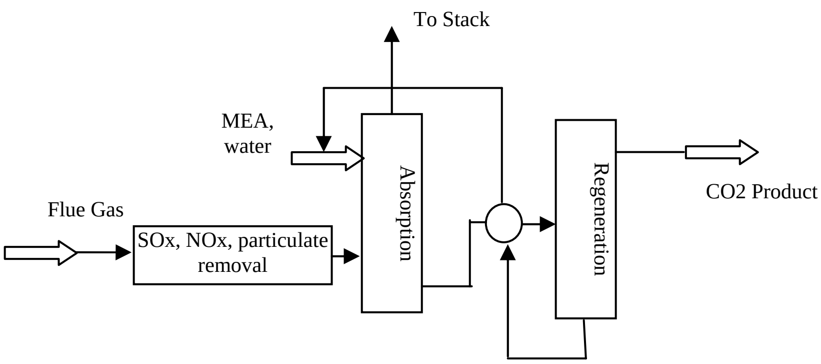

Figure 3.1 Chemical absorption process

3.2.2 Physical absorption process

Besides chemical absorption of CO_2, the gas can be physically absorbed in a solvent in accordance with Henry's law. By applying heat or reducing pressure or combining both, the gas can be regenerated. Industrial solvents used for this purpose are Selexol (dimethylether of polyethylene glycol) and Rectisol (cold methanol). However, they have to be applied at high pressures which can make the process economically prohibitive. At lower pressures, the chemical absorption processes can prove more economical. Another problem of this technology is related to C3+ hydrocarbons which are soluble in the physical solvent.

Physical absorption may prove a viable option for the integrated gasification combined-cycle (IGCC) process (Anderson and Newell, 2003), as shown in Figure 3.2. According to this technology, the coal is gasified forming a synthesis gas (syngas) which is a mixture of carbon monoxide (CO) and hydrogen (H_2) (Davison *et al.*, 2004). In an IGCC without capture, syngas is directly combusted in gas turbines. If the capture technology is applied to an IGCC, the syngas undergoes a reaction with steam in the presence of catalysts forming a mixture of H_2 and CO_2. The H_2 is separated and used in a combined-cycle gas turbine, leaving a pure stream of CO_2 that can be directly compressed and stored. Despite the fact that several IGCC demonstration projects operate (e.g. in Florida, Indiana and Tennessee) and several companies are planning to use coal gasification technologies in future power plants (USDOE, 2003), so far, there have been no demonstration plants with CO_2 capture.

For source streams with high concentrations of CO_2, as is the case for the IGCC plant, physical absorption using a solvent like Selexol (dimethylether of polyethylene glycol) or Rectisol (cold methanol) can be less costly than chemical absorption. Increasing external gas pressure and decreasing the temperature improves the absorptive capacity of these solvents. Consequently, applying heat or diminishing the external pressure regenerates the solvents and releases the CO_2. Regeneration of physical solvents is not as energy intensive as for chemical absorption, and energy penalties for IGCC plants are about 15% (David and Herzog, 2000). The estimated cost of electricity for new IGCC plants without capture is only slightly higher than for a new conventional coal plant, and costs are expected to fall with further development (Herzog, *et al.*, 1997). However, conventional gas plants are more competitive than both conventional and IGCC coal technologies if gas prices are sufficiently low (David and Herzog, 2000).

If the CCS technology is applied to a new IGCC plant, the incremental cost is currently about \$140/tC, with near-term technology improvements expected to reduce the costs to about \$100/tC (David and Herzog, 2000).

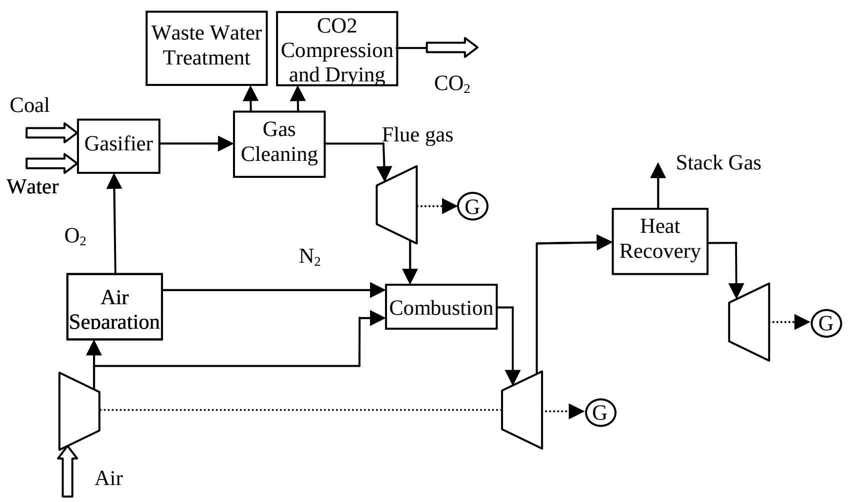

Figure 3.2 IGCC power plant with CO_2 removal by means of Selexol scrubbing (IEA, 1998)

Hybrid solvents combine the best characteristics of both the chemical and physical solvents and are usually composed of several solvents that complement each other. Tailor-made solvents made of complementary solvents where the proportions are varied to suit the application are a promising field. Typical solvents are A-MDEA, Purisol, Sulfinol and UCARSOL. All such absorption processes operate in essentially the same manner by scrubbing the flue gas in towers to collect the CO_2 and regenerating the solvent and releasing the CO_2.

Physical and chemical absorption currently represent the most developed technical options for CO_2 capture but significant research efforts are being made for more 'exotic' capture technologies. Most of these technologies have been developed for use in other applications and some are used in niche applications. However the answer to the question whether they would be competitive and economically viable for CCS compared to alternative capture techniques (i.e., MEA and physical absorption) in, say, the electric power sector, remains uncertain.

3.2.3 Adsorption

Adsorption is a process in which a gas fixes to the surface of a solid substance by either chemical or physical attraction; the scheme for its application in CO_2 capture is illustrated in Figure 3.3. The nearest adsorption technology to a CCS application in current commercial use is separation of CO_2 from CO_2-H_2 gas mixtures during the production of hydrogen. Some porous solids with large surface areas are able to adsorb large quantities of gas per unit of volume. For separation of CO_2 from power plant flue gases, adsorbent beds of alumina, zeolite molecular sieves (natural or manufactured aluminosilicate) and activated carbon are at present considered to be most applicable. The trade-off between the stronger attraction of a gas to an adsorbent solid and the energy cost of regeneration (i.e., removal of the adsorbed gas) defines the economic performance of the process.

After the gas has been adsorbed, the adsorbent bed may be regenerated using a variety of methods. Four methods are used commercially for regeneration (Anderson and Newell, 2003):

1) Pressure swing adsorption (PSA), in which the external pressure of the scrubber is lowered until trapped gases are released from the adsorbent bed (which can be made of the activated carbon). PSA is the most common method used in hydrogen production from steam-reformed natural gas.
2) Thermal (or temperature) swing adsorption (TSA) employs high temperature regeneration gas to drive off trapped gases. The disadvantage of this process is that the regeneration cycles are quite slow (may take hours) and larger quantities of adsorbent are required than for PSA. TSA requires heating the system until captured gases are driven from the adsorbent bed.
3) Washing away the trapped gases by running a stream of fluid over the adsorbent bed.
4) Applying a gas stream that contains materials causing the trapped gas to 'bump' from its location, Riemer, *et al.* (1993) describe a process which uses an electrically conductive bed of activated carbon. This bed selectively adsorbs CO_2, and then releases it when electricity is applied, allowing for regeneration without costly temperature and pressure changes.

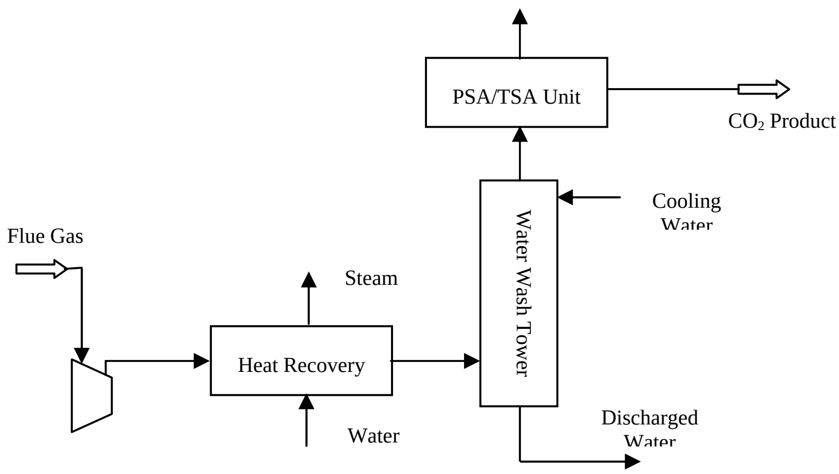

Figure 3.3 Adsorption process

3.2.4 Membrane separation

Another feasible technology for capture of CO_2 is gas separation membranes. Gas separation membranes use the difference in physical or chemical interaction between components of a gas mixture with the membrane material. This difference causes one component to permeate faster through the membrane than another (Figure 3.4). The gas component dissolves into the membrane material and diffuses through it to the other side.

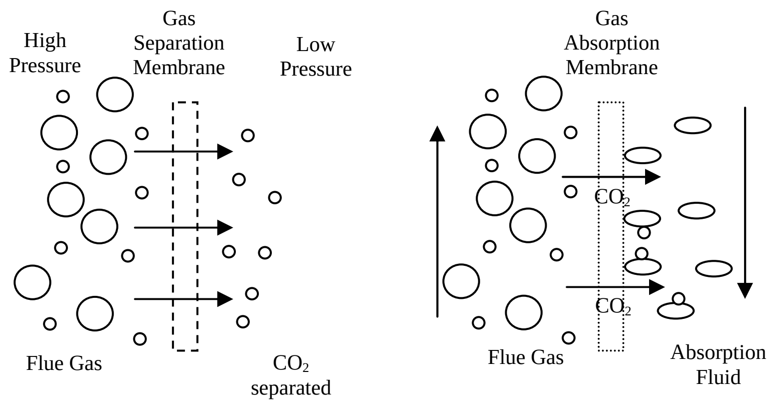

Figure 3.4 Gas separation membrane and gas absorption membrane

The separation process is determined by the *permeability* and *selectivity* of the membrane. The permeability of a gas through a membrane is its rate of flow through the membrane, given its pressure differential across the membrane. The selectivity of a membrane is the ability of one gas to permeate faster than another.

The ideal option would be the separation of CO_2 from a concentrated CO_2 source stream with some contaminant gases, combined with a permeable membrane that is highly selective with respect to CO_2. However, in practical terms, source streams generally have low pressures, low concentrations of CO_2, and many component gases (e.g., NO_X, SO_X, and water vapour). In addition, it's very difficult to produce membranes with true high selectivity: increasing the permeability of one gas often increases the permeability of another, thus decreasing selectivity. In practice, the selectivity of membranes is not sufficient to achieve desired purity on the first pass. Hence multistage processes are required which imply increased compression and capital costs. Several gas separation membranes are available: polymer membranes, palladium membranes, facilitated transport membranes and molecular sieves - though some have been used only in laboratory settings (Riemer *et al.*, 1993).

Another type of membrane whose potential benefits are being investigated at present are gas absorption membranes (IEA, 1998). They serve as a contacting device between gas mixtures (e.g., flue gases) and liquid absorbents (e.g., MEA solvents), increasing the efficiency of physical or chemical absorption.

Gas absorption membranes are membranes which are used as contacting devices between a gas flow and a liquid flow (Figure 3.4). The separation is caused by the presence of an absorption liquid on one side of the membrane which selectively removes certain components from a gas stream on the other side of the membrane. In contrast with gas separation membranes, it is not essential that the membrane has any selectivity at all. It is only needed to provide a contacting area without mixing gas and absorption liquid flow. The membrane's function is to keep the gas and liquid flows separate, minimizing entrapment, flooding, channelling, and foaming. The selectivity of the process is determined by the absorption liquid.

Removal of flue gas components, such as SO_2 or CO_2, is achieved through the use of porous, hydrophobic membranes in combination with suitable absorption liquids, such as sulphite, carbonate or amine solutions.

The equipment in a process using gas absorption membranes is more compact than for conventional membranes, thus reducing capital costs (Miesen and Shuai, 1997). However the limitation of using membranes in this process is that the absorption liquid and gas stream should have similar pressure levels.

Overall, despite being used commercially in some processes close to CO_2 capture process (e.g. in hydrogen separation), the membrane technology used in the separation process (Figure 3.5) still needs significant development before it can be used on a significant scale for the capture of CO_2. So far, it is not clear to what an extent their present high cost could be reduced. One attraction of membranes is that they require less energy for operation than other methods of capture.

Studies have shown that CO_2 removal using gas absorption membranes in conjunction with MEA are significantly better than the membrane on its own (IEA, 1998). This is particularly promising as new improved gas absorption membranes are expected on the market shortly.

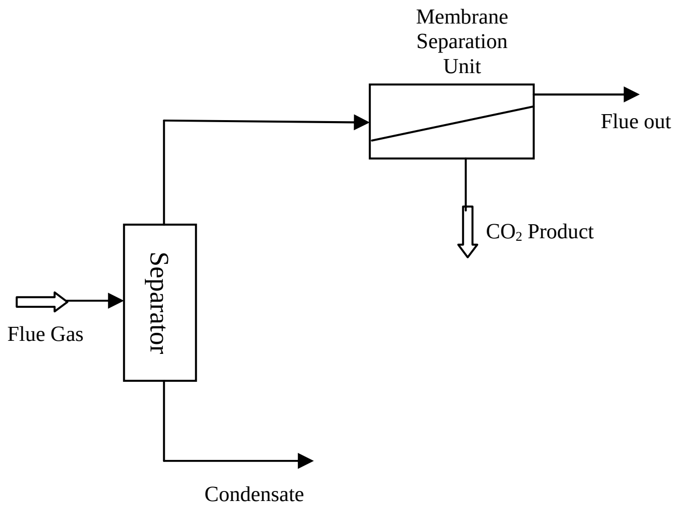

Figure 3.5 Membrane separation process

3.2.5 O_2/CO_2 recycling process

The main idea behind an O_2/CO_2 recycling process is that oxygen (95% purity or higher), rather than air, is fed into a boiler where the fossil fuel is combusted (Figure 3.6). Most of the flue gas (70-80%), which is rich in CO_2, is recycled back to control the combustion temperature (Jordal *et al.*, 2004)

The remaining part of the flue gas, consisting mainly of CO_2 and water vapour and small quantities of Ar, N_2, NO_x, SO_x and other substances from air leakage and fuel, is cleaned, compressed and transported to storage or another application. Since the nitrogen is removed from the process, the flue gas contains much less NO_x, and the need for scrubbing is significantly reduced.

Unlike pre-combustion and post-combustion techniques for CO_2 removal, the oxyfuel process removes water and other non-condensable gases, purifying the CO_2 rich output stream. If it is not possible to store the CO_2 with traces of the remaining impurities, de-SO_x and de-NO_x equipment of much smaller sizes will be required than for other capture technologies.

The present air separation technologies are still rather costly and account for higher costs of the oxyfuel process in comparison to other techniques (Gottlicher *et al.*, 1997). The electric power consumption of a Cryo-ASU may account for roughly 20% of the plant gross power output for the O_2/CO_2 recycle combustion power plant, which of course is very detrimental to plant efficiency (Jordal *et al.*, 2004)

However the latest intensive developments in air separation technologies, such as ion transport membranes, oxygen transport membranes and mixed conducting membranes may prove to be promising solutions for lowering high costs of the O_2/CO_2 process (Simmonds *et al.*, 2004).

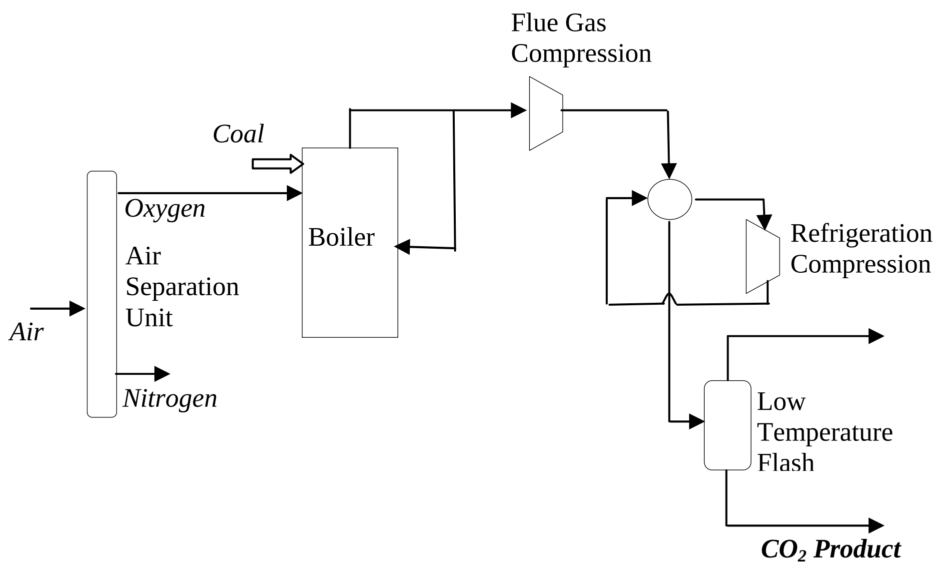

Figure 3.6 O_2/CO_2 recycling process

3.2.6 Cryogenic Separation

Cryogenic systems are low temperature physical systems, in which the CO_2 is separated directly or by using a solvent. CO_2 can be physically separated from other gases by condensing the CO_2 at cryogenic temperatures (Singh. *et al.*, 2001). Cryogenic separation is widely used commercially for purification of CO_2 from streams that already have high CO_2 concentrations (typically >90%) but it is not normally used for more dilute CO_2 streams. Methane is difficult to separate from CO_2 but some processes have been developed specially for the methane-CO_2 system to separate CO2 from natural gas before use). Water also presents problems in cryogenic systems, so the feed gas has to be dried before being cooled (Davison and Thambimuthu, 2004).

Cryogenic separation leads to phase changes in CO_2 and other gases induced by compression and cooling of gas mixtures in multiple stages. This process proves to be most effective when feed gases contain components with significant differences in boiling points (Herzog *et al.*, 1997). However the process is often complicated by contaminants (water vapour, SO_2 and NO_X) that can impede cryogenic processes. Moreover, the phase transformation of CO_2 is also complicated and can lead to the formation of solids that plug equipment and reduce heat transfer rates. The need for pressurization and refrigeration makes cryogenic processes very energy intensive and hence expensive. Nonetheless, cryogenic separation could be effective for certain large, highly concentrated source streams of CO_2, in pre-combustion capture processes, or O_2/CO_2 combustion with high concentrations of CO_2 in input gas.

3.2.7 Chemical-looping combustion

In chemical-looping combustion oxygen is transferred from the combustion air to the gaseous fuel by means of an oxygen carrier. The fuel and the combustion air are never mixed and the gases from the oxidation of the fuel, CO_2 and H_2O, leave the system as a separate stream. The H_2O can easily be removed by condensation and pure CO_2 is obtained without any loss of energy for separation. This makes chemical-looping combustion an interesting alternative to other CO_2 separation schemes, which have the drawback of considerable energy consumption. The system is composed of two reactors, an air and a fuel reactor, as shown in Figure 3.7. The fuel must be in a gaseous form and is introduced to the fuel reactor, which contains a metal oxide, MeO. The fuel and the metal oxide react according to Equation 3.1.

Equation 3.1

$$(2n+m)\mathrm{MeO}+\mathrm{C}_n\mathrm{H}_{2m}\rightarrow(2n+m)\mathrm{Me}+m\mathrm{H_2O}+n\mathrm{CO_2}$$

The exit gas stream from the fuel reactor contains CO_2 and H_2O, and almost pure CO_2 is obtained when H_2O is condensed. The reduced metal oxide, Me, is transferred to the air reactor where the metal is oxidized according to Equation 3.2.

Equation 3.2

$$\mathrm{Me} + \tfrac{1}{2}\,\mathrm{O_2} \rightarrow \mathrm{MeO}$$

The advantage of chemical-looping combustion compared to normal combustion is that CO_2 is not diluted with N_2 but obtained in a relatively pure form without any energy needed for separation (Lyngfelt, *et al.*, 2001). At present there are still not enough experimental data for different oxygen carriers at high temperatures and high pressures for its commercial application.

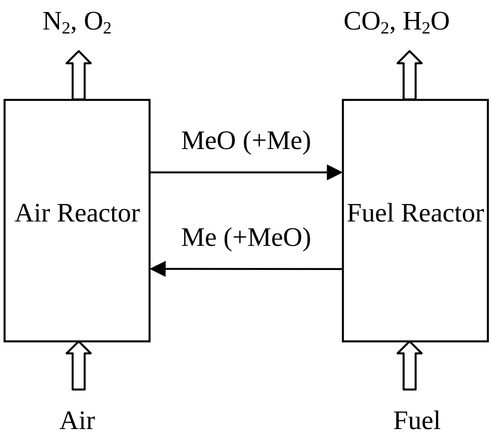

Figure 3.7 Chemical-looping combustion (Lyngfelt, *et al.*, 2001)

3.3 Techno-economics of CCS

In the following section we describe opportunities for reducing the concentration of various pollutants, including CO_2, through process design and management of a total site and present a framework for implementing this approach. A total site is a set of interacting processes connected to a central utility system through several steam mains. Some processes may be able to generate power or intermediate levels of steam that can be used by other processes. As a result, these interactions provide possibilities for a site to save utility and power and thus reduce gaseous emissions. Different fuels might be used in the central boiler house to generate high pressure steam. In addition, if there are a number of combustion devices using different fuels we need to determine the best combination of these fuels to be used to meet regulations at minimum cost. Some fuels are also used in local furnaces of different processes that require high temperature heat. The steam produced in the central boiler house is passed through a network of turbines to various steam mains at lower pressures. The steam headers deliver steam to the processes and receive steam generated from the processes. The steam turbines are either connected to pumps and compressors or electrical generators to produce power. The site can also import or export power from a local power station depending on the power demand of the site and the power generated from the steam turbine network (Klemeš *et al*, 1997, Varbanov *et al.*, 2005).

Process design and integration require the selection of a series of processing steps and their combination to form a complete manufacturing system. Process integration techniques provide a reliable tool for emission reduction since the products of combustion can be best minimised by making the processes efficient in the use of energy through efficient heat recovery and avoiding unnecessary thermal oxidation of waste (Figure 3.8).

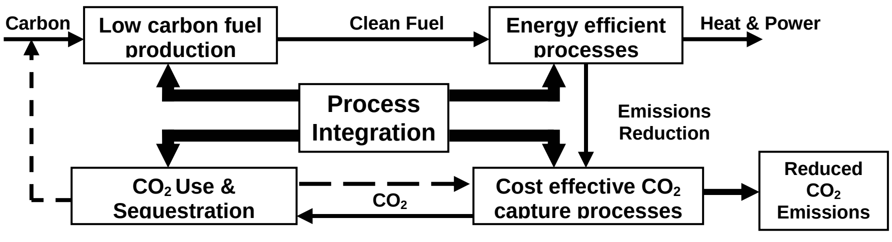

Figure 3.8. The role of process integration in cutting down emissions

A total site can be divided into three parts: heat generation, heat distribution and heat consumption (Figure 3.9).

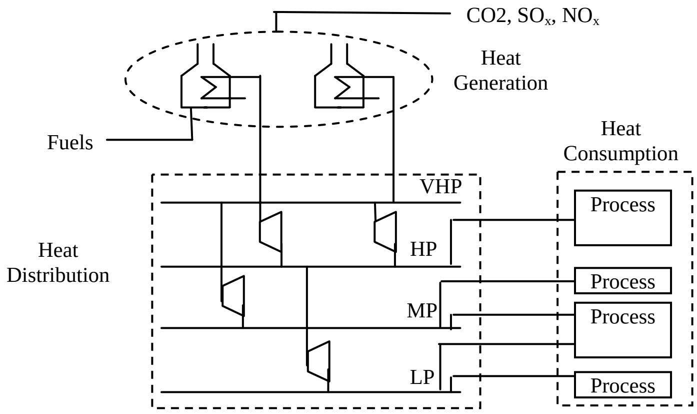

Figure 3.9 Total site representation

There are several options for reduction of flue gas emissions from the three parts of a total site. They can be summarised as follows:

1) Increased energy efficiency at the point of use (e.g. better heat integration). This results in reduction of energy consumption in the processes hence reduction of steam production in boilers. This implies less fuel used and consequently less emission produced from the site.
2) Process changes: changes to the processes can reduce the steam consumption in them and hence decrease the amount of steam produced in boilers. This again leads to reduction in emission produced from the site.
3) Increased energy efficiency of the utility system. Changes in the configuration of the existing steam turbine network: this leads to a better energy efficiency in the steam system and hence more production of power. Thus for the same power generation these changes lead to less fuel consumption and less emissions production
4) Use of different fuels in boilers and process furnaces: different fuels have different chemical composition. Therefore, a fuel switch in boilers and local furnaces may reduce the amount of emissions produced.
5) Integration of gas turbine: a gas turbine consumes fuel, produces power and can generate steam from the hot exhaust gases. As a gas turbine uses cleaner fuel, integration of gas turbines can reduce the emissions produced.

Other remaining options will affect the NO_x and SO_x production by the plants and the total site: installation of low-NO_x burners; flue gas recirculation (reduces NO_x); installation of deSO_x and deNO_x units which absorb SO_x and NO_x in the flue gas.

The options for emission reductions described above operate in the context of the following dual objectives

1) Essential goal: to achieve the emission limits of the site set by the environment legislation. This is essential for a site to operate legally.
2) Desirable goal: to achieve the emission limits of the site in the most cost-effective manner. This is necessary for a site to operate in an economic way and hence maximise the profits.

The existence of several options along with factors such as the existence of many firing sources, the constrained nature of the retrofit problem, the dual objectives of the problem and interaction among processes and utility system makes the practical site emission reduction a very complex problem. Because of this, a hierarchical method is used to solve the problem. The method uses an economic function to choose among different options to arrive at the final solution.

The proposed method (Singh, *et al.*, 1998) combines physical understanding of the problem with optimisation techniques. The physical insights are used to generate and screen options. This leads to identification of the most promising options from the site. These options are modelled with the existing site into a superstructure.

3.3.1 Achieving the Essential Goal

The essential goal is to satisfy the emission limits of the site using end-of-pipe (EOP) techniques. Carbon emissions may be controlled through a tax on the amount of CO_2 discharged to the environment[1]. It is assumed here that a tax paid on the discharge of carbon dioxide is implemented in order to achieve the essential goal.
The cost associated with satisfying the essential goal is termed the EOPCost. This term is a function of the CO_2 produced by the site and load on $deSO_x$ and $deNO_x$ units. The current level of CO_2 (and SO_x) emission production depends on composition of the fuel and can be calculated easily. NO_x can be estimated using charts for certain types of boilers and amount of excess air. The EOPCost has two components: capital cost, CC_{EOP}, and operating costs $OP_{EOP.}$ The CO_2 tax is incorporated in the OP_{EOP} since it alters the operating cost of the site.

3.3.2 Achieving the Desirable Goal

This step concentrates on improving the economics of the reference case. A three stage procedure can be used to accomplish the desirable goal. In *the first stage*, the options analysis stage, options other than that used in the reference case are analysed. In the *second stage,* a screening process removes the uneconomic options to reduce the solution space of the problem. In *the third stage*, the options selected after screening are modelled as a superstructure. The model is subjected to optimisation to find the best economic mix of options to achieve the emission limits.

The emission limits of the site can be met by using the EOP techniques which require an annual investment or EOCost. Therefore the total annualised cost (TCost) equals EOPCost (i.e. emission limits are satisfied by EOP techniques). This however, may not be the most economical way to achieve the limits since other cheaper options may exist. Therefore the objective of the problem is to minimise the total annualised cost of the site for emission reduction (Equation, 3.3, Figure 3.10) (Singh, 1998).

Equation 3.3

$$\min TCost = EOPCost - \sum_{\text{all modifications}} ModGain$$

where the term ModGain is derived from other options such as process changes, fuel switch, installation of a low-NOx burner, flue gas recirculation and gas turbine integration, etc.

[1] In the UK there is currently no direct taxation on CO_2 emissions, although the Climate Change Levy acts as an indirect tax on high energy users.

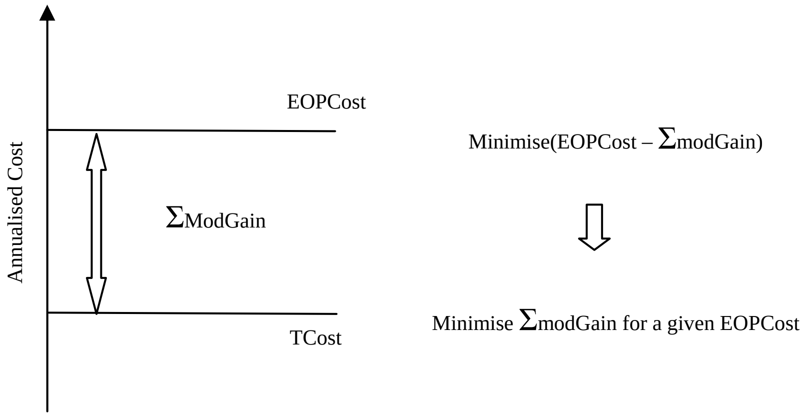

Figure 3.10 The objective function of the problem (Singh, 1998)

By definition, the value of EOPCost is fixed for a given site and given environmental legislation. The higher the value of other options (ModGain) the less the total cost. A minimum value of total cost (TCost) can be achieved by maximising the value of ModGain for all the modifications. The objective of the problem then becomes to maximise the value of ModGain for all modifications for a given EOPCost. The maximum value of TCost is EOPCost which corresponds to a zero value of Mod Gain. This occurs when the sole use of EOP technique is the most economic way to satisfy the emission limits. The sum of ModGain for all modifications greater than zero implies that TCost is less than EOPCost and this is always the most desirable case. A negative value of TCost may be obtained when the sum of values of ModGain exceeds that of EOPCost, which implies that the reduction in operating cost exceeds the net annualised investment to implement the required modifications. A positive value of TCost implies a net investment to achieve the environmental limits.

Options Analysis. EOP methods are not the only options available for emission reduction. The other options are process related and utility related modifications.

Process related options alter the amount of steam used in the processes, by changing the steam flows in the steam system and the boiler house. Equipment such as boilers and steam turbines operate within maximum and minimum limits. Due to this, it is necessary to analyse the feasibility of reduction in steam flows of different levels, the limit of those changes and the benefit achieved from such changes.

The utility related options affect the way that different utilities are generated in the site. Several options may be considered:

1) Integration of a gas turbine which generates power and produces steam in the heat recovery steam generator (HRSG) from hot exhaust gases. The integration of a gas turbine may reduce the amount of the steam produced in the boiler house. This reduction leads to a decrease in amount of the fuel used in boilers and hence reduction in the amount of carbon tax paid (and also reduction in loads on deSO_x and deNO_x units) compared with the reference case. However there is a trade-off as additional deSO_x and deNO_x units may be needed to install and additional carbon tax needed to be paid on the exhaust flue gas from the HRSG. Furthermore the gas turbine may require a more expensive fuel that the required by the boiler.

2) Fuel switching replaces an existing fuel with an alternative fuel. As different fuels have different chemical composition and heating values, they produce different quantities of CO_2, SO_x and NO_x.

Also included in the integrated methodology are the utility options dealing with the NO_x and SO_x flue gas components. These options include flue gas recirculation and installation of a low-NO_x burner.

Screening Stage. After several different options for emission reduction are generated in the options analysis stage, it is necessary to screen them to select the economically promising options. As a result, only economic and feasible options are modelled in the optimisation stage.

Optimisation Stage. All options selected are optimised to determine which options are to be implemented to satisfy the emission limits (Figure 3.11).

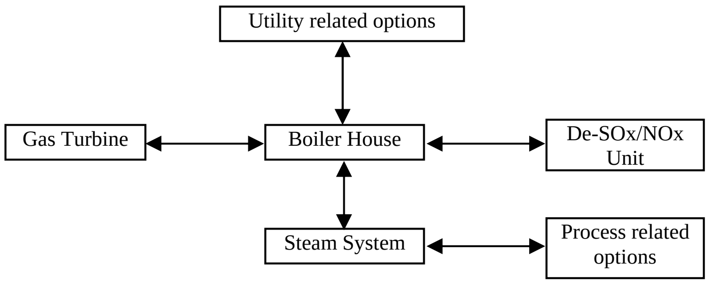

Figure 3.11 The general structure for the optimisation model (Singh, 1998)

A maximum superstructure is formulated by incorporating the options selected after screening along with the reference case. As the superstructure contains only feasible and economic options, the solution space of the problem is drastically reduced. As an example, an existing site emission limits have been analysed using this methodology (Figure 3.12).

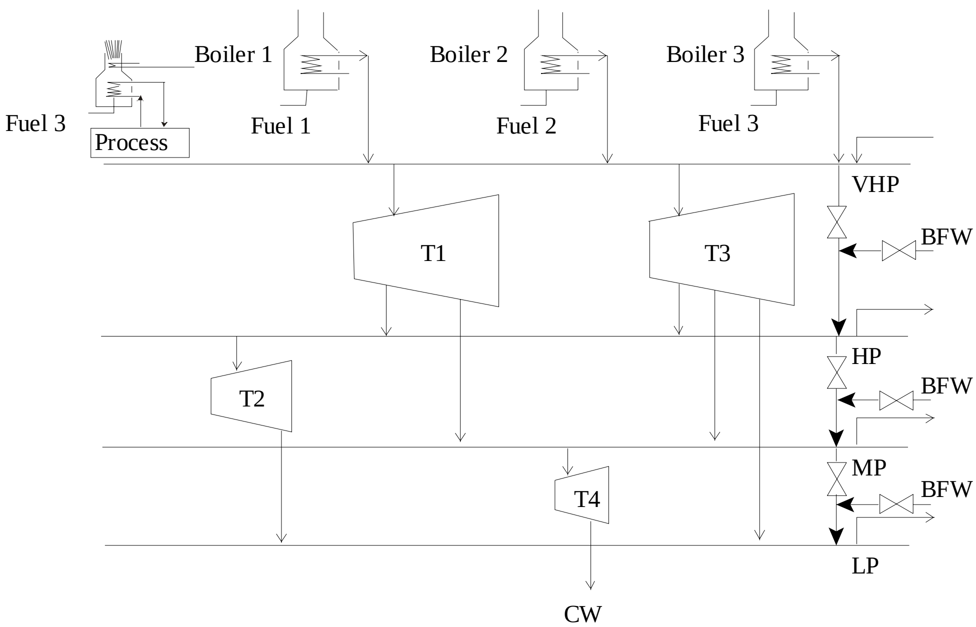

Figure 3.12 The existing site emission system (CPI UMIST, 2004)

The site utility system consists of four steam levels, three boilers, six process heaters and four steam turbines one of which is used as a process driver. The utility system satisfies heating and cooling demands of twenty four processes. The objective was for the system to comply with specified SO_x and NO_x concentration limits and be economically profitable with a tax on carbon emissions imposed on it (a generic tax on carbon emissions was assumed to be equal 15 $/t). Following the analysis of 43 options, the best solutions include EOP, fuel switch, low-NO_x burner, flue gas recirculation and heat exchanger network optimisation. The carbon emission tax making energy more expensive provided a very strong incentive to implement energy saving projects. Savings in operating costs proved to be much lower since tax on carbon affected the operating costs. Process integration designs generated by the new method showed better economics than designs obtained by combination of fuel switch and EOP techniques.

Process integration methodology described here is a general framework in which the conceptual and detailed design and analysis of processes and total sites can be carried out. CO_2 capture has tended to focus upon flue gas emissions from power stations. There are, however, a number of other important opportunities for capturing CO_2 from process industries. In some cases, such opportunities can be cost effective enough. A recent development of process integration methodology (Varbanov, 2005) reports how the process integration can provide cost-effective de-carbonisation options. The optimised plant utility system (Figure 3.13) provides emission reduction options. Their analysis leads to the following conclusions: (i) increasing the system efficiency is the cheapest option for CO_2 abatement, but has a relatively limited scope; (ii) the next economic option for the particular problem is to close the carbon cycle by using biofuels; (iii) CO_2 capture and storage is the third option to be adopted.

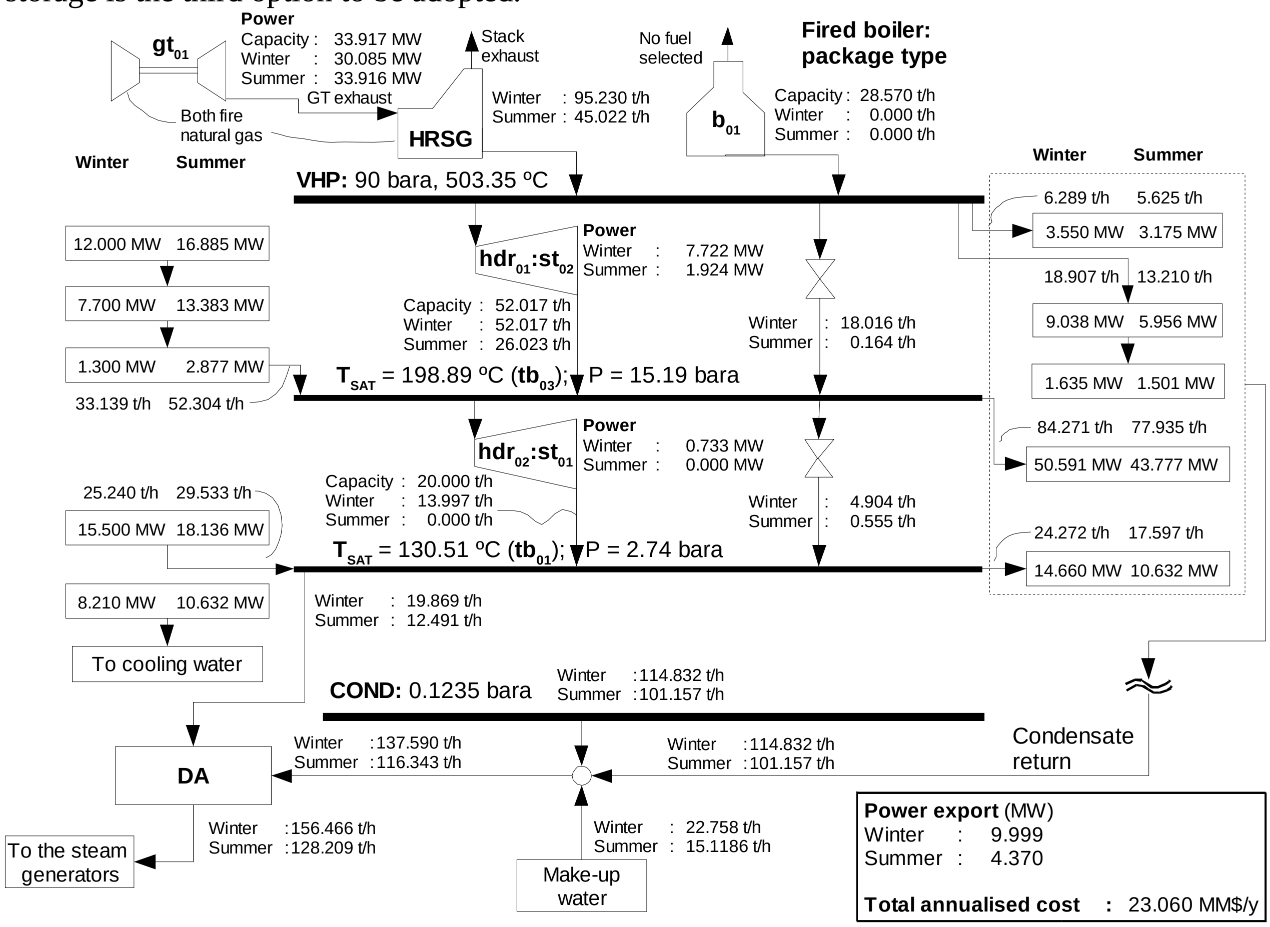

Figure 3.13 Optimal utility system for one of the case studies, Varbanov *et al*, (2005) © 2005 reprinted with permission from Elsevier

Biomass-based industries, rich in self-generated biomass residues have an inherent potential to implement low-carbon production. The Kraft pulp industry, for example, belongs to this group of industries. In the Kraft pulp process, a mixture of lignin and inorganic chemicals known as black liquor is a by-product of fibre extraction from wood. Slightly more than half of the biomass entering a Kraft pulp mill is dissolved in the black liquor. Black liquor is burned in recovery boilers which recover important pulping chemicals and feed steam to the mill combined heat and power (CHP) system. In modern Kraft market pulp mills, the fuel requirement for the CHP system is typically covered through black liquor and internally generated bark, whereas integrated pulp and paper mills need to import fuels to satisfy the process demand for medium pressure (MP) and low pressure (LP) steam. Most pulp mills and all integrated mills rely on electricity imports to cover part of their electricity demand.

Möllersten *et al*., (2004) show that Kraft pulp mills and integrated pulp and paper mills have the potential to be net producers of biomass-based electricity while at the same time removing substantial amounts of CO_2 from the atmosphere for each tonne of pulp or paper produced. Including the CO shift option has a quite favourable impact on the overall CO_2 budget of the production.

3.4 Cost estimates for CCS Power Plant

The economics of Carbon Capture and Storage schemes is currently a subject of great interest, as evidenced by the many recent publications. Here we provide a brief summary of the various estimates of CCS available in the literature (see also Table 3.7).

Hendriks *et al.* (2000) estimate costs for CO_2 removal projects in the Netherlands under various scenarios. For a range of fuel prices and discount rates their estimated capture cost was: natural gas combined cycle $ 41-66 and furnace/combined heat and power up to $ 45.

Anderson and Newell (2003) review the technical and economic feasibility of a range of carbon capture and storage options. The cost of carbon capture for new and retrofitted plants was 45–58 $/ t CO_2 captured. They forecast that in the near future, with the technology improvements, the cost reduction will go down to 34–42 $/ t CO_2 captured.

Johnson and Keith (2004) explore the competitiveness and assumptions of carbon prices and carbon capture and storage (based on assumptions for future technology around year 2015). Their findings revealed that CCS can contribute significantly to carbon reductions when carbon prices are below 27 $/t CO_2. New coal-fired power plants with carbon capture become competitive when the prices are around $20. Retrofitting existing power plants is not competitive below $82. Gas-fired power plants with carbon capture become competitive only at a much higher carbon price of $48.

Kallbekken and Torvanger (2004) consider different scenarios for carbon capture and sequestration technologies and conclude that the cost ranges might be $7-21 (low cost estimate), $40-50 (medium cost estimate) or $75-95 (high cost estimate).

The UK Department of Trade and Industry (DTI, 2003) present the overall cost of carbon capture and storage obtained through a range of case studies. The results show the overall cost of CCS to be of the order of 28-35£/t CO_2 for Enhanced Oil Recovery (EOR) and 22-27£/t CO_2 for storage in depleted gas reservoirs with ±30% uncertainty. The DTI report also provides cost estimates for new IGCC (£13-34 ≈ $24-63) or new GTCC (£21 ≈ $39).

Holt *et al* (2000) estimate the total CCS cost to lie in the range $29-45, though they do not provide a detailed breakdown of capture, transportation and injection (storage) costs in the North Sea.

An interesting work presented Kosugi *et al.* (2004) evaluate five CCS technologies: chemical absorption, physical adsorption, membrane separation, O_2/CO_2 recirculation boiler and integrated hydrogen separation gas turbine technologies, from the point of the total R&D time.

As the above discussion shows, cost estimates for CCS schemes vary significantly in the literature. This is understandable as different authors consider different technologies, scenarios, reference cases and so on. There is therefore a need for a consistent methodology for comparing CCS options for possible future deployment in the UK. For this reason a computer-based techno-economic whole system model of CCS schemes has been developed (described in Chapter 4).

Comparison of the literature data (e.g. Rao and Rubin, 2002) brings a conclusion that amine-based scrubbing process is currently considered the best technology available for post-combustion CO_2 capture. The O_2/CO_2 recycling process, which involves burning the coal with O_2 in an atmosphere of recycled flue gas, has also gained much interest. One of the most comprehensive works on this topic, (Singh *et al*, 2000), compares these two technologies and concludes that the capital and operating cost in terms of \$/t of CO_2 avoided were similar for both cases. The data on other existing processes necessary for development of cost functions are rather scarce and unfit for the cost function development.

3.5 Cost functions for CO_2 capture processes

A CCS power plant system comprises three major components (Figure 3.14), specifically:

1) The power plant and CO_2 capture system
2) A means of transporting the captured CO_2, which for the purposes of the current study is a super-critical pipeline
3) A storage reservoir and injection system.

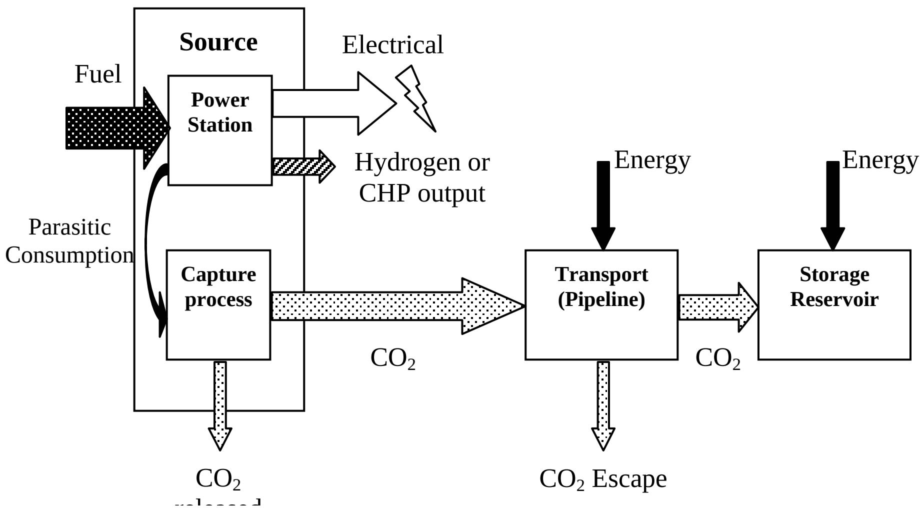

Figure 3.14 Major components of the CCS model

In this section we describe the modelling process for component 1 (components 2 and 3 in the above list are described later in Chapter 4). The model adopts a parametric approach, wherein values are estimated using straightforward functions, obtained by fitting to data. It is obvious that a separate set of functions is be required for each combination of power station and storage technology, although some simplification may be possible. There are two types of information that has to be estimated. Firstly, for the design phase of the model, information about the overall cost and performance of the power station and capture equipment as a function of its maximum output power is required. Secondly, for the operation 'simulation' and on-going cost evaluation phase of the model, functions allowing the fuel consumption and carbon dioxide production to be calculated are required. For each CO_2 source considered, the following must be estimated as a function of the parameter(s) in brackets:

- Construction cost (station rated power)
- Construction time (station rated power)
- Overall conversion efficiency (instantaneous output power)
- Annual plant O&M costs (rated power, average utilisation)
- CO_2 concentration in flue gas (instantaneous output power)
- Flue gas flow rate (instantaneous output power)
- Capture equipment costs (Maximum CO_2 throughput, CO_2 output conditions)
- Capture effectiveness (CO_2 concentration in stream, flue gas flow rate)
- Capture O&M costs (Maximum carbon dioxide throughput, average utilisation)
- Onsite parasitic electrical power consumption (CO_2 concentration in stream, flue gas flow rate)

These specifications are flexible, allowing some variation on a case by case basis. The essential feature is that it is possible to estimate the listed parameters. Furthermore there is no requirement that the relationships are analytic – functions that rely on interpolation between data points are quite acceptable. Cost estimation relationships that have been obtained this way for CO_2 sources are described below.

Aimed at processing very large amounts of CO_2 the system inevitably generates large amounts of waste (MEA) and by-products. The developed overall model incorporates waste, as far as possible to specify an MEA replacement rate and cost. At this stage, it also includes a by-product – hydrogen - flow which is treated in the same way. The model is easily extendible and can include any other by-product and waste flows.

To obtain accurate cost estimation of CO_2 capture process it is necessary to have results of detailed simulation runs of CO_2 capture processes. Detailed analysis of some capture processes has been done by a Carnegie Mellon University research group - Center for Energy and Environmental Studies, one of the leading research centres in this field. They considered a detailed amine scrubbing plant performance model (Figure 3.15) implemented in the IECM-CS software (CEES CMU, 2003). Based on the simulation results of the performance model, the capital costs, as well as the operating & maintenance costs for the amine scrubbing process can be estimated.

The level of detail in this model exceeds the requirements and the scope of CCS model (described in Chapter 4) and certainly cannot be fit directly into it. Hence, with permission of the Center for Energy and Environmental Studies (Carnegie Mellon University), the CMU model and IECM-CS, (version 3.5.5) software tool has been applied to develop parametric Cost Estimation Relationships (CERs); these are an integral part of the overall CCS model (Chapter 4) and have been defined at three CO_2 removal efficiencies: 90%, 85% and 95% on plants ranging between300 to 2000 MW in size (Annex 1).

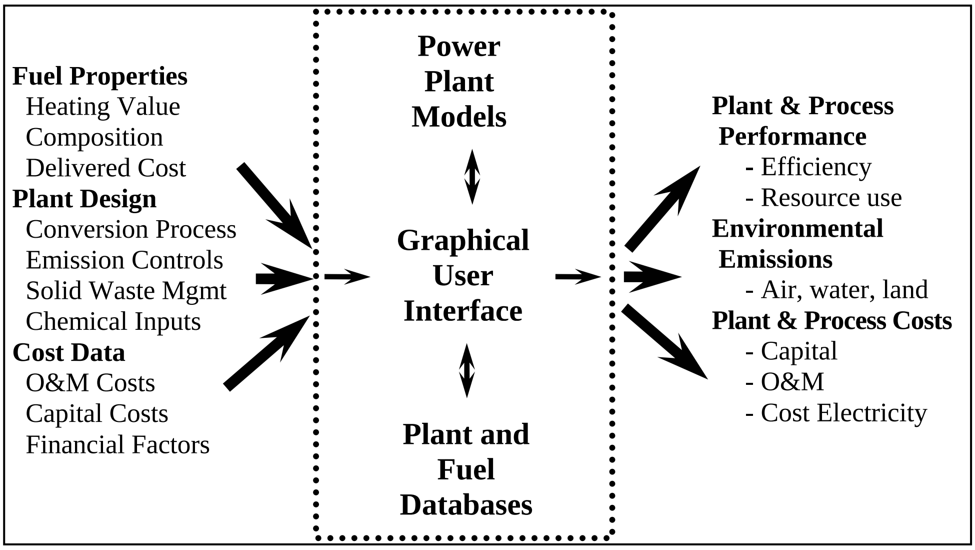

Figure 3.15 Amine scrubbing plant performance model implemented in IECM (version 3.5.5) software, Center for Energy and Environmental Studies (2004)

3.5.1 Cost Estimation Relationships against Plant Size

From the data described in Annex 1, Cost Estimating Relationships (CERs) for eleven economic evaluation values can be defined according to Equation 3.4 and using the coefficients shown in Table 3.1. Equation 3.4 specifies Process Facilities Cost – PFC [M$], Total Capital Requirement – TCR [M$], Annual TCR [M$/y], Variable Operating and Maintenance – O&M [M$/y], Fixed O&M [M$/y], Total O&M [M$/y], Sorbent [MS/y], Steam [M$/y], Electricity [M$/y], Waste Disposal [M$/y] and Total Annual Cost [M$/y] against Plant Size (capacity in MW).

Equation 3.4

$$Cost = A + B \cdot Plant\ Size$$

Table 3.1a "A" Coefficients for PFC, TCR, Annual TCR, Variable O&M, Fixed O&M, Total O&M, Sorbent, Steam, Electricity, Waste Disposal and Total Annual Cost for CER against Plant Size

Removal Efficiency	Coefficient	PFC (M$	TCR (M$)	Annual TCR (M$/y)	Variable O&M (M$/y)	Fixed O&M (M$/y)	Total O&M (M$/y)
85%	A	9.5321	14.641	1.5139	5.3107	1.0122	6.3230
90%	A	9.4351	14.680	1.5180	5.5448	1.0085	6.5650
95%	A	9.6639	14.8438	1.5349	5.780	0.9879	6.7679

Removal Efficiency	Coefficient	Sorbent [M$/y]	Steam [M$/y]	Electricity [M$/y]	Waste Disposal [M$/y]	Total Annual Cost [M$/y]
85%	A	0.0017	2.8858	2.4054	0.0054	7.8369
90%	A	0.0010	3.0525	2.4855	0.0055	7.7814
95%	A	0.0015	3.2269	2.5528	0.0056	7.7258

Table 3.1b "B" Coefficients for PFC, TCR, Annual TCR, Variable O&M, Fixed O&M, Total O&M, Sorbent, Steam, Electricity, Waste Disposal and Total Annual Cost for CER against Plant Size

Removal Efficiency	Coefficient	PFC (M$/MW)	TCR (M$/MW)	Annual TCR (M$/yMW)	Variable O&M (M$/yMW)	Fixed O&M (M$/yMW)	Total O&M (M$/yMW)
85%	B	0.2471	0.3795	0.0392	0.1060	0.0094	0.1155
90%	B	0.2582	0.3965	0.0410	0.1107	0.0099	0.1200
95%	B	0.2693	0.4137	0.04278	0.1159	0.0104	0.1262

Removal Efficiency	Coefficient	Sorbent ($/yMW)	Steam ($/yMW)	Electricity ($/yMW)	Waste Disposal ($/yMW)	Total Annual Cost ($/yMW)
85%	B	0.0225	0.0204	0.0170	0.0054	0.1547
90%	B	0.0231	0.0215	0.0176	0.0055	0.1614
95%	B	0.0238	0.0228	0.0180	0.0056	0.1690

An example of capital costs series at 90% removal efficiency is given in Figure 3.16 and an example of Operating and Maintenance costs at the same removal efficiency is shown in Figure 3.17.

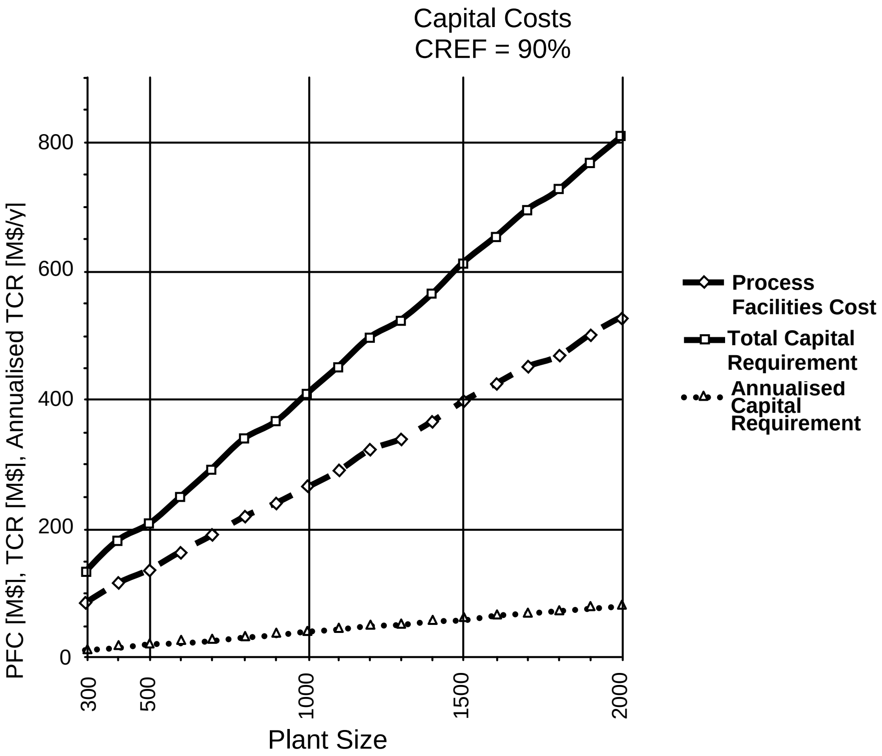

Figure 3.16 Capital costs against plant size at 90 % removal efficiency

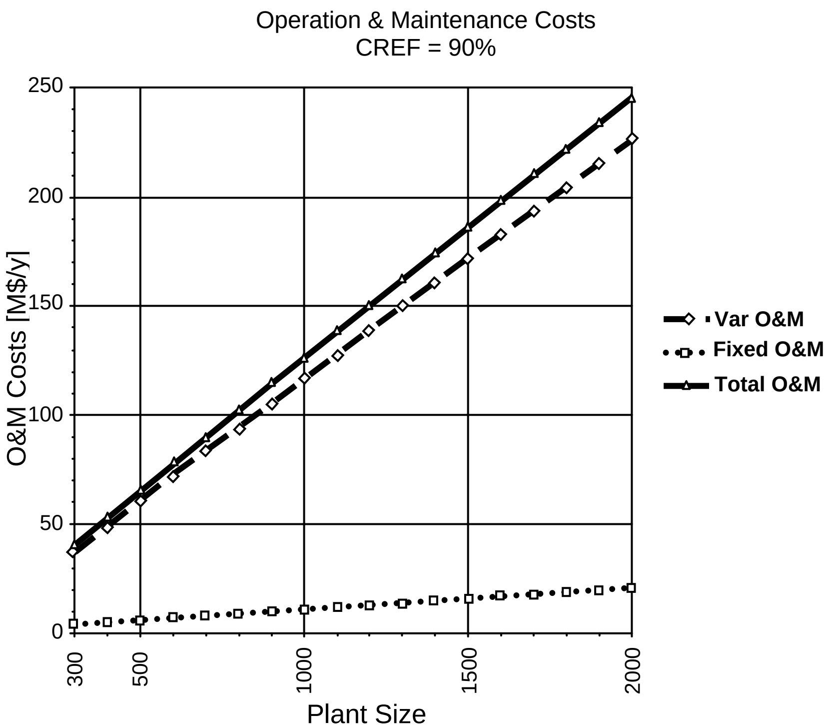

Figure 3.17 O&M costs against plant size at 90% removal efficiency

More detailed analysis of the Process Facilities Cost (PFC) has been carried out. As can be seen from the plant facility cost breakdown (Figure 3.18), the units that contribute most to the capital costs are the CO_2 absorber vessel (30%), sorbent regenerator (17%), drying and compression unit (17%) and direct contact cooler (11%).

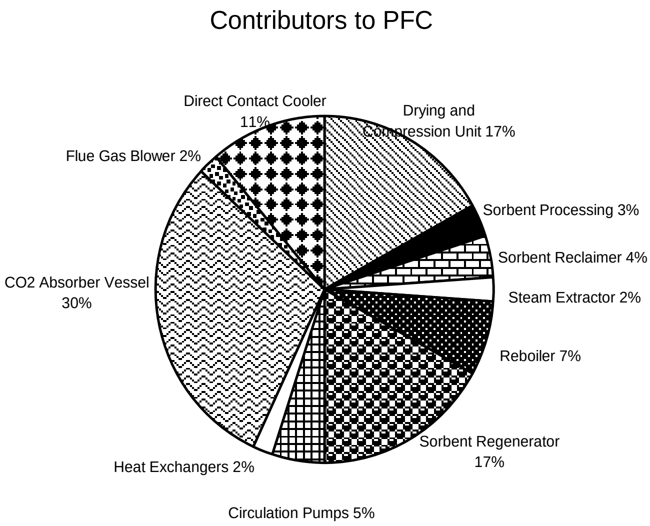

Figure 3.18 Composition of process facilities cost at CO_2 removing efficiency 90% (IECM-CS - version 3.5.5 - software tool, CEES CMU, 2004)

3.5.2 Costs of Avoided CO_2 against Plant Size

Analysts often express the cost of an environmental control system in terms of the cost per unit mass of pollutant removed. However, for energy-intensive CO_2 controls there is a big difference between the cost per tonne CO_2 *'removed'* and the cost per tonne *'avoided'* based on *net plant capacity*. Since the purpose of adding a CO_2 unit is to reduce the CO_2 emissions per net kWh delivered, the 'cost of CO_2 avoided' is the economic indicator that is most useful. It can be calculated as described by Equation 3.5.

Equation 3.5

$$Cost\ of\ CO_2\ Avoided\ [\$/t] = \frac{(\$/kWh)_{after} - (\$/kWh)_{before}}{(t_{CO_2}/kWh)_{before} - (t_{CO_2}/kWh)_{after}}$$

In contrast, the cost per unit of CO_2 removed or captured is simply the additional expense incurred in the capture of CO_2, divided by the total quantity of CO_2 captured. This can be calculated as the difference between the total annualised cost of the plant (TRR, M$/yr) with and without CO_2 control, divided by the total quantity of CO_2 captured (tonne CO_2/ yr), with the net power generated by the two plants remaining the same. Hence, the CO_2 avoidance cost is quite different from the cost per unit of CO_2 captured. In case of CO_2 control using an energy-intensive technology like amine scrubbing, the cost of CO_2 *avoided* may be substantially higher than cost of CO_2 *captured*.

Costs of CO_2 avoided are shown in Annex 1. The decrease in CO_2 avoidance costs with increase in plant size is quite expected, due to economies of scale. Differences in costs at different capture efficiencies are not very substantial. The cost ranges for different capture efficiencies are presented in Figure 3.19. From this and Figure 3.19, Cost Estimating Relationships (CERs) can be defined (Equation 3.6, Table 3.2)

Equation 3.6

$$Cost\ of\ CO_2\ Avoided\ [\$/t\ CO_2] = A \cdot ((PZ/100)-2)^2 - B \cdot ((PZ/100)-2) + C$$

where PZ – Plant Size

Table 3.2 Coefficients for Cost of CO_2 Avoided against Plant Size CERs

Removal Efficiency	Coefficient A ($/t MW^2) B($/t MW) C ($/t)	Value of Coefficient
90 %	A	0.1098
	B	3.4086
	C	56.533
85 %	A	0.1175
	B	3.6693
	C	59.736
95 %	A	0.1005
	B	3.1301
	C	53.596

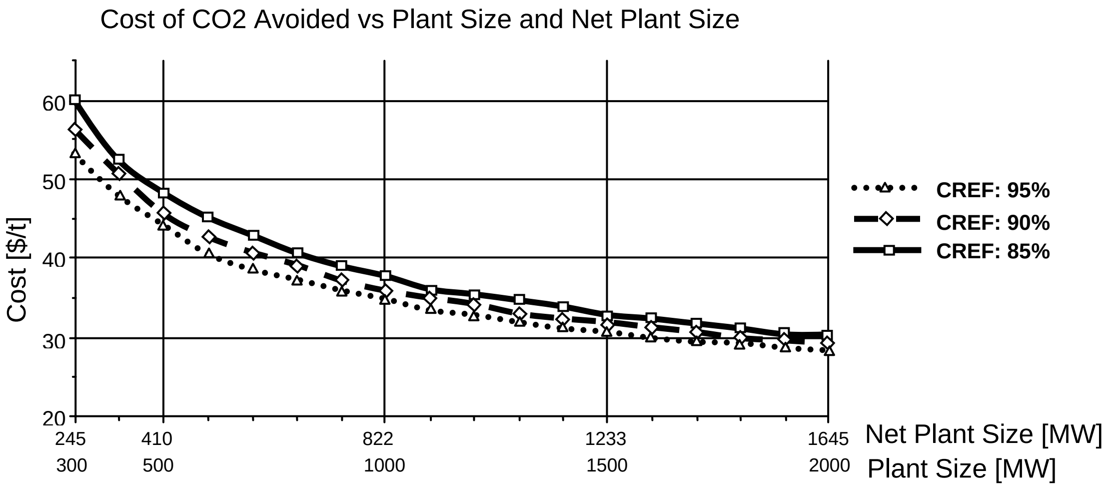

Figure 3.19 Costs of Avoided CO_2 against Plant Size and Net Plant Size

3.5.3 Capital and O&M Cost Estimation Relationships against of CO_2 Avoided

Capital and operating cost data sets at different amounts of CO_2 avoided and removal efficiencies of 85%, 90%, and 95% have been similarly obtained using IECM-CS software. From the Annex 1 data, Cost Estimating Relationships can be defined according to Equation 3.7 (Table 3.3).

The Equation 3.7 specifies Process Facilities Cost – PFC [M$], Total Capital Requirement – TCR [M$], Annual TCR [M$/y], Variable Operating and Maintenance – O&M [M$/y], Fixed O&M [M$/y], Total O&M [M$/y], Sorbent [MS/y], Steam [M$/y], Electricity [M$/y], Waste Disposal [M$/y] and Total Annual Cost [M$/y] against amount of CO_2 avoided

Equation 3.7

$$Cost = A + B \cdot Amount\ of\ \mathrm{CO_2}\ Avoided$$

Table 3.3a "A" Coefficients for PFC, TCR, Annual TCR, Variable O&M, Fixed O&M, Total O&M, Sorbent, Steam, Electricity, Waste Disposal and Total Annual Cost for CER against CO_2 avoided

Removal Efficiency	Coefficient	PFC [M$]	TCR [M$]	Annual TCR [M$/y]	Variable O&M [M$/y]	Fixed O&M [M$/y]	Total O&M [M$/y]
85%	A	9.5210	14.6240	1.5121	5.3062	1.0118	6.3181
90%	A	9.3908	14.613	1.5109	5.5257	1.0068	6.5442
95%	A	9.6090	14.7590	1.5261	5.1791	0.9858	6.1649

Removal Efficiency	Coefficient	Sorbent [M$/y]	Steam [M$/y]	Electricity [M$/y]	Waste Disposal [M$/y]	Total Annual Cost [M$/y]
85%	A	0.0008	2.8850	2.4047	0.01792	7.8302
90%	A	0.000	3.0488	2.4824	0.0002	8.3837
95%	A	0.000	3.2222	2.5490	0.0000	7.6910

Table 3.3b "B" Coefficients for PFC, TCR, Annual TCR, Variable O&M, Fixed O&M, Total O&M, Sorbent, Steam, Electricity, Waste Disposal and Total Annual Cost for CER against CO_2 avoided

Removal Efficiency	Coefficient	Process Facilities Cost [M$ y/Mt CO_2]	Total Capital Requirement (TCR) [M$ y /Mt CO_2]	Annual TCR [M$/Mt CO_2]	Variable Operating & Maintenance (O&M) [M$/Mt CO_2]	Fixed O&M [M$/Mt CO_2]	Total O&M [M$/Mt CO_2]
85%	B	52.005	79.8800	8.2596	22.3110	1.9950	24.306
90%	B	51.338	78.8200	8.1500	22.019	1.9690	23.983
95%	B	50.7210	77.9070	8.0556	21.824	1.9490	23.773

Removal Efficiency	Coefficient	Sorbent [M$/Mt CO_2]	Steam [M$/Mt CO_2]	Electricity [M$/Mt CO_2]	Waste Disposal [M$/Mt CO_2]	Total Annual Cost [M$/Mt CO_2]
85%	B	4.7427	4.2982	3.5820	1.1282	32.566
90%	B	4.6091	4.2924	3.4900	1.0953	32.089
95%	B	4.4890	4.2994	3.4055	1.0512	31.820

These parametric functions can make the Emission Sources part of the overall model more flexible by enabling the user to explore the effect of different amounts of CO_2 avoided and different power station capacities. An example of the capital cost series at 90% removal efficiency is given is Figure 3.20 and an example of Operating and Maintenance costs at the same removal efficiency is shown in Figure 3.21.

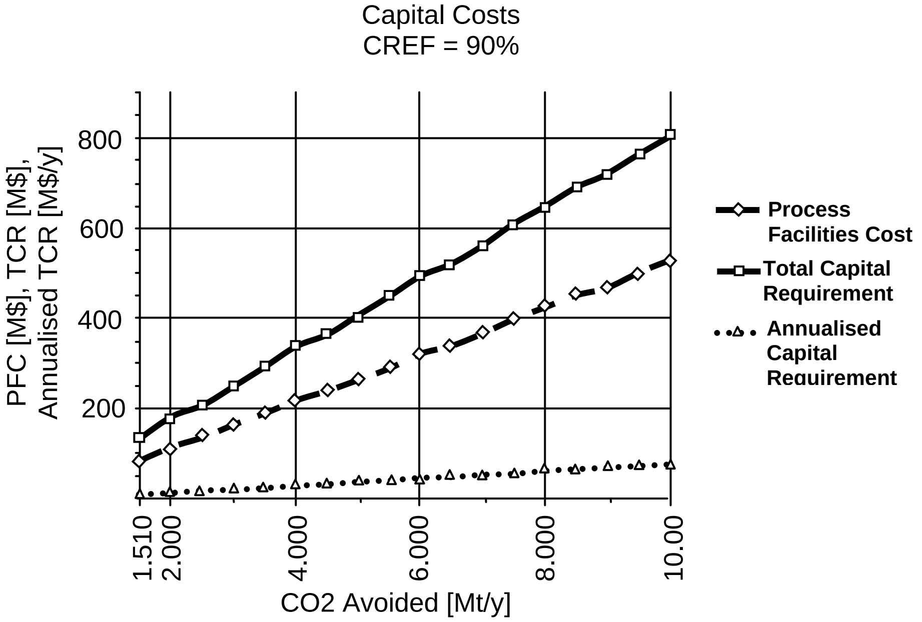

Figure 3.20 Capital costs against amount of CO_2 avoided

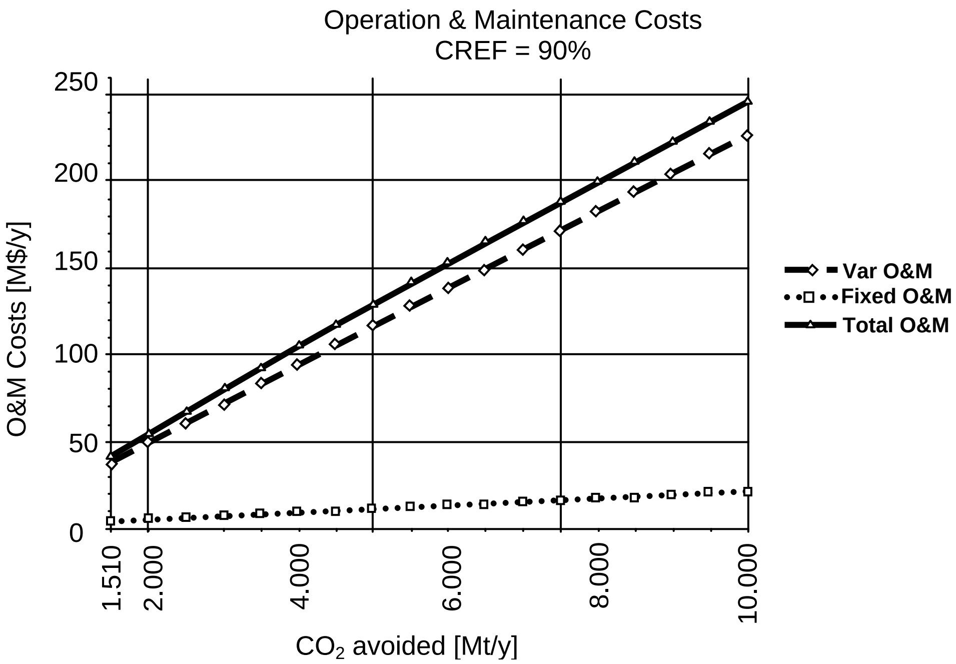

Figure 3.21 O&M costs against amount of CO_2 avoided

3.5.4 Costs of Avoided CO_2 against Amount of CO_2 Avoided

Data sets of cost of avoided CO_2 were obtained using IECM-CS for the same removal efficiencies. From these data sets, polynomial functions of the second order were developed (Equation 3.8). Coefficient values in these functions are given in Table 3.4.

Equation 3.8

$$\text{Cost of } CO_2 \text{ Avoided} = A \cdot ((CAV/0.503)-2)^2 - B \cdot ((CAV/0.503)-2) + C$$

where CAV = Amount of CO_2 avoided

Table 3.4 Coefficients for Cost of CO_2 Avoided against Amount of CO_2 Avoided CERs

Removal Efficiency	Coefficient A ($ y^2/t^3) B ($ y/t^2) C ($/t)	Value of Coefficient
	A	0.1175
85 %	B	3.6693
	C	59.736
	A	0.1098
90 %	B	3.4086
	C	56.533
	A	0.1005
95 %	B	3.1301
	C	53.596

3.5.5 Influence of Plant Life

Sensitivities of the plant life and interest rate parameters were also analysed. For the analysis of plant life influence on capital, operating, total annualised costs and the cost per tonne of CO_2 avoided are generalised in Equation 3.9 and Table 3.5. The base case plant output was 1000 MW with a removal efficiency of 95 %. The basic discount rate used was in cost estimate runs was 6%.

Equation 3.9

Cost = A + B · Plant Life

Table 3.5a Plant Life CER "A" coefficients for capital costs, O&M, total annualised cost and costs of CO_2 avoided

Coefficient	PFC [M$]	TCR [M$]	Annual TCR [M$/y]	Variable O&M [M$/y]	Fixed O&M [M$/y]	Total O&M [M$/y]
A	281.4	433.70	87.33	140.00	11.44	151.50
Coefficient	**Sorbent [M$/y]**	**Steam [M$/y]**	**Electricity [M$/y]**	**Total Annual Cost [M$/y]**	**Cost of CO_2 avoided [$/t]**	
A	23.84	36.51	28.91	238.80	72.34	

Table 3.5b Plant Life CER "B" coefficients for capital costs, O&M, total annualised cost and costs of CO_2 avoided

Coefficient	Process Facilities Cost [M$/y]	Total Capital Requirement (TCR) [M$/y]	Annual TCR [M$/y^2]	Variable Operating & Maintenance (O&M) [M$/y^2]	Fixed O&M [M$/y^2]	Total O&M [M$/y^2]
B	0.00	-0.05	-1.48	-0.632	0.00	-0.636
Coefficient	**Sorbent [M$/y^2]**	**Steam [M$/y^2]**	**Electricity [M$/y^2]**	**Total Annual Cost [M$/y^2]**	**Cost of CO_2 avoided [$/t y]**	
B	0.00	-0.35	-0.28	-2.114	-1.29	

3.5.6 Influence of Interest Rate

Similar analysis of the behaviour of these parameters was carried out in relation to variations in the interest rate (Equation 3.10 and Table 3.6). The base case plant output was also 1,000 MW with a removal efficiency of 95 %.

Equation 3.10

Cost = A + B · Bond Interest Rate

Table 3.6a Interest Rate CER "A" coefficients for capital costs, O&M, total annualised costs and costs of CO_2 avoided

Coefficient	PFC [M$]	TCR [M$]	Annual TCR [M$/y]	Variable O&M [M$/y]	Fixed O&M [M$/y]	Total O&M [M$/y]
A	281.4	422.5	35.96	117.5	11.44	129.0
Coefficient	**Sorbent [M$/y]**	**Steam [M$/y]**	**Electricity [M$/y]**	**Total Annual Cost [M$/y]**	**Cost of CO_2 Avoided [$/t]**	
A	23.84	23.97	18.98	164.9	26.77	

Table 3.6b Interest Rate CER "B" coefficients for capital costs, O&M, total annualised costs and costs of CO_2 avoided

Coefficient	PFC [M$]	TCR [M$]	Annual TCR [M$/y]	Variable O&M [M$/y]	Fixed O&M [M$/y]	Total O&M [M$/y]
B	0.000	2.124	1.940	0.944	0.000	0.936
Coefficient	**Sorbent [M$/y]**	**Steam [M$/y]**	**Electricity [M$/y]**	**Total Annual Cost [M$/y]**	**Cost of CO_2 Avoided [$/t]**	
B	0.000	0.524	0.415	2.884	1.822	

3.6 Summary of CO_2 capture costs

This section has presented a model that has been developed to compare carbon capture costs for different power station configurations. This model is based on simple and reliable relationships developed from a more detailed model (IECM-CS). The original model was not suitable for application directly in this context due to the large number of input and output parameters required and software compatibility. However, the detailed IECM-CS model has provided data series for development of the parametric CERs. These relate to capital expenses, operating costs, sorbent cost, steam cost electricity cost and cost of CO_2 avoided to plant size and to amount of CO_2 avoided for three CO_2 removing efficiencies of 85%, 90% and 95 %.

Table 3.7 compares cost estimates obtained in the current study with those found in the literature. The prices and cost were updated and levelled to late 2004 $ levels and the technologies studied are coal-fired plant, IGCC, GTCC and amine scrubbing technology. These results show a good agreement of the newly developed model with the previous studies.

Analysis of the data series provided three power plant capacity ranges (2,000 – 1,500 MW, 1,500 - 900 MW and 900 – 300 MW) in which the patterns of CO_2 avoidance costs become steeper. The model provides the option of studying power plants of specific capacities with increased accuracy.

The cost functions presented can be applied for both grassroots design problems and for retrofit as well, although cost adjustments which consider the cost of retrofitted capital equipment relative to similar equipment installed in a new plant would need to be taken into account. These factors affect the capital costs directly and the operating and maintenance costs indirectly.

Table 3.7 Comparison of cost figures

Source	Cost levelled to Nov/2004 $/t
Cost figures obtained in this study for Coal-fired plant (the UK) – MEA technology	
300 – 900 MW	**65-45**
900 – 1,500 MW	**45-33**
1,500 – 2,000 MW	**33-30**
Anderson and Newell (2003)	
- Coal/gas power plant, MEA technology	45.7 - 59
- Integrated gasification combined-cycle	28.5
Dijkstra and Jansen (2004)- Combined cycle, MEA technology	59 – 71.5
DTI, UK, (2003)	
- with Enhanced Oil Recovery	52 - 65
- with storage in depleted gas reservoirs	41 - 50
- New IGCC	24 - 63
- New GTCC	39
- Coal PF Retrofit	35

3.7 Novel routes to CO_2 Capture and Utilisation

3.7.1 Fertiliser (NH_4HCO_3) production from CO_2

The main idea of this technology is to sequester CO_2 as ammonium bicarbonate using aqueous ammonia (West and Marland, 2002). Selective catalytic reduction (SCR) - injection of gaseous NH3 or aqueous NH3 for removing NO_x from flue gas - is widely applied in power plants. Similarly, it might also be economical to use NH_3 for capturing CO_2 in utility systems. By taking advantage of the acidic nature of CO_2 in aqueous media, ammonia/water liquors can be used to scrub out CO_2 in the form of ammonium bicarbonates and carbonate as a stable chemical compound:

Equations 3.11 and 3.12

$NH_3 + H_2O + CO_2 = NH_4HCO_3$, ammonium bicarbonate
$2NH_3 + H_2O + CO_2 = (NH_4)_2CO_3$, ammonium carbonate

These ammonia salts, which can be used as nitrogen fertilizers, contribute to storing organic carbon in the soil, both in large quantities and for a long duration. The removal of CO_2 by ammonium bicarbonate (ABC) has two benefits: formation of biomass with the assistance of nitrogen furnished by ammonium (NH4 +) and the permanent sequestration of CO_2.

ABC was used as a nitrogen fertilizer in developing countries, until the 1980s. Since then, modern fertilizers, such as urea, ammonium nitrate and ammonium sulphate have been replacing ABC because they contain more nitrogen and are more stable. However, research has continued to improve the features of ABC. In the 1990s a modified ABC, known as long-effect ABC, was developed. It is a product of nanosized co-crystallized dicyanodiamide (DCD) and ABC. The hydrogen bonds between the DCD and the ABC affect physical properties of ABC such as volatility, stability and ability to remain in the soil for as long as 100 days. Compared to the modern nitrogen fertilizers such as urea, ammonium nitrate and ammonium sulphate, in terms of nitrite (NO_2 -) and nitrate (NO_3 -) run-off, the utilisation of ABC with DCD has generated a very favourable environmental impact.

A lot of data on plant growth exist with respect to different plants, soils and climates with respect to ABC. A study on the effect of ammonium bicarbonate on methane emission from soil indicated that no significant influence was found. Preliminary studies show that using ammonia to capture the CO_2 emitted from fossil-fuel combustion can be an effective and economical method to manage carbon; however the quantitative estimation remains to be done (Lal *et al*., 1999).

3.7.2 Recovery & sequestration of CO_2 by photosynthesis of microalgae

Microalgae and cyanobacteria are groups of micro-organisms which photosynthesise using water as the reducing agent. Biomass production from terrestrial plants requires near atmospheric concentrations of CO_2 whereas the growth of aquatic plants is restricted by the low rate of transport of CO_2 from the atmosphere to the oceans. The productivity of microalgae is dramatically increased by artificially increasing the transfer rate of CO_2 to the aqueous environment (Pedroni *et al*., 2004; Brown and Zeiler, 1993).

Only visible light has sufficient energy for inducing processes involved in the photosynthesis reaction. Conceptually the radiation of higher wavelength (e.g. the infrared), could be filtered and used additionally as solar heat. Microalgae have much higher growth rates than plants (up to ten times that of trees), and they can process higher concentrations of CO_2 (Benemann, 1997). Fast reproduction rates can provide faster development of suitable strains in comparison with plants. Besides which they can grow under conditions in which higher plants are unable to develop, makeing their potential use applicable in places such as deserts, where growth of higher plants is impossible, utilising salt water supplied from deep aquifers or from the sea. Cell suspensions of microalgae can be handled as liquids.

For large scale application of microalgae based CO_2 capture and disposal, it is important that the conventional CO_2 capture and compression cost is avoided. For this purpose, the microalgae suspension should be tolerant to:

1) High CO_2 and HCO_3 concentrations and consequently be able to withstand direct aeration by flue gases
2) Low pH (down to pH =2) caused by the presence of SO_2 and NO_x, higher than ambient temperatures
3) Low concentrations of heavy metals.

Several examples of microalgae and cyanobacteria strains that have properties which satisfy many of the above criteria are already are known. The highest CO_2 removal rate so far reported is 4.44g CO_2/L/day using a culture of marine Synechococcus sp.(a cyanobacterium) in a photobioreactor (International Energy Agency, 1998). Other research reports about the CO_2 removal capacity of the Chlorella- and Synechocystis-based system as 50 g CO_2/m2/d (Otsuki, 2001).

To capture the CO_2 from a 500 MW power plant, large open ponds of about 50-100 km^2 with microalgae suspension, into which power plant flue gas or pure CO (captured from power plants) is introduced as small bubbles would be required. The estimated mitigation costs for this type of scheme would be up to $100 per t CO recycled (with significant opportunities for further cost reduction) (Benneman, 1993). After harvesting, the biomass could be converted to a fossil fuel replacement, preferably a high value liquid fuel such as biodiesel.

Another way to make the process more efficient is by increasing the value of the biomass products. In this case, genetically engineered enzymes could increase lipid production relative to carbohydrate production which makes them better fuels because of the higher fat content.

Other biological options have been reported in the literature which has the combined potential to sequester 1-3 Gt C/y (IEA, 1998):

1) Cultivation of halophytes on salt contaminated land for use as biomass fuel or animal feedstock could utilise 0.7 Gt C/y (Glenn *et al*., 1992)
2) Enhancement of marine algae growth by fertilisation with Fe and by open algae farming could utilise 1-2 Gt C/y (Ritschard, 1992).

Microalgae systems require considerable portions of land and water and also certain climate resources the combination of which is seldom found in the vicinity of power plants. These factors currently constrain the likely reductions by microalgae systems on a large scale. But nevertheless this could be an element of a diverse set of mitigation options. Benemann (1997), however, notes that despite 50 years of development of closed system photo-bioreactor systems; commercial viability has not yet been achieved.

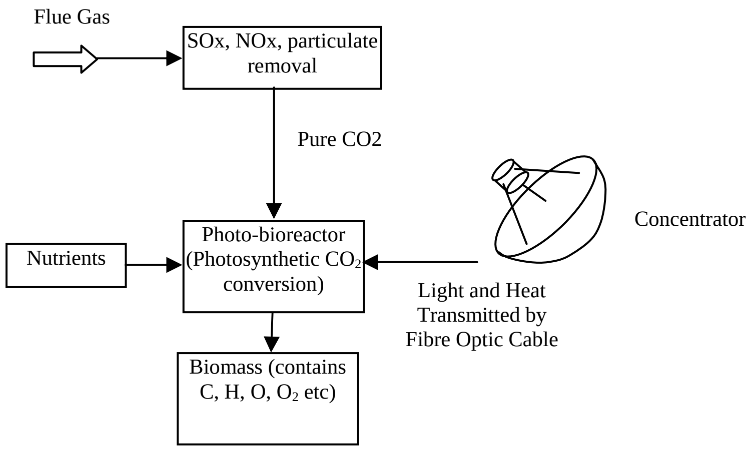

Figure 3.22 Conceptual design of a photo-bioreactor system for CO_2 conversion (Stewart, 2005)

To enhance the efficiency of the photosynthesis process, photo-bioreactor technology is being developed (Figure 3.22). In designing a photo-bioreactor Degen *et al* (2001) made use of the 'flashing light effect'. This is when the conversion of light to biomass can be enhanced by repeatedly cycling cells from the dimly lit interior of the reactor to the higher illumination of the exterior.

3.7.3 Sequestration by mineral carbonation

A further possibility is to use CO_2 to make stable solid products such as carbonate minerals that can be returned to the environment. The CO_2 mineral sequestration option might have its own benefits - carbonates have a lower energy state than CO_2; therefore, at least theoretically, no energy inputs are required. On the contrary, energy could be produced (Herzog, 2002) as these reactions are exothermic:

Equations 3.13 and 3.14

$CaO + CO_2 = CaCO_3 + 179$ kJ/mol
$MgO + CO_2 = MgCO_3 + 118$ kJ/mol

Compared to the heat released in the combustion of carbon (394 kJ/mol), these reactions release substantial heat. However, in nature, calcium and magnesium are rarely available as binary oxides, but mainly as calcium and magnesium silicates. Although the carbonation reaction is still exothermic for common calcium and magnesium bearing minerals the heat release is considerably reduced. An example for forsterite and serpentine respectively (Herzog, 2002):

Equations 3.15 and 3.16

$^{1}/_{2}Mg_2SiO_4 + CO_2 = MgCO_3 + ^{1}/_{2}SiO_2 + 95kJ/mol$
$^{1}/_{3}Mg_3Si_2O_5(OH)_4 + CO_2 = MgCO_3 + ^{2}/_{3}SiO_2 + ^{2}/_{3}H_2O + 64\ kJ/mol$

The raw materials are plentiful. Calcium and magnesium carbonates are solid which is desirable in above ground disposal; the products formed can be stored at the mine as landfill and will not leave the disposal site.

Commercially viable reaction pathways for mineral sequestration have not yet been identified. Hence it is very hard to do a detailed cost estimate, although Lackner *et al.*, (1995) have done some preliminary calculations on this concept. According to Lackner *et al.*,,this method's costs for significant CO_2 mitigation are around 30 \$ per t of CO_2 sequestered (not including costs of capture). Cost estimates used by the proponents of mineral sequestration are 70 \$ per t of CO_2 sequestered if one scaled up current laboratory processes. Eliminating pre-treatment and solving the dewatering problem would reduce the cost to 30 \$ per t of CO_2 sequestered.
Among the methods suggested or currently being developed are:

1) Exposing calcium and magnesium silicates (Kojima, 1997). This is based on a natural process of CO_2 sequestration in which, the authors suggest pulverisation and dissolution of olivine sand and wollastonite, and their subsequent reaction with power plant CO_2 to form magnesium and calcium carbonates to increase the rate of the natural process, Energy needs for the pulverization generate CO_2 is from 1 to 15% of the CO_2 sequestered. The process seems feasible; however, large amounts of rock must be transported and handled (up to several times the weight of the CO_2 sequestered) as well as significant amounts of hydrochloric acid.
2) Application of underground brines rich in chlorine and sulphate to produce carbonates (Dunsmore, 1992). The brines could be pumped to a CO_2 contacter and the precipitate slurry could be re-injected. An *in situ* processing option also exists. About 2.2 t of precipitate would be formed per t of CO_2 reacted. The drawback of the method is that the suitable brines are available in only a few locations and the environmental management of the acidic wastes presents a major problem. The quantities of solid materials that require handling, the large waste streams, and the transport distances to bring power plant CO to the disposal site probably make this an impractical option for mitigation.

Permanence is very important for a sequestration technology, and all else being equal, an option with higher permanence would be preferable; in reality however, choices will come down to trade-offs, such as cost versus permanence.

3.7.4 Chemicals Manufactured from CO_2

Approximately, 110 Mt CO_2 per year is used as a raw material for production of urea, methanol, acetic acid, polycarbonates, cyclic carbonates and speciality chemicals. The largest use is for urea production which reached about 90 Mt per year in 1997 (Creutz and Fujita, 2000) More than a dozen chemical catalytic reactions are known that can convert CO_2 into various chemical products. The summary of the reactions is given in Table 3.8. Their operating conditions, catalysts, selectivity and other parameters are well known and systematised (Xu *et al*, 2003)

Table 3.8 Some catalytic reactions of CO_2 conversion into products (Xu *et al*, 2003)

Hydrogenation		**Hydrolysis and Photocatalytic Reduction**
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$	methanol	$CO_2 + 2H_2O \rightarrow CH_3OH + O_2$
$2CO_2 + 6H_2 \rightarrow C_2H_5OH + 3H_2O$	ethanol	$CO_2 + H_2O \rightarrow HC{=}O\text{-}OH + 1/2O_2$
$CO_2 + H_2 \rightarrow CH_3\text{-}O\text{-}CH_3$	dimethyl ether	$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$
Hydrocarbon Synthesis		
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	methane and higher HC	
$2CO_2 + 6H_2 \rightarrow C2H_4 + 4H_2O$	ethylene and higher olefins	
Carboxylic Acid Synthesis		**Other Reactions**
$CO_2 + H_2 \rightarrow HC{=}O\text{-}OH$	formic acid	CO_2 + ethylbenzene → styrene
$CO_2 + CH_4 \rightarrow CH_3\text{-}C{=}O\text{-}OH$	acetic acid	dehydrogenation of propane $CO_2 + C_3H_8 \rightarrow C_3H_6 + H_2 + CO$
		reforming $CO_2 + CH_4 \rightarrow 2CO + H_2$
Graphite Synthesis		**Amine Synthesis**
$CO_2 + H_2 \rightarrow C + H_2O$		methyl amine and higher amines $CO_2 + 3H_2 + NH_3 \rightarrow CH_3\text{-}NH_2 + 2H_2O$
$CH_4 \rightarrow C + H_2$		
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$		

Carbon dioxide is thermodynamically stable, so any use of CO_2 as a feedstock requires a significant amount of energy input. This makes a major challenge to commercial implementation of the processes. Another problem are low levels of demand imposed by the market considerations to utilisation of the CO_2 which is generated by power stations and industry. Some of the examples of reactions are briefly discussed below.

3.7.5 Reduction of CO_2 by alkanes

Typical reactions are illustrated below.

Equations 3.17 and 3.18

$CO_2 + C_3H_8 \rightarrow CO + C_3H_6 + H_2O$ (metal oxide based catalysts)

$CO_2 + C_3H_8 \rightarrow CO + BTX + H_2O$ (Zeolite based catalysts)

These types of reactions are well known with those based on the Mobil HZSM-5 series of catalysts being particularly effective. The hydrogen form of the catalyst is normally cation exchanged with Ga, Zn or Pt. These cation exchanged catalysts can convert small chain alkanes (e.g. propane) into aromatics and, with the necessary temperature and pressure, produce a reasonable yield of aromatic mixtures of Benzene, Toluene and Xylene (BTX). A series of tests over ZSM-5 and similar catalysts, showed that yields of BTX could be increased by the addition of CO_2 to the alkane feed. The best reported performer was Zn-ZSM-5 which had a conversion of 71.4% of propane to over 43% aromatic product. Without CO_2 additions the figures are 57% and 37% respectively (I E A, 1998). The use of CO_2 for this type of reaction scheme is limited by the demand for BTX and for the methanol by-product.

3.7.6 The oxidative coupling of methane with CO_2

In this reaction, a reverse water gas shift reaction uses methane as a reducing agent for CO_2 converting it to hydrogen and carbon monoxide. Though technically feasible, the economic prospects of this method are not very good. Even if the product stream is altered to produce methanol, the quantities involved for using the CO_2 from one 500MW power plant is about twice the demand of a large economy such as that of Japan (IEA, 1998).

3.7.7 CO_2 polymers

The problems of plastic waste, its utilisation and its effect on the environment have raised considerable interest in the development and production of biodegradable plastics. Polyhydroxyalkanoates (PHAs) are polyesters that accumulate as inclusions in a wide variety of bacteria. These bacterial polymers have properties ranging from stiff and brittle plastics to rubber-like materials. Because of their inherent biodegradability, PHAs are regarded as an attractive source of nonpolluting plastics and elastomers that can be used for speciality and commodity products. The possibility of producing PHAs at a large scale and at a cost comparable to synthetic plastics has arisen from the demonstration of PHA accumulation in transgenic Arabidopsis plants expressing the bacterial PHA biosynthetic genes. The environmentally benign process of utilisation of CO_2 and sunlight in the production of plastic makes this approach attractive. There are three groups of organisms that accumulate PHA from carbon dioxide: chemoautotrophic bacteria such as hydrogen-oxidizing bacteria, genetically engineered higher plants and cyanobacteria (Asada, 1999).

Although CO_2 has not been regarded as a promising monomer it can feature in a number of reactions, particularly to form alkylene oxides and alkylene poly-carbonates. The reaction normally involves organometallics such as diethylzinc with a hydrogen donor (water, an amine or an aromatic dicarboxcylic acid). These products are currently used as binders in the electronics industry and are being further developed for film applications in the food and medical areas. The predicted market is around 100 t/y and as these developments have already been commercialised, these 'new' polymers may substitute for other more conventional oil based polymers. However today, the cost of these polymers is high, although this is mainly due to the catalyst cost and further development could reduce the cost.

3.7.8 CO_2 Sequestration into fuels - methanol

The idea of 'recycling' the CO_2 back to a fossil fuel that could reduce the use of virgin fossil fuels could be attractive. However, reducing CO_2 back to carbon requires at least 80% of the energy that is generated from burning a typical coal, and with processing losses taken into account, there may be even a loss of energy. Also, unless this energy comes from non-fossil sources, additional CO_2 is generated. Additionally if non-fossil energy is available, in most cases it would be better used to substitute for the burning of coal in the first place (Herzog *et al*., 1997). Alternatively the possibility of converting CO_2 to a transportation fuel, such as methanol, using hydrogen, can be viable in practical terms.

Equation 3.19

$$CO_2 + 3H_2 = CH_3OH + H_2O$$

In this reaction, each molecule of CO_2 reacts with three molecules of hydrogen to produce one molecule of methanol. But energy is required to produce hydrogen. The most efficient pathway to hydrogen today is through steam-methane reforming, which is about 80% efficient.

Equation 3.20

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

Production from coal gasification is about 50% efficient; production from electrolysis of water, about 30% efficient (Rosen and Scott, 1996).

There is considerable research, especially in Japan and Korea, on improved catalysts and catalytic pathways, both liquid and gas phase, to achieve high conversion and minimal energy loss in using H to convert CO to methanol. However efficient the conversion is, the fundamental energy requirements to recycle CO to methanol still make the conversion of very limited practical use from an energy utilisation viewpoint. Currently, technologies in this field are still in their early stages and it still is too early to judge whether there is a scope for efficiency improvement for the process to become economically viable.

3.7.9 Dimethyl carbonate (DMC)

The increased demand in DMC for a number of organic syntheses is caused by recent moves away from the use of phosgene, dimethyl sulphate and various formats. DMC is used as a solvent in those processes and in motor fuel as an octane booster. A process to produce DMC from CO_2 is now in commercial operation using cobalt based catalysts. Assessments are that globally, 1 Mt of CO_2 per year might be used in DMC production (www.peer.caltech.edu/projects/cat_chem_2.htm). In practice, methyl tertiarybutyl ether (MTBE) is already established as a vehicle fuel additive, with a large capacity installed worldwide, so DMC would have problems in becoming competitive with MTBE in a large scale market.

Overall the current use for CO_2 in the chemical industry is rather limited by the industry's capacity to utilise large quantities of CO_2. Further intensive research is going on aimed at improving commercial potential of the CO_2 utilisation processes. Xu et al (2005) developed a methodology for selecting new energy-efficient and environmentally acceptable processes. The selection criteria include operating conditions, energy requirement for reactions, thermodynamic feasibility and equilibrium conversion of reactions based on Gibss free energy change. Catalyst conversion and selectivity, cost and life of the catalyst and the methods of its regeneration were also considered. As a result of complex analysis, the authors provide a range of technologies that can be economically viable in comparison with the base case industrial area.

3.7.10 Summary of novel approaches

The novel approaches to CO_2 capture and sequestration described here, include diverse opportunities for industrial utilisation of power plant CO_2. However, most of them still offer relatively small scale solutions compared to the total quantities of CO_2 emitted by the power and industry sectors. For example, chemical conversion of the CO_2 from a large power plant to methanol requires so much energy that the mitigation benefit would be marginal, if any. All of the options described require further development towards large scale testing and evaluation. Conversion of power plant CO_2 emissions to biomass using microalgae is another promising option, but still considerable research effort is needed to achieve a boost in productivity to reduce land requirements and costs. CO_2 conversion to and storage as carbonate minerals is another possibility, again intensive research is needed on materials processing and waste issues. In the short term, biomass energy production, coupled with co-firing of farmed or waste biomass with fossil fuels looks like a viable option. In the long term, research on hydrogen bio production and on artificial photosynthesis may deliver results needed for economically promising and efficient ways for mitigation.

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Chapter 4

A whole system model of CCS in the UK

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Note: The project partner was unable to finish this chapter to meet the submission deadline. This is the latest version of the unfinished Chapter supplied by Reading University.

4.1 Overview

The objective of the work reported in this chapter was to investigate the impact of several technical parameters on the cost and performance of electricity producing Carbon Capture and Storage (CCS) systems, as they might be implemented in the UK. At the simplest level, a CCS system may be viewed as being composed of four subsystems as illustrated in Figure 4.1, and specifically, the electricity producing power plant, the CO_2 capture system, the CO_2 transport system and the finally the CO_2 repository and associated injection equipment. In practice new build CCS power plant are likely to employ designs that integrate the combustion and capture technologies, but the essential points of this discussion remain valid.

An intrinsic difficulty in the technical and techno-economic assessment of entire CCS systems is the interdependence of the component subsystems. By way of example the conditions at which the capture equipment produces carbon dioxide will have an impact on the optimal pipeline design. The pipeline design in turn will impact on the conditions at which carbon dioxide is delivered to the storage repository and hence the specification of any injection equipment.

In any study of the techno-economics of CCS, it is only sensible to consider optimal overall system configurations. The definition of optimum in this context is not crucial to the discussion here, but in general we will be interested in combinations that give the lowest energy cost. It is clearly possible to devise a wide range of perfectly functional CCS plant that are composed of non-optimal component combinations. However in view of the expense of construction, plant engineers would expend considerable effort in identifying optimal component configurations. Thus a realistic cost modelling study must make efforts to optimise system configurations. The interdependence of the subsystems complicates this.

To perform an entirely rigorous parameter study of costs requires that optimal CCS plant are designed and costed for the range of interesting parameter values. In principle the optimal parameters for any system can be identified through sensitivity studies. An engineer designing a CCS plant, may, for example, wish to investigate how the cost of energy varies with the rated output of the power plant. There is no exceptional difficulty in identifying local optimal parameters for each of the subsystems of a CCS plant. However, subsystem optimisation is unlikely to result in an optimal overall system.

Identification of whole system optima requires that the designer takes full account of the interactions between the subsystems. The complex, integrated nature of CCS makes this difficult to do. For this reason an integrated, computer based, technical model of the entire CCS system was developed for this project, in order to facilitate rapid investigation of how system cost and performance varies as a function of several technical parameters.

4.1.1 Economic considerations

The over-riding purpose of the model is to place a cost on carbon abatement for various technologies. Such abatement costs can only be considered in a comparative way, that is by citing the *differences* in energy cost and carbon dioxide production per unit of electricity between two or more technologies. By comparing two similar technologies, the additional expense required to produce less carbon dioxide per unit of energy can easily be seen. A commonly used measure is the cost of carbon avoided, that is

$$(CC)_{avoided} = \frac{(COE)_2 - (COE)_2}{(CE)_2 - (CE)_1}$$

where

CC	=	Cost of carbon (dioxide) avoided (£/kWh)
COE	=	Cost of energy (levelised production cost)
CE	=	Total carbon (dioxide) emissions per kWh (kg/kWh)

and the subscripts denote respective technologies.

To calculate the levelised energy production cost for a system, a methodology recommended by the IEA is employed. With a test discount rate *d* and project economic lifetime *L*, the net present value of the whole project is given by:

$$NPV = .-C_s - C_T - C_D - C_E - \sum_{i=1}^{i=L} \frac{c_{S,i} + c_{T,i} + c_{D,i} + c_{E,i}}{(1+d)^i} - \sum_{i=1}^{i=L+N} \frac{c_{D,MON,i}}{(1+d)^i} - \frac{D_S + D_T + D_D}{(1+d)^L}$$
$$. + \sum_{i=1}^{L} \frac{i_{S,i} + i_{E,i}}{(1+d)^i} - \sum_{i=1}^{L} \frac{c_{T,E,i} + c_{D,E,i}}{(1+d)^i}$$

where N is the number of years beyond project completion that reservoir monitoring must be maintained, and C_T , C_D etc. represent the sums of relevant capital costs listed in table 4.1. The levelised energy cost is therefore

$$COE = \frac{-NPV \times CRF}{E}$$

where the capital recovery factor is given by

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1}$$

and E is the average annual energy production.

Table 4.1: Major costs in the techno-economic analysis of CCS. Note that not all of the costs listed are considered in detail by the current study.

Major System	Cost	Type	Symbol	Note
Source (generator)	Plant	Capital	$C_{S,P}$	Only included for new-build plant, regarded as a sunk cost for re-fit cases.
	FGD	Capital	$C_{S,FGD}$	Flue gas desulphurisiation equipment cost. Not included if already fitted to an existing plant.
	Fuel	On-going	$c_{S,FUEL,i}$	Fuel cost in year *i* from start of sequestration project.
	O&M	On-going	$c_{S,P}$	Plant O&M cost in year *i* from start of project.
	Income	On-going	$i_{S,i}$	e.g. Income from CHP or hydrogen in year *i*.
	Decommissioning	End of life	$D_{S,P}$	
Source (capture process)	Purchase & construction	Capital	$C_{S,C}$	
	O&M	On-going	$c_{S,C,i}$	
	Energy	On-going	$c_{S,E,i}$	Cost of energy required for capture plant operation – where possible will be treated implicitly as parasitic consumption of generated electricity.
	Decommissioning	End of life	$D_{S,C}$	
Transport	Collection network construction	Capital	$C_{T,NET}$	Only required if multiple sources used.
	Pipeline construction	Capital	$C_{T,1}$	
	Pumping station construction	Capital	$C_{T,2}$	
	Other construction costs…	Capital	$C_{T,3}$…	Other large capital costs (case specific).
	O&M	On-going	$c_{T,OM,i}$	
	Energy	On-going	$c_{T,E,i}$	Cost of energy required for pumping carbon dioxide through pipeline.
	Decommissioning	End of life	D_T	
Disposal	Well drilling	Capital	$C_{D,1}$	
	Well head equipment	Capital	$C_{D,2}$	
	Other construction costs…	Capital	$C_{D,3}$…	Other large capital costs (case specific).
	O&M	On-going	$c_{D,OM,i}$	
	Completion	End of life	D_D	
	Monitoring	On-going	$c_{D,MON,i}$	This cost is unique in that it continue after project completion.
EOR	Equipment	Capital	$C_{E,1}$	
	Transport	On-going	$c_{E,T,i}$	Cost of transporting oil to shore.
	O&M	On-going	$c_{E,OM,i}$	

	Income	On-going	$i_{E,i}$	Benefits from oil sales.

4.1.2 Modelling approach

The model views the entire CCS system very much as shown in figure 4.1. The essence of the modelling approach is that the user defines certain overall parameters for the CCS system, such as the rated power and type of the electricity generation plant, together with details of the pipeline route and storage reservoir. Model algorithms then ‘size’, in the sense that their major technical parameters are determined, the subsystems needed to produce a whole CCS system. Routines within the model also ‘match’ the various subsystems to produce, so far as possible, an overall optimal design. Finally the cost and performance of the overall system is predicted and output to the user.

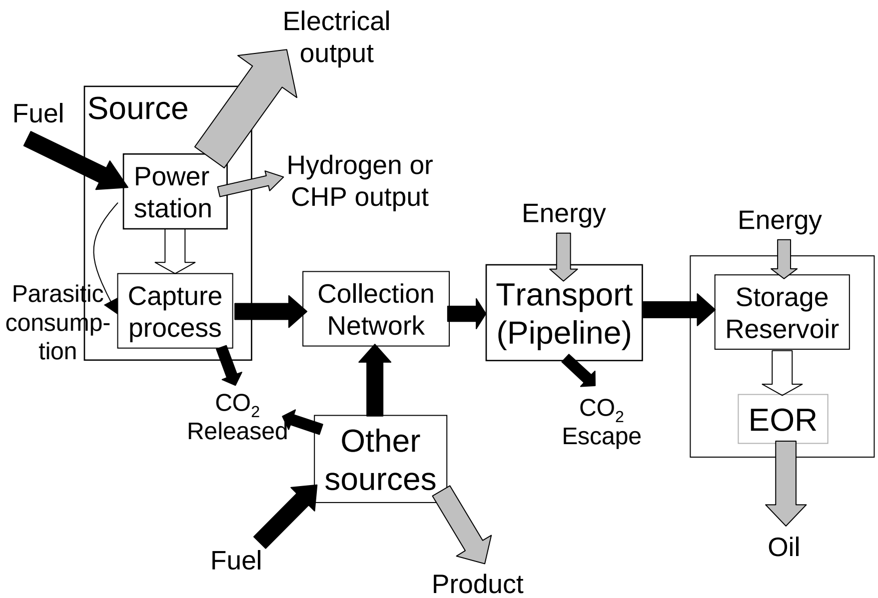

Figure 4.1: Overview of CCS systems as seen by the techno- economic model.

Techno economic models have been developed that predict the cost and performance, in terms of both energy output and carbon dioxide production, for each of the subsystems. So far as practicable the subsystems models are based in rigorous technical analysis, but the scope of the problem means that resort has to be made to empiricism, especially for cost prediction.

The model has been written as a computer code in Visual Basic. Some details of the implementation are described in an appendix. This chapter provides a relatively high level overview of the modelling principles and the results.

4.1.3 Simplifying assumptions

Attempting to model all possible options for each of the subsystems was beyond the scope of the project. To make the problem tractable, only a limited number of possibilities were treated in detail, these being listed in table 4.2. The modelling approach and the computer code framework however are perfectly general and could be easily extended to treat a wider range of systems.

Table 4.2: Overview of technical options considered by the model.

Systems modelled	**Limitations and comments**
Power plan and capture system	
Coal fired pulverised fuel with flue gas desulphurisation and chemical (MEA) scrubbing (PFFGD+MEA)	In principle can model any rated capacity station but data availability limits capabilities
Integrated coal gasification cycle with physical scrubbing (IGCC)	In principle can model any rated capacity station but data availability limits capabilities
Combined cycle gas turbine with chemical (MEA) scrubbing (CCGT)	In principle can model any rated capacity station but data availability limits capabilities
Carbon dioxide transport system	
Pipeline transport, including repressursation stations where needed	Only deals with single source to single sink transport. Routes must be determined using a GIS that is currently independent of the CCS model
Storage reservoirs	
Offshore oil and gas reservoirs	Data describing the reservoirs must be provided by the model user.

4.1.4 Major technical parameters treated by the model

Conceptually there are two parts to the model. Firstly, there is a modelling framework provided by the model computer code. This provides a mechanism by which the techno-economics of CCS may be investigated; build on rigorous analysis so far as practicable. Secondly, there is a set of component performance and cost data that inform instances of the model calculations. This is essentially empirical in origin, having been derived from literature sources, and in certain cases, from parameter studies with other models. As will become apparent, the greatest constraint is due to the limited cost and performance data available.

The modelling framework has been designed to allow study of the following main parameters:

- Power station rated capacity
- Power station type
- Power plant utilisation, including variations over time.

- Capture plant CO_2 capture efficiency
- Rate of solvent consumption (for MEA plant, due to sulphur products not removed by FGD)
- Fuel composition (in so far as it impacts on CO_2 produced per unit of energy)
- Pipeline route
- Storage reservoir capacity and (limited) geological parameters.
- 'Consumables' costs i.e. energy supplied, fuel, solvent etc

The extent to which it is practical to investigate the performance of any system concept depends on the availability of component cost and performance data. As will become apparent, the greatest constraint on model use is due to the limited component cost and performance data available

4.1.5 4.1.5 A note on the issue of leakage

It is likely that carbon dioxide will leak from CCS storage reservoirs. The cost of carbon avoidance from CCS is therefore a function of time in the sense that, over time, less carbon dioxide is avoided. Cost calculations in this report assume that all the carbon dioxide captured remains permanently within the storage reservoir.

4.2 Power plant model and capture system model

4.2.1 Design and capital cost estimation

Formulation of a detailed engineering model for the characterisation of the power plant and carbon dioxide capture system is beyond the scope of the work described here. Instead the calculations rely on a look-up table approach, with tables populated by data produced either from specific simulation tools (see for example) or from literature derived data.

For each power plant type and capture system type, tables have been formulated that give the plant capital cost and performance data as a function of rated capacity. Slightly different table formats are required to deal with retro fit and integrated cases.

For the non-integrated power plant, the performance data comprises the overall efficiency of the energy conversion process from fossil fuel to electricity. Simple combustion calculations allow the peak rate of flue gas production and concentration of carbon dioxide in the flue gases to be estimated. This is then matched with data from look up tables describing the capture plant, and the cost of the capture plant thereby estimated. The modelling framework allows the capture efficiency to be specified as an input, so that the effect of having more or less effective capture equipment can be investigated. Cases that do not match data within the look-up tables are dealt with via linear interpolation.

For integrated plant, a similar methodology is used. However the procedure is simpler as by definition, there is no requirement to be able to 'mix and match' production plant and capture plant. Thus, the look up tables directly provide data on the proportion of carbon dioxide from fuel combustion that is captured and fed to the storage reservoirs.

In practice, it was found that insufficient reliable data was available in the open literature to make full use of the model capabilities. For example, there is little data on the variation of the capital cost of capture equipment with overall capture efficiency. The poor data availability has constrained the extent of the study, rather than any limitations in the model itself.

4.2.2 On-going cost estimation

The major on-going costs associated with CCS power plant operation are

- Fuel costs
- Solvent replacement costs, where a chemical process is used to capture carbon dioxide.
- Operation and maintenance costs

Fuel costs are calculated directly from the plant load factor, the per unit calorific value of the fuel and the overall efficiency of the electricity production process. The model has a time dependent mode which allows the effect of varying the plant load factor over time to be investigated, for example to represent the gradual run down of a plant as it approached the end of its life. The calculations reported here, however, all assume a constant load factor.

Solvent replacements costs arise in MEA based carbon dioxide capture plant because the MEA is gradually poisoned by combustion products in the flue gases. Sulphur dioxide is a particular problem in this case. The calculations reported here-in assume that the flue gas from coal fired plant pass through FGD before the capture plant, but clean-up is far from perfect and quantities of sulphur dioxide will reach the MEA.

Only limited data on the impact of sulphur dioxide on MEA consumption is available in the open literature. Once again, this constrains the validity of the calculations reported here.

Operation and maintenance costs are treated in a simple manner. The annual expenditure is assumed to be a small percentage of the total capital cost of the plant, with values taken from the literature.

4.3 Pipeline design model

4.3.1 Overview

Realistic options for transport of carbon dioxide from commercial scale UK CCS plant to offshore reservoirs are pipeline, or in some cases bulk ship. The work reported here considered only pipeline transport as this is the most general solution, and from the limited studies in the literature, appears to offer the most economic solution.

In general, previous studies have found that pipeline accounts for a relatively small proportion of the capital cost of CCS. Nevertheless, it is important to expend some effort in modelling pipeline as they have potential to dominate disposal site selection decisions. They key point here is that costs associate with the disposal site are largely independent of the site itself, at least to the extent that they can currently be modelled. The only economic basis for reservoir selection that is currently justifiable, for an overview study at least, is the relative cost of pipeline construction compared to the capacity of the storage reservoir.

There is some discussion in the literature of the conditions under which captured carbon dioxide can be most economically transported. Outline calculations demonstrate that, for CCS on a commercial scale, unfeasibly large diameter pipelines will be required unless transport takes place under supercritical conditions, and these have been assumed here.

The choice of transport conditions also has implications for the requirement for repressurisation stations, needed to overcome the frictional losses associated with the flow of the carbon dioxide through the pipe and maintain the pressure and temperature of the carbon dioxide. Over the relatively short distances involved in implementing CCS in the UK, parameter studies have demonstrated that the exact transport conditions have a negligible impact on the need for repressurisation stations so long as supercritical conditions are adopted.

4.3.2 Design and costing approach

Design and capital costs. Pipeline capital costs are divided into material costs, and those associated with construction operations. In principle, both classes of cost depend on the same parameters, specifically:

- the chosen route, defined here as the distance the pipeline extends over different types of terrain. Costs are calculated from a cost per unit distance associated with each type of terrain.
- the pipeline diameter, which is assumed to be constant over the entire route
- the flow conditions, which in combination with the above impacts on the specification of the pipeline and the need for repressurisation stations along the length of the route.

The cost model as written contains a facility to model complex interactions between the parameters. For example, it is possible to identify optimum diameters that minimise the overall cost of the pipeline. Again the utility of this has been rather constrained by the limited cost data available in the open literature. In particular, the work reported has not accounted for the impact of pipeline diameter and specification on construction cost.

The cost model requires that details of the route be input describing distances travelled across a limited number of terrain types. For the results reported here, unit costs for crossing each type of terrain have been obtained via a literature survey. However there is a facility for the model user to input revised costs.

The need for re-pressurisation stations is determined by a physical simulation of the flow through the pipeline. Pressures and temperatures, accounting for frictional effects, heat transfer from the pipe surface, and changes in elevation are calculated at stations along the length of the pipeline. If the pressure falls below a user specifiable value, then a re-pressurisation station is inserted into the pipeline, which restores the pressure and temperature to specifiable conditions. The model framework can cost stations based on the throughput of carbon dioxide and the effort of re-pressurisation (which influences the size of the plant required), but the limited cost data available means that the numerical results use a fixed cost.

Construction of repressurisation stations offshore would be prohibitively expensive.

At pipeline landing points therefore, the model checks to see if any repressurisation will be required before the pipeline reached the storage site. If so, then a repressurisation station is inserted at the landing point.

On-going costs. On-going costs associated with pipeline transport are those of maintenance and the energy consumed in any re-pressurisation equipment. Annual maintenance costs are taken to be a fixed fraction of the construction costs, which can be specified by the model user and for the work reported here was based on literature data.

A physical calculation estimates the power required to re-pressurise the carbon dioxide in each pumping station. Taken with an assumed re-pressurisation plant efficiency, this allows the energy consumed by any pumping station to be calculated. The user may specify the per unit carbon dioxide release and monetary cost associated with this energy. For the studies reported here it has been assumed that this energy has been supplied electrically, with the current UK average per unit cost and carbon dioxide release.

4.3.3 Pipeline routing

In order to cost pipelines on the basis of their routes, a route description is required. Producing a detailed pipeline route for each case considered was beyond the scope of this project, so a simplified semi-automated methodology for devising representative pipeline routes was devised. It is important to note that the objective of this portion of the study was only to produce routing data that would reflect the general characteristics of the location considered, and not fully considered pipeline proposals.

After a review of the readily available literature and data it was concluded that attempting to custom-design the offshore portion of the pipeline routes required for the study cases was impractical. There are many factors, including seabed obstacles, that can constrain offshore pipelines, and accounting for them all was beyond the scope of the project. To simplify the analysis, therefore, it was assumed that the offshore portions of pipelines follow the routes of existing offshore oil and gas pipelines, as descried in the IDEAL database XXX. Informal consultations revealed that it is unlikely that owners of existing pipelines would be prepared for CCS pipelines to be constructed in close proximity, but again, the intention here is merely to produce representative data.

It turns out that pipelines originating from the UK already connect all the storage sites of interest. Thus, by re-using these existing routes, the on-shore pipeline routing problem is ‘reduced’ to one of devising routes from carbon dioxide sources to the five existing pipeline landing points, shown in figure XXX. To this end a GIS, using the ArcView software, has been established that can calculate least cost routes from carbon dioxide sources to landing points. Sample output from the GIS is shown in figure XXX.

Details of the GIS implementation are discussed in a separate project report XXX, but it is pertinent to outline the major points. Based on a literature survey, a cost is allocated to constructing a representative pipeline across several types of terrain.

Drawing on terrain use information derived from the UK portion of the 'Digital Chart of the World' XXX, a map can be produced that shows the per kilometre cost of building the representative pipeline at any point in the UK. A least cost routing routine can then be used to identify the cheapest route from any carbon dioxide source to pipeline landing points. The following features are amongst those accounted for in developing the cost maps:

- Urban areas
- Major roads.
- Major rail lines,
- Large rivers and other water features,
- The effect of elevation on accessibility and construction costs

For safety reasons, it is likely that there are constraints on the routes over which it is practicable to build CCS pipelines. A survey of the literature revealed no guidance on the construction of supercritical carbon dioxide carrying pipelines. British Standard BSXXX does however refer to the construction of high-pressure carbon dioxide pipes, and although the range of conditions considered do not approach those proposed here, the most extreme constraint was adopted. The major constraint is that pipelines are not permitted to pass within a kilometre of populated areas.

The GIS system has been used to conduct studies investigating the relative cost of constructing pipelines from candidate CCS sites to landing points. In order to assess the impact of wider considerations on the construction costs routes were developed with varying degrees of environmental sensitivity. Table 4.3 compares the relative cost of constructing pipelines from several large UK carbon dioxide sources to the five offshore pipeline landing points that serve the UK. Figure XXX also provides a graphical indication of the results.

Table 4.3 Relative costs of onshore CCS Pipelines between some UK sources and landing points

Landing Pt	**Station**		
	Fiddlers Ferry	*Ratcliffe*	*Teesside*
Point of Ayr	1.55	3.52	5.87
Barrow	4.81	5.10	3.57
Teesside	5.01	4.80	1.00
Easington	4.78	3.76	2.84
Theddlethorp	4.46	2.54	3.93
Bacton	6.61	4.06	6.87

It must be pointed out that the 'Digital Chart of the World' data is rather approximate. As a result, the generated routes should be regarded as indicative rather than definitive. Several parameter studies have demonstrated that in practice the uncertainty in the geographical and land use data does not have a great influence on the calculated routes.

4.4 Disposal site model

4.4.1 Overview

The disposal site model considers primarily the cost of constructing injection wells. Calculations follow closely the approach of a JOULE funded study XXX, as no more rigorous approach could be identified from the literature. On-going costs to be considered by the model are the income from enhanced oil recovery (EOR) and the cost of long monitoring of stored carbon dioxide.

It was originally intended to include a facility to model use of a distribution hub that could convey carbon dioxide to one of a number of reservoirs. However once again cost data availability rendered this impractical and the model only treats single source to single sink CCS schemes. The code has been written in such a way that this facility could easily be added.

4.4.2 Capital cost of injection wells

The cost of each injection well required is calculated using the methodology of the JOULE funded study, but with costs updated to 2005 values. The number of wells required is calculated from the maximum carbon dioxide flow rate and an estimate of the maximum rate at which carbon dioxide can be injected into a well. This latter value is estimated using a simplified version of a methodology due to Hendricks and Block xxxx, which relies on estimates of the reservoir permeability and thickness. It is assumed that no additional compression takes place at the injection site, so that injection is driven only by the pressure at the well head and gravity. As such, there is no energy consumption at the injection site.

In addition to each well, there is also a cost associated with the mechanical equipment needed to complete each well head, so called well-head completion costs. These are assumed fixed for each well head and are again updated versions of the JOULE project estimates

4.4.3 Enhanced Oil Recovery

The model includes a very simple facility to include income streams from enhanced oil recovery (EOR), as described in the appendix, but this has not been used for the current studies.

4.4.4 Monitoring

It is likely that storage sites will require long term monitoring in order satisfy regulatory requirements. There is currently much uncertainty around the form and extent of any monitoring that will be required, and the associated costs. As such, developing a cost model of monitoring processes proved to be prohibitively difficult. Monitoring is not therefore included in the model explicitly, although the user can enter an annual monitoring cost derived from other sources.

4.5 Integrated system design

The overall system design is driven by the power station with all components being sized to deal with peak carbon dioxide flow.

There may be cases where an improved energy cost can be achieved by

4.6 Validation

There are three areas of concern in the validation of cost models such as the one described here, and in particular

- Validation of the overall model and its cost predictions
- Validation that the model code performs correctly
- Validation of the theory underlying the model calculations.

Validation of the entire model is not practical, as it is predictive in nature and models systems for which no prototypes exist. Moreover many of the cost calculations depend on data taken from the literature which almost by definition cannot be validated.

The validity of the theory underlying the model is also difficult to assess rigorously. The calculation methods are derived from published sources, and it has been assumed they are correct. Given that the code itself has been tested, it is unlikely that

It is possible to assess whether the model code functions correctly. This has been achieved through a series of test cases run on the separate elements of the model have been used to test the validity of the implementation.

4.7 Application to UK Case Studies

The methodology has been applied to assess the techno-economics of several combinations of carbon-dioxide source capture technology and storage reservoir. The number of parameters that can influence scheme techno-economics mean that it is only possible to present overview data here. For detailed assessment of particular combinations of technology and storage reservoir, it is suggested that the reader uses the model, which can be made available on request.

4.7.1 Assumptions

The techno-economic results are dependent on the unit costs of several consumables and products. For the indicative results described here, the costs in table XXX are assumed. All other consumables and products are assumed to have no value associated with them. To calculate carbon abatement costs, comparison has been made with the cost and CO_2 emissions of supplied electricity, taken to be equal to UK grid supply averages.

Quantity	**Assumed value**
Coal cost	
Gas cost	
Supplied electricity cost	
Supplied electricity CO_2 emissions	

4.7.2 Case studies

The case studies considered comprised permutations of power station location, power station type and storage location. The combinations of power station location and storage location considered are shown in table XXX.

Power station location	**Storage reservoir**
Midlands (Ratcliffe on Soar)	

4.7.3 Results

The ranges of costs of carbon dioxide avoidance for each of the power station technologies is shown in table XXX. It should be noted that the ranges reflect the effect of the variations in the case studies, rather than uncertainties in the input data,

Power plant	**Carbon avoidance costs**
PFFGD + MEA	
IGCC	
CCGT	

4.8 Conclusions

4.8.1 Achievements

The major outcomes from this work are as follows:

- A whole system cost model for the implementation of CCS plant in the UK has been developed and demonstrated.

- The model has been used to investigate the techno-economics of building CCS systems in the UK, as a function of plant type and geography. Some consideration was also given to the impact of energy supply scenarios. However as the model has been formulated only for single source to single sink analysis, this was not treated in detail in the current work.

- The extent of the study was largely limited by poor data availability on the capital cost of carbon dioxide capture plant as a function of the overall technical parameters. For techno-economic assessment purposes, a detailed parameter of the costs of capture equipment would be of great values. This however would only be practical with significant industry involvement and issues of commercial confidentiality would need to be tackled.

- Due to the data uncertainties, the developed modelling framework and computer code are the primary outputs from the study. The capabilities of the model significantly exceed the validity of the input data available from the open literature. Thus the model, and its underlying methodology provide a basis for future studies of CCS in the UK as more reliable data becomes available.

- A GIS for the techno-economic investigation of candidate pipeline routes from carbon dioxide sources to offshore pipeline landing points has been developed. The GIS has been used to investigate the impact of routing constrains, and in particular environmental impact considerations, on the relative pipeline construction cost.

4.8.2 Recommendations for further work

The work described has fulfilled the objectives set out in the original proposal. A major difficulty encountered, which was not fully anticipated at the outset, was the poor availability of cost data for components. The data availability, rather than the capabilities of the developed model, has constrained the study and thus the main suggestions for further work are oriented around the collation of better input data. Specific recommendations are as follows:

- The key recommendation from this work is that the scope for assessment and overall design optimisation of CCS systems is severely limited by the availability of cost data in the open literature. There is an urgent need for collation of cost data associated with the fossil fuel supply chain. It is unlikely that reliable decisions regarding the viability of CCS in the UK can be taken until such data is collated.

- The issue of monitoring of storage sites needs to be considered in more detail. In particular a detailed model for the cost of monitoring, which is currently almost impossible to predict, should be developed. Although not discussed substantially on the main text there is considerable debate in the community over the extent of the monitoring required and the linked question of the time period over which it is desirable that carbon dioxide is retained in storage reservoirs. These questions can only be answered through an economically oriented risk analysis, which in turn requires a cost model for the monitoring processes.

- There is a need for design guidance on the construction and routing of CCS pipelines. Existing UK guidance, perhaps unsurprisingly, makes no reference to the construction of long pipelines carrying supercritical carbon dioxide.

4.9 References

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Chapter 5

Geological Carbon Dioxide Storage and the Law

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5.1 Introduction

Whilst geological carbon dioxide capture and storage (CCS) remains a potentially attractive climate change mitigation option, there are uncertainties and complexities surrounding the legality of such projects. The importance of the legal position when considering geological CCS cannot be understated. Even if suitable storage sites for CO_2 have been identified, the technologies for transportation and injection are feasible and available, and there is broad support from within government, industry, and the public for such projects taking place, the significance of these is limited if the current applicable laws prevent or restrict such projects from taking place. This chapter identifies the relevant international and European legislation that potentially impinges on offshore geological carbon dioxide storage projects taking place and considers the key legal questions of ambiguity concerned with geological CCS beneath the waters surrounding the United Kingdom (UK). Although this chapter focuses on the legal position in relation to the UK, any conclusions that are reached will be relevant to others in the international community. It is clear that the international community would benefit from greater legal clarification of existing relevant legislation. The chapter cannot, and its aim is not to, always offer definitive answers as to whether certain geological CCS projects are legal or not. Where there is uncertainty as to the legal position, comment is provided on why this is the case and, where appropriate, the authors' opinion as to what might be the correct legal interpretation.

Any geological carbon dioxide storage project taking place under the seas surrounding the United Kingdom (UK) will most likely fall within the remit of a number of overlapping legal regimes. In other words, they will be covered by international, European Community and national legal regimes. This is because the UK is a signatory to many of the international laws which are potentially relevant to geological carbon dioxide storage projects, and is also a member of the European Community, and as such is bound by Community law. It is important to note that there is currently no legislation, either national, European or international, which specifically covers the legal issues surrounding carbon dioxide storage. The laws that could apply to geological CCS were not designed with this is mind. The storage of CO_2 is a relatively new concept and was not envisaged until relatively recently, whereas for example, some of the international marine conventions are thirty years old. Although carbon dioxide storage is not specifically mentioned in legislation it can of course still fall under the legislation's remit. Many laws in particular are still developing and evolving and can react to such changes in society. Laws can also be amended or replaced to reflect the changing objectives of national governments, members of the European Community or the international community. However, amending and replacing laws can be time consuming and difficult in practice because they often require unanimous or majority agreement.

Although this chapter only comments on the legislation as it currently stands, the procedures for amending individual laws are discussed, where appropriate.

The question whether the legal principles that are currently in place in existing legislation will apply to the storage of CO_2 is also untested water in the courts. Comparative jurisprudence concerning the storage of other materials in the seabed provides some clues as to the direction the courts might be willing to take but this is not certain. There has also been very little sustained legal analysis in academic books and journals on geological carbon dioxide storage. Much of the published legal analysis is also only partly relevant, because it has primarily focused on the legal issues associated with the storage of CO_2 directly in the oceans, which no longer seems to be a well backed mainstream mitigation option. Research conducted by the author early on in this project revealed a dearth of in-depth research studies on geological carbon dioxide storage, combining international, European and national legal dimensions, in the United Kingdom, and other European and developed countries (Purdy and Macrory, 2004).

The importance of a systematic analysis of the legal dimension of the long term sub-strata storage of CO_2 is increasingly being recognized in the United Kingdom (UK), as has some of the uncertainties and complexities involved. A report by the Royal Commission on Environmental Pollution[1] (RCEP) in 2000 (RCEP, 2000) concluded that it was 'open to interpretation whether disposal of carbon dioxide into the ocean or under the seabed would be permissible under current international law' (RCEP, 2000). The UK Government started to consider the legal implications of CCS after the Royal Commission's report. In 2001 a Department of Trade and Industry (DTI) report acknowledged the uncertainties of the current legal status of sub-seabed storage, concluding that 'there is a strong case for assessing in a systematic way the legal, scientific, engineering and economic aspects of both EOR [enhanced oil recovery] and geological CO_2 capture and storage. Such an assessment needs to precede any further analysis of the policy case for support for steps to use CO_2 in this way' (DTI, 2001). The Cabinet Office's Performance and Innovation Unit's energy review in 2002 also recognized these legal uncertainties and supported the recommendations of the DTI in stressing the need for a more detailed assessment (Cabinet Office, 2002).

In early 2002, the UK Government concluded that it was premature to finance a carbon capture demonstration project because, amongst other things, the uncertainty over the legal status of disposal in sub-seabed strata. The DTI, however, continued to examine the feasibility of carbon dioxide capture and storage in the UK. The legal services section in the Department of the Environment Food and Rural Affairs (DEFRA) produced a short report in August 2002 for the Sustainable Energy Policy Unit of the DTI, advising them on the main legal issues arising from CO_2 storage (DEFRA, 2002). Towards the end of the year the DTI organized a CO_2 capture and storage stakeholder meeting in London. A conclusion of this meeting was that one of the main economic and commercial barriers to capturing and storing CO_2 was its legality; one of the recommended steps was for the Government to determine the legality of CCS. Delegates pointed out that there appeared to be a lack of framework and disagreement between the international laws as to whether geological dioxide storage could take place. Most recently, the UK Government concluded in its formal response to the RCEP that any disposal of carbon dioxide into submarine strata would also depend on the resolution of legal issues under the international marine conventions, such as the London and OSPAR Conventions (UK Government, 2003).

A reading of the UK Government response to the Royal Commission report suggests that they appear to have adopted a wait and see approach until the legal issues are resolved at international level (UK Government, 2003). However, it is clear that in practice the UK Government has been particularly active in promoting international discussion as to the legal issues surrounding CO_2 capture and storage, and the possible need for changes to legislation. The UK Government

[1] The Royal Commission on Environmental Pollution is an independent standing body established in the United Kingdom in 1970 to advise the Queen, the Government, Parliament and the public on environmental issues

organized a seminar on CO_2 storage in London for OSPAR Contracting Parties in October 2003 and is coordinating the current legal review for the Contracting Parties to the London Convention (IMO, 2005).

Similarly, at an international level there has been increasing interest and discussion in the last few years as to whether the storage of CO_2 in the seabed is consistent with international law. It should be noted that CO_2 storage is not a new concept and some actors in the international community anticipated it becoming a potentially thorny legal issue for many years. CO_2 storage in the seas was first brought to the attention of the London Convention at the fifteenth meeting of its Scientific Group as far back as 1992. In 1997 GESAMP[2] conducted a study that noted that 'dumping from vessels and platforms of both liquid and solid CO_2 is prohibited by the LC (London Convention) and the 1996 Protocol and unless these instruments can be amended to permit such dumping, it seems unlikely that any of the current parties could give approval to such a practice' (GESAMP, 1997). This conclusion was significant because GESAMP comprises some of its members from the London Convention Secretariat and several delegates from London Convention Contracting Parties.

The next most significant review into the legal issues raised by CO_2 storage then took place during 1999, when the Scientific Group to the London Convention examined whether CO_2 fell within the definition of industrial waste (IMO, 1999). They concluded at their twenty-second meeting that fossil fuel derived CO_2 was an industrial waste, and that delegations at the twenty first consultative meeting should be consulted concerning the priority to be accorded to consideration of these issues. The consultative meeting were presented with the Scientific Groups report and a further report on Ocean Storage of CO_2 put together by the International Energy Agency (Brubaker and Christiansen, 2001). The conclusion of the Consultative Parties at the twenty-first meeting was that the Scientific Group should continue to keep a watching brief on the relevant research being carried out and that they would consider the legal, political and institutional dimensions of a potential proposal to amend the London Convention or the 1996 Protocol at a later stage (IMO, 2000).

The initiative to examine the legal implications of CO_2 storage was again lost for a number of years, before Norwegian CO_2 trials in the North Sea brought it back into the political spotlight[3]. These trials fell under the direct geographical remit of the OSPAR Convention, a regional marine environmental protection law. In June 2002, the Secretariat of the OSPAR Commission, who manages the OSPAR Convention, asked its legal experts in the Group of Jurists and Linguists to provide advice on the compatibility with the Convention of possible placements of carbon dioxide in the sea and the seabed. In a press release the OSPAR Commission agreed that it was desirable to establish as soon as possible an agreed position on whether such placing of CO_2 in the sea or the seabed was consistent with the OSPAR Convention (OSPAR Commission, 2002). The OSPAR Commissions Group of Jurists and Linguists completed a preliminary legal paper in May 2003 (OSPAR Group of Jurists and Linguists, 2003), and this was discussed at the meeting of the parties to the OSPAR Convention in Bremen in June 2003 (OSPAR Commission, 2003). The Group of Jurists and Linguists final report was accepted by the OSPAR Contracting Parties in May 2004 and was published shortly afterwards (OSPAR Commission, 2004). The Group of Jurists and Linguists main conclusion was that compatibility with the Convention depended on the method by which the carbon dioxide was placed in the maritime environment. They decided that further consideration was needed on the interrelations between the current legal position, the possible physical impacts of the placement of CO_2 on the marine environment, and the appropriate regulatory approach. The current legal framework does not appear to have been the subject of any further discussion by

[2] GESAMP is an advisory body consisting of specialized experts nominated by the Sponsoring Agencies (IMO, FAO, UNESCO-IOC, WMO, WHO, IAEA, UN, UNEP)

[3] The Norwegian Institute for Water Research wanted to release 5.4 tonnes of CO_2 into the sea off the coast of Norway at a depth of 800 metres.

OSPAR Contracting Parties since the Group of Jurists and Linguists report was agreed, although the OSPAR Commission organized a workshop in October 2004 looking at the environmental impact of CO_2 placement in the marine environment and the technical options for placement.

Early legal interest in carbon dioxide storage was dominated by bodies associated with marine environmental protection. Since then other international actors in the fields of energy and climate change have also been increasingly drawn into the debate. The International Energy Agency (IEA)[4] developed an interest in CO_2 placement and held a workshop in July 2004 looking specifically at the legal issues surrounding CO_2 storage, in both international law, and some national laws. In 2005 they published an extensive report examining the legal issues of CO_2 storage, which concluded that existing national and international regulations were not fitted to large-scale experiments in CO_2, and that urgent legislative work was needed to keep pace with technical progress (IEA, 2005). The IEA noted that in their opinion 'the contracting parties to these [marine] agreements need to interpret, clarify or, as the case may be, amend these treaties with a view to accounting for some form of controlled carbon dioxide storage. There is significant room for such interpretation and clarification under these treaties' (IEA, 2005).

The Intergovernmental Panel on Climate Change[5] (IPCC) published a report on CO_2 capture and storage in September 2005 (IPCC, 2005). The IPCC report considered many variables concerning carbon capture and storage (CCS), including new and emerging technologies, transportation, costs and market potential, inventories and accounting and risks. The report concluded that the 'actual use of CCS is likely to be lower than the estimates for economic potential indicated because of barriers including perceived environmental impacts, risks of leakage, lack of a clear legal framework and public acceptance' (IPCC, 2005). The report, which only included a limited analysis of the legal framework, arrived at the same conclusion as the International Energy Agency, that 'generally, it is unclear whether cases of offshore CO_2 injection into the geological sub-seabed or the ocean are compatible with international law' (IPCC, 2005).

In late 2004 the Contracting Parties to the London Convention revived their interest in the issue of CO_2 placement. They agreed at their 26th Consultative Meeting that this issue should be formally included in their work programme, and that they would initially focus on storage of CO_2 in geological structures in the marine environment (IMO, 2004). A correspondence group was established under the lead of the United Kingdom to consider the legal issues associated with CO_2 placement in geological structures under the London Convention and Protocol. The United Kingdom was charged with preparing and communicating a list of legal questions, which were delivered to the Contracting Parties in March 2005 (IMO, 2005). The United Kingdom Government have prepared a consolidated paper on the legal views of Contracting Parties for submission to the 27th Consultative Meeting in October 2005. This document, which is not yet in the public domain, will be discussed by the Contracting Parties at this meeting, who will then decide on what further work is needed to establish a consensus.

Although there has been increasing discussion in the international community on CO_2 storage offshore, there is, however, probably no international consensus on the interpretation of key provisions in these marine conventions at present. Some of the reviews that have already taken place have reached similar conclusions as to the existing legal position. However, many of the bodies undertaking reviews have their own agendas, ranging from environmental protection to economic growth. The International Energy Agency and the Intergovernmental Panel on Climate Change, for example, are concerned with energy and climate change frameworks respectively, rather than marine environmental protection - where existing legislation creates potentially serious impediments to some CO_2 storage projects taking place.

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[4] The International Energy Agency acts as an energy policy advisor for its developing country members.

[5] The Intergovernmental Panel on Climate Change was established by the WMO and UNEP to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation.

Whilst it is convenient to blame any existing legal uncertainties on the current drafting of marine conventions and call for these to be revised, this might be considered to be something of a distraction. In many ways the current marine conventions are drafted reasonably clearly. Any CO_2 projects that can take place at the current time, are arguably only because of loopholes in the marine legislation, as CO_2 storage was not envisaged at the time that these laws were adopted. The current marine legislation therefore only needs amending if there is a need (e.g. states want to go ahead or restrict such projects) and there is political will to amend legislation. One might argue that the existing legal framework concerning climate change is actually less clear in relation to geological CO_2 storage in marine waters. If the climate change legal regime, expressly allows and creates binding rules concerning geological CO_2 storage in marine waters to be classed as an emission reduction then there could be a potential need to change other legislation. Additionally, if a consensus of international states sees CO_2 storage in geological formations in marine waters as more important than greenhouse gases entering the atmosphere, then this provides the political will to amend the marine legislation. If the climate change regime restricts, or alternatively is ambiguous as to whether geological CO_2 storage in marine waters does count as an emission reduction, then there is arguably less incentive and need to amend the marine conventions. This chapter will therefore consider all of the major legislation affecting CO_2 storage, because their objectives and how they operate together are, in practice, extremely important. Although the importance of the law cannot be understated, it should also be considered alongside the objectives and political will of countries, as laws can be amended to reflect the changing objectives of the European and international community.

5.2 Applicable International and European Laws

5.2.1 International Laws

There are a number of international laws that could be relevant to geological CO_2 storage. International conventions normally become operational in two stages. The first stage is when a certain number of countries sign the convention, signalling their intention to become parties to it. The United Kingdom is a signatory to all of the international laws discussed below. The second stage in becoming legally operational is when a sufficient number of states have acceded to the convention and it becomes international law. There are a couple of international laws covered in this chapter that have not yet entered into force because not enough states have acceded to them. Details of the legal status of each international convention are summarized in Table 5.1.

Four of the international laws contained in Table 5.1 are marine conventions. In practice these marine conventions operate together, not separately, in strengthening environmental protection. The most important convention concerning marine waters is the United Nations Convention on the Law of the Sea (UNCLOS). This Conventions aim is to regulate all uses of the sea and it establishes basic legal rules for all aspects of the use and protection of the sea, including shipping, scientific research, exploration of natural resources, disaster prevention, avoidance of pollution and protection of the marine environment. The Convention is constructed in a framework nature, leaving the elaboration of precise rules to other bodies, such as national Governments and international Organizations. All the states which are Contracting Parties in UNCLOS are obliged to issue laws and to take other measures to regulate pollution by dumping, and they must not be less effective than the ‘global rules and standards’[6]. It is generally accepted that these ‘global rules and standards’, in relation to marine pollution, are found in the rules and standards of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention) and its 1996 Protocol. At the current time the London Convention (and then the

[6] United Nations Convention on the Law of the Sea, Article 210.

Protocol when it enters into force) is the most significant global convention to protect the marine environment and conserve its species and ecosystems. States which have ratified both UNCLOS and these conventions are obliged to uphold the laws and regulations in accordance with UNCLOS.

Table 5.1: International laws relevant to geological CO_2 storage in marine waters

Convention	Purpose	In force
United Nations Convention on the Law of the Sea (1982)	Marine - Regulates Uses of the Sea	Yes
London Convention (1972)	Marine Environmental Protection	Yes
OSPAR Convention (1992)	Marine Environmental Protection	Yes
Protocol to the London Convention (1996)	Marine Environmental Protection	No
Framework Convention on Climate Change (1992)	Climate Change	Yes
Kyoto Protocol to the Climate Change Convention (1997)	Climate Change	Yes
ESPOO Convention (1991)	Environmental Assessment	Yes
Kiev Strategic Environmental Assessment (SEA) Protocol (2003)	Environmental Assessment	No
Convention on Biological Diversity (1992)	Habitat Protection	Yes

In order to enhance protection of the marine environment, parties to both the London Convention and the 1996 Protocol are encouraged to create regional agreements which further their objectives[7]. The regional agreements can provide a greater degree of environmental protection in the regions that they cover but they must endeavour to be consistent with the Convention and Protocol. For the purposes of this chapter, the OSPAR Convention is a relevant regional agreement, because the United Kingdom falls within its geographical coverage and is a signatory. Whilst the OSPAR Convention is similar to the Protocol and London Convention, it is stricter in scope as it is more modern and takes into account other sources of pollution.

As noted above, the United Nations Convention on the Law of the Sea encourages the adoption of further international legislation on marine pollution, which was created through the London Convention and Protocol, which in turn anticipates the creation of regional agreements. This means that in practice, each convention envisages compliance with the other more specific or regional convention, and indeed, encourages it. In practice, the conventions contain provisions making sure the objectives and provisions of their convention are followed and establish procedures for co-operation between them in order to develop harmonized procedures to be followed by Contracting Parties to the different conventions concerned[8]. This means that every effort is made to make the provisions of prior treaties consistent with the provisions of more recent treaties.

In general, states are only bound to conventions to which they ratify or accede. As the UK is a party to all of the conventions mentioned above, it is obliged to follow the laws of them all. In

[7] London Convention Article VIII; 1996 Protocol, Article 12.
[8] E.g. London Convention, Article VIII.

practice it is obvious that if there is overlapping conventions, then it is possible that one will contain more stringent provisions than another. If consistent reading is not possible between two conventions and neither contains a provision expressly stating which will prevail, the legal position under international law is that the provision of the most recent treaty controls over an older treaty, and a specific treaty controls over a general treaty. In the context of this chapter, in such cases of inconsistency, the Convention, 1996 Protocol, and OSPAR regimes should be viewed as being distinct, although, in order to adhere to international obligations, a state would need to apply the standard of the most specific and stringent treaty. As the OSPAR Convention often goes further than the London Convention and Protocol, Contracting Parties to all of these marine conventions will most likely be obliged to take OSPAR as setting the standard in such cases. The UK Government's view seems to be that if there were conflicting provisions then they would follow OSPAR over the other conventions (DEFRA, 2002). Where there is inconsistency between the London Convention and the 1996 Protocol, the UK Government consider that the latter will prevail in terms of the obligations they impose, but this would not mean that there would not be a breach of OSPAR obligations (DEFRA, 2002).

The position, in relation to a conflict between the marine conventions and the international laws concerning climate change, namely the United Nations Framework Convention on Climate Change and Kyoto Protocol, is not so clear. It is not known whether there was some discussion in the drafting of the latter conventions over the impact that CO_2 storage could have with the compatibility with other international obligations under the marine conventions. If one follows the rule that a specific treaty controls over a general treaty, it seems that marine conventions are the more specific laws relevant to controlling CO_2 storage under marine waters. In the absence of any reference in these conventions to one another, the guidance contained in the Vienna Convention on the Law of Treaties will also have to be considered[9].

5.2.2 Applicable European Laws

There are also a number of European laws that could be relevant to geological carbon storage below marine waters. The United Kingdom is a member of the European Community (EC) and must adhere to the laws of the Community. Most European environmental legislation is in the form of Directives, which are addressed to Member States and require implementation into national law. If the European law is not implemented fully or applied correctly the European Commission can take enforcement action against the Member State. In addition, national courts are obliged to as far as possible to interpret national law consistently with EC Directives, and where public authorities are involved, precise and certain provisions of Directives may in certain circumstances still be legally binding on those authorities even where national legislation has not yet been implemented. Details of the purpose and legal status of the relevant directives are summarized in Table 5.2.

The three European Community Directives which seem most relevant to carbon dioxide storage projects, and which are examined in this chapter, include: the Environmental Impact Assessment (EIA) Directive, the Strategic Environmental Assessment (SEA) Directive and the Habitats Directive. An important consideration is whether these Directives have legal application in marine waters. It seems that the European Community Treaty itself does not explicitly deal with the territorial application of treaty rules, it simply states that it shall apply to the United Kingdom of Great Britain and Northern Ireland[10]. It is generally agreed that this implies that the Treaty can extend to areas within the jurisdiction of Member States. Although Community law can be applied outside the land and territorial waters of Member States, and this has indeed been the practice in

[9] See Article 30 on the application on of successive treaties relating to the same subject matter.
[10] European Community Treaty.

many areas of Community law, not all Community legislation has such a widened territorial scope. Each Community law has to be examined individually.

Table 5.2: European legislation relevant to geological CO_2 storage in marine waters

Directive	Purpose	Date coming into force
Habitats Directive	Habitat Protection	June 1994
Environmental Impact Assessment Directive	Environmental Assessment	March 1999 (in its amended form)
Strategic Environmental Assessment (SEA) Directive	Environmental Assessment	July 2004

It is clear that the EIA Directive extends to certain marine waters because the UK Government has implemented regulations applying the Directive to offshore installations. The Department of Trade and Industry has also carried out an SEA in the UK's continental shelf. The UK Government has also conceded the point in relation to the Habitats Directive, after a judicial review case brought by Greenpeace challenging the nineteenth licensing rounds for offshore exploration and drilling initiated by the Secretary of State in 1997[11]. The UK Government tried to claim that by its very nature the Habitats Directive was restricted to land and the territorial waters of European Community Member States. The High Court held in 1999 that the UK Government was wrong in its view that the Habitats Directive did not extend beyond the UK's twelve mile territorial limit and accepted Greenpeace's argument that the Habitats Directive applies to the continental shelf and the two hundred mile fishing limit. Therefore it is highly likely that CO_2 projects taking place in the territorial waters or continental shelf of the UK will be subject to the legal conditions and principles laid out in the Environmental Impact Assessment Directive, Strategic Environmental Assessment Directive, and the Habitats Directive. These European Directives will not apply to projects taking place in the high seas.

As European Community (EC) environmental law is drafted by the same body there are usually no concerns with Directives being in conflict with one another. With Directives dealing with a similar subject area there is usually a provision referring to the other Directive and how it should be considered[12].Whilst there are unlikely to be conflicts between European laws, there are questions of competency between EC laws and international laws. Most international environmental agreements are for the purposes of EC law, mixed agreements, in that both the EC and Member States have the power to ratify. The scope of their respective competences is determined in part by Treaty provisions and in part by the extent to which Community measures have been made covering particular areas. The precise boundaries though are often unclear, especially when international agreements are ratified, and within the EC this is ultimately a matter for the European Court. In a number of areas the European Court of Justice has been called to rule on the question of competence, and in the past has generally favoured a Community approach at the expense of Member States in order to preserve the unity of the Community legal order.

The United Nations Convention on the Law of the Sea Convention (UNCLOS) is an example of a mixed agreement. In 2003 there was an illustration of how questions of competence could be raised in an international dispute between Ireland and the United Kingdom (UK), in relation to

[11] R v Secretary of State ex parte Greenpeace, Queens Bench Division, 5 November 1999, CO/1336/99.

[12] E.g. in the Environmental Impact Assessment Amendment Directive 1999, there is a provision in Schedule 3 (2) (v) concerning habitats.

radioactive discharges from the Sellafield nuclear engineering centre into the Irish Sea[13]. Only five days before the hearing in this dispute before the Arbitral Tribunal established under UNCLOS, the European Commission had given a written answer to the European Parliament indicating that it was examining the question of whether to commence proceedings before the European Court of Justice against Ireland to prevent it taking unilateral action before the Law of the Sea Tribunal, on the grounds that under Community law it no longer had the competence to do so. Neither Ireland nor the UK argued that all the provisions of UNCLOS fell within the exclusive competence of the European Court, but the Tribunal accepted that it could not be certain that the European Court of Justice would not adopt such a view. The Tribunal considered that some provisions of UNCLOS could be exclusive to the European Community (EC), but not all of them. As it was not clear at this stage of the hearing who had competence in this case, the Tribunal suspended the proceedings for six months until the matter was resolved at EC level. In doing so it recognized the need to avoid conflicts between different international judicial bodies.

As with the UNCLOS, the European Community (EC) is also a party to the OSPAR Convention. Ireland also bought a case in 2003 before the Arbitration Tribunal established under the OSPAR Convention, concerning access to information about the MOX reprocessing plant at Sellafield[14]. In contrast to the parallel Irish action before the Law of the Sea Tribunal, the Commission does not appear to have raised concerns about Ireland's competence to take unilateral action under OSPAR, nor did the Tribunal appear so concerned about possible conflict between these two regimes. For now, the substantive legal issues concerning the dispute have shifted to the EC stage. If proceedings are brought by the Commission before the European Court of Justice, the Court may decide to use the opportunity to give a significant and broad ruling on the complex constitutional issues involved in the relationship of the Community and the Member States concerning the marine environment.

5.3 CO_2 Storage and Marine Legislation

5.3.1 UNCLOS

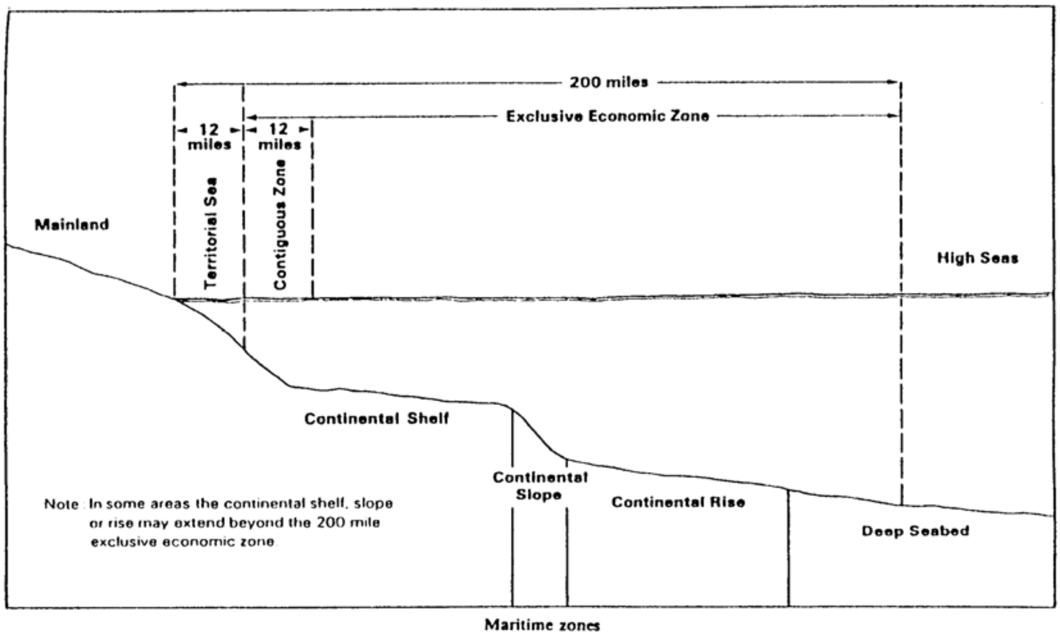
Background and Objectives of UNCLOS. The most significant international marine convention is the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which came into force in 1994. The United Kingdom acceded to the Convention and became a Contracting Party in 1997. The aim of the Convention is to regulate all uses of the sea so it contains provisions governing all aspects of ocean space, such as delimitation, environmental control, marine scientific research, economic and commercial activities, transfer of technology, and the settlement of disputes relating to ocean matters. UNCLOS is therefore considerable in length and comprises 320 articles and nine annexes. Although the text of the Convention is extremely large it provides little in the way of substantive regulations itself and contains few detailed rules of substance. The Convention is more of a framework document, leaving any precise rules to be elaborated further in other more specific international conventions.

Zones of the Sea. From a legal perspective, different locations of the ocean are subject to different prescriptions under the UNCLOS. This is important in relation to the location storage sites of CO_2, because there are different rights and duties for each zone. The zones divided by UNCLOS are repeated and adhered to in all other international marine laws, such as the London Convention and 1996 Protocol. Nations have the greatest amount of coastal jurisdiction and control over the waters closest to shore with increasing responsibility to accommodate uses by other nationals as the

[13] Ireland v United Kingdom. The Mox Plant Case. Law of the Sea Arbitral Tribunal Order no.3, 24 June 2003.

[14] Ireland v United Kingdom. Dispute concerning access to information under Article 9 of the OSPAR Convention, Final Award, Permanent Court of Arbitration, The Hague, 2 July 2003.

distance from shore increases. The primary zones in increasing distance from shore are the internal waters, the territorial sea, the exclusive economic zone, the continental shelf and the high seas. These can be seen in Figure 5.1 below.



Source: Churchill, 1996.

Figure 5.1: The Zones of the Sea

It is important to consider the implications of each of these different zones in the sea, as this could prove crucial in selecting CO_2 disposal sites. Whilst the United Kingdom has full sovereignty over its territorial sea, its rights over the waters beyond this boundary are more limited, and the role that other states could have in objecting to such projects varies significantly.

The territorial sea is the region of ocean that extends up to a rough limit about twelve miles from the coastline. The territorial sea of the United Kingdom as prescribed by UNCLOS is implemented by the Territorial Sea Act 1987, and the baselines are contained in the Territorial Waters Order in Council 1964[15]. Within this zone, coastal state sovereignty over activities is limited only by the freedom of navigation[16]. In relation to CO_2 storage, it seems that the territorial sea could be of limited relevance. In the unlikely event that suitable disposal sites were available in the 12 mile territorial sea of a state then this would only require the consent of that state. The same applies if a pipeline is to be placed across the territorial waters.

The exclusive economic zone (EEZ) extends from the end of the territorial sea out to a maximum of two-hundred nautical miles from the baselines of the coast. Within this zone the coastal state has sovereign rights of exploration, exploitation and management of the natural resources of the EEZ in both the seabed and waters above it[17]. It is possible that a state could claim that their right to exploit the EEZ extends to exploiting the empty spaces in the geological formations for storage purposes. It is regarded as more likely that the CO_2 is considered to be dumped. Dumping can be carried out in the EEZ by a coastal state as long as they have due regard to the rights and duties of other states, they respect their obligations under other international

[15] Territorial Waters Order in Council 1964, SI 1965, Part III, p 6452A.
[16] United Nations Convention on the Law of the Sea, Article 2(3).
[17] Ibid, Articles 55–57.

marine pollution legislation, and they are placed under a duty not to cause damage by pollution to the territory of other states or areas beyond national jurisdiction[18]. Dumping and the construction of platforms or pipelines by other states cannot be undertaken in a coastal state's EEZ without the approval of the coastal state, who can permit it if they wish[19]. Coastal states have the power to regulate pollution arising from or in connection with seabed activities[20].

If CO_2 is planned to be dumped/stored then the coastal state has the option to approve or prohibit the activity, after consideration of the relevant provisions of related international and national legislation. A coastal state also has jurisdiction to authorize pipelines within their exclusive economic zone (EEZ). If a nearby coastal state complained that any storage project affected their rights or caused damage in some form then presumably the burden of proof of proving this would be on them. The jurisdiction of a coastal state also extends to controlling research and development in their EEZ, so trials of CO_2 could in theory take place. Under UNCLOS, research and development projects can also take place which may introduce harmful substances into the marine environment[21]. An EEZ can be claimed by a coastal state around its territory, if they want to exercise their rights to explore and exploit natural resources in the two-hundred mile radius from their coastline. Jurisdiction over the EEZ can only be claimed in so much as international law is acceptable and before a state can exercise EEZ rights conferred by UNCLOS, there has to be legislation at national level which vests such rights with an authority competent to exercise them. States are not under any obligation to claim an EEZ, but if a coastal state does not claim jurisdiction to the extent international law provides for, jurisdiction remains limited. The United Kingdom has not declared an EEZ, choosing only to register an established Exclusive Fisheries Zone in which it exercises EEZ fisheries rights only.

The continental shelf extends from the natural prolongation of the land territory to the outer edge of the continental margin or a minimum distance of two-hundred nautical miles from the territorial sea baselines, subject to a maximum of three-hundred and fifty miles from the baselines or one hundred miles beyond the two-thousand and five-hundred metre isobath[22]. Within two-hundred miles of the coast the continental shelf and an exclusive economic zone (EEZ) can overlap. Coastal states have sovereign rights to explore and exploit the natural resources of the seabed and subsoil of the continental shelf[23]. Their control over an area is limited to the regulation of interference with minerals and other non-living resources, and sedentary species of living organisms only. The Law of the Sea Convention (UNCLOS) also confers jurisdiction over dumping on the continental shelf, whereby the coastal state has the same rights and obligations to control dumping of matter such as CO_2 onto the continental shelf, as it has in the EEZ[24].

In practice, the continental shelf of some states can be co-existent with an EEZ, which provides much wider jurisdiction, but the concept of the continental shelf remains significant where no EEZ has been declared or the continental shelf extends beyond such a zone. The continental shelf can extend beyond two-hundred miles, as it does in the United Kingdom (UK), so the UK has not declared an EEZ, and instead has relied on its continental shelf rights under the Geneva Convention on the Continental Shelf 1958, not UNCLOS. The continental shelf was defined in the Geneva Convention on the Continental Shelf 1958 as 'the seabed and subsoil of the submarine areas adjacent to the coast but outside the territorial sea to a depth of two-hundred metres or, beyond that limit, to where the depth of the super adjacent waters admits of the exploitation of their natural

[18] Ibid, Article 194(2).
[19] Ibid, Article, 210(5).
[20] Ibid, Article 194(3).
[21] Ibid, Articles 56 & 246.
[22] Ibid, Article 76 (note – this is subject to a maximum of 350 miles from the baselines or 100 miles beyond the 2,500 metre isobath).
[23] Ibid, Articles 76 and 77.
[24] Ibid, Articles 210 – 216.

resources'[25]. The UK has implemented this Convention through the Continental Shelf Act 1964 and other secondary legislation[26]. This provides the legal basis in international law for the UK to prospect for and to extract oil and gas from the continental shelf. The reference to the seabed and subsoil and their natural resources could be construed to cover things such as CO_2 storage. The UK's rights to explore and exploit the Continental Shelf are vested in the Crown Estate (the Queen). The Crown Estate can grant leases or licences as appropriate to permit such activities. In the case of oil and gas, the power to licence exploration and extraction on the Continental Shelf, is vested in the Secretary of State for Trade and Industry. Development consents and regulatory control of marine activities are matters for the appropriate Government Department.

The waters beyond the 200 mile limit of the EEZ are known as the high seas. The high seas are open to all states, but fall under what is known as 'the common heritage of mankind'. The body empowered to administer the common heritage of mankind and to regulate its exploration and exploitation is the International Seabed Authority[27]. All states enjoy the freedom to act within this zone but are required to give due regard to the interests of other states[28] and also due regard to the rights under UNCLOS with respect to activities in the international seabed area[29]. No specific requirements over duties to protect the marine environment exist within the articles that specifically address the high seas and a separate part of UNCLOS is concerned with protecting the marine environment. CO_2 projects will not be prohibited in the high seas under international law, although states where the CO_2 has originated from and who are storing it must have due regard for any states whose interests would be affected,[30] and observe any legal obligations under international marine laws. The due regard obligation may well impose restrictions on the storage of CO_2 in the high seas (Churchill, 1996). Other states may complain that the CO_2 storage affects their interests, for activities like fishing, and may require international arbitration. It may be that access to storage sites in the high seas would prove too costly to transport the CO_2 and build new platforms anyway. It is clear it would also generate a significant amount of international opposition and would not be a particularly politically sensitive decision.

Protection of the Marine Environment. Although the text of UNCLOS is often framed in general terms there are a number of relevant provisions that control activities impacting marine environments. Article 192 of UNCLOS imposes a general obligation on states to protect and preserve the marine environment in all of the territorial zones of the seas. Article 194 requires states to take individually or jointly all measures necessary to prevent, reduce, or control pollution using the best practicable means at their disposal and in accordance with their capabilities. This duty increases under this article where the activity threatens to damage the territory of another state, whereby states must take all measures necessary to ensure that the activity does not cause damage to other states. Article 194 states the measures taken pursuant to this part shall deal with all sources of pollution of the marine environment, including dumping. UNCLOS defines dumping to be 'any deliberate disposal of sea of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea', but does not include 'placement of matter for a purpose other than mere disposal'[31]. If CO_2 is transported by ship or by a pipeline to a disposal site and then injected from a platform or a ship then it might be considered to be dumping under the purposes of the Convention.

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[25] Geneva Convention on the Continental Shelf 1958, Article 1.

[26] Section 1(1) of the Continental Shelf Act 1964 states that 'any rights exercisable by the United Kingdom outside territorial waters with respect to the sea bed and subsoil and their natural resources, except so far as they are exercisable in relation to coal, are hereby vested in Her Majesty'.

[27] The International Seabed Authority is an autonomous international organization established under UNCLOS.

[28] United Nations Convention on the Law of the Sea, Article 86.

[29] Ibid, Article 87(2).

[30] Ibid, Article 86.

[31] Ibid, Article 1(5) (a+b).

The definition of dumping in UNCLOS is the same as that in both the London Convention and the 1996 Protocol and this will be considered in more detail below.

In effect, UNCLOS sees the open sea as open-access commons, where any use can be regulated, unless it causes harm to other states or is prohibited by international law. UNCLOS does not specifically prohibit or even refer to the legality of CO_2 storage offshore, but it seems the provisions in Article 194 will apply if the proposed activity is determined to be pollution. Pollution is defined as 'the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities'[32]. It is not clear from this definition whether CO_2 is pollution. Some commentators have argued that it probably is not a pollutant, although if large quantities of CO_2 are stored then this could cause pollution if it resulted in harm to living marine resources (McCullagh, 1996). It should be noted that UNCLOS makes no explicit reference to the precautionary principle in determining whether some activity might cause harm to others.

As UNCLOS is very broad based, it obliges other international Organizations and states to introduce more specific laws, or as it call it 'global rules and standards'[33]. In the case of marine pollution and dumping these are widely accepted to be contained in the London Convention and its 1996 Protocol. Contracting Parties to both UNCLOS and the London Convention should follow the requirements under the London Convention first, as it is the more stringent treaty, and they will in practice not refer to the general requirements imposed by UNCLOS.

5.3.2 The London Convention and the 1996 Protocol

Background and Objectives. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (known more commonly as the London Convention) was the first truly global convention to control and regulate the deliberate disposal at sea of wastes and other material in the seas. In the 1990s there was recognition that a more modern approach to waste management at sea was needed, to enhance the level of environmental protection. The Contracting Parties to the 1972 London Convention adopted a Protocol in 1996 to revise the London Convention. This 1996 Protocol (hereafter the Protocol) is in fact an entirely new Convention, modifying and adding to virtually every aspect of the London Convention. The Protocol has not yet entered into force, but when it does it will supersede the London Convention, for those parties to the Convention which have subsequently become parties to the Protocol[34]. The requirements under the London Convention and Protocol are of global application to all signatories. The provisions contained in the Convention and Protocol are not always the same and will be dealt with separately where appropriate.

The London Convention controls ship and platform based dumping activities. The principle objective of the London Convention is to prevent, reduce and where practicable, eliminate pollution caused by disposal or incineration at sea. It does not define pollution, but recognizes that dumping is one of the many sources of marine pollution and seeks to control pollution by controlling dumping of wastes and other matter that is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the sea. Therefore, on a basic level if CO_2 injection and storage into geological formations under the sea could cause pollution then it could be prohibited. The Protocol embodies a more simplified, modern and comprehensive regulatory framework than the London Convention, and is intended to provide greater protection to the marine environment. It is based far more on precaution and prevention.

[32] Ibid, Article 1(4).
[33] Ibid, Article 210.
[34] 1996 Protocol, Article 23.

Instead of regulating dumping like the Convention its objective is to prevent, reduce and where practicable eliminate pollution. Unlike the Convention it does define pollution - as meaning the 'introduction, directly or indirectly, by human activity, of wastes or other matter into the sea which results or is likely to result in such deleterious effects as harm to living resources and marine ecosystems, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities'[35].

The UK is a Contracting Party to the London Convention 1972 and is bound by its provisions. The 1996 Protocol is not yet in force as not enough states have ratified it. This delay in implementation is not unusual in international law, where conventions can take many years to receive ratification by the required number of countries before they come into force. The UK ratified the Protocol in December 1998. The Department of Environment Food and Rural Affairs comment on their website that they consider that the Protocol is unlikely to come into force for several years. As the Protocol is not yet in force the London Convention continues to apply. The UK Government have commented that it is current UK policy to apply the requirements under the Protocol where possible (DEFRA, 2002), but they are under no legal obligation to apply the latter Protocol, though under general principles of international law they are, as a signatory party, obliged not to frustrate its objectives.

Geographical Coverage and Application to the Seabed. The London Convention and Protocol applies to all marine waters world-wide other than the internal waters of states[36]. The London Convention does not refer to the seabed anywhere in its text and only concerns dumping in the 'sea', which is defined as meaning 'all marine waters other than the internal waters of states'[37]. This would probably not be enough cover the storage of CO_2 in the seabed or subsoil of the seabed. The only way that the seabed can be included in the Conventions remit is if a purposive approach is adopted when interpreting this provision, so that it could be argued that the purpose of the Convention was not just to protect the sea but also activities in the seabed that have the potential to harm the sea as well. The Protocol goes further in its scope than the Convention and applies to the 'sea, seabed and subsoil'[38]. However, it expressly excludes 'sub-seabed repositories accessed only from land'[39]. This inclusion of 'seabed and subsoil' would appear at first sight to cover the storage of CO_2 in geological formations. The International Energy Agency commented that the 'Protocol will therefore prohibit without distinction the storage of CO_2 both in the water column and in sub-seabed repositories' (IEA, 2005). It could be that the Protocol possibly prohibits the storage of CO_2 in geological formations, but this is dependant on what exactly subsoil is legally interpreted as meaning. For example, it is arguable that the 'subsoil' could just be the layer of rock and soil immediately under the seabed, not the geological formations underneath.

The UK Government have commented on this point and concluded that the Protocol, has been drafted with the purpose of covering activities in areas below the sea column and that the Convention should be interpreted in that light (DEFRA, 2002). They considered that if there was a possibility that the storage of CO_2 in sub-seabed reservoirs could result in pollution to that environment, with an effect on such life or ecosystems, which is possible through leakage, the Protocol should be interpreted in such a way as to give effect to this wider purpose, that is protection of the marine environment from pollution[40], including the prevention of pollution liable

[35] Ibid, Article 1(5)(10).

[36] London Convention, Article III (3); 1996 Protocol, Article 1(7). Note - the term 'internal waters' carries a specific meaning in international parlance and does not include certain bays, estuaries, navigable rivers and other inland waters as defined by international law.

[37] Ibid, Article III (3).

[38] 1996 Protocol, Article 1 (5) (7).

[39] Ibid.

[40] London Convention, Article 1, 1996 Protocol, Article 2.

to harm living resources and marine life[41]. The UK Government's position is that their express policy of adhering to the more stringent requirements of the Protocol, and that the limitation of the London Convention in this area should not be taken as denying its application to sub-seabed CO_2 storage; rather it should be read in the light of the current standards set by the Protocol (DEFRA, 2002). However, there is no obligation in international law to interpret conventions in light of current developments[42], i.e. in this case, before the Protocol enters into force.

Legality of CO_2 Storage. There are several important considerations in determining the legality of CO_2 storage under the London Convention and 1996 Protocol. The first legal question to consider is how the CO_2 gets into the storage site. The operational framework for the London Convention is based on controlling the input of substances into the sea. It provides a framework for general considerations which determine the acceptability of dumping in the sea. The Protocol only allows approved wastes to be dumped. The Convention and the Protocol both define dumping to be 'any deliberate disposal of sea of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea'[43]. If CO_2 is transported by ship or by a pipeline to a disposal site and then injected from a platform or a ship then it will be covered by the provisions of both the Convention and the Protocol and considered to be dumping, as the purpose is to dispose of CO_2 – subject to the exemptions discussed later in this chapter. However, the Convention and Protocol only applies to activities using ships or platforms to inject CO_2 into the marine environment and there are no controls governing pipeline discharges from land based sources. This can be supported by the provision in the Protocol stating that its remit does not extend to sub-seabed repositories accessed only from land[44]. This was confirmed at the thirteenth meeting of the consultative parties to the London Convention in 1990 (Snelders, 2002). The use of pipelines from land based sources to transport CO_2 direct to off-shore repositories is therefore a legitimate activity under the Convention and Protocol.

The second key legal question is whether CO_2 is a waste or not? The London Convention prohibits the disposal of all wastes or other matter specified in Annex I (known as the black list) [45]. This is because these are known to cause harm to aquatic organisms, even in low concentrations. Wastes or other matter listed in Annex 2 (known as the grey list) requires special consideration if the quantity exceeds 'significant amounts', and a permit can be issued under certain circumstances[46]. CO_2 is not specifically referred to in any of the lists that are prohibited for disposal in Annex 1. Similarly it is not listed in Annex 2, which covers wastes requiring a permit. What is relevant in considering whether CO_2 is a waste or other matter, is whether it is classed as an 'industrial waste', which was added to the Annex 1 list with effect from 1 January 1996. 'Industrial waste' means 'waste materials generated by manufacturing or processing operations' and the Convention lists a number of substances that this does not apply to[47]. These exclusions are probably not relevant to CO_2. The OSPAR Secretariat examined the definition of 'industrial waste' in the London Convention as part of its CO_2 review (OSPAR Group of Jurists and Linguists, 2003). They considered it was far more unclear whether the generation of electricity is covered by either 'manufacturing or processing', and thought that electricity generation might be claimed to be an activity of a different kind. The United Kingdom Government have commented that they consider that CO_2 would fall within this definition of 'industrial waste' (DEFRA, 2002).

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[41] Ibid, Article 1.

[42] E.g. Ireland v United Kingdom. Dispute concerning access to information under Article 9 of the OSPAR Convention, Final Award, Permanent Court of Arbitration, The Hague, 2 July 2003.

[43] London Convention, Article III; 1996 Protocol, Article 1(4).

[44] 1996 Protocol, Article 1(5) (7).

[45] London Convention Article IV.1 (a).

[46] Ibid, Article IV.1(b).

[47] Ibid, Annex I Paragraph 11.

Consultative parties to the London Convention have recognized that the text of Annex I(II) to the Convention is ambiguous and open to varying interpretations with regard to the definition of ‘industrial waste’. They have considered providing policy interpretations of ‘industrial waste’, but no consensus amongst the Contracting Parties could be reached. The Consultative Parties agreed to discuss this in the future with the aim of achieving consensus on the interpretation of industrial waste. The operating procedures of the London Convention have placed a strong reliance on high quality scientific advice and there is a permanently constituted scientific group which reviews existing provisions. The scientific group were asked to advise on the issue of whether CO_2 derived from fossils fuels was considered to be an ‘industrial waste’ at their twenty-second meeting in 1999 (IMO, 1999). They concluded that CO_2 was an industrial waste and that the twenty-first consultative meeting of all the parties to the Convention should be consulted concerning the priority to be accorded to these issues. The scientific group can only provide advice, and it is up to the Consultative Parties if there should be any amendment to the Convention or introduction of guidance. At the consultative meeting there was no consensus about whether or not storage at sea of CO_2 derived from fossil fuels should be seen as industrial waste. Some state delegations supported the conclusion that fossil fuel derived CO_2 falls within the definition of ‘industrial waste’, some were opposed and other states decided that it was premature to be decided at this time. The chairman to the consultative meeting decided that no consensus existed on whether CO_2 disposal would be considered an ‘industrial waste’ (Brubaker and Christiansen, 2001). The debate whether CO_2 is a waste is still ongoing, and is included in one of the questions in the current London Convention review on the legal issues associated with CO_2 storage in geological formations (IMO, 2005).

In conclusion, if it can be shown that the CO_2 that is captured derives from manufacturing or processing operations, it will fall under the ‘industrial waste’ category and be prohibited under the London Convention. If it is considered not to be an ‘industrial waste’, it will not be prohibited by Annex I and will instead be subject to the permit procedure contained elsewhere in the Convention. Permits are issued by the state where the waste originates, who must take into account the provisions contained in Annex III of the London Convention. These include such general factors as the possible effects on marine life, or other uses of the sea, and the practical availability of alternative land-based methods of treatment or disposal.

The position under the 1996 Protocol is a little more straightforward because there is a general prohibition on the dumping of wastes or other matter with the exception of those wastes or other matter listed in Annex I[48]. It is extremely unlikely that CO_2 would fall under any of the categories approved for dumping in Annex I. The UK Government are also of the opinion that none of the seven categories listed in Annex 1 could be read as including CO_2 (DEFRA, 2002). The OSPAR Secretariat have commented that they too believe that there is considerable doubt whether CO_2 could be said to be included in any of the categories in the Protocol, but thought that there could be arguments where CO_2 deriving from combustion could fall under the category concerning ‘organic material of natural origin’ (OSPAR Group of Jurists and Linguists, 2003). This was because they considered that there was a respectable body of opinion that ‘organic chemistry’ and ‘organic compound’ covered any carbon compound. They also considered that CO_2 produced as a burning of fossil fuel could probably be regarded to be ‘of natural origin’ as burning is a natural process. However, they concluded that CO_2 storage offshore would probably be in conflict with the 1996 Protocol. At the current time it seems likely that CO_2 would be covered as a waste under the Protocol and the dumping of CO_2 from man-made structures and ships would be prohibited. In the

[48] 1996 Protocol, Article 4.1.1. Waste includes: ‘1.dredged material; 2. sewage sludge; 3. fish waste, or material resulting from industrial fish processing operations; 4. vessels and platforms or other man made structures at sea; 5. inert, inorganic geological material; 6 organic material of natural origin; and 7. bulky items primarily comprising iron, steel, concrete and similarly unharmful materials for which the concern is physical impact, and limited to those circumstances where such wastes are generated at locations, such as small islands with isolated communities, having no practicable access to disposal options other than dumping’.

unlikely event that it is considered to fall under one of the seven categories in Annex 1 then it may be authorized for disposal dependent on a permit being required from the Contracting Party[49].

The third key legal question is whether the Convention and Protocol contains any exclusions that might possibly be relied upon in storing CO_2 in sub-seabed storage sites. The first exclusion considered here is the storage of CO_2 derived from off-shore platforms. Both the Convention and the Protocol specifically excludes from the definition of 'dumping' the 'disposal of wastes or other matter incidental to, or derived from, the normal operations of vessels or aircraft, platforms or other man made structures at sea and their equipment, other than wastes or other matter transported by or to vessels, aircraft, platforms or other man made structures at sea, operating for the purpose of disposal of such matter or derived from the treatment of such wastes or other matter on such vessels, aircraft, platforms or other'[50]. Therefore, if CO_2 was transported to such a site to store it to prevent it from entering the atmosphere, rather than being part of the operation of the installation, this exclusion could not be relied. If however, the CO_2 ends up in the sub-seabed during the operations of the installation and it is stored there because it has nowhere else to go this might be allowed. It was decided at the seventeenth consultative meeting of the London Convention that 're-injection' of produced water and other matter associated with offshore oil and gas operations does not fall within the Conventions definition of dumping (Brubaker and Christiansen, 2001). This would suggest that CO_2 operations involving enhanced oil recovery, or separating CO_2 at source, could be permissible under the Convention, but CO_2 that is transported to the site is not.

The second possible exclusion covers placement in the maritime area. The London Convention and Protocol both specifically exclude from the definition of 'dumping' the 'placement of matter for a purpose other than the mere disposal thereof, provided that such placement is not contrary to the aims of this Convention [Protocol]'[51]. It could be argued that the CO_2 is not in fact disposed of, but placed, arguably until the deteriorating climate change situation is bought under control with new clean technologies. It is unclear what 'placement' is intended to constitute and its scope. One could guess it is intended to cover things such as the placement of artificial reefs. 'Placement' could be read in terms of the purpose behind the original placement of the installation or structure (if it was for the purposes of undertaking offshore activities, it will be an offshore source, if not, then a land-based source) regardless of any subsequent change of use, or, alternatively, placement in the light of its present use (i.e. the placement is deemed to have occurred at the commencement of the new use for it). The former more literal interpretation would give the benefit of the doubt to the object and purpose of the Convention, to protect the marine environment, in the case of a conversion of a redundant offshore installation. But the latter interpretation has a degree of logic to it, and would avoid an inconsistency in the permissibility of CO_2 storage depending on the original purpose of the installation or structure used. On balance, the former interpretation is more likely because of its consistency with the aims of the Convention.

The term 'placement of matter for a purpose other than mere disposal thereof' was considered at the twenty-second Meeting of the Consultative Parties in 2000 (IMO, 2000). The Contracting Parties considered having guidance on this point, but the United Kingdom delegation expressed the view that guidance on placement would be undesirable, because it should be allowed provided that such placement is not contrary to the aims of the Convention. The meeting agreed that any guidance to be developed on this issue should include that placement should not be used as an excuse for disposing of waste, that placement should not be contrary to the aims of the convention and that information of the placement activities be provided to the secretariat, as available. The meeting report noted that no consensus could be reached on whether or not 'placement' was covered by the Convention (IMO, 2000).

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[49] 1996 Protocol, Article 4(1)(2).

[50] London Convention, Article III 1(b)(i); 1996 Protocol, Article 1(4)(2)(1).

[51] Ibid, Article III(1)(b); 1996 Protocol, Article 1 (4)(2)(2).

The Precautionary Principle. Disposing of CO_2 in sub-seabed storage could bring into play the precautionary principle. In general the precautionary principle recognizes that it is often advantageous to prohibit or limit an activity despite the absence of scientific certainty that the activity will result in a detrimental result (McCullagh, 1996). Both the Convention and the Protocol embrace the precautionary principle approach. Although the precautionary principle is not mentioned in the Convention, the Contracting Parties agreed to apply the precautionary approach in environmental protection within the framework of the London Convention in a Resolution to the Convention[52]. Article 3 of the 1996 Protocol also states that in implementing this Protocol 'Contracting Parties shall apply a precautionary approach to environmental protection from dumping of wastes or other matter whereby appropriate preventative measures are taken where there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even where there is no conclusive evidence to prove a causal relation between inputs and their harm effects'. It would seem if the precautionary principle is correctly applied that the weight would seem overwhelmingly to fall on the side of caution, unless there is compelling scientific evidence and opinion that the CO_2 will remain in the seabed repository throughout the whole of the storage period or for a very significant length of time.

Potential for Future Storage of CO_2 under the London Convention and Protocol. If a Contracting Party to the London Convention went ahead with a carbon dioxide storage project at the current time and this was against the wishes of one or more of the Contracting Parties, this could result in some form of action being taken against them. This would normally take the form of resolution in the first instance by negotiation or conciliation, and then possibly arbitration in the second instance. Contracting Parties can agree to sidestep arbitration and use one of the procedures for court action listed in the United Nations Convention on the Law of the Sea. As noted above, the Contracting Parties to the London Convention are currently considering the legal questions associated with CO_2 storage in geological formations. This could identify the Contracting Parties which are in favour or against such projects and their opinions as to the current legal position. If CO_2 disposal is found to be in conflict with the Convention in certain circumstances, the only means by which Contracting Parties could still pursue this as an option would be to amend the Convention. The London Convention allows for Contracting Parties to review and adopt amendments to the Convention and its Annexes[53]. Amendments to the Convention may be passed by a two-thirds majority of those present at consultative or special meetings. Any amendment will only come into force for those Parties accepting it on the sixtieth day after two-thirds of all the parties (i.e. not just those present at the meeting) have deposited an instrument of acceptance for the amendment[54]. It is expected that this could be time consuming as there is no limit set out as to when states have to accept the amendment by.

Contracting Parties may also make amendments to the Annexes of the Convention. In relation to CO_2 it is most likely that the definition of 'industrial waste' in the Annexes will be amended. This procedure is easier than changing the Convention because all that is required all is a two-thirds agreement of those present at the meeting. The amendment will then enter into force immediately for any party agreeing to it, and for all other parties (whether they agreed to it or not) after a period of a hundred days following the relevant meeting, unless a declaration against acceptance is made by a party within that period[55]. It is unclear whether a two-thirds majority of the Contracting Parties would support CO_2 storage proposals, particularly in light of the fact that there was no consensus on the issue of whether it was an 'industrial waste' at an earlier consultative party meeting (IMO, 2000). Amendments to the Annexes also have to be based on scientific and technical considerations

[52] Resolution LDC.44(14)) 1991.
[53] London Convention, Article XIV (4)(a).
[54] Ibid, Article XV1(a).
[55] Ibid, Article XV1(b).

and previous research by the Scientific Committee to the Convention have suggested that it is probably an industrial waste (IMO, 1999).

It is unlikely that the Protocol will be amended, as it has not even entered into force. When it does enter force there are provisions contained in the Protocol that allow for meetings or special meetings to be held to review and amend the Protocol[56]. There is a requirement that any amendment to an article or annex proposed by a Contracting Party must be notified by the International Maritime Organization to all Parties at least six months prior to its consideration at such a meeting[57]. The position on voting and entry into force of amendments to articles and of annexes is the same as for the London Convention[58]. Similarly, it would seem easier for an amendment to be made to the permitted list in Annex 1 under the Convention. The International Energy Agency have commented that ‘necessary amendments might include putting CO_2 on the “reverse list” of the 1996 protocol of the London Convention, after its entry into force’ (IEA, 2005).

In the unlikely event that the UK would seek to withdraw from the Convention and Protocol there are procedures allowing for this. The London Convention allows Contracting Parties to withdraw from the Convention by giving six months notice to the depositary[59]. As the Protocol is not yet in force, the UK would not have to wait for a period of time to withdraw. However, once the Convention enters into force Contracting Parties are not permitted to withdraw from the Convention for two years[60]. After this date, withdrawal takes effect one year after receipt of the notice to withdraw from the Protocol.

If a Contracting Party to the London Convention proceeds with a geological CO_2 storage project they could be liable for any damage caused in the event of an escape. Both the Convention[61] and Protocol[62] contain provisions stating that liability is in accordance with the principles of international law regarding state responsibility for damage caused to the environment of other states or to any other area of the environment. The Contracting Parties to the Convention and Protocol must also undertake to develop procedures regarding liability arising from the dumping of wastes or other matter.

5.3.3 OSPAR Convention

Background and Objectives of OSPAR. The OSPAR Convention is a framework document which sets out the overall principles of the Convention. The main text contains legal obligations, provisions on definitions, and the managerial aspects in the implementing and application of the Convention. An integral part of the Convention is a number of annexes and appendices which contain more detailed provisions than in the main text. The five separate annexes to the Convention cover pollution from land-based sources (Annex I); pollution by dumping and incineration at sea (Annex II); pollution from offshore installations and structures (Annex III); monitoring and assessment of the marine environment (Annex IV); and the protection of ecosystems and biological diversity (Annex V).

The primary objective of the OSPAR Convention is to protect the marine environment against the adverse effects of human activities, so as to safeguard human health and to conserve marine ecosystems and, when practicable, restore marine areas which have been adversely affected.[63]. This is significant because the older Conventions, such as the London Convention, refer to the prevention of pollution of the sea, whereas the OSPAR Convention refers to the protection of the

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[56] 1996 Protocol, Article 18(1)(1).
[57] Ibid, Articles 21(1) and 22(1).
[58] Ibid, Protocol, Article 21(2) + (3), Article 22(2) + (4).
[59] London Convention, Article XXI London Convention.
[60] 1996 Protocol, Article 27 1996 Protocol.
[61] London Convention, Article X.
[62] 1996 Protocol, Article 15.
[63] OSPAR Convention, Article 2(1)(a).

marine environment. The Contracting Parties to OSPAR must adopt measures to achieve the protection of the marine environment - this objective is the minimum legal obligation placed on them. The only discretion a Contracting Party has is the decision whether to adopt even more stringent measures than the main objective to protect the maritime area[64]. The main objective of the Convention is extremely important because in questions of interpretation of the legal text the court or tribunal will look too the underlying purpose of the Convention.

It is clear from the OSPAR Convention that its general purpose is to stop adverse activities and subsequently the risk of pollution taking place in the marine environment. The Convention is concerned with 'the introduction by man, directly or indirectly, of a substance into the marine area which results, or is likely to result, in hazards to human health, harm to living resources and marine ecosystems, damage to amenities or interferences with other legitimate uses of the sea'[65]. As compared to its predecessors, such as the London Convention, the OSPAR Convention also has increased scope of coverage and is legally tighter. It gives legally binding status to the precautionary principle and the polluter pays principle and Contracting Parties must also take into account best available techniques and best environmental practice in any measures they adopt.

Geographical Coverage and Application to the Seabed. The OSPAR Convention is a regional agreement and it applies to the waters of the Contracting Parties in the geographical maritime area around the North Sea and parts of the Atlantic and Artic oceans. The Convention applies to pollution in the 'maritime area', which includes in its interpretation 'the bed of all those waters and its subsoil'[66]. This would appear at first sight to cover geological CO_2 storage projects which would store CO_2 under the sea. There might well be argument over the legal interpretation of what is the 'the bed of all those waters' and its 'subsoil' and in geological terms whether the storage grounds for the CO_2 fall under this definition. The United Kingdom Government have already considered this point in an internal document and commented that it could be argued that if the CO_2 was placed in the sub-seabed this would not be caught by the Convention because 'subsoil' would only refer to the layer of broken rock immediately under the seabed (DEFRA, 2002). However, they went on to adopt a purposive approach in interpreting this legal point and after considering that the overriding objective of the Convention was the protection of the marine environment from pollution and the conservation of ecosystems, they concluded that seabed was intended to be given a broad interpretation, encompassing oil and gas reservoirs. They considered the Convention had been drafted with the purpose of covering activities in areas below the sea column and if there was a possibility that the storage of CO_2 in sub-seabed reservoirs could result in pollution to that environment, with an effect on such life or ecosystems, which was possible through leakage, the OSPAR Convention should be interpreted in such a way as to give effect to this wider purpose. The Group of Jurists/Linguists to the OSPAR Commission concluded that the definition of maritime area covers placements onto or into the seabed and the underground strata beneath it (OSPAR Group of Jurists and Linguists, 2003).

There is no case-law to guide us as to a complete definition of seabed and subsoil. A strong counter argument is that geological formations are not intended to be protected under the OSPAR Convention. If a purposive approach is adopted it seems that the OSPAR Convention was drafted to protect marine ecosystems against pollution and the risk of pollution. The OSPAR Convention has provisions concerning pollution from land-based sources (Article 3); pollution by dumping and incineration (Article 4); and pollution from offshore sources (Article 5). These do not specifically cover underground geological formations, but rather particular forms of pollution, and when drafted they plainly did not have CO_2 in mind. If OSPAR's purpose is to protect the maritime area, this

[64] Ibid, Article 2(5).
[65] Ibid, Article 1(d).
[66] Ibid, Article 1(a).

itself might not include oil and gas reservoirs as an area for protection. If consideration is given as to what activities under OSPAR might affect the areas protected, this might encompass pollution from underground reservoirs, because geological storage of CO_2 could pose a risk to the maritime area. Article 2 of the OSPAR Convention sets out the general obligations under the Convention and Contracting Parties must 'take all possible steps to prevent and eliminate pollution and shall take the necessary measures to protect the maritime area'. Therefore, even if geological formations are not classed as the subsoil and are not covered in articles 3-5, states are still under a general duty to protect the marine environment under Article 2 of the Convention.

Legality of CO_2 Storage. There are several important considerations in determining the legality of CO_2 storage under the OSPAR Convention. The first key legal question to consider is how the CO_2 gets to the storage site. There are three methods by which CO_2 could reach an offshore location for subsequent disposal: transportation from a land-based source by a pipeline directly to the sub-seabed storage site; by ship for direct injection from the ship; or transportation by pipeline or ship to an installation such as a rig and then injection into the sub-seabed storage site. For the purposes of this study only the third method seems to apply to geological storage. The OSPAR Convention institutes three separate regimes to control pollution. It covers (i) pollution from land-based sources[67]; (ii) pollution from dumping and incineration[68]; and (iii) pollution from offshore activities[69]. These regimes are mutually exclusive. Annex I covers pollution from land-based sources and for the purposes of this study relates to offshore pipelines. The OSPAR Convention introduces a general prohibition against incineration and the dumping of all waste from ships in Annex II, except for certain wastes that are listed in the Convention. Annex III applies to offshore installations, and this states that any dumping of wastes or other matter from offshore installations is also prohibited.

Under the OSPAR Convention the Contracting Parties must take all possible steps to prevent and eliminate pollution from land-based sources[70]. 'Land-based sources' is defined in the Convention as including 'point and diffuse sources on land from which substances or energy reach the maritime area by water, through the air, or directly from the coast'[71]. It includes 'sources associated with any deliberate disposal under the seabed made accessible from land by tunnel, pipeline or other means and sources associated with man-made structures placed, in the maritime area under the jurisdiction of a Contracting Party, other than for the purpose of offshore activities'[72]. It is clear from the above definition that the transportation of CO_2 by pipeline from land *directly* (emphasis added) to sub-seabed storage sites falls within the scope of the Convention. To be clear, it should be pointed out that the situation is quite different if the CO_2 is transported by pipeline to an installation before being injected into the seabed. This part of the Convention is covered by Annex I and anyone could in practice release CO_2 into storage sites direct from a pipeline, subject to the authorisation of the Contracting Party[73]. The disposal of CO_2 in this way could be authorized by a Contracting Party as it could be classed as pollution from a land-based source. However, this discretion is limited by the fact that Contracting Parties are obliged to use the best available techniques for point sources and follow best environmental practice for point and diffuse sources[74].

It is worth noting that although pollution from land-based sources may be permissible in some situations (i.e. if best practice and best techniques are adopted), Contracting Parties to the Convention are also under a duty to prevent and eliminate pollution from land-based sources in

[67] OSPAR Convention, Article 3 and Annex I.
[68] Ibid, Article 4 and Annex II.
[69] Ibid, Article 5 and Annex III.
[70] Ibid, Article 3.
[71] Ibid, Article 1(c).
[72] Ibid, Article 1(e).
[73] Ibid, Article 4(1); and Annex I, Article 2(1).
[74] Ibid, Annex I Article 1(1).

accordance *with the provisions of the Convention*[75] (emphasis added). This suggests that if the general obligation of the Convention is to ‘prevent and eliminate pollution’[76], the storing of a substance under the sea which risks causing pollution to the maritime area may not be compatible with the discretion of the Contracting Parties. Contracting Parties must also take into account decisions made by the OSPAR Commission, which bind the Contracting Party - i.e. the contracting parties to OSPAR could decide to pass a decision prohibiting the disposal of CO_2 in this manner. The OSPAR Jurists/Linguists Group also concluded that there was no prohibition on introducing substances from a land-based source into the marine environment and such means are therefore permissible for placing CO_2 in the marine environment, irrespective of the purpose of their placement (OSPAR Group of Jurists and Linguists, 2003). We merely take note of this here as it may apply to proposals for direct ocean storage since geological CO_2 storage entails the use of an intermediate installation between transport and disposal.

CO_2 will not be disposed from aircraft so this is not relevant to this study. It is possible that CO_2 could be disposed of directly from a ship. It appears that the dumping of CO_2 directly from ships will be prohibited by the Convention, unless it can be said to be one of the wastes contained in Annex II. This is because Annex II prohibits dumping of waste from ships unless it is an approved waste under Article 3(2). Whether it is a waste will be discussed further later. The OSPAR Jurists/Linguists group also concluded that placements of waste from ships, constituted dumping and were prohibited (OSPAR Group of Jurists and Linguists, 2003).

The most likely way that CO_2 will be disposed of is from some form of offshore installation after being transported by ship or pipeline before being injected into the storage site. Annex II covers offshore installations and states that any dumping of waste from these is prohibited, but this prohibition does not apply to discharges or emissions from offshore sources[77]. If the CO_2 is piped or shipped to an offshore installation before going into the storage site then the less stringent requirements contained under Annex I (pollution from land-based source) could be superseded by other provisions in the Convention. Anyone wishing to dispose of CO_2 will try and show that the pollution comes from a land-based source, so the disposal operation will not be prohibited under the Convention.

In the case of ships transporting CO_2 to an installation it seems that although the pollution comes from an onshore source, the transport of the CO_2 cannot be treated as an offshore source. This is because the definition of land-based source states that ‘it includes sources associated with any deliberate disposal under the seabed made accessible from land by tunnel, pipeline or other means’. This would seem to not include ships, and it would be classed as dumping of wastes under Annex III. The OSPAR Commission also reached the conclusion that ships could not be treated as other means for the purposes of the definition of ‘land-based sources’, and after consideration of the *ejusdem generis* rule (OSPAR Group of Jurists and Linguists, 2003). This rule says that ‘where general words follow an enumeration of person or things, by words of a particular and specific meaning, such general words are not to be construed in their widest extent, but are to be held as applying only to persons or things of the same general kind or class as those specifically mentioned’ (Garner, 1999).

In the case of pipelines transporting CO_2 to an offshore installation the definitions in the Convention are crucial. ‘Offshore Installations’ are defined as including man-made structures and vessels placed for the purpose of offshore activities. ‘Offshore activities’ is defined as ‘activities carried out in the maritime area for the purposes of the exploration, appraisal or exploitation of liquid and gaseous hydrocarbons’[78]. It is likely that the CO_2 that is captured will be transported to an offshore installation that already exists. If an offshore platform already exists it would have been

[75] Ibid, Article 3.
[76] Ibid, Article 2(1)(a).
[77] Ibid, Annex III, Article 3.
[78] Ibid, Article 1(j).

used for oil and gas drilling and would fall under the hydrocarbon provision. The prohibition on disposal from offshore installations would therefore catch CO_2 disposal from such installations.

However, the definition of 'offshore activities' seems to offer a potential exemption in the Convention as it only applies to activities in the maritime area concerning liquid and gaseous hydrocarbons. Hydrocarbons cover a wide range of carbons containing hydrogen and carbon molecules, but probably do not include CO_2. Therefore a Contracting Party could in theory build a platform or other form of fixed structure, or even use an installation that has not been used for previous offshore activities for the specific purpose of disposing of CO_2. Activities such as these would therefore not fall within the more restrictive provisions of the Convention and would be regulated by the provisions contained in Annex I as they would be a land-based source. The requirements in Annex 1, relating to land-based sources were discussed above.

It is worth noting that although pollution from offshore sources may be permissible in some situations (i.e. if it is transported to the installation by pipeline and the installation has not been used for the exploitation of hydrocarbons), Contracting Parties to the Convention are also under a duty to take all possible steps to prevent and eliminate pollution from offshore sources in accordance *with the provisions of the Convention*[79] (emphasis added). This suggests that if the general obligation of the Convention is to 'prevent and eliminate pollution'[80], the storing of a substance under the sea which risks causing pollution to the maritime area may not be compatible with the discretion of the Contracting Parties.

The second key legal question is determining whether CO_2 is a waste or not. In general terms it is open to interpretation whether CO_2 can be classified as a waste. 'Wastes or other matter' is left undefined in the Convention, except to give a number of exclusions to this definition[81], which have no relevance to CO_2. The concept of waste in the Convention is drafted in very wide terms and the inclusion of the phrase 'other matter' is designed to provide a catch all situation to respond to evolving threats. Under the Convention the dumping of all wastes or other matter is prohibited, unless these are specifically listed[82]. This means that if CO_2 is not expressly listed in the Convention its disposal will not be authorized. The categories of waste that are currently authorized for dumping include: dredged material; inert materials of natural origin, that is solid, chemically unprocessed geological material the chemical constituents of which are unlikely to be released into the marine environment; fish waste from industrial fish processing operations; and vessels or aircraft[83]. This corresponds closely with the list in the Protocol to the London Convention. It is clear that none of the above categories of waste could be said to include CO_2. The Group of Jurists/Linguists of the OSPAR Commission also considered that the disposal of CO_2 would not fall under any of the exceptions in Annex II (OSPAR Group of Jurists and Linguists, 2003).

Dumping is defined in the OSPAR Convention as (i) any deliberate disposal of wastes or other matter from vessels or aircraft or from offshore installations, and (ii) any deliberate disposal in the maritime area of vessels or aircraft or offshore installations and offshore pipelines[84]. The second provision in the Convention relating to dumping is obviously not relevant to CO_2 storage. The key words in the definition of dumping are 'deliberate disposal', which are undefined. The notion of disposing is inherent in most definitions of waste in most countries around the world. The use of this term is the decisive factor in determining whether a material is a waste and whether it falls within the remit of the Convention. Some jurisdictions such as the European Union have indicated in case law that in certain circumstances discarding can take place even when arguably the opposite occurs. Examples of this include, keeping a substance rather than transferring it to another owner, or

[79] Ibid, Article 3.
[80] Ibid, Article 2(1)(a)
[81] Ibid, Article 1(o).
[82] Ibid, Annex II and Article 3(1).
[83] Ibid, Annex II and Article 3(2) (a, b, d, e).
[84] Ibid, Article 1(f).

being able to use or treat it in an environmentally sound manner. It seems clear that this approach is often adopted to achieve the objectives of the legislation – i.e. environmental protection, even if this distorts the ordinary sense of the word. In the case of CO_2 there can be little argument that the CO_2 still has a use, as the intention of the person wishing to store the CO_2 would be to put it into another location to get rid of it. For the purposes of the Convention it seems that CO_2 is dumped if it is stored in geological formations in marine waters.

The third key legal question is whether the OSPAR Convention contains any exclusions that might possibly be relied upon in storing CO_2 in sub-seabed storage sites. The first exclusion considered here is the storage of CO_2 derived from an off-shore platform. The Convention specifically excludes from the definition of 'dumping' any 'disposal of wastes or other matter incidental to, or derived from, the normal operations of vessels or aircraft or offshore installations other than wastes or other matter transported by or to vessels or aircraft or offshore installations for the purpose of disposal of such wastes or other matter or derived from the treatment of such wastes or other matter on such vessels or aircraft or offshore installations'[85]. This exclusion is also contained in the London Convention. This provision clearly does not exempt the storage of CO_2 that is collected on land and transported for injection. Some commentators have argued that if the CO_2 is generated on an offshore platform during normal operations, then this falls outside the definition of dumping and is therefore permitted under the Convention (Snelders, 2002). It would seem on closer analysis that the sub-seabed storage of CO_2 produced in this manner would more likely to still be prohibited under the OSPAR Convention.

The reason why this exemption would probably not come into play for CO_2 storage is because Article 3 of the Convention states that this exemption applies to *discharges* and *emissions* (emphasis added) from offshore sources[86]. It seems that the injection of CO_2 into a sub-seabed storage site would not constitute a discharge or emission through the normal operations of an offshore installation. CO_2 capture and storage projects will involve CO_2 going to such a site to store it to prevent it from entering the atmosphere, rather than being part of the operation of the installation. This would suggest that locating power stations offshore with the intention of collecting the CO_2 and disposing of it at source would not fall under this exemption. If however, the CO_2 ends up in the sub-seabed during the operations of the installation and it is stored there because it has nowhere else to go this might be allowed. This would suggest that operations involving enhanced oil recovery are only permissible under this part of the Convention.

The second possible exclusion covers placement in the maritime area. The OSPAR Convention also specifically excludes from the definition of 'dumping' the 'placement of matter for a purpose other than the mere disposal thereof, provided that, if the placement is for a purpose other than that for which the matter was originally designed or constructed, it is in accordance with the relevant provisions of the Convention'. This exclusion is also contained in the London Convention. It could be argued that the CO_2 is not in fact disposed of, but placed in the seabed, arguably until the deteriorating climate change situation is brought under control with new clean technologies e.g. the CO_2 is basically stored for a period of time before it is released back into the atmosphere. Although this does provide a form of an exemption the last part of this exclusion is crucial because it says it must be in accordance with the relevant provisions of the Convention. In Annex II, which concerns the prevention of pollution by dumping, this says that although placement of matter may take place in certain situations, this provision shall not be taken to permit the dumping of wastes or other matter otherwise prohibited under this Annex. It seems that the competent authority of the relevant Contracting Party gives the authorisation for this[87]. In the United Kingdom, this will be the Government's responsibility to decide whether matter can be

[85] Ibid, Article 1(g)(i).
[86] Ibid, Article 3(2).
[87] Ibid, Annex II Article 5

placed in the sub-seabed. This authority is however curtailed by the fact that their authorisation must in accordance with the relevant applicable criteria, guidelines and procedures adopted by the OSPAR Commission - who are under a legal duty to issue such guidance[88]. It is not known whether such guidance exists.

It is unclear from the 'placement' provision in the Convention what this is intended to constitute and its scope. It could determine whether dumping from an installation or structure constitutes pollution from an offshore or land-based source, and thus whether it is permissible or not. 'Placement' could be read in terms of the purpose behind the original placement of the installation or structure (if it was for the purposes of undertaking offshore activities, it will be an offshore source, if not, then a land-based source) regardless of any subsequent change of use, or, alternatively, placement in the light of its present use (i.e. the placement is deemed to have occurred at the commencement of the new use for it). The former more literal interpretation would give the benefit of the doubt to the object and purpose of the Convention, to protect the marine environment, in the case of a conversion of a redundant offshore installation. But the latter interpretation has a degree of logic to it, and would avoid an inconsistency in the permissibility of CO_2 storage depending on the original purpose of the installation or structure used. On balance, the former appears to be most consistent with the aims of the Convention. The Group of Jurists/Linguists to the OSPAR Commission thought that CO_2 was a substance that was not wanted in its present form or location (OSPAR Group of Jurists and Linguists, 2003). They considered that the placement of it in the maritime area was a deliberate action to dispose of it by putting it somewhere else and this was not an action to achieve another purpose. They concluded that the dumping regime would therefore seem to exclude it from the cases to which that regime applied.

The Precautionary Principle. An important legally binding provision in the Convention is the incorporation of the precautionary principle both in the definition of pollution[89] and the general obligations of the Convention[90]. Whilst this does not provide an exemption it will be very important in relying on any exemption. The Contracting Parties must apply the precautionary principle, by virtue of which preventive measures are due to be taken where there are reasonable grounds for concern that substances or energy introduced, directly or indirectly, into the marine environment may bring about hazards to human health, harm to living resources and marine ecosystems, damage to amenities or interfere with other legitimate resources of the sea, even where there is no conclusive evidence of a causal relationship between the input and the effects.

Unlike some definitions of the precautionary principle in other Conventions, which merely state that scientific uncertainty should not delay the taking of preventative measures (e.g. Climate Change Convention), the formulation in the OSPAR Convention is more proactive and positively requires preventative measures to be taken when there is a reasonable apprehension of a hazard[91]. Secondly, it does not require the potential damage to be serious or irreversible before action is taken. This is essential for a truly precautionary approach, for if there is uncertainty in other respects it may not be certain how serious the potential damage may be. Thirdly, the formulation does not even require 'damage', but only the possibility of a hazard, which is the mere risk that damage might occur. If it can be shown the CO_2 storage projects could cause a hazard the precautionary principle may be relied upon to prohibit them.

Potential for the Future Storage of CO_2 under the OSPAR Convention. It is not known whether the legal review that was undertaken by the OSPAR Commission in 2003/4 will result in any amendments to the Convention. The OSPAR Commission may choose instead to give a decision or

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[88] Ibid, Annex II Article 6
[89] Ibid, Article 1(d).
[90] Ibid, Article 2(2) (a).
[91] Ibid.

a recommendation taken under the procedures of the Convention[92]. Any recommendation given by the OSPAR Commission is not legally binding[93]. Although the Committee can adopt a decision as to the correct interpretation of the relevant provisions in the Convention it will not become binding until adopted by voting of the Contracting Parties. The Commission needs a three-quarters majority of the Contracting Parties to obtain this[94]. It seems however that the decision is only binding on the Contracting Parties which have notified that they accept the decision[95].

There is provision in the Convention for dispute resolution[96]. If any Contracting Parties to the Convention have a dispute relating to the interpretation or application of the Convention, they may request arbitration. If both parties agree to arbitration the dispute will go before a tribunal consisting of three appointed members. The rules concerning the running of this tribunal are contained in Article 32 of the Convention. The cost of going to the tribunal will usually be borne by the parties in dispute in equal shares. The OSPAR Commission will in practice notify the other Contracting Parties to the Convention, who can intervene in the proceedings if they have an interest in the legal nature in the subject matter of the dispute which may be affected by the decision in the case. The tribunal will reach a decision according to the rules of international law, and in particular, those of the Convention. The decision made by the tribunal is final and binding upon the parties to the dispute.

A further option for Contracting Parties pursuing the geological storage option is to propose amendments to the Convention. Under Articles 15 and 17, any Contracting Party may propose an amendment to either the main text or the Annexes of the OSPAR Convention. A Contracting Party proposing the amendment must do so at least six months before the meeting of the Commission at which it is proposed for adoption. Any changes to the Convention could in practice prove time consuming in practice. An amendment to the main text of the Convention itself requires the unanimous vote of all the Contracting Parties. If the amendment is accepted it will enter into force on the thirtieth day after deposit of the instrument of ratification, acceptance or approval by at least seven of the Contracting Parties. Amending the Convention may prove difficult in practice, as it is likely that one Contracting Party will object, particularly as this is such a controversial topic.

It seems that a Contracting Party would be more likely to consider proposing amendments to the Annexes under Article 17 of the Convention. This only requires a three-quarters majority vote by the Contracting Parties bound by the Annex concerned. However, the entry into force procedures are the same as for changes to an article under Article 15. It would seem sensible for the United Kingdom to try and forge consensus for such an amendment amongst Contracting Parties from the European Community. European countries negotiate climate change as a group at the Conference of Parties for the Climate Change Convention. Amongst the Contracting Parties to the OSPAR Convention are twelve European Member States[97] as well as the Commission of the European Communities. Only three Contracting Parties to the OSPAR Convention are not members of the European Community[98]. As the European Community countries make up the three-quarters majority they could come to some agreement as to the benefits in terms of sharing emissions reduction credits and cost. It is still likely though that many of the Contracting Parties might still not agree to CO_2 storage.

If geological CO_2 storage is incompatible with the OSPAR Convention, any proposed amendment to the Convention is dismissed, and the United Kingdom (UK) Government is still determined to press ahead with using such technologies, then the only option would be for them to

[92] Ibid, Article 13.
[93] Ibid, Article 13(5).
[94] Ibid, Article 13(1).
[95] Ibid, Article 13(2).
[96] Ibid, Article 32.
[97] Belgium, Denmark, Finland, France, Germany, Ireland, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom.
[98] Iceland, Norway, Switzerland.

withdraw from the Convention. In practice it is unlikely that the UK Government would withdraw from the OSPAR Convention, but if they do chose to do so they may withdraw from the Convention by notification in writing[99]. The withdrawal takes effect one year after the notification is received. If they go ahead with CO_2 storage projects before this year is reached then the OSPAR Commission can call for steps to bring about full compliance with the Convention[100].

If a Contracting Party to the OSPAR Convention went ahead with a geological CO_2 storage project there could also be financial consequences in case of an escape. As with many other international and regional agreements, the polluter pays principle has been added to the OSPAR regime[101]. It refers to the legal obligation of polluters to pay for damage caused by their operations to human health and the environment. It is assumed that this will cover the cost of clean up after an accident, and by paying compensation for any consequences of harm to human health and the environment. It is debateable whether CO_2 would cause much damage to human health or the environment, even if released in large quantities, but a Contracting Party could be under a legal duty to clean up any CO_2 that has escaped. A key question will be whether the polluter pays principle exempts excluded activities or not.

5.4 CO_2 Storage and Climate Change Legislation

The United Nations Framework Convention on Climate Change (UNFCCC) was concluded in 1992 with the purpose of stabilising concentrations of greenhouse gases in the atmosphere at a level that prevents dangerous disruption to the climate. All greenhouse gases, including CO_2, fall within the scope of the UNFCCC, which came into force in 1994. The commitments under the Convention depend on which Annex to the Convention a state falls under. The industrialized countries, including the United Kingdom are Annex 1 countries and have to take a greater burden in reducing greenhouse gas (GHG) emissions. The UNFCCC is a framework Convention which requires contracting parties to adopt policies aimed at the stabilisation of concentrations of GHG in the atmosphere at ‘levels that prevent dangerous (…) interference in the climate system’. It provides for a review of the adequacy of commitments and for annexes and protocols to be attached to the framework document, as more information becomes available[102].

The United Nations Framework Convention on Climate Change (UNFCCC) provides a general obligation to adopt policies to limit emissions, and the Kyoto Protocol (the Protocol), which was agreed in 1997, provides for actual targets - quantified emission limitation and reduction commitments. The Protocol must be read in conjunction with the UNFCCC, because the latter is the parent law and the definitions contained in Article 1 of the UNFCCC apply in the Protocol. The Kyoto Protocol to the UNFCCC, adopted in 1997, established binding obligations for the reduction of emissions of greenhouse gases in an attempt to stabilize these anticipated changes to the global climate. Under this Protocol developed countries agreed to reduce their emissions to 5.2 per cent below 1990 levels over the period 2008-2012. The scale of these cuts in greenhouse gas emissions required over the next few decades has meant that many developed countries are considering various mitigation options because a rapid move away from fossil fuels is unlikely to be achievable without serious disruption to the global economy. The Kyoto Protocol entered into force in 2005.

The underlying objectives of the Climate Change Convention (UNFCCC) is to both prevent greenhouse gas emissions from entering into the atmosphere, as well as to remove greenhouse gases (GHG) once they have been emitted. Under the UNFCCC emissions and removals are recognized as contributing to stabilisation of GHG concentrations in the atmosphere. There is an important legal distinction between what is an ‘emission’ and what is an ‘emission reduction’. An emission is

[99] OSPAR Convention, Article 30.
[100] Ibid, Article 23.
[101] Ibid, Article 2(b).
[102] United Nations Framework Convention on Climate Change (UNFCCC), Article 4(2)(d).

defined in the UNFCCC as 'the release of greenhouse gases and/or their precursors into the atmosphere'[103]. If CO_2 is captured at source and stored, it does not find its way into the atmosphere and therefore does not become an emission for the purposes of the Convention. Therefore, if a GHG does not find its way into the atmosphere, there is no emission, but an emission reduction.

The significance of the distinction between emissions and emission reduction is that parties to the Convention are more constrained in how they can deal with emissions. If the GHG is released into the atmosphere, it can be the subject of a storage project which removes the GHG from the atmosphere by storing it in what is known as 'sinks'[104]. The location where the greenhouse gas is stored is known as a 'reservoir'[105]. Oceans or forests can both be used as reservoirs to capture released emissions. The UNFCCC and Protocol encourages the protection and increase of natural CO_2 'sinks´ and 'reservoirs', and allows Annex 1 parties to implement projects which reduce greenhouse gases at source, or to increase their removal by obtaining sinks and to credit the resultant emission reduction units against their own emission targets[106]. CCS is therefore certainly not incompatible with the UNFCCC or Protocol because it is an active use of a sink and reservoir. Neither the UNFCCC nor the Protocol specifically mentions offshore CO_2 storage, and Contracting Parties may only offset their emissions from land based sources by afforestation, reforestation and deforestation sinks[107]. The Independent World Commission on the Oceans (IWCO) commented in 1998 that in relation to using the oceans as sinks, 'the Framework Convention on Climate Change and its Kyoto Protocol do not provide for parties to dump or store CO_2 in international waters and thereby to offset their emissions' (Johnston *et al.*, 1999). It seems that the IWCO is correct, but additional sink activities may be agreed at a later date by the Conference of Parties to the UNFCCC, although under the current drafting of the Protocol these are also limited to land-use activities, not offshore activities[108].

The term 'sequestration' is therefore often used in connection with the mitigation of greenhouse gases, but it is clear that the type of geological sequestration considered here is in principle concerned with emission avoidance by capturing CO_2 at sources such as industrial power stations. The Protocol allows Annex 1 parties to implement projects which reduce greenhouse gases at source[109], and these can be counted as an emission reduction. It would seem if the CO_2 is captured at an industrial power station or similar facility then it cannot be released into the atmosphere and will not be counted as an 'anthropogenic emission' under the Protocol[110]. The UNFCCC and Protocol provides a clear option for the use of emission reductions, but are silent on how the emissions could be reduced at source and make no reference to storage sites. There is therefore nothing in the UNFCCC or Protocol which expressly prohibits captured CO_2 from being stored in geological formations under the sea. In fact the Protocol requires Annex 1 parties 'to implement policies and research, on the promotion, development and increased use of carbon dioxide sequestration technologies'[111].

The International Energy Agency are also of the opinion that 'neither the UNFCCC nor the Protocol include or exclude CCS as an encouraged or permitted emission reduction device giving rise to emission credits (IEA, 2005). The Intergovernmental Panel on Climate Change Report also found that both the UNFCCC and Protocol allows for projects that reduce greenhouse gases at their

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[103] Ibid, Article 1(4).

[104] The definition of a 'sink´ is given in Article 1(8) UNFCCC: *'Sink' means any process or activity which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere'.*

[105] The definition of reservoir is given in Article 1(7), UNFCCC: 'Reservoir' means a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored'.

[106] Kyoto Protocol, Article 6.

[107] Ibid, Article 3(3).

[108] Ibid, Article 3(4): 'additional human-induced activities related to changed in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories'.

[109] Ibid, Article 6.

[110] Ibid, Article 5(2).

[111] Ibid, Article 2(1) (a)(iv).

sources. The UK Government are similarly under the opinion that geological storage of greenhouse gases is not incompatible with the Convention, and have even commented that any Annex 1 Party that does not deploy CCS as provided for in Article 2(1)(a)(iv) might be presumed to be failing to develop the full range of policies and measures provided for in the Protocol (DEFRA, 2002).

Whilst it would appear that emission reductions by CCS are not prohibited, the UNFCCC appears to endorse using a precautionary approach, where policies and measures taken to deal with climate change are cost-effective, to ensure global benefits at the lowest possible cost[112]. It is unlikely that the construction of pipelines and direct injection into rocks below the seabed could be said to be currently the most cost effective means of dealing with climate change. Environmentalists could argue that it might be more cost effective to promote cleaner technology. If it is determined that the presently considered options for using the sub-seabed as a storage site for CO_2 do not ensure global benefits at the lowest possible costs, a higher level of scientific certainty may be required before allowing these activities (McCullagh, 1996).

Although sequestration projects appear to be encouraged under international climate change legislation, it should be noted that the Kyoto Protocol also provides that greenhouse gas emission reductions from sources and removals by sinks shall be reported in a transparent and verifiable manner. This is because there are concerns over the permanence of the CO_2 storage (i.e. that it is not spontaneously released to the atmosphere by fire or escape). There is an obvious problem about counting these as reductions because then there is potentially less or no incentive to minimize the risk of their escape after the credit has been given. With regards to geological sequestration where CO_2 could be stored for a scientifically uncertain period of time, legitimate concerns can be raised regarding leakage and security. The use of sequestration projects generally to count towards emission reductions and removals has also already attracted much controversy amongst Contracting Parties to the UNFCCC. Most of the focus of debate to date has been on terrestrial biosphere sequestration projects which are notably different from long-term CO_2 storage in geological reservoirs. The result of this is that methodologies for inventories and accounting of greenhouse gas reductions still need to be developed and approved by Contracting Parties to the UNFCCC and Kyoto Protocol (IPCC, 2005).

As the UNFCCC stands, it appears to distinguish between two types of methodologies for measuring greenhouse gas reductions. These are inventories for the sake of yearly national inventories of greenhouse gas emissions, and accounting of greenhouse gas reductions in flexible mechanisms in the Kyoto Protocol; i.e. carbon trading. At the current time, Intergovernmental Panel on Climate Change (IPCC) Guidelines and Good Practice Guidance Reports are used in preparing inventories under the UNFCCC framework. The IPCC guidelines do not yet specifically include CO_2 capture and storage options, though revised Guidelines providing guidance on incorporating CCS in greenhouse gas inventories are planned to be published in 2006 (IPCC, 2005). The recent IPCC report commented that capture and storage of CO_2 could then be incorporated in emission factors of industry and the power sector, meaning that carbon capture and storage would be a mitigation option reducing CO_2 from the source, rather than a sink enhancement option (IPCC, 2005).

It is clear that key greenhouse gas accounting and inventory issues must be addressed before CO_2 capture and storage activities can be included in the portfolio of climate change mitigation mechanisms. There are however potential problems in addressing these issues, such as the uncertainty regarding leakage rates, fraction retained and chances of accidental release of CO_2. It is unclear whether IPCC guidelines will suffice and maybe binding rules will required to be agreed by Contracting Parties to the Convention and Kyoto Protocol to resolve this. One solution under consideration is the introduction of compulsory insurance, and/or parties only being allocated temporary renewable credits, which will expire unless monitoring demonstrates that the stored

[112] United Nations Framework Convention on Climate Change, Article 3(3).

greenhouse gases remain in place. The value of the temporary storage of CO_2 will ultimately have to be decided through national and international political processes (IPCC, 2005).

5.5 CO_2 Storage and Environmental Assessment Legislation

5.5.1 Environmental Impact Assessment

Environmental impact assessment (EIA) is a procedure that seeks to ensure the acquisition of adequate and early information on likely environmental consequences of development projects or activities, on possible alternatives, and on measures to mitigate harm (Kiss and Shelton, 2000). The person who seeks to undertake the project or activity may be required to complete an environmental assessment before the project can receive authorisation. An environmental impact assessment could be required under international, European or domestic legislation.

The Law of the Sea Convention (UNCLOS) contains provisions concerning the environmental assessment of potentially damaging activities that take place in the oceans. UNCLOS provides that 'when states have reasonable grounds for believing that planned activities under their jurisdiction or control may cause substantial pollution of or significant and harmful changes to the marine environment, they shall, as far as practicable, assess the potential effects of such activities on the marine environment'[113]. This obligation applies to any part of the marine environment including marine waters under national jurisdiction. After the state undertaking the project has completed an assessment of the environmental effects they must communicate the results of the assessment to competent international organizations, which will make this available to all states[114].

The environmental assessment provision in UNCLOS is loosely drafted and it appears it will only be triggered if a state considers that their project or activity could cause pollution or significant and harmful changes to the marine environment. The use of the word 'practicable' suggests that a full assessment of the environmental impacts could in practice be somewhat limited, as states could provide the barest information to other states if they considered that this was 'practicable'. The state where the activity originates is also placed under a separate duty to monitor the risk or effects of pollution after the environmental assessment is complete and the activity is underway[115]. UNCLOS requires continuous environmental monitoring to determine whether the activities taking place are likely to pollute the marine environment, although the state is again only obliged to go as far as is 'practicable'. A Contracting Party to UNCLOS could challenge another Contracting Party under the procedures laid down in the Convention, if they considered that the environmental assessment provisions in UNCLOS had not satisfactorily been complied with.

The Convention on Environmental Impact Assessment in a Transboundary Context (hereafter ESPOO Convention) is another international agreement that stipulates the obligations of parties to assess the environmental impact of certain activities at an early stage of planning. The ESPOO Convention entered into force in 1997 and has been ratified by the European Union and the United Kingdom. The ESPOO Convention is more specific and detailed than UNCLOS in setting out the procedures and substantive requirements as to the EIA. It applies to the area under the Contracting Parties jurisdiction, which can include offshore projects on the continental shelf because certain projects at sea are included in the Annexes[116]. Contracting Parties must establish procedures with regard to listed activities that are likely to cause significant adverse transboundary impact. Impact is defined to mean any effect caused by a proposed activity on the environment, including on human

[113] UNCLOS, Article 206.
[114] Ibid, Article 205.
[115] Ibid, Article 204.
[116] ESPOO Convention, e.g. Annex I (15).

health and safety, flora, fauna, soil, air, water, climate, landscape and historical monuments or other physical structures, or the interaction among these factors[117].

The ESPOO Convention lists specific activities in Appendix I that are subject to the EIA requirements. Among the activities listed are major storage facilities for chemical products[118]. It is questionable whether geological formations under the oceans can be classed as storage facilities. Appendix I also include oil and gas pipelines[119], which could be relevant if the CO_2 is transported by pipeline to the storage site. Non-listed activities may be subject to the Convention requirements if the party of origin and the affected party or parties agree.

The most significant aspect of the Convention is that it lays down the general obligation of states to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries[120]. This limits its application to situations where impacts from activities of one state affect another state's territory. It is arguable whether geological carbon dioxide storage might have an impact on another state and this is most likely to be dependant upon where the activity takes place. If a state considers that another party could be affected they must notify the affected party who then have the right to participate in the environmental impact assessment process. The public in the territories affected also have the right to be informed of, and participate in the assessment procedure

A Directive on EIA was also introduced into European law in 1985 (and was later amended in 1997). Member States had to transpose the directive in its amended form by 1999. The EIA procedure under the Directive is more significant in its impact than the ESPOO Convention because it ensures that environmental consequences of projects are identified and assessed *before authorisation is given* (emphasis added). The process of EIA under the Directive can be broken down into a number of discrete stages. The first is to determine whether or not the project falls within the criteria for the requirement of EIA. The EIA Directive outlines which project categories shall be made subject to an EIA, and this determines which procedure shall be followed. Projects are categorized into Annex I, where EIA is compulsory; and Annex II, where an EIA is only needed if there are such significant effects on the environment by virtue of their nature, size or location.

There are no clear project categories in Annex I of the Directive that CO_2 storage projects could expressly fall under. One category covers waste disposal installations for the incineration or chemical treatment of waste[121]. Although there is a strong argument that CO_2 is a waste it is not incinerated and probably not treated. Another possible category that CO_2 geological storage might fall under is installations for the storage of petroleum, petrochemical, or chemical products with a capacity of 200,000 tonnes or more[122]. This might catch CO_2 storage and require an assessment of whether geological formations can be interpreted to be installations, CO_2 can be determined to be a chemical product, and whether more than 200,000 tonnes is stored. If the CO_2 is transported by pipeline an EIA will also be required if the chemicals pipeline is more than 800 mm diameter and a length of more than 40 km[123]. Where there is any degree of uncertainty over whether or not a project falls within Annex I of the Directive, a ruling on the need for an assessment can be obtained in the UK from either the Secretary of State or the local planning authority.

There are similarly no clear projects categories contained in Annex II that cover CO_2 storage projects. Some project categories are similar to those in Annex I, and include installations for the storage of petroleum, petrochemical, or chemical products (without the minimum tonne requirement)[124] and oil and gas pipeline installations (without the size and length requirement)[125].

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[117] Ibid, Article 1(vii).
[118] Ibid, Appendix 1 (16).
[119] Ibid, Appendix 1 (8).
[120] Ibid, Article 2(4).
[121] Directive on the assessment of the effects of certain public and private projects on the environment, Annex I (9, 10).
[122] Ibid, Annex I (21).
[123] Ibid, Annex I (16).
[124] Ibid, Annex II (6c).

Other categories that CO_2 storage could possibly fall under are deep drillings[126], or installations for the disposal of waste[127]. It seems that what is most likely to catch CO_2 storage is the provision in Annex II that covers 'any change or extension of projects listed in Annex I or Annex II, already authorized, executed or in the process of being executed, which may have significant adverse effects on the environment; Projects in Annex I, undertaken exclusively or mainly for the development and testing of new methods or products and not used for more than two years'[128]. It seems that an environmental assessment is currently required for the erection of floating installations such as oil and gas rigs[129]. If these rigs are modified to inject CO_2 into the seabed then it appears an EIA will be required.

If a project falls within Annex II of the Directive this does not necessarily mean that an EIA is required. It depends whether the project or activity is likely to have significant effects on the environment by virtue of factors such as its nature, size or location. The Directive contains explicit guidance on when an EIA is required. Schedule 3 now contains selection, or screening criteria to which the decision maker must have regard. These are grouped together under general headings of:

the characteristics of the development;
the location of the development;
the characteristics of the potential impact.

Under heading 1) factors such as the size of development, its use of natural resources and its waste production must be considered.

If an EIA is required the statement should include information on the direct and indirect effects of a project on a variety of factors, including human beings, fauna, flora, the environment and material assets and the cultural heritage. The developer must submit certain specified information to the authority dealing with the application. This crucially includes information on alternatives studied – which could mean the developer having to argue why other CO_2 reduction or storage alternatives were not chosen. The developer must also consult and make information available to statutory consultees, other authorities likely to be concerned with the project, and members of the public. The Directive also implements the ESPOO Convention in respect of the European Community and Member States affected are given rights to participate in the decision making process. Members of the European Economic Union must also be supplied with information about the project but they have no rights to participate in the decision making process. In the case of CO_2 storage projects in the North Sea the United Kingdom therefore has obligations under European law (the Directive) to engage Member States and under international law for countries such as Norway who are signatories to the ESPOO Convention but who are not members of the European Community. The results of all of this consultation are taken into account in the authorisation procedure of the project. In the event of a dispute over whether an EIA is required, it rests with national courts and possibly the European Court of Justice to interpret the Directive.

5.5.2 Strategic Environmental Assessment

The European Community adopted a Strategic Environmental Assessment (SEA) Directive[130] which became law in July 2004. SEA is a process for predicting and evaluating the environmental implications of a policy, plan or programme and the SEA is a key input to decision making. Authorities which prepare and/or adopt a plan or programme that is subject to the Directive will

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125 Ibid, Annex II (10i).
126 Ibid, Annex II (2d).
127 Ibid, Annex II (11b).
128 Ibid, Annex II (13).
129 E.g. see The United Kingdom Offshore Petroleum Production and Pipe-lines (Assessment of Environmental Effects) Regulations 1999.
130 Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (the SEA Directive).

have to prepare an environmental report on the plan or programme's likely significant effects on the environment[131]. The SEA Directive is similar to the Environmental Impact Assessment (EIA) Directive but the actual assessment is done earlier at a broader, more strategic level. This contrasts with EIA which is carried out for a specific development or activity. Both an EIA and SEA can be carried out and they are not mutually exclusive.

The SEA Directive has quite complicated criteria and the European Commission has issued guidance on when SEA is applicable (European Commission, 2003). It seems that whether the SEA Directive applies depends firstly on whether there is a plan or programme, and secondly whether it falls under one of the categories listed in the Directive. The Directive applies to plans and programmes which public sector bodies and a limited number of private sector bodies (principally privatized utility companies) are 'required' to produce and/or adopt[132]. No detailed explanations of the terms 'plan' or 'programme' are given, but it is likely that these will be interpreted widely. For a plan or programme to be 'required', essentially an authority must have no discretion as to whether or not it prepares the plan or programme.

An SEA is mandatory if it falls under one of the categories listed in the Directive. Four project categories could be relevant to CO_2 capture and storage:

1) plans and programmes which are prepared for energy;
2) waste management;
3) water management;
4) plans or programmes requiring appropriate assessment under the Habitats Directive[133].

Other plans or programmes which set the framework for development consent of projects (here not limited to project types listed in the EIA legislation) require SEA if they are determined by screening to be likely to have significant environmental effects. Minor modifications to plans and programmes in the categories which generally require mandatory SEA and those for small areas at local level only require SEA where screening determines that they are likely to have significant environmental effects[134]. Screening can be carried out on a case-by-case basis and/or by specifying categories of plans or programmes[135]. The Directive sets out criteria to be used for screening and these include such things as effects on internationally and nationally designated sites.

The assessment takes place during the preparation of the plan and programmes and before their adoption. An environmental report should be prepared which identifies, describes and evaluates the likely significant environmental effects on the environment of implementing the plans or programmes and reasonable alternatives. Measures to avoid, mitigate or compensate for serious adverse impacts must be included, as must a description of proposed monitoring measures. The public and environmental authorities must be consulted and can give their opinion. All the results from the consultation process are integrated and taken into account in the course of the planning procedure. After the adoption of the plan or programme the public is informed about the decision and the way it was made – particularly what environmental considerations were integrated into the plan or programme. In the case of significant transboundary effects, the affected Member State and its public are informed and have the possibility to make comments which are integrated into the national decision making process.

There has already been a significant amount of activity by the United Kingdom Government into how SEA could come into play in offshore waters (House of Commons, 2004). The Department of Trade and Industry (DTI) have already begun undertaking a series of SEAs for the offshore oil and gas sector based on the requirements of the Directive. An SEA has already been carried out to inform offshore oil & gas licensing with the purpose to make sure these are developed

131 Ibid, Article 3(1).
132 Ibid, Article 2.
133 Ibid, Article 3(2).
134 Ibid, Article 3(3).
135 Ibid, Article 3(5).

in an environmentally sensitive manner. The DTI are examining the geological structures of the area by conducting seismic surveys and exploration drilling. This is to determine where hydrocarbons could accumulate and be retained by examining the size of the reserves and extent of the reservoirs. The SEA will also examine areas of the continental shelf to identify areas that may require special protection or consideration after examining the environmental effects on seabed fauna, whales, dolphins and other marine mammals. The DTI is also carrying out an SEA looking at offshore renewables such as wind farms and the risks and uncertainties with developing these.

It is not completely clear whether an SEA for geological CO_2 storage will be a legal requirement under the SEA Directive. This will in part be dependent on whether the Government prepares any plans or programmes that come within the scope of the Directive. The government is currently conducting SEAs for offshore oil and gas installations and renewables and is hoping to tie the results of these SEAs together. There is an argument that the remit of these SEAs could be extended to include carbon dioxide storage as there are obvious overlaps. It seems likely that there could be a Government commitment to do an SEA for CO_2 storage in the near future.

At a meeting in Kiev in May 2003, the parties to the ESPOO Convention adopted a new international convention called the Strategic Environmental Assessment (SEA) Protocol. Thirty five countries signed the Protocol, including the UK, together with the European Union. The SEA Protocol is not yet in force, but when it is ratified will require its parties to evaluate the environmental consequences of their official draft plans and programmes. It is similar to the European SEA Directive but will have greater application – in the sense that it will also apply to countries not belonging to the European Community (EC). This is important in relation to geological CO_2 storage projects because the UK may have to consult North Sea neighbouring countries such as Norway (which is not an EC Member State). The Protocol could take many years before receiving the required number of ratifications allowing it to enter into force.

5.6 CO_2 Storage and Habitat Protection Legislation

5.6.1 Habitat Protection under International Law

The United Kingdom Government has ratified a number of international conventions which concern habitat protection. The most relevant of these is the Biodiversity Convention of 1992, which came into force in 1993. This Convention requires parties to adopt national strategies, plans and programmes for the conservation and sustainable use of biological diversity. It requires Contracting Parties to integrate the conservation and sustainable use of biological diversity into relevant sectoral or cross-sectoral plans, programmes and policies[136]. The aim of this is to establish protected areas to conserve and protect ecosystems, habitats, and threatened species.

The Convention recognizes the traditional sovereign rights of states to exploit their own resources and their responsibility to ensure that activities within their jurisdiction do not cause damage beyond the limits of national jurisdiction[137]. The application of the Convention extends to marine waters, and at the second conference of the parties to the Convention in 1995 it was agreed that marine biodiversity should be a priority area for action. The Jakarta Mandate on Marine and Coastal Biological Diversity was subsequently adopted and this sets out a strategy for marine biodiversity with special emphasis on integrated marine and coastal area management and the precautionary approach. The Convention and Mandate provide support that some assessment of the impact of geological carbon storage on marine biodiversity could be required. Whether or not such an activity will be in conflict with this Convention depends on what such an assessment of

[136] Biodiversity Convention, Article 6.
[137] Ibid, Article 3.

biodiversity reveals - i.e. what impact CO_2 geological storage will have on the biodiversity around the storage sites.

Even if there is an impact on biodiversity this does not necessarily mean that the Convention will prohibit CO_2 storage from taking place. The Convention states that 'Contracting Parties, as far as possible and as appropriate, shall take into account the environmental consequences of its programmes and shall initiate action to prevent or minimize conditions that present an imminent or grave danger or damage to biological diversity'[138]. The use of the words 'as far as possible' and as 'appropriate' weakens the legal status of the Convention. It seems likely that CO_2 storage could still take place as long as there is not a significant impact on habitats and the Government has taken into account these environmental consequences and proposed some form of mitigation measures.

The OSPAR Convention was discussed in detail in the section 5.3.3. While the OSPAR Convention has marine pollution as its main focus, it also contains important provisions in Annex V aimed at the protection and conservation of the ecosystems and biological diversity of the maritime area. Contracting Parties to the OSPAR Convention must 'take the necessary measures to protect and conserve the ecosystems and the biological diversity of the maritime area, and to restore, where practicable, marine areas which have been adversely affected; and cooperate in adopting programmes and measures for those purposes for the control of the human activities identified by the application of the criteria in Appendix 3'[139]. This appears to place a legal duty on Contracting Parties, although it uses similar weak language as the Biodiversity Convention – e.g. 'where practicable'. The Biodiversity Committee of the OSPAR Commission has to draw up plans and programmes designed to achieve programmes and measures for the control of human activities[140]. They can then impose measures for instituting protective, conservation, restorative or precautionary measures related to specific sites or a particular species[141]. It is possible that the OSPAR Commission could seek to protect habitats or species in an area where CO_2 disposal is planned, and thus block potential projects in certain locations, although very little seems to be have been done under these provisions so far.

In March 2002, the United Kingdom signed up to the Bergen Ministerial Declaration[142]. This agreed to 'the strengthening of cooperation in the spatial planning processes of the North Sea states related to the marine environment' to prevent and resolve the potential problems created by conflicts 'between the requirements for conservation and restoration of the marine environment and the different human activities in the North Sea'[143]. The Declaration also invites the OSPAR Biodiversity Committee, 'to investigate the possibilities for further international cooperation in planning and managing marine activities through spatial planning of the North Sea states taking into account cumulative and transboundary effects'[144].The Declaration agrees that close cooperation of regional governments, local authorities and other stakeholders, is important for future development of a marine planning system in the North Sea[145]. Similarly, OSPAR's own work is examining how the role of spatial planning will help to improve co-operation and management of the range of different activities that take place in coastal waters.

[138] Ibid, Article 14(1)
[139] OSPAR Convention, Annex V, Article 2.
[140] Ibid, Article 3(1)(a)
[141] Ibis, Article 3(1)(b)
[142] Ministerial Declaration of the Fifth International Conference on the Protection of the North Sea. Bergen, Norway 20–21 March 2002.
[143] Ibid, Section XI, paragraph 76.
[144] Ibid, Section XI, paragraph 77(ii).
[145] Ibid, Section XI, paragraph 78.

5.6.2 *Habitat and Species Protection under European Law*

The European Community adopted the Habitats Directive, in 1992[146]. The Directive seeks to preserve/restore natural habitats and wild fauna and flora, by obliging Member States of the EC to provide a comprehensive network of special areas of conservation for endangered and vulnerable species and habitats[147]. This nature network established under the Habitats Directive in conjunction with the Birds Directive, consists of sites of international importance. The Habitats Directive provides measures to protect conservation areas[148] and measures to protect species[149]. The Annexes to the Directive list the broad categories of natural habitat types and the specific animal and plant species of interest. The network will consist of sites containing the one-hundred and sixty nine natural habitats types listed in Annex I of the Directive and sites containing the six-hundred and twenty three habitats of the species listed in Annex II.

The Habitats Directive calls for the creation of a network of protected areas known as Natura 2000, to consist of Special Areas of Conservation. EC Member States are required through a statutory, administrative and/or contractual act to propose sites for designation as special areas of conservation, drawn up by reference to the criteria laid down in Annex III, and send these to the European Commission. There is also provision for EC designation in exceptional circumstances where a site hosts a priority natural habitat type or priority species. A mandatory duty of care is placed on the Member State in which that habitat is found.

The Habitats Directive covers marine biodiversity in its scope. The United Kingdom (UK) Government was once of the opinion that the Directive did not extend beyond its territorial waters[150]. This cumulated in a court case in 1999 with Greenpeace taking the UK Government to court, where the judge ruled in favour of Greenpeace. The current UK policy is that the Habitats and Birds Directives should apply to waters up to two-hundred nautical miles from the coast and to adjacent designated areas of continental shelf. One implication of the Greenpeace case is that the UK regulations implementing the Directive[151] will need to be revised so that they cover the continental shelf. The UK Government is currently taking steps to implement the Habitats Directive in offshore waters and draft Regulations were consulted upon in 2003 (DEFRA, 2003). The draft Offshore Marine Regulations (Natural Habitats) Regulations do not appear to have been approved by Parliament as yet. Several Member States, have also struggled to designate special areas of conservation in sea areas outside their territorial waters. At the current time, a number of coastal areas around the UK are designated as special areas of conservation, but no sites on the continental shelf are designated. The UK will probably begin to designate sites in this area after the regulations come into force.

Although marine biodiversity falls within the scope of the Directive, marine habitats and species are poorly represented in the Directive itself, which has an almost exclusive focus on territorial and coastal habitats. To enable identification of offshore habitats and species, and comply with the requirements of the Directive, the Joint Nature Conservation Committee (JNCCC) have been asked by the United Kingdom government to provide information on special areas of conservation. The 'Offshore Natura 2000 Project' is being conducted by JNCC under a steering group consisting of representatives from sponsoring government departments. Under this review special areas of conservation may be put forward for habitats of conservation importance (listed in Annex I to the Habitats Directive) or for species of conservation importance (listed in Annex II).

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[146] Council Directive 92/43 on the Conservation of natural habitats and of wild fauna and flora
[147] Ibid, Article 2.
[148] Ibid, Articles 3-11.
[149] Ibid, Articles 12-16.
[150] R v Secretary of State ex parte Greenpeace, Queens Bench Division, 5 November 1999 CO/1336/99.
[151] Conservation (Natural Habitats) Regulations 1994

Some areas of possible Annex I habitat in offshore waters have been mapped using existing British Geological Survey geological seabed map interpretations. This does not cover all of the United Kingdom continental shelf and for a number of areas of potential Annex I habitat there are no, or limited, biological data. The JNCC have identified a number of habitats that occur in United Kingdom offshore waters and these are produced in Table 5.3 below.

Table 5.3: Habitats from the EC Habitats Directive occurring in United Kingdom Offshore Waters

Annex I habitats (from Directive 92/43/EC amended by 97/62/EC)
Sandbanks which are slightly covered by seawater all the time
Reefs
Submarine structures made by leaking gases
Submerged or partially submerged sea caves

Source: Taken from the Joint Nature Conservation Committee website.

Shallow sandbanks are concentrated off north and north-east Norfolk, in the outer Thames Estuary, off the south-east coast of Kent and off the north-east coast of the Isle of Man. Reef habitat occurs in the English Channel, Celtic Sea, Irish Sea and west and north of Scotland extending far out into the North Atlantic. Reef is scarce in the North Sea. Shallow sandbanks are found in United Kingdom (UK) offshore waters. In the northern North Sea, 'pockmarks' containing carbonate structures deposited by methane-oxidising bacteria occur, these structures may fit within the definition of the Annex I habitat of 'submarine structures made by leaking gases'. No sea caves have yet been identified in UK offshore waters. There are only a limited number species listed in Annex II of the Habitats Directive which are known to occur in UK offshore waters. The JNCC have identified a number of species that occur in UK offshore waters and these are produced in Table 5.4 below.

The loggerhead turtle, lamprey, and sturgeon are all rare in United Kingdom (UK) waters and without regular places of occurrence in offshore waters it is unlikely that special areas of conservation (SAC) could be selected for them. Of the species listed, only four are commonly seen in UK waters: the grey seal, common seal, bottlenose dolphin and harbour porpoise. These four species are typically wide ranging, thus making it difficult to identify specific areas which may be deemed essential to their life and reproduction, and which may, therefore, be considered for proposal as a SAC. For the two seal species, coastal SACs have already been proposed in the UK to protect their selected breeding colonies and moulting and haul out sites, and three SACs have been proposed for bottlenose dolphin within UK territorial waters. The UK currently has no proposed SACs for harbour porpoise.

Table 5.4: Species from the EC Habitats Directive occurring in United Kingdom Offshore Waters

Annex II species(from Directive 92/43/EC amended by 97/62/EC)
Harbour porpoise *Phocoena phocoena*
Bottlenose dolphin *Tursiops truncatus*
Common (or harbour) seal *Phoca vitulina*
Grey seal *Halichoerus grypus*
Loggerhead Turtle *Caretta caretta*
Lamprey *Petromyzon marinus*
Sturgeon *Acipenser sturio*

Source: Taken from the Joint Nature Conservation Committee website.

It is possible that CO_2 storage may impact on the marine eco-system as a result of injections into the seabed, or the laying of pipelines and other seabed infrastructure used during operations. The possibility of CO_2 escaping and its effects on biodiversity will also require closer scientific consideration. The most foreseeable impact on habitats and species will be dependent on the location of the platforms and storage sites, as well as the routes followed by pipelines (if they are the method of transportation). The question therefore is whether these habitats or species that are present in these areas are likely to be affected by licensing CO_2 storage. Clearly if they are not, then they are unlikely to be protected as special areas of conservation. Even if an area has been designated as a special area of conservation, and none have as yet in UK's offshore waters, this still does not provide absolute protection against interference - only restrictions. The Directive states that in the absence of alternative solutions, Member States may permit interference for 'imperative reasons of overriding public interest' – which expressly include social or economic interests. If Member States rely on this clause then appropriate compensatory measures must be provided to preserve the coherence of Community habitats. 'Priority' habitat types, however, generally may only be interfered with for environmental, human health or public safety reasons. Other reasons of overriding public importance may only be invoked 'further to an opinion from the Commission'. It is possible that one might argue that CO_2 storage is in the 'overriding public interest', and/or they are interfering with the site for 'environmental, human health or public safety reasons'.

A further example of the limitations of the Habitats Directive, can be seen in the case brought by Greenpeace in 1999[152]. Greenpeace argued that reefs fell within Annex I of the Directive and the oil and gas licences issued by the United Kingdom Government would have an adverse effect on these. The Directive requires Member States to establish 'a system of strict protection of animals listed in the Directive'[153]. The Directive also prohibits the following activities, (i) all forms of deliberate capture or killing of specimens of the species in the wild, (ii) deliberate disturbance of the species especially during breeding seasons, (iii) deterioration or destruction of breeding sites. Greenpeace argued that these prohibited activities were merely illustrative of the overarching requirement to establish a strict system of protection. But the court agreed with the Government and the oil companies that they are not an exhaustive list of the means of protection. The court then considered the meaning of the word 'deliberate' which qualified the prohibition on capture, killing and disturbance of species. The word is not defined in the Directive, and, as the court noted, it is not a concept normally used in UK law. Greenpeace argued that when an oil company conducted operations which they knew were likely or possible to result in killing or disturbance, that was a deliberate act which fell within the Directives prohibition. Again the court agreed with the Government and the oil companies and did not think it was deliberate disturbance. But the prohibited act covering the deterioration or destruction of breeding sites – is not qualified by the word 'deliberate'. The question in the Greenpeace case then was whether this was an absolute prohibition, which was therefore incompatible with the general defence under the UK regulations which related to incidental actions. The judge found that whilst the Directive requires a prohibition, it did not follow that it obliged Member States to create criminal offences.

5.7 Conclusions

Increasingly, geological carbon dioxide storage has been gaining attention as a potential technological solution to climate change, both in the United Kingdom and internationally. At national and international level there has also been growing discussion as to whether the storage of CO_2 in this manner is consistent with existing international laws, but there has been no consensus as

[152] R v Secretary of State ex parte Greenpeace, Queens Bench Division, 5 November 1999 CO/1336/99.
[153] Council Directive 92/43 on the Conservation of natural habitats and of wild fauna and flora, Article 12.

yet. This is because the current legal framework is often ambiguous because laws were not drafted with this mitigation option and its technologies in mind.

Most of the focus on the storage of CO_2 under existing international laws to date has been on marine laws. A review of these laws does not offer definitive answers as to the correct legal position, but certain observations may be made. Firstly, it is not clear whether geological reservoirs and formations are caught under the definitions of sea, seabed or subsoil under the conventions. Secondly it is also unclear as to whether CO_2 should be treated as a waste under the conventions. On balance, the author considers that geological reservoirs and formations are probably within the remit of the conventions' scope and that CO_2 is also probably a waste. The method by which the CO_2 reaches the storage site also strongly influences the legality of such projects. Under each of the marine conventions it seems likely that if CO_2 is transported by ship then disposed of from an offshore installation (such as an oil rig), this will be prohibited. In the case of a pipeline carrying CO_2 to an installation, this will be prohibited under the London Convention and the 1996 Protocol. This is not always the case under the OSPAR Convention, where the prohibition against dumping only applies to installations carrying out activities concerning hydrocarbons. Since is not a hydrocarbon it is permissible under the OSPAR Convention to pipe CO_2 to offshore installations provided they have not already been used for activities involving hydrocarbons. Under OSPAR, however, states have general environmental obligations with respect to land-based pipelines.

Recent studies into the legality of CO_2 storage have tended to call for immediate reviews into the current drafting of the marine conventions. This was a recurring theme in the recent report of the International Energy Agency; an example comment being - 'the contracting parties to these agreements need to interpret, clarify or, as the case may be amend these treaties with a view to account for some form of controlled carbon storage. There is significant room for such interpretation and clarification under these treaties' (IEA, 2005). The IEA thought that the contracting parties should also proactively 'take into consideration not only their marine environment protection objectives, but also their objectives regarding climate change mitigation', especially 'if they want a coherent international framework for carbon storage to be developed' (IEA, 2005). The Intergovernmental Panel on Climate Change were less forceful in their recent report, but still concluded that 'it will be essential to resolve these [marine laws] issues if CCS [carbon capture and storage] is to become part of the portfolio of mitigation options' (IPCC, 2005).

Although it is correct to point out that there are uncertainties under the current legal regime for marine protection, this is only because they were not drafted with the relatively new concept of CO_2 storage in mind. What, in the authors' opinion, is perhaps more important in relation to taking geological dioxide storage as a mitigation option forward, is the status of CO_2 storage under the UNFCCC and Kyoto Protocol. At the current time it seems clear that both the UNFCCC and Kyoto Protocol allow for projects that reduce greenhouse gases at their sources and CO_2 storage can in theory be counted as an emission reduction. However, methodologies and rules for accounting of greenhouse gas reductions still need to be developed and approved. Without agreement on these, no CO_2 storage projects will be undertaken, because it is unlikely that costly projects will be financed without any incentive e.g. that they are counted as an emission reduction.

Focusing on changes to marine legislation alone is not the way forward, when greater clarification and certainty is also needed in relation to climate change legislation and rules. However, because of the slow pace of international law it is probably correct to raise all of the legal issues concerning CO_2 storage projects and consider them all in advance. What is needed before the holy grail of *greater legal certainty* (authors' emphasis) is international consensus as to whether a large enough group of the international community want offshore geological CO_2 storage as a significant mitigation option. Some commentators might argue it is merely distributing pollution, whilst others consider that it is only feasible way of meeting climate targets in the short term. Other solutions including nuclear power, development of alternative energy sources, or carbon trading may also be viewed as difficult choices. The international community has to become engaged in facing these difficult choices and decide which options to pursue, because business as usual scenarios will not provide a solution. Only when looking at difficult environmental choices such as climate change in the context of other international environmental laws, and considering all of the options including geological carbon dioxide storage, can politics reach a solution that can then be backed up by introducing adequate international laws.

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Chapter 6

The Public Perception of Carbon Dioxide Capture and Storage in the UK: Results from Focus Groups and a Survey

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6.1. Introduction

As carbon dioxide capture and storage (CCS) rises on the climate policy agenda in a number of countries, the study of public perceptions and perceived acceptability of it is at an early stage and comprises only a handful of studies (Curry *et al.*, 2004; Gough *et al*,. 2002; Huijts, 2003; Itaoka *et al*,. 2004; Palmgren *et al*,. 2004; Shackley *et al*,. 2004). One of the few experiences of a related mitigation approach is the Ocean Field Experiment in Hawaii, a case-study of which has illustrated how bureaucratic obstacles, a few dedicated activists and slow recognition of the need for public outreach derailed the project (de Figueiredo, 2002).

We know, however, that public perceptions can have a very significant, and frequently unanticipated, effect upon major planned projects involving new technologies and infrastructure. Examples include: the effects of public opinion on the planned disposal of the Brent Spa oil platform in the mid-1990s, and the on-going debates over genetically modified organisms (GMOs), and nuclear waste disposal (Smith, 2000; Irwin & Michael, 2003; Hunt & Wynne, 2000). Closer to the issue of CO_2 storage, proposals for underground natural gas storage schemes have generated public opposition in some localities in the UK, despite similar facilities operating very close by with out apparent concern (Gough *et al.* 2002). In two such cases, concerns about uncertain and difficult to assess risks to health and safety emerged. The effect that such perceived risks could have on local property prices also caused concern. The local media played an active role in disseminating the concerns about these natural gas storage proposals to a wider public audience (Overwyrefocus, Nogasplant websites, no date).

In response to such reactions, there has been a general shift by decision-makers to gathering better prior intelligence of possible public reactions to major new technologies, and also towards more consultative and 'deliberative' decision-making styles (RCEP, 1998; House of Lords, 2000). Clearly, possible public reactions to CCS, and how developments in the area might proceed so as to take such reactions into account, are important areas of research.

Research on the public perceptions of CCS is, however, challenging because of: a) the relatively technical and 'remote' nature of the issue, meaning that there are few immediate points of connection in the lay public's frame of reference to many of the key concepts; b) the early stage of the technology, with very few examples and experiences in the public domain to draw upon as illustrations. An in-depth research approach is frequently useful for understanding public perceptions of an unknown technology, whereby technical information is provided in an incremental fashion to the target public sample. Methodologically, focus groups and in-depth discussion groups can therefore make a valuable contribution. The disadvantage is that only small samples can be surveyed using in-depth methods, as opposed to surveys which can, ideally, offer a representative sample and their findings subject to more robust statistical testing. In the study we report on here, we combine the strengths of both methods, by designing a questionnaire administered through face-to-face interviews on the basis of prior discussions in extended in-depth groups which we call 'Citizen Panels' (see Figure 6.1).

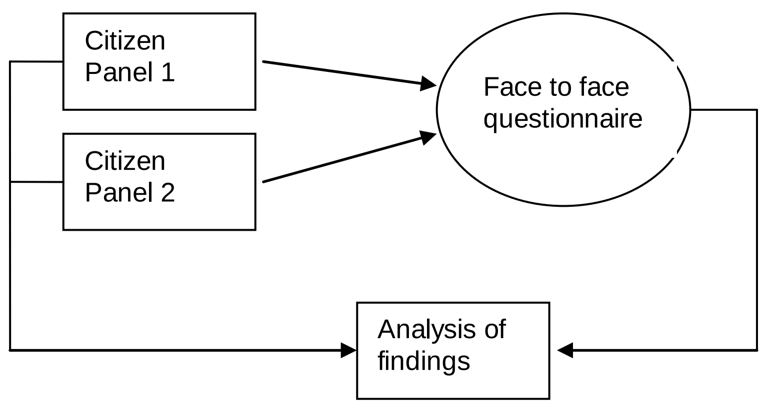

Figure 6.1 Methodology

6.2. Research Objectives and Methodology

The main objectives of the research were:

1) To explore and understand what the public perceptions of off-shore CO_2 capture & storage (CCS) are, both when first presented with the idea and when more background information is provided.

To explore and understand perceptions of the key risks and concerns surrounding CCS and what information, policies and processes would make CCS more and less acceptable to the public.

We only considered off-shore CO_2 storage because our earlier research suggested that, where there is a viable off-shore storage option it is much preferred to on-shore storage. Given the availability of potentially highly suitable off-shore storage sites in the UK we decided that involving the respondents in a discussion of on-shore storage would be distracting and create unnecessary confusion.

We ran two Citizen Panels over two five week periods in the last quarter of 2002 and the first quarter of 2003. Each Panel met for ten hours in total. A Citizen's Panel is a moderated group of between eight and ten individuals who meet over an extended period to discuss a set of related issues and who provide an informed opinion on those issues at the end of the Panel. Similar to a focus group, the key differences are that there is a gradual build-up of information on the particular topic of discussion, usually with expert witnesses, whom the Panel has the opportunity to question. The methods are described in detail in Kasemir *et al*. (2003). We recruited two demographically distinct Citizen Panels. The York group was all male with six participants from socio-economic group B and three participants from socio-economic group C. The Manchester group was all-female and composed of six participants from group C and three participants from group B.

Our intention in recruiting distinct groups was to provide a clear and interesting contrast between the two Citizen Panels. Expert witnesses representing a range of viewpoints gave presentations and then took part in a Question and Answer (Q&A) session. This included speakers from: British Geological Survey (BGS), BP, IEA Greenhouse Gas R&D Programme, Tyndall Centre for Climate Change Research and Friends of the Earth.

We then designed a questionnaire by drawing upon the citizen panel findings. The Citizen Panel work led us to exclude ocean and onshore storage options. It also highlighted the need to: measure the extent of belief in, and concern regarding, climate change; make an explicit comparison between CCS and other low-carbon energy options; and to analyse the effect of introducing information about the purpose of CCS upon the sample's responses. We also drew upon other climate change questionnaires (e.g. Lorenzoni, 2003; Shackley *et al.*, 2001). We tested the design of the questionnaire with a small sample (5 people) and modified it in the light of their comments and suggestions. A team of six interviewers conducted 212 face-to-face interviews over two days in August 2003 at the Liverpool John Lennon International Airport. The acceptance rate was between 40 and 50%. The questionnaire took between 10 and 20 minutes to complete, depending on the level of interest of the respondent.

In order to ascertain the extent to which the socio-economic profile of the travellers at Liverpool John Lennon International Airport reflects the population of the UK as a whole, we compared the information collected on annual income of the sample to the information on the income bands of the UK as a whole. Although our sample covered a wide range of household income levels, compared to the distribution of UK household incomes (Department of Work and Pensions, 2003) it was skewed towards higher incomes (i.e. above £30,000). The highest incomes (i.e. above £40,000), were the most over represented. This distribution is to be expected given that research by the Civil Aviation Authority has shown that those in the top three income brackets are more than four times as likely to fly as those in the lowest three brackets (Environment Audit Committee, 2003).

Whilst clearly not statistically representative of the UK population, it is possible to calculate the accuracy of the responses, relative to the target population of the airport on the days that the survey was conducted, given that the sample size of 212 represents approximately 2% of the people (10,500) travelling to and form the airport over the period in which the survey was conducted (CAA 2004). The Normal approximation to the Binomial distribution was then used to calculate the confidence intervals to be calculated (Upton and Cook, 1997): $ps \pm 1.96\sqrt{(ps(1-ps)/n)}$, where ps is the proportion of the sample who respond in a particular way to a given question, and n is the sample size. The value obtained is the error at 95% probability.

6.3. Main Findings of the Survey

None of the respondents were familiar with $C0_2$ Capture and Storage prior to the interview. We found that, on first contact with the idea of CO_2 capture and storage, and without any information on its purpose, most people (48±7%) are neither for nor against CCS or say that they do not know, with a significant number (38±6.5%) expressing slight or strong reservations (see Figure 6.2). Only 13% (±4.5%) volunteered support for the idea. Table 6.1 outlines the information which was provided to the respondents and the order in which it was presented. Researchers filled in response forms as the respondents verbally answered the questions. On these response forms there were various instructions for the researchers and specified sections to read to the respondents. The Table indicates the chronological order of information presented to the respondents to the survey.

Table 6.1 Information provided to the survey respondents and the order in which it was provided

Question	**Information to respondent**	**Guide/actions for researcher**
		Half day training session
	“In this section we are interested in your first impression of an idea. It may seem odd that there is little information given but your immediate response is what interests us here. The Government is currently looking at putting Carbon Dioxide in to underground storage sites under the North Sea. This process is called Carbon Storage. Carbon Dioxide is the gas which is produced by burning coal, gas and petrol.”	
1. What is your initial reaction to this idea?		
	“The words Climate Change are generally used by scientists to describe the way that the climate of the world may be changing as a consequence of human activities. If human beings are influencing the climate, there will be changes in temperature, rainfall and weather patterns, which will affect the natural world and human beings”.	
2. Do you believe that human activities are affecting the climate? 3. Are you concerned about climate change? 4. In general, would you say that climate change receives too much or too little attention by politicians at the present time? 5. Do you think that the public should be actively involved in deciding what should be done about climate change ? 6. Do you think that policies to combat climate change should be decided mostly by government experts and scientists?		
	“Most experts believe that in order to have a significant impact upon climate change we must achieve a 60% reduction in emissions such as carbon dioxide. By using Carbon Storage the United Kingdom could significantly reduce its carbon dioxide emissions while continuing to use fossil fuels. This could allow society to continue to use existing levels of fossil fuels for many decades to come. It could also act as an “in-between” strategy while longer-term solutions are further developed, such as renewable energy technologies.” A simple diagram of CCS was then show to the respondents (showing capture at a power station, pipelines to the coast, pipelines along the sea bed and injection to a depleted oil or gas well or aquifer).	
7. Do you think that there may be any negative effects of doing this? 8. Do you think there may be any positive effects of doing this?		Do not prompt the respondent, classify their responses based on training and pre-agreed set definitions.
Remainder of questions. No new information presented.		

When more detailed information was provided on the reasons *why* CCS is being proposed, i.e. as a way of reducing CO_2 emissions into the atmosphere, support increased substantially. Half of the survey respondents (±7%) developed a more positive attitude towards CCS, though a sizeable minority (35±6.5%) did not change their opinion and 16±5% became more negative. Respondents shifted primarily from the 'don't know' or 'neither support nor not support' categories to the 'slightly support' category (see Figure 6.3).

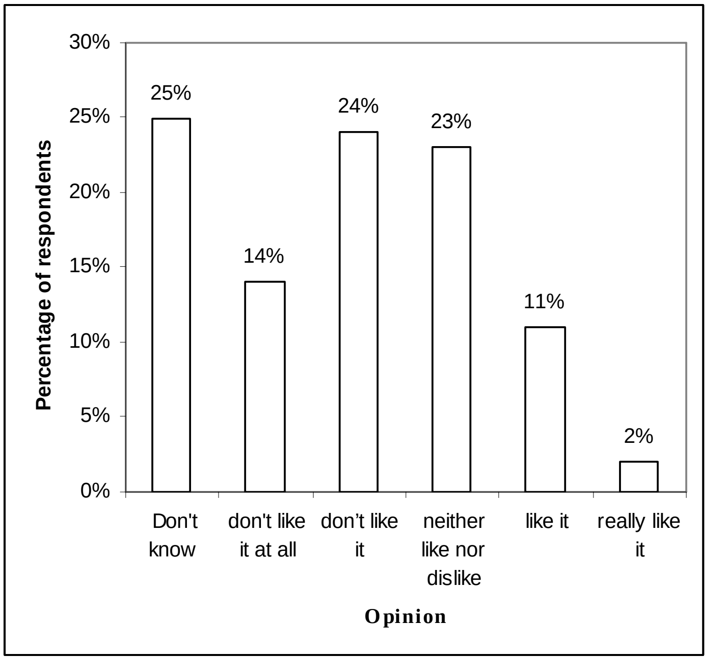

Figure 6.2 Initial reaction to CCS without any information on its purpose

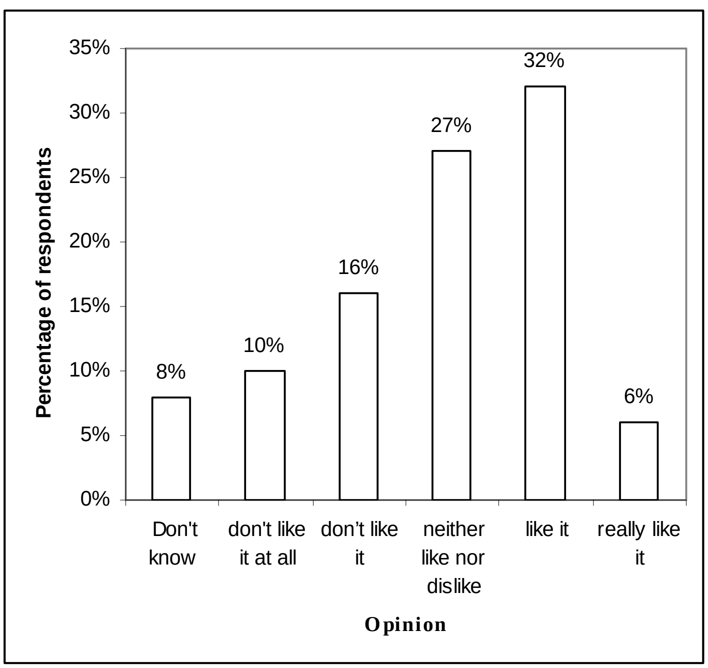

Figure 6.3 Opinion of CCS at the end of the survey

We also asked respondents about their support for CCS relative to other low- or zero-carbon energy options (wind, solar, wave & tidal, nuclear, energy efficiency and higher energy bills). We found that support for CCS was somewhat greater when compared to the main other options than when considered in isolation. A larger number of respondents also said that they did not know, or were neither in favour nor against, when asked specifically about their support for CCS than other decarbonisation options (at 35±6.5% compared to 24±6%). This suggests that CCS is more favourably regarded when it is compared alongside the other principal decarbonisation options, than when it is considered in isolation. This might reflect the ability to perceive options more negatively when they are considered in isolation, rather than compared to the other main options for achieving a given objective (in this case low carbon emissions).

Overall, support for CCS on the basis of this survey can best be described as moderate or lukewarm compared to strong support in general for wind, solar and energy efficiency (see Figure 6.4). Whilst over 80±5.5% of respondents ‘strongly supported’ wind, solar and energy efficiency (and with a further 10±4% or more slightly supporting these options) 12±4.5% of the sample strongly supported CCS with a further 43±7% offering slight support, and 23±6% slightly or strongly against it. CCS is much preferred, however, to nuclear power and to higher energy bills (see Figure 6.4).

The large majority of our sample believed that human activities are causing climate change (either strongly or moderately). Only 7.5±3.5% of the sample disagreed or did not express a view either way. There was also a generally moderate to high concern about climate change, though there was also a substantial number (22±5.5%) who did not express a view either way, and a further 15±5% who were not concerned about climate change. This suggests that whilst many people now accept that human activities are a major cause of climate change, there is less consensus on whether climate change is a problem, though still over 60±7% say there are “very concerned” or “concerned”. The high level of belief and concern regarding anthropogenic climate change meant that these factors could not be used to explain preferences with regards to CCS. There were no significant differences in the perceptions of CCS in our sample according to the other demographic variables measured (age, income, gender).

Note, however, that we did not request the respondents to rate the importance of climate change as an issue compared to other contemporary socio-economic, political and environmental ‘problems’. This may have led to greater concern being expressed for climate change than would have been the case if an explicit comparison with such other issues had been made.

6.4.1. Perception of Negative and Positive Attributes of CCS

When asked, **unprompted**, if they could think of any negative effects of CCS respondents’ most frequent answer was leakage (49%) (see Figure 6.5). (Note that these answers are not expressed as a percentage out of 100% since respondents were not restricted in the number of issues that they identified). The next most frequently mentioned items were ecosystems (31%), the new and untested nature of the technology (23%) and human health impacts (18%). Whilst these practical, physical and environmental risks were the most frequently mentioned, there were also a number of negative attributes mentioned in relation to CCS as a part of climate change abatement policy. Avoiding the real problem (13%), short termism (12%) and the policy demonstrating reluctance to change from government (11%) were all mentioned regularly. Grouping these last three responses into a general concern that CCS is treating the ‘symptoms’ not the cause of excessive CO_2 emissions, this would constitute, at 36%, the second most frequently mentioned negative aspect of CCS after leakage. (Whilst these responses are not entirely independent the fact that the same individual might have identified two or three of the three areas is itself indicative of the extent of their concerns). 46 people (22%) did not offer any response. When asked if they could think of any positive effects of CCS, by far the most frequent response was its role in abating climate change (58% of all responses). The notion that using CCS could “buy time” to develop other solutions was the next most frequently mentioned at 7%.

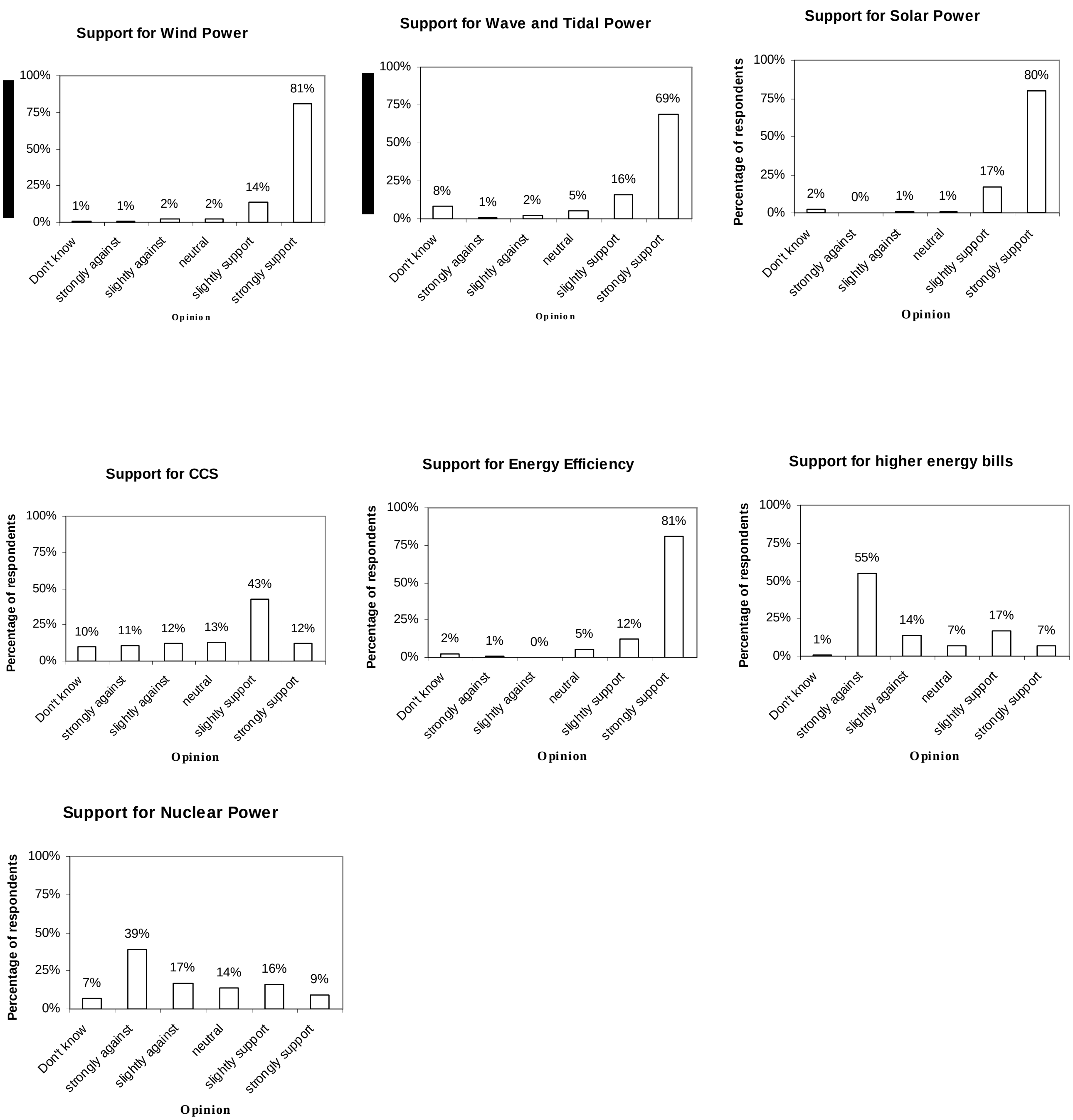

Figure 6.4 CCS compared to other low- or zero-carbon options

6.4.2. Perception of Negative and Positive Attributes of CCS

When asked, **unprompted**, if they could think of any negative effects of CCS respondents' most frequent answer was leakage (49%) (see Figure 6.5). (Note that these answers are not expressed as a percentage out of 100% since respondents were not restricted in the number of issues that they identified). The next most frequently mentioned items were ecosystems (31%), the new and untested nature of the technology (23%) and human health impacts (18%). Whilst these practical, physical and environmental risks were the most frequently mentioned, there were also a number of negative attributes mentioned in relation to CCS as a part of climate change abatement policy. Avoiding the real problem (13%), short termism (12%) and the policy demonstrating reluctance to change from government (11%) were all mentioned regularly. Grouping these last three responses into a general concern that CCS is treating the 'symptoms' not the cause of excessive CO_2 emissions, this would constitute, at 36%, the second most frequently mentioned negative aspect of CCS after leakage. (Whilst these responses are not entirely independent the fact that the same individual might have identified two or three of the three areas is itself indicative of the extent of their concerns). 46 people (22%) did not offer any response. When asked if they could think of any positive effects of CCS, by far the most frequent response was its role in abating climate change (58% of all responses). The notion that using CCS could "buy time" to develop other solutions was the next most frequently mentioned at 7%.

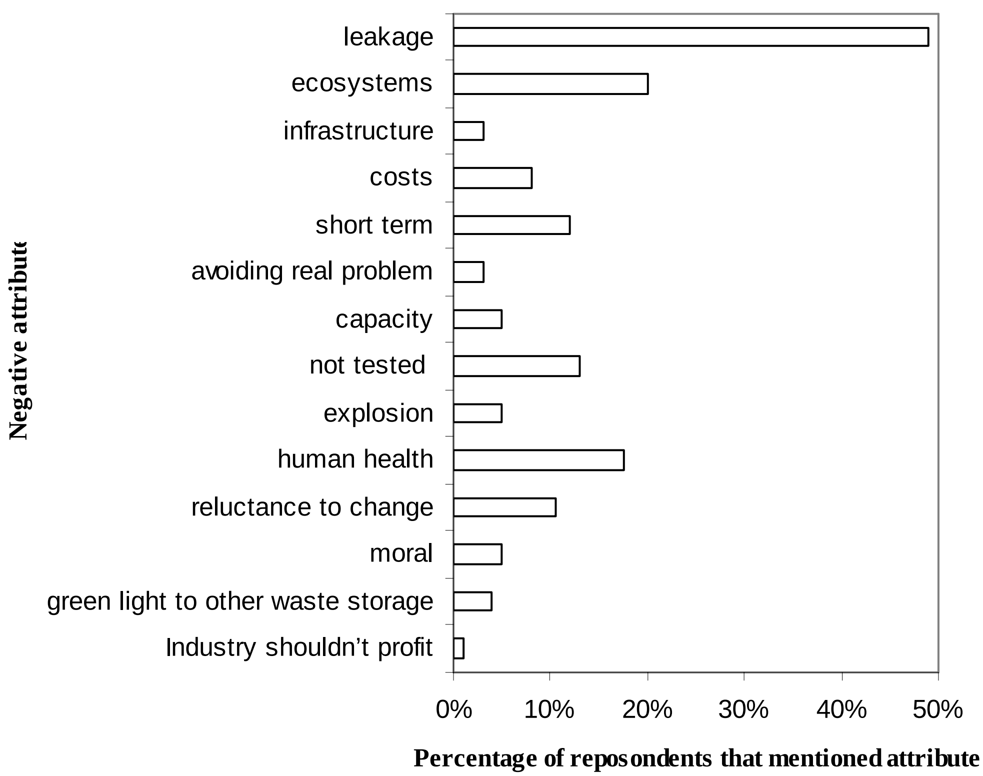

Figure 6.5 Negative attributes of CCS mentioned unprompted by respondents

More certainty about the environmental and safety risks of CCS in the long-term would help people to come to a clearer decision about the desirability of CCS. Many respondents indicated that they would like more information and more certainty in the assessments of CCS with regards to the above issues. When we asked about who should regulate the implementation of CCS, the Government was the most common answer (46%), followed closely by the Environment Agency (43%), Environmental groups (34%) and the oil industry (32%). It is interesting that environmental NGOs were regarded by many respondents as an important part of the regulatory system, in many cases along with government, the Environment Agency and the oil industry.

A number of other surveys have now been undertaken of public perceptions of CCS in different countries (Curry *et al*., 2004; Palmgren *et al.*, 2004; Huijts, 2003 and Itaoka *et al.*, 2004). It is difficult to make detailed comparisons between the various surveys because of differences in research design and implementation, phraseology, sampling methods and the underlying rationale of the research. Similar to the findings of our work, Curry et al. (2004) found a low level of knowledge of CCS amongst a representative sample of the US public, whilst Huijts (for the Netherlands) and Itaoka *et al.* (for Japan) found higher levels of knowledge. Our survey showed a reasonably strong move towards more support for CCS upon provision of more information. This was not corroborated by Itaoka *et al.* or by Palmgren *et al.* (the latter of which showed a decrease in acceptance of CCS upon provision of more information). The general perception of CCS in our survey was somewhat more positive than in the other surveys but there are methodological and sampling issues that might explain this difference (apart from, or in addition to, national political or cultural difference). Clearly, more systematic and directly comparable research will need to be conducted to shore-up comparative analyses of public perceptions.

6.4. Main Findings of the Citizen Panels

To recap, the Manchester nine strong panel was all-female and composed of two-thirds socio-economic group C and one-third group B, with an average age of 32 and an age range of 21 to 52. The York nine strong panel was all-male and composed of two-thirds group B and two-thirds group C, with an average age of 42 and an age range of 21 to 58. Socio-economic group B makes up approximately 14% of the UK population and is made up of middle management, more senior officers in the civil service and local government and owners of small to medium sized businesses. Socio-economic group C makes up approximately 26% of the UK population and is composed of junior management, owners of small establishments and non-manual office and retail workers. The York group was predominantly professionals and managers, whereas the Manchester group was predominantly administrators though with three professionals, so there was some overlap in the socio-economic composition.

The schedule for each group is shown in Table 6.2 indicating which topics were covered when and how, including the involvement of external experts. The selection of experts was intended to provide a range of perspectives on CCS from industry, environmental NGOs, geology and 'systems' views of energy. We should note that our selection of the geological experts was intended to reflect the present consensus amongst many geologists who have looked at the issue in detail on the scale of the likely risks (e.g. as reflected in IEA GHG, 2004).

The following discussion will dwell at somewhat greater length on the Manchester panels, in part because some of the same findings emerged from the York panel. Hence, the discussion of the York panel will focus in particular upon the differences which emerged compared to the Manchester panel.

The discussion will include selected quotes from panel members to illustrate the argument. The Manchester panel session 1 is referred to as MS1, session two as MS2, and so on, whilst the York panel session 1 is YS1, YS2, etc. The number following the MS and YS label refers to the page number of the transcription from the recording made of each panel.

Table 6.2 Programme for Each Panel

Manchester Citizen Panel	**York Citizen Panel**
Session 1: Warm-up discussion on quality of life	*Session 1:* Expert presentation on climate change & round-table discussion
Session 2: Expert presentation on climate change & round-table discussion	*Session 2:* Expert presentation on CCS & initial discussion
Session 3: Expert presentation on CCS & initial discussion	*Session 3:* Two contrasting expert perspectives on CCS & discussion
Session 4: Two contrasting expert perspectives on CCS & discussion	*Session 4:* Criteria Weighting for selection of storage sites
Session 5: Participants summing-up	*Session 5:* Weighting of different decarbonisation options

The following discussion will dwell at somewhat greater length on the Manchester panels, in part because some of the same findings emerged from the York panel. Hence, the discussion of the York panel will focus in particular upon the differences which emerged compared to the Manchester panel.

The discussion will include selected quotes from panel members to illustrate the argument. The Manchester panel session 1 is referred to as MS1, session two as MS2, and so on, whilst the York panel session 1 is YS1, YS2, etc. The number following the MS and YS label refers to the page number of the transcription from the recording made of each panel.

6.4.3. The Manchester Group

As with other focus group work in the UK, we found that local and visible issues such as waste are those which are most evident in everyday experiences of the 'environment' (Darier *et al.*, 1999, 1999a). The Manchester group did respond, however, with surprise and concern at the account of climate change, and its possible impacts from the global to the local scales, which was provided in the second session. The panel was generally quite positive about the idea of CCS after Session 3, when it was presented by a British Geological Survey (BGS) scientist. There appeared to be three underlying reasons for their positive perception:

1) Confidence in the ability of government to undertake appropriate assessment and regulation:

> 'They [government] never go in blind do they. They never just do things just for the sake of doing things' (Sarah, MS3:18)

2) Participants could not initially identify any real negatives associated with CCS, in part because the location of the CO_2 storage off-shore meant that local opposition was unlikely.

> '… It [CCS] just seems a nice little neat way of doing it. Cause you know it's 'not in my back yard' is it? That would get round all the critical NIMBYs like me wouldn't it?' *(Elizabeth, MS3:19)*

> 'Its not in anyone's backyard' *(Jo, MS3:19)*

3) Avoidance of damage from climate change through CCS. The potential risks of climate change were regarded as greater than those arising from CCS.

‘You just look at the costs and benefits and Greenpeace will weigh them up for themselves but my personal opinion from what I’ve seen is that it [CCS] is more beneficial than …’ (Sara, MS3:19)

‘We’re doing more damage by not doing anything’ (Sue, MS3:19)

Note, however, that the other options for reducing CO_2 had not been presented to the group at this point. Some participants struggled at this stage to see why CCS would be opposed:

‘why would Greenpeace oppose it? I just don’t see why they would ….’ *(Samantha, MS3:18)*

Despite this generally positive initial reaction to CCS various concerns were raised during the panels, in response to presentations by the invited experts.

Integrity of Reservoir Stores. Various technical questions emerged during the geologist’s presentation regarding the nature of the geological stores. For example, it was asked where the water in an aquifer would be displaced to. The possible effect of past human utilization of fossil fuel reservoirs was also raised as a problem for their future integrity (MS3:5). After the geologist had left, Samantha commented that:

‘…. Yeah it [oil & gas field] does store it for all these years but then drilling into it when they get the oil out ….. you just don’t know where …. The holes have been filled, but she [the geologist] said the cement wasn’t that great …. So they need to research into it that or ....

…… they were saying that with some of the sites … they can’t be 100% sure if there is a fault or not, so what if they start pumping all the CO_2 down there?’ *(Samantha, MS3:13-14)*

One participant picked up upon the geologist’s use of the term ‘bubble’ to describe the CO_2 storage in the underground aquifer. This participant, Sue, was concerned that a large bubble of CO_2 might burst with catastrophic consequences.

Sue: ‘ … you mentioned the world ‘bubble’ … its looking for an escape …

If it’s that large, that much of an area that its [the CO_2] going to be in, its going to be more than just catastrophic isn’t it really? [if it bursts]’

Geologist: ‘…. Well it’s not explosive ……. Underground it’s not a bubble and I probably shouldn’t have used that word.

…. We term it the CO_2 bubble but it’s not really a bubble because it’s not existing on its own ….. it’s actually in the rock pore spaces ….. there will be dissolving in some of the water, it will be reacting with some of the minerals in the rock’
(MS3:6,7,8)

Sue later returned to the issue when the geologist had left the room:

‘… me saying bubble! She scared the living daylights out of me, [saying] there’s this bubble …..!’
(MS3:24)

This exchange indicates the importance of the terminology which is used by experts in communicating with the public. Associated with this dialogue were questions about the fate of the CO_2 in the Sleipner field aquifer, seismic images of which had been shown by the geologist. One participant was concerned that the CO_2 in the aquifer appeared to have "risen quite a lot" (MS3:7), raising a concern for her about long-term integrity. Such movement in just 5 years led her to wonder what would happen to the CO_2 in 200 years. Samantha[i] picked up on the time scale issue to return to her concern about the integrity of large geological structures over hundreds of years:

> "… they can't possibly foresee whether it's going to … whether something else might happen … I mean they won't have done a seismographic on the whole of the section because it's too expensive… they'll have only done it on a few parts" (Samantha, MS3:15)

Questions were also asked about the subsurface potentially changing and its subsequent impact on storage integrity. These questions were, in general, not answered in detail due to a lack of time, a change of focus in the conversation or simply that the expert speaker could not address all the points raised. Samantha, in particular, expressed concern over the level of uncertainty and the difficulty of extrapolating findings from small test sites over small time periods to potentially huge sites over hundreds of years.

Technical Fix. Several participants were concerned that CCS would result in society becoming complacent in addressing other ways of reducing CO2 emissions because the problem would be perceived as having been 'fixed'. The group pointed to the, in general, low level of recycling in the UK as evidence of 'laziness' in responding to environmental problems. Any 'solution' which meant that individuals or other sections of society did not have to make wider changes would allow such 'laziness' to continue. It was widely felt in the panel that CCS might well constitute such a 'technical fix' that would stop or delay other desirable actions and steps.

> Sue: '….. if we decide that we were going to do this [CCS] it would be easier ….. because we're lazy to an extent aren't we? …. We don't recycle enough ……. It's been taken out of our hands and somebody else is doing it for us then …..'
>
> Facilitator: 'Is that good or bad?'
>
> Sue: 'It's a bad thing because that's us being lazy'.
>
> Heather: 'Because people would just think, like a quick fix think, "oh, they've fixed it, so I don't have to do anything"' *(MS3:20)*

A further development of this argument was that CCS might even create a 'false sense of security' in our ability to cope with climate change and carbon abatement and that this could, perversely, result in an increase in CO_2 emissions.

> Elizabeth: '….people will just think, "oh, well that's alright then, that's kind of been fixed…. There's this invisible body out there that's taking care of it …. I'll just shove my carbon emissions …." We'd become more blasé wouldn't we just like the car drivers? [driving more dangerously in response to safer design & seat belts]. We'd think, well, this has all been sorted'.
>
> Heather: 'Maybe we just shouldn't tell anyone about it then. Maybe it should be a secret?'

> Samantha: '….. can you imagine if there was a leak or something and everyone would go, "oh my god, the government are hiding this"'
> (MS:21-22)

This above exchange shows a 'risk compensation' type argument being used (Adams 1995): as peoples' perceptions of the risks of carbon emissions are potentially reduced due to application of CCS, they may compensate by higher CO_2 emitting behaviours and lifestyles. The idea of withholding information from the public to avoid such CO_2 compensation was seen by many other participants as highly risky for the government's image. It was generally agreed within the groups that individuals were partly to blame for CO_2 emissions and therefore had to share some of the responsibility for reducing CO_2 emissions into the atmosphere. It was also felt that individuals *could* make a change in their lifestyles, but that some sort of 'crisis mentality' might be required before they would be prepared to do so.[ii]

A Shift to More Uncertain and Ambiguous Perceptions. A critical presentation by an academic energy expert followed that by an oil industry representative in session 4, and challenged the panel members to re-think their earlier generally positive endorsement of CCS. For example:

> 'Last week to me it [CCS] sounded really good, it sounded like the only option (…) and then this week it just sounds as though there's more options, (…) and then are we prepared, as a day to day person doing your day to day job ….. are we prepared to make sacrifices we would have to make, like you say if we want to reduce that 60%, we're not going to be able to do it are we?' *(Sue, MS4:10)*

This comment was elicited in response to the academic's analysis of the benefits of greater energy efficiency compared to CCS (including the energy penalty associated with the latter). Thinking about CCS, and its energy penalty, in a systems way relative to energy efficiency was not a perspective that had emerged within the group prior to then. The second part of Sue's quote refers to the extent to which individuals would be prepared to change their lifestyles (possibly dramatically) in order to reduce CO_2 emissions and hence avoid the need for extensive reliance on CCS. This need for lifestyle change had been an implicit part of the academic's preferred approach. The industrialist had stressed that achieving a 60% reduction in CO_2 emissions was a huge challenge and had made the argument that people had to decide between options such as nuclear and CCS. Without major new low- or zero- carbon dioxide emitting supply side options, he argued that it would be necessary for a large scale reduction in energy consumption, which would require a major shift in the use of energy and in lifestyles.

He asked the panel whether they could envisage reducing CO_2 emissions arising from their own lifestyles by 50%. Several participants, e.g. Sue in the above quote, acknowledged in response that such lifestyle changes could be difficult to envisage. Such doubts about the feasibility of lifestyle changes made the comparison of options more complex and uncertain for the group than for the academic presenter, who was more confident in the prospects of energy demand reduction through lifestyle change.

In effect, the industrialist raised for the group an uncertainty about how effective household or individual actions to reduce CO_2 emissions by a large proportion of the population would be *in reality*. The panel had itself raised similar concerns during Session three. Whilst there appeared to be admiration for the academic's belief in energy demand reduction, the industrialist perhaps validated the view on the panel that energy demand reduction was not very likely in current socio-economic conditions.

As a consequence of having been presented with an assessment of the alternatives to CCS, together with information on their unknown effectiveness at the present time, the panel was left more uncertain and undecided than they had been after session 3, when there was a reasonably positive position on CCS. Furthermore, the fact that both experts were perceived by the panel as open-minded and not overtly pushing a single option also highlighted the uncertainty associated with choosing an appropriate option.

> 'I think we all expected these guys to come in and go 'right its green, green, green, green', ….and you to come and go 'you've got to do it this way .... there's no other way'. I think that's what we expected , I know I did, I didn't expect anything else but its more of an option' *(Sue, MS4:10)*

Towards the end of Session 4, a 'rapprochement' between CCS and lifestyle change as options for reducing CO_2 emissions appeared to emerge in the thinking of several participants.

> '….. if we were going to do the storage way [i.e. CCS], could we not do both? Could we, as the general public, do more [in reducing energy use] so that you wouldn't have to dig up as much ground [for laying CO_2 pipes] ….' *(Sue, MS4:9)*

> '…..that would be a bit of a sight wouldn't it? Everyone working together …… we'll have 50% of it [CCS], we'll have 50% of that [demand reduction]' *(Sue, MS4:11)*

The industrialist certainly encouraged such a consensual approach, but Sue herself, and other panel members, recognized the practical difficulties associated with such 'joined-up' thinking and working.

> '… they're usually working against each other aren't they … Greenpeace against whoever, but then it would be nice for all to work together and say well if we do it together we'll get more out of it' (Sue: MS4:11)

Emergence of Three Positions. For most panel members, the extent of the challenge had impressed upon them the difficulty of achieving a 60% reduction by lifestyle change alone.

> 'I certainly thought about it a lot this week, really …. I've had a lot of discussions with (…) but it seemed interesting to me, people who're not involved in it - I've had the same reaction, I changed my view (…), once I'd listened to [the industrialist], and then it came across that we're not all going to be able to do it on our own, ….. we've gone that far'

> 'I don't think you're going to get as dramatic change in everyone's lifestyle as we want to ….. [get] each household [to reduce CO_2] by 60%' *(Sue, MS5:2)*

Whilst most participants shared this somewhat negative assessment of lifestyle change on the part of the public, there were perhaps three categories of response to it.

1) The view that because of the reasonably long timescales involved, it would still be possible for the 60% reduction to come from lifestyle change and introduction of energy efficiency and renewable energy technologies. This group was not in favour of CCS, because it was placing CO_2 out of effective control and taking an unnecessary risk if the 60% reduction could be done through safer means.

> 'I would prefer to do it ourselves rather than store anything underground that I can't see and can't control, don't know what's happening with it' (Sue, MS5:6)

Those holding this view were in favour of measures imposed upon companies, councils and, ultimately, households to make sure that emissions of CO_2 were steadily brought under control, i.e. incentives, fines, taxation instruments, etc.

2) Against this argument was the position that control is in any case 'in your head' (meaning that it is a psychological belief that the carbon dioxide has been safely stored and controlled and that you do not necessarily need to see something literally to have an understanding of it, or confidence in it). Holders of this view saw the benefits of CCS as outweighing the risks. A worst case-scenario, for this group, would involve CO_2 escaping from storage reservoirs in large volumes, but it was argued that this CO_2 would have been in the atmosphere in any case.

3) A third view was one which expressed more ambivalence about the role of CCS. Like perspective (i) there was strong support for government to take more action on energy efficiency, demand reduction and renewable energy. Any support for CCS was tempered by the perception that fossil fuels are, in any case, running out, hence other sources of energy are going to be required. In addition, it was felt that the risks of CCS are somewhat too high and uncertain at the current time and that there need to be more definitive answers to questions about the various risks encountered. However, a possible role for CCS as part of a wider package of decarbonisation measures was identified, provided that some of the key questions about the risks could be better addressed.

6.4.4. The York Group

Our discussion of the York Panel highlights some of the key areas of difference from the Manchester Panel, hence is some what briefer. The concept of using CCS as a "bridging strategy" to more renewable energy was presented by one of the expert witnesses and well understood and fairly well supported by the panel. However the need for longer term solutions was also stressed.

> 'It [CCS] just bides time to figure out, if it doesn't work or if we get a bit more time ….. hopefully get some more ideas about how to sort it out... it just does buy a bit more time doesn't it even if we don't put much [CO_2] down there?' *(Andrew YS2:18)*

The majority of the group were reasonably supportive of CCS due to the significant impact it could have over a short period of time, and to the fact that no other technology could do this.

> 'It's not an ideal solution but it looks like a solution that can achieve drastic reductions in the short term' *(Russell YS5:6)*

Safety issues were ranked consistently highly by the entire group, and it was agreed that minimum standards would need to be met before any project was undertaken.

> 'If you can lock it [the CO_2], fine, I can understand why they are putting so much time in to this technology. If you can't, if there's still potential of it leaking, that strikes me as a bomb, because if it goes pop…' *(Mark YS2:18)*

As in the Manchester group, images of explosions such as this were common throughout the panel discussions despite expert witnesses informing them of the inert nature of CO_2. CCS was also perceived as an "end of pipe" technology and this was discussed frequently as a negative attribute by the panel.

> 'We are treating the symptoms not the causes [of] doing this' *(Mark YS2:21)*

The uncertainty associated with this technology (given that it has not been used on a long term basis or on a wide scale before) generated a number of concerns throughout the meetings.

> 'In one hundred, two hundred years time we may actually be paying the penalty for putting a pollutant back in to the earth …. It could do anything couldn't it? … but that is the risk that we're taking today isn't it, doing all of this?' *(John YS2:15)*

This uncertainty and long term implication conjures-up analogies with previous events.

> '… that's what they did with asbestos… suddenly they did a test for it and it has become catastrophic really… we have used lots of chemical products that we've found out after the time – we shouldn't have done it.' *(John YS2:15)*

It was stressed by one participant that the idea of CCS needs to be very carefully and thoroughly explained if it is to be supported. If it is not properly assessed, with input from local participation, then he suggested that there could be serious consequences:

> 'I can imagine if it was discussed quite widely in the community there would be a lot of alarm. These things do provoke that sort of reaction.' *(Andrew YS2:15)*

CCS (in particular) and also the Government's approach to climate change (in general), were frequently criticised for not being radical enough, though the panel was not well informed about what government is actually doing.

> 'Have the government tried to sell any green issues apart from a few silly adverts about filling your kettle? They don't seem to do much' *(Graeme YS2:4)*

> 'They don't seem to be thinking outside the box do they? They are actually trying to find somewhere to store it, to keep it, when surely can we not try to use it [CO_2] as another form of energy that dissipates naturally creating heat or whatever' *(John YS2:22)*

The above quote is a prime example of how several members of this, rather technically minded group, were very keen to suggest solutions to problems but were not able to explain the feasibility of such solutions or how they might be implemented in practice. These few individuals tended to assume that their suggested technologies or approaches were feasible but had simply not been thought of by others, or had not been the subject of sufficient research activity. The idea of using CO_2 in the process of making something else was often discussed by the panel. This technological optimism demonstrates a "utilitarian" type approach, preferring to re-use and recycle CO_2, rather than just storing it. For this reason the York panel was strongly in favour of using CO_2 for Enhanced Oil Recovery (EOR). We suspect that the emphasis and interest of these panellists in novel technologies not having being explored sufficiently by 'the experts' reflects a distrust in those experts and in their capacity to be truly innovative.

A number of moral and emotional arguments against CCS were also expressed, though by only two participants.

> 'Our deep irrational fears …., I think you've come up with deep irrational fears about injecting mother earth. I think that is an irrational fear but I feel it as well.' *(Graeme YS2:25)*

These concerns are often linked for these few participants with a sense of responsibility to not cause problems for future generations.

> 'I just don't like the idea about pumping another pollutant back in to the earth, we're doing it all the time aren't we? We are storing up another problem for the future' *(John YS2:23)*

There was widespread support for what one participant referred to as an 'encyclopaedia of facts' that would be presented in a digestible format for the public and the media. Some members of the group suggested that the encyclopaedia could include different opinions on the same issue to allow for inevitable disagreement and uncertainty. The groups were asked to consider how trust in the information presented in the encyclopaedia could be developed. One suggestion was that it would be a 'living document' where the encyclopaedia could be "challenged" by lay members of the public or experts. Information would have to be given to defend an entry in the encyclopaedia or that entry would have to be altered. It was stressed that this needed to be a very visible process if the public was to be convinced that the encyclopaedia was a reliable and unbiased source of information. How this "challenging process" could actually be carried out was also discussed. Some support for using the internet was expressed, as was some severe scepticism of the internet as it is not felt to include everybody. The use of moderated web-based discussion fora was also strongly supported by one member of the group.

6.5. Summary and Discussion

The citizen panel participants had the advantage over the survey respondents of lengthy discussions between themselves and with expert witnesses. Their ability to cross-examine experts does appear to have influenced their perceptions and to have provided some greater reassurance on the potential risks than was available to the questionnaire respondents. This might, however, be a function of the particular experts chosen and the panel might have responded differently if a 'sceptical geologist', for instance, had spoken to the group, i.e. one who might have posed more basic questions about the integrity of geological reservoirs for storing CO_2. Leakage of carbon dioxide from reservoirs was a commonly expressed concern amongst both panels, as was the perception of CO_2 as a potentially explosive substance. In their interactions with the panels, the experts tended to present the risks of leakage (and adverse consequences if it should occur) as low to very low.

The questionnaire highlighted leakage as *the* major issue of concern, whereas leakage was only one amongst a range of concerns discussed within the citizen panels and, on balance, not the overriding one. We speculate that the reason for this is that the citizen panels were first presented with information about CCS from an academic geologist who shaped the context for discussion. Not only did this expert raise many other issues that were less 'intuitive' than leakage (e.g. providing information on the time scales over which natural gas can remain in geological formations) she also allayed fears of leakage by characterising them as low to very low (provided appropriate controls are in place). Many of the survey respondents, bereft of the inputs from the expert geologist, may have employed a cognitive model in which the principal risk arising from storage of a gas underground is the escape of that gas back to the atmosphere. Support for the existence of such a cognitive model is provided by panel participant Sue, who picked-up on the geologist's use of the term 'bubble', possibly using it to construct a cognitive model of CO_2 underground in a gaseous form ready to escape.

The two Citizen Panels, whilst composed of very different demographic samples, came to rather similar views about CCS, albeit it through sometimes different reasoning processes and arguments. In both Panels there was a reasonable level of consensus surrounding the potential need for CCS given the scale of the decarbonisation challenge and the uncertainty and difficulty of achieving a 60% reduction in emissions through behavioural and lifestyle change and other routes. Support for CCS was conditional upon the implementation of a range of other decarbonisation options – in particular renewable energy and energy efficiency. An integrated approach towards decarbonisation was generally preferred by both Panels in which all options were considered, including social change as well as the 'harder' technological options. There were rather similar concerns regarding the possible risks, though the York group relied more upon 'analogous' cases of environmental and health and safety risks than the Manchester group. The results of the Citizen Panels are also broadly consistent with the findings from the survey and we can describe support for CCS as 'moderate' or 'lukewarm' compared to strong support in general for wind, solar and energy efficiency. From the citizen panels and questionnaire we suspect that gender, socio-economic status and education all play a role in influencing perceptions of CCS, though our analysis suggests that their role is not large.

On the basis of our analysis of, and reflection upon, the findings of the citizen panels and survey, we would suggest that a basic concern about climate change and recognition of the need for massive CO_2 emission reductions might well be a prior requirement for the consideration of CCS as a legitimate option for evaluation. We suggest that there are (at a minimum) three conditions which provide the context for regarding CO_2 capture and storage as a potential option, namely:

1) Acceptance of the basic underlying science of human-induced climate change;
2) Acceptance of the seriousness of the potential threat of climate change impacts to society and the environment in the UK and more generally;
3) Acceptance of the need to make very large reductions in carbon emissions (e.g. 60% cuts) over the next 50 years.

The survey found that not only was there a high level of belief that human activities are causing climate change (78%) but that the majority of respondents (62%) were 'concerned' or 'very concerned' about climate change. This confirms the findings of many existing surveys from the UK, and Europe more generally, which have indicated fairly widespread concern over the problem of global climate change, and a prevailing feeling that the negative impacts outweigh any positive effects (Poortinga & Pidgeon, 2003; Eurobarometer, 2003; Hargreaves *et al.*, 2003; Shackley *et al.*, 2001). On the other hand, some survey and focus group research in the UK suggests a less homogeneous, and more sporadic, perception of the occurrence and seriousness of global climate change (and in particular the need for large reductions in CO_2 emissions) (Darier *et al.*, 1999a; Lorenzoni 2003; Hargreaves *et al.*, 2003). In partial support of these latter findings, we found that even amongst the most climate change aware of our citizen panel participants, no one comprehended the enormous scale of the challenge of a 60% reduction in carbon dioxide emissions, and there was in general a lack of awareness and knowledge of what different carbon mitigation options had to offer (cf. Curry *et al.*, 2004; Palmgren *et al.*, 2004).

Three Broad Positions vis-à-vis CCS ‘Pro-‘, ‘Anti-‘ and ‘Ambivalent’ were identified in the Citizen Panels. The Citizen Panels elucidated broadly different perspectives on CCS which did appear to relate, at least to some extent, to underlying beliefs and different sets of values.[iii] A small minority was in favour of CCS, mainly for utilitarian reasons that it is an effective use of geological reservoirs and removes CO_2 so reducing the risks of global climate change, which are regarded as larger than the risks of CCS itself. Another small minority was opposed to CCS, mainly for moral reasons that it is basically wrong to ‘inject mother earth’ with an industrial waste by-product. Humans have responsibility, according to this perspective, for changing their ways – through new technologies and lifestyle changes – such that CO_2 emissions are not produced in the first place.

The third, and most common perspective, was essentially ambivalent – at times in favour, at other times against, CCS. The citizen panels were opposed to regarding CCS as a single ‘fix it’ solution and expressed concerns that such use of CCS would be to treat the symptoms rather than the causes of climate change. There was a sense that CCS could "let us off the hook" of making more fundamental, deep-rooted changes and this avoidance of change was perceived generally negatively. There was also concern expressed that CCS would divert R&D resources and attention away from renewable energy technologies, demand reduction and energy efficiency. This concern was largely allayed when the level of new resources being directed to renewable energy R&D, demonstration and support schemes was indicated, alongside the very small amount going into CCS R&D at present.

Whilst many in this third group were initially sceptical of CCS for the above reasons, they became more favourably inclined as the scale of the decarbonisation challenge was appreciated, as the risks of CCS were more thoroughly discussed, and as the risks and opportunities associated with the other major decarbonisation options were also discussed. The majority view tended to find more support for CCS when the latter was combined with other options which had a (seemingly) more favourable cost-benefit profile than CCS itself, in particular renewable energy, energy efficiency, energy demand reduction, and (more speculatively) the hydrogen economy (based at least initially on fossil fuels with decarbonisation). This finding strongly supports the need to embed CCS within a portfolio of decarbonisation options and to promote CCS as a ‘bridging strategy’ to other low- or zero-carbon energy sources.

6.6. Implications for Policy and Research Needs

Zaller (1992) argues that the lay public does not have well formed opinions on most issues which are not of immediate salience or relevance to their everyday life and livelihood. Converse (1964) similarly criticise the ‘expectation of opinionness’ which is an underpinning assumption of much survey research. Opinions and perceptions are, instead, shaped by (*inter alia*) the media and other marketing efforts of stakeholders. There are several very good examples of such shaping having taken place, e.g. in the case of disposal of the Brent Spa platform, Greenpeace was successful in convincing the media, and consequently the general public, that disposal at sea would incur unacceptable environmental risks (Smith 2000). A further example is the role of the media and campaign groups in shaping perceptions of GMOs in Europe in the late 1990s. Feedbacks between the media and public opinion are also documented, and have been formalised in the theory of risk amplification (Jaeger et al. 2001), which maintains that risk perceptions can become amplified through media presentations, and subsequent stakeholder responses.

The implication of such theory and real-cases is that because there is not a strong *a priori* belief in favour or against CCS, public opinion on CO_2 storage could, at some future stage, be strongly shaped by stakeholder groups, including the media or NGOs, who come themselves to formulate a strong opinion. As Wynne (1995, 1996) notes, bereft of sufficient technical knowledge, the public may come to rely upon their sense of trust in the organisations involved, and in their past institutional performance, when assessing a new technology such as CCS. Research is not able to anticipate how public perceptions might change, possibly dramatically and rapidly, in response to pro-active stakeholder and media interventions and real-world events, though it can provide lessons from the past and guidance on ‘good practice’ in the communication of risks and uncertainty (Powell & Leiss 1997).

With the above proviso clearly in mind, the results suggest that public reactions to CCS could be reasonably supportive of the technology, provided that its purpose is well understood and that the key risks are acknowledged. This research suggests that proponents of CCS need to put their case clearly in the context of reducing the risks of global climate change, and the concomitant need for large long-term reductions in CO_2 emissions to the atmosphere. The use of CCS as part of a portfolio of decarbonisation options which range from new technologies, to lifestyle change, should be stressed, rather than presenting CCS as a ‘stand alone’ option. A partnership approach to control and regulation of CCS would be generally welcomed, in which government, industry and environmental NGOs each have a role to play.

With respect to public decision-making, the citizen panels could be reconvened to explore more specific CCS proposals or projects once they are on the table or in the pipeline. Alternatively, a new ‘bespoke’ panel could be established to discuss a specific CCS proposal or project, e.g. drawn from the local occupants and stakeholders near to the proposed project.

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[i] Samantha was one of the more vocal of the participants. She was a 21 year old administrator with no particular prior socio-economic or educational reason for her high level of engagement that we could ascertain.

[ii] The group (and the facilitator) did not make any explicit distinction in the above discussion between 'individual' behaviours and behavioural change, and more 'collective' behaviours and their potential for change. On the other hand, the group were implicitly distinguishing between actions taken voluntarily by individuals (e.g. recycling, or reduction of energy consumption, use of public transport, etc.) and the actions of government which did not involve voluntary change by individuals. Some of the tension in the discussion reflected the need for collective governmental actions given individual apathy on the one hand, but the suspicion of policy by dictate from the centre on the other.

[iii] The exact relationship between these perspectives and beliefs and values would require precise definitions of 'beliefs' and 'values' and empirical research to identify and measure beliefs and values.

Chapter Seven

Carbon Dioxide Capture and Storage in the North West of England

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7.1 Introduction

In this chapter we set out to explore the potential for CO_2 storage in the East Irish Sea (Part A), and the perceptions of a range of stakeholders from the public and private sectors in the North West of England regarding the role of CCS in the long-term future of the region's energy sector (Part B). We are especially interested in asking the following questions:

1) What is the potential for CO_2 storage in oil and gas field and saline aquifers beneath the East Irish Sea?
2) How do different energy scenarios of the North West region for 2050 compare in terms of their perceived benefits and disadvantages against a set of pre-defined criteria?
3) How do different types of stakeholders (private sector, public sector, non-governmental organisations) evaluate the scenarios and what does this tell us about those stakeholders and their thought processes regarding different energy futures?

In addition to the geological assessment we have used a multi-criteria assessment (MCA) methodology (Stirling & Mayer 2001, Stewart & Scott 1995, Brown *et al.* 2001) to examine the trade-offs between different scenarios of the future of the energy system regionally. Each of the energy scenarios has a different role for CCS, ranging from no contribution, to a major contribution to 2050. We decided to focus the study upon a region because it is a scale for governance which can, potentially, overcome the problems that have arisen between the centre and the local levels in the UK in the last few decades (Stoker 2004, cf. Wilbanks & Kates 1999). For example, the region has a specific characterisation in terms of its portfolio of power stations, its opportunities for renewable energy development and in terms of the availability and closeness of suitable off-shore geological storage sites for CO_2. A regional focus also reduces the complexity of considering energy scenarios at the national scale, for example the respondent can focus upon a handful of power stations rather than having to grapple with hundreds of power stations at the national scale.

We created the framework of the scenarios, and the criteria for their assessment, through an earlier project, which is described elsewhere (Gough & Shackley, 2006). It was necessary to use scenarios of the energy system because: a) we were looking at the long-term (to 2050) and over these periods of time the energy system will change, possibly dramatically; b) given that CCS is just one element in a complex energy system, it is necessary to create alternative visions of the relative extent to which CCS will be employed in a new energy system.

7.2 Characterisation of the rocks beneath the East Irish Sea

7.2.1 Reservoir unit

The main reservoir rocks in the East Irish Sea Basin form the Sherwood Sandstone Group. The Sherwood Sandstone Group extends westwards over most of the East Irish Sea Basin from onshore UK (Figure 7.1), and is the equivalent of the Bunter Sandstone Formation in the southern North Sea. It is more than 2000 m thick in the centre of the East Irish Sea Basin and has an average thickness of 1450m (Jackson *et al*., 1987).

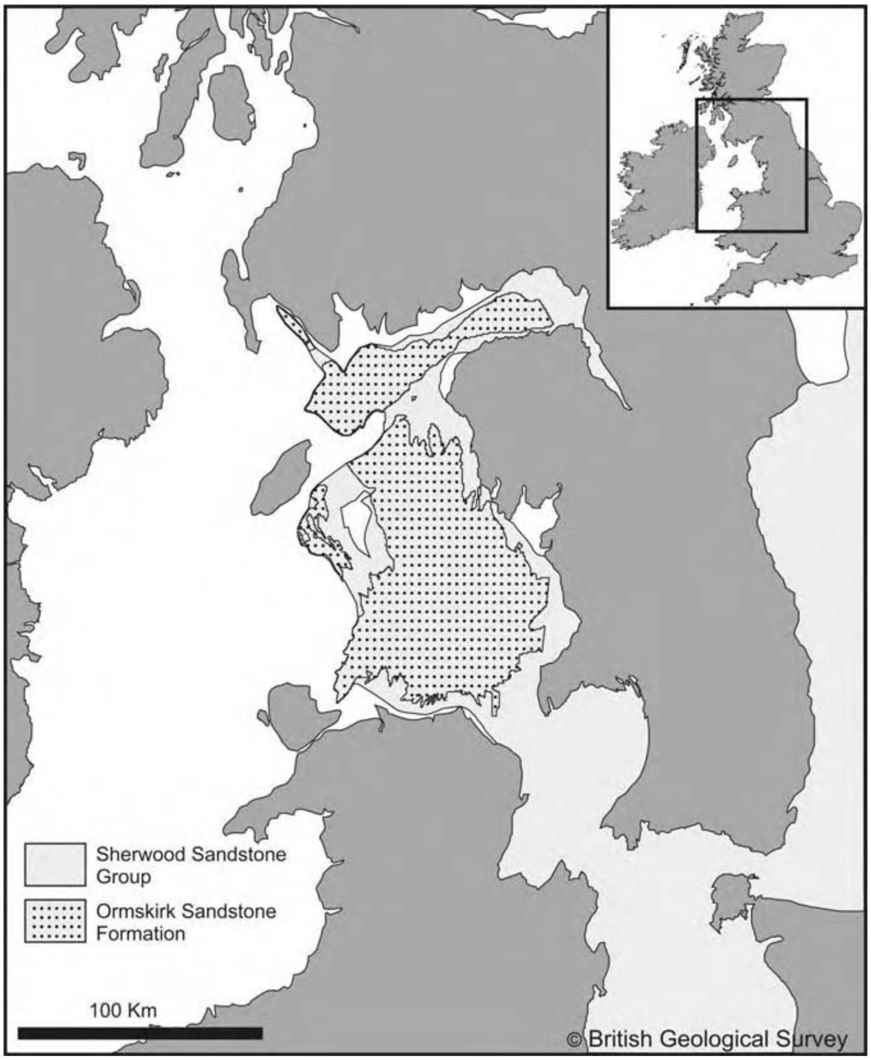


Figure 7.1 Map showing the extent of the Sherwood Sandstone Group and the Ormskirk Sandstone Formation

Most of the hydrocarbon discoveries are entirely within the uppermost unit of the Sherwood Sandstone Group; the Ormskirk Sandstone Formation. Discoveries also extend downwards into the upper parts of the St Bees Sandstone formation. The top of the Ormskirk Sandstone Formation lies at depths of 250-3000m. It has an average thickness of 250m. The Ormskirk Sandstone Formation demonstrates all of the required characteristics for CO_2 storage including closed structures (traps for buoyant fluids), high porosity and permeability and it is overlain by an effective seal, the Mercia Mudstone Group.

7.2.2 Porosity and permeability of the Ormskirk Sandstone

There are huge porosity and permeability variations in the Ormskirk Sandstone. These are the result of diagenesis - the post-burial alteration of the original sandstone (Levison, 1988; Meadows and Beach, 1993). Porosities range from 8–30%, and permeabilities from 0.05-10000 mD. The most important diagenetic effect is the precipitation of illite within the pore spaces. Thin illite crystals (small clay plates) can grow perpendicular to the sandstone grain faces, making it more difficult for fluids to pass through the reservoir (see Figure 7.2). They clog up the pore throats (pathways between pore spaces) affecting the permeability rather than the porosity of the reservoir (Ebbern, 1981).

The illite-affected layer in the South Morecambe field is >304 metres thick in the north of the field, but only about 137 metres thick in the south of the field, where it passes downwards into sandstones characterised by poorly developed fibrous illite. It is not, therefore, completely ubiquitous outside the oil and gas fields, giving hope that there might be reasonable permeability in some of the non-hydrocarbon-bearing closures. However, the presence of platy illite in the Sherwood Sandstone may greatly limit the amount of CO_2 which can be stored within the non-hydrocarbon-bearing closed structures that are described below.

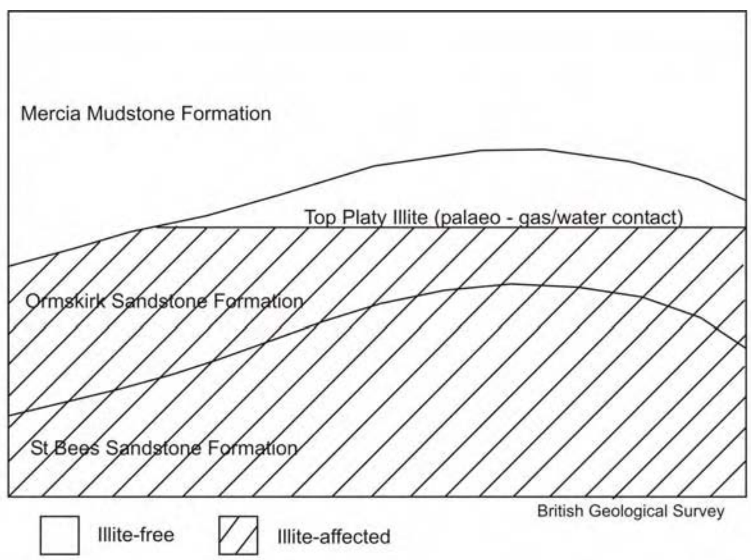


Figure 7.2 Simplified diagram illustrating the relationship of the palaeo-gas/water contact with the illite-free/illite-affected areas of the reservoir (not to scale)

7.2.3 Caprock/seal

The Mercia Mudstone Group forms an effective seal over the top of the Ormskirk Sandstone (Figure 7.3), this is proven by the hydrocarbon discoveries in this area. Up to 3200m thick in the East Irish Sea Basin (Jackson *et al.*, 1987), it comprises silty mudstones interbedded with commonly thick units of halite (rock salt). Rock salt comprises some 35 to 55 percent of the Basinal Mercia Mudstone succession, and occurs at 5 levels (Jackson *et al.* 1995). It is almost impermeable unless fractured.

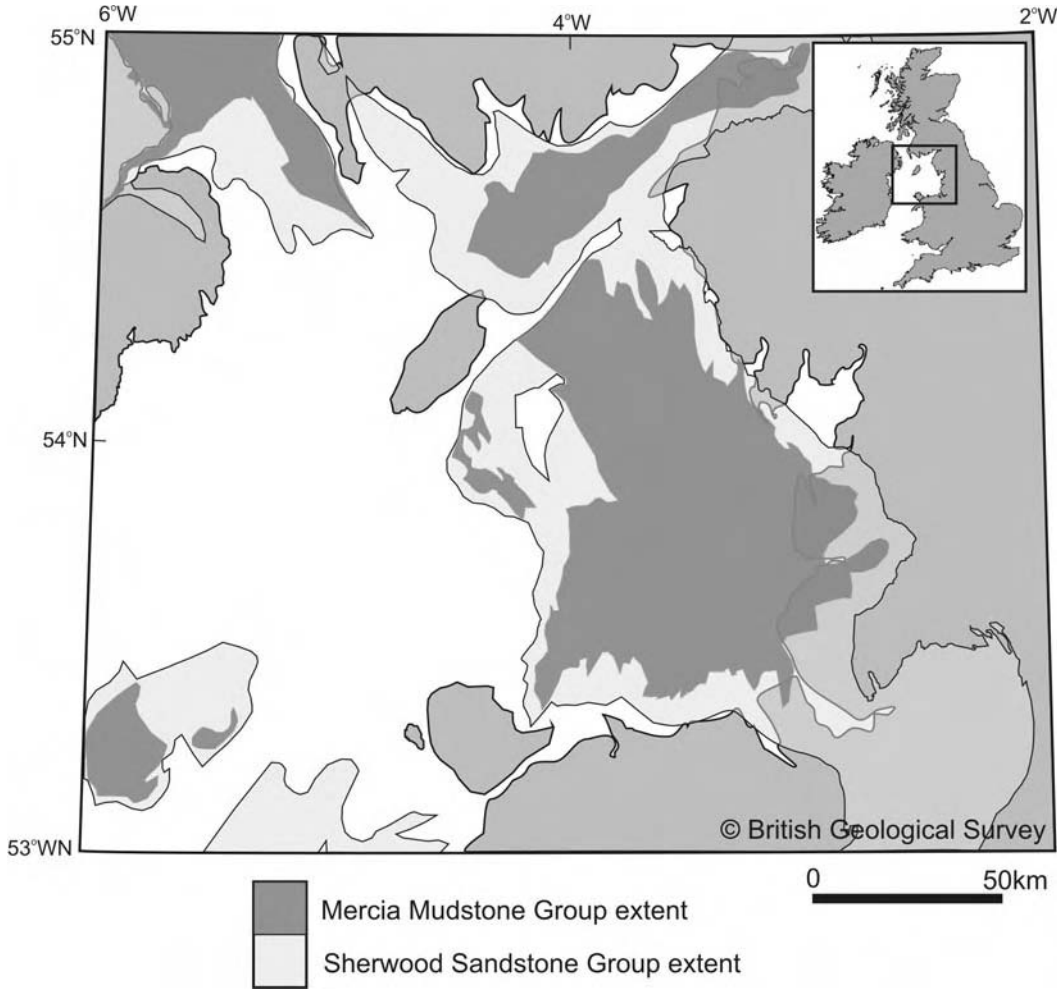


Figure 7.3 Extent of the Mercia Mudstone Group in and around the Irish Sea (adapted from Jackson *et al.* 1995)

7.3 CO_2 Storage Potential

The major CO_2 storage potential in the East Irish Sea Basin is within:

1) hydrocarbon fields;
2) structures within which gas could potentially be trapped but which do not contain hydrocarbons (reservoir rocks that contain saline water in their pore spaces; the so-called saline aquifers).

7.3.1 CO_2 storage capacity of the oil and gas fields in the East Irish Sea basin

Both oil and gas fields are found in the East Irish Sea Basin (Table 7.1 and Figure 7.4), indicating that reservoir rocks present are capable of storing buoyant fluids. Oil and gas generation probably started in Jurassic times, but the Jurassic accumulations of oil and gas that are believed to have developed in most of the fields is thought to have escaped during the first period of basin uplift and erosion - at the end of the Jurassic times (Bastin *et al*., 2003; Stuart & Cowan, 1991; Cowan & Boycott-Brown, 2003; Yaliz & Chapman, 2003; Yaliz & Taylor, 2003; Yaliz & McKim, 2003). The oil and gas presently found, for example, in the South Morecambe field gas was probably trapped in latest Cretaceous to early Tertiary times (Bastin *et al.* 2003) and thus may have been stored for some 50 million years or so.

Table 7.1 shows the estimated CO_2 storage capacity of the gas and oil fields in the East Irish Sea Basin. The storage capacity of the gas fields was estimated according to the Equation 7.1 (Wildenborg *et al.*, 2004):

Equation 7.1

$M_{CO2} = (V_{GAS}\ (stp) / Bg) \times \rho CO_2$ (Equation 1)

Where:

M_{CO2} = CO_2 storage capacity (10^6 tonnes)

Stp = standard temperature and pressure

V_{GAS} (stp) = volume of ultimately recoverable gas at stp ($10^9\ m^3$)

Bg = gas expansion factor (from reservoir conditions to stp)

ρCO_2 = density of CO_2 at reservoir conditions ($kg\ m^{-3}$)

The volume of ultimately recoverable gas at stp and the gas expansion factor were obtained from the DTI oil and gas website, Meadows *et al.* (1997) and Gluyas and Hichens (2003). The density of CO_2 was calculated from the reservoir temperature and pressure of the individual fields. The main problem with Equation 1 is that it assumes that all the pore space originally occupied by the ultimately recoverable reserves of natural gas could be filled with CO_2. There is uncertainty about this because the reservoir may compact slightly as the pore fluid pressure within it decreases. Moreover water invasion may reduce the pore space available for CO_2 storage. Ideally, the percentage of the pore space originally occupied by natural gas that could subsequently be filled with CO_2 would be determined using numerical reservoir simulations. However, no reservoir simulations were available and in their absence the following factors have been used to adapt Equation 1 (from studies by Bachu & Shaw (2003) on oil and gas fields in Alberta):

1) In gas fields with depletion drive, i.e. those where the wells are opened up and the pressure in the gas field simply depletes as it would if the gas were being produced from a sealed tank, it is assumed that 90% of the pore space could be occupied by CO_2.
2) In gas fields with water drive, i.e. those where water encroaches into the pore space formerly occupied by the produced natural gas reserves, it is assumed that 65% of the pore space could be occupied by CO_2.

The Douglas oil field has no gas cap and is being water-flooded to maintain reservoir pressure during production. This means that little of the pore space formerly occupied by the produced oil reserves will be available for CO_2 storage when water flooding ceases. The absence of a gas cap does not necessarily imply that the field is not gas tight. Gases originally present are believed to have been removed by a process called water washing, in which gas is dissolved by ground waters causing a low gas/oil ratio (Yaliz & McKim, 2003).

The storage capacity for Douglas was calculated by assuming that at some stage in its development the field would undergo enhanced oil recovery using CO_2 as an injectant. A 7% incremental oil recovery could be achieved as a result of enhanced oil recovery using CO_2.

The Lennox oil field consists of a thin oil column (44 m) overlain by a thick gas cap (232 m). In the early stages of production, the oil and its dissolved gas were produced. The dissolved gas was separated from oil, and injected into the gas cap, along with gas from the Douglas field, to maintain pressure during production of the oil. Gas production was scheduled to begin in 2004 (Yaliz and Chapman, 2003). It is likely that water drive will be observed when gas production starts. Because the oil was to all intents and purposes replaced by gas during its production, the CO_2 storage capacity of the Lennox field was calculated by treating the field as a gas field with water drive.

Table 7.1 CO_2 Storage capacities of the oil and gas fields in the East Irish Sea Basin

Field name	Ultimately Recoverable Reserves (billion cubic metres)	CO_2 storage capacity (Mt)
South Morecambe	146.8	734.4
North Morecambe	27.9	139.1
Hamilton	14.33	65.9
Lennox (gas cap)	10.31	42.6
Millom	6.07	24.3
Hamilton North	5.34	22.7
Dalton	2.87	11.5
Bains	1.36	5.4
Calder		
Darwen		
Hamilton East		
Crossans		0.0
Subtotal		**1045.9**
Douglas (oil)	0.00224	1.7
Total		**1047.6**

To put these figures in context, the nearby Connah's Quay power plant on the Dee Estuary, (Figure 7.4) emitted 4.3 Million tonnes of CO_2 in 2002. The estimated total CO_2 storage capacity available in the East Irish Sea Basin oil and gas fields amounts to some 243 years of emissions from this plant. However, given a plant lifetime of 25 years, and the fact that CO_2 capture would itself create significant extra emissions, it is clear that only the North Morecambe and South Morecambe fields have the potential to store the lifetime emissions from such a plant. The location of oil and gas fields accessible from the Point of Ayr and Barrow Shore Terminals is shown in Figure 7.4. Additional significant potential currently accessible from the Barrow terminal includes Millom and Dalton. A combination of the Hamilton, Lennox and Hamilton North fields, all currently accessible from the Point of Ayr terminal, could also be used. It is unlikely that any of the fields smaller than Dalton would be used for CO_2 storage from a large power plant such as Connah's Quay as they would have a very short operational lifetime. Moreover, under the assumptions made above, little CO_2 would be stored as a result of EOR in the Douglas field.

7.3.2 Further information on the oil and gas fields of the East Irish Sea basin

The Morecambe field (Figure 7.4) is volumetrically the second largest gas field on the UK continental shelf. It contains 12.1% of the proven UK gas reserves and is divided into north and south fields by a deep narrow graben filled by the Mercia Mudstone Group. Morecambe’s main reservoir lies within the Ormskirk Sandstone Formation, which on average is 250m thick, though in crestal parts of the South Morecambe field, the top 200m of the St Bees Sandstone Formation is above the gas-water contact (1143m). The north and south Morecambe fields together comprise approximately 83% of the available storage capacity in the oil and gas fields of the East Irish Sea.

The development plan for south Morecambe is based on using the facility for high rate seasonal gas supplies during the winter months; the first gas was produced in January 1985. South Morecambe has 34 producing wells, the top of the gas reservoir is 900m below sea level and the original recoverable reserves were 5.1 trillion cubic feet (tcf). It is believed that this reservoir shows tank-like behaviour in that there appears to be no evidence of water influx or of further significant gases being introduced from the surrounding rocks (Bastin *et al.*, 2003). The design life for the facilities here is 40 years, and they were installed in 1990. This site is therefore not likely to be available for storing CO_2 until at least the year 2030.

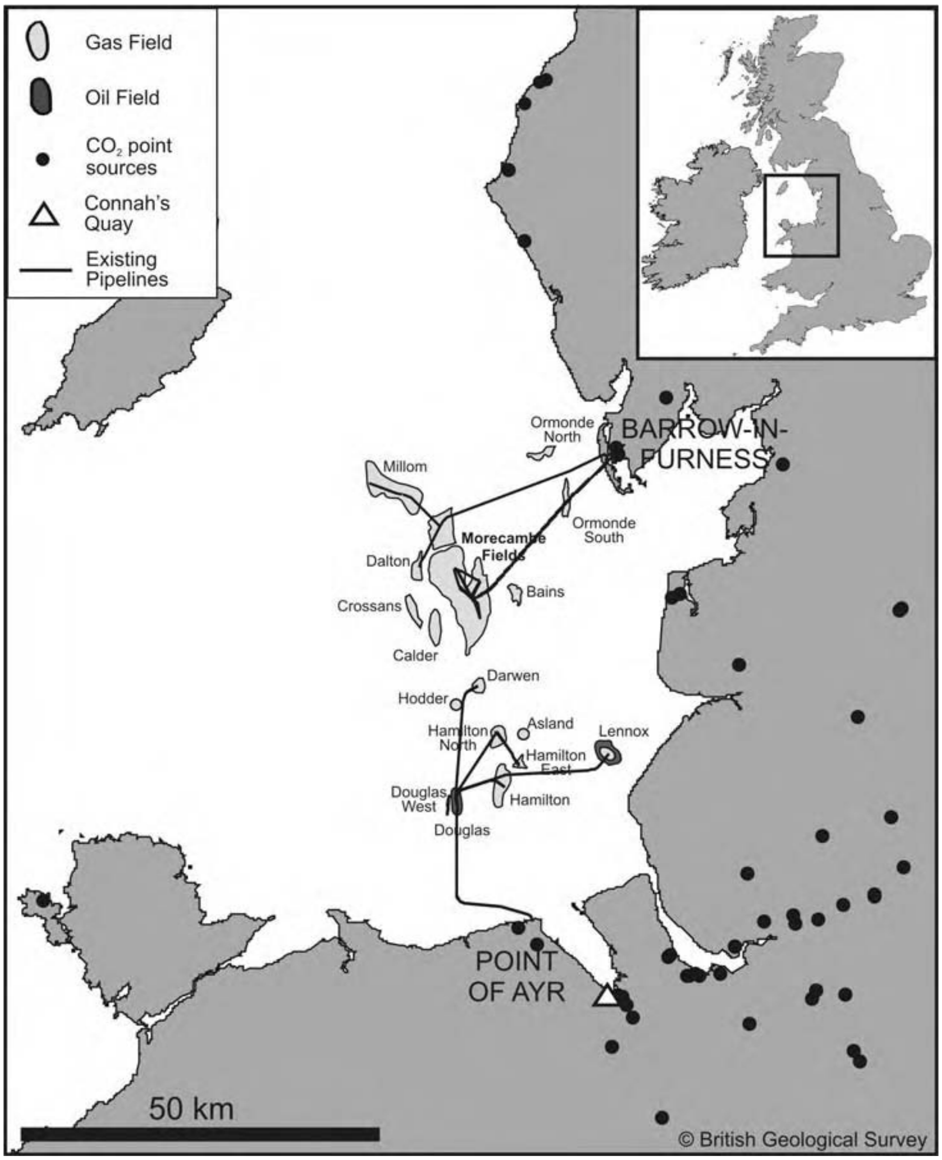


Figure 2.4 Map of the oil and gas fields near the Point of Ayr

Production at the Millom and Dalton fields began in 1999, with estimated combined recoverable reserves of 300 billion cubic feet (bcf). The expected lifespan of these two fields is 20 years. The earliest therefore that they would be expected to be available for CO_2 storage is approximately 2019. The Rivers fields (Calder, Crossans, Darwen, Asland and Hodder) are only now being developed and coming on line. Production started at Calder in 2004, whilst Crossans and Darwen are to be implemented by 2007. The five fields are estimated to contain a combined total of 250 bcf of gas.

The Liverpool Bay fields (Douglas, Douglas West, Lennox, Hamilton, Hamilton East and Hamilton North) have estimated initial recoverable gas reserves of 1.2 trillion cubic feet of gas, and more than 160 million barrels of oil. Production began 1996.

The Bains field has estimated gas reserves of 50 bcf and only started production in 2002. Bains has no production platform and is remotely operated from south Morecambe. The gas produced from Bains and south Morecambe are mixed and transported onshore.

It is unlikely that the Rivers, Liverpool Bay and Bains fields will be available for storage for many years yet.

7.3.3 Oil and gas composition

Table 7.2 summarises the composition of the oil and gas fields in the east Irish Sea. A gas containing high levels of hydrogen sulphide (H_2S) is referred to as a 'sour gas' and a gas containing low levels is referred to as a 'sweet gas'. Both the H_2S and CO_2 in gas are highly corrosive and therefore specialist chromium steels are required for transportation pipelines and for the casings in the production wells.

The gas from the Rivers fields contains high levels of H_2S. The Douglas Field, which produced the first offshore oil from the East Irish Sea basin, contains high levels of H_2S and other sulphur compounds that are removed during processing (Yaliz & McKim, 2003).

North Morecambe contains high levels of CO_2 (approx 6%), and due to the corrosive effects a new pipeline had to be installed. The CO_2 is removed during processing on the north Morecambe terminal (Cowan and Boycott-Brown, 2003).

Therefore, there are fields in the east Irish Sea where the infrastructure is already sufficient to cope with the corrosive effects expected whilst injecting CO_2.

Table 7.2 Composition of the oil and gas in fields in the East Irish Sea Basin

Field name	**Field type**	**Gas/oil composition**
Millom	Gas	Sweet
North Morecambe	Gas	High CO_2 & N_2
South Morecambe	Gas	Sweet
Dalton	Gas	Sweet
Hamlton North	Gas	Sweet
Darwen	Gas	Sour
Hamilton East	Gas	Sweet
Hamilton	Gas	Sour
Calder	Gas	Sour
Bains	Gas	Sweet
Crossans	Gas	Sour
Lennox	Gas	Sour
Asland	Gas	Sour
Douglas	Oil	High H_2S
Lennox	Oil	High H_2S

7.3.4 Storage capacity of saline aquifers in the East Irish sea

The combined total of CO_2 that it is estimated can be stored in the closed structures of the saline aquifer is 630 million tonnes (Mt). This is the equivalent of 146 years of emissions from Connah's

Quay power plant. Closed structures were identified from a map of the top Ormskirk Sandstone Formation derived from seismic data (British Geological Survey, 1994) and are shown in Figure 7.5. Because water has to be displaced from the pore space in aquifers, and the reservoir is heterogeneous, much of the pore space can be bypassed by migrating CO_2 when it is injected into such structures. This results in a less than perfect sweep of CO_2 through the pore space and relatively low CO_2 saturation of the reservoir rock. Based on reservoir simulation of closed structures in the Bunter sandstone (Obdam *et al.*, 2003), it is expected that the maximum CO_2 saturation of the pore space that could be achieved is approximately 40%. Other parameters used in calculating CO_2 storage in the saline aquifers are given below:

Average surface temperature	10°C
Geothermal gradient	25°C km^{-1}
Porosity	15%.
Pressure gradient	1.1 bar m^{-1}

Although the reservoir unit demonstrates all of the necessary properties required for geological storage, several of the structures do not lie at depths greater than 800m. The CO_2 therefore will not be in its dense supercritical phase where it occupies less space. This does not mean however that CO_2 cannot be stored; it just means that less will be stored (Brook *et al.*, 2003).

The fact that they do not contain gas (or oil) suggests that either they are not gas-tight or they do not lie on the migration path of any oil and gas generated in the basin. Further work is required to establish which of these reasons accounts for the absence of oil and gas in the non-hydrocarbon-bearing structures.

7.4 Summary of geological assessment of East Irish Sea

The East Irish Sea Basin has considerable CO_2 storage potential, particularly in its gas fields. On depletion these have a CO_2 storage capacity estimated to be in the order of 1046 million tonnes. More than half of this lies in the South Morecambe field, and more than 1040 million tonnes lies within fields with an estimated storage capacity of more than 10 million tonnes.

There is considerable further potential in the Ormskirk Sandstone aquifer. Here 630 million tonnes of CO_2 might be stored in mapped closed structures. However, further work is required to prove whether or not these structures are gas-tight.

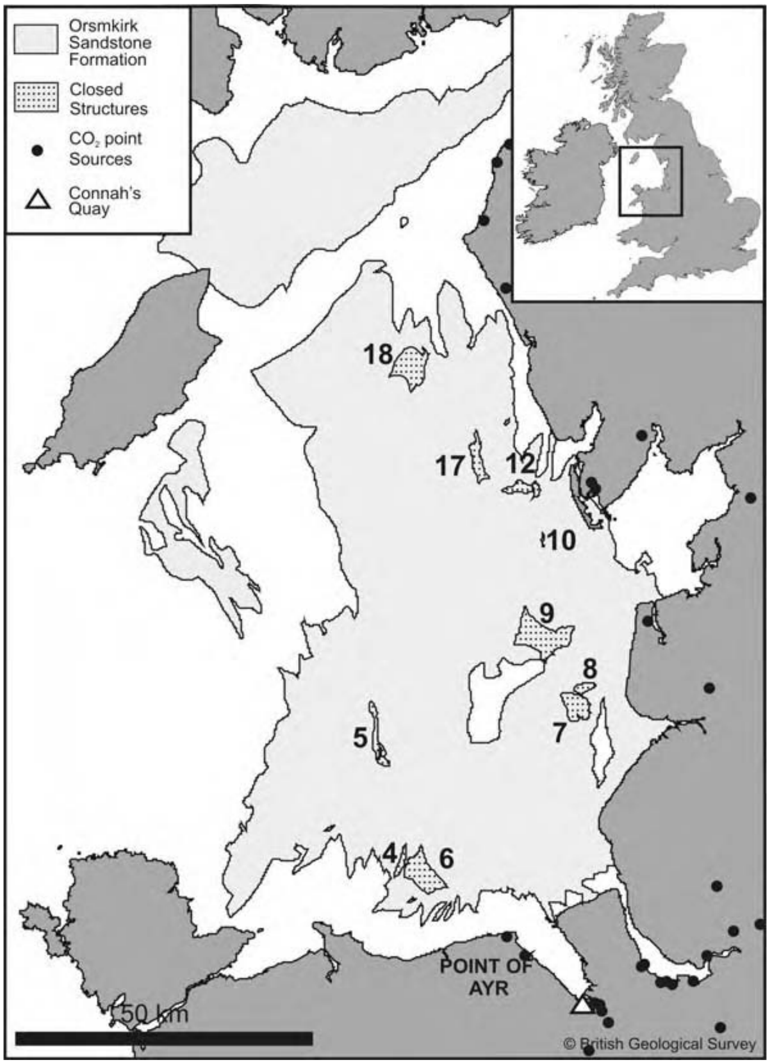


Figure 7.5 Map of the closed structures in the saline aquifer near the Point of Ayr

7.5 Multi-criteria assessment of different energy futures

7.5.1 Methodology

We selected a range of key regional stakeholders to perform the Multi Criteria Assessment (MCA). The aim was to conduct detailed in-depth interviews (typically lasting 1.5 to 2 hours) with a range of key stakeholders from across the region rather than to undertake a less detailed survey of a larger number of stakeholders. The stakeholders were selected to represent key interests and expertise from the energy business, government and NGOs. The following list details the organisational affiliation of the interviewees. We have used the letters in attributing comments or information in the paper to these interviewees. A and A* are work colleagues who conducted the MCA together and came to a consensus score between them. We have included them as a single individual in the data analysis (as A) but have distinguished between them where quotations have been employed.

A: Renewable energy business manager
A*: Renewable energy business manager
B: Renewable energy business development manager
C: Nuclear energy business manager
D: Environmental regulator
E Environmental Non-Governmental Organisation Manager
F: Environmental Non-Governmental Organisation Manager
G: Energy & environment consultant
H Energy & environment official in regional government

In addition to this list, we also interviewed a specialist on the environmental assessment and construction of long pipeline routes [I] in order to ensure that we had included all the potential key impacts of bespoke CO_2 pipelines.

The stakeholders were presented in advance with: a) a short explanation of CCS (see Annex 3); b) a one page summary of each of the five scenarios, including a summary in words and numbers of the energy mix and a map showing the location of any new power plants and pipelines. At the start of the interview, respondents were asked whether they wished to clarify any of the information provided or specific facts concerning CCS.

Respondents were then asked to score each of the scenarios against the nine criteria that the project team previously developed (Gough and Shackley, 2006). These criteria and their meaning are described in Table 7.3.

Stakeholders were also given the opportunity to add their own criteria, though only one respondent opted to do this (see Table 7.3). Scoring took place by asking the respondents to assign 100 points across the five scenarios for each of the criteria, allowing the relative performance of each scenario to be indicated. Respondents were then asked to weight the importance of the nine criteria, again having a total of 100 points to assign. The criteria scores for each scenario were then multiplied by the relevant weighting and summed to give an overall score. The scorings and weightings were entered directly during the interview into an Excel spreadsheet. Respondents were invited to revisit, and if necessary, change their scorings once they had seen the final ranking of the scenarios. On completion of the MCA process respondents were asked for their opinion on two further issues: whether enhanced oil recovery (EOR) using CO_2 would act to increase their acceptance of CCS; and the desirability or otherwise of CO_2 being exported from the region for storage elsewhere. Throughout the MCA process, respondents were invited to enter into discussion to explain their approach to the scoring and weighting. We recorded, and transcribed, the interviews. All of the respondents performed the MCA exercise as we intended, with the exception of E, who found the scoring method too prescriptive and opted not to score the two Spreading the Load scenarios at all, preferring instead to use the remaining three scenarios (which E found to be more intuitively understandable).

7.5.2 Description of the Scenarios

The five energy scenarios are: Nuclear Renaissance, Fossilwise, Renewables, Spreading the Load (High CCS) and Spreading the Load (Low CCS). All of these scenarios have been designed to achieve an approximately 60% reduction in CO_2 emissions by 2050, though we have not at this stage undertaken the necessary quantification to guarantee that this level of emissions reduction would ensue. Such a quantification is far from straightforward in the UK because: a) the energy system is highly integrated (Anderson *et al.*, 2005); b) key energy data, such as electricity consumption, is not available at the regional scale. Hence, at this stage, the scenarios are *indicative* to allow comparison of alternative pathways and this was explained to, and accepted by, the stakeholder interviewees.

Table 7.3 The Criteria Used in the Assessment of the Scenarios

Criterion	**Explanation of the Criterion**
Cost	The financial outlay required to implement the scenario using respondent's own knowledge of current, and estimate of future, costs (including capital, operation and maintenance costs)
Infrastructure	The disruption and level of change in infrastructure required now and in the future (as distinct from costs)
Adverse lifestyle impacts	Perceived effects (if any) arising from the scenario upon peoples' sense of well-being (excluding overt public opposition to individual power plant developments)
Security of energy resource	The security of the fuel inputs to the energy system (i.e. coal, gas, oil, nuclear fuels and renewables)
Environmental impacts	The environmental impacts from the scenario excluding CO_2 (which is controlled equivalently in each scenario)
Public opposition	The public opposition to the scenario (from local to national)
Reliability of supply	The extent to which the scenario implies a challenge in delivering a constant and reliable electricity supply (e.g. 'keeping the lights on' when faced with problems of intermittency)
Risk of major disaster	The risk of large-scale failure with adverse consequences for the environment and/or human health and safety
Lock-in	The extent to which decisions taken in the shorter term may come to limit the opportunities for changing those decisions in the longer term
ADDITIONAL RESPONDENT CRITERIA	
Deliverability	The extent to which the scenario could be delivered in practice, given the future (short term) perceived direction of policy, economic, social and technological drivers

We have assumed that the overall demand for electricity remains constant across all five scenarios. This assumption was made in order to make the key supply-side features of the scenarios more readily comparable. If there were differences in both supply *and* demand then it would have been difficult to have clearly differentiated respondents' assessment of the change in demand from the changes to the supply-side. A more elaborate assessment exercise would have been required in order to consider both the supply- and demand-side changes (as in Anderson *et al.*, 2005). The scenarios reflect a reasonable range of the key options on the future generation side for the UK, though are by no means comprehensive. A larger number of scenarios would have been unwieldy in the stakeholder process and hence a decision had to be taken on the basis of prior discussions with stakeholders on presenting a suitable range of alternatives (Gough & Shackley, 2006).

At this stage, the scenarios also refer only to the electricity generating sector. Whilst it would have been possible to extrapolate the storylines to the transport sector and to the direct use of fuels in the domestic sector, this would have created a further level of complexity involving consideration of new fuels such as hydrogen which have multiple potential generation routes. It was decided to limit the complexity of our scenarios, in part because we did not have the resources to extend the technical modelling, and also to ensure that the respondents would understand them reasonably quickly in the time prior to the interview.

The scenarios were formulated to be applicable to the North West region of England, home to 6.7 million people and including the major metropolitan areas of Greater Manchester and Merseyside (including Liverpool). It also includes large rural areas in Cumbria, Cheshire and Lancashire. In terms of energy, the North West has some features which make it distinctive in the UK context. These include: a strong presence of the nuclear industry, with most of the UK's nuclear fuel preparation and re-processing facilities within the region; a number of gas fields in the eastern Irish Sea (Morecambe Bay and Liverpool Bay) and associated Combined Cycle Gas Turbine (CCGT) plants; potential for large amounts of renewable energy, especially on- and off-shore wind; and relatively little coal-powered generation (with one large coal power station in the region) (NWRA, 2005). Overall, the North West region is approximately in balance vis-à-vis its energy imports and exports, though this is largely achieved through exporting gas supplies and importing coal-generated electricity from outside of the region (Carney, 2005).

The North West regional version of the scenarios was developed with these distinctive features in mind. A summary of each of the scenarios is provided in Table 7.4. The Nuclear Renaissance scenario (no CCS) therefore reflects the strong presence of the nuclear industry with a large increase in capacity through refurbishment of existing nuclear power plants and construction of two new plants on existing nuclear installation sites. Nuclear power provides over 80% of electricity in this scenario, with the balance being made up by equal amounts of gas CHP and renewables[i]. The Renewable Generation scenario reflects a massive increase in the amount of off-shore wind and significant development of on-shore wind. Renewable electricity contributes 45% of capacity, with the remainder being made up in equal measure from CHP (partly bio-CHP) and gas CCGT. There is a small amount of CCS occurring from gas plants in the period up to 2050, as renewable energy replaces fossil-fuel based power.

The Fossilwise scenario sees a doubling of coal-fired power stations, this fuel coming to supply 53% of overall electricity generating capacity. Gas CCGT constitutes a further 24% and gas-fired CHP 18%. There is very little renewable electricity and no nuclear power in this scenario. CO_2 is collected

[i] In these scenarios we have referred to changes in capacity as a surrogate for actual electricity generation. Capacity is, of course, not the same as actual generation because of load factors, whether the latter are influenced by intermittency or commercial factors. We have made an allowance for the intermittency of renewables by increasing the overall capacity of the regional electricity supply system in proportion to the penetration of renewables within the scenario. Hence, the capacity figures reflect the need for greater installed capacity due to intermittency.

from the re-furbished and new build power stations and piped for storage in the depleted gas fields of the eastern Irish Sea several miles out to sea. We selected the locations for new build power stations based upon submitted planning proposals available in the public domain, but focusing upon the major areas of demand in the southern part of the region (see Figure 7.6) (Electricity Association, 2003).

Table 7.4 Quantitative Summary of the Five Scenarios

	Electricity Generation Capacity in the North West (GW)					
	CCGT	**Coal**	**CHP**	**Nuclear**	**Renewable Generation**	**Total Capacity**
Baseline	2.9	2	0.75	2.6	0.23	8.5
% of total capacity	34%	23%	9%	31%	3%	
Fossilwise	2	4.5	1.5	0	0.5	8.5
% of total capacity	23.5%	52.9%	17.6%	0.0%	6.0%	
Nuclear Renaissance	0	0	0.75	7.5	0.75	9
% of total capacity	0.0%	0.0%	8.3%	83.3%	8.3%	
Renewable Generation	3	0	3	0	5	11
% of total capacity	27.3%	0.0%	27.3%	0.0%	45.4%	
Spreading Load I (high CCS)	2	2.5	1	2	2	9.5
% of total capacity	21.0%	26.3%	10.5%	21.0%	21.0%	
Spreading Load II (low CCS)	1.5	1	2	2.5	3.5	10.5
% of total capacity	14.3%	9.5%	19.0%	23.8%	33.3%	

The routes for the CO_2 pipelines were determined using a Geographical Information Systems (GIS)-based model supplied by a project partner (Cockerill, University of Reading). The GIS model works out the optimal pipeline route given the source, and the reservoir for the storage of, the CO_2, the costs of the pipeline and the need to avoid sites with nature designations such as National Parks, Areas of Outstanding Natural Beauty and EU designated sites such as Special Protection Areas and Special Areas of Conservation (SPAs, SACs). The route also remains at a minimum of 1km from villages and larger habitations in line with guidelines from the British Standards Institute (BSI, 1992). For simplicity we also assumed that there would be a single pipeline from each power station to the depleted gas field reservoir and, furthermore, that the pipeline would enter the Irish Sea at the existing landing sites for the natural gas pipelines (north and south). In the Fossilwise scenario we also allowed for an additional pipeline to be constructed from one of the new coastally-located power stations (see Figure 7.7). Not surprisingly the Fossilwise scenario has the largest amount of CCS and, within the course of the current century under this scenario, the capacity of the gas fields for storing CO_2 would be readily exceeded. This implies that after several decades the CO_2 in the Fossilwise scenario would have to be exported for storage in reservoirs elsewhere, probably in the North Sea.

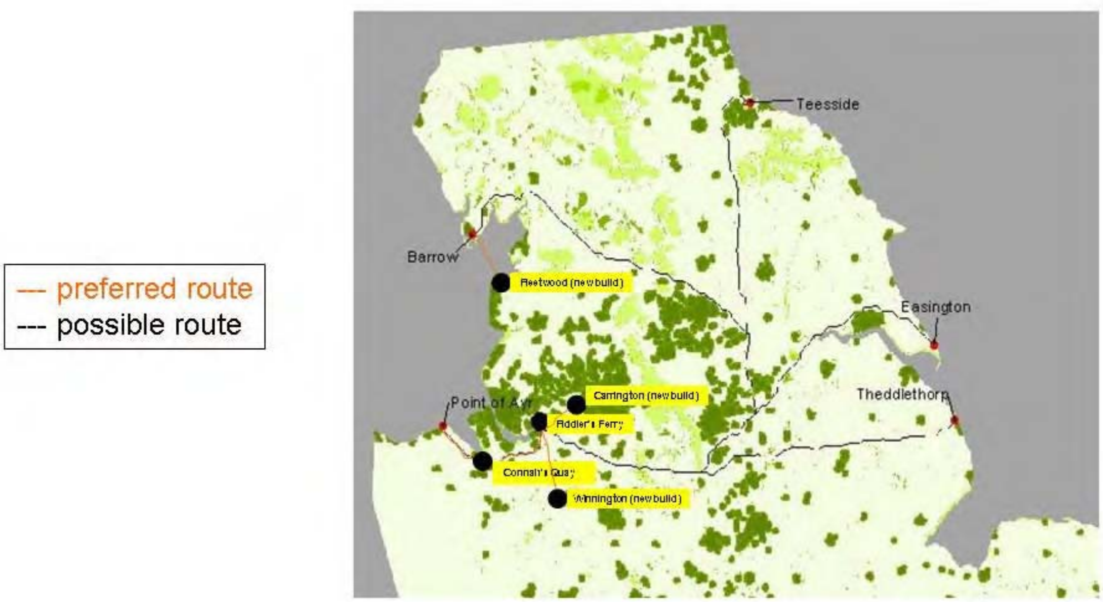
Scenario Summary: Fossilwise

- 2.5GW increase in coal- 3 new coal fired power stations:
  - Carrington (1GW)
  - Feetwood (0.75GW)
  - Winnington (0.75 GW)
- Existing coal fired power stations are refurbished to extend life
- 0.75GW increase in CHP spread throughout the region
- Public opposition leads to all planned round 2 wind projects being abandoned
- No nuclear
- **High levels of CCS from existing and new sources** (e.g Fiddler's Ferry, Connah's Quay and new builds at Carrington, Fleetwood and Winnington – see pipeline map).

Electricity Generation in the North West in terms of Capacity (GW)

	CCGT	Coal	CHP	Nuclear	Renewables	Total Capacity
Baseline	2.9	2	0.75	2.6	0.23	8.5
% of total capacity	34%	23%	9%	31%	3%	
Fossilwise	2	4.5	1.5	0	0.5	8.5
% of total capacity	23.50%	52.90%	17.60%	0.00%	0.06%	

Figure 7.6 Fossilwise scenario summary



North West will fill its storage capacity around 2075

Figure 7.7 Fossilwise CCS pipeline routes

7.5.3 Clustering of the Weightings

In discussing the results we begin by looking at the criteria weightings of respondents A to H. It appears that there is a reasonably clear division amongst the stakeholders with respect to the pattern of criteria weightings.

On the basis of the interviews and of our own judgement, we categorized the criteria into two groups as shown in Table 7.5. The **business-focused criteria** are those which are important for the commercial activity of supplying energy to customers. They are: costs, infrastructural change, security, reliability and (for respondent B) deliverability. The **environment and socially-focused criteria** are those which relate to the wider environmental, social and political impacts arising from change in the energy system. They are: adverse lifestyle impacts, security, environmental impacts, public opposition, disaster and lock-in. It will be noticed that the issue of security overlaps both categories which reflects the fact that energy insecurity has huge adverse implications for business and for society at large. Some consideration of energy security issues is increasingly part of the commercial decision-making context for energy supply firms due to factors such as conflict in the Middle East, the high oil price and the depletion of the UK's gas and oil reserves.[ii] In Table 7.5 we have added up the weights for both categories, including the security criteria for both categories. Since there are six environment and socially-focused criteria and four business-focused criteria, when they are added up there is something of a bias towards the former. However, the selection of the criteria reflects the priorities of an earlier cohort of stakeholders (Gough & Shackley, 2006) in addition to which the current group of stakeholders were invited to add additional criteria. It can be seen that the respondents fall into two clusters, with B, C and A clearly weighting business criteria more highly, and E, F D and H weighting environment & social issues more highly. Respondent G is less easy to categorise and effectively spans both clusters. Given the fact that there are more environment and social focused criteria than business ones, we decided to locate G in the business-focused criteria category.

Table 7.5 Aggregation of the Criteria Weightings

Respondent	Cluster	Sum of Business-Focused Criteria Weightings	Sum of Environment & Socially Focused Criteria Weightings
B	**Energy as**	**78**	27
C	**Business**	**65**	50
A (A*)		**64**	55
G		56	58

[ii] It might be argued that reliability is a criterion which spans both business and environment / societal concerns, since 'keeping the lights on' is clearly a vital social service. However, the way that we defined the scenarios and the criterion of reliability in Table One implies that the energy system will have to find a way of being reliable given the changes that it has undergone. E.g. it is assumed that the problem of intermittency has been solved in some way in the renewables scenario. Hence, the respondents were encouraged to score the reliability criterion in terms of how challenging it would be within that scenario to provide a reliable energy system. For this reason, we have categorised this as a business criterion.

E	**Environment and**	5	**100**
F	**Society First**	45	**70**
D		50	**67**
H		49	**65**

Legend:
A, A* and B: renewable energy industry
C: nuclear energy industry
D and H: environmental regulator / government official
E and F: environmental NGO
G: consultant

7.5.4 Environment and Socially Focused Criteria Cluster

However, we did not identify a consistent pattern of scoring across the nine criteria. In some cases, similar patterns of scoring did emerge for a few respondents with respect to a few criteria but not across all criteria. Furthermore, the similarity in scoring was not consistent between respondents across all criteria, but only across a sub-set of them. In other words, clusters of consensus emerged for some criteria, for some respondents, but not consistently across all criteria for these same respondents.

E stands out as having an exceptionally high weighting on the environment criterion (80 out of 100 points) (see Figure 7.8), the scoring against which therefore comes to dominate the performance of the scenarios. E was uncomfortable at being asked to score elements that were not directly related to nature conservation (the respondent's particular area of expertise). This response reflects E's role in an ENGO where he feeds specialist knowledge on the impacts of development upon biodiversity into public policy making decisions.

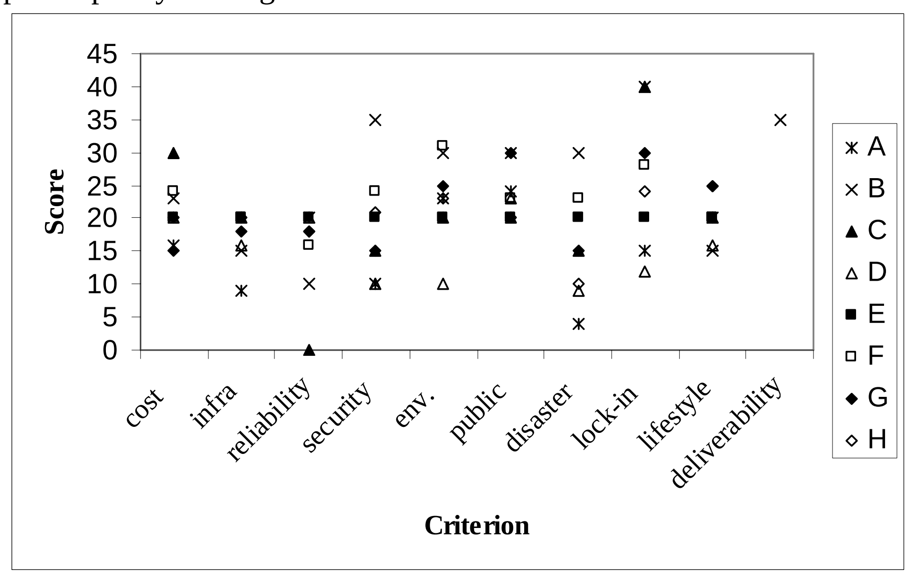


Figure 7.8 Criteria weighting

F, D and H illustrate a more even balance in their weightings between criteria (see Figure 7.8). This includes recognition of the business criteria such as cost and reliability, though the meaning given to the cost criterion was not always the investment, operation and maintenance cost (which is what we intended). One respondent was thinking rather of cost implications of the scenarios for the fuel poor.

The respondents in this cluster were also in general not confident in making judgements on the costs of the technologies in the various scenarios, with one stating that "it is up to others to make the economic arguments" (H).

7.5.5 *Energy as a Business Cluster*

Whilst, overall, respondents A (A*), B and C shared a focus upon the business-related criteria, there were some important differences in their criteria weighting. Opinion on the importance of infrastructural change varied, with some regarding this as effectively the same as the cost criterion, whilst others considered the logistics of infrastructural change to be the key factor. Environmental impact is weighted highly by A, at a medium level by G and at a low level by B and C. The difference in weighting reflects the importance accorded to the non-climate change environmental impacts such as fuel extraction, preparation, transportation and waste disposal. Public opposition was weighted highly by C and G, at a medium level by B and a low level by A. The key difference here seemed to be the extent to which the respondents believed that public opinion was not so important or at least 'malleable' and hence could be overcome in one way or another through appropriate government policies and given appropriate political will (the view of A and B). As A put it:

> 'What people think about it [the future energy supply mix] is neither here nor there for me because in the end the population of this country is going to have to be told what is good for them. You can't be democracy about everything. Government should govern' (A)

B, on the other hand, argued that public opinion was likely to be highly fragmented, hence there would be no clear consensus on what the public was opposed to. This is contrasted to criteria over which there would be a much stronger consensus, e.g. reliability. C and G, meanwhile, felt that public opposition could well have a major influence on the viability of future energy technologies such as nuclear (C works in the nuclear industry).

7.5.6 *Clustering of the Scoring*

We assessed each respondent's scoring for each criteria across the five scenarios. We identified high and low scores and then compared the pattern of scoring across the nine criteria. We then sought clusters from consistent patterns of high and / or low scoring by respondents. If there was no consistency in the scoring across all criteria, we looked for clusters related to a smaller number of criteria.

Clustering of the Nuclear Renaissance Scenario Scorings. Scoring varied most between respondents for Nuclear Renaissance on the three criteria of: costs, security and environment (see Figure 7.9). Three clusters emerged: Nuclear Sceptics (B, A and F) who thought that the nuclear scenario would be very expensive, with high environmental risks and would not perform well in energy security terms; Nuclear Advocates (C) and Nuclear Ambivalents (D, E, G, H). The nuclear ambivalents scored nuclear poorly with respect to environment, and relatively highly with respect to security. The ambivalents were divided with respect to costs.

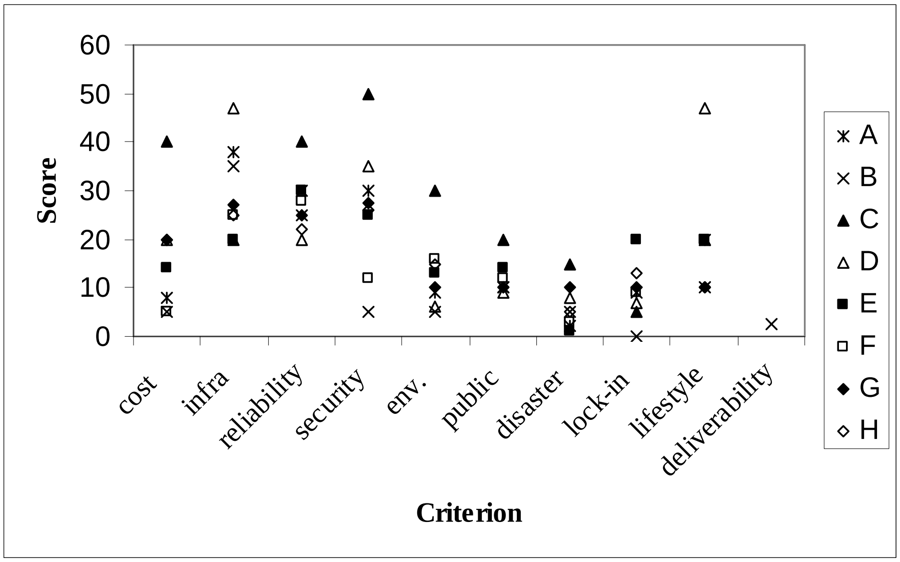


Figure 7.9 Scoring of the Nuclear Renaissance scenario

Clustering of the Fossilwise Scenario Scorings. The scorings for Fossilwise were more complicated than for Nuclear Renaissance and are summarised in Table 7.6 and Figure 7.10 The blanks in Table 7.6 indicate criteria against which there is little variation in scoring between the respondents. Since we are mainly interested in the comparison between respondents, we have not included those respondents in Table 7.6 whose scores are in the mid-range. The bold letters indicate those respondents around whom we can begin to identify prototype clusters.

Table 7.6 Summary of the Scorings for the Fossilwise and Renewable Generation Scenarios

Criterion	**Fossilwise**		**Renewable Generation**	
	Higher performance	Lower performance	Higher performance	Lower performance
Costs	A,B,**D**,E,F,**G**,H	C	**B,F,A,H**	**C,G**
Infrastructure			H	A,B,D,**G**
Lifestyle			B,G,H	**C**,D
Security	G	**A**,B,C,D,**E**,F,H	**A,B**,D,E,**F,H**	**C,G**
Environment	D	**A,**C,**E**	A,B,C,D,E,G,H	
Public opposition	**A,**C,**E**			**C,G**
Reliability				**A,B,C**,E,**F**,**G**,**H**
Disaster	C,**G**,H,**D**	**A,E**	**A,B**,D,E,**F**,G,**H**	**C**
Lock-in	C,H,G,F	**A**,B,D,**E**	**A,B**,D,**F**,G,**H**	**C,**E

Legend:

A, A* and B: renewable energy industry
C: nuclear energy industry
D and H: environmental regulator / government official
E and F: environmental NGO
G: consultant

There is a high level of consensus between participants on two criteria: that the costs of Fossilwise are lower than those of other scenarios, but also that the scenario does not perform so well in terms of energy security due to the need for imported gas and (to a lesser extent) coal. C disagrees on the cost consensus, regarding the construction of new fossil powered generation with CCS to be much more expensive than the other respondents. G disagrees with the consensus view that fossil fuels perform poorly with respect to security, arguing that supplies are more readily available to the extent required in the scenario than is assumed by the other respondents.

Respondents A and E provide the nucleus of a **Fossilwise Sceptics** cluster, rating the scenario poorly in terms of the (non-CO_2) environmental impacts, disaster and lock-in, although they see little potential for public opposition. It is some what more difficult to identify a **Fossilwise Advocates** cluster, though D & G do (between them) appear to have a positive view of Fossilwise with respect to security, environment, disaster and lock-in. It is perhaps surprising to note that only D thought that Fossilwise performed well with respect to the environment given that the problem of CO_2 emissions had (by definition) been removed. What is more, other emissions associated with coal burning are subject to control by the EU's Large Plant Combustion Directive (as well as by the requirements of the CO_2 capture process), though we did not provide this information to respondents. For a few respondents, the poor environmental performance of Fossilwise arose from the impacts of the extraction of coal in other parts of the world, though most respondents did not include impacts arising outside of the UK.

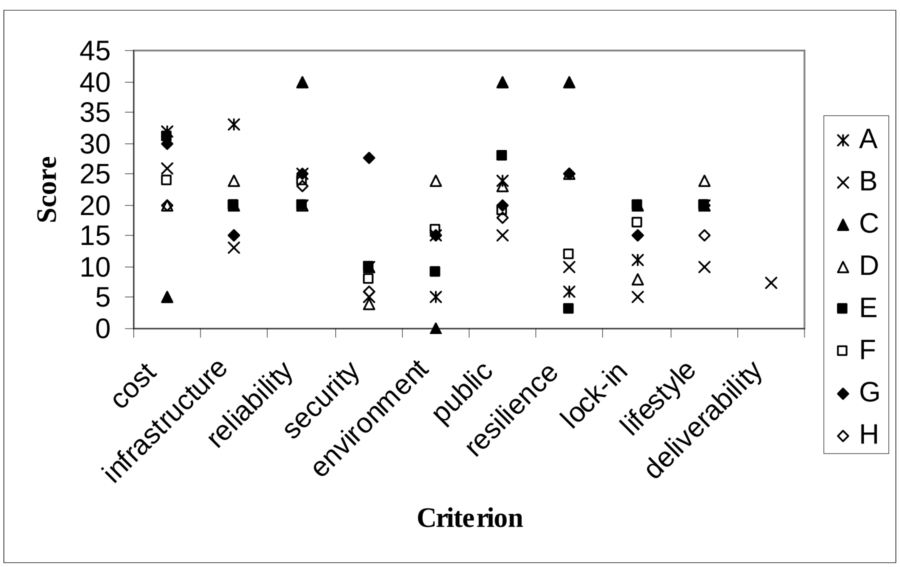


Figure 7.10 Scoring of the Fossilwise scenario

Clustering of the Renewable Generation Scenario Scorings. There is a high degree of consensus with respect to the scorings for Renewable Generation on five criteria, namely a high score for security, environment, disaster and lock-in; and a low score for reliability (see Table 7.6 and Figure 7.11). There appears, perhaps surprisingly, to be more consensus over the performance of Renewable Generation than there is disagreement. Nevertheless, a **Renewables Advocates** cluster emerges (A, B, F and H) on the basis of the above criteria but also with respect to costs and (to some extent) adverse lifestyle impacts. C is a consistent **Renewables Sceptic** who is joined in his scepticism at times by G.

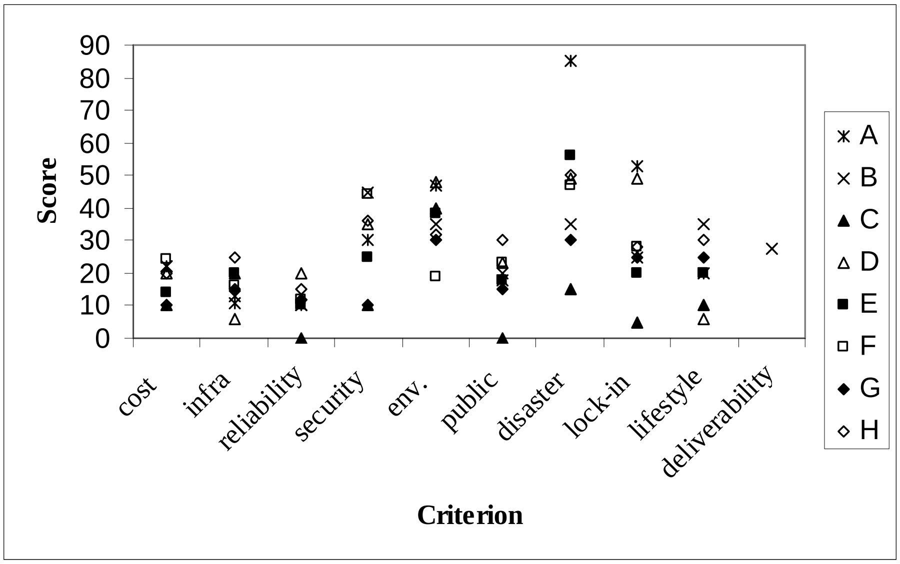


Figure 7.11 Scoring of the Renewable Generation scenario

Respondent H was alone in believing that the infrastructural performance of Renewable Generation was high. H accepted that the large-scale implementation of Renewable Generation would necessitate extensive infrastructural change. However, his perception was that a large-scale change of the infrastructure was, in any case, necessary under all future energy scenarios. Hence through stimulating the development of such a modified infrastructure, the Renewables Generation scenario could be regarded positively with respect to this criterion.

Clustering of the Spreading the Load (High CCS) Scenario Scorings. The scorings for Spreading the Load (High CCS) are summarised in Table 7.7 and Figure 7.12. There are no clear clusters for or against this scenario, in part because it does not evoke strong pro- or anti- assessments on the part of stakeholders. Both B and C rate the scenario quite favourably in terms of its having few adverse impacts on lifestyles (it is perhaps the closest of all the scenarios to current baseline conditions). The only really poor scoring of the Spreading the Load (High CCS) scenario is by A in relation to disaster, a result of A's perception that CCS entails high risks given that this scenario entails a reasonably high level of CO_2 storage.

Clustering of the Spreading the Load (Low CCS) Scenario Scorings. Opinion on the Spreading the Load (Low CCS) scenario is more varied than that for the high CO_2 storage version of Spreading the Load (see Table 7.7 and Figure 7.13). Respondents A and D demonstrate elements of a **Sceptical Spreading the Load (Low CCS)** perspective, in particular with respect to infrastructure and disaster. There is stronger evidence of support for this scenario on the part of B, F and G. The scenario scores particularly well with respect to environmental impacts, public opposition, security and lock-in.

Table 7.7 Summary of the Scorings for the Spreading the Load High CCS and Low CCS Scenarios

Criterion	**Spreading the Load (High CCS)**		**Spreading the Load (Low CCS)**	
	Higher performance	Lower performance	Higher performance	Lower performance
Costs			C	
Infrastructure		A		**A,D**
Lifestyle	B,C		**G**,H	D
Security		B,D,H	**B,F**	
Environment		C	**G**,**B,F,**H	
Public opposition			**G**,**B,F**,D	
Reliability				C
Disaster		D,A,H	**B,F**	**A,D**,H
Lock-in	B,D,C		**G**,B,C	

Legend:
A, A* and B: renewable energy industry
C: nuclear energy industry
D and H: environmental regulator / government official
E and F: environmental NGO
G: consultant

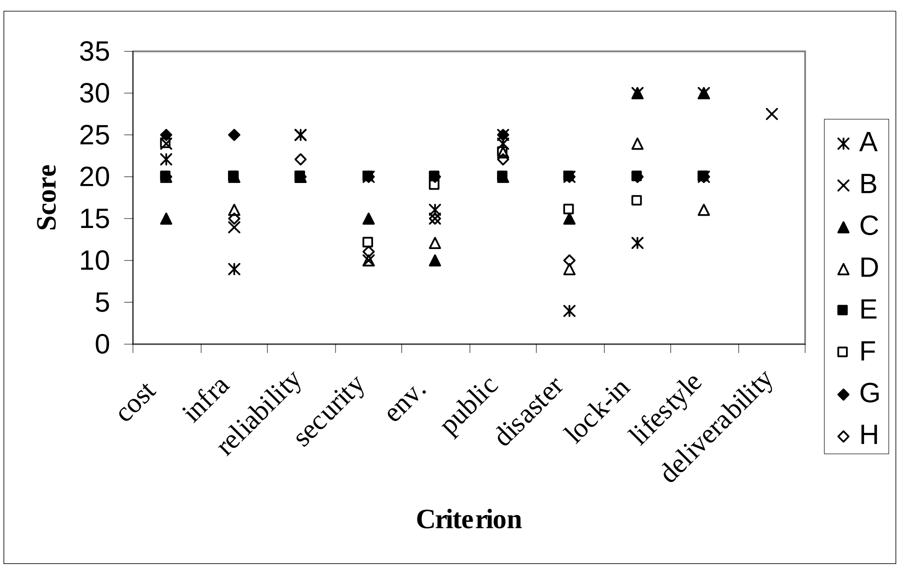


Figure 7.12 Scoring of the Spreading the Load (High CCS) Scenario

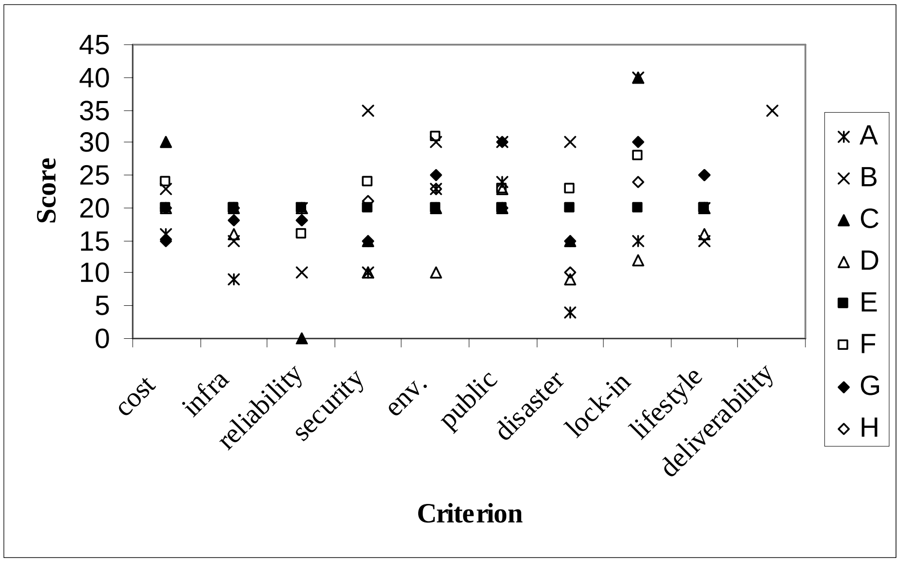


Figure 7.13 Scoring of Spreading the Load (Low CCS) Scenario

7.5.7 Aggregating the Results for Scoring of Individual Respondents

We now summarise each individual's scoring for each scenario (i.e. with no criteria weightings, so that each criteria is assumed to be of equal importance).

Respondent A: Not only is the Renewable Generation scenario favoured, but A is quite sceptical of the other scenarios with Fossilwise scoring slightly above the others in second place.
Respondent B: Favours equally the Renewable Generation and the Spreading the Load (Low CCS) scenarios. Spreading the Load (High CCS) comes in third, whilst Nuclear and Fossilwise are both much less preferred.
Respondent C: Strong advocate of Nuclear Renaissance, but also demonstrating reasonably high levels of support for Fossilwise, Spreading the Load (Low and High CCS), but sceptical of Renewable Generation.
Respondent D: Favours Renewable Generation but also quite favourably inclined to Nuclear and Fossilwise.
Respondent E: Favours Renewable Generation with other scenarios more or less evenly scored.
Respondent F: Supportive of Renewable Generation and of Spreading the Load (Low CCS), but sceptical of Nuclear Renaissance.
Respondent G: Supports a range of scenarios, Fossilwise, Spreading the Load (Low and High CCS), and Renewable Generation but less enthusiastic about Nuclear Renaissance.
Respondent H: Renewable Generation is a long way in front, with Nuclear and Fossilwise the least favoured.

7.5.8 Combining the Effects of the Scoring and Weightings

Including the criteria weights affects the overall ranking of the scenarios by the respondents. We now describe the influence of the weightings for each respondent.

Respondent A: The inclusion of weightings does not make a large difference to the scenario rankings.

Respondent B: The attractiveness of the Renewable Generation scenario is reduced through including the effect of the weightings, whilst the Spreading the Load (Low CCS) and Fossilwise scenarios both become more attractive.

Respondent C: The weightings render the Nuclear Renaissance scenario even more attractive. The Spreading the Load (Low CCS) comes out more favourably due to its nuclear component, whilst Renewables Generation comes out less favourably.

Respondent D: Renewable Generation is scored more highly with the weighting, whilst nuclear is slightly worse off.

Respondent E: The Renewable Generation scenario does much better with inclusion of weightings, whilst Fossilwise and Nuclear Renaissance do worse.

Respondent F: The weightings make the Renewable Generation scenario slightly more favourable.

Respondent G: The weightings do not make a large difference, though Nuclear does some what better and Renewable Generation does some what worse.

Respondent H: The inclusion of weightings does not make a large difference to the scenario rankings.

The weightings make a major difference in the ranking of the scenarios for respondents B, C and E. Both B and C exemplify business-focused criteria weightings.

7.5.9 Strategies of Scoring and Weighting

From the analysis of the respondents' explanations of the scoring and weightings during the interview stage, it would appear that there are two different ways in which the scoring and weighting are undertaken by respondents. Some of the respondents seem to have a clear idea of the pattern of scenario rankings that they wish to obtain at the end of the exercise as they are proceeding with the MCA process. We term this approach **strategic scoring and weighting**. Those who employ a strategic approach appear to have worked out, to a greater or lesser extent, how the MCA tool works and how to use the scorings and weightings to achieve their own preferred ranking of the scenario options. Other respondents seem to use the MCA in a much more explorative, experimental fashion, and generate scenario rankings which appear on occasions to surprise them. We term this approach **explorative scoring and weighting.** For these respondents there is less of a sense of approaching the MCA with a view to confirming a pre-defined favourite, even though the respondents may indeed have their own subjective preference. Below we provide evidence of strategic and explorative approaches to both weighting and scoring.

Strategic Weighting and Scoring. We identified two different ways in which the weighting and scoring of criteria was performed strategically.

Delegating Responsibility on Specific Issues: Respondent E massively weighted environment relative to the other 8 criteria. This ensured that the weighting of the environmental criteria dominated the ranking of the scenarios. E justified this approach by effectively **delegating responsibility** to others for the assessment of the economic and other more socially-focused criteria. This perhaps reflects E's role in representing the environmental interests in planning applications and policy developments more generally. Much of E's work is taken up in commenting on the environmental aspects of development applications on behalf of an environmental Non-Governmental Organisation and communicating this to planning authorities and other policy makers and stakeholders. Hence E appears to have extended such a delegatory approach to the conduct of this MCA exercise, despite the researchers' explanation that the purpose of the MCA is to grapple with the trade-offs that individual stakeholders might not normally have to confront. To a much lesser extent, D also shows some of the same approach, with the environmental impact criterion again given a high weighting, which D explained in terms of his responsibilities as an environmental regulator. However, in the case of D the initial environmental criterion weighting (60 out of 100 points) was revised downwards (to 33 points) as the purpose and rationale of the MCA exercise began to become more apparent. Hence, D's response appears to be somewhere between the strategic and explorative approaches.

Early Identification of a Clear Favourite … and of Less Favoured Options. Respondent C clearly preferred Nuclear Renaissance to the other scenarios and used the scorings and weightings to favour the high nuclear scenario. Other options, in particular Renewable Generation, were clearly less favoured by C and down-scored, even on some of the more socially-oriented criteria such as security, public opposition, risk of major disaster and lock-in. Most respondents gave higher scores to the Renewable Generation scenario on such criteria. Fossilwise tends to score reasonably highly for C (outperforming nuclear with respect to public opposition, risk of major disaster and lock-in, but not doing so well as nuclear with respect to costs, security and environmental impacts). The other scenarios are evaluated by C largely with respect to the amount of nuclear relative to renewables (more nuclear and less renewables tending to improve the performance of the scenario). C's stronger weighting of the business-focused criteria acts to exacerbate what is already a strong preference for the Nuclear, followed by the Fossilwise, scenarios.

Clearly, it is not just the advocate of nuclear power who has clear likes and dislikes. D, who works in environmental regulation, is an example of a respondent who expressed a strong belief that the energy system would have to change quite radically in order for it to become sustainable in the future. Even with respect to infrastructural change, for example, the scoring was not lower than for the other scenarios, with Renewable Generation in fact being scored jointly first (the most favourable scoring with respect to this criterion for the Renewable Generation scenario of all respondents). The explanation given by D is that the infrastructure will have to change in any case because of the necessary transition to sustainability, implying that modification for distributed and intermittent generation is a secondary issue. It is interesting to note that those respondents most directly involved in renewable energy development (A and B) scored Renewable Generation either lowest or very nearly lowest with respect to infrastructural change.

D is also very optimistic about low levels of public opposition to renewables, considerably more so than A, who is a renewables energy developer. D considered that there would be less public opposition to the Renewable Generation scenario than to any of the other scenarios, basing his assessment on general opinion surveys of the acceptability of renewables versus other energy technologies. By contrast, renewable energy developer A scored renewables as second worst vis-à-vis public opposition, with only Nuclear Renaissance scoring more poorly. B, who is also employed in the renewable energy business, is somewhere in between D and A in the scoring of this criterion, with

Nuclear Renaisssance and Fossilwise scoring worse with respect to public perceptions, but the two Spreading the Load scenarios doing better.

Respondent A presents a third interesting example of strategic scoring and weighting in favour of one option (Renewable Generation), and sceptical of some other scenarios. In this case it is interesting to compare the response of A with that of B, since both work in the renewable energy business. Respondent A falls within the business-focused weightings cluster, yet whilst he shares the high weighting of reliability and costs with B, A considers infrastructure to be one of the least important criterion. To some extent this might be a function of the way that the criterion has been interpreted, with A regarding it as effectively equivalent to the cost criterion, hence downplaying it here as a separate criterion.

The weighting of the security of supply criterion is a further example where A and B differ quite markedly, with A including it as one of the top three criteria, whilst B weights it very low. It is unclear from the accompanying interviews why such a difference occurred amongst two individuals both involved in renewable energy development. The effect of a high weighting for the criterion is to enhance the performance of scenarios with more renewables and nuclear and to downplay that of fossil-fuel dependent scenarios.

With respect to public opposition, B gave a mid-level weighting, whilst A gave it the lowest weighting of all the criteria. The rationale behind the weightings by A and B was the same however: namely that the public does not have sufficient knowledge and information to make an informed decision. Hence, it would be necessary to find a way of persuading the public to accept renewable energy. It was assumed by both A and B that the public could, in general, be so persuaded.

A’s more highly weighted criteria are costs, reliability, security and environment. In A’s scoring Nuclear Renaissance does well with respect to security and reliability, but falls down on the cost and environmental impact criteria, whilst Fossilwise does well on cost and reliability, but falls down on security and environmental impact criteria. Fossilwise receives the lowest score of all the scenarios with respect to environmental impacts, with mention made of the problem of NO_x and SO_x and ash. Respondent A was not referring to the environmental impacts of coal extraction in other parts of the world, an issue that was explicitly raised by a few other respondents and which accounted for the poor scoring of the Fossilwise scenario by D.

On the other hand, Renewable Generation does exceptionally well for A against the environmental criterion. Respondent A stated that he considered wind turbines to be an attractive addition to the rural landscape, so his scoring might reflect a sense that renewables will actually have a net positive environmental impact. Renewable Generation, whilst not performing as well with respect to reliability, also manages to score well against the security and cost criteria and accordingly comes out as the preferred option for respondent A.

Whilst difficult to ‘prove’, the pattern of scoring by A appears to demonstrate aspects of strategic scoring in favour of renewables. Where renewables score well, they tend to do so by a very large margin compared to the other scenarios, e.g. with respect to environment, lock-in and risk of major disaster. Yet where renewables do not score as highly, then their relative disadvantage compared to other scenarios is much less evident, i.e. there is more ‘bunching-up’ of the scores across the five scenarios, e.g. for public opposition and for reliability (where the Renewable Generation scenario is indeed the lowest scoring, but it is not the lowest by very much). From analysis of the results and of the interview transcript it appears to us that respondent A has a clear pre-defined preference for the Renewable Generation scenario and then uses the scorings to ensure that this scenario comes out as the clear favourite. The criteria weightings of A do not make such a large difference to the rankings, though as noted above the pattern of the weightings will tend to work in favour of the Renewable Generation scenario.

Explorative Strategies of Scoring and Weighting. Respondents B and G both demonstrate a more explorative approach to the weightings and scorings. For **B** the older and more conventional energy generation types tended to score most highly on the more highly weighted business-focused criteria. Conversely, the scenarios with higher levels of renewable energy tended to score poorly with respect to those criteria: i.e. costs, infrastructural change and reliability. The high renewables scenarios perform very well under the criteria which are least weighted: adverse lifestyles, security of supply and environmental impacts. The spreading the load scenarios do better on one criterion – that of deliverability. The cumulative effect of this is that whilst B has actually scored the Renewable Generation scenario highly across many criteria, his overall ranking is quite strongly influenced by the way in which the criteria have been weighted. Hence, using equal criteria weights, the Renewable Generation scenario comes out as slightly preferred over the other scenarios; including weighting, the two Spreading the Load scenarios overtake the Renewable Generation scenario. This type of response illuminates that for a respondent such as B many of the benefits and advantages of renewables (beyond their zero-carbon status) arise from the 'social' and 'public good' quality of such forms of energy generation rather than because of their 'commercial' benefits. Conversely, putting their carbon status to one side, many of the benefits of fossil fuels and nuclear power reside in their good performance in commercial terms, including reliability, costs and infrastructure.

Respondent G is the only respondent who did not fall easily into *either* a business-focus or environment / society focus response to criteria weighting. G's scoring is also characterised by relatively little differentiation between the scenarios. Not surprisingly, therefore, there was little difference in the scenario rankings, although the weightings did, to some extent, bring out the business-advantages of nuclear power (reliability, security and infrastructure) and the disadvantages of renewables with respect to reliability and costs.

7.6 Discussion and Conclusions

This study has involved the participation of a small, though varied, number of stakeholder respondents. The sample was never intended to be representative of energy stakeholders in the North West region of England. Clearly, we cannot conclude too much about stakeholder opinion more widely on the basis of the evidence from such a small sample. Rather, the current study was designed to explore the combined use of future energy scenarios and multi-criteria assessment to investigate the perceptions of stakeholders at the regional scale. As such, the value of the work does not lie in the number or representativeness of the respondents but rather in the insights which emerged from even a limited number of stakeholders.

The Renewable Generation scenario was preferred by five of the eight respondents, whilst the remaining three respondents preferred Nuclear Renaissance, Spreading the Load (Low CCS) and Spreading the Load (High CCS). It is also interesting to note that the Renewable Generation scenario was a very clear favourite for four of the five respondents who preferred this particular scenario. The respondents for whom the Renewable Generation scenario was most popular were a renewable energy developer, a sustainable development planner, an environmental regulator and two environmental campaigners. The nuclear professional rated the Nuclear Renaissance scenario most favourably whilst the Spreading the Load (Low CCS) was preferred by a renewable energy professional and the Spreading the Load (High CCS) by an energy consultant. To a large extent, the preferred scenario of the respondent reflects what would be anticipated intuitively on the basis of their occupation and professional background. I.e. we tend to expect that environmental professionals will favour a scenario containing the most renewable energy, and that nuclear energy professionals would prefer nuclear energy. However, we also note that one of the respondents who works in renewable energy development actually preferred the Spreading the Load (Low CCS) scenario, so illustrating the danger of assuming that occupation or profession will overly determine preferences.

Opinion (expressed through criteria scoring and overall scenario ranking) across all respondents varied most markedly with respect to the Nuclear Renaissance and Renewable Generation scenarios, with much less variation expressed with respect to the other three scenarios. In other words, both these scenarios elicited strong reactions from the respondents, either positive or negative. Such reactions reflect commonly observed opinion amongst stakeholders regarding both renewable and nuclear energy. Opinion on Spreading the Load (High CCS) was most uniform across respondents, followed by Spreading the Load (Low CCS) and Fossilwise. It is interesting to note that where there is greater convergence in criteria scoring of a scenario between individuals, there tends to be less difference in the individual criteria scoring of each respondent. Conversely, where there is greater divergence between respondents, there tends also to be greater divergence in the criteria scoring within an individual's response. This suggest that there are specific aspects of nuclear and renewable energy technologies which elicit strong opinions, rather than strong opinions emerging across all the criteria with respect to those technologies, e.g. environmental impacts and risk of major disasters in the case of nuclear energy.

The Spreading the Load (High CCS) deliberately adopts a mixed-approach to the supply-side, and it is reasonable to assume that this accounts for the some what subdued reaction to the scenario. The same reasoning applies to the response to the Spreading the Load (Low CCS) scenario, though the higher amount of renewable energy it includes compared to Spreading the Load (High CCS) scenario probably accounts for the some what stronger reactions. Fossilwise elicits moderately strong positive and negative reactions, depending on the respondents and the specific criterion of interest.

Having identified two strategies for using the MCA tool, how can we explain these different responses? And within the strategic approach, how can we explain the different stances taken towards particular favoured options? Since the purpose of an MCA approach is to explore trade-offs between options, it might be argued that the strategic approach to scoring and/or weighting is, at best, somewhat missing the point and, at worse, a misapplication of the MCA tool to get the 'desired answer'. We would not accept such an argument, however, since an inclusive approach to engaging stakeholders cannot be overly selective or prescriptive. Since we are interested in the subjective assessments of stakeholders we cannot censor opinions on methodological grounds that they have not been reached in what the researcher considers to be the 'correct' way. MCA as a tool is not per se concerned with the validity of the reasons why respondents have the views that they do, though of course asking the respondents why they give the answers they do can provide material for such interpretation subsequently and is desirable in terms of transparency. Therefore, we do not feel able to say whether either the strategic or explorative approaches to MCA are 'better' or 'worse', though clearly it is useful to be aware of such stakeholder differences in approaching MCA.

It might be argued that the strategic approach would be found most strongly amongst respondents who were clearly energy experts, and hence have already come to a clear opinion on the relative strengths and weaknesses of different generation types. The two respondents who illustrated the explorative approach, however, were undeniably experts in energy assessment, more so than four of the other respondents. On the other hand, one of the strategic-behaving respondents was not an energy expert and only involved in energy related issues as part of a much wider portfolio of duties.

It is probably not a sufficient explanation to argue that a strategic approach illustrates the pursuit of self or organisational interest, the reason being that all of the respondents have some institutional or commercial agenda or mission to pursue, as was clear in all the interviews. Nevertheless, businesses usually have a more clearly defined and articulated organisational mission than public bodies and regulatory agencies, which typically have to attempt to balance competing interests. Hence, it may have been easier for business interests to employ a strategic approach. It is interesting to observe that the two explorative-mode respondents were an energy consultant and a public-private sector facilitator of renewable energy developments. Both occupations require considerable diplomacy and mediation skills between competing interests, and consideration of energy from a wide-range of perspectives. Development of such skills is likely to make such respondents more comfortable with utilising an explorative approach. There may also be differences in perceived identity when performing the MCA. Some respondents in the public sector took on the mantle of a 'public servant', trying to look for the answer that was in the best public interest. Such respondents will inevitably use the MCA differently and more 'neutrally', though we have to be careful to remember that this is an issue of assumed identity as the public servant of which we have no empirical evidence.

Amongst the strategic weighters / scorers, the influence of particular commercial agendas, and / or personally-held values, can nonetheless be quite evidently witnessed; hence, the pro-nuclear and pro-renewables stances adopted by some respondents. What, then, can be concluded regarding the application of the MCA tool to evaluate stakeholder perceptions of CCS in the context of different energy scenarios more generally?

One important finding is that different respondents employed a different knowledge and information base in justifying their opinions. Sometimes respondents with particular specialist knowledge, e.g. of reliability, had a different perspective from other respondents who were not themselves experts in that topic. At other times, respondents used secondary sources of information which have been challenged in the academic literature (e.g. the finding of public opinion surveys that 'the public' is generally in support of renewable energy (Devine-Wright, 2005; Upham & Shackley, 2005)). We wonder, therefore, whether greater consensus on the information and knowledge 'baseline' against which assessments are being conducted could be attempted. This would mean that all assessments are being made in relation to the same agreed information and knowledge on the technical, organisational, commercial, social or political conditions and context. Even if a consensus was not possible between respondents, a description and explanation of the different opinions regarding the knowledge baseline would be informative for the respondents. For example, where there is disagreement on a technical issue, it is better for the respondents to be aware of this when scoring the scenarios, rather than proceeding on the basis of information which they assume (incorrectly) to be correct and widely accepted.

In order to operationalise this more collective approach to assessment it will be necessary to pay particular attention to the selection of appropriate experts who can between them reasonably reflect the range of technical opinion. A more collective approach to the assessment of the information and knowledge baseline would also be necessary, involving workshops and possibly use of methods such as Delphi.

Clearly, further work is also required to extend the number and type of stakeholders included. The results here also provide some potential lines of enquiry to follow-up, e.g. regarding the role of pre-defined 'interests' and the use of different strategies of scoring and weighting.

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Chapter 8

Carbon Dioxide Capture and Storage in East Midlands and Yorkshire and Humberside

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8.1. Introduction

This Chapter describes a follow on study from the exploration of the potential for CCS in North West England, described in Chapter 7, adopting a similar approach for the regions of East Midlands and Yorkshire and Humberside combined (EMYH). Here, we are interested in the potential for CO_2 storage at locations in the southern North Sea basin, how this relates to potential storage requirements emanating from the region and the perceptions of a variety of stakeholders from the public and private sectors of the role of CCS within the region. As a follow-on study, the research explores similar questions, namely:

1) What is the potential for CO_2 storage in gas fields and saline aquifers beneath the southern North Sea?
2) How does this potential relate to CO_2 captured from power stations within the region for different energy scenarios to 2050?
3) How do different stakeholders evaluate these different energy scenarios and their implications for the region?

Again we have conducted a geological assessment, scenario analysis and a Multi Criteria Assessment of future power generation scenarios to explore these questions. This area of the UK has been chosen for two reasons: i) it is adjacent to a large concentration of gas fields and saline aquifers in the North Sea representing a large potential for offshore geological CO_2 storage and ii) many of the UK's fossil fuelled power stations are located within the two regions. We chose to combine the two administrative regions of East Midlands and Yorkshire and Humberside in order to include this large amount of generating capacity and hence gain greater insight into the relative potential for storage in relation to the potential for CO_2 capture.

This combined region includes almost 35% of the UK's fossil fuel generating capacity, of which over 20% is coal, and is adjacent to the main area of North Sea gas fields. In 2000, the region generated 101 TWh electricity - equivalent to 31% of the UK's demand for electricity (final consumption) in that year (DTI, 2004). Any strategy for significant uptake of CCS in the UK will have a major impact on these regions.

The approach adopted here was similar to that in the NW case study region – in which we developed a set of scenarios describing electricity generation and potential carbon dioxide storage within the region to 2050, followed by stakeholder review of the scenarios using a Multi-Criteria Assessment (MCA) process. The main difference in approach was that we developed the scenarios in greater detail (although the final figures were presented in a similar format) and, based on responses from the stakeholders in the NW region, made slight alterations to the criteria set used.

This Chapter begins with a review of the storage potential in the Southern North Sea. In Section 8.3 we present the scenarios to 2050 for the region, incorporating both alternative power generation and storage regimes. Section 8.4 describes the MCA process through which these scenarios were reviewed by stakeholders.

8.2. Geological assessment of carbon storage potential in the Southern North Sea

This section discusses the potential for storing CO_2 in the Bunter Sandstone Formation (saline aquifer) and gas fields in the Southern North Sea Basin of the UK. The estimated storage potential in the closed structures of the Bunter Sandstone Formation and gas fields is 14.3 Gt and 3.9 Gt of CO_2 respectively. Many of the Southern North Sea gas fields are produced by depletion drive with very little aquifer support during production. This makes them particularly favourable for CO_2 storage; the reservoir pressure after production is low, making CO_2 injection less costly. The gas fields also have gas seals proven over geological timescales. Most of the closed structures in the Bunter Sandstone Formation have not stored gas and the injectivity of the Bunter Sandstone Formation is largely unknown, as a result storage in this aquifer carries more uncertainties than in the gas fields. It is important that before CO_2 injection takes place at any geological storage site a full site investigation, characterisation and testing should be carried out. The storage sites identified in this study were used to produce the scenarios, outlined here (Section 8.3). The purpose of the scenarios is to present stakeholders with a range of options for reducing CO_2 emissions using geological storage of CO_2.

8.2.1. The southern North Sea Basin

The southern North Sea Basin lies to the east of England (Figure 8.1). It contains three major reservoir rocks; the Leman Sandstone Formation, of early Permian age, the Bunter Sandstone Formation, of Triassic age, and Carboniferous sandstones of Silesian age.

The CO_2 storage potential of the Carboniferous sandstone aquifer has not been investigated in detail, as there is insufficient data available on the distribution and structure of these sandstones to make a meaningful analysis. It is the reservoir rock for several gas fields, which are discussed further.

The CO_2 storage potential of the Leman Sandstone Formation lies principally in its gas fields. There is good reason to suppose that all closed structures in the Leman Sandstone Formation were originally full of gas and thus its CO_2 storage capacity can be estimated with a high degree of confidence on the basis of its recoverable gas reserves.

The CO_2 storage potential of the Bunter Sandstone is mainly aquifer potential. It contains some very large dome-shaped structures, the majority of which do not contain natural gas. The pore spaces in these structures are filled with highly saline water that could be displaced by CO_2. There are a few gas fields in the Bunter Sandstone, but these do not represent the bulk of its potential storage capacity.

Location of the Bunter Sandstone Formation. The Bunter Sandstone Formation is a major sedimentary rock formation which is widely distributed in northern and central England (Figure 8.1). It is continuously present beneath a large area that stretches from its outcrop (the places where it comes to the surface) between Nottingham and Teesside, beneath the East Midlands and eastwards without interruption beneath the southern North Sea. This study focuses on the Bunter Sandstone in the UK sector of the southern North Sea.

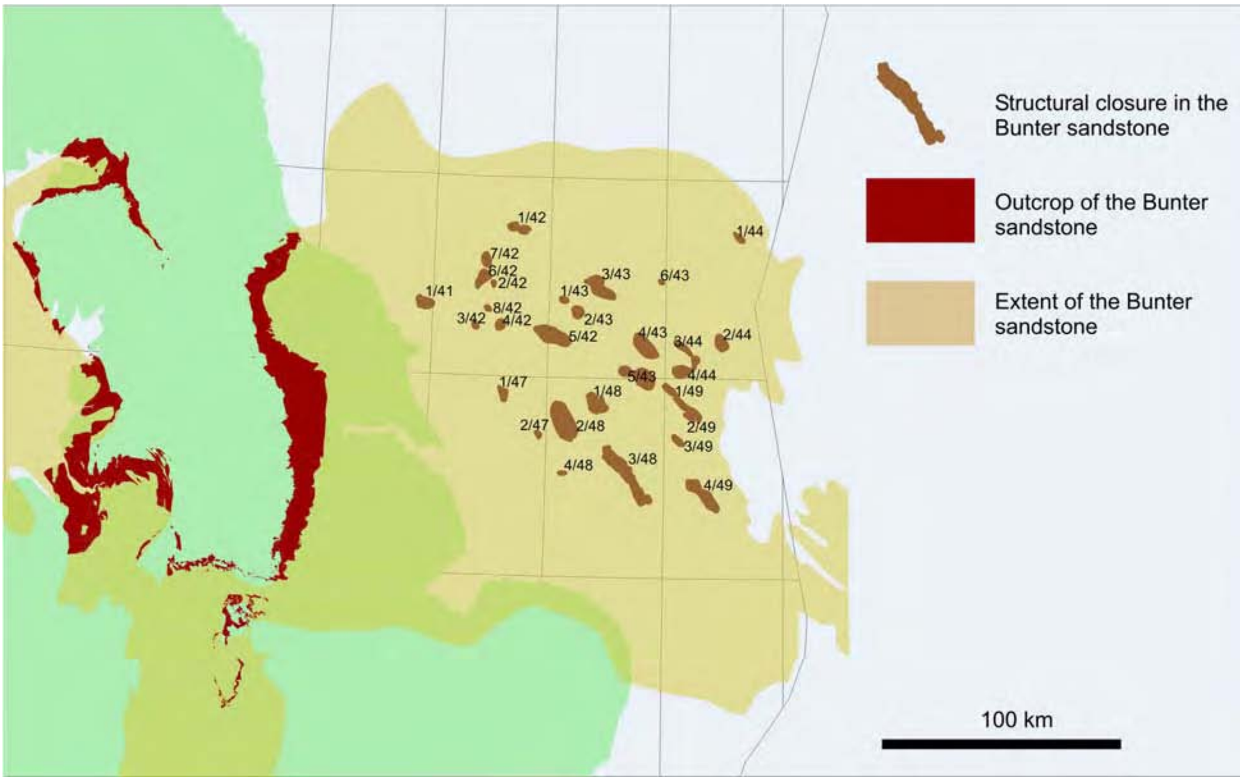

Figure 8.1 Extent and closures of the Bunter Sandstone Formation in the UK sector of the southern North Sea

The Bunter Sandstone has many of the characteristics required for CO_2 storage, including large closed structures (domes), good average porosity and permeability, and a good seal in the overlying Haisborough Group, which consists of mudstones and evaporites (evaporites are rocks that have been formed by the evaporation of saline water, and those in the Haisborough Group include thick beds of rock salt). The Bunter Sandstone is a proven gas reservoir in the southern North Sea Basin and the Irish Sea Basin. Nonetheless, it is not possible to demonstrate conclusively that the large structures in the southern North Sea will not leak if filled with CO_2; many of the structures are cut by faults and the sealing efficiency of these faults is not known.

Closures within the Bunter Sandstone Formation with the potential for CO_2 storage were identified using a combination of existing maps, offshore well data and 2D seismic data (Brook *et al.*, 2003). The location of the closure sites is shown in Figure 8.1. The volumes of the closures and their CO_2 storage capacities were estimated using Equation 8.1:

Equation 8.1

CO_2 storage potential (tonnes) = (Area x thickness x porosity x density of CO_2 at reservoir conditions) x 0.4

Where 0.4 is the estimated fraction of the pore space in the structure that could be filled with CO_2. This factor was derived from reservoir simulation using the Esmond field reservoir model (Obdam *et al.*, 2003).

This produces a figure of 89.4 $GTCO_2$ total storage capacity, although this is best regarded as a theoretical estimate of the maximum as some of the structures are likely to prove to be unsuitable for CO_2 storage, for a variety of geological reasons, e.g. they might leak through faults. Nonetheless, UK power plants currently emit in the order of 176 Mt CO_2 per year, so it is likely that a very large proportion of CO_2 emissions from UK power plants could be stored within closures in the Bunter Sandstone Formation for several decades and possibly hundreds of years. The individual structures are discussed in more detail in Section 8.3.3.

8.2.2. Southern North Sea gas fields

The first gas to come ashore from the UK sector of the southern North Sea was from the West Sole gas field, in 1967. Most of the major gas discoveries have been in the Lower Permian, Upper Carboniferous and Triassic sandstone reservoirs (Figure 8.2). Gas has also been found in the Upper Permian carbonate reservoir, e.g. in the Hewett field (Cameron *et al.*, 1992). The major source of the gas in the southern North Sea is coal seams in the Upper Carboniferous Coal Measures. After the gas was generated it migrated to fill reservoirs in the Carboniferous, Permian and Triassic. The Permian Leman Sandstone Formation contains the majority of the gas in the southern North Sea and as a result has the greatest potential for CO_2 storage. The total storage capacity of gas fields in this region is estimated at 2.8 GT CO_2.

CO_2 storage may be made more difficult due to various geological conditions within the reservoir discussed here. Compartmentalised fields such as Barque, Indefatigable, Schooner, Viking and Leman may require more wells to access all of the available storage in each compartment. Faults present within the reservoir that act as barriers to flow during production will make injection harder and more complicated. Fields in which the reservoir has been artificially fractured to allow increased production rates may also make CO_2 injection more problematic, examples of such fields are Clipper and Trent. Gas fields, which have more than one separate accumulation in different reservoirs, for example Trent, may prove more costly to inject CO_2 into, as more wells or deviated wells may have to be drilled to access each depleted reservoir.

Large amounts of water influx into the gas fields after production, for example South Sean field, will be a problem as CO_2 injected into the field will have to push the water back out of the pore spaces making injection more difficult. Fields without any evidence of water ingress back into the field after production (e.g. Clipper, Barque and Leman) would be a better choice for CO_2 storage because empty pore spaces at lower pressure than the initial reservoir would make CO_2 injection back into the reservoir much easier.

As fields are depleted and the pressure decreases the caprock may become damaged, allowing CO_2 migration out of the reservoir during re-injection. However, the ability of salt (which is a major component of the Zechstein cap rocks overlying the gas fields) to creep may counteract any cracking due to compression of the reservoir. As a general rule the initial reservoir pressure of the gas field should not be exceeded in the injection period, unless the seal is tested before injection.

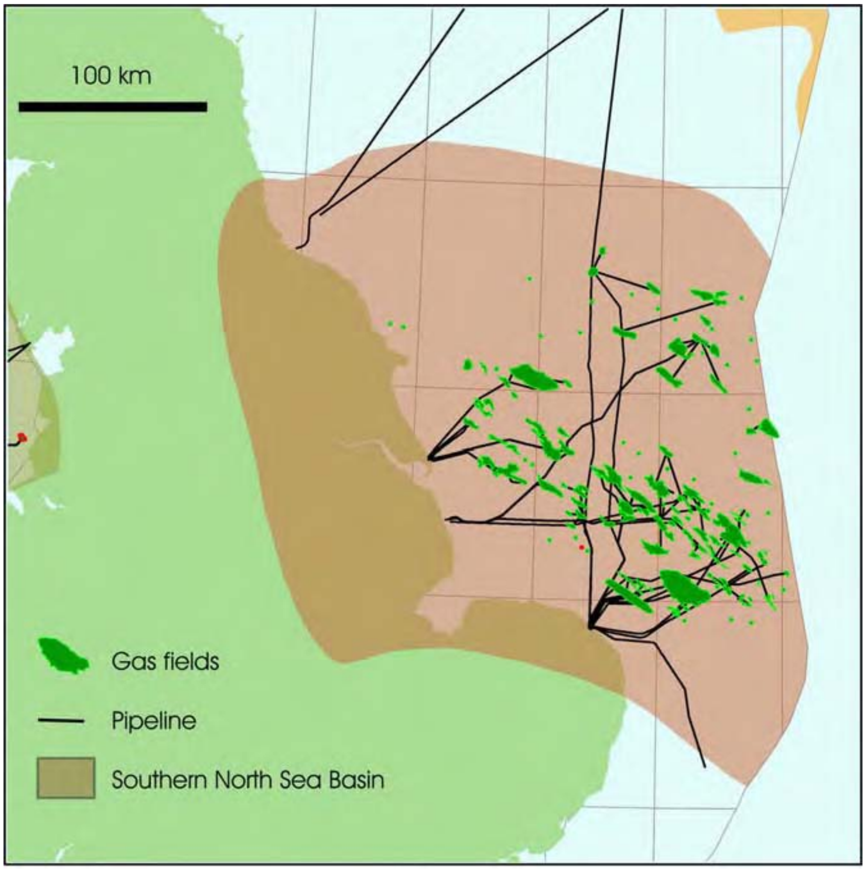

Figure 8.2 Location of gas fields in the southern North Sea

The storage capacities of the southern North Sea gas fields were calculated in the GESTCO study, according to Equation 8.2 (GESTCO, 2003). The calculation assumes all the gas produced from the field can be replaced by CO_2.

Equation 8.2

$V_{CO2} = (V_{GAS}\ (stp) / Bg) \times \rho CO_2$

Where:
V_{CO2} = CO_2 storage capacity (10^6 tonnes)
Stp = standard temperature and pressure
V_{GAS} (stp) = volume of ultimately recoverable gas at stp (10^9 m^3)
Bg = gas expansion factor (from reservoir conditions to stp)
ρCO_2 = density of CO_2 at reservoir conditions (kg m^{-3})

The factor of water invasion into the reservoir after gas production will affect the amount of CO_2 that can be injected back into the gas field. This was not factored into the GESTCO calculations. The effect of this can be most accurately calculated by using reservoir simulation. But for this study no reservoir simulations are available. In the absence of simulation the following factors have been used to adapt Equation 1 (from studies by Bachu & Shaw (2003) on oil and gas fields in Alberta):

1) In gas fields with depletion drive, i.e. those where the wells are opened up and the pressure in the gas field simply depletes, as it would if the gas were being produced from a sealed tank, it is assumed that 90% of the pore space could be occupied by CO_2.
2) In gas fields with water drive, i.e. those where water encroaches into the pore space formerly occupied by the produced natural gas reserves, it is assumed that 65% of the pore space could be occupied by CO_2.
3) In gas fields where the drive mechanism is both pressure depletion and water drive it has been assumed that each mechanism is acting equally on the reservoir, it is assumed that 77.5% of the pore space could be occupied by CO_2.

Where the drive mechanism is unknown, the following assumptions have been made. If the reservoir rock for the gas field is the Leman Sandstone the drive mechanism is depletion drive. This assumption has been made on the basis that most of the Leman Sandstone fields are depletion-produced fields. If the reservoir is in the Triassic or Carboniferous it has been conservatively assumed that the field is acting under water drive, as are most of the fields within these reservoirs.

8.3. Carbon Dioxide Capture and Storage Scenarios

The scenarios for this region were developed in much greater detail than for the first Case Study region (described in Chapter 7). It was felt that this was necessary given the greater concentration of fossil fuelled power generation in EMYH and its role in the national electricity supply network. This also enabled a more detailed analysis of the implications of the scenarios in terms of the potential for CO_2 storage from the region at suitable offshore sites. These scenarios can be seen as a logical progression from those constructed for the NW.

The basic methodology in developing the scenarios for the EMYH region is as follows:

1) For the baseline year (2000), identify baseline data describing current generating capacity by fuel type, current electricity generation and demand within the region.
2) For each scenario identify plausible projections for each fuel type, such that total electricity supply is maintained at 2000 levels, based on assumed load factors. In the case of renewables, figures for 2050 are based on the accessible resource for the two regions (AEAT, 2002; EMRA, 2003).

The data used in generating the energy scenarios can be found in Annex 5. We have not explored different views of energy demand explicitly in these scenarios. There is currently an active debate surrounding the evolution of electricity demand in the UK - whether it will continue to increase or whether demand side measures will take effect. For the purposes of this study this was considered to add an unnecessary level of complexity to the scenarios that would inevitably divert discussion away from the key issue of CCS. The aim was to consider the relative trade offs and issues associated with different electricity supply technologies; hence keeping electricity demand constant across scenario, while unrealistic, avoids diverting discussion away from specific concerns relating to supply technology onto demand side issues (which are outside the scope of the present study), and enables us to restrict the number of alternative scenarios to five. The Tyndall Scenarios project (Anderson *et al.* 2005) presents national energy scenarios which do explore alternative projections for energy demand and supply technologies on a national scale.

8.3.1. Power generation scenarios

Five scenarios were developed for EMYH as follows: Fossilwise; Renewable Generation; Nuclear Renaissance; Capture as a Bridge; Spreading the Load.

The main difference from the NW scenarios (see Chapter 7) is the move to a single Spreading the Load scenario; adopting two quite different scenarios as variations using the same name (with high and low exploitation of CCS) was felt to be confusing. The fifth scenario became Capture as a Bridge developed to explore the implications of adopting a more short term approach to CCS as the renewables capacity is built up.

Table 8.1. Key features of the Scenarios

	Summary	**Electricity balance (2050)**	**Dominant CCS technology (coal)**
Fossilwise	Large scale exploitation of CCS	Increase in electricity generated within the region	IGCC with capture
Renewable Generation	Maximise use of renewables	Reduce electricity generated within the region	None
Nuclear Renaissance	Maintain or expand nuclear power generation	Reduce electricity generated within the region	None
Capture as a Bridge	CCS adopted in near term, to be phased out as renewables capacity is developed	Reduce electricity generated within the region	Ultra supercritical with capture
Spreading the Load	A broad mix including renewables, CCS and nuclear	Maintain electricity generated within the region	IGCC with capture

As already stated, the region generates considerably more electricity than is consumed within the region – predominantly due to the concentration of coal fired plant. It was thus assumed that this balance would vary across the scenarios with the relative importance of coal fired power generation. This implies that there will be a corresponding change in generating capacity in other regions or that demand changes; since we wanted to focus the impacts to a particular region we have not specified the details of these implications to other regions, merely noting the necessary increase in capacity of the relevant type to make up any shortfall associated with a reduction in assumed fossil fuel capacity within EMYH. The key features of the scenarios are summarised in Table 8.1 and the fuel mix in Figure 8.3 and Table 8.2; more detailed presentation of scenarios and the data used in their development can be found in Technical Annex 5. In the case of Renewable Generation and Nuclear Renaissance it was assumed that CCS would not be adopted. Consequently, coal capacity is reduced with the assumption that other UK regions must increase electricity production from either renewable or nuclear respectively to compensate (or implicitly there must be a reduction in demand); the generating capacity required to make up the shortfall is illustrated in Figure 8.3. There is currently no nuclear power plant within EMYH and it was considered that even in the Nuclear Renaissance scenario it would be unlikely that new plant would be constructed within the region, rather that any new build would be made at sites with existing nuclear capacity.

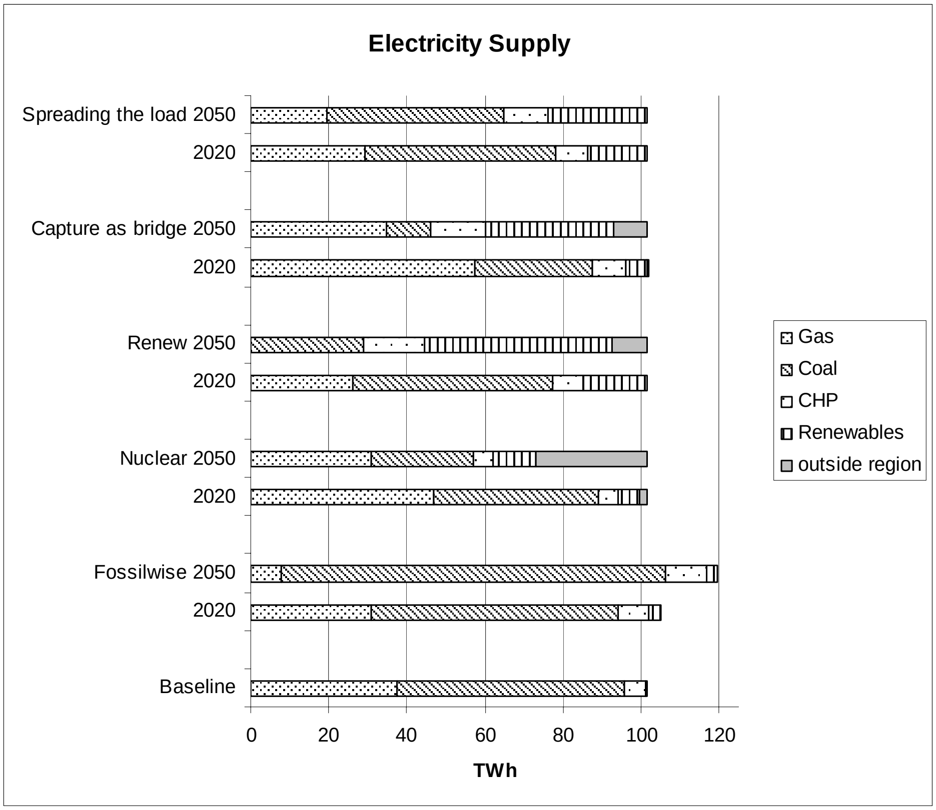

Figure 8.3. Summary of fuel mix in the five scenarios

In addition to the above summary shown in Figure 8.3 and Table 8.2, each scenario was accompanied with a visual summary of the generating mix, an example of which is shown for the Fossilwise scenario in Figure 8.4. Note also that in this Case Study we have not presented the scenarios in relation to the 60% CO_2 reduction targets. This would require applying the scenario methodology to all demand sectors and adopting some means of allocating emission reductions across national regions. The level of CO_2 reduction is calculated for electricity generation in this case study region, this will have implications for measures required in other regions and sectors (and indeed demand for energy) if a national target of 60% reduction is to be met. In this way, the scenarios expose the relative contribution the supply technologies included in the scenarios make towards achieving that target.

Table 8.2 Quantitative summary of fuel mix and CO_2 storage in the five scenarios

	CCGT	Coal	CHP	Renewables	Total
Baseline					
Generating Capacity (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	
Fossilwise					
2020 (GW)	3.8	12.8	2	0.8	19.4
% (supply)	23%	66%	8%	3%	
Capture ($MTCO_2pa$)					75.8
2050 (GW)	1.2	15	2.6	0.8	19.6
% (supply)	7%	82%	9%	2%	
Capture ($MTCO_2pa$)					55.1
Nuclear Renaissance					
2020 (GW)	6.4	8.7	1.3	1.5	17.9
% (supply)	44%	45%	5%	6%	
Capture ($MTCO_2pa$)					0
2050 (GW)	5	5	1.3	2.5	13.8
% (supply)	39%	39%	8%	14%	
Capture ($MTCO_2pa$)					0
Renewable Generation					
2020 (GW)	2.8	10.9	2	4.5	20.2
% (supply)	18%	58%	8%	16%	
Capture ($MTCO_2pa$)					0
2050 (GW)	0	5	4	11	20.0
% (supply)	0%	31%	17%	52%	
Capture ($MTCO_2pa$)					0
Capture as a Bridge					
2020 (GW)	7.4	8.8	2.2	1.4	19.8
% (supply)	45%	41%	8%	5%	
Capture ($MTCO_2pa$)					52.8
2050 (GW)	5.5	2.0	3.5	9.1	20.1
% (supply)	38%	12%	15%	36%	
Capture ($MTCO_2pa$)					18.6
Spreading the Load					
2020 (GW)	3.8	10.6	2.4	4.5	21.3
% (supply)	24%	50%	9%	16%	
Capture ($MTCO_2pa$)					59
2050 (GW)	3.0	7.5	2.8	6.5	19.8
% (supply)	20%	46%	11%	24%	
Capture ($MTCO_2pa$)					34

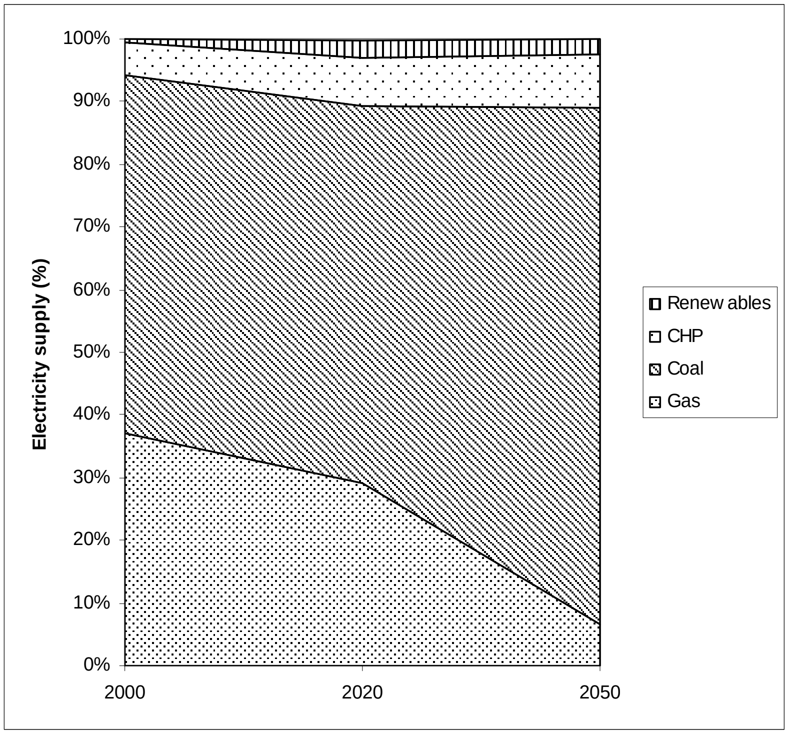

Figure 8.4 Fuel mix in the Fossilwise scenario

As noted earlier a high proportion of the UK's coal fired electricity generation is located within this case study region; in order to explore the implications of large scale CCS with respect to potential storage sites it was necessary to estimate amounts of CO_2 to be captured in the different scenarios. This requires assumptions of the efficiency of different plant types to be made; as CCS is such a new technology, there is a large range of estimates for potential performance characteristics available in the literature. In preparing the scenarios we have employed different estimates according to the particular scenario. Past experience has shown that as new technologies develop, expertise and economies of scale lead to improvements in the cost and performance of those technologies, known as technology learning (Argote and Epple, 1990); there is a large literature in this area and methods for estimating learning rates for different technologies and how these may be influenced by policy have been developed (for example, Goulder and Mathai, 2000; McDonald and Schrattenholzer, 2001)[1]. By using different studies from the literature and consulting experts within the industry we have implicitly allowed for different technology learning rates without developing our own detailed models; this was not considered to be necessary for the purposes of developing indicative scenarios and would have been beyond the scope of this study.

8.3.2. Geological storage scenarios

For the three scenarios that include CCS, an amount of CO_2, derived from power plants in EMYH, is made available for storage in geological formations beneath the southern North Sea. It has been

[1] Riahi *et al.* (2004) have explored alternative scenarios using different learning curves for CCS; their research demonstrates that different assumptions about the technology learning make a significant difference to the relative use of CCS in future mitigation approaches.

assumed that the CO_2 from the power stations is collected and delivered via a pipeline to one coastal gas terminal before being piped out to the storage site. The amount of CO_2 available for storage is detailed at the beginning of each scenario, the potential storage sites for these emissions are described in Section 8.2, i.e. the aquifer potential in the Bunter Sandstone Formation and the southern North Sea gas fields. Only gas fields which could store over 40 MT where considered. These are listed in Table 8.3.

Table 8.3 Gas fields with the potential to store over 40 MT of CO_2

Field Name	CO_2 storage capacity in Million Tonnes (MT) GESTCO	CO_2 storage capacity in Million Tonnes (MT) New figures*
Schooner	46	41
South & North Sean	49	45
Amethyst west & east	51	63
Audrey	55	53
Clipper North	55	60
Vulcan	59	63
Victor	82	70
Barque & Barque south	99	108
Ravenspurn	107	146
Galleon	143	137
West Sole	151	143
Viking	238	221
Indefatigable	246	357
Leman	966	1203
Total Storage Capacity	**2437**	**2710**

*based on calculations described in Section 8.2

All of the Bunter Sandstone Formation closures shown in Figure 8.1 were considered for the scenarios and a selection was made based on their storage capacities and proximity to the gas fields. Closures were selected based on the proximity to the gas fields identified and if the scenario dictated use of an aquifer site.

It should be noted that insufficient geological data was available to properly characterise the individual potential CO_2 storage sites presented here. They were chosen solely because of their potential storage capacity and location, and their actual geological suitability is not known at this stage. Enhanced gas recovery and gas field abandonment dates were not considered in this study. Each of the scenarios used a different rationale for choosing storage sites, e.g. to use gas fields only or storage sites near to the Bacton gas terminal. The rationale is explained at the beginning of each scenario.

Fossilwise. Total accumulated CO_2 available for storage in this scenario is 1.9 Gt. This scenario uses all of the available storage sites closest to existing onshore gas terminals, using one pipeline from the terminal to a cluster of storage sites where it branches to reach each site, as shown Figure 8.5. The gas fields were preferentially filled up with CO_2 before moving on to the nearest aquifer sites, creating a storage hub. This is considered to be a ‘cost averse’ strategy in which a hub of reservoirs is chosen, in contrast to a ‘risk averse’ strategy in which a broader network of gas fields is used before saline aquifers are deployed. The total capacity of the reservoirs highlighted in Figure 8.5 is estimated at 2.5 Gt CO_2. It should be noted that the aquifer reservoirs are not as well understood as the gas fields, and due to a lack of data the presence of faults within the aquifers cannot be ruled out. The aquifers would require geological characterisation before they could be used as storage sites with a high degree of certainty.

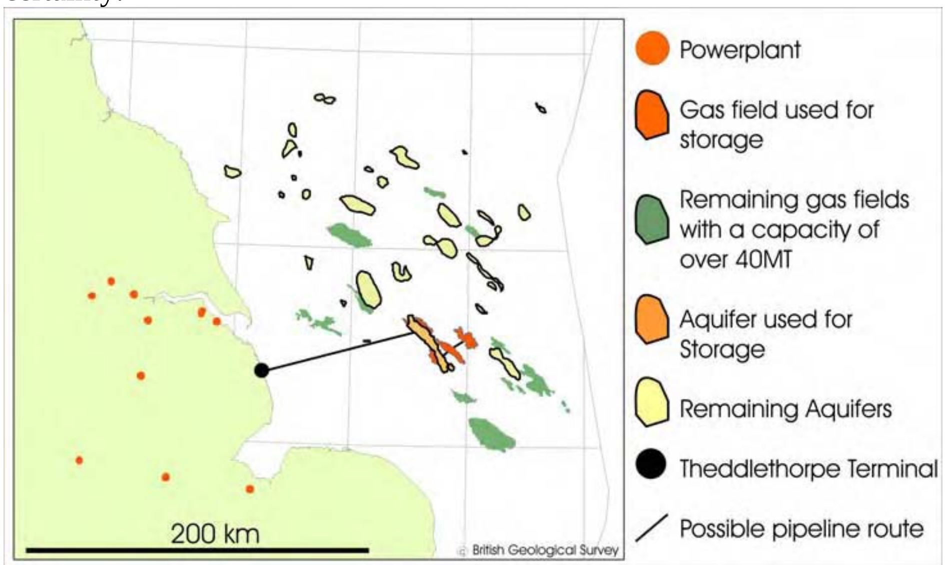

Figure 8.5 Map of the Fossilwise scenario (2050)

Capture as a Bridge. Total accumulated CO_2 available for storage is 212 Mt in 2020 and 1279 Mt in 2050. Storage has been considered in gas fields only. This is because there is enough storage in the gas fields between now and the projected end of the scenario in 2050, when CCS is phased out; commencing storage in gas fields is considered to be a risk averse strategy. The scenario was played out only from the Bacton terminal and aimed to use as few gas fields as possible, adding nearby gas fields onto the system when required. A snapshot of the scenario was taken in 2020 (Figure 8.6) and 2050 (Figure 8.7). The total capacity of the reservoirs highlighted in Figure 8.7 is estimated at 1560 Mt CO_2.

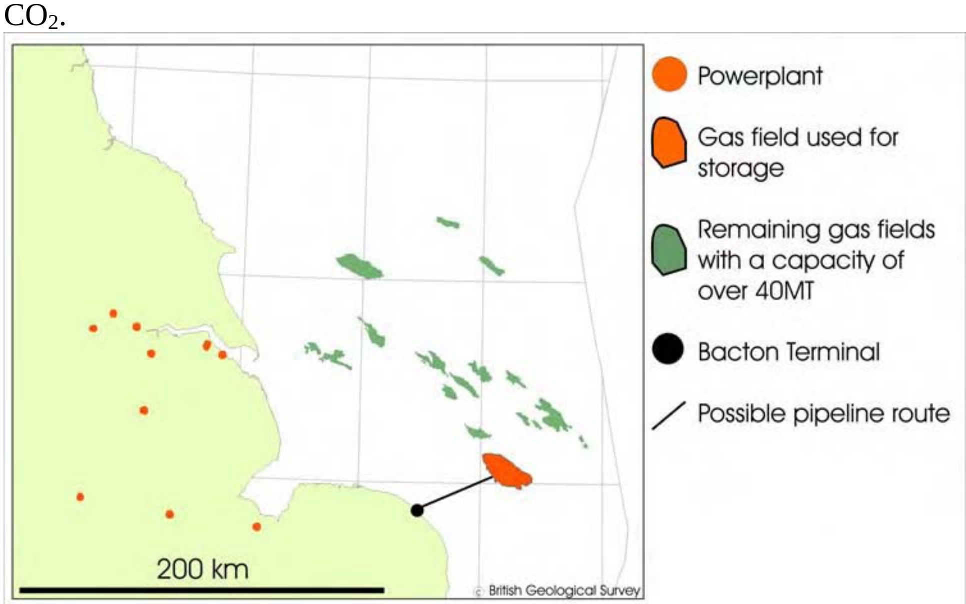

Figure 8.6 Map of the Capture as a Bridge scenario (2020)

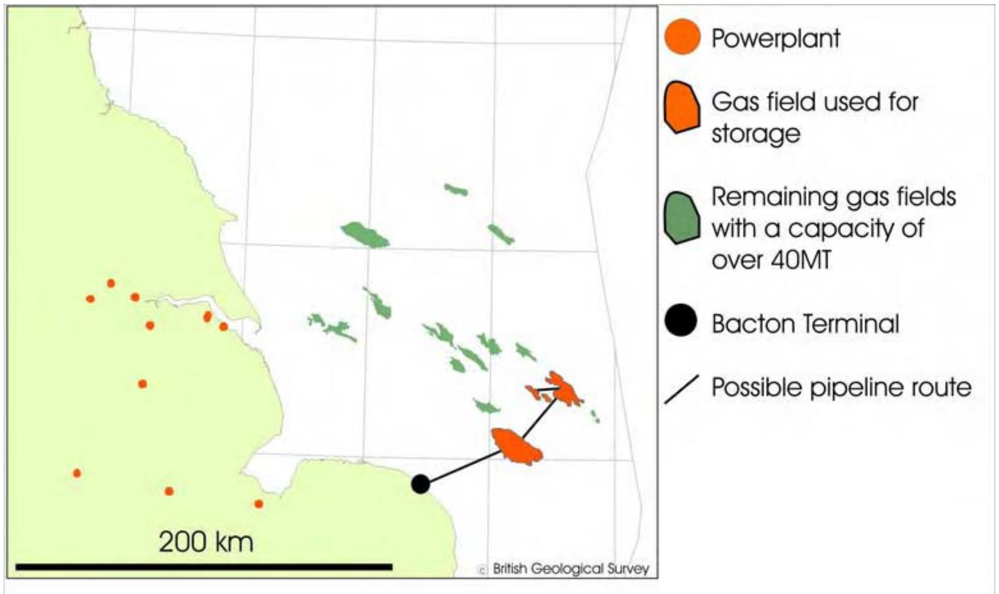

Figure 8.7 Map of the Capture as a Bridge scenario (2050)

Spreading the Load. This scenario uses the same rationale as Fossilwise - a 'cost averse' strategy, using gas fields followed by nearby aquifers, shown in Figure 8.8. Total accumulated CO_2 available for storage is 1.4 GT. The total capacity of the reservoirs highlighted in Figure 8.8 is estimated at 2.4 Gt CO_2.

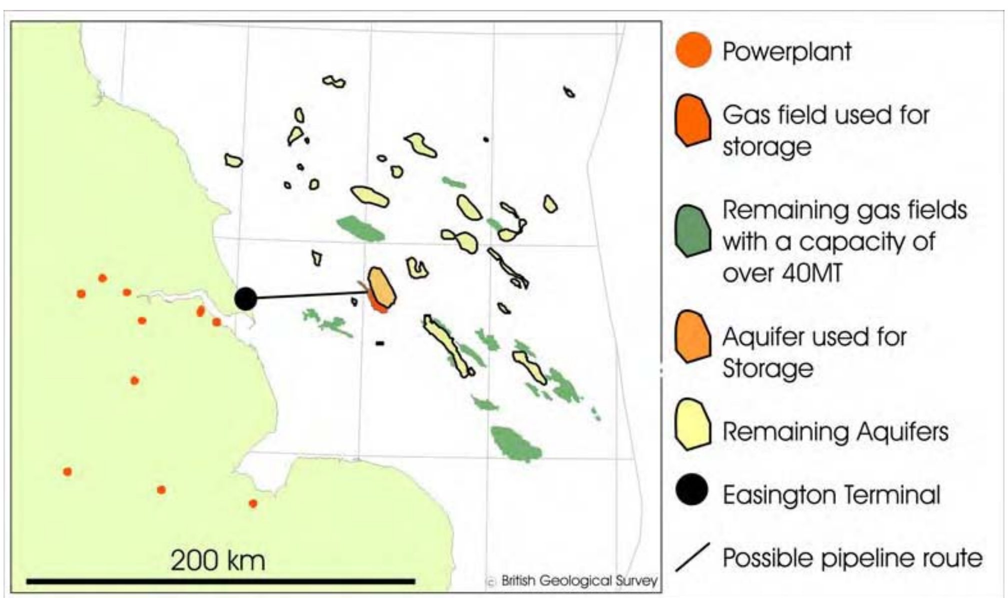

Figure 8.8. Map of the Spreading the Load Scenario (2050)

8.3.3. Summary.

Five alternative scenarios have been defined – suggesting possible power generation futures for the EMYH region. These are:

1) Fossilwise, in which large scale exploitation of CCS is adopted with an emphasis on coal fired generation. The region maintains its significance as an exporter of electricity. CO_2 is stored in both gas fields and saline aquifers.
2) Renewable Generation, in which the use of renewable energy is maximised, CCS is not adopted. The region generates slightly less electricity than in the present day.
3) Nuclear Renaissance, in which there is a revival of nuclear power in the UK, although new nuclear power plant are not constructed within EMYH, which produces less electricity (although it is still a net exporter). CCS is not adopted in this scenario.
4) Capture as a Bridge, in which CCS adopted in near term, with storage in gas fields only, to be phased out as renewables capacity is developed.
5) Spreading the Load, which utilises a broad mix of supply technologies including renewables, nuclear and CCS using gas fields and saline aquifer storage sites.

There is a huge potential for CO_2 storage in the southern North Sea, in both depleted gas fields and the Bunter Sandstone Formation. However, any of the storage sites considered would have to undergo a rigorous geological site characterisation and risk assessment before use. Although the scenarios are theoretical and designed to provoke stakeholders' views of the different CO_2 reduction options, they do give an overview of how a CO_2 capture and storage scheme might work. Because there is greater geological uncertainty associated with the aquifer storage sites, a sensible strategy for those scenarios using a combination of gas fields and aquifers storage sites might be to test CO_2 injection into the aquifers (to find out whether or not they leak) whilst filling the gas fields.

8.4. Stakeholder Multi Criteria Assessment

The stakeholder interviews and multicriteria assessment framework adopted in this case study region was the same as that used in the NW study. Respondents were presented in advance with material described in section 8.3: a) a one page summary of each of the five scenarios, including a very short summary in words, a summary of the energy mix (see Figure 8.3 and Table 8.2) and a chart showing the fuel mix for each scenario (see for example, Figure 8.4) b) a map showing utilisation of CO_2 storage sites and offshore pipelines (Figures 8.5 - 8.8). It was assumed that all respondents were familiar with the concept of CCS and at the start of the interview, respondents were asked whether they wished to clarify any of the information provided or specific facts to do with CCS.

Eight interviews were conducted as follows:

A: Environmental Non-Governmental Organisation Campaigner
B: Energy Business Director, Regional Development Agency
C: Environmental Modeller, Electricity Supplier
D: National Coal Mining Company
E: Chair, Regional Sustainable Energy Forum / Politician
F: Energy Coordinator, Regional Government
G: Low Carbon Economy Advisor, Regional Development Agency
H: Equipment Manufacturer

Respondents were then asked to score each of the scenarios against the nine criteria that the project team previously developed (Gough and Shackley, 2006). The wording of the criteria was adapted slightly to facilitate the scoring process by making it clearer that in all cases a high score reflected a positive performance against the criteria (for example, environmental impact was changed to environmental performance). The criteria and their meaning are described in Table 8.4. These criteria broadly match those used in the NW Case Study (see Chapter 7) with the exceptions that the 'lifestyle' criterion has been removed and replaced by a criterion reflecting the relative contribution to achieving a 60% national CO_2 reduction target. The lifestyle criterion proved difficult to score and it was felt that there was too much overlap with the public perceptions criterion. The CO_2 target criterion was added to account for the differing levels of emission reduction achieved in the EMYH scenarios; this criterion was intended to capture not just the perceived performance of the scenarios, in terms of CO_2 reductions, but also the extent to which the measures adopted in the power sector within this region facilitate achieving targets across the economy at a national level.
Stakeholders were also given the opportunity to add their own criteria, which five did (see Table 8.4). The scoring procedure is the same as that used in the North West case study, whereby respondents are asked to allocate 100 points across the five scenarios for each criterion allowing the relative performance of each scenario to be indicated. Thus, if all scenarios are considered to be equal for a particular criterion, each would score an average of 20. Respondents were then asked to weight the importance of the nine criteria, again having a total of 100 points to assign. The criteria scores for each scenario were then multiplied by the relevant weighting and summed to give an overall score. The scorings and weightings were entered directly into an Excel spreadsheet so allowing immediate ranking of the scenarios to be apparent to the respondent. Respondents were invited to revisit, and if necessary change, their scorings once they had seen the final output. Throughout the MCA process, respondents were invited to enter into discussion to explain their approach to the scoring and weighting. We recorded, and transcribed, all of the interviews. All the respondents performed the MCA exercise as we intended.

8.4.1. Criteria weighting

Adopting a similar approach to the analysis of the results taken in Chapter 7, we begin by considering how the respondents weighted the criteria, as shown Figure 8.9. However, unlike in the NW Case Study it is not possible to identify the two clusters of business versus environmentally and socially focused criteria in the weighting. Overall the two criteria reliability of supply and security of supply emerge as clearly important to the respondents, all of whom assigned weights of 10 or higher for these criteria. As respondent E put it:

> 'I can tell you if the lights went off for 24 hours, my God there'd be a revolution' (E)

The cost effectiveness criterion also receives a middle to high weight by all respondents and is given the highest weight of any criteria by C. This respondent is in the electricity supply business and initially gave cost a weight of 40 (although subsequently reduced this to 20 during the process of weighting the remaining criteria) on the grounds that it would be cost that would drive whether or not a technology would be adopted and whether or not government would support it.

The quality of environment criterion received the narrowest range of weights, with all respondents assigning a mid-weight.

Table 8.4 The Criteria Used in the Assessment of the Scenarios

Criterion	Explanation of the Criterion
Cost Effectiveness	The economic performance of the scenario
Infrastructure	The disruption and level of change in infrastructure required (as distinct from costs)
Security of energy resource	The security of the fuel inputs to the energy system (i.e. coal, gas, oil, nuclear fuels and renewables)
Quality of Environment	The environmental performance of the scenario excluding CO_2 (e.g. air, water quality, landscape etc)
Public perceptions	The public reaction to the scenario (from local to national)
Reliability of supply	The extent to which the scenario implies a challenge in delivering a constant and reliable electricity supply (e.g. 'keeping the lights on' when faced with problems of intermittency)
Resilience to major disaster	The protection against large-scale failure with adverse consequences for the environment and/or human health and safety
Avoidance of lock in	The extent to which decisions taken in the shorter term may come to limit the opportunities for changing those decisions in the longer term
Consistency with achieving 60% target	The extent to which the scenarios facilitate the achievement of a 60% CO_2 reduction in the UK.
Additional Criteria	
Technical feasibility (deliverability)	The extent to which the scenario could be delivered in practice (proposed by B and E)
Political Feasibility	The extent to which the political decisions required to realise the scenario are likely to be taken (proposed by F)
Fit with an international effort to reduce CO_2	Synergistic effects of multilateral approaches to carbon reduction (in terms of technology) (proposed by D)
Consistency with reaching global targets	Transferability of technology to other countries (proposed by H)
Benefits to UK commerce and industry	The relative economic opportunities to the UK across the scenarios (Proposed by D)

Public perceptions and avoidance of lock in both generated a broad range of weights – public reactions were seen as very important by C and E and as relatively unimportant by A and H both of whom considered that any negative public reactions to a technology may quickly reverse as a technology becomes more familiar (A) or in the event of disruptions to the power supply. Avoidance of lock-in was awarded a particularly low weight by D, who couldn't envisage anything new coming in quickly enough to make potential lock-in a problem, and H (who weighted it zero). Avoiding lock in was considered to be important by A because once you start down a particular energy pathway you are committed to that technology for 20 or 30 yeas.

Resilience to major disasters was not generally weighted highly, with the lowest weighting given by C and D - both business sector respondents. It appears that the other criteria were simply seen as being more important rather than that this criterion is seen as being unimportant; it was also considered that there is a low probability of a major disaster occurring (C).

The compatibility with existing infrastructure criterion was assigned a weight of 10 or less by all correspondents indicating that this was widely viewed as not being a significant issue across the scenarios – generally respondents considered that over the timescale of the scenarios, to 2050, significant infrastructural changes would occur irrespective of the mode of power generation and that problems encountered could be overcome.

Compatibility with CO_2 targets received a pattern of weighting somewhat similar to resilience to disaster, only D and E assigning particularly low weights.

F proposed the additional criterion 'political feasibility' but gave it a low weight on the grounds that she did not believe political expedience was a good basis on which decisions about energy should be made.

Respondent B opted to weight all criteria the same, on the grounds that they were all, effectively, equally important criteria and that to some extent they are all interrelated – for example, if something is not reliable and is incompatible with existing infrastructure it will not be cost effective and similarly an option performing poorly on environmental quality will be more subject to public opposition. This interrelationship of criteria does not mean that the criteria are insufficiently independent to be used as different criteria within an MCA – in which case it would be necessary to know the performance of one criterion in order to score another.

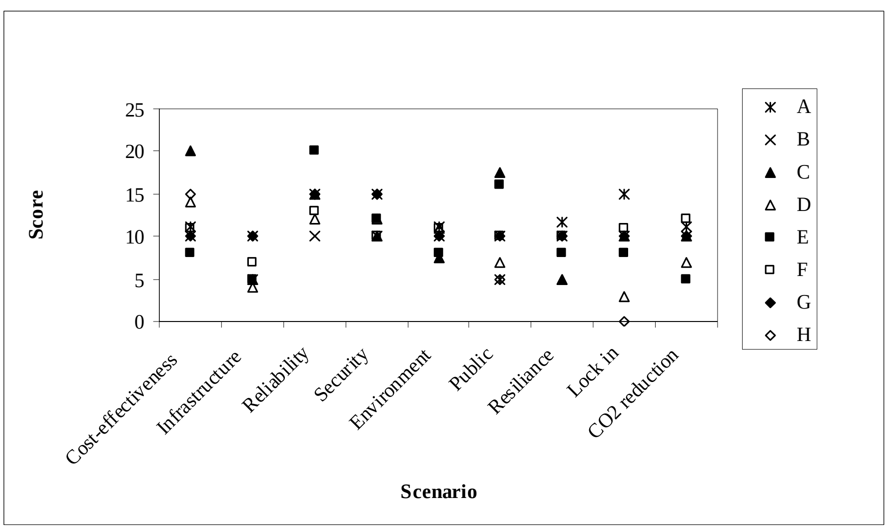

Figure 8.9 Chart showing criteria weighting

8.4.2. *Scoring the scenarios*

In the following section we describe how the scenarios were scored against the nine criteria. As explained earlier, each respondent was asked to allocate 100 points across the five scenarios for each criterion, thus if al scenarios are considered to be equivalent for a particular criterion (i.e. all are thought to perform equally well/ poorly) then an 'average' score of 20 points would be given to each scenario.

Fossilwise. Figure 8.10 shows that some clustering can be identified in the scoring of this scenario – which in general performs better under economic and business criteria (costs, infrastructure, reliability) than for the environmentally or socially focused criteria (environment, public perceptions, resilience, lock in and compatibility with CO_2 targets). A notable exception to the clustering on business focused criteria is respondent A (the environmental campaigner) who generally scored this scenario low for all criteria but particularly costs and infrastructure due to the dominance of CCS in this scenario. Despite performing less well overall against environmentally and socially focused criteria, there does not appear to be any clustering of respondents.

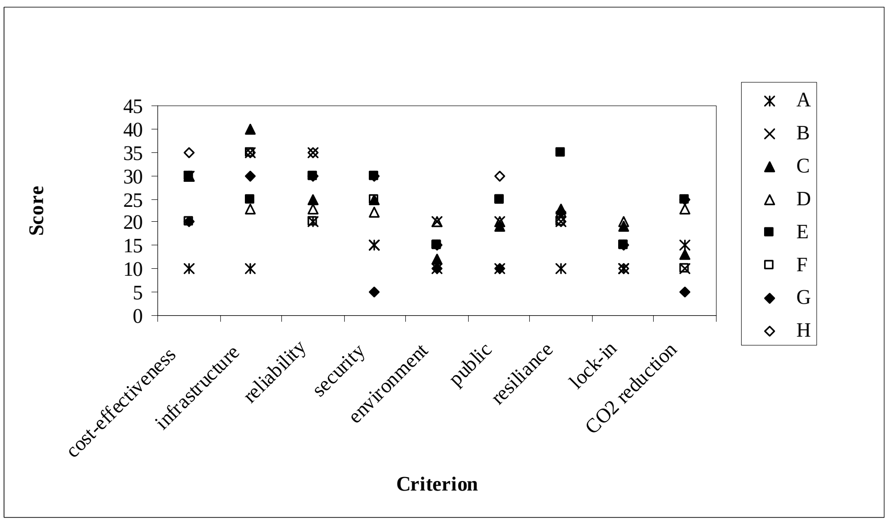

Figure 8.10. Scoring of the Fossilwise scenario

Reasons cited for the relatively poor environmental performance of this scenario are generally concerned with emissions (CO_2 emissions are not included in this criterion), such as so-called 'rare earth metals', waste products associated with burning coal and from the capture process but also the environmental impact of coal extraction (A, D, G). Despite being the scenario that delivers one of the highest levels of CO_2 reductions (for this region and sector), Fossilwise did not receive a particularly high score for this criterion from any of the respondents – only D, E and H gave it a score slightly above the average despite some strong statements that CCS is essential in achieving CO_2 targets. Other respondents considered that CCS does not advance the necessary reduction in fossil fuel (and other energy) use (C, F), that it does not genuinely address the CO_2 problem (G) or that leakage rates might negate any early benefits (A). This first point is also reflected in a poor score for avoidance of lock in awarded by all respondents.

There is a fair spread of opinion about the extent to which Fossilwise provides a secure energy supply. Respondents C, D, E, F, H all gave a positive score, citing large global coal reserves, generally from stable countries and the option for exploiting domestic coal reserves if necessary. Respondent G gave Fossilwise a very low score for security because of its reliance on a single fuel; A was concerned about global demand for coal.

There was also a range of views of how Fossilwise performs against public opinion - some considered that as a broadly 'business as usual approach' there would be little public reaction – reflecting a view that CCS will not generate a large public response (unless something goes wrong (F)); those predicting a more negative public response attributed this to the introduction of CCS rather than the use of fossil fuels *per se*.

Table 8.5. Clusters of scoring for Fossilwise and Nuclear Renaissance Scenarios

	Fossilwise		**Nuclear Renaissance**	
	Higher performance	Lower performance	Higher performance	Lower performance
Costs	B, C, D, E, H	A	H	A, B, C,D, E, F, G,
Infrastructure	B, C, D, E, F, G, H	A	A, B, G, H	E, F
Reliability	B, C, D, E, G, H		B, C, F, G, H	A, E
Security	C, D, E, F, H	A, B, G,	A, B, C,	E, F, G, H
Environment		A, C, E, F, G, H	H	A, B, E, F, G
Public	E, F, H	A, C,		A, C, D, E, F, G, H
Resilience	C, D, E, G	A,		A, B, C, E, F, G, H
Lock in		A, B, C, E, F, G, H		A, B, C, E, F, G, H
CO_2 targets	D, E, H	A, B, C, F, G	C, H	A, B, E, F, G

Nuclear Renaissance. The scoring for the Nuclear Renaissance scenario is illustrated in Figure 8.11. This scenario generally scored poorly for all criteria except compatibility with infrastructure, reliability and security of supply, reflecting a level of scepticism towards this scenario, particularly on the part of A, E and F. The socially and environmentally focused criteria and, in particular, costs were all given a low (or at best average) score by all respondents except H who thought that nuclear will be cheaper than renewables (in his view, the most expensive option) and that it will have the best environmental performance of all the scenarios, not being personally concerned about nuclear waste (although he did consider this to be a major problem for public perceptions). Nuclear was widely viewed as an uneconomic option, only kept open, in D's opinion, by effective lobbying from within the industry. Several respondents (e.g. B and E) made a point of distancing themselves from campaigning opponents of nuclear power whilst still giving it a low score. The following statement from respondent E characterizes this viewpoint; this respondent did not score the nuclear scenario higher than 15 for any of the criteria.

> 'I'm not against nuclear, I've never been phobic about nuclear , I just think we've constantly subsidised the nuclear industry, the amount of money we've poured into that industry … why do you have to turn it into a whole generating industry that produces enormous amounts of power as baseload at excessive cost' (E)

The scoring for security of supply is fairly spread around the centre for this scenario – the lower scores related to the significant amount of gas assumed in the scenario. Should the gas component have been converted to coal in the scenario it would have been ranked highest for this criterion by H instead of the low score given by this respondent.

Only C and H give this scenario a positive score for its compatibility with reaching CO_2 reduction targets. Because this scenario still deploys significant fossil fuel power generation (assumed to be without CCS), much of which is located within the study region, CO_2 emissions remain relatively high in the region. Respondent B and D thought this made it harder to reach the broader targets:

> 'if that's what it then implies, that by doing things with nuclear, is we've got do an awful lot in transport and energy efficiency then I just don't see that' (B)

> 'any scenario with lots of CCS is consistent with that because nuclear doesn't take you through the transport, unless you produce hydrogen from nuclear which is still a quite distant prospect … but you have to crack transport emission and if you're still reliant on fossil fuels then that really does point to CCS at some point in the supply chain' (D)

Scepticism about the scope for establishing a hydrogen economy, even by 2050, was also voiced by respondent G.

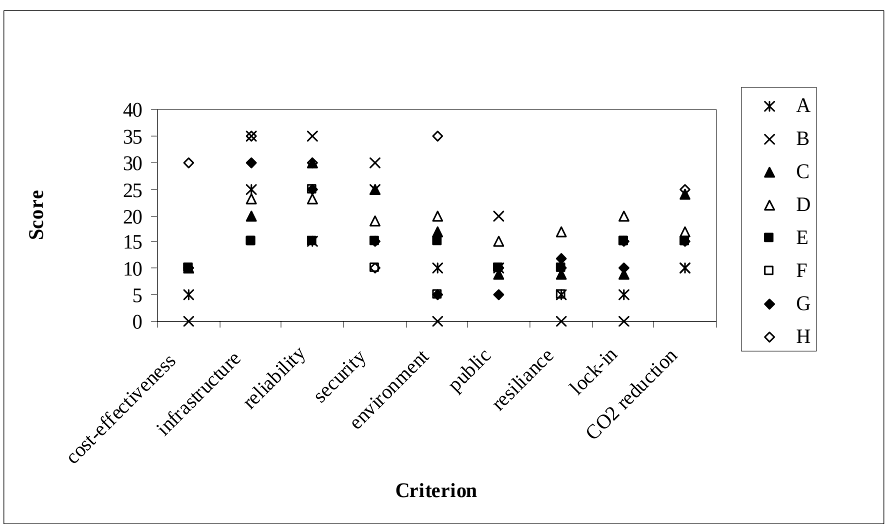

Figure 8.11 Scoring of the Nuclear Renaissance Scenario

Renewable Generation. In contrast to Fossilwise and Nuclear Renaissance the Renewable Generation scenario performs poorly against economic and business focused criteria and well against the environmentally and socially focused criteria – the pattern illustrated in Figure 8.12 for this scenario is almost the mirror of the scoring for Nuclear Renaissance shown in Figure 8.11.

Although there appears to be fairly high consensus in the pattern of scoring outlined above it is not so easy to identify clusters of individuals in the scoring. The strongest advocates of renewables are A and F, with A (an environmental campaigner) consistently awarding higher scores to this scenario. Despite this positive scoring, F considered the scenario to fare poorly against public perception – mainly on the grounds of visual intrusion, which was expected to be an issue particularly for large wind farms off the East Midlands coast. The split scoring for public perceptions seems to reflect the idea that the general public are in favour of renewables *in principle* but frequently opposed *in practice*.

B and D appear to be the most sceptical about renewables being adopted on a large scale, with B specifying an additional ‘technical feasibility’ criterion for which renewable generation is scored zero. Respondent D was very sceptical about renewables and felt that the technology was surrounded by a myth widely perpetuated (particularly in schools):

> ‘the solution is presented as being renewable energy , everything’s green … they’re being sold a dream which isn’t ever going to happen but those seeds are sown and therefore we have a population which is going to be largely anti nuclear and anti fossil’ (D)

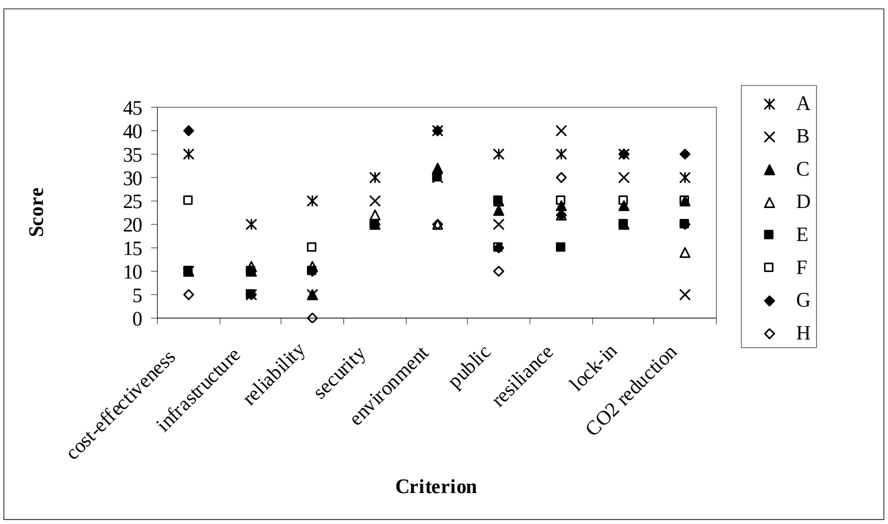

Figure 8.12 Scoring for the Renewable Generation scenario

There is a large spread of opinion over the costs of renewables across our respondents – with A and G both giving a particularly high score. Given the general acknowledgment that all energy technologies have an environmental impact in some way or another, the key impact of renewable energy (in particular wind) on the landscape was not felt to be important by any of the respondents; F went as far as to comment on the potential positive environmental effects that offshore wind structures might have by acting as an artificial reef.

Capture as a Bridge. The scoring of this scenario (Figure 8.13) often reflects the two phase structure of this scenario – the first half being similar to the Fossilwise scenario (although using different boiler technology for coal firing) while the end phase becomes more like the renewables scenario; consequently the overall pattern most resembles the renewables scoring. This transition caused respondent F concern over potential risks of using “*one technology to push for another*”, introducing a ‘pinch point’ during the transition phase, when coal generation is in decline and the renewables component expanding. If the risk paid off, however, respondent F thought that this scenario could bring about the necessary step change and this is reflected in the scoring against CO_2 targets criterion. In fact, with the exception of A (who doesn’t like CCS) and H (who doesn’t like renewables), all respondents considered this scenario to be more compatible with achieving the UK’s CO_2 targets than the Renewable Generation scenario.

Table 8.6 Clusters of scoring for Renewable Generation, Capture as a Bridge and Spreading the Load Scenarios

	Renewable Generation		Capture as a Bridge		Spreading the load	
	Higher performance	Lower performance	Higher performance	Lower performance	Higher performance	Lower performance
Costs	A, F, G	B, C, D, E, H	A, B, C, E	H	A, B, D, E, H	C, G
Infrastructure		B, C, D, E, F, G, H	E	B, C, F, G, H	A, E	B
Reliability	A,	B, C, D, E, F, G, H		B, C, E, H	C, E, H	B, G
Security	A, B		G	A, B, C, D, E, F, H	C, F, G, H	A
Environment	A, B, C, E, F, G		B, E, F, G	A, H	A, B, F, G, H	C, E, G, H
Public	A, D, E,	F, G, H	A, F, G		C, F, G, H	
Resilience	A, B, F, H	E,	A, F,G	E	A, C, E, F	
Lock in	A, B, F, G, H		B, E	C, F	A, B, C, F	
CO_2 targets	A, F, G	B, D	A,B, F, G	F, H	B	

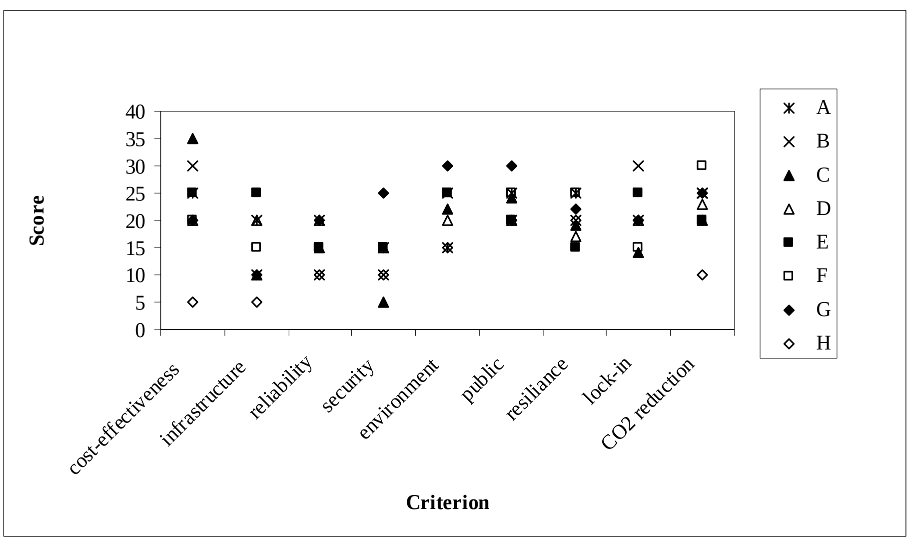

Figure 8.13 Scoring for the Capture as a Bridge scenario

The majority of respondents saw this scenario as being more cost-effective than the Renewables Generation scenario; for example, C thought it would be cheaper to implement the upgrading to supercritical technology that is deployed on coal plant in this scenario than the new IGCC technology adopted under Fossilwise. The two respondents that thought renewables to be the most cost effective option (A and G) however, did not agree. Respondent H scored the costs criterion solely on the basis of significant renewables being expensive and maintained the low score for this scenario.

Spreading the Load. The scoring for this scenario (Figure 8.14) tends to be somewhat 'flat' around the central average - because it has a broad mix of supply options, it features both respondents' favoured and disliked technologies. No patterns appear between the business or environmental/social criteria – although public perceptions, resilience to disaster and lock in receive no scores below the average. Scores are generally positive for all criteria, although moderate - around 25 – with only very high scores from G for security and public perception. The key strength of this scenario was seen to be its diverse fuel mix - that no single supply option dominates, which is widely seen as beneficial with respect to both security and public perceptions.

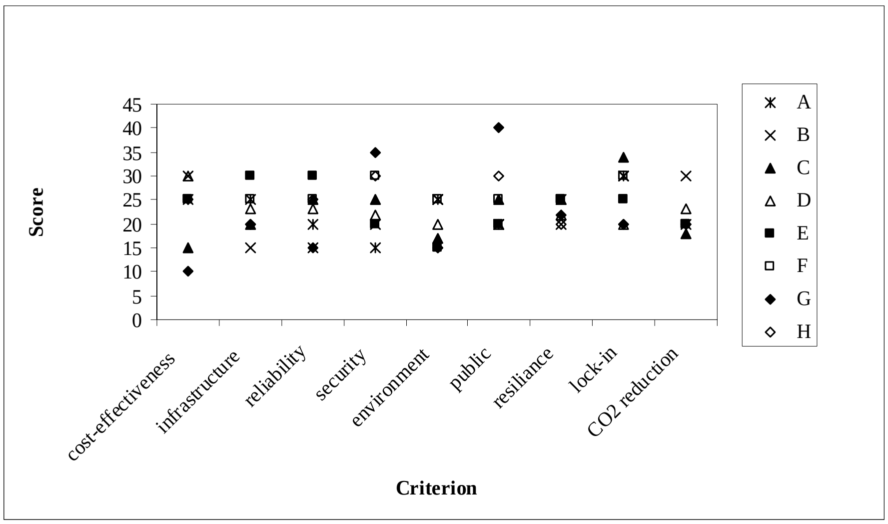

Figure 8.14 Scoring for the Spreading the Load scenario

8.4.3. Aggregating scores across the scenarios

As in the NW England Case Study we have carried out a linear additive approach to combining the criteria scores and weights across the scenarios. Unlike the first Case Study the weighting made no difference to overall order of the scenario ranking for individual respondents (i.e. each respondent's final ranking was in the same final order with or without the weightings). Including weights had the effect of increasing the range of the final scores, i.e. made the scoring slightly more extreme, and had a small effect on the relative magnitude of the totals for the different respondents. Here we illustrate (Figure 8.15) and describe the overall ranking taking account of the respondents' criteria weighting.

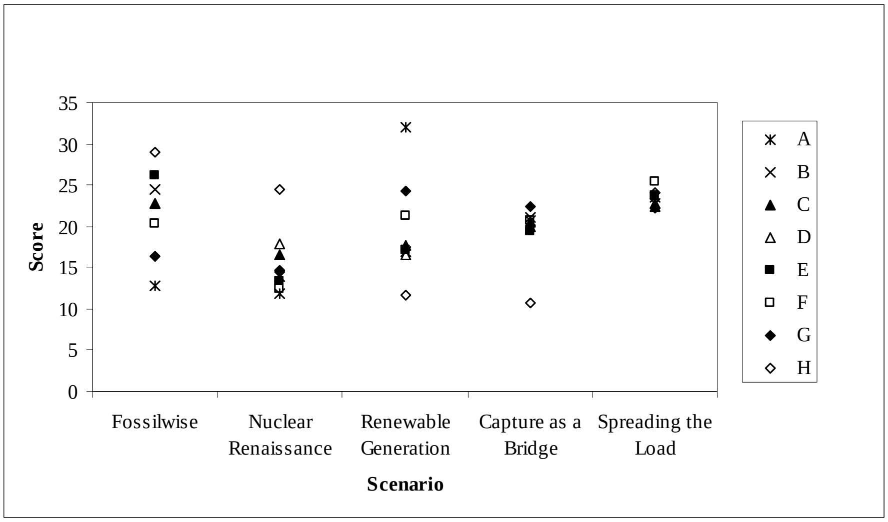

Figure 8.15 Final ranking of scenarios

The greatest range in scoring is associated with the Renewable Generation scenario and the smallest range with Spreading the Load which achieves a relatively high score from all respondents.

Respondent A: clearly favoured the Renewable Generation scenario, gave Spreading the Load then Capture as a Bridge mid-range scores and very low scores to Fossilwise and Nuclear Renaissance.

Respondent B: awarded highest scores to Fossilwise, followed by Spreading the Load and Capture as a Bridge. Renewable Generation then Nuclear Renaissance received the lowest scores.

Respondent C: favoured Fossilwise and Spreading the Load followed by Capture as a Bridge (the three scenarios in which CCS is adopted) with Renewable Generation then Nuclear Renaissance both less favoured.

Respondent D: showed similar final scores to respondent C, with the exception that Nuclear was very slightly preferred over Renewable Generation.

Respondent E: clearly favoured Fossilwise and dislikes Nuclear Renaissance; Spreading the Load and Capture as a Bridge then Renewable Generation lie between these two.

Respondent F: preferred the Spreading the Load scenario, with Renewable Generation, Capture as a Bridge and Fossilwise also faring well. This respondent is clearly very sceptical of the Nuclear Renaissance scenario.

Respondent G: favoured Renewable Generation then Capture as a Bridge and Spreading the Load and was also very sceptical of Fossilwise and Nuclear Renaissance

Respondent H: showed the most extreme response, clearly favouring Fossilwise but also supportive of Nuclear Renaissance and Spreading the Load and deeply sceptical of Capture as a Bridge and Renewable Generation.

In general, those that preferred the Renewables Generation scenario tended to be sceptical about the Fossilwise and Nuclear Renaissance scenarios and vice versa.

8.4.4. Approaches to scoring

The MCA process in the NW Case Study region revealed strategic and explorative approaches to the scenario scoring; a similar response was observed in the EMYH Case Study.

A strategic approach to scoring was manifested as a bias either against a particular scenario (negative strategy) or in favour of a particular scenario (positive strategy) or component thereof, or in some cases both. For example, respondent H clearly demonstrated a negative strategy, with a deep scepticism of renewable energy dictating the scoring. This respondent gave the Renewable Generation scenario a score of 0 or 5 for costs, compatibility with existing infrastructure and reliability; the scoring of these criteria for the other scenarios was made according to the amount of renewables in the scenario. This respondent did, however, give a high score to renewables against the avoidance of lock in criterion but then went on to weight it at zero, effectively removing it from the assessment. Although to a lesser extent than for renewables, this respondent also demonstrated negative strategic scoring against gas fired generation; this is illustrated in his scoring of the resilience to major disaster criterion in which he considered the risks associated with an LNG storage facility to be equivalent to those at a nuclear power station – a concern raised several tines during the interview. Similarly, for security of supply he made it clear that the low score for Nuclear Renaissance was due to the gas component of the scenarios and that if gas were to be replaced by coal this would be his preferred scenario. Respondent H works for a manufacturer of fossil and nuclear power generation and offshore oil and gas equipment.

In contrast to H, respondent A was clearly implementing a positive strategic scoring approach in favour of renewable energy combined with negative scoring against nuclear and CCS. For example, A, an environmental campaigner, awarded a high score of 30 or more to the renewable generation scenario for all criteria, except infrastructure and reliability to which he gave 20 and 25 respectively – no other respondent scored renewable generation above 15 or 11 for these two criteria. In fact, this respondent was alone in considering that the Renewable Generation scenario would be the most reliable of the five when all respondents considered it to be the least reliable:

> ‘I think if you’ve got them well spread out then you’re virtually always going to have somewhere which is windy’ (A)

This view is in contrast with the same respondent’s idea of nuclear which suggests a somewhat selective view of the relative performance of the two technologies:

> ‘I’m still a bit concerned about how often they do have to not operate at full capacity it does seem to happen quite often’ (A)

The highest score that A managed for Fossilwise is 20 for reliability of supply (considering it to be less reliable than wind energy) – although discussion focused on the relative reliability of renewables and nuclear for this criterion, the respondent seems to have struggled with the implications of capture processes on reliability. Generally, as each criterion was scored, this respondent focused on negative attributes of CCS for each criterion. As this respondent is an environmental campaigner it would be easy to simply attribute this approach to scoring as a ‘knee jerk’ reaction to the technology but it should be pointed out that A had read widely on CCS and was well-informed about the technology, leading him to feel ‘less confident about CCS’ than the official position of his organization.

Both A and F gave consistently low scores to Nuclear Renaissance for all criteria except Infrastructure (A: 25), Reliability (F: 25) Security (A: 25), which were still only slightly above average. Respondent F explicitly refers to the influence of her scepticism of nuclear power by saying ‘I’m loathed to score it too highly’ despite considering it to perform well against, in this case, the reliability criterion.

The Capture as a Bridge scenario brought out some of the strategic approaches to scoring; since it begins with a large proportion of fossil fuel with CO_2 capture which is subsequently replaced by renewable power it contains elements of the preferred and less favoured options. In the case of the strategic scorers this appears to have the affect that scoring was focused on the component of the scenario that was disliked rather than on a view of the scenario as whole. For example, despite the final fuel mix comprising a large proportion of A's favoured renewables, this respondent did not give this scenario anywhere near the high scores seen for the Renewable Generation scenario. Likewise, H gave consistently low scores for this scenario despite it deploying significant CCS in its first phase, disliking this scenario on the grounds that he couldn't envisage a reason for moving away from CCS in the second phase.

Respondent B displayed the clearest example of explorative scoring with some extreme scoring, both positive and negative, within individual scenarios. This respondent gave Nuclear Renaissance a score of zero for cost effectiveness, environmental performance and resilience to disaster and avoidance of lock in whilst giving the same scenario a score of 30 or more for compatibility with existing infrastructure, reliability and security of supply. Similarly, B gave Renewable Generation very low scores for cost effectiveness, compatibility with existing infrastructure, reliability and contribution to achieving CO_2 targets and high scores for environmental performance, resilience and avoidance of lock in. Similarly, Respondent G demonstrated an explorative approach to scoring by awarding a broad spread of scores to several of the scenarios depending on the criterion. For example, Renewable Generation, which comes out as this respondent's preferred scenario in the final ranking is given a score of 35 or more for cost effectiveness, environmental performance, avoidance of lock in and contribution to achieving CO_2 targets, while receiving a score of 15 or less for compatibility with existing infrastructure, reliability and public perceptions.

8.4.5. Implications of CCS

During the course of the MCA interviews, certain recurring topics were raised that relate to the implications of introducing CCS in the UK.

IGCC or Supercritcal? Two quite different techniques for coal fired power generation are described in the scenarios after 2020 - Ultra Super Critical (USC) with capture and Integrated Gasification Combined Cycle (IGCC) (these technologies are described in Chapter 3). It is currently not clear which of these is likely to become the dominant technology for coal fired power generation in the UK and there are many factors governing the diffusion of a new technology (technical, economic, political, social, cultural etc). USC technology allows for incremental upgrades on existing plant whereas IGCC would entail a total redesign and redevelopment of plant. Even though there are several demonstration projects, IGCC is not yet proven on a commercial scale; however, most of the coal fired power stations in the UK are approaching their end of life.

Respondent H was sceptical of IGCC being suitable for large scale integration to the power generation network because it would be better suited for baseload generation and not sufficiently flexible for load following. The remainder of those that expressed opinions on this subject all considered that, while in the short to medium term upgrading to USC would be the most straightforward and cost-effective option, IGCC would appear over the longer term:

> 'its [retrofit] not a long term solution because you've got to get an IGCC plant up … but what they'll do is go to supercritical boilers because its cheaper, quicker and easier ' (E)

> 'the first phase of that [Capture as a Bridge] should be one of the least expensive options … first of all you upgrade to supercritical and then you probably make a decision at some point about whether you're

> going to go onto capture so you have a situation where you have a more efficient plant and you weren't investing totally straight away in the new technology' (C)

The importance of the global context was also raised by respondent D in relation to these technologies, notably what happens in China. Although they are not currently pursuing IGCC technology for power generation, the rate at which the Chinese are developing new coal fired capacity suggests that the next 10-20 years could see significant changes.

British coal. The security of supply criterion raised the issue of the potential for domestic coal reserves. Currently 59% of the UK's coal use is imported (DTI, 2005) and large global supplies are available from a variety of sources (in contrast to gas supplies). However, Respondent D (a representative of the coal industry in the UK) noted that should the current trend for increased coal prices continue or should the supply of imports be challenged in some way, the UK does still have significant reserves of coal that could be exploited. Accessing these reserves may involve developing a new mine to access coal seams previously mined elsewhere (where the mines have been closed and cannot be reopened).
A corollary to this was voiced by B – that although the region has a strong identity with coal, there is a distinction between coal for power generation and coal mining; although there is a long history of coal mining in the region:

> 'Even with communities like Wakefield, the Coalfield Community Campaign etc,…its actually not all that long before they get to coal mining is a horrible industry. […] In that sense is it coal or is it gas – at the economic level is not seen as a big issue' (B)

The concept of CCS. Beyond the responses to specific criteria most of the respondents made clear statements about their opinion of the principle of using CCS as an approach to Climate Change mitigation. Since all the scenarios incorporate different combinations of power generation technology and three incorporate CCS, we have separated these comments from the scenario analysis – in order to highlight particular opinions relating to the concept of CCS. The respondents fit into one of three groups:

1) Resistant to CCS – deep seated opposition, because of scepticism about the risks associated with the technology or both;
2) Ambivalent – somewhat sceptical of the technology but see that it may have a role to play;
3) CCS advocates - believe it to be an essential element of any climate policy, that it will be impossible to meet CO_2 targets without it.

1) Resistant to CCS – three respondents, A, F, and G expressed fundamental concerns about the use of CCS. A held the strongest views of the two and was concerned about the legacy to future generations, clearly not identifying CCS with long term benefits in climate change terms:

> 'So if you're basically producing something that has to be monitored for thousands of years, I'm not sure that's a good idea, that we should be passing that sort of thing on to future generations where they're getting the cost and no benefit. […] That's what I don't like about it that its basically forcing your descendents to monitor an area virtually for ever potentially' (A)

In addition A, along with F and G expressed doubts about the long term storage security of reservoirs and the integrity of the cap rock. Although in the final scoring respondent F ranked the three scenarios that incorporated CCS relatively high, this appears to be a function of her strong opposition to nuclear rather than support for CCS. This respondent made various statements that revealed a fairly deep scepticism against CCS:

> 'its not really going to deal with the major issue, its using CCS as a an easy way out - in the longer term you're not restructuring the whole thing. […] for whatever reason its not going to cause a change, its not going to make us think in a different way about how we use the resources that we've got' (F)

2) Ambivalent – respondents B and C identified CCS as being part of our future energy policy, although C saw it as a relatively short term solution, in the absence of any better alternative currently available:

> 'I'm not seeing it as a long term issue around the UK …over 50 years you could do it and by then hopefully you've got some other technology' (C)

> '… reflecting the inability of the other technology in my view to fill the gap, best will in the world its not credible to have so much renewable or nuclear is unlikely to significantly increase' (C)

Respondent B on the other hand was simply sceptical about whether CCS could be made to work on a larger scale:

> 'I am predisposed towards clean coal as a good way of doing it, however I do think the idea of piping CO2 offshore and sticking it in the wells is ridiculous. It seems to me what we're very good at doing as human beings is building plants with Process Integration … the idea of carbon abatement where you're doing it (process engineering) it seems to me we have a track record, the moment you start bringing lots of links in the chain and pipelines and moving things off site … somehow as human beings we're not ever so good at doing that.' (B)

3) CCS Advocates – E, D and H were all strongly in favour of CCS as a necessary technological approach to CO_2 reduction in the context of the challenges to achieving reductions in other sectors and through demand and efficiency measures:

> 'its got to happen it's the only way to do it - to run a modern industrial economy, you cannot transform the economy to a low energy economy to the extent its required, you cannot reduce your energy demand far enough you've got to have CO2 capture' (E)

> 'any scenario with lots of CCS is consistent (with achieving national CO_2 targets) [ ] CCS … gives other sectors of the economy a hook on which they can attach their emissions as well' (D)

Respondent E (a politician) even identified CCS as a personal goal:

> 'If we can get to CO2 capture and IGCC by 2050 I will die a happy man –with carbon capture in the North Sea we've effectively turned around the power industry in the right direction' (E)

Although all respondents were presented with maps (Figures 8.5 – 8.8) showing potential storage locations adopted in each of the scenarios there was a general reluctance to engage in discussion over the relative merits of different types of storage reservoir. Since the majority of respondents were drawn from the energy sector and hence would not be familiar with the geological debate in this area, this is perhaps not surprising. The two exceptions to this are A, our strongest opponent of CCS who was very sceptical about the long term storage security of aquifers, and E, our strongest supporter of CCS, who considered that large capacity of aquifers to be a great asset to the region.

8.5. Summary

The MCA process implemented here with seven regional stakeholders (and one more from outside the region), has highlighted some key points of disagreement (and agreement) concerning future power generation technologies. Whilst the number of respondents is too small draw general conclusions about stakeholder opinion within the region (which was not the intention of the study) it has been successful in exposing some of the different opinions that might be expected from a variety of perspectives.

The Yorkshire and Humberside and East Midlands regions have been dominated by coal, both mining and for power generation, in recent history. There is thus a significant economic benefit to the region in maintaining a fossil fuel economy in general and coal firing in particular. This is reflected in the popularity of the Fossilwise scenario in most cases – the exceptions being the environmental campaigner and the two of the respondents with a regional sustainable energy remit. Although the combined region has a large coastline there is generally less enthusiasm for the large scale deployment of renewables from the group as a whole. This scenario incorporated a very high penetration of renewables (just over 50% of generation) and many respondents were highly sceptical about the feasibility of this. One aspect of renewable energy that did yield some highly contrasted views was cost, with three of the respondents considering it to be the cheapest of the scenarios and the remaining five considering it to be the most expensive. One factor considered by one respondent to make renewables a cheaper option was the rising price of fuels as global demand increases.

Nuclear Renaissance was the lowest ranked of any of the scenarios by six of the respondents, next to lowest by one, leaving just one respondent (manufacturer of nuclear technology from outside the region) giving it a second place ranking. Several of these respondents made a point of stating that they held no opposition to nuclear power *in principle* but it was widely felt to be an expensive option with high environmental risks that would be unpopular with the public and vulnerable to potential major disasters. The fact that there are no nuclear power stations located within the region in any of the scenarios removes the effect of any potential employment or regional economic benefits leaving respondents to focus on the negatives. The two more mixed scenarios (Capture as a Bridge and Spreading the Load) produced a high degree of consensus amongst the respondents. Spreading the Load was the highest ranked scenario for two of the respondents and second highest for the remainder, the key strength of this scenario was widely viewed as being its diversity of supply.

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Technical Annex 1

Detailed ICEM modelling of cost functions

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A1.1 Introduction

Using the ICEM-CS (version 3.5.5) software provided by Carnegie Mellon University (CMU), we have modelled the CO_2 capture system (Table A1.3) and further developed a number of cost estimating functions relating capital expenses, operating costs, sorbent cost, steam cost electricity cost and cost of CO_2 avoided to plant size and to amount of CO_2 avoided for three different CO_2 removing efficiencies (85%, 90% and 95%).

Process Facilities Capital (PFC) considered in this work includes the following elements:

PFC *= Direct Contact Cooler + Flue Gas Blower +* CO_2 *Absorber Vessel + Heat Exchangers + Circulation Pumps + Sorbent Regenerator + Reboiler + Steam Extractor + Sorbent Reclaimer + Sorbent Processing + Drying and Compression Unit.*

Equation A1.1

The unit cost of *each component* of this system (absorber, regenerator, flue gas blower *etc.*) is scaled based on the flow rate of the material being handled by that particular device, using the 0.6 power law commonly used in chemical engineering costing. For example, the cost of an absorber is scaled on the basis of the flue gas flow rate entering the CO_2 system, with the data obtained from Fluor Daniel serving as the reference basis for this scaling. Thus, in general, the capital cost of a component of arbitrary size (less than the maximum size) may be estimated as:

$$C_i = C_{i,ref} \cdot \left(\frac{X_i}{X_{i,ref}} \right)^{0.6}$$

Equation A1.2

where,

Ci = Component cost

Ci,ref = Cost of reference size

X = actual flow rate (for scaling)

Xi,ref = Flow rate of reference plant

Once the cost of particular equipment (Ci) is calculated, it needs to be multiplied by the total number of equipment installed (Zi) in order to get the total cost of installation for that process area (i).

The overall amine system is divided into a number of process areas for which some physical quantity is identified as the basis for scaling of the capital cost. For example, flue gas flow rate, sorbent flow rate, CO_2 product flow rate, CO_2 compression energy requirement, steam flow rate, and makeup MEA flow rate are used for scaling he capital cost of various process areas.

The direct capital cost (process facilities cost) of CO_2 capture and separation system consists of the following cost areas:

Direct contact cooler: In case of coal-fired power plant applications that have a wet FGD (flue gas desulphurisation) unit upstream of the amine system, the wet scrubber helps in substantial cooling of the flue gases, and additional cooler may not be required. In case of gas-fired power plants or majority of coal-fired power plants that do not have wet scrubbers for SO_2 removal, a direct contact cooler has to be installed to bring down the temperature of the flue gas stream to acceptable levels. A direct contact cooler is a large vessel where the incoming hot flue gas is made to contact with the cooling water. The size of this unit is a function of the volumetric flow rate of the flue gas, which in turn depends upon the temperature and pressure conditions of the flue gas stream. The capital cost of the unit is estimated as:

$$C_{dcc} = C_{dcc,ref} \cdot \left(\frac{V_{fg}}{V_{fg,ref}} \cdot \frac{T_{fg}}{T_{fg,ref}} \right)^{0.6}$$ **Equation A1.3**

Flue gas blower: The cooled flue gas is pressurized using a blower before it enters the absorber. The size (and the cost) of the blower is again a function of the volumetric flow rate of the flue gas as it enters the blower. So, the cost may be estimated as:

$$C_{blower} = C_{blower,ref} \cdot \left(\frac{V_{fg,1}}{V_{fg,1,ref}} \cdot \frac{T_{fg,1}}{T_{fg,1,ref}} \right)^{0.6}$$ **Equation A1.4**

Absorber: This is the vessel where the flue gas is made to contact with the MEA-based sorbent, and some of the CO_2 from the flue gas gets dissolved in the sorbent. Again, the size of this unit is mainly a function of the volumetric flow rate of the flue gas, which in turn depends upon the temperature and pressure conditions of the flue gas stream, as it enters this vessel. The cost of the unit is again estimated on the basis of the cost information available for a particular reference case:

$$C_{absorber} = C_{absorber,ref} \cdot \left(\frac{V_{fg,in}}{V_{fg,in,ref}} \cdot \frac{T_{fg,in}}{T_{fg,in,ref}} \right)^{0.6}$$ **Equation A1.5**

Rich/lean cross heat exchanger: The rich (CO_2-loaded) and lean (regenerated) sorbent streams are passed through this cross heat exchanger, where the rich sorbent gets heated and the lean sorbent gets cooled. So, the size (and cost) of this unit is a function of the volumetric sorbent flow rate in the absorber. It is assumed that this volumetric flow rate is constant in the range of temperature and pressure conditions found in this system. The capital cost of the unit is estimated as:

$$C_{crossHEx} = C_{crossHEx,ref} \cdot \left(\frac{V_{solvent}}{V_{solvent,ref}} \right)^{0.6}$$ **Equation A1.6**

Regenerator: This is the column where the CO_2-loaded sorbent is regenerated with the application of heat. Sorbent flow rate is the main physical quantity that decides the size (and cost) of this unit, for a given residence time, which is a function of many parameters including the sorbent concentration, desired CO_2 capture efficiency, *etc*. So, the cost may be estimated as above:

$$C_{regenerator} = C_{regenerator,ref} \cdot \left(\frac{V_{solvent}}{V_{solvent,ref}} \right)^{0.6}$$ **Equation A1.7**

Reboiler: The regenerator is connected with a reboiler, which is a heat exchanger where low-pressure steam extracted from the power plant is used to heat the loaded sorbent. So, the size (and cost) of this unit is a function of mainly the flow rate of the sorbent as well as the flow rate of steam. The cost of the unit is estimated as:

$$C_{reboiler} = C_{reboiler,ref} \cdot \left(\frac{V_{solvent}}{V_{solvent,ref}} \cdot \frac{M_{steam}}{M_{steam,ref}} \right)^{0.6}$$ **Equation A1.8**

It may be noted that the ratio of mass flow rates of LP steam (Msteam/ Msteam,ref) has been used in place of the ratio of volumetric flow rates of LP steam, assuming that the temperature and pressure conditions of the LP steam in both cases (actual and reference) are approximately the same.

Steam extractor: Steam extractors are installed to take LP steam from the steam turbines in the power plant. The size (and the cost) of the steam extractor is assumed to be a function of the steam flow rate.

$$C_{steam\_extractor} = C_{steam\_extractor,ref} \cdot \left(\frac{M_{steam}}{M_{steam,ref}} \right)^{0.6}$$ **Equation A1.9**

This cost item is included if the CO_2 capture system is configured to make use of steam extracted from the steam cycle of the base plant. Alternatively, an auxiliary NG boiler and a secondary steam turbine may be used, and the next two cost items (CNG_boiler and CST2) are included in its place.

Auxiliary boiler without steam turbine: If a NG boiler is installed to provide only LP steam (and not to generate any electrical power using a secondary steam turbine), then the boiler cost is lower than that of high-pressure boiler discussed earlier. According to Rao (Rao *et al*. 2004) the cost is estimated as:

CNG_boiler = USD15 · (steam flow rate expressed in lb/h) **Equation A1.10**

Since the steam flow rate (msteam) in the model is given as tonnes/hr, the following expression is obtained after accounting for the unit conversions

CNG_boiler = USD33000 · (msteam) **Equation A1.11**

The cost of the secondary steam turbine is estimated on the basis of the electrical power generated from this new turbine again using a cost estimation formula reported by Simbeck (Simbeck and McDonald 2000):

CST2 = USD300 · (EST2) **Equation A1.12**

where

EST2 = Power generation from secondary steam turbine expressed in MWe

Auxiliary boiler without steam turbine: If a NG boiler is installed to provide only LP steam (and not to generate any electrical power using a secondary steam turbine), then the boiler cost is lower than that of high-pressure boiler discussed earlier. According to Simbeck (Simbeck 2002) its cost is estimated as:

CNG_boiler_only = USD22000 · (msteam) **Equation A1.13**

MEA reclaimer: In order to avoid accumulation of the heat stable salts in the sorbent stream and to recover some of the lost MEA sorbent, a part of the sorbent stream is periodically distilled in this vessel. Addition of caustic helps in freeing of some of the MEA. The amount of MEA makeup requirement may be taken as an indicative of the amount of heat stable salts formed and the quantity of sorbent to be distilled in the reclaimer. So, the mass flow rate of makeup MEA requirement is used as a scaling parameter to estimate the cost of this unit:

$$C_{MEA\_reclaimer} = C_{MEA\_reclaimer,ref} \cdot \left(\frac{M_{MEA\_makeup}}{M_{MEA\_makeup,ref}} \right)^{0.6}$$ **Equation A1.14**

Sorbent processing area: The sorbent processing area primarily consists of sorbent cooler, MEA storage tank, and a mixer. It also consists of an activated carbon bed filter that adsorbs impurities (degradation products of MEA) from the sorbent stream. So, the size (and cost) of this unit (together) will be a function of the total sorbent flow rate, and may be estimated as follows:

$$C_{solvent\_proc} = C_{solvent\_proc,ref} \cdot \left(\frac{V_{solvent}}{V_{solvent,ref}} \right)^{0.6}$$ **Equation A1.15**

CO_2 drying and compression unit: The multi-stage compression unit with inter-stage cooling and drying yields the final CO_2 product at the specified pressure (about 2000 psig) that contains only acceptable levels of moisture and other impurities (e.g. N2). The size (and cost) of this unit will be a function of the CO_2 product flow rate, and may be estimated as follows:

$$C_{CO2\_compr} = C_{CO2\_compr,ref} \cdot \left(\frac{M_{CO2}}{M_{CO2,ref}} \right)^{0.6}$$ **Equation A1.16**

Thus the sum of all these individual process area equipment costs is termed as process facilities capital (PFC).

For ***Total Capital Requirement (TCR)*** calculation in this study, the process facility capital has to be increased by additional 53.6 percent (which includes such items as General Facilities Capital, Eng. & Home Office Fees, Process Contingency Cost, Pre-production (Start-up) Cost, etc):

TCR *= CAPEX · 1.536 [M USD/y]* **Equation A1.17**

Capital cost annualisation is carried out multiplying the Total Capital Requirement by Fixed Charge Factor (FCF) which is a function of Inflation Rate, Plant or Project Book Life, Real Bond Interest Rate, Real Preferred Stock Return, Real Common Stock Return, Percent Debt, Percent Equity (Preferred Stock), Percent Equity (Common Stock):

Annualised Capital Cost *= TCR · Fixed Charge Factor (FCF)* **Equation A1.18**

As can be seen from model description above, the capital cost follows the two-thirds power-law relationship. However the graphs in figures are clearly linear. The reason for this is that with the increase in the plant size, the number of CO2 trains increases. This is a linear relationship. As we increase the size of the individual CO2 vessels, we increase the cost via a power-law relationship. Because the maximum vessel size is rather small, the large plants in this report showed more of the multiple train cost factor, hence, a linear cost relationship to plant size. If a single CO2 vessel were able to treat the entire flue gas stream produced by a 500 MW power plant, we would see the power-law relationship between plant size and cost.

Year 2000 USD are used in this research at current stage for calculations. The figures can be updated to 2004 USD by multiplying by conversion factor of 1.085 (http://oregonstate.edu/Dept/pol_sci/fac/sahr/sahr.htm)

Operating and Maintenance Cost
The major operating and maintenance (O&M) cost consists of fixed costs and variable cost elements as listed in Table 4

Table A 1.1 MEA O&M cost model parameters and nominal values used in this study

O&M Cost Elements	Typical Value
Fixed O&M Costs	
Total Maintenance Cost	2.5% TPC
Maintenance Cost Allocated to Labour (fmaintlab)	40% of total maint. cost
Admin. & Support Labour Cost (fadmin)	30% of total labour cost
Operating Labour (Nlabour)	2 jobs/shift
Variable O&M Costs	
Reagent (MEA) Cost	USD1200/ t
Water Cost	USD0.8/ 1000 gallon
Solid Waste Disposal Cost	USD175/ t waste
CO_2 Transport Cost	USD0.02/ t CO_2 per km
CO_2 Storage/Disposal Cost	USD5/ t CO_2

Fixed O&M Costs
The *fixed O&M* (FOM) costs in the model include the costs of maintenance (materials and labour) and labour (operating labour, administrative and support labour). They are estimated on annual basis (USDM/y) as follows:

$FOM = FOMlabor + FOMmaint + FOMadmin$ **Equation A1.19**
$FOMlabor = labor \cdot Nlabor \times 40(h/week) \cdot 52(weeks/y)$ **Equation A1.20**
$FOMmaint = \Sigma i\ (fmaint)i \cdot TPCi$ **Equation A1.21**

where i = process area

$FOMadmin = fadmin \cdot (FOMlabor + fmaintlab \times FOMmaint)$ **Equation A1.22**

where,
labour = the hourly wages to the labour (USD/h)
Nlabour = number of operating labour required
(fmaint)i = total annual maintenance cost expressed as the fraction of the total plant cost (TPC)
fadmin = the administrative labour cost expressed as the fraction of the total labour cost

Variable O&M Costs
The *variable O&M* (VOM) costs depend on the capacity factor (or load factor) of the plant. They include costs of chemicals consumed (MEA, inhibitor, other reagents such as caustic and activated carbon), utilities (water, steam, power), fuel (natural gas, in case of auxiliary boiler) and services used (waste disposal, CO2 transport and storage). These quantities are determined in the performance model. The unit cost of each item (e.g., dollars per ton of reagent, or dollars per ton of CO2 stored) is a parameter specified as a cost input to the model. The total annual cost of each item is then calculated by multiplying the unit cost by the total annual quantity used or consumed. Total annual quantities depend strongly on the plant capacity factor, which is defined as the ratio of total annual generation (kWh per year) to maximum possible generation (which is the product of plant capacity times total hours per year). The plant capacity factor is one of the crucial assumptions that influences the overall economics of the plant, especially in the case of a capital-intensive technology. The individual components of variable O&M costs are as follows:

Cost of MEA reagent (VOMMEA): The makeup MEA requirement estimated in the performance model is transformed into dollar amount by using the unit cost of MEA, which is a user-controlled cost input variable.

$VOMMEA = MMEA,makeup \cdot UCMEA \cdot HPY$ **Equation A1.23**

where, UCMEA is the unit cost of MEA, and HPY is the equivalent annual hours per year of plant operation at full capacity (*e.g.*, a capacity factor of 75% is equivalent to about 6575 hours per year, assuming an average of 365.25 days per year).

Cost of inhibitor (VOM inhibitor): Addition of inhibitor makes it possible to use higher concentrations of MEA sorbent in the system with minimal corrosion problems. Inhibitors are special compounds that come at a cost premium. The cost of inhibitor is estimated as 20% of the cost of MEA.

VOMinhibitor = 0.2 · VOMMEA **Equation A1.24**

Cost of other reagents (VOM reagents): The cost of other reagents, such as, caustic and activated carbon are also calculated from their physical quantities estimated in the performance model and the unit costs of these reagents.

VOMreagents = VOMCaustic + VOMact-C
= {(mCaustic · UCCaustic) + (mact-C · UCact-C)} · HPY **Equation A1.25**

where UCCaustic and UCact-C are the unit costs of the reagents caustic and activated carbon, respectively.

Cost of waste disposal (VOMwaste): Another important variable operating cost item is the cost incurred in disposal of the spent sorbent *i.e.*, the reclaimer waste. The quantity estimated in the performance model is:

VOMwaste = Mwaste,total · UCwaste · HPY **Equation A1.26**
where UCwaste is the unit cost of waste disposal for the reclaimer waste.

Cost of CO_2 transport (VOMtransport): Transportation of CO_2 product is assumed to take place via pipelines. The cost of CO_2 transport is estimated on the basis of two user specified parameters, *viz*., transportation distance (TD, in km) and unit cost of transport (UCtransport, USD/km per t CO_2), plus the CO_2 product flow rate (calculated result from performance model).

VOMtransport = MCO2 · UCtransport · TD · HPY **Equation A1.27**

Cost of CO_2 storage (VOMdisposal): Depending upon the method of CO_2 disposal or storage, either there may be some revenue generated (as in enhanced oil recovery, or enhanced coal bed methane), or an additional cost (all other disposal methods). The total cost or revenue of CO_2 disposal/ storage is estimated from the unit cost and CO_2 product flow rate (UCdisp).

VOMdisposal = MCO2 · UCdisp · HPY **Equation A1.28**

Cost of energy (VOMenergy): By default, all energy costs are handled internally in the model by de-rating the overall power plant based on the calculated power requirement. The CO_2 capture unit is charged for the total electricity production foregone because of CO_2 capture and compression (ECO2, tot).

For power plants with multi-pollutant controls the desire to quantify costs for a single pollutant requires an arbitrary choice of how to charge or allocate certain costs. This is especially relevant for energy-intensive processes like CO_2 capture systems.

The unit cost of electricity (COEnoctl) is estimated by the base plant module, or may be overridden by a user-specified value if this energy is assumed to be supplied from an external source. Since energy cost is one of the biggest O&M cost items for the CO_2 unit, the way in which it is accounted for is important when calculating the mitigation cost.

VOMenergy = ECO2,tot · HPY · COEnoctl **Equation A1.29**

Alternatively, when regeneration steam and additional electricity is provided by an auxiliary NG boiler, the cost of energy is estimated from the total annualised cost of the new boiler and secondary steam turbine, which takes into account their capital cost requirements and cost of natural gas fuel.

Cost of water (VOMwater): Water is mainly required for process cooling and also as process makeup. Generally this is a minor cost item in the overall plant operation, but it is included over here for the sake of completeness, based on the amount of water needed (Mw) and the unit cost of water (UCwater):

VOMwater = Mw · UCwater · HPY **Equation A1.30**

The total variable O&M (**VOM**, USD/y) cost is obtained by adding all these costs:

VOM = VOMMEA + VOMreagents + VOMwaste + VOMtransport + VOMdisposal + VOMenergy + VOMwater

Equation A1.31

Finally, the **total annual O&M cost** (**TOM**, USD/y) may be obtained as:

TOM = FOM + VOM **Equation A1.32**

As can be seen from the above description of the CMU model, it is quite detailed by nature. It is neither impossible nor expedient to follow such a comprehensive approach in this Tyndall project (CMU spent more than 3 years and a lot of money on it). A simpler way which uses some relatively simple scaling rules based on literature data and some external calculations is preferred by project partners. To provide more accurate and reliable cost estimation to the project, even when follow some rather simpler scaling rules, ICEM-CS software was used to obtain Cost Estimation Relationships (CERs) for power plants with different sizes and different operating conditions. This would be of great help on techno-economic analysis of the amine-based CO_2 capture processes.

Financial data used in the major part of the study is shown in Table A1.2.

Table A 1.2 Financial data used for determining CERs

Year Costs		**2000**
Constant or Current USD		Constant
Fixed Charge Factor (FCF)	Fraction	0.1034
Discount Rate (Before Taxes)	Fraction	6.125e-02
Or, alternatively:		
Inflation Rate	%/y	0.0
Plant or Project Book Life	y	30.00
Real Bond Interest Rate	%	4.60
Real Preferred Stock Return	%	5.20
Real Common Stock Return	%	8.70
Percent Debt	%	50.00
Percent Equity (Preferred Stock)	%	15.00
Percent Equity (Common Stock)	%	35.00
Federal Tax Rate	%	36.70
State Tax Rate	%	2.00
Property Tax Rate	%	2.00
Investment Tax Credit	%	0.0

Table A 1.3 Modelling Data

Plant Size	CO_2 throughput	CO_2 remove efficiency	Net CO_2 output	CO_2 avoided	Net plant size	PFC	Var O&M	Sorbent	Steam	Electricity	Cost of CO_2 avoided
MW	ton/h	%	ton/h	M$/y	MW	M$/y	M$/y	M$/y	M$/y	M$/y	$/t CO_2
300	294.4	90	29.44	1.510	245.4	86.7	37.82	6.958	9.009	7.325	56.33
400	392.5	90	39.25	2.013	327.7	117.6	49.33	9.277	11.41	9.276	50.76
500	490.7	90	49.07	2.516	410.1	135.9	60.73	11.6	13.75	11.18	45.63
600	588.8	90	58.88	3.019	492.4	163	72.05	13.91	16.04	13.04	42.81
700	686.9	90	68.69	3.522	574.7	189.8	83.3	16.23	18.3	14.88	40.71
800	785	90	78.5	4.026	657.1	221	94.5	18.55	20.52	16.69	39.26
900	883.1	90	88.31	4.529	739.4	238.6	105.7	20.87	22.72	18.48	37.19
1000	981.3	90	98.13	5.032	821.7	265.4	116.8	23.19	24.9	20.25	36
1100	1079	90	107.9	5.535	904	292.1	127.8	25.51	27.06	22.01	34.96
1200	1177	90	117.7	6.038	986.4	323.5	138.9	27.83	29.21	23.75	34.27
1300	1276	90	127.6	6.541	1069	340.8	149.9	30.15	31.14	25.48	33.05
1400	1374	90	137.4	7.045	1151	367.5	160.9	32.46	33.45	27.2	32.35
1500	1472	90	147.2	7.548	1233	398.8	171.9	34.78	35.55	28.91	31.89
1600	1570	90	157	8.051	1316	425.6	182.8	37.1	37.64	30.61	31.31
1700	1668	90	166.8	8.554	1398	452.2	193.8	39.42	39.72	32.3	30.77
1800	1766	90	176.6	9.057	1480	469.4	204.7	41.74	41.79	33.98	29.98
1900	1864	90	186.4	9.560	1563	500.8	215.6	44.06	43.85	35.66	29.68
2000	1962	90	196.2	10.060	1645	527.5	226.4	46.38	45.9	37.32	29.27
300	294.4	85	44.16	1.426	245.4	84.66	36.2	6.763	8.517	7.098	59.96
400	392.5	85	58.88	1.901	327.7	105.8	47.21	9.017	10.78	8.987	52.5

500	490.7	85	73.6	2.376	410.1	132.6	58.13	11.27	13	10.83	48.31
600	588.8	85	88.32	2.852	492.4	159	68.96	13.52	15.16	12.64	45.24
700	686.9	85	103.035	3.327	574.7	185.2	79.73	15.78	17.3	14.41	42.95
800	785	85	117.75	3.802	657.1	206.3	90.45	18.03	19.4	16.17	40.65
900	883.1	85	132.465	4.277	739.4	232.7	101.1	20.29	21.48	17.9	39.13
1000	981.3	85	147.195	4.753	821.7	258.9	111.8	22.54	23.54	19.62	37.83
1100	1079	85	161.85	5.226	904	275.4	122.4	24.79	25.59	21.32	36.17
1200	1177	85	176.55	5.701	986.4	306.1	132.9	27.05	27.61	23.01	35.46
1300	1276	85	191.4	6.178	1069	332.4	143.5	29.3	29.63	24.69	34.62
1400	1374	85	206.1	6.653	1151	358.5	154	31.55	31.62	26.36	33.86
1500	1472	85	220.8	7.128	1233	374.9	164.5	33.81	33.61	28.01	32.78
1600	1570	85	235.5	7.604	1316	405.7	175	36.06	35.59	29.66	32.36
1700	1668	85	250.2	8.079	1398	431.8	185.5	38.31	37.55	31.30	31.80
1800	1766	85	264.9	8.554	1480	457.9	195.9	40.57	39.51	32.93	31.28
1900	1864	85	279.6	9.029	1563	474.2	206.3	42.82	41.46	34.55	30.49
2000	1962	85	294.3	9.504	1645	505	216.7	45.08	43.4	36.16	30.21
300	294.4	95	14.72	1.594	245.4	88.82	39.45	7.153	9.519	7.538	53.25
400	392.5	95	19.625	2.125	327.7	120.5	51.45	9.537	12.05	9.546	48.13
500	490.7	95	24.535	2.656	410.1	148.4	63.34	11.92	14.53	11.5	44.31
600	588.8	95	29.44	3.187	492.4	167.1	75.15	14.3	16.95	13.42	40.76
700	686.9	95	34.345	3.718	574.7	194.5	86.89	16.69	19.33	15.31	38.82
800	785	95	39.25	4.249	657.1	226.5	98.56	19.07	21.69	17.18	37.48
900	883.1	95	44.155	4.780	739.4	254	110.2	21.46	24.02	19.02	36.11
1000	981.3	95	49.065	5.312	821.7	281.4	121.8	23.84	26.32	20.84	34.94
1100	1079	95	53.95	5.843	904	304.1	133.3	26.22	28.6	22.65	33.72
1200	1177	95	58.85	6.374	986.4	331.6	144.9	28.62	30.87	24.45	32.87

1300	1276	95	63.8	6.905	1069	359	156.4	30.99	33.12	26.23	32.12
1400	1374	95	68.7	7.436	1151	386.3	167.8	33.37	35.35	28.00	31.44
1500	1472	95	73.6	7.967	1233	418.3	179.3	35.76	37.57	29.76	30.99
1600	1570	95	78.5	8.498	1316	436.3	190.7	38.14	39.78	31.51	30.13
1700	1668	95	83.4	9.029	1398	463.6	202.1	40.53	41.98	33.25	29.63
1800	1766	95	88.3	9.560	1480	495.7	213.5	42.91	44.17	34.98	29.31
1900	1864	95	93.2	10.090	1563	523	224.8	45.29	46.34	36.7	28.89
2000	1962	95	98.1	10.621	1645	550.3	236.2	47.68	48.51	38.42	28.49

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Technical Annex 2

Outline of the new carbon dioxide storage cost model

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Note: The project partner was unable to finish this chapter to meet the submission deadline. This is the latest version of the unfinished Chapter supplied by Reading University.

1 Introduction

The prime purpose of the model is to calculate the costs associated with CO_2 avoidance, in pounds sterling per tonne of CO_2 saved for a range of capture, transport and disposal options, based on high level input data. The model builds upon a previous model developed as part of a JOULE II project (Docherty and Harrison 1996). Much of this old model will be re-used here, but there are many new elements. When complete the model will be used to compare carbon sequestration options at a limited number of locations within the UK, and for studies of the sensitivity of the cost of disposal to changes in the major parameters of the most promising solutions identified. The results will form an input to a forthcoming MCDA, and thus the model should focus on those engineering parameters of greatest significance for the MCDA. The model should also be usable by those with a good understanding of carbon dioxide disposal but without specialist engineering expertise.

One of the greatest areas of direct interaction between 'the public' and carbon dioxide sequestration will be during the transport of the gas from the place of production to the place of disposal. In general this will take place by means of a pipeline. To maximise the value of its output to the MCDA, the cost model must pay more attention to the pipeline than has been the case in preceding studies.

This Annex provides an outline of the cost model and the techno-economic study it has been used for.

2 Breakdown of costs

Figure A2.1 shows the view of the capture and disposal process encapsulated in the model. The major parts are as follows:

- The carbon dioxide source which will usually be a fossil fueled power station coupled with a carbon dioxide capture plant, but could potentially be any carbon dioxide producing industrial process,
- The transport process, which for the purpose of the current study will always be a pipeline,
- The storage reservoir, for which there is a wide range of possibilities to be considered, but in the present study will always be offshore.

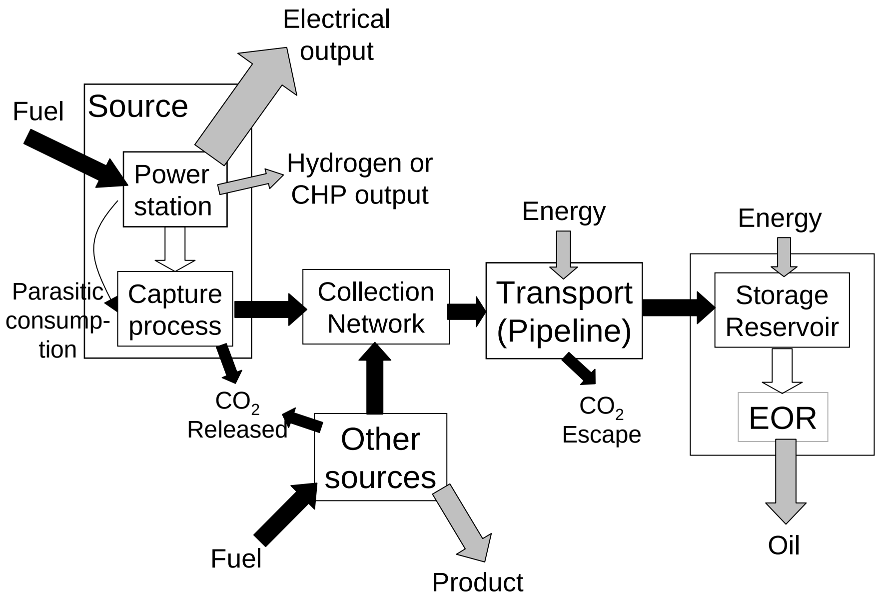

Figure 1: Overview of the sequestration process.

The model calculates capital and annual on-going costs for each subsystem, along with estimates of carbon dioxide emissions, which can be used to compare technologies as discussed in section 3. Aspects of some technologies, for example enhanced oil recovery, generate an income that must also be accounted for. The broad breakdown of costs as considered by the model is shown in table 1, although many of the costs will need to be broken down further for detailed analysis. Note that it is *not* assumed that on-going costs will be the same each year.

The model can only analyse a single carbon dioxide source in detail at any one time. Provision is made for considering that the source is part of a wider network of sources that share the costs of storage in proportion to the quantity of carbon dioxide stored, but the techno-economic details for each member of the network must be considered separately.

Table A2.1: Major costs considered

Major System	Cost	Type	Symbol	Note
Source (generator)	Plant	Capital	$C_{S,P}$	Only included for new-build plant, regarded as a sunk cost for re-fit cases.
	FGD	Capital	$C_{S,FGD}$	Flue gas desulphurisiation equipment cost. Not included if already fitted to an existing plant.
	Fuel	On-going	$c_{S,FUEL,i}$	Fuel cost in year *i* from start of sequestration project.
	O&M	On-going	$c_{S,P}$	Plant O&M cost in year *i* from start of project.
	Income	On-going	$i_{S,i}$	e.g. Income from CHP or hydrogen in year *i*.
	Decommissioning	End of life	$D_{S,P}$	
Source (capture process)	Purchase & construction	Capital	$C_{S,C}$	
	O&M	On-going	$c_{S,C,i}$	
	Energy	On-going	$c_{S,E,i}$	Cost of energy required for capture plant operation – where possible will be treated implicitly as parasitic consumption of generated electricity.
	Decommissioning	End of life	$D_{S,C}$	
Transport	Collection network construction	Capital	$C_{T,NET}$	Only required if multiple sources used.
	Pipeline construction	Capital	$C_{T,1}$	
	Pumping station construction	Capital	$C_{T,2}$	
	Other construction costs…	Capital	$C_{T,3}$…	Other large capital costs (case specific).
	O&M	On-going	$c_{T,OM,i}$	
	Energy	On-going	$c_{T,E,i}$	Cost of energy required for pumping carbon dioxide through pipeline.
	Decommissioning	End of life	D_T	
Disposal	Well drilling	Capital	$C_{D,1}$	
	Well head equipment	Capital	$C_{D,2}$	
	Other construction costs…	Capital	$C_{D,3}$…	Other large capital costs (case specific).
	O&M	On-going	$c_{D,OM,i}$	
	Completion	End of life	D_D	
	Monitoring	On-going	$c_{D,MON,i}$	This cost is unique in that it continue after project completion.
EOR	Equipment	Capital	$C_{E,1}$	
	Transport	On-going	$c_{E,T,i}$	Cost of transporting oil to shore.
	O&M	On-going	$c_{E,OM,i}$	
	Income	On-going	$i_{E,i}$	Benefits from oil sales.

3 Overall structure of the model

The model has two major parts, one that deals with the design of the infrastructure. and a second that considers the operation and overall economics of the disposal network.

The design part of the model is similar to the existing JOULE II model. By considering maximum values of the design giving parameters, it designs appropriate components. Capital costs for those components are then predicted from cost estimating relationships (CERs). The nature of the CERs depends on the specific components. By way of example, the capital costs of a particular type of power station might be estimated using a function of rated power obtained by fitting to real data on power station costs. As the CERs will be developed throughout the project, they will not be further discussed here.

The structure of the 'design model' mirrors that of the physical processes outlined above, in that discrete sections deal with each of the major stages – i.e production, transport and storage. The JOULE II study implicitly assumed that there is a one-way flow of information in the treatment of each component, such that there is no feedback from the reservoir design to the pipeline. While this makes for a much simpler model, it does mean that the designs obtained are not always 'optimal' in that there may be cheaper configurations.

Consider for example the relationship between the pipeline and the reservoir injection processes. Is it better to build a cheap, lower pressure pipeline, but then have to re-compress the carbon dioxide before injection, or should a high pressure pipeline be constructed dispensing with the need for well head compression? It is unlikely that there is a general answer to this question. Rather it will depend on the specifics of each particular case. To answer it requires that the pipeline and the well be considered as an integrated system, with several possible combinations compared. The new model includes a limited amount of 'feedback' of this type to ensure that least cost solutions are identified.

The greatest difference between the new model and previous work (including JOULE II) is the inclusion of some time dependent effects in considering the economics and operation of the capture and sequestration system. Previous work has only considered average parameter values that remain constant over the lifetime of the project. While acceptable for a very first evaluation, there are many potentially important effects that cannot easily be considered this way, such as:

- Substantial variations in oil price part way through the project
- Impact of the rate of carbon dioxide injection on the capacity (or other properties of the storage reservoir)
- Impact of any non-availability of the storage reservoir – for example when switching between storage locations.

In contrast, the new model evaluates parameters over time. An energy production profile must be specified for any power plant, describing the power output at any time over its lifetime. Other potentially time dependent parameters, such as the price for EOR oil, can also be specified as a function of time. The model uses this information to assess carbon dioxide flows, on-going costs, and incomes at instants over the lifetime, and integrates over time to obtain the total values. At this stage it is envisaged that the typical 'time step' for this calculation will be weekly, allowing long term trends in power station utilisation to be analysed. There does not seem to be any fundamental reason to prevent the use of shorter time-steps, perhaps hourly, that would allow differences between say peak and base-load operation to be assessed, but this requires further investigation and may result in impractical, long calculation times.

4 Economic considerations

The over-riding purpose of the model is to place a cost on carbon abatement for various technologies. Such abatement costs can only be considered in a comparative way, that is by citing the *differences* in energy cost and carbon dioxide production per unit of electricity between two or more technologies. By comparing two similar technologies, the additional expense required to produce less carbon dioxide per unit of energy can easily be seen. A commonly used measure is the cost of carbon avoided, that is

$$(CC)_{avoided} = \frac{(COE)_2 - (COE)_2}{(CE)_2 - (CE)_1} \qquad \textbf{Equation 1}$$

where

CC	=	Cost of carbon (dioxide) avoided (£/kWh)
COE	=	Cost of energy
CE	=	Total carbon (dioxide) emissions per kWh (kg/kWh)

and the subscripts denote respective technologies.

4.1 Calculating the cost of energy

The cost model estimates the cost of the major product, the electricity from the power station, using a conventional discounting approach as recommended by the IEA (Nitteberg, *et al.* 1983) to produce a levelised energy cost. How representative such values are of 'real world' costs is open to debate, but they are generally accepted as a reliable mechanism of comparing the economic performance of electricity generating technologies. The calculation is relatively complicated due to the need to account for EOR and parasitic electricity consumption.

To achieve this, a value must be put on the secondary products, such as EOR derived oil, hydrogen or low-grade heat. The model accounts for that fact that production and prices may vary over the course of a year. If the instantaneous rate of oil production is $y(t)$ units per second, and the current oil price is $p_O(t)$ the income in year i is given by

$$i_{E,i} = \int_{t_i}^{t_{i+1}} y p_O \, dt \qquad \textbf{Equation 2}$$

where t_i is the time at which the year starts and t_{i+1} is the beginning of the following year. The annual income figure can be used directly in a conventional cash flow analysis. Income from CHP or hydrogen production can be considered in a similar way.

The capture and sequestration equipment will consume electricity 'parasitically'. Power used at the power station site will be taken at 'no cost' from the local generator, and the station net output power adjusted to account for this. Power for offsite equipment, such as pumping stations, injection etc. will be sourced externally, and both the cost and carbon implications of this should be accounted for. In principle the electrical costs could be included with the yearly costs of EOR, transport etc, but it is safer to consider them separately as this externally generated power has carbon dioxide implications. The parasitic consumption will vary with the rate of carbon dioxide production at any time.

With a test discount rate *d* and project economic lifetime *L*, the net present value of the whole project is given by:

$$NPV = .-C_s - C_T - C_D - C_E - \sum_{i=1}^{i=L} \frac{c_{S,i} + c_{T,i} + c_{D,i} + c_{E,i}}{(1+d)^i} - \sum_{i=1}^{i=L+N} \frac{c_{D,MON,i}}{(1+d)^i} - \frac{D_S + D_T + D_D}{(1+d)^L}$$

$$.+\sum_{i=1}^{L} \frac{i_{S,i} + i_{E,i}}{(1+d)^i} - \sum_{i=1}^{L} \frac{c_{T,E,i} + c_{D,E,i}}{(1+d)^i}$$

Equation 3

where N is the number of years beyond project completion that reservoir monitoring must be maintained, and C_T , C_D etc. represent the sums of relevant capital costs listed in table 1. The levelised energy cost is therefore

$$COE = \frac{-NPV \times CRF}{E}$$ **Equation 4**

where the capital recovery factor is given by

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1}$$ **Equation 5**

and E is the average annual energy production.

4.2 Annual electricity production

The annual electricity production is required for calculation of the cost of energy. It is unlikely that the plant utilisation will remain constant over its lifetime. A power delivered 'regime' $P_{net}(t)$ will be defined for each case representing how the net power output of the plant varies over its lifetime. This is not intended to represent short term changes in output due to grid fluctuations, but rather the effect of longer term changes in use. For simple analysis, this can be a constant value. The average annual power output of the plant is then given by

$$E = \frac{\int_0^L P_{net}\, dt}{L}.$$ **Equation 6**

where *L* is measured in years. The actual power generated by the plant P_G will in general be larger than that delivered to the grid, due to parasitic power P_P drawn by the carbon dioxide capture equipment. Knowledge of the parasitic energy consumption is required, and for each power plant considered a relationship must be developed that allows it to be calculated from the power supplied to the grid.

4.3 Estimating carbon dioxide emissions

For a conventional fossil fuel power station combustion is by far the largest source of carbon emissions. With non-fossil technologies, the major source of carbon emissions is usually the energy expended in their construction and eventual decommissioning. For completeness, the methodology within the cost model will be programmed to account for construction/decommissioning emissions as well as those from fuel, even though the former will be relatively small in most cases. Where there is significant offsite parasitic consumption the associated carbon emissions must be accounted for also.

The carbon dioxide released from energy production depends on the overall efficiency of the power plant and the nature of the fuel burned. For each type of power plant considered, an overall efficiency curve as a function of power output must be formulated $\eta(P_G)$. This, together with the composition of the fuel and the power generation regime described above can be used to estimate the carbon dioxide produced over a period. If possible, a relationship giving the concentration of the carbon dioxide in the flue gases as a function of power output should also be formulated, although in general this will not vary too much.

Carbon dioxide capture equipment is not completely effective, and there will always be some atmospheric emissions. For each capture technology considered a function must be developed giving the capture effectiveness $\eta_{cap}(Q_c,X_c,\ldots)$ as a function of the throughput of carbon dioxide Q_c, concentration in the flue gases X_c and any other specific factors. The carbon dioxide captured and emitted can then be calculated.

Estimating the carbon dioxide due to construction is difficult, and this requires further investigation. Ideally relationships would be developed giving the released carbon dioxide as function of power plant rated capacity, but is over ambitious in the time available here. The EXTERNE project (2000) is a useful source of further information. Carbon dioxide will also be emitted during the construction of other parts of the system including the pipeline and the well, but accounting for this seems to be entirely impractical. Operation and maintenance activities will also release further carbon dioxide, but again these seem to be very difficult to account for and are probably best neglected.

The total lifetime carbon dioxide emissions associated with the plant are given by

$$T = T_f + T_D + y_{fuel}\int_0^L \eta_{cap}\eta P_G\,dt + y_{ext}\int_0^L P_E\,dt + \sum_{i=1}^{i=L+N} T_{O,i} \qquad \textbf{Equation 7}$$

where

T_f	=	CO_2 emissions during construction
T_D	=	CO_2 emissions during decommissioning
y_{fuel}	=	CO_2 emissions per unit of energy from combustion
$T_{O,i}$	=	Other CO_2 emissions in year *i*
y_{ext}	=	CO_2 production per unit of externally sourced electricity
$P_E(t)$	=	External electrical power consumption (by pipeline etc) as function of time

The lifetime average carbon dioxide emissions per net unit of electricity are then given by $\frac{T}{LE}$.

4.4 Application to new build power plant.

Where an existing power station is fitted with carbon capture equipment, the obvious approach is to compare emissions and costs 'before and after' (although there are some complications here as discussed later). With new build, the way to proceed is less clear. One option is to have a reference plant, and quote all carbon avoidance costs relative to the reference. This works well where a range of similar technologies are being compared internally within a project. It is less convenient when making reference to external work, for example comparing the benefits of carbon sequestering fossil fuel plant with the life cycle CO_2 emissions of renewables. Such comparisons require extra computation, converting the externally source values into the adopted 'reference' frame.

It is more sensible to compare two technologies of interest directly. For this reason it is proposed avoid the use of a reference plant and instead quote two order of merit figures for the new build plant considered in this project – the cost of energy and the carbon dioxide emissions per unit of net output. It will be left to the user of the data to compare these results to other technologies.[1] Explicitly presenting the cost of energy for carbon sequestering plant also allows a more ready assessment of viability of such plant in the wider energy market. This in turn makes the policy implications much clearer.

A major implication of this approach is that it is not possible to quote general results along the lines of 'the cost of carbon abatement by using technology Y rather than technology X is …' Instead, all statements of abatement cost include specifics about the types of plant being compared. This however is just a reflection of the practical economics.

4.5 Application to refit power plant

As already noted, the obvious approach here is a 'before and after' comparison to evaluate the cost of energy increase due to CO_2 sequestration. However on closer inspections matters are more complex. A particular concern is that the net electrical output of any retrofitted plant is lower than that of the original plant. There is a strong argument that only plants of the same output should be compared, as any difference would have to be made up from other unknown generating capacity, with equally unknown carbon implications. Of course in practice this is exactly what would happen, but comparing plants of identical output provides certain 'purity' to the results and avoids any need to consider other technologies. As such it seems appropriate to adopt this approach.

To achieve this, any retro-fitted plant must somehow be scaled to match the electrical output of the original un-fitted plant, with consequent impacts on cost and carbon emissions. In the JOULE II project, a simple linear scaling was employed wherein the

[1] It is advisable to avoid quoting cost of energy estimates in public documents, as this can be the source of much unnecessary controversy. Thus in practice, carbon abatement costs, compared to (as yet undefined) reference cases will be quoted in any external documents.

emissions and costs of the retrofitted plant were increased by a factor P_1/P_2 where P_1 is the rated power output of the original plant and P_2 is the rated output of the same plant with sequestration. So long as the parasitic losses from the plant are not too high, this linear scaling is a reasonable approach. It would be preferable to 'design' a retro-fitted plant with the same power output as the original using the cost model to 'fit' storage equipment to a larger initial plant. The resulting costs and emissions can then be used directly.

In summary, retro-fitting existing plant is assessed by comparing plant pairs with the same net rated electrical power. Where possible, this has been achieved by using the cost model to scale up the original plant when sequestration is fitted. In other cases the JOULE II linear approach will be used.

A further issue is how to deal with the capital cost of the original plant when comparing the costs of carbon storage with alternatives such as closing the power plant and building renewable capacity. In both cases the cost of the power plant is 'sunk' and has to be paid by the operating company whatever decision is made[2]. A fair comparison of carbon storage with the alternatives then requires that the original costs of the power plant are neglected, and the technologies compared using only the additional capital costs and the whole on-going costs.

5 CO_2 sources

5.1 Approach

The existing model includes a limited set of 'fixed' power station designs. All necessary values, such as costs, efficiency and carbon dioxide output have been precompiled. There is very little explicit modelling of the power station sources.

The new model maintains a minimalist approach, as there was insufficient time to develop detailed thermodynamic models of power stations. However some more sophistication than the JOULE II model was desirable, and in particular the ability to estimate parameters as a continuous function of rated power output. In cases where this was difficult to achieve, a series of fixed rated powers across a range of interests was used.

For simplicity the model relies on a parametric approach, wherein values are estimated using straightforward functions, obtained for instance by fitting to data. A separate set of functions was required for each combination of power station and storage technology, although some simplification has been possible. There are two types of information that must be estimated. Firstly, for the design phase of the model, information about the overall cost and performance of the power station and capture equipment as a function of its maximum output power, or other appropriate parameter, is required. Secondly, for the operation 'simulation' and on-going cost evaluation phase of the model, functions allowing the fuel consumption and carbon dioxide production to be calculated are required. For each CO_2 source considered, the following must be estimated as a function of the parameter(s) in brackets:

- Construction cost (station rated power)
- Construction time (station rated power)
- Overall conversion efficiency (instantaneous output power)
- Annual plant O&M costs (rated power, average utilisation)

[2] It will be assumed that a closed plant has no significant realisable value.

- Carbon dioxide concentration in flue gas (instantaneous output power)
- Flue gas flow rate (instantaneous output power)
- Capture equipment costs (Maximum carbon dioxide throughput, CO_2 output conditions)
- Capture effectiveness (Carbon dioxide concentration in stream, flue gas flow rate,…?)
- Capture O&M costs (Maximum carbon dioxide throughput, average utilisation,…?)
- Onsite parasitic electrical power consumption (carbon dioxide concentration in stream, flue gas flow rate)

The essential feature is that the listed parameters can be estimated. Furthermore there is no requirement that the relationships are analytic – functions that rely on interpolation between data points are quite acceptable.

It was not originally intended to deal with fuel transport costs explicitly, however this is important for some of the studies. This presents many complications. Firstly, it is difficult to estimate fuel transport costs without drawing up very specific proposals. This is not sensible for a forward-looking project. What will the transport network will be like in 20 years time? Secondly it is not easy to identify what costs should be included, particularly where fuel is imported from outside the EU.

A good compromise has been to adopt the (idealised) viewpoint of the operator of an isolated plant. The model supposes that fuel can be delivered to the UK at a competitive price (else why is the supplier bothering?) and only models transport costs from the point of delivery to the power station. For coal it was assumed that bulk shipping can deliver coal to a nearby suitable port for the 'market' price, and a distance related cost added on to account for transport to the power station. It is impractical in the first instance to incorporate detailed modelling such as differences between road and rail cost and multi-modal transport.

With gas, moving the plant has an impact on the cost of constructing a pipeline. This is difficult to deal with in a general way, particularly since gas may be imported via a large international pipeline with costs shared between many participants. Rather than getting entangled with such complications, it was assumed that gas can be delivered to a limited number of points on the UK coastline for the 'market price', irrespective of the real source. An estimate of the cost of constructing a pipeline from the coast to the power station location will be calculated, along with appropriate annual on-going costs. These estimates will be based primarily on distance. While somewhat idealised, these approaches allow the impact of location to be studied without too much loss of generality.

Fuel transport will of course result in significant carbon dioxide emissions. However it is not proposed to account for these in the analysis, which appears to be standard practice in all previous studies surveyed. Including such emissions would be complex, but will be considered towards the end of the project if time allows.

If carbon dioxide is taken from a single power station the rate of supply is likely to vary over time with plant outages, variations in demand etc. The model does not consider significant facilities for temporary storage beyond a small quantity of buffering, perhaps amounting to one day's production, necessary for reliable operation of the pipeline network. The rate of carbon dioxide disposal must therefore always be less than or equal to the instantaneous rate of production. As discussed in section 7, fluctuations in carbon dioxide production may therefore influence the ultimate capacity of the repository. With EOR, where oil prices play a strong role in the overall economics, there may be further impacts particularly if periods of low carbon dioxide supply coincide with high oil prices and vice versa. With a network, rather than a single carbon dioxide source, production fluctuations will tend to ‘average out’ but there may still be some impacts. The model allows a carbon dioxide production profile to be specified on a daily basis, so that these effects can be studied in detail. For a power station, the carbon dioxide production profile follows directly from the daily electricity production profile, and representative data will be developed for each type of station considered.

It is not necessary to sequester all the carbon dioxide produced by a source. There may be circumstances in which sequestering only a proportion of the carbon dioxide has advantages. Consider for example a source that in general produces only 80% of its maximum carbon dioxide output, only exceeding this during a few days each year. In such cases it was decided that it was better to construct a storage scheme that can only deal the 80% maximum production, and accept that on a few occasions there will be direct carbon emissions. The model therefore includes provision for partial capture and storage.

5.2 Cases to be considered

The following cases are considered:

Existing Large CCGT (similar to Teesside Power Station)
Retro-fitted with chemical (MEA) CO_2 recovery
Approx rated power range: 1-2 GW

Existing PFCC (similar to Ratcliffe-on-Soar)
Retro-fitted with MEA CO_2 scrubbing
Approx rated power range: 0.6-1.5 GW

New-Build GGCT with a range of capture technologies including end pipe MEA both with and without flue gas recirculation.

New-Build IGCC with integral shift-reactor and chemical CO_2 recovery
Approx rated power range: 0.6-2GW

Central collection of carbon dioxide from a number of point sources.
In this case it was assumed that a range of industries that produce carbon dioxide collaborate in carbon storage, including one station chosen from the types outlined above. The cost implications for the power station were examined for a range of gross CO_2 flow rates. It was assumed that the cost of CO_2 recovery for the other producers is born by those producers alone and that other costs are shared according to the total quantities of CO_2 produced.

In all cases the costs associated with fitting NO_X and SO_X controls were included where necessary.

6 Carbon Dioxide Transport

The old model considered only a simple straight pipe, with pumping stations at intervals determined by pressure losses. A single unit cost was used for onshore pipes and offshore pipes, and pumping stations were assumed to have a fixed cost. Energy requirements for any pumping stations were estimated from the flow rate and pressurisation of the carbon dioxide.

The general approach of the original model has been maintained, but with enhancements. A better theoretical basis for the pipe design has been formulated, estimating the required diameter from rigorous theory. The approach has been extended to include determination of the need for, design of, and energy consumed by pumping stations.

Table A2.2: Terrain types

Terrain type	**Description**
Urban	City centre
Suburban	Outer regions of city
Obstacle	Crossing a fixed obstacle such as major road or river
Flat Rural	Lightly populated areas with few hills
Hilly rural	Lightly populated areas with gentle hills (eg rural Northamptonshire)
Very hilly rural	Lightly populated areas with substantial hills (e.g. pennines)
Mountainous	Terrain dominated by large hills
Beach	Beach, usually only built on as means of access to the sea.
Near Shore	Offshore, but within ~5km of land
Offshore	>5km from land, but still significantly sheltered
Far Offshore	Offshore, subject to full force of marine conditions

Since pipelines are of quite some significance in this study, a slightly more sophisticated means of estimating their cost has been required. Several types of terrain have been defined, as shown in Table 2.2. A cost per unit length has been determined for each terrain, dependent on the pipe diameter and depth (including on surface). The model user is able to specify a pipeline routine in terms of section lengths and the type of terrain passed through, using an interface similar to that suggested in Figure 2.2.

Section No	**Length (km)**	**Terrain**	**Depth**	**Diameter**	**Cost**
1	10	Urban	15	(Calculated automatically)	
2	15	Suburban	15		
3	0.5	River Crossing	20		
4	16.4	Flat rural	10		
5	12	Mountainous	10		
6	5	Flat rural	10		
7	1	Beach	30		
8	10	Offshore	40		
9	60	Offshore	100		

Figure 2.2 : Example of pipeline interface

Pipeline diameters has been determined automatically by considering the impact on the construction cost and the energy consumed in pumping to minimise the NPV of the pipeline and its operation, although the construction cost is dominant. Separate diameters have been defined for onshore and offshore portions of pipelines, as the breakdown of costs are very different and there are advantages in having a smaller diameter offshore.

Pumping stations are inserted automatically to maintain pressure. More sophisticated costing of the construction of pumping stations proved difficult, as there are few analogous existing structures. However, it was possible to produce cost estimates for construction in each of the terrain types (including connection to electricity in remote areas). The overall cost of the pipeline depends significantly on the location of the stations, and so a simple optimisation routine tries out various combinations of locations to produce the cheapest result. It is immediately clear that offshore pumping stations will be prohibitively expensive, other than at the disposal site itself, and have not been included in the model.

Energy requirements for operating pumping stations have been determined by considering the work that must be done to repressurise the fluid. As discussed in the economics section, it has been assumed that this energy is purchased from outside generators.

Developing original capital cost functions for pipelines is difficult, due to sparsely available data. A recently published IEA report (Woodhill engineering Consultants, 2002) has developed a fairly detailed cost model for carbon dioxide pipelines, and the new model has drawn heavily on this work for cost information. The engineering calculations differ substantially however.

7 Storage Reservoir

7.1 Approach

The model considers the following types of disposal site

- Offshore and onshore saline aquifers in UK waters,
- Offshore gas fields in UK waters,
- Offshore oil fields in the North Sea, optionally including enhanced oil recovery.

In all cases the possibility of including a 'hub' making use of multiple locations of CO_2 storage is available, since smaller sinks may not be large enough to make the economics attractive.

In each case costs have been accounted for as follows:

- Drilling costs, for creation of appropriate injection wells. These are predominantly be a function of depth, with a fixed mobilisation cost,
- Cost of injection plant, including additional pressurisation etc.,
- Cost of an offshore facility, either platform or seabed mounted depending on local circumstances, except where EOR is employed,
- Costs of constructing and operating a local CO_2 disposal system in the case of a 'hub' system. There are also multiple drilling and plant costs in this case,
- Energy costs in operating the injection plant,
- Cost of maintaining the disposal system during active storage, estimated as a percentage of the construction cost,
- Cost of monitoring, both during and for a period after active storage of carbon dioxide.

Where enhanced oil recovery is employed, it has been assumed that the oil can be transported to the shore using the existing infrastructure from the original exploitation of the oil field. It has also been assumed that the injection plant can be integrated with the existing offshore platform, removing the need for construction of an entirely new facility.

7.2 Injection model

In the present context, injection has been taken to mean process from the end of the transport pipe up to and including entry into the geological store. The major conceptual issues specific to injection include:

- The number of wells required for any reservoir,
- The diameter of the wells,
- The need for additional compression equipment, and if required, the injection pressures to be used,
- The maximum flow rate of the carbon dioxide injection, which could potentially be limited by the gas delivery rate or by the physical properties of the well or storage medium,
- The impact of the well bottom pressure, flow rate and the number of wells on the maximum usable storage capacity of the geological formation.

Most of these issues are closely interlinked and the often only sensible way to choose between competing options is by means of their cost impact. For example the cost of drilling two smaller wells will be greater than that of a single large well, but may be justified if it allows a greater storage capacity to be realised. Equally, using additional compression at the well-head is expensive, but may be worthwhile if additional gas can be stored extending the lifetime of the reservoir. While cost must be the deciding factor, in both these examples the physics of the injection process also plays a vital role. This is true generally, and in some cases the physics will dominate the decision, perhaps limiting the maximum flow rate from a well and making multiple wells the only option to deal with the expected flow rate of carbon dioxide. Clearly it is desirable that the injection process is ‘simulated’ in some way within the model to allow trade offs to be examined.

The old JOULE II model adopts a simplified version of a methodology due to Hendricks and Blok (1993) which considers only the maximum injection flow rate achievable without additional compression at the well-head, given by the heuristic expression:

$$q = \frac{\rho_r}{\rho_c} \frac{2\pi k h}{\ln\left(r_e / r_w \right) \mu} \Delta P \qquad \textbf{Equation 8}$$

where

q	=	Volume flow rate
k	=	Reservoir permeability
h	=	Reservoir thickness
ΔP	=	Overpressure of injection fluid above reservoir pressure
μ	=	Viscosity of carbon dioxide in reservoir
ρ_r	=	Density of carbon dioxide in reservoir
ρ_c	=	Density of carbon dioxide under stabilised conditions.

The number of wells required was determined by dividing the expected rate of carbon dioxide delivery by maximum injection rate. The capacity of the reservoir was assumed to be independent of the injection mechanisms, and the pressure at the well bottom was calculated without any consideration of the flow process within the well itself.

Hendricks' approach, as detailed in the published version of his thesis (Hendriks, 1994), is very similar to that described, but takes some account of the flow processes in the well which cause the enthalpy of the carbon dioxide to rise at it descends. Hendricks assumes that the flow of the gas through the well is adiabatic. Since the descent can take several minutes this seems rather unlikely, and it is notable that other authors assume it to be isothermal. In practice the injection process is somewhere between the two, but fortunately the details do not have a great impact on the wider issues.

Of more importance are the processes when the injected gas leaves the well and enters the geologic formation. Many studies have found that the rate of injection (and by implication the well bottom pressure) has an influence on the total amount of carbon dioxide that may be stored in the reservoir, although the nature of the impact is open to debate. It would be valuable to include these effects in the model, but to do so in general would require numerical simulation of the injection process, which was not practical in the time available. There are two possible ways to proceed:

1. Information on the impact of injection rates/processes for particular storage locations could be provided by other participants (BGS) and/or obtained from the limited literature. This data could be used directly by the model. This method has many advantages, but may be limited by the availability of information
2. A simple simulation of the injection process using analytic or semi-analytic solutions of the flow equations. It would have to be assumed that the reservoir was homogenous and of simple geometry, but this will be insignificant compared to other approximations in the model. Recent publications (Saripalli and McGrail, 2002) suggest that this approach can provide quantitatively useful information.

Both these approaches are entirely compatible with the simple time dependent 'simulation' used in the production and transport parts of the model.

For each individual reservoir to be considered, at least the following data was required:

- Geographic location,
- Nominal total storage capacity (i.e. free volume within reservoir),
- Reservoir depth,
- Reservoir geometry (areal extent & thickness),
- Water depth (if offshore),
- Nominal surface temperature,
- Local geothermal temperature gradient,
- Local (hydrostatic) pressure gradient,
- Local seabed conditions (if available),
- Permeability.

If the impact of injection conditions on the storage capacity is included using the second approach outlined above then some further information will be required for each reservoir considered. It is not possible to be specific until the necessary theory has been fully developed.

A further issue for aquifers is dissolution of the injected carbon dioxide within the water they contain. The JOULE II model (following Hendricks) ignores this, using a displacement approach wherein it is assumed simply that water is replaced by supercritical carbon dioxide. If the analytic calculation of the injection process proves viable then it is relatively straightforward to calculate the quantity of carbon dioxide in aqueous solution from the pressure distribution within the aquifer and simple equilibrium considerations.

7.3 EOR Model

EOR is difficult to model accurately, and a first principles calculation as discussed above for aquifer storage is entirely impractical. The approach used in the original JOULE II model has been maintained, which simply considers the displacement of oil by injected carbon dioxide. The extraction of oil from a reservoir was treated as taking place in three phases:

- Primary production wherein oil is produced under reservoir pressure alone.
- Secondary production, where extraction is increased by means of injecting water or gas to maintain pressure.
- Tertiary production, or enhanced recovery, where liquid carbon dioxide is used to dissolve trapped oil.

It is assumed herein that the total carbon dioxide disposal volume, $V_{disposal}$ available is equal to the sum of the volumes of oil extracted in the primary and tertiary phases, such that:

$$V_{disposal} = (P + E)V_{OOIP} \qquad \textbf{Equation 9}$$

where

P	=	Primary production fraction
E	=	Tertiary production fraction
V_{OOIP}	=	Original oil in place

It has been assumed that carbon dioxide disposal begins during the secondary oil production phase, simply filling the voids in the reservoir. If *c(t)* is the instantaneous disposal rate of carbon dioxide per second, which may be a function of time, the duration of the first injection phase L_1 (when no EOR takes place) is given by

$$\int_0^{L_1} c\, dt = PV_{OOIP}\,. \qquad \textbf{Equation 10}$$

It is desirable that this first injection phase continues until just before the primary and secondary oil production fractions are exhausted and EOR based tertiary extraction is ready to begin. If the instantaneous rate of oil extraction from the reservoir at any time is *e(t)*, then tertiary production is ready to begin at time t_1 after the opening of the reservoir such that

$$\int_0^{t_1} e\, dt = (P + S)V_{OOIP} \qquad \textbf{Equation 11}$$

otherwise there will be a temporary cessation either in oil production or carbon dioxide disposal which will have a negative impact on the economics.

The fate of the oil recovered and its impact (if any) on the global oil market must also be considered as this may influence the overall balances of the system. It will be assumed here that the enhanced oil production has no net impact on oil consumption and hence that no additional carbon dioxide is produced as a result. In view of this assumed neutral impact on the overall oil market, the EOR oil produced is sold on the open market without influencing the oil price. The income from this sale in any period was calculated following Equation 2. As already noted, the carbon dioxide injected was treated as simply displacing the oil extracted by EOR and thus the total volume 'exchanged' during this second phase of storage is

$$\int e\,dt = \int c\,dt = EV_{OOIP}\,. \qquad \textbf{Equation 12}$$

A proportion of the carbon dioxide injected into the active reservoir escapes with the extracted oil and must be recovered, recompressed and re-injected. There are additional capital and on-going costs associated with this that must be included in the calculation. The carbon dioxide escapes at atmospheric pressure p_{atm} and must be re-compressed to the injection pressure p_{inj}. The energy required to recompress a kilogram of the carbon dioxide is

$$\int_{p_{atm}}^{p_{inj}} \frac{dp}{\rho} \qquad \textbf{Equation 13}$$

which was evaluated numerically using the state information for carbon dioxide described elsewhere. The total recompression energy requirement over any period of operation is therefore

$$\frac{\rho_0 r_r}{\eta_c} \int_{t_1}^{t_2} e\,dt \int_{p_{atm}}^{p_{inj}} \frac{dp}{\rho} \qquad \textbf{Equation 14}$$

where

ρ_0	=	Density of carbon dioxide at atmospheric conditions
r_r	=	Recycle ratio: volume of carbon dioxide released per volume of oil from EOR
η_c	=	Compressor efficiency (assumed constant)

and as with the pipelines it has been assumed that this is supplied as electrical energy purchased from an external source. It is not clear what to use as the unit price of this electricity. Since it will be supplied offshore, it is not appropriate to use the same market price as taken onshore. Most likely the electricity will be taken from the general supply for the offshore rig, and further work is required to determine a representative value. There will also be carbon dioxide emissions associated with the energy consumed, but again further work is required to determine a realistic value.

To model EOR, the following geological information is required for each reservoir therefore:

- Original quantity of oil in place,
- Primary, secondary and tertiary (EOR) production fractions,
- Lifetime *or* oil extraction profile (quantity as a function of time) for primary and secondary extraction phases.

7.4 Monitoring

This is a very uncertain area of carbon dioxide disposal. Any projects will require provision for monitoring in order to present a credible safety case. There will be capital costs for monitoring equipment, but more likely to be significant are the on-going costs as the monitoring may need to be maintained for decades.

Monitoring was ignored by the JOULE II project, and there is hardly any useful quantitative information in the literature. Costs though are likely to scale with the size of the carbon dioxide store, simply because larger reservoirs will require more monitoring equipment. In the absence of better information, the monitoring equipment costs and the annual monitoring costs were taken as small fractions of the capital cost of constructing the carbon dioxide repository.

Another very uncertain point is how long the monitoring operation must be maintained. There are two issues that influence the minimum period. Firstly, how long must the carbon dioxide be contained in order to ameliorate climate change? If the carbon dioxide begins to escape very slowly in the distant future, will this be of any significance? Slow leakage when the immediate problem of climate change has passed is unlikely to matter, and there is no need to maintain monitoring beyond this point. Secondly, after what period can we conclude that the carbon dioxide is permanently stored and very unlikely to ever escape? It would be reasonable to stop monitoring after the shorter of these periods.

The discounted cash flow methodology means that far future costs have little impact on the overall economics of a scheme. Using a discount rate of 5%, and assuming equal annual monitoring costs, more than 99% of the cost contribution due to monitoring is captured by restricting the calculation to 100 years. Since we have not used discount rates lower than 5%, the monitoring was treated as lasting only 100 years.

Prolonged monitoring is undertaken to detect any unexpected failure in carbon dioxide containment, presumably with the intention of taking corrective action if anything untoward should be detected. The cost of any such action is likely to be very high and in principle some provision for this should be included in the overall costing of the scheme. There are many problems with this, particularly since the quantity of resource set aside (presumably in the form of an on-going insurance premium) should be determined with respect to the risk of failure. Carbon dioxide disposal technology is extremely immature and hence making quantitative estimates of the risk of failure is almost impossible. Furthermore, it is also possible that governments may underwrite the risk of future failure. In view of these uncertainties, the model takes no account of the costs of possible future reservoir failure.

8 Treatment of uncertainties

Most of the data employed in this project is subject to considerable uncertainty. This is particularly true of cost data, where the objective is to estimate costs for currently unrealised equipment. With the calculations intended to influence investment decisions, knowledge of the uncertainty inherent in results is almost as important as the results themselves. It is essential that the uncertainty in the cost model predictions is considered from the outset therefore.

There are two basic approaches to dealing with such uncertainty. One is to develop a deterministic model where every parameter has a definite value, and then accommodate the uncertainty using Monte Carlo' type multiple evaluations. This has several advantages, particularly in simplification of the model development, but complicates subsequent use. The alternative method is to accept from the outset that data is uncertain and treat all data as having a Bayesian style degree of belief probability density function (PDF) rather than a distinct value. An advantage of this approach is that all results are then produced as PDFs themselves and it is easy to consider the implications of their inherent uncertainty.

The cost model broadly adopts the second approach. In particular all cost values were treated as a PDF, and all cost predictions presented as PDFs. The PDF methodology was only partly extended to include physical (as opposed to economic) parameters, as there are considerable difficulties in implementation for some types of scientific calculation.

9 Parameter studies

The cost model has a stand-alone value, and also must feed into the later stages of the project. The model has been used to investigate:

- Cost of energy, carbon emissions and hence carbon abatement costs,
- Major design parameters for the 'least cost' solution i.e. detailed breakdown of costs, pipeline diameters and pumping station requirements, outline reservoir configuration,

for the following cases:

1. Combinations 'base case' power station and reservoir options.
2. Advanced technology carbon dioxide sources – the details of this are still to be determined – in combination with the base case sinks.
3. Impact of location changes for both the source and the sink, including fuel transport costs.
4. Impact of pipeline routings. For the base case combinations at least three pipeline routings will be considered with varying degrees on (perceived) environmental impact.
5. Impact of carbon dioxide source parameters, including rated power station size, utilisation factor, power station efficiency.
6. Impact of reservoir parameters including size, permeability, quantities of oil available in each phase of production, water depth.
7. Impact of 'external' parameters including electricity price, initial fuel price, oil price (for EOR), other energy prices (e.g. hydrogen and heat where applicable), and including outline consideration of the level of carbon taxes required to make sequestration commercially viable assuming it is exempt from such taxes.

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Annex 3

NW Case Study: Supporting Information

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The following information was sent out to all respondents to the NW England Case Study (Chapter 7) prior to the interviews.

Carbon Capture and Storage (CCS)

There is growing consensus that significant reductions in CO_2 emissions are required in order to avoid or lessen the impacts of climate change. The United Kingdom could significantly reduce its emissions while continuing to use fossil fuels by removing carbon dioxide from large point sources (such as power plants and industrial sites) and storing the carbon in geological structures, including on and offshore oil and gas fields and saline aquifers.

The CO_2 would be transported from its point of capture to the storage site by pipeline. CCS could act as a bridging strategy while longer-term solutions are further developed, such as renewable energy technologies. Although CCS has not yet been adopted in the UK, a site off the Norwegian coast has been storing a million tonnes of CO_2 per year since 1996. CCS is also used in the USA for Enhanced Oil Recovery (EOR) (discussed below).

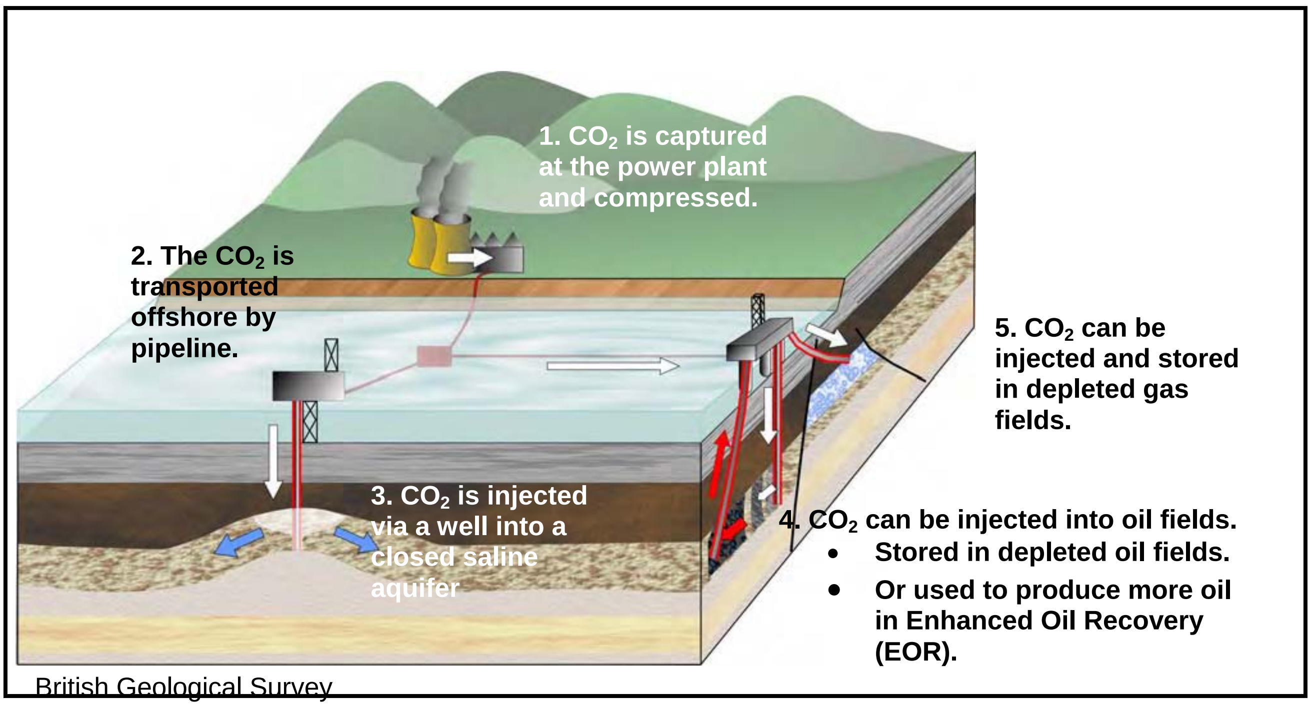

Figure A3.1 A Schematic Illustrating Carbon Dioxide Capture and Storage

Options for storing CO_2 in the UK

Storage in Oil Fields

CO_2 is injected into oil fields. It remains in the oil field and thus is prevented from reaching the atmosphere.

Storage in Oil Fields with Enhanced Oil Recovery (EOR)

CO_2 is injected into producing oil fields, which increases the oil production of that field. In the process the CO_2 is stored. Because of the increase in oil production, this technique could offset the cost of CO_2 storage and provide some of the infrastructure required.

Storage in Gas Fields

CO_2 can be stored in depleted or depleting gas fields, which have already been proven to store gases over hundreds of thousands of years. In some case injecting CO_2 into gas fields can also produce more gas

Storage in Saline Aquifers

A saline aquifer is rock containing minute spaces which are filled with sea water, a bit like a sponge. Some saline aquifers have the required criteria for CO_2 storage. CO_2 would be injected under pressure into the geological structure. The reservoir rock must be deeper than 800m as under these conditions CO_2 is like a dense liquid (therefore it occupies less space underground). Once injected the CO_2 displaces the sea water that occupies pore spaces. Under its own buoyancy the CO_2 rises to the top of the reservoir and becomes trapped under an impermeable layer called a caprock.

Potential Storage Timescales

The potential storage capacity off the coast of the North West is approximately 3450 million tonnes (MT) CO_2. The North West currently emits approximately 64MT CO_2 per annum. Around one third of this comes from large point sources with the potential for CCS. Therefore, at current levels, CCS could continue for over 160 years before CO_2 would have to be "exported" from the region.

Energy Scenarios

The scenarios offer five different visions of the energy system for 2050. They are not predictions, rather possible futures that, given their diversity, will allow a wide ranging discussion of CCS and energy issues.

All the scenarios are based on achieving the 60% reduction in emissions by 2050. They also all assume that there is no reduction or increase in demand. Capacity is increased in some of them to allow for the intermittency of renewable sources.

Wind energy in the scenarios

Wind farms that are under consideration or have been consented to under round 1 and round 2 have a cumulative proposed capacity of 2,200 MW. In some scenarios e.g. Renewable Generation it is assumed that all of these projects are completed, in others e.g. Fossilwise it is assumed that they were abandoned due to public opposition.

Annex 4

Scenario data for EMYH Case Study

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The summary data presented in Chapter 8 (as presented to stakeholders) for the EMYH scenarios is based on more detailed background quantification. In this Annex we present the complete list of scenario data as it was presented to participants to the MCA and underlying data on which the scenarios are based.

A4.1 The Energy Supply Scenarios

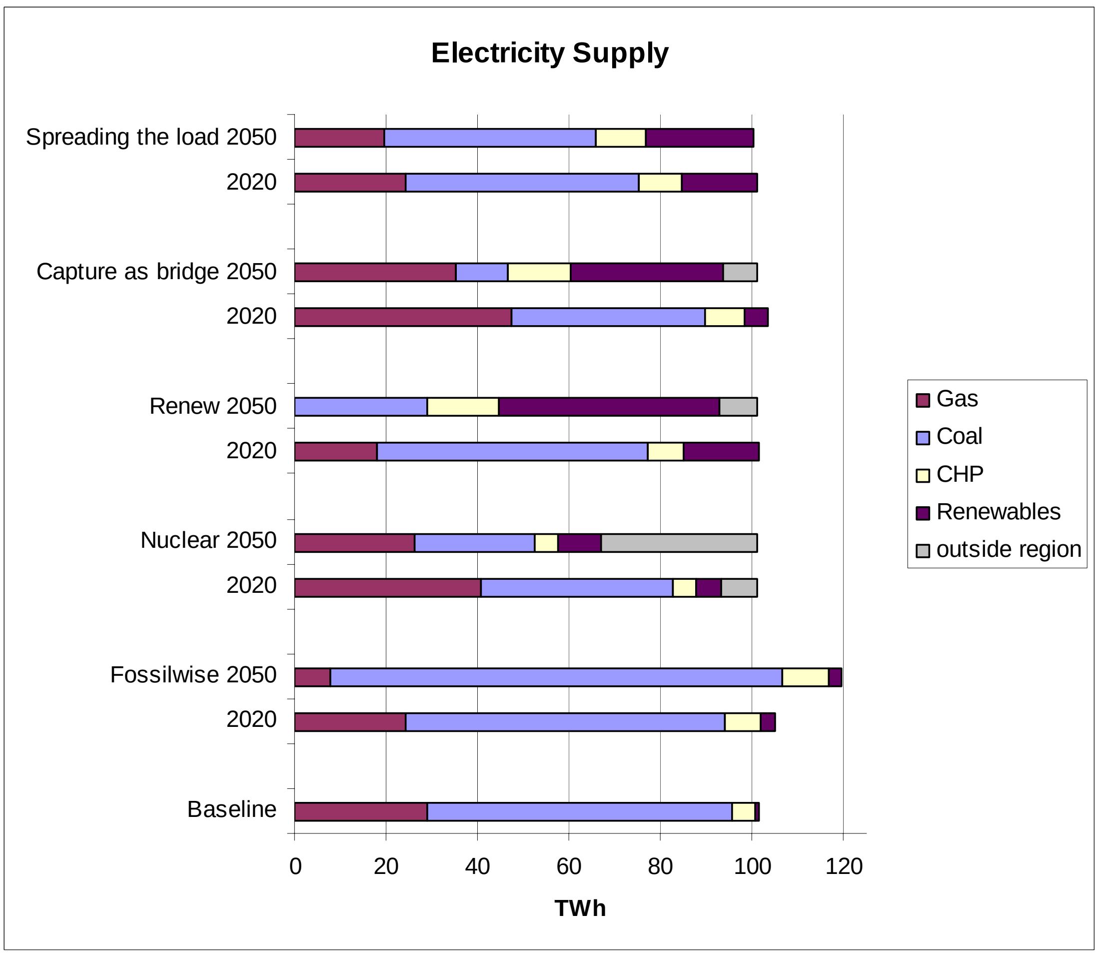
In this section we present the material relating to the energy supply mix in the scenarios that was circulated to all stakeholders participating in the MCA process for the East Midlands and Yorkshire and Humberside (EMYH) Case Study Area. In addition to this information, participants were also given maps showing CO_2 storage sites used in the scenarios; thee are not presented again here since they are included in full within Chapter 8.

East Midlands and Yorkshire and Humberside

These scenarios only consider the electricity generation sector for the case study region in 2020 and 2050. No assumptions are made about other demand sectors and demand for electricity is assumed to remain constant at current levels. In each scenario, we have aimed to maintain total electricity generated at current levels. In the case of "Nuclear Renaissance", "Renewable Generation" and "Capture as a Bridge" the total electricity generated within the region falls slightly – as a means of illustrating this we have estimated the implied additional capacity required (assumed to be outside the region) to make up this shortfall; we assume that this additional capacity will be made up of nuclear or renewable generation respectively. We have assumed different rates of technology learning for various technologies across the scenarios – this allows us to incorporate the large range of estimated performance characteristics available in the literature.

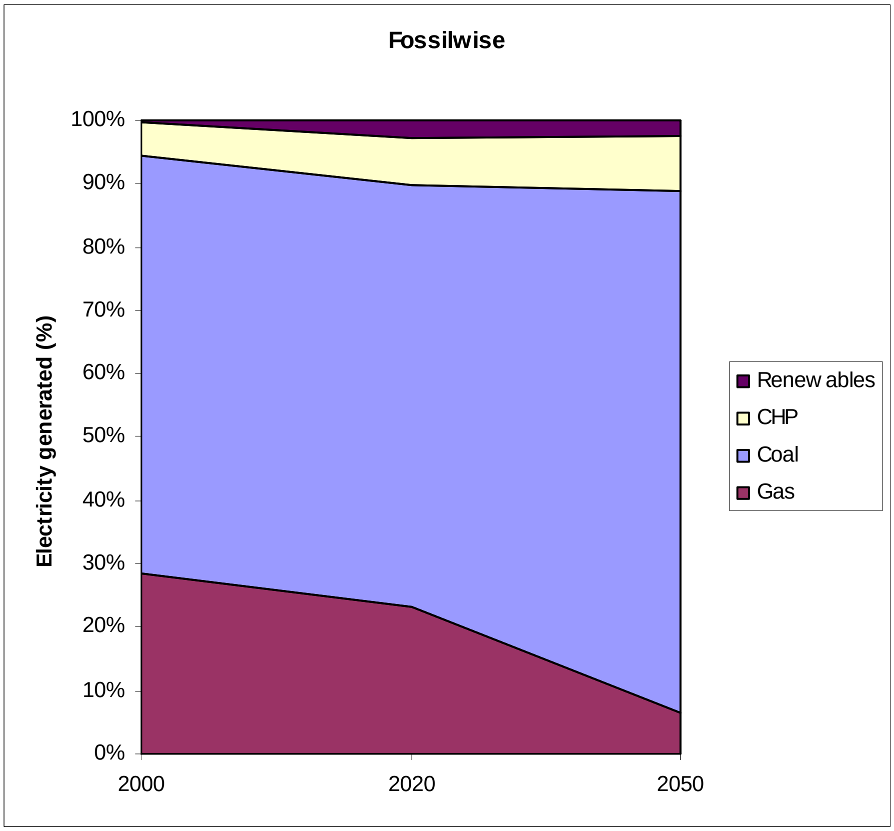
All scenarios assume that CO_2 reduction is a key driver.

A detailed breakdown of electricity supply and emissions is available but here we present a simple overview of each scenario.



Fossilwise

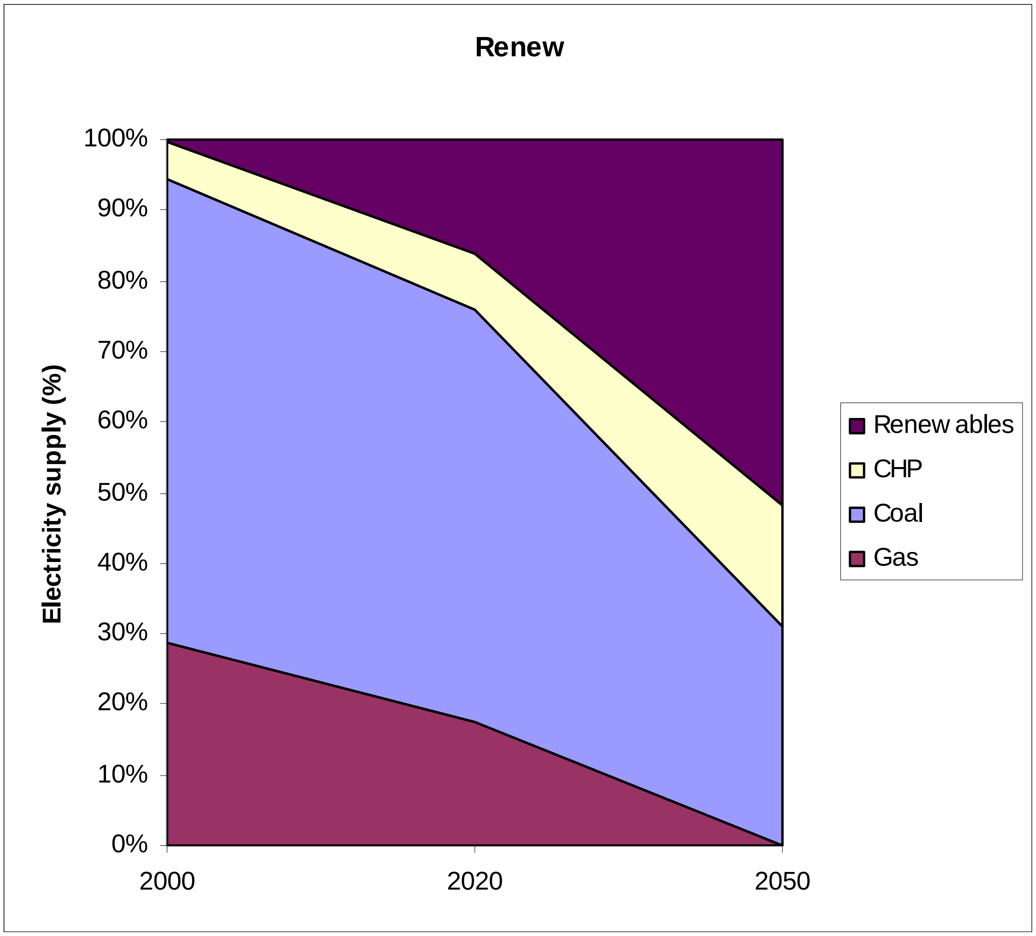
Continued dependence on fossil fuels with carbon capture as key CO_2 abatement technology (storage commencing 2020). Dominant technology within region: IGCC with capture (by 2050)



	Gas	Coal	CHP	Renewables	Total
2000 (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	100%
2020 (GW)	3.8	12.8	2	0.8	19.4
% (supply)	23%	66%	8%	3%	100%
Capture ($MTCO_2$ p.a)					75.8
2050 (GW)	1.2	15	2.6	0.8	19.6
% (supply)	7%	82%	9%	2%	100%
Capture ($MTCO_2$ p.a)					55.1

Renewable Generation

Renewable energy pursued as mainstay of CO_2 reduction. No CO_2 capture, maximum exploitation of renewables, reduction in total electricity generated within the region.

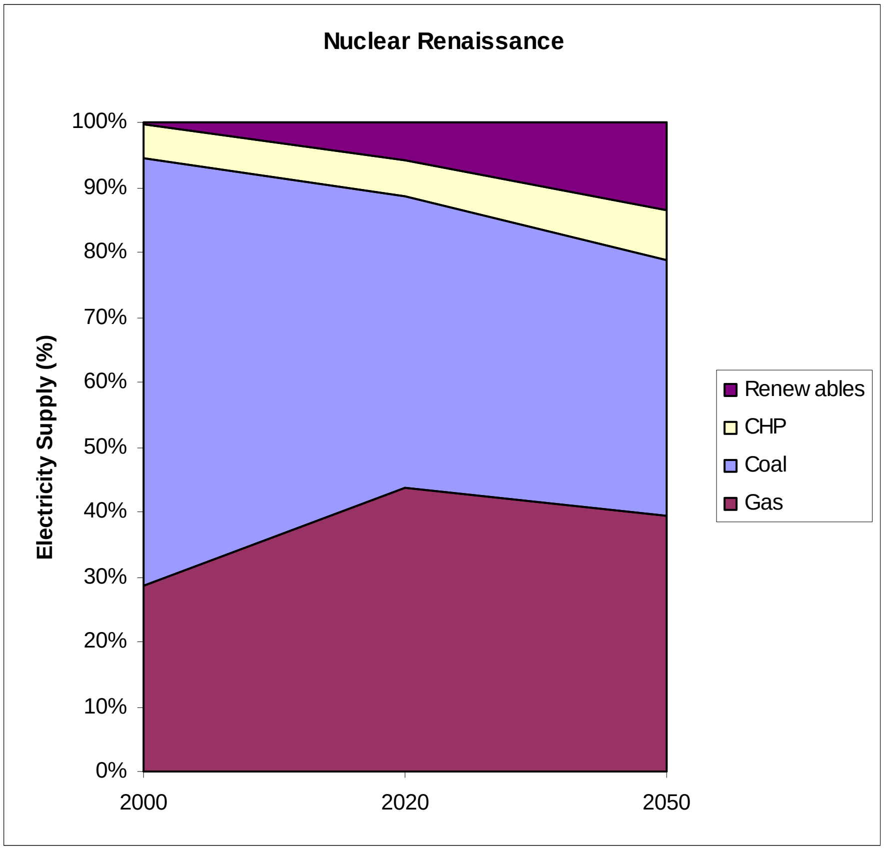


Renew	Gas	Coal	CHP	Renewables	Total
2000 (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	100%
2020 (GW)	2.8	10.9	2	4.5	20.2
% (supply)	18%	58%	8%	16%	100%
Capture ($MTCO_2$ p.a)					*0*
2050 (GW)	0	5	4	11	20.0
% (supply)	0%	31%	17%	52%	100%
Capture ($MTCO_2$ p.a)					*0*

Nuclear Renaissance

Nuclear power seen as key approach to CO_2 reduction. We assume that new plant will be built on existing sites only – of which there are none within the study region; the scenario explores the implications of this to the region.

No CO_2 capture, region provides main Fossil Fuel generation for UK to match increased baseload nuclear outside the region.

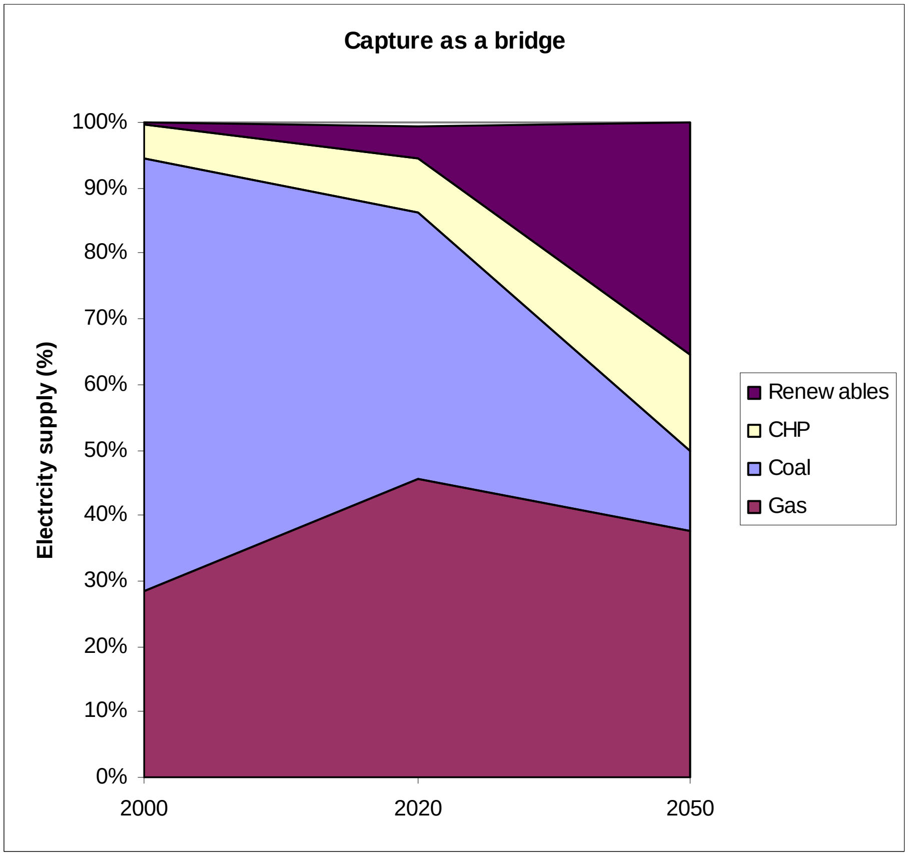


Nuclear renaissance

	Gas	Coal	CHP	Renewables	Total
2000 (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	100%
2020 (GW)	6.4	8.7	1.3	1.5	17.9
% (supply)	44%	45%	5%	6%	100%
Capture (MTCO$_2$ p.a)					*0*
2050 (GW)	5	5	1.3	2.5	13.8
% (supply)	39%	39%	8%	14%	100%
Capture (MTCO$_2$ p.a)					*0*

Capture as a Bridge

Short term approach to carbon dioxide capture (storage commencing 2015) while renewables capacity is built up, existing coal plant upgraded to supercritical pf with capture.

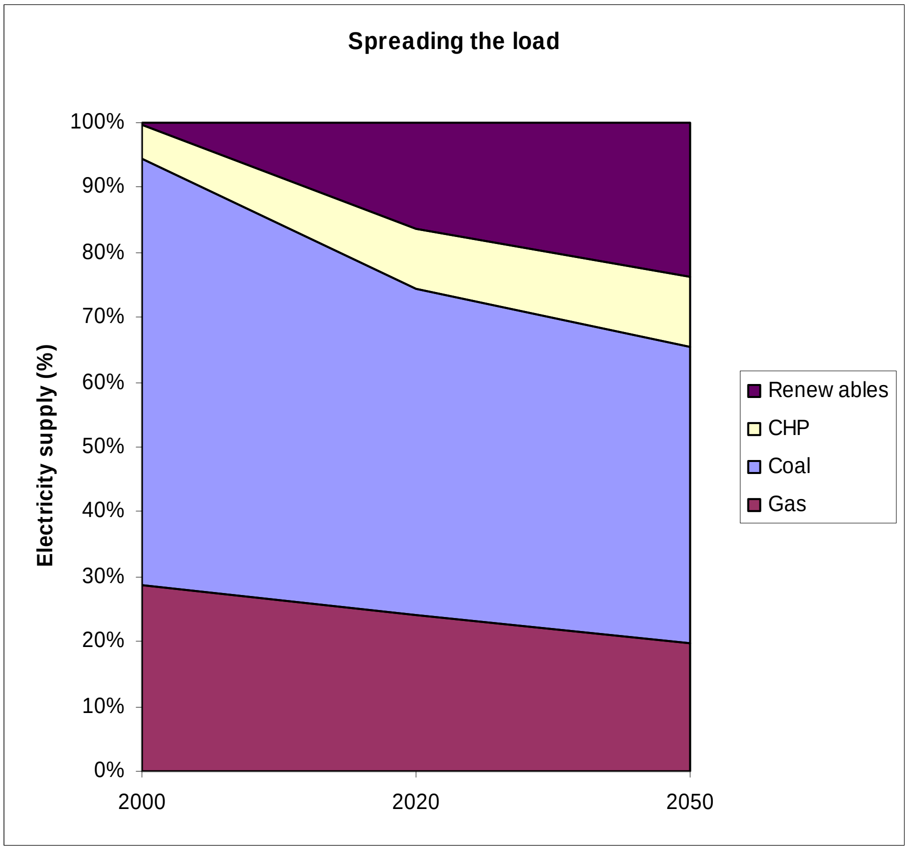


capture as a bridge

	Gas	Coal	CHP	Renewables	Total
2000 (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	100%
2020 (GW)	7.4	8.8	2.2	1.4	19.8
% (supply)	45%	41%	8%	5%	100%
Capture *($MTCO_2$ p.a)*					52.8
2050 (GW)	5.5	2.0	3.5	9.1	20.1
% (supply)	38%	12%	15%	36%	100%
Capture *($MTCO_2$ p.a)*					18.6

Spreading the Load

Broad portfolio, including a greater penetration of renewables and IGCC with capture (storage commencing 2020).



spreading the load

	Gas	Coal	CHP	Renewables	Total
2000 (GW)	4.5	13.8	1.3	0.1	19.8
% (supply)	29%	66%	5%	0%	100%
2020 (GW)	3.8	10.6	2.4	4.5	21.3
% (supply)	24%	50%	9%	16%	100%
Capture *($MTCO_2$ p.a)*					59
2050 (GW)	3.0	7.5	2.8	6.5	19.8
% (supply)	20%	46%	11%	24%	100%
Capture *($MTCO_2$ p.a)*					34

A4.2 Data and Methodology

This section presents the methodology and the data with which the scenarios were developed. The starting point for each of the scenarios is baseline data for 2000 for the two regions – as shown in Table A4.1.

Table A4.1 Baseline data for EMYH region

	Capacity (GW) CCGT	Coal	CHP	Nuclear	Renewables	Total Capacity	Electricity Distributed (TWh)	Electricity Generated (TWh)
Yorkshire & Humberside	4.12	7.9	0.96	0	0.09	13.08	34.36	64.50
East Midlands	1.60	5.94	0.37	0	0.04	7.95	17.31	37.18
Combined Region	5.73 (27%)	13.84 (66%)	1.33 (6%)	0	0.13 (1%)	21.03 (100%)	51.67	101.68

Source: AEAT (2002); DTI (2003a, b); EMRA (2003)

With the aim of maintaining the electricity generated roughly constant generating capacities were increased or decreased according to the rationale for each scenario. For each fuel type, TWh generated was estimated according to the following formula (the totals in Table A4.1 are taken from DTI energy trends):

Equation A4.1

$$\text{Electricity Generated} = \text{Capacity} \; * \; \text{Load Factor} \; * 365 \; * 24$$

Assumptions for load factors are shown in Table A4.2. There is a large variation in load factor between the different renewables technologies (ranging from 0.1 for solar to 0.65 for biomass); the load factor used for renewables is made up of an average for an assumed mix of renewables technologies (shown in Table A4.3); in general this is based on the mix included in the regional renewable energy targets for 2010 (AEAT, 2002; EMRA, 2003) with the exception of the Renewables Generation scenario which uses the data in the column labelled '2050'. The estimates of potential renewable energy capacity in this scenario are informed by the most optimistic estimates available for the two regions (AEAT, 2002; REF, 2002; EMRA, 2003) and assumed improvements in the load factor for offshore wind.

This methodology allows us to take into account parasitic energy losses associated with capturing CO_2; in order to maintain levels of electricity output the capacity is increased to accommodate the associated loss of efficiency. Since CCS equipment has not yet been adopted at a commercial scale, all estimates of its performance characteristics remain somewhat academic. In order to incorporate different opinion from across the literature about how capture technologies might evolve in the scenarios we have used different estimates for thermal efficiency, capture rate and load factor in the two time horizons in each scenario; these are indicated in Table A4.2. (FW: Fossilwise; REN: Renewable Generation; NUC: Nuclear Renaissance; CAB: Capture as a Bridge; STL: Spreading the Load)

Table A4.2. Thermal Efficiency and Load Factors (%)

Scenario	Technology	Thermal Efficiency	Load Factor	CO_2 Capture rate	Source
All	Nuclear		74%		DTI (2003a)
REN old	Coal	36.0%	48%		DTI (2003a)
REN, NUC old	CCGT	46.5%	75%		DTI (2003a)
NUC 2020	CCGT state of art	55.6%	73%		Fluor (2004)
NUC 2050	CCGT 2020	65.6%	60%		Marsh *et al.*(2002)
REN 2050	IGCC	37.5%	66%		Chapter 3, this report
REN 2020	IGCC	45.0%	66%		WCI (2001) / IEA coal
REN 2050	IGCC 2020	50.0%	66%		WCI (2001)
NUC 2020	advanced supercritical	45.0%	55%		King (2004)
NUC 2050	Ultra Supercritical (USC)	55.0%	60%		coal research forum world coal institute
all	CHP	70.0%	45%		DTI (2003a)
all	biomass + landfill		65%		calculated from AEAT (2002a)
all	wind (onshore)		30%		calculated from AEAT (2002a)
	wind (offshore)		35%		DTI (2002)
REN 2050	wind (offshore)		50%		Anderson (2004)
all	hydro		37%		
all	solar		10%		jardine and lane, ECI
All retrofit	Gas MEA	30.0%	73%	90%	
FW retrofit	coal MEA	24.0%	55%	90%	Marsh (2002)
CAB new	USC + capture	40.0%	65%	85%	estimate based on best case 55% minus 15% for capture
CAB old	USC + capture	34.8%	55%	85%	Fluor (2004)
CAB/STL 2020	CCGT + capture	47.4%	73%	85%	Fluor (2004)
STL 2050	CCGT + capture (2020)	56.6%	75%	90%	Marsh *et al.* (2002)
FW 2050	CCGT + capture (2040)	66.0%	75%	90%	Marsh *et al.* (2002)
STL 2020 / FW 2020	IGCC + capture	32.3%	60%	90%	Chapter 3, this report
STL 2050	IGCC + capture (2020)	42.3%	70%	90%	Marsh *et al.* (2002)
FW 2050	IGCC + capture (2040)	49.0%	75%	90%	Marsh *et al.* (2002)

CO_2 emissions are calculated according to the Equation A4.2:

Equation A4.2

$$CO_2 \text{ emission} = [(\text{Capacity} * \text{Load Factor} * 365 * 24) / \text{Thermal Efficiency}] * \text{Emission Factor}$$

CO_2 captured is calculated by multiplying the emissions as calculated above by the removal rate (the remainder being emitted). Emission factors are shown in Table A4.4. It has been assumed that emission from nuclear plant and renewables are zero. The main purpose of calculated emissions in the scenarios is in order to estimate CO_2 available for storage; although emission estimates were shown to most of the stakeholders they the figures were not central to the discussion of the scenarios; thus it was felt that the small underestimate implied by excluding biomass from the emission estimates was acceptable.

Table A4.4 Emission Factors

Fuel type	Emission Factor ($Kg\ CO_2$ / KWh)
Coal	0.29
Gas	0.18

Source: JWGEE (2002)

Table A4.5 and A4.6 show the complete scenario data developed using this methodology. This material was not presented to respondents unless they requested further information or the discussion introduced the need to present the scenarios in greater detail.

Table A4.5 Detailed Summary of scenarios (2020)

	Baseline (2000)	**Fossilwise**	**Nuclear**	**Renewable Generation**	**Capture as bridge**	**Spreading the load**
CCGT proportion generated	*5.7* *27%*	4.8 29%	7.2 47%	4.0 26%	9 57%	4.6 29%
Coal proportion generated	*13.8* *66%*	11.7 60%	8.7 42%	9.9 50%	6.2 30%	9.3 48%
CHP proportion generated	*1.3* *6%*	2.0 8%	1.3 5%	2.0 8%	2.2 9%	2 8%
Renewables proportion generated	*0.1* *1%*	0.8 3%	1.5 5%	4.5 16%	1.4 6%	4.3 15%
Total capacity GW	*21.0*	19.3	19.3	20.4	18.8	20.2
extra GW outside region fuel type	*0*		*0.3* *nuclear*	*0.0*	*0.0*	
Electricity generated within region (TWh)	*102*	105	100	102	101	102
Emissions from power sector ($MTCO_2$)	63.6	10.8	50.4	48.4	12.8	8.6
Annual Carbon captured ($MTCO_2$)	*0*	75.8	0.0	0.0	52.6	59.0
Total carbon captured ($MTCO_2$)	*0*				212	
% CO_2 reduction from regional total		44%	16%	18%	43%	46%

Table A4.5 Detailed Summary of scenarios (2050)

	Baseline	**Fossilwise**	**Nuclear**	**Renew**	**Capture as bridge**	**Spreading the load**
CCGT proportion generated	*5.7* *27%*	1.2 7%	5.9 42%	0.0 0%	5.45 37%	2.95 19%
Coal proportion generated	*13.8* *66%*	15.0 82%	5.0 36%	5.0 31%	2.0 12%	7.4 45%
CHP proportion generated	*1.3* *6%*	2.6 9%	1.3 7%	4.0 17%	3.5 15%	2.9 11%
Renewables proportion generated	*0.1* *1%*	0.8 2%	3.0 15%	11.0 52%	9.1 35%	7 25%
Total capacity GW	*21.0*	19.6	19.6	20	20.1	20.3
extra GW outside region fuel type	*0*		*4.4* *nuclear*	*2.1* *renewables*	*2.0* *renewables*	*0.0*
Electricity generated within region (TWh)	*102*	120	73	93	93	102
Emissions from power sector ($MTCO_2$)	63.6	8.8	24.0	21.1	6.9	6.8
Annual Carbon captured ($MTCO_2$)	*0*	55.1	0.0	0.0	18.6	34.0
Total carbon captured ($MTCO_2$)	*0*	1963			1279	1394
% CO_2 reduction from regional total		45%	35%	37%	47%	47%

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