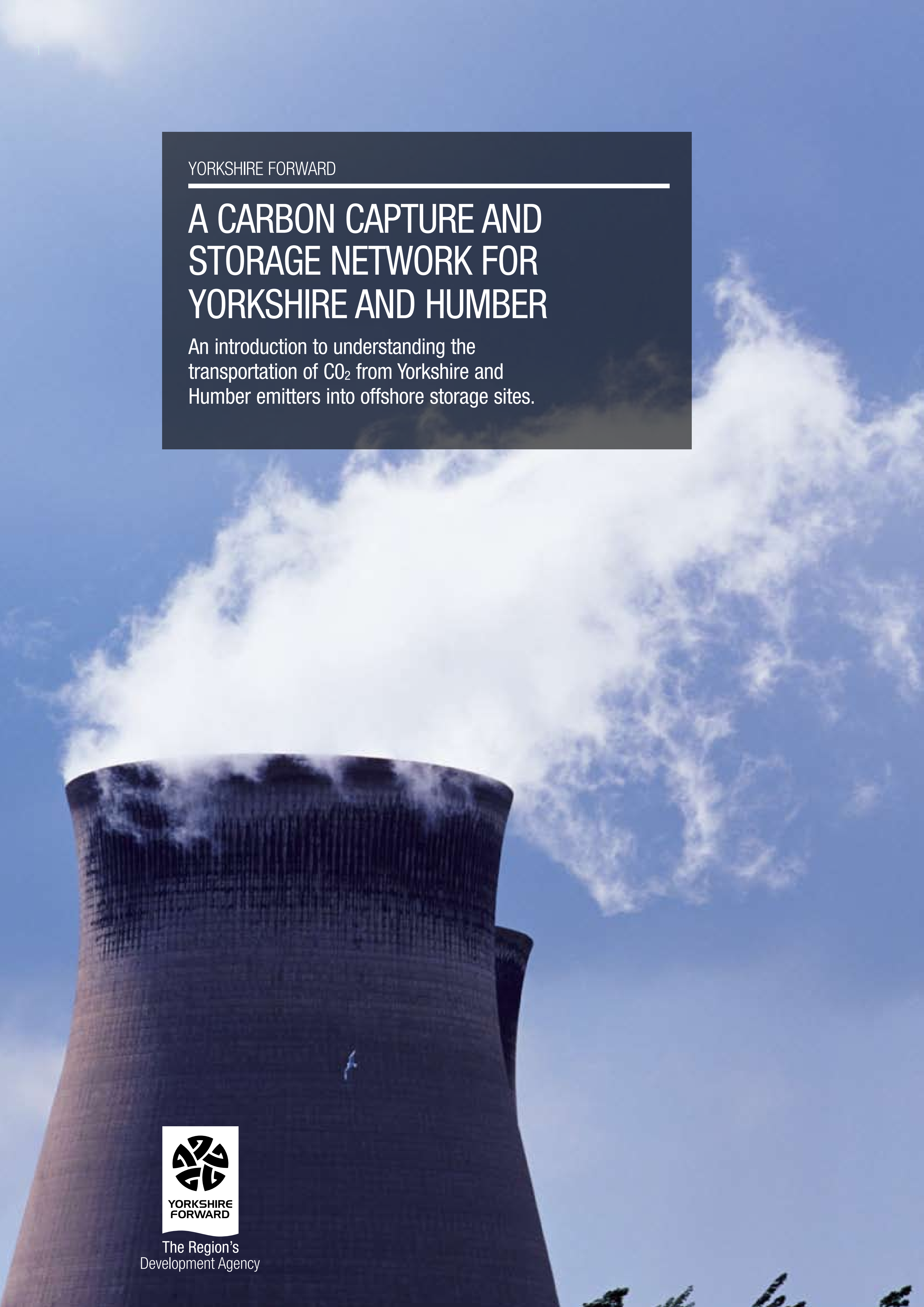
YORKSHIRE FORWARD

A CARBON CAPTURE AND STORAGE NETWORK FOR YORKSHIRE AND HUMBER

An introduction to understanding the transportation of CO_2 from Yorkshire and Humber emitters into offshore storage sites.



YORKSHIRE FORWARD
The Region's
Development Agency

CONTENTS

Tables

Figures

1.0 NON-TECHNICAL SUMMARY

Climate change is a reality that we now have to face. Over the last century emissions into the atmosphere of greenhouse gases has risen exponentially and now threatens to fundamentally change the world in which we live. It is now accepted that this increased growth must be stopped by controlling our energy needs and developing new industrial processes and ways of generating power that emit far less of these harmful gases. The single largest contributor to this change is the level of atmospheric carbon dioxide (CO_2) from use of fossil fuels. It is this gas that is the focus of a global effort to reduce emissions.

The challenge for policymakers and industry is to accelerate deployment of capture technology and developing the necessary transportation and storage infrastructure. Key to this acceleration is in understanding the technical and economical issues of developing infrastructure, and the timeframes involved, in order to allow investment decisions to be made.

The Yorkshire and Humber region produces around 90mt of CO_2 emissions annually, the majority from single point industrial or power generation sources. The region also has a coastline adjacent to the rapidly depleting gas reservoirs of the southern North Sea. This unique coincidence of high levels of CO_2 emissions and proximity to storage sites means that the development of a low cost CO_2 transport network would position the region to be the first and potentially lowest cost user of these depleting gas fields for carbon storage.

Carbon capture and storage (CCS) is one approach that is considered by the Stern Review as essential to provide a lower carbon future. Fitted first to large point sources of CO_2, CCS will allow the continued use of fossil fuels through carbon abatement, until replacement low carbon processes can come to maturity. Therefore CCS is an essential requirement to combat climate change whilst maintaining security of energy supply.

It is important to understand how CCS works and the elements involved. It begins when CO_2 is produced by an industrial process such as burning coal or natural gas. The CO_2 produced is first separated, then normally compressed into a liquid and transported by pipeline to a suitable storage or sequestration site where the CO_2 can be permanently stored. The transport system encompasses compressors, pumps, onshore and an offshore pipeline to deliver the CO_2 to the storage site. This study considers the provision of a transport system for the Yorkshire and Humber region, illustrated by the sections show in blue in figure 1.1.

This work was commissioned under the auspices of the Carbon Capture and Storage Partnership for Yorkshire and Humber. This is a stakeholder group convened by Yorkshire Forward to stimulate the development of a CCS network in the region. The study was managed by a steering group led by Yorkshire Forward with contributions from steering group members.

The study aimed to understand the options for the most economic network for transport of CO_2 to storage from the emitters in the region, based mostly on publicly available data. The area of concern is essentially a rectangle, bound by the coast in the east and Castleford in the west. The northern boundary to the study area is taken as a line across the southern edge of Beverley whilst the southern boundary by a line from the southern edge of Scunthorpe, see figure 1.2. Contained within this area are 12 large emitters plus 10 medium and 14 small emitters. The large emitters alone represent over 60 million tonnes of CO_2 emissions a year, approximately 10% of the total CO_2 emissions for the UK.

The report uses scenarios covering all currently foreseen stationary emitters of over 5 thousand tonnes CO_2/year, and capturing between 33% and 73% of emissions by 2030. The study shows that there is storage available under all scenarios for these emissions out to at least 2050.

To address the health, safety and environmental questions regarding CO_2 transport this study has allowed for the maximum use of existing infrastructure, however further discussions will be required with the Health and Safety Executive and other stakeholders to ensure consent for any new infrastructure. It is fortunate that the area already has much larger and more complex industrial activities which the local community and work force has experience of and can use for comparison when considering this new infrastructure.

The study shows that with an appropriate level of industrial co-operation including the re-use of suitable existing infrastructure, a transport network can be initiated at reasonable cost using existing pipelines to complement the need for new infrastructure. Furthermore, continuing R&D on CCS processes should also enable a reduction in costs.

Currently each carbon capture project has to develop its own transport and storage solution. Earlier studies have assumed that CO_2 transport networks would develop as a matter of course. In reality strategic leadership will be required to bring them to fruition.

On a like for like basis, and with the support of public and private bodies to initiate a network in Yorkshire and Humber, **this study shows that for every emitter linking into a network is more cost effective than a stand-alone solution**. Even for the ideally located emitter with ideal emissions profile, entering a network is the cheapest option and other emitters, both large and small, have higher CO_2 transport costs in the absence of a network.

This study assumes that the current level of industrial activity will continue. However, a viable CO_2 transport network could also attract new economic activity attracting companies seeking a system for safe and cost effective CO_2 transport and storage.

By 2030 CO_2 capture and storage using this network could be adding about £1.2bn per year of economic activity to the region through EU-ETS credits alone.

If the transport network was constructed in 2008 the total investment described in this study has a cost of approximately £2 billion. This excludes the investment in capture plant at the emission source and the storage site facilities, which are not within the scope of this transport study.

The system described in this study could transport approximately 320 million tonnes of CO_2 in total up to 2030, 850 million tonnes in total by 2040, and may store 1,500 million tonnes of CO_2 by 2050. To give a sense of scale 1,500 million tonnes is equivalent to the emissions from all the present cars in the UK for 75 years.

For the central scenario used in this study the average present cost is approximately £1.70 per tonne for all the CO_2 transported by 2040, depending on the assumptions used.

This study presents a cost, as opposed to a revenue model. Therefore, it is not linked to the European Emissions Trading Scheme price of CO$_2$ or financing of the investment in the transport infrastructure. In addition the commercial rate paid by an emitter will depend on how quickly the network grows and how ownership of the network is managed. Of particular importance is the financial cost of the timing difference between expenditure in transport infrastructure and revenue from transporting CO$_2$. For example an early plant unable to share a transport pipeline and linked to one store will have high costs, but strategic coordination of capture plant, pipelines and equipment with shared offshore storage will reduce costs.

The ability to develop a cluster of large capture sites and suitable storage sites will be the key to a successful network. Depleted gas reservoirs must be decommissioned to be available for use as CO$_2$ storage sites. The study area compactly offers a timely combination of these opportunities as shown in figure 1.2.

The study recommends that Yorkshire Forward and other regional bodies promote the development of a cluster of carbon capture ready industrial sites to be an early material action to justify investment in an efficient CO$_2$ transport and storage system, driven by the co-operation by the capture site organisations and regional bodies. The UK government clarifies a process for funding support through an appropriate mechanism to facilitate investment in this clustered approach to CCS deployment. And that Yorkshire Forward commissions a cost benefit analysis to understand the wider economic, social and environmental enhancements that would arise from a region wide CCS network.

In conclusion this study has evolved the work of the North Sea Basin Task Force by focusing on a key region by considering in some detail the CO$_2$ transport component of a regional CCS network. The study provides realistic costs for consideration by government, regional bodies and industry when planning for the strategic options to significantly reduce CO$_2$ emissions in the UK through the development of carbon capture and storage.

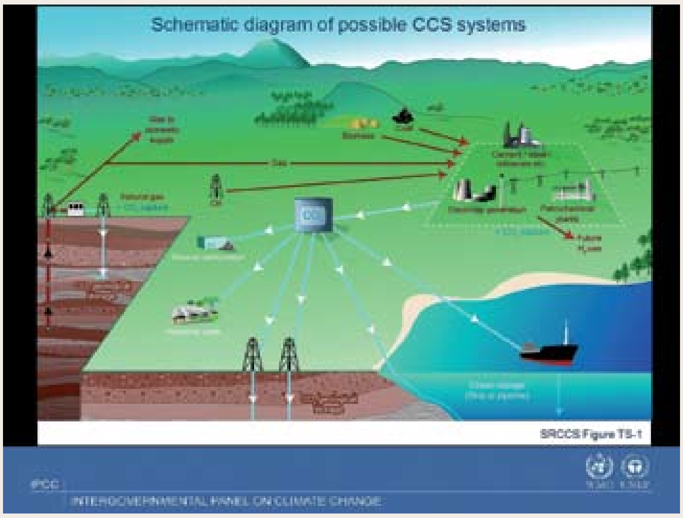


Figure 1.1 Schematic of possible CCS systems

Reproduced courtesy of the IPCC from IPCC Special Report on carbon dioxide capture and storage, page 4 Fig SPM.1

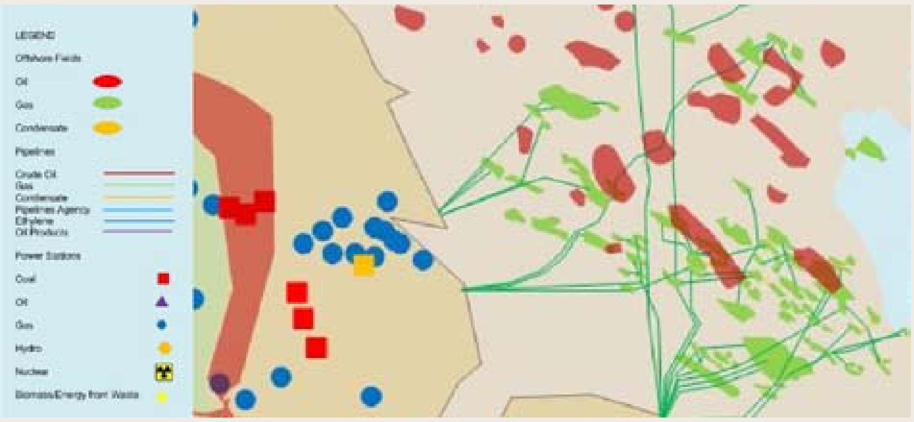


Figure 1.2 Emitters and storage possibilities in the Humber

2.0 INTRODUCTION

Removal of CO_2 from flue gases in power stations or other large single point emitters and storing it underground is potentially one of the most cost effective methods of tackling climate change. The UK government is keen to develop and deploy CCS, and the study area represents the largest cluster of CO_2 sources in the UK. The UK also has an abundance of underground storage possibilities in the form of depleted North Sea oil and gas fields, saline aquifers, salt caverns and disused coal mines.

The Energy White Paper of 2007 [13] highlights two major challenges for the UK; tackling CO_2 emissions and the maintenance of secure and affordable energy supplies. The deployment of CCS is one approach of addressing both challenges and the White Paper makes the case for CCS, particularly in conjunction with cleaner coal power generation. Coal still offers an abundance of relatively cheap, reliable energy that can be sourced from UK and, is likely to remain one of the UK's main sources of power generation for at least the next 25 years.

The Stern Review [1] investigated the impact of climate change on the world's economy. It highlighted that carbon capture and storage has a role in the medium term, whilst alternative energies and industrial processes are given time to develop and mature. To prevent the consequences mentioned in the Stern Review and detailed by the IPCC [6], levels of CO_2 must peak in the near future with concentrations of CO_2 stabilising between 440ppm and 550ppm. Figure 2.1 opposite identifies possible scenarios on global CO_2 emissions. CCS has the potential to contribute up to 55% of the CO_2 mitigations required to ensure that emissions peak early.

Government legislation could drive this market; however, global CCS deployment necessitates a stable, global price for carbon, above the costs required for this technology, to ensure a reasonable rate of return. Applications of CCS to China and India's coal powered plants are crucial to ensure that global emissions peak as shown in the graph.

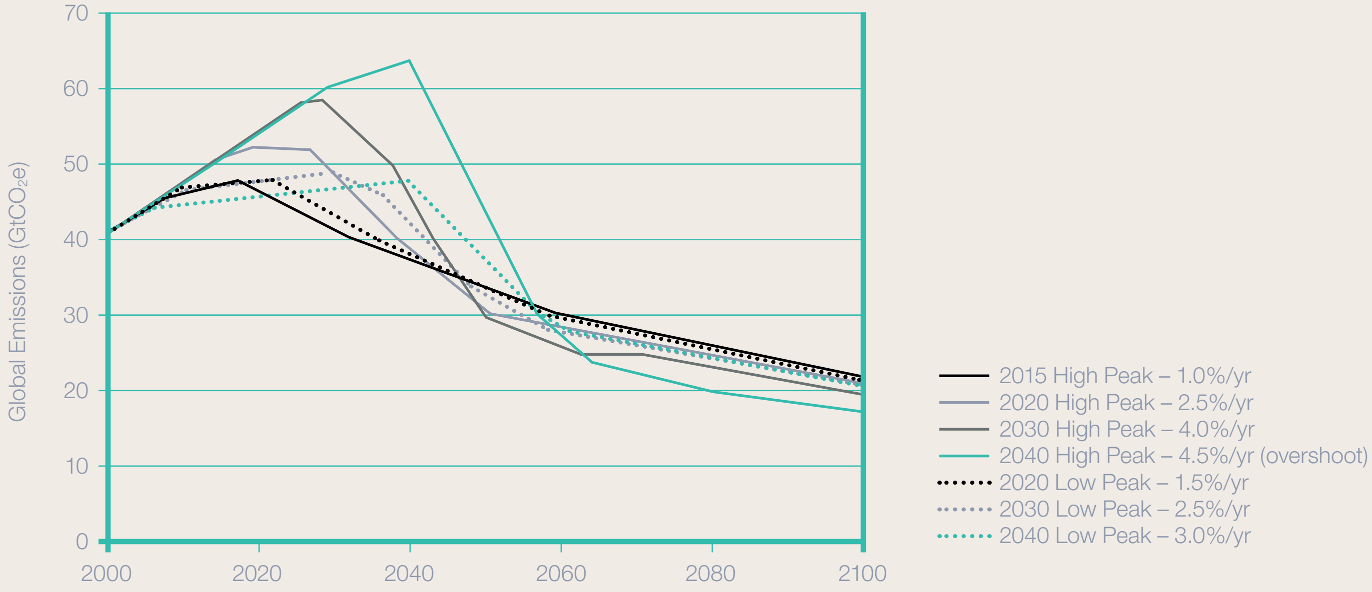
Current methods of extraction can remove around 90% of the CO_2 from flue gases; however this then must be cleaned, dried and compressed for transportation via pipeline to the storage locations. This report will examine the transportation issues and solutions, producing network designs to accommodate various scenarios envisaged, finally arriving at a cost for transportation of the CO_2.

This study arose from discussion between Yorkshire Forward and AMEC, and engagement with the major emitters in the Yorkshire and Humber area and some operators of southern North Sea gas fields, unions, and other interested parties.

A meeting of the Carbon Capture and Storage Partnership for Yorkshire and Humber led to this work, funded by Yorkshire Forward with contributions from AMEC, ConocoPhillips, Corus, Drax Power Ltd, E.ON UK, Hydrogen Energy, Power Ltd, Scottish & Southern Energy plc, and Shell. A steering group to oversee the study comprised these organisations and the TUC. The steering group was chaired by Yorkshire Forward.

The work builds on a previous study done for the International Energy Authority Greenhouse Gas R&D Programme (IEA GHG) which included discussion of a potential network for the Mersey-Dee area on the west coast [14]. The model used for that study was used with kind permission of IEA GHG, with additional analysis. It differs by more economic analysis, doing stepwise development of the network through time under different growth scenarios, and multiple offshore storage constraints.

Figure 2.1 Global emission scenarios



3.0 SCOPE OF WORKS

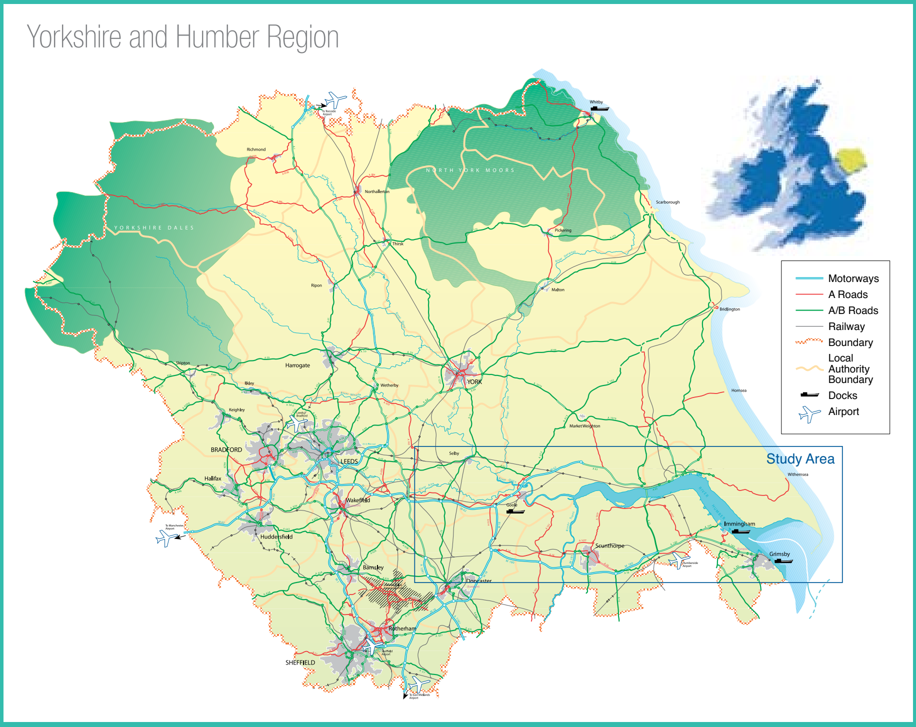


Figure 3.1 General study area

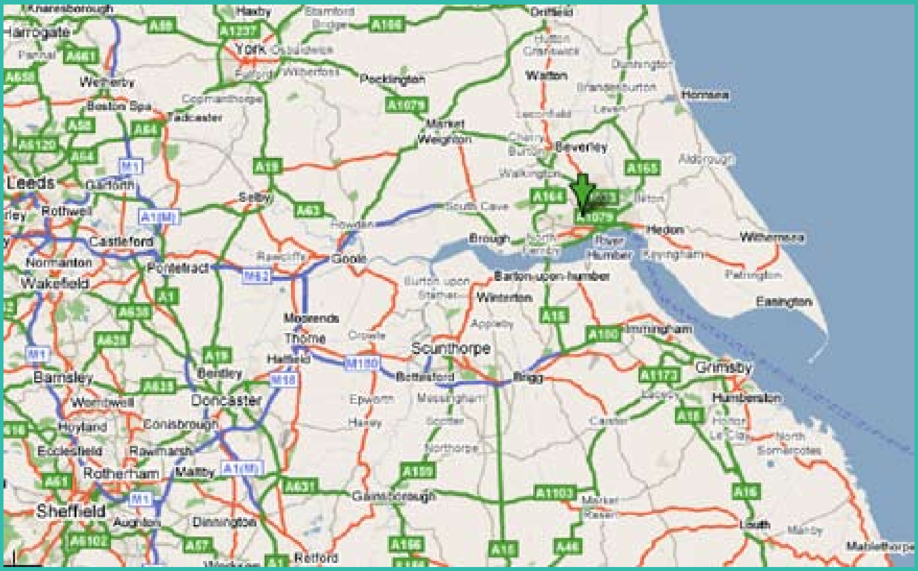


Figure 3.2 Study area with Tier 0 emitters and existing gas terminals

3.1 INTRODUCTION

The scope of this project and subsequent report is summarised in three aims:

- Develop the most economic network to transport available CO_2 emissions from stationary emitters in the region from capture to permanent storage.
- Provide CO_2 emitters an effective route to storage that is on balance (cost, safety, environmental consenting, planning approvals, public perception, timely) more attractive to them than a standalone solution.
- Create a network group to mutually inform members, execute work including studies and public engagement and generate collective value that is jointly owned.

As a first step to achieve these aims a number of tasks were undertaken:

- Data collection for the region
- Discussion with emitters and storage site owners
- Evaluating storage solutions
- Develop a technical basis for gas quality entering the system
- Develop network scenarios
- Model and cost the network.

3.2 STUDY AREA

The area indicated in figure 3.2 represents the catchment area for the stationary emitters of CO_2. This area falls within Yorkshire Forward's boundaries and contains the main clusters of large emitters in the region. The area around Immingham and Grimsby has a high concentration of emitters in the form of refineries, steelworks and power stations. Three large coal-fired power stations, located along the M62, are also captured in this study area. The steel plant at Scunthorpe also lies within the study area. The Humberside area, figure 3.1, is considered feasible for carbon capture and storage as it has a large amount of emitters located close to possible storage sites.

Table 3.1 Definition of Tier emitter classifications

Tier Classification	Emitter Size (Generalisation)	Emitter Range Tonnes CO_2/year	Typical Emitter Types
0	Large	+1 million	Coal fired power station Major hydrocarbon refinery Major steel works Large CCGT power station
1	Medium	50,000 to 1 million	Chemical, glass, food processors, large CHP & power stations CCGT power station
2	Small	1,000 to 50,000	CHP units, hospitals, Varied Industrial process

Figure 1.2 shows the location of the larger emitters (over 1mtCO_2/year) in the study area. Large thermal power plants are indicated by red squares and blue dots, whilst the purple squares represent possible future projects. Non-energy producers of CO_2 are shown in orange. Yellow dots shown indicate potential export points; both shown are Easington (northerly) and Theddlethorpe (southerly). Although the existing pipelines and gas export facilities will not be utilised, it was assumed that it would be easier to obtain planning consent if the proposed pipelines crossed the coast at the same point.

3.3 TIERED SOURCES

3.3.1 Division by emitter flow

Emitters can be ranked by their allowances allocated under the EU-ETS. This allows the consideration of an area in terms of not only size of emitter but also the capability and economic ability of an emitter to join a transmission network. This methodology was previously used in a project for the International Energy Agency (IEA GHG) [14] to test a network design and costing programme. Table 3.1 shows the definitions applying to the classification of an emitter by size, and a detailed list of emitters can be found in Appendix B.

In considering a network and how emitters can connect to it a number of factors must be considered including the size of the emitter, the capacity to capture and transmit CO_2, and the location of the site. Small emitters such as hospitals will not necessarily have the technical capability to operate complex compression equipment for example. By applying tiers to the emitters in any area a simple but coarse measure can be applied and some sources, even whole tiers can be discounted.

It may be more appropriate for Tier 1 and 2 sources to be part of a suction system, transmitting low pressure CO_2 to a central collection point such as larger capable Tier 0 or Tier 1 sites.

A map of the location of the emitters in the region is included in figure 3.1 and Appendix A.

3.3.2 Tier 0 sources

Sources with volumes of CO_2 greater than 1mt/year are categorized as Tier 0 sources. Sources of this magnitude in this area are power stations, refineries and steel works. Carbon capture and storage is most economical in Tier 0 sources due to large amounts of CO_2 available for capture, as well as the availability of land at these sites for extraction units. There are 12 such sources for this study.

3.3.3 Tier 1 sources

Sources with volumes of CO_2 ranging from 0.05mt/year to 1mt/year are categorized as Tier 1. These include power and CHP plants, chemical producers, cement & lime works, large food & drink producers and glassworks. Extraction and conditioning of CO_2 from most of these sources is considered less economic and there is less drive to reduce CO_2 emissions below Best Available Techniques (BAT).

3.3.4 Tier 2 sources

Those ranging from 1kt CO_2/year to 0.5mt CO_2/year are Tier 2 sources. These smaller emitters include local small power generators, services, hospitals, food & drink manufacturers as well as small chemical producers. The relatively small amounts of CO_2 produced at these sites make them uneconomic or unpractical for CCS, furthermore most are scattered throughout the area, or located in densely populated areas, making transportation of the gas problematic.

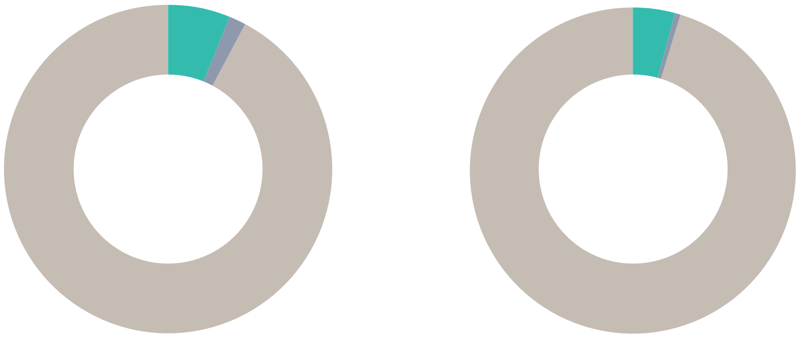
3.3.5 Proportion of emissions

Emissions taken from the EU-ETS have resulted in the following proportions shown in the chart below. The current bulk of the emissions, 92%, are from Tier 0 sources and only 8% from combined Tier 1 and Tier 2 sources, figure 3.4a. Adding future proposed programmes changes this proportion to 95.4% for Tier 0, figure 3.4b. This suggests that the trunk line could be sized to accommodate the Tier 0 emitters, as there is little impact from smaller emitters joining the network.

Figure 3.3 Emitter locations in study area

A larger version of this drawing can be found in Appendix A

Figure 3.4 Proportion of emissions



Tier 1: 6.17%
Tier 2: 1.73%
Tier 0: 92.09%

(a) Current proportions of emitters in study area

Tier 1: 4.23%
Tier 2: 0.67%
Tier 0: 95.10%

(b) proportion of emitters in study area, including known future projects

3.4 STUDY PERIOD

This report considers the development of a CCS network over the period of 2013 to 2030. This study period was agreed upon by the steering group, based on a number of factors. These being:

- Perceived lifetimes of new builds and existing emitters and the proposed timescale for new builds in the area.
- The range of dates that coincide with the availability of depleted gas fields in the southern North Sea.
- CO_2 capture may become a broadly commercially attractive proposition during this period as, for example, the EU-ETS matures and CCS is demonstrated.
- That the perceived impact from new technologies (such as nuclear fusion) has little effect on emissions in this area over the specified study period.

3.5 HYDROGEN NETWORK

The steering group wished to review the interaction of transport of CO_2 and hydrogen because of the possible production of the economic production of de-carbonised hydrogen in the context of developing CCS for other reasons.

The production of hydrogen occurs during the capture of CO_2 in the pre-combustion process, see figure 4.1, where CO_2 is separated before hydrogen and air is used for power production. The hydrogen can be simply processed and piped rather than used immediately once it is produced. This enables large quantities to be made available for other users.

Comparing the spending for hydrogen production, supply and vehicles with the savings to be gained from replacing conventional fuel and conventional vehicles over time, the simulations of the EU HyWays project [9] predict that the break-even point would be most likely reached between 2025 and 2035. There are a wide range of applications for hydrogen; in 2030 there may be 16 million hydrogen cars and the total cumulative investment for infrastructure build-up will amount to €60 billion. This report [9] states that “CCS technologies extends the time available to develop a full and durable solution for a sustainable power and fuel provision. The use of hydrogen in electricity production will broaden the sectors where such a carrier can be used in a sustainable way. It will provide the opportunity to utilise the advantages offered by hydrogen as demonstrated in the transport sector, enabling the power sector to diversify its feedstock’s with very low CO_2 emissions.”

There is another comment that for the UK besides production of hydrogen from natural gas, biomass and wind energy, nuclear energy was seen as an option as was the use of coal. The report showed that the production of hydrogen from fossil fuels using carbon capture and storage could make a significant contribution to reducing CO_2 emissions. Furthermore, the introduction of hydrogen into the energy system offers the opportunity to increase the ratio of renewable energy, and help the large-scale introduction of intermittent resources such as wind energy through its use as a temporary energy storage option.

De-carbonising the fuel is one solution to the mitigation of CO_2 emissions. Sources of pure hydrogen are already located in the area in the form of refineries and steel works. Steel works and refineries are also major hydrogen customers. There are a range of applications for hydrogen in other industrial processes but to date there is no reason to capture the CO_2 by-product except for some relatively small uses. The advent of CCS opens the possibility of a new low carbon energy vector at a significant scale.

Whilst the transport and domestic fuel sectors are longer term, the shorter term opportunity for CSS is its use in the power industry, to supply de-carbonised fuel to neighbouring CCGT’s and CHP plant via a local pipeline. There are fewer drivers for extraction of CO_2 from CCGT’s, for reasons covered in section 4.2, and many existing turbines will not be convertible to run purely on hydrogen. Replacing burners and utilising suitable gas turbines will enable a number of power stations to burn a percentage of piped hydrogen with natural gas, thus eliminating the need for a discrete carbon capture unit.

Developing a wider hydrogen pipe system on the back of the CO_2 network may be a cost effective development of these new market opportunities, and will gradually link to the “hydrogen highways” concepts which is suggested to extend north to Teesside.

We have found it too early to be specific about the scale of a viable network, but recommend that the issues of a shared way-leave between CO_2 and H_2 pipes be understood and, for certain routes, way-leaves are designed with this option in mind.

3.6 EU FLAGSHIP PROGRAMME FOR CCS

To enable commercial deployment of CCS by 2020, the EU plans to partly fund 10 to 12 full-scale CCS demonstration projects, all to be operational by 2015. To maximize the benefits of this scheme, the selection criteria will be based on:

- Plant process and capture technology
- Method of CO_2 storage
- Transport and communications infrastructure
- Related public
- Risk profile

The scheme envisaged that 10 to 12 x 400MW power plants would require a total funding of €6 to €10billion investment, based on a Capital Expenditure range of 1500-2300€/kW [15]. This programme could provide funding for a ‘cluster’ of large emitters, initiating the Yorkshire and Humber CO_2 network.

4.0 YORKSHIRE AND HUMBER REGION EMITTERS

4.1 INTRODUCTION

Identification of CO_2 emitters, planned and existing, was carried out in conjunction with Gastec at CRE Ltd. Emitters highlighted in the EU/UK ETS National Allocation Plan data as well as knowledge of proposed facilities through questionnaire response, and discussion with these organisations and desktop research, provided the basis for a detailed examination. Feasibility of each of the emitters joining the network will also effect the likely dates of entry into the network; this is considered in this section of the report.

4.2 INFORMATION ON TIER 0 EMITTERS

Feasibility of CCS for each of the emitters greatly depends on the process involved; therefore each will be categorised by process.

- **Existing coal fired power stations**
  - Drax (Drax Power Ltd)
  - Eggborough (British Energy)
  - Ferrybridge "C" (Scottish and Southern Energy)
- **Potential IGCC schemes**
  - Hatfield (Powerfuels Power Ltd)
  - Killingholme (E.ON UK)
  - ConcocoPhillips
- **Existing CCGT power stations/CHP**
  - South Humber Bank (Centrica)
  - Killingholme (Centrica),
  - Killingholme (E.ON UK),
  - Immingham CHP (phase 1)
  - Keadby (Scottish and Southern Energy)
  - Saltend Congeneration Plant (International Power)
- **Steel making facility**
  - Scunthorpe (Corus)
- **Refineries**
  - Lindsay Oil (Total)
  - Immingham (ConocoPhillips)

The capture technology used varies with each process; figure 4.1 simply depicts the processes involved.

Coal fired power stations represent the bulk of the emissions and would derive greater benefits from CCS. Any energy intensive industry that uses coal may be inclined to seriously consider CCS as the allowances allocated under the National Allocation Plan reduces in line with UK and EU targets.

Integrated gasification combined cycle (IGCC) power stations are based on gasification technology also used in large process plants. CCS is perceived to be less problematic for IGCC power stations as the reformed syngas is purely CO_2 and hydrogen. This option for production of de-carbonised fuel allows the facility to operate continuously to produce power or hydrogen, which then can be sold on to neighbouring CCGTs or other users. This increased flexibility will result in higher average efficiencies if the gasifier component operates continuously whilst the power island matches electrical demand.

Combined cycle gas turbines burn natural gas to produce relatively low concentrations of CO_2, as the fuel is less carbon intensive and the process has a higher efficiency compared with coal-fired power plants. The economics of operating CCS at a CCGT plant do not compare favourably with IGCC and post-combustion coal. This is mainly due to the lower concentrations of CO_2 in the flue gases, as well as the increased fuel costs to counter the drop in plant efficiency. This discussion is explored in more detail in the "Capturing CO_2" document produced by the IEA GHG R&D Programme [16]. Figure 4.2 provides an insight into the predicted costs of operating power plants of varying processes. Estimated costs per kWh reflect the predicted price of fuels; however do not consider the transportation and storage of CO_2.

Based on current knowledge and understanding, the following assumptions are made for each process category.

IGCCs able to produce hydrogen as well as electrical power benefit greatly from CCS. The ability to operate the gasifier continuously would be a major advantage to an IGCC and therefore it is expected that they would be the first to join a CO_2 pipeline network, assuming it was feasible to do so.

Due to economics of scale, it is assumed that post combustion coal power plants will enter the network around the 2020s. They are unlikely to enter earlier, unless supported by incentive schemes.

CCGTs are inherently flexible and cleaner, thus overcoming the issues with coal. CCS would appear less cost effective and not as beneficial; therefore it is assumed that half the CCGTs will enter the network at the tail-end of the study period, with the remaining half operating with a mix of hydrogen or simply decommissioned.

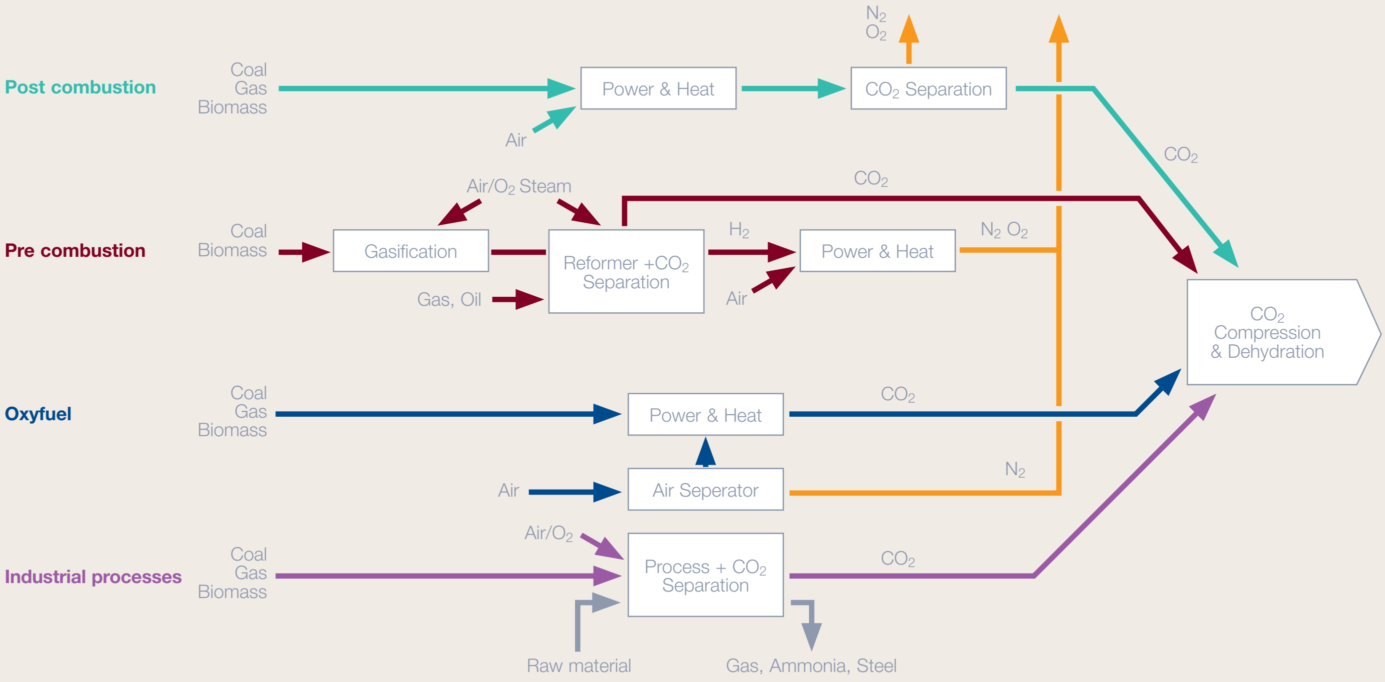
Non-energy producers account for a reasonable portion of CO_2 emitted in this region, each with varying processes and methods of capture to consider. Arguments for whether CCS will be adopted at these facilities would be based on the impact the EU-ETS will have on their businesses.

- **Steel making industry**
  - It may be that emissions allowances will enable global competitive production, assuming that BAT is adopted, but what the effect of changes in the National Allocation Plan for this industry is not certain.
- **Refineries**
  - Requirements of the EU-ETS will probably be upgrades to the ageing UK refineries, again adopting BAT. Allocation of allowances will be problematic as processes and emissions at refineries vary with changes in feed stocks (light, sweet North Sea oil being replaced by imported, sour, heavy crude oil from the Middle East), changing products (demands for aviation fuels increasing) and accommodation for biofuels processing.

Despite the difficulties surrounding the allocation of carbon credits in the second phase of the EU-ETS, further reductions and increasing CO_2 costs could encourage industries to cut their emissions below BAT. In this sense, the opportunity to join a low cost network would seem attractive, assuming a suitable CO_2 capture unit can be found to suit the process.

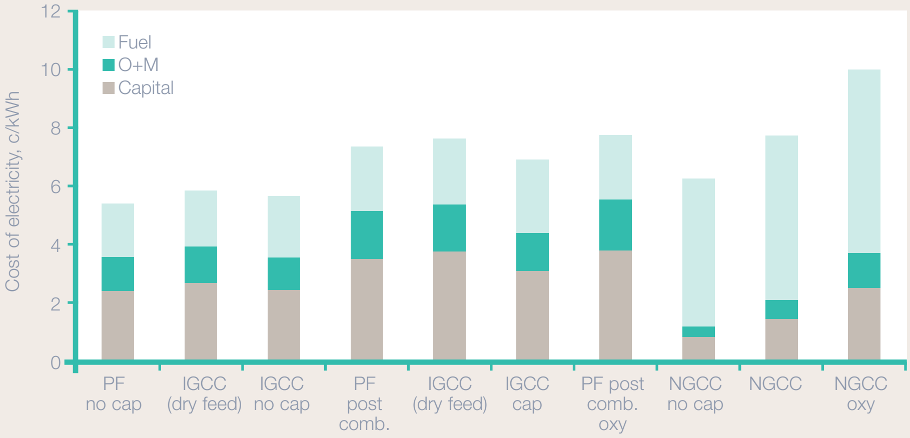
Figure 4.1 Carbon capture systems

Overview of CO_2 capture processes and systems



Reproduced courtesy of the IPCC from IPCC Special Report on carbon dioxide Capture and Storage, Fig TS-3

Figure 4.2 Predicted operating costs for power station technologies



5.0 CARBON DIOXIDE ENTRY SPECIFICATION

5.1 INTRODUCTION

The quality of carbon dioxide (CO_2) entering any system may have a significant impact on the storage and transportation aspects of any CCS network. Any capture process is a balance providing a cost and energy efficient solution for extracting the CO_2. This process will inevitably mean that some of the other contaminants are captured as well, which may have negative impact on CCS schemes in several ways:

- Health and safety implications
- Capture energy usage and power station efficiency
- Transportation implications, property changes and costs.

Therefore the quality of the CO_2 stream needs to be defined. For proposed networks this definition becomes the entry specification to the network to which emitters must comply in order to enter the system.

5.2 POSSIBLE IMPURITIES

The impurities present in a CO_2 stream depend greatly on the source. For non-anthropogenic sources carbon monoxide, hydrogen sulphide and methane are common impurities. Anthropogenic, man-made, sources will inevitably vary but will commonly produce the following contaminants.

- Methane
- Carbon monoxide
- Water
- Hydrogen
- Oxygen
- Nitrogen
- Argon
- Hydrogen sulphide
- Sulphur oxides
- Nitrogen oxides

The impurities can be treated and removed to a certain extent, and would have to be for a successful CCS scheme. However trace amounts will remain and a limit needs to be set to enable the design of the cleaning operations particularly for H_2S, SOx and NOx. The cause of the impurities is the combustion processes itself and the fuel stock. Considering a clean coal IGCC then an incomplete shift gas reaction will introduce methane, carbon monoxide and water as well as hydrogen into any process gas stream. Consequently when the CO_2 is recovered so will some of the impurities. Hence the affect of these impurities on a CO_2 stream need to be understood and controlled.

5.3 PROPERTIES OF CARBON DIOXIDE

Carbon dioxide is a common gas, and widely used in the food, pharmaceuticals and chemicals industry. However its physical characteristics make transportation complex. Unlike other commonly transmitted gases such as methane, hydrogen or ethylene the critical conditions of CO_2 are relatively low, 74 bar and 31°C, as shown in figure 5.1.

This means that the transportation of CO_2 can occur as a solid, gas, liquid, or as a supercritical fluid over a relatively narrow range of conditions. Typically CO_2 is transported as a gas or liquid, to local sources or into process or as a liquid for bulk transfer. In the case of a CCS network the denser the fluid the better as this generally reduces the pipe diameter required. However above the critical point the supercritical fluid state allows for a mixture of gas and liquid properties, the fluid has the density of a liquid with the compressibility and viscosity of a gas. These physical conditions make transportation in this state attractive given the efficiency gains from lower friction and lower pressure drops.

It should be noted that information on the properties of CO_2 with contaminants is scarce. No specific testing has been carried out in the public domain, although some work is ongoing. Modelling of properties is possible using Equations of State such as Peng Robinson, although this modelling must be validated against test results to validate its accuracy. This is particularly important when considering a supercritical fluid mixture.

5.4 CONTAMINATION ISSUES

The purity of potential industrial CO_2 sources is dependent on the combustion process and the method of capture. For example is the source a power station, pre-combustion or IGCC, ammonia or amine capture, desiccant drying or glycol? Typically the common contaminants are:

- Methane
- Non-condensable gases, nitrogen, oxygen, argon, hydrogen
- Hydrogen sulphide
- Sulphur oxides
- Nitrogen oxides
- Carbon monoxide

Other contaminants may include mercury or complex chemicals such as dioxins or furans depending on the feed stock and process.

The presence of methane as a contaminant may be possible for some processes. However the discussion around methane as a contaminant applies more to the geological sources of CO_2 where methane is a much more common contaminant.

There are two effects to consider, the safety impact and that on the physical properties. Key physical parameters of a fluid will be altered given a change in the mixture; specifically of interest to CCS is the change in the critical point and the phase boundaries. The importance of understanding this relationship is critical, as a change in the levels of one contaminant could adversely affect the properties of the mixture such that a phase change may occur, or a change from a supercritical to liquid phase.

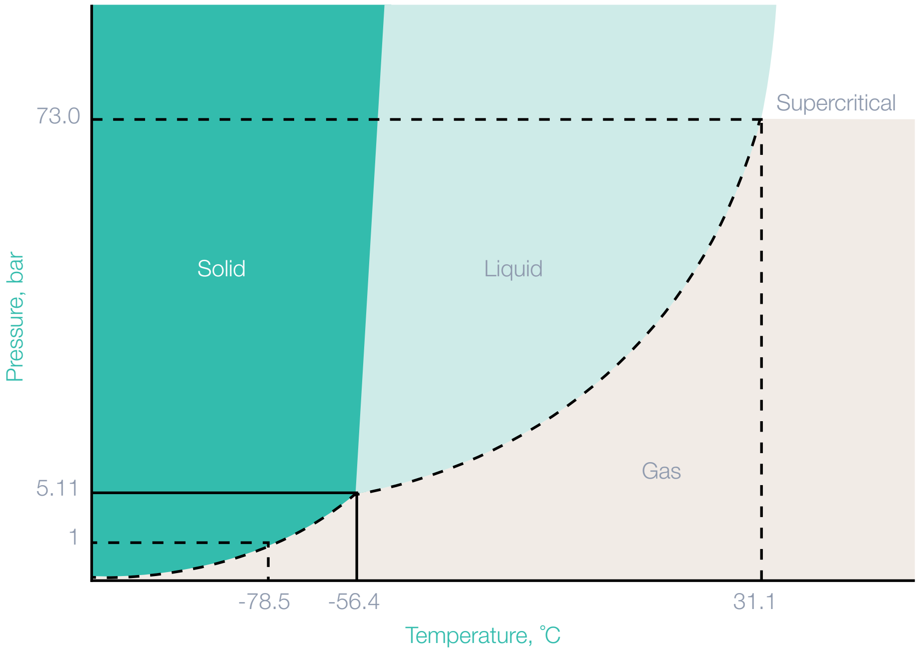
5.5 PROPERTIES OF CARBON DIOXIDE MIXTURES

The properties of CO_2 mixtures typical to CCS schemes are not well examined by industry or academia. Experience in the USA so far has been of CO_2 from either anthropogenic (man-made) sources (25%) or geological sources (75%) that are relatively clean and these are used for enhanced oil recovery (EOR).

In the UK there are no geological sources. Industrial sources range from those used to produce food grade CO_2 to contaminated CO_2 emitted under environmental consents.

The considerable variation in the quality of gas has an appreciable effect on the physical properties. For instance a pipeline run at 84 bar is 10 bar above the critical point for pure CO_2 and providing pressure drop is low two phase flow will not occur. Introduce a contaminant and the critical point changes as does other properties.

Figure 5.1 Carbon dioxide phase diagram



If the critical pressure were to increase for the mixture, or the contaminant change the phase to vapour, then the system hydraulics will change.

The following figure shows one example as an illustration. Figure 5.2 and figure 5.3 shows the deviation from pure CO_2 caused by the presence of nitrogen. In all cases pure CO_2 is one, the deviations are from this baseline, for example a data point of 1.2 for density shows that the mixture is 20% denser than pure CO_2.

As can be seen from the chart a 4% concentration of nitrogen imposes an 11% increase in pressure drop. The critical points for this mixture become 26.6°C and 82.3 bar.

Similar effects can be seen considering the other contaminants. Typically the common contaminants generally correlate to a +/- 20% deviation in most properties at around 5% mol in a binary mixture.

For critical temperature and pressure the general pattern is that an increase in the percentage of a contaminant increases the critical pressure and decreases the critical temperature. There are three notable exceptions; H_2S, SO_2 and NO_2 increase both critical temperature and pressure.

Changes in the critical point represent changes in the phase envelope. As the critical point shifts with contaminant concentration it could impact on the operating point or envelope of the main system. Introducing a high contaminant source could push the phase envelope past the operating point of the network and may cause a change in phase. Figure 5.4 shows the change in phase envelope for a CO_2 – nitrogen mixture with increasing levels of nitrogen.

Consider point A on the graph as the optimum operating point of a pipeline normally operating in a 4% nitrogen in CO_2 mixture, just below critical temperature but with a 10%, in this case 8 bar margin on pressure. An increase of 2% to a 6% contamination level reduces the margin above critical pressure, but reduces the critical temperature, the fluid is now supercritical.

To avoid these changes in physical properties within a pipeline the variance that can occur must be controlled. To this extent an entry specification provides a design point around which the pipeline can be designed as to eliminate phase changes within the operating network.

5.6 TECHNICAL IMPACT

Key to a pipeline's design is not only the physical constituents of the fluid but also its condition. The pressure and temperature for entry must be kept at a near uniform level to avoid local pressure problems such as two phase flow or changes in bulk temperature. Therefore a specification must include a minimum pressure and a maximum temperature. Generally given the critical point, temperature is limited to a condition that it must be less than 30°C. For pressure the critical point should be avoided, therefore a minimum pressure of 100 bar would be acceptable, this gives a 30 bar margin from the critical point to allow for pressure drop within the system.

For a network that has to deal with multiple individual sources the design must accommodate all reasonable variations of flow that may occur. To achieve this, a network specification is required to limit the variability of the fluid properties to a reasonable level so that equipment design has a narrow range of key physical properties as possible. It is generally accepted that a design factor of 10% is applied to process equipment based on the averages of the streams involved. If the variation in properties is wide then the overall design range may be excessive, a 20% variation in physical properties in addition to a 10% design factor places a very wide envelope when considering optimum equipment design and selection.

Typically for staged implementation the equipment will be staged as well, for example a network may start with two compressor booster stations but expands to four at network completion.

5.7 LEGISLATIVE REQUIREMENTS

The legislative framework for pipelines and associated fixed equipment is well established and understood. The applicability of the legislation to carbon dioxide pipelines however is less well defined.

The transportation of CO_2 is covered by existing legislation in the form of the Pipeline Safety Regulation 1996, PSR, and COMAH. Currently CO_2 is not a hazardous material under PSR but the Health and Safety Executive (HSE), consider that it should be in this context and new legal guidance for CO_2 is expected in 2008. In the interim the HSE stance is that the current regulations should be applied and CO_2 would only be exempt where it can be proved that the legislation does not apply. Therefore under the PSR CO_2 and the other constituents of the stream will count as a hazardous fluid and should be considered as such.

5.8 OFFSHORE LEGISLATION

The prime constraints on CCS schemes operating offshore are OSPAR and the London Protocol. These treaties regulate the activities that can occur in the ocean and apply in and around the UK.

Both are now modified to allow for CCS/EOR activities. OSPAR was recently amended to include the provision for CCS worded such that carbon dioxide sequestration would be exempt from the disposal at sea restrictions as long as:

i. Disposal is into a sub-soil geological formation

ii. The streams consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used

iii. No wastes or other matter are added for the purpose of disposing of those wastes or other matter

iv. They are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

OSPAR defines a CO_2 stream as;

"those streams that consist overwhelmingly of carbon dioxide from carbon dioxide capture processes for storage in geological formations in the sub-soil of the OSPAR maritime area. Provided that no wastes or other matter are added for the purpose of disposing of those wastes or other matter, the carbon dioxide streams may contain incidental associated substances derived from the source material and the capture, transport and storage processes used."

The definition of "overwhelmingly of carbon dioxide" is vague, however a general acceptance of 95% or more CO_2 is considered appropriate. However the statement precludes the addition of other waste streams and additives, such as odourising agents that may have been considered for onshore pipelines.

5.9 TYPICAL STREAM COMPOSITIONS POST CAPTURE

Without significant facilities operating for anthropogenic carbon capture the amount of information available to define an entry specification is low. However a number of sources have been summarised by reference 6 and other projects.

Table 5.1 to table 5.3 indicate quoted compositions of CO_2 streams from proposed CCS power stations from the IPCC, Special Report on Carbon Capture and Storage, section 3 [6].

Figure 5.2 Property deviations for carbon dioxide - nitrogen

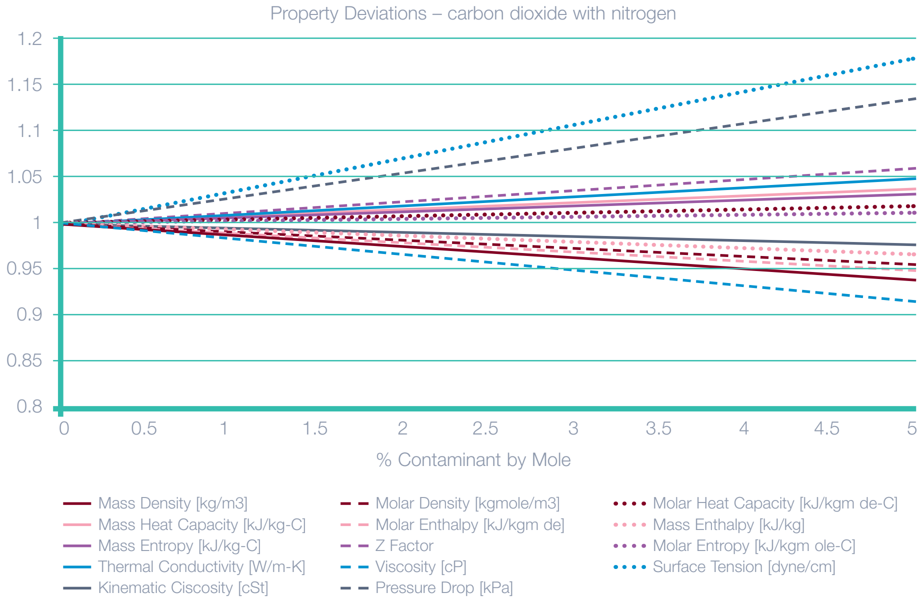


Figure 5.3 Variation in critical parameters for carbon dioxide - nitrogen

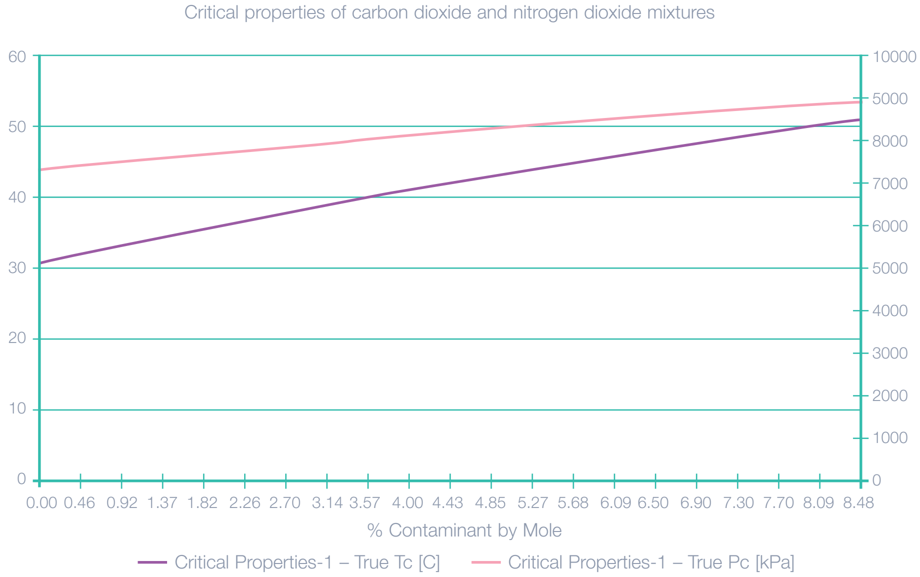


Figure 5.4 Phase envelope changes with increasing impurity

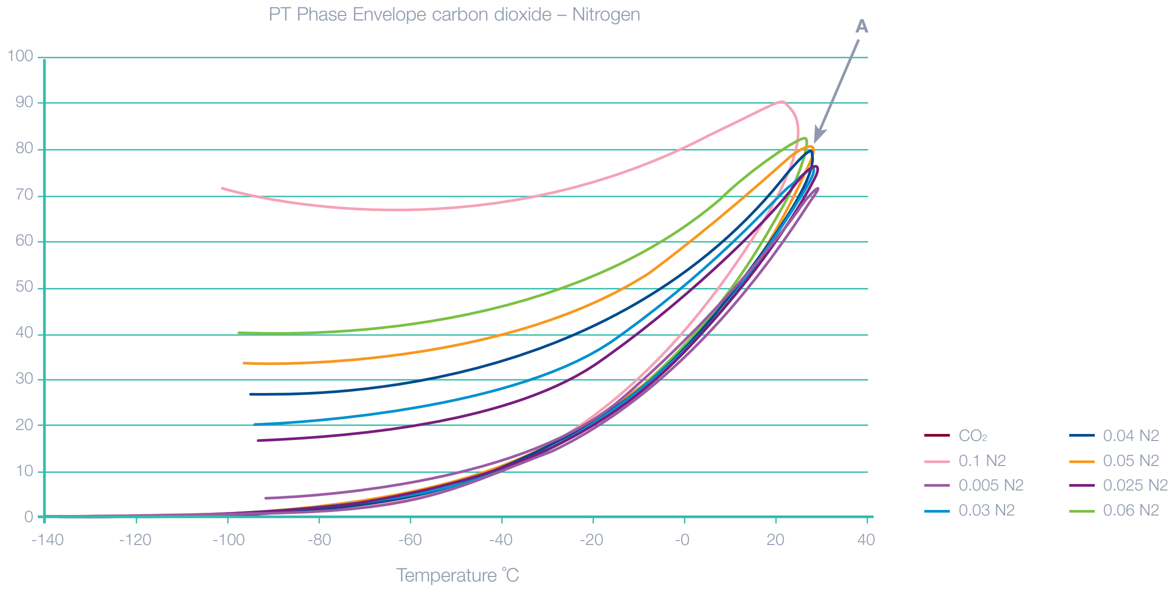


Table 5.1 Coal fired plant post comb capture

Component	Limit
$N_2/Ar/O_2$	0.01%
Hydrocarbons	0
H_2	0
H_2S	0
CO	0
SOx	<0.01%, <100ppm
NOx	<0.01%, <100ppm

Table 5.2 Coal fired plant IGCC

Component	Limit
$N_2/Ar/O_2$	0.03 – 0.06%
Hydrocarbons	0.01%
H_2	0.8 – 2%
H_2S	0.01-0.6%
CO	0.03-0.4%
SOx	<0.01%, <100ppm
NOx	<0.01%, <100ppm

Table 5.3 Coal fired plant oxy fuel

Component	Limit
$N_2/Ar/O_2$	4.1%
Hydrocarbons	0
H_2	0
H_2S	0
CO	0
SOx	0.5%
NOx	0.01%

The following data set, table 5.4, is the entry specification for the Weyburn/Dakota Gasification Plant where CO_2 is used for EOR in the Weyburn field in Canada. In the absence of legislation or regulation in the US & Canada this data set is used as guidance for operators in that area

Table 5.4 Weyburn/Dakota gasification plant entry specification

Component	Limit
CO_2	>95%
Non-condensable, N_2, O_2, Ar etc	<4%
Hydrocarbons	<5%
H_2O	<100ppm
H_2S	<1450ppmv

One more comprehensive specification is from the Dynamis project. This project is EU funded and concerned with the production of hydrogen and the associated capture of and sequestration of CO_2. The SP3 project group is concerned with gas handling issues including CO_2 quality. In January 2008 Dynamis presented the following information [17], table 5.5, as its proposed standard for CO_2 entering a transportation system for sequestration.

5.10 WATER CONTENT

Water and CO_2 together can form carbonic acid which is detrimental to pipelines causing corrosion on the internal surfaces. Additionally hydrates could be formed at low temperatures which could cause blockages in equipment, valves and scaling of the pipeline.

This requires that the formation of free water in the pipeline be prevented, typically by drying. Whilst water solubility in CO_2 is understood, the effects of contaminants in the stream on the solubility is not. It has been shown that corrosion will not occur if the saturation levels are below 60% approximately 1576 mg/m³. Given that industry accepted levels of water are specified as 288-480 mg/m³ this specification is accepted for CO_2 pipelines as well. To avoid the formation of free water the specification is generally kept low.

Therefore any CO_2 stream requires drying or a high specification of corrosion resistant material. For long distance pipelines the economic solution is more likely to be to require a high drying specification with a sufficiently low concentration of water permitted.

5.11 SAFETY IMPACTS

Any specification for a CO_2 pipeline must consider the safety issues associated not only with CO_2 but with each of the contaminants. Whilst the consideration of the safety impact was not strictly within the scope of this report it has been considered in depth.

The danger from a CO_2 transmission system is essentially the occurrence of leaks both short term and long term. Whilst the CO_2 is hazardous the impurities it may contain, such as hydrogen sulphide are significantly higher. Therefore in considering dispersion and the effects of a release the contaminants must also be considered ensuring as a minimum they stay within their short term exposure limit (STEL) and the SLOT/SLOD data from the HSE.

5.12 PROJECT SPECIFICATION

Given the discussion in the previous section the specification from the Dynamis project provides a reasonable basis. The contaminant levels specified are such that they minimise the risk of hydrate and free water formation, ensure the stability of the fluid at a typical pressure range. In addition the hazardous contaminants H_2S, CO, SO_2 and NO_2 have limits such that they are significantly lower than their accepted STEL values.

Table 5.5 Dynamis SP3 recommended entry specification

Component	Limit	
CO_2	>95%	
N_2	<4% (for non-condensable gases)	<4% for all non-condensable gases and Hydrocarbons
Ar		
H_2		
O_2	<4% EOR 100-1000ppm	
CH_4	Aquifer <4% EOR <2%	
H_2S	<200ppmv	
CO	<2000ppmv	
H_2O	<200ppm	
SOx	<100 ppm	
NOx	<100 ppm	

Table 5.6 Recommended entry specification

Component	Limit	
CO_2	>95%	
N_2	<4% (for non-condensable gases)	<4% for all non-condensable gases and Hydrocarbons
Ar		
H_2		
O_2	<4% EOR 100-1000ppm	
CH_4	Aquifer <4% EOR <2%	
H_2S	<200ppmv	
CO	<2000ppmv	
H_2O	<200ppm	
SOx	<100 ppm	
NOx	<100 ppm	

Minimum pressure = 100 bar
Maximum temperature <30°C

6.0 ONSHORE AND NETWORK DESIGN

6.1 NETWORK AND SCENARIO DEFINITIONS

There are two distinct aspects to consider in the formulation of a concept scenario for connecting the region's emitters; the scenario and the shape of the network.

The scenario defines the requirements of a network; who, what, when and to some extent where, when considered alongside the availability of potential storage sites.

The network is the physical shape of the system to accommodate the scenarios, constrained by the process and mechanical design, local environment and implementation of regulations and good practice.

6.2 NETWORK

6.2.1 Primary factors for pipeline route selection

The design of any network should consider a number of factors and the acceptance that the shortest route may not be the most suitable. The primary factors that should be considered include:

- Public and personnel safety
- Pipeline fluid and operating conditions
- Environmental impact including designated areas
- Geological conditions, including topography, geotechnical and hydrographical conditions
- Land use, existing and future, including:
- Third-party activities
- Agricultural practice
- Existing facilities and services
- Access
- Transport facilities and utility services
- Construction, testing, operation and maintenance
- Security
- Any other hazards.

In order to develop the pipeline route efficiently, three phases of routing are usually adopted:

1) Route corridor selection

2) Route investigation and consultation

3) Design and approval of final route.

This report is a high level feasibility study for the region. Therefore the only one of the three phases appropriate is the selection of potential routes.

6.2.2 Design assumptions

The key design assumptions relate to the design of the pipeline, the network shape and constructability.

The pipeline design is limited to 125 bar operating pressure, this places the fluid into the dense phase but not supercritical as the entry temperature will be limited to below the critical temperature.

Onshore booster stations for pressure control will not be provided, the network shape selected to route the pipeline acts as a central 'rail' with spurs to each emitter. Provision of an onshore booster station would necessitate a significant establishment along the pipe route or adjacent to an existing industrial site. To determine the optimum location of such a station a more detailed network analysis would be required than is available here.

The provision of intermediate distance safety or block valves has been assumed to fall at 15km for high pressure systems.

Onshore pipeline sizes are limited to a maximum of 1000 mm diameter. The pipelines are buried and require significant top cover, typically 1.2m up to 1.8m for special crossings such as railways. This would entail a trench depth in excess of 3m. To generate reasonable cost metrics the trench excavation depth was limited to 3m, thus limiting the pipe size.

Flow rates to the network are taken as a viable percentage of total carbon dioxide based on DEFRA's NATS tables. Where appropriate and permitted actual or planned capture figures have been used. Typically the capture efficiency is taken as 90%. For refinery complexes such as the Total and ConocoPhillips facilities on Humberside a much lower figure of 50% is utilised. The distributed nature of point sources of release on these mature facilities would require major design and infrastructure changes at each site. Other issues such as the nature of the emission would challenge the way carbon dioxide is captured, for example emissions from a flare would be impossible to capture. 50% is used as a generalisation of what might be expected to be within reach of capture technology.

6.2.3 Operating philosophy

The network is sized to accommodate the flows from the emitters with a margin allowance for peak excursions. The operational capacity of the emitters to capture CO_2 in the area range from 50% – 98%. With such scales to consider, peak demands would necessitate multiple or a significantly larger, thicker pipeline, which, in turn, have a negative effect on the economics. Capture plant and stores will have various license terms which will have to be realistic for the processes used. The operating regime for the transport system will be primarily governed by commercial agreements on line use and recognise the risk of CO_2 losses as a very low but a possible operational risk. There is no offline storage in the system except if it was connected to a shipping facility for the CO_2. The lines are sized above the average flow to account for plant down time and peak flows from all sites, but there is an economic limit of the ETS CO_2 value at which it is cheaper to not capture or export CO_2.

Given the points of failure in capture, transport and storage facilities the transport pipelines and pumps are not duplicated for 100% standby capacity. Maintenance regimes, equipment specifications and reliability and availability levels would all be considered and designed to accepted best practice. As the repair down time would be reasonably short, the value of the CO_2 vented back at source due to the lack of or reduced amount of transmission capacity is low compared with additional capital spend on what is not a life critical or high marginal value product.

It should be noted that government legislation in future might require that all facilities with CCS must endeavor to capture all available CO_2, similar to those large power stations with flue gas desulphurisation units.

6.2.4 Design life

The design life of the onshore and offshore pipelines is 40 years, and compressors, valves, meters, etc is as typical as used for that equipment. These design lives depend critically upon the dryness of the CO_2 entering the system and this and other risks are important issues to be addressed further by OEMs and system designers. Operational costs are assumed to cover necessary maintenance of that equipment and all equipment considered in this study will be new and designed with this lifespan in mind.

6.2.5 Metering

As the impetus for building a distributed collection system is likely to be financial (based on selling carbon credits), metering of CO_2 sent for disposal would be necessary at all sources prior to injection into the network. Metering would also be required at the point of storage/sequestration for regulatory purposes, i.e. to ensure that all CO_2 injected into the network is sequestered.

6.2.6 Corrosion protection

Steel pipelines are routinely protected against external corrosion by the use of cathodic protection systems, and a design allowance in the wall thickness. These are included in the costs for steel pipelines presented here. Internal corrosion would only be a problem if water was present in the CO_2 stream.

6.2.7 Network phasing

The key factor on the network design is that the network forms in a number of phases to accommodate emitters that come online in similar time periods. This way no single emitter would be faced with the initial full cost of a pipeline without commitment from other parties. For example consider plants A, B & C, bringing CCS on line in 2015, 2017 and 2030 respectively. Here simple sources A & B would be grouped with the pipeline coming on line in 2017 at the latest. The 2030 emitter would require a pipe solution in another deployment stage. This does mean however that there will exist multiple pipes running in proximity to each other at the end of the project particularly the shore line stations would have several incoming lines in the same pipe corridor.

Figure 6.1 shows an example of part of a phased network. The red line indicates the projected path of a pipeline installed in 2017, the blue a pipeline installed in 2030 to accommodate the second phase of development.

6.2.8 Network design tool

The network design and cost information is provided using a pre-existing spreadsheet based tool created for the International Energy Agency Greenhouse Gas R&D Programme. Specifically designed for the networking of carbon dioxide the spreadsheet was created by AMEC and Gastec at CRE Ltd in 2006. The tool allows networks to be created and cost estimated using several matrices for standard equipment and pipeline costs.

The costing information used in this model was generated by AMEC in 2006. It consists of information from project and proposal databases on current and historical projects. Each cost was subject to scrutiny and the cost used was based on engineering assessment as to whether the price was valid. Where historical data was not available standard estimating metrics used in house by AMEC have been used.

6.3 AREA ANALYSIS

6.3.1 General description

The Yorkshire and Humber region is ideally suited to carbon capture and storage schemes given the intensity of emitters and the availability of potential offshore storage solutions. In addition there already exist gas terminals at Theddlethorpe and Easington. Boundaries for the study area are defined loosely as the Humber sub-region, but more exactly by the regional border of Yorkshire to the south and the town of Castleford to the west. The northern boundary for the study area is loosely defined as not further north than Beverley. Although there is a cluster of emitters in and around York they are not included in the study, due the distance to the nearest suitable tie-in point. Appendix A contains a project area map.

To the west the area is also bound by the metropolitan areas of Leeds, Wakefield, Barnsley, Sheffield and Rotherham. Running significant piping solutions to emitters in this area was viewed as a challenge, particularly where some emitters would have required crossing the M1 motorway. For the purposes of the study, given that the area already defined captured all of the Tier 0 emitters the area west of Castleford and the A1 was not included.

6.3.2 Area restrictions

In examining an area for pipeline routing the area is scrutinised for major obstructions. Here given that the fluid is carbon dioxide, a precautionary routing of the pipeline is taken, trying where possible to maximise the distance away from residences and urban centres whilst optimising the pipeline length. As well as the conservative line run approach there a number of pinch points along the route.

Firstly the area to the north of Hull, figure 6.2, and south of Beverley is congested, a large number of distributed dwellings exist in the area. This means that the pipeline must snake through an area or encroach into urban areas. Whilst encroaching on residences is allowed to a specified separation distance, under the UK regulations and codes, it should where possible be avoided. The area does not preclude its use of a pipe run, but it would be a difficult area to traverse.

Secondly to the west of Scunthorpe lies the River Trent the east bank of which forms a steep gradient to the north of the town until the Humber, figure 6.3. Such inclines with rapid increases or decreases in height should be avoided if possible. Here the proximity to the river edge and the town itself does not lend itself easily to a pipe bridge solution.

Two routes do exist, the first to the south of Scunthorpe represents a major detour from the direct path, and as can be seen from the basic map in Appendix A a band of forests litter the area to the east, some of which and the surrounding area are SSSI's. The second route would be to cross in the area to the north of Scunthorpe where the incline is not so pronounced.

Figure 6.1 Example of phased network pipelines

6.4 NETWORK FORMATION

6.4.1 Ring main

The simplest and most effective method of connecting distributed emitters is a ring main, much like those used to distribute a fluid rather than receive. The ring main could receive all fluids and route to one of two export points allowing sections to be dropped for inspection or the ring main to be built up gradually. Figure 6.4 shows a basic example of a ring main system for the region. However the size of the network would require a split main pipe, two parallel pipes working in operation of a significant size. This has obvious benefits for staging the development and capital outlay but has significant impact on the construction and operational elements. If several pipes are being used to perform a function of a ring main then that suggests a more distributed approach, allowing a network to develop over time. For a ring main the first few users would bear the cost of a pipeline they may not have the capacity to use efficiently.

6.4.2 Tree/distributed structure

A tree structure, figure 6.5, is more suited to the efficient operation and construction of a network such as the one proposed for Humberside. It allows phased development into stages that meet the requirement of emitters as they come on line not forcing future need costs on to early emitters. This system also lends itself more efficiently to the collection from the lower Tier sources. For the majority of Tier 1 and 2 sources it may not be appropriate to compress gases at site. Instead the lower tier sites are envisaged to be part of a suction system tied to a larger emitter station. At the larger emitters the lower tier gas is collected by compressors sucking the carbon dioxide away from the emitter. For the purposes of this study a tree structure has been adopted for the networks.

Figure 6.2 Pipeline route congestion point – Hull - Beverley Gap

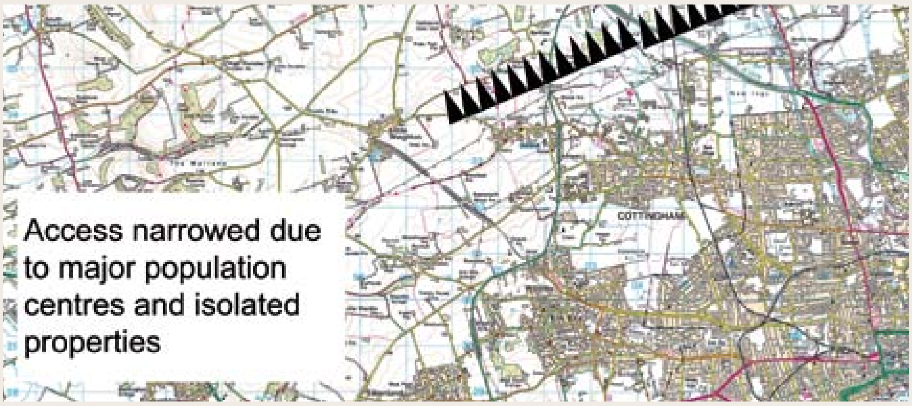
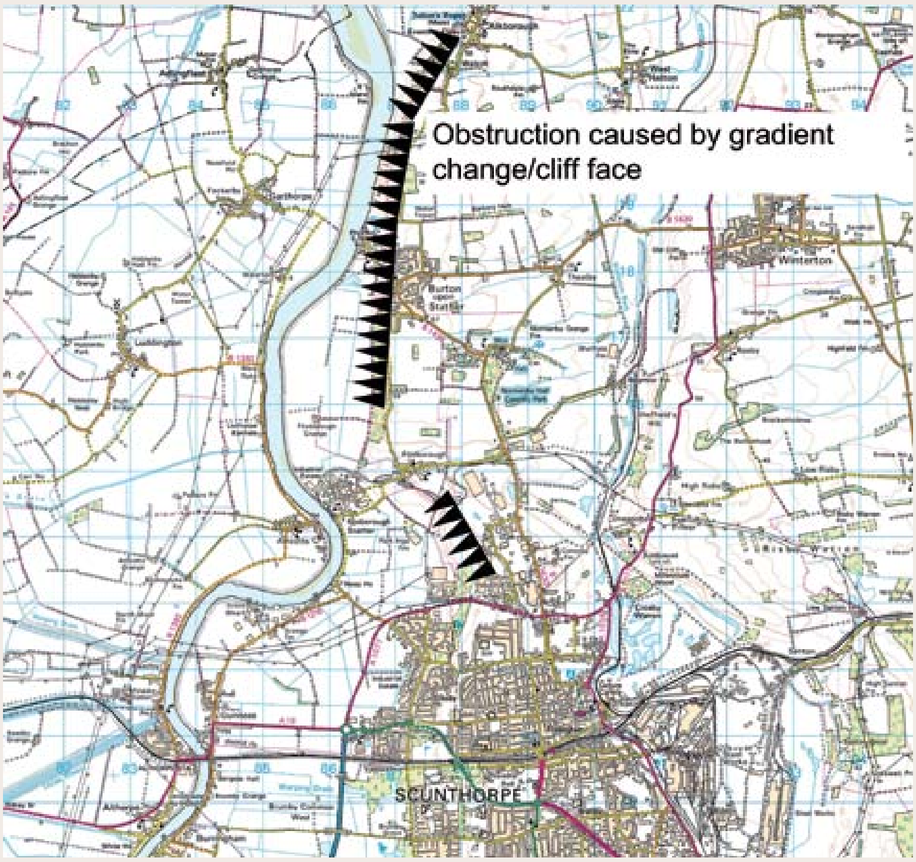


Figure 6.3 Pipeline route congestion point – Trent Crossing



6.5 SELECTION OF EXPORT TERMINAL LOCATION

To a certain extent the shape of the network is also defined by the practical access to the offshore stores, with the onshore options being to the north or south of the Humber estuary in the shape of Easington/Dimlington and Theddelthorpe as both host existing gas import terminals, and therefore known facilities and track records for assessing beach and near shore pipe installations. The preferred network route is to the south, via Theddlethorpe for a number of reasons;

- Area analysis indicates that the northern route around Kingston upon Hull is congested, particularly so when considering phased pipelines. Whilst it may possible to lay a single or two pipelines the required easement and way leaves would infringe on residences.
- The bulk of the reservoir destinations are to the south east, nearer Theddlethorpe.
- The majority of major emitters, by number of sources lay to the south of the Humber, crossing the river to gain entry to Easington would be a major expense and multiple crossings due to phased developments should preferably be avoided.

A non-phased solution for the area including Tiers 1 and 2 would make Easington more attractive, however running the major pipeline required to facilitate Drax, Eggborough and Ferrybridge would be significantly difficult and disruptive.

Therefore the preferred destination is an export point on the shore in the general area of Theddlethorpe.

Figure 6.4 Schematic example of a ring main network

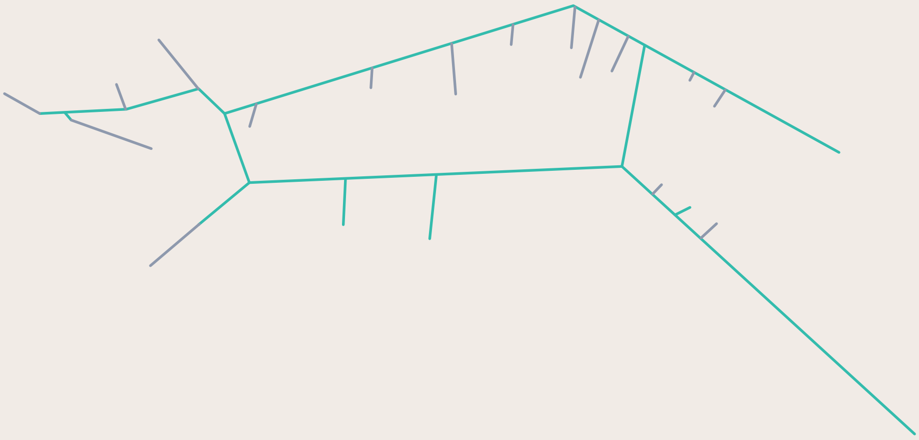
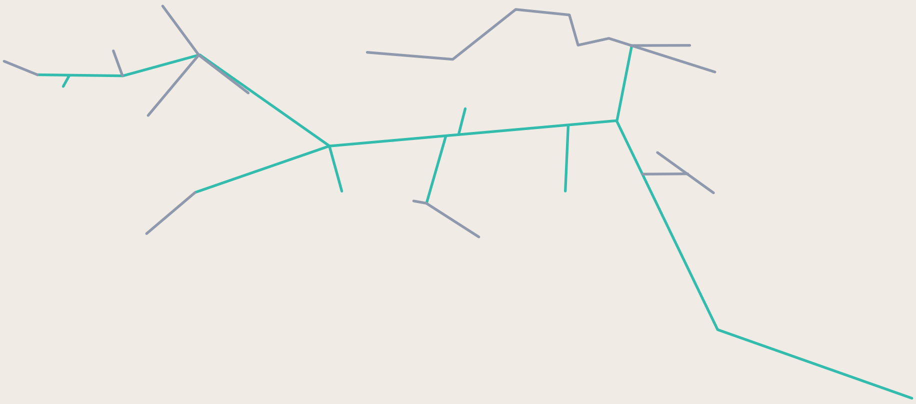


Figure 6.5 Schematic example of a tree structure network



7.0 OFFSHORE ROUTES AND STORAGE

7.1 STORAGE OPTIONS

Storage sites for CO_2 from the Yorkshire and Humber area of any useful size are located to the east in the southern North Sea. These comprise many large producing natural gas reservoirs, which are the main focus of this study, but also saline aquifers (shown in figure 7.1). The interesting saline formations in the area are a depth of between 1km and 1.5km and have been extensively drilled in the southern North Sea as many overlie natural gas fields. However they have not been characterised and whilst their theoretical storage potential is significant, their actual capacity and storage security are far from proven. In order to develop and produce from them, natural gas fields have been extensively characterised and it is by their nature to be more certain about their storage potential since they have contained natural gas for tens of millions of years. However, there is timing uncertainty about cessation of production and decommissioning of gas fields. But for this study all fields of useful size have assumed to be available for CO_2 storage in the period between 2008 and 2050.

7.2 DATA SOURCES

Data for storage sites was derived primarily from the Tyndall working paper No 85 [3] with input from other public sources including WoodMac and DBERR publications including the North Sea Task Force report and study [4, 5 and 6]. There was sufficient consistency in their details for the purpose of this study. The information is summarised on table 7.1 and table 7.2.

7.3 ALTERNATE STORAGE AND COMPETING USES FOR DEPLETED GAS FIELDS

The northern North Sea includes the Utsira saline aquifer which has been proven by the Sleipner CO_2 storage project. This Norwegian project has been injecting 1mt/y CO_2 into the Utsira aquifer since 1996. This has been monitored and is proving very successful. Also associated with the northern North Sea is the possibility of enhanced oil recovery (EOR). Proven onshore, but not offshore or in the North Sea, this uses CO_2 injected into oil formations to help recover more of the oil through CO_2's solvent properties mobilising the oil in rock pores. When CO_2 is recovered with the oil it is separated and re-injected so that it is contained, and following decommissioning of the oil field it is stored in the same manner as in a depleted gas field.

Both of these possibilities require either shipping the CO_2 or quite long pipelines. As solutions for the period of this study the costs are unattractive compared to local storage. However for EOR the additional oil is the main revenue driver. Testing the opportunities for EOR is recommended to compliment this study.

It should be noted that some depleted gas fields may be converted to natural gas storage facilities. Such facilities already exist in the North Sea, for examples at the Rough Field, with proposals for the Esmond and Gordon fields but such fields are smaller than the fields in this study.

7.4 CO-ORDINATION OF DECOMMISSIONING AND RE-USE OF EXISTING ASSETS

There has been a presumption that it is desirable to co-ordinate the decommissioning of a gas field with the planning of CO_2 storage. With respect to well abandonment and the re-use of existing infrastructure this is undoubtedly true. We have however had to assume the use of new pipelines due to the volumes, timescales and pressures of CO_2 to be transported. The consensus is clearly that we must also assume the transport system terminates at new injection wells and platforms without offshore recompression. This is because of the high operating costs of the alternatives and the diversity of field combinations to be considered. It may be that in some instances the reuse of existing infrastructure is feasible, but it would be misleading to base this report on the assumption that asset re-use is economic.

To justify investment in a long life asset, such as a high pressure and capacity pipeline and injection wells, and with network flow rates ranging from 2 to 40 million tonne per year (2-40mt/y) we reviewed the available fields and settled on a cut-off of a minimum 40mt storage capacity for a depleted gas field. This may seem low but we wanted to ensure useful reservoirs along a pipe route were not overlooked.

Barring inappropriate well abandonment it is reasonable to consider that substantial gas fields that are decommissioned before CO_2 storage is required can be re-accessed. Storage site characterisation as distinct from the present gas characterisation would be required in accordance with the emerging regulatory regime. At this time only the Shell Indefatigable field is categorised as unavailable because it is abandoned, but it is included as a store available when the remainder of Indefatigable is decommissioned and is assumed to be used by the network.

7.5 INJECTION PRESSURE

A pipeline pressure requirement of up to 170 bar is recommended to be used for the purposes of this study given the lack of detailed knowledge of the individual reservoir and well differences, and the need to serve multiple fields over the life of the offshore trunk pipelines. Though some fields do not require this high injection pressure the initial pipeline will be extended to higher pressure stores. The additional wall thickness does mean an increase in initial installation cost for the pipeline but the opportunity to operate at lower design loads must be for well over 10 years to prompt installing a second pipeline due to the high fixed costs of offshore pipe construction.

7.6 SALINE AQUIFERS

There are no saline formations that have been characterised sufficiently to have good estimates of their storage potential and leakage risk. They are also not closer than depleted gas fields. However, by co-incidence three with storage capacities of over 1000mt over lay producing gas fields. Unfortunately there are no robust geological studies to suggest that these formations are sealed unlike gas fields which have obviously trapped rising gases for a very long time. For those aquifers that lie at a shallower depth than an explored gas field there is data because of seismic and borehole results, though it requires analysis to focus on the aquifer rather than the much deeper gas field. However much analysis is done, the final proof is in drilling and injection and monitoring of a measurable amount of CO_2, as that will provide confidence to rely on that geological store for CO_2 for large volumes. Further to the Sleipner experience a number of other CO_2 injection and monitoring aquifer injection trials are underway, all with extensive monitoring and modelling. Routing ideally needs to enable access to, and assessment of, these three aquifers because of their large storage potential.

7.7 GAS FIELD SELECTION

7.7.1 Availability timeline

For pre-2020 availability Leman has the best date and size features, followed by Perenco's Indefatigable & SW, Viking, Victor, Vulcan, Hewett, Ravenspurn North, Audrey, Amethyst E & W, and Pickerill. Considerable caution is required about the availability of Leman as the operator of half the field is not likely to decommission before 2025. There is potential in a minority of scenario options for an overlap between gas recovery and CO_2 injection which because of connectivity within the field may be a problem. This can be resolved before a pipe route committing to use Leman is sanctioned.

7.7.2 Distance selection

For a minimum distance for first stage capacity, or desirable if near a pipeline route to larger stores, the best fields are Amethyst E & W then Pickerill, followed by Ravenspurn North and, if via Theddlethorpe, then Hewett.

7.7.3 Injectivity

Ranking by injectivity, a measure of how easy it is to inject CO_2 into a formation and size the preferred fields are Viking and Indefatigable, and Leman and Hewett, with consideration to Victor, Sean N & S, Vulcan, Audrey, Barque & Barque S, and Ravenspurn North. Injectivity is primarily driven by rock permeability, but other geological and well design factors influence the flow rate that will be achieved in practice.

Fields are often a complex of gas retaining structures which have varying degrees of interconnection. The amount of connectivity impacts the number and design of wells for gas recovery, and the same will be true for CO_2. Therefore the connectivity of a field's storage volume is an important part of the overall economic flow rate for a storage site. Existing gas field data will help, but saline fields need more characterisation. More work on target fields is required to establish costs and injectivity flow rates before finalising a commitment to use a particular field for CO_2 storage.

7.7.4 Decommissioning of gas fields in the study period

This study does not assume reuse of existing offshore facilities, however there should be cost reduction opportunities including the re-use of some wells, better geological and operational knowledge transfer into the new activities and deferred expenditures if CO_2 storage neatly followed gas depletion. There are risks that other fields besides Shell Indefatigable (currently decommissioning) will have to commit to decommissioning before a CO_2 store commitment can be made.

These include:

- Pickerill by about 2013
- Amethyst E & W, Indefatigable & SW and Hewett by about 2015
- Audrey by about 2017
- Ravenspurn N
- Vulcan by 2020.

Given the lack of a business case for storage it is difficult to see why existing operators will manage field decommissioning, including well abandonment details of penetrated aquifers, in a way that is ideal for future CO_2 storage. Providing a viable business case, plus interpretation of current decommissioning plans in the light of potential CO_2 storage, is therefore important in reducing costs.

Figure 7.1 Overview of UK oil and gas fields including the Utsira Aquifer

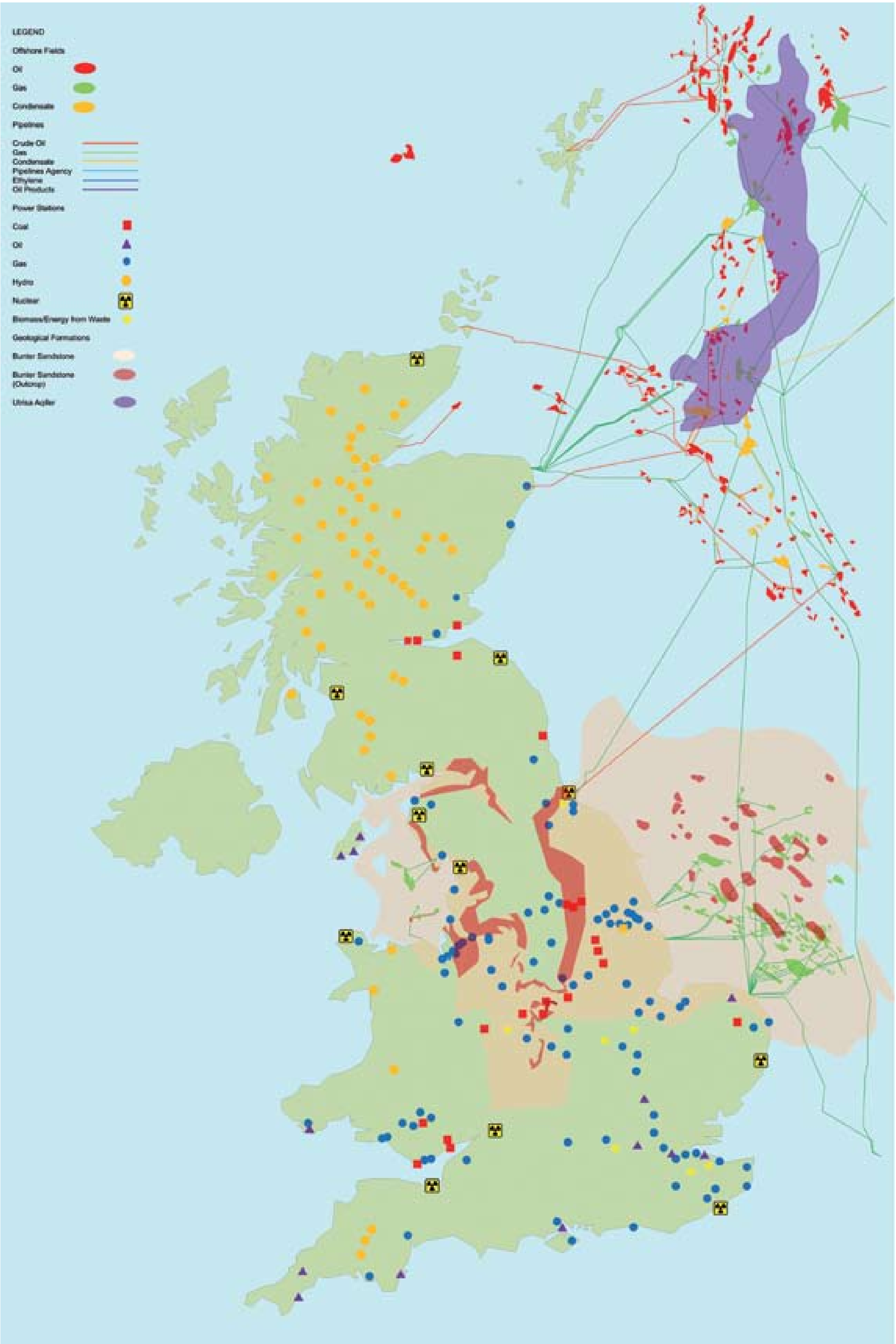


Table 7.1 Potential storage sites – gas field

Gas Storage Field	Availability Range		Storage Capacity (mt)	Distance from Easington (km)	Distance from Theddlethorpe (km)	Injectivity
Leman (Permenco + Shell)	2013	2025+	870	160	140	Good
Indefatigable & SW	2012	2015	222	180	160	Reasonable
Viking	2013	2018	214	180	170	Good
West Sole	2020	2030	136	70	80	Tight
Galleon	2022	2032	128	145	130	Tight
Hewett	2010	2015	216	130	100	Good
Indefatigable (Shell)	2005	2007	111	260	230	Reasonable
Barque & Barque S	2020	2030	89	100	100	Good
Victor	2015	2020	73	220	180	Good
Ravenspurn North	2013	2018	59	70	90	Tight
Vulcan	2015	2020	53	160	140	Reasonable
Audrey	2012	2017	49	140	140	Reasonable
Clipper N	2030	2035	46	135	125	Tight
Amethyst E & W	2010	2015	46	45	55	Tight
Sean N & S	2035	2040	44	220	200	Reasonable
Schooner	2019	2024	41	155	170	Tight
Pickerill	2008	2013	40	70	65	Tight

Table 7.2 Potential storage sites - saline aquifer

Saline Aquifer (Tyndall ref)	Storage Capacity (mt)	Depth (m)	Underlying Gas field(s)	Remarks from Tyndall
2/48	3169	1100	approximately congruent to West Sole	Large normal fault cuts through the structure.
3/48	2302	1200	linear under Barque and Clipper N.	Galleon nearby. Many faults in the seal on the above lying Bunter sandstone.
4/49	1114	1400	Viking block 48/17	Movement of salt has caused faulting on the flanks of the structure. Faults extend upwards to the seabed.

For consistency all data is from the Tyndall report [3] except the capacity for Hewett is doubled given the information in the EEGR report [2]. Injectivity assumptions in calculations of fill rates use the EEGR report figures. Other minor differences are by this study.

In analysing the ability of a single field to meet demand out to 2030 only four targets stand out; Leman, Hewett, Indefatigable and Viking. This is a somewhat simple view given the ownership issues and multiple platform developments actually in place, but is useful from a trunk pipeline point of view.

The total volumes available appear to be large, but leaving aside 308mt capacity of isolated and some low injectivity fields, and ignoring saline aquifers, the volume available is 2066 million tonnes. This is sufficient to meet high end projections out to 2050. With added sources after 2030 “Low” to 2050 is 1072mt, “High” to 2050 is 1681mt. The residual storage after 2050 if storage was at a rate of 50mt/year is about 8 to 20 years. This is not an immediate problem but consideration needs to be given to the likelihood that unforeseen circumstances make a large field unavailable, that the saline aquifers cannot contribute to local storage capacity, and that other regions are looking to store CO_2 in this area. These plus options for storage after 2050 suggest that improving surety of local storage and routes to storage further away are areas for further study.

7.8 PIPELINE ROUTES

We discussed and agreed an assumption that route landfalls would be at either Dimlington-Easington or Theddlethorpe because of the existing facilities for compression/pumping plant and a history of environmental approvals and construction experience for pipelines across the beach and near shore seabed profiles.

The other major assumption was that storage site facilities would not be assumed to have CO_2 compression/pumping equipment due to the cost of maintenance. The pipeline therefore must be able to deliver at the pressure required near the point of maximum storage capacity for the field or saline aquifer, at the required flow rate, though the well may be designed for a higher pressure. Unmanned offshore facilities are therefore possible when the pipeline pressure rating is sufficient.

Routing design then focused on options between the two gas terminals and the major storage opportunities. However pipelines to those areas pass near to other smaller fields and it is this which makes the optimisation more difficult. Notably Leman, easily the most important area with over 800mt storage, will see Shell looking to decommission a large part by 2025 whilst Perenco will continue production past 2030, thus requiring management to avoid the risk of interference between gas production and CO_2 storage. Hewett is on the way to Leman from Theddlethorpe, with as early or earlier availability, so the obvious plan is to inject in Hewett until the early 2020s, then extend the trunk line to Leman. We label this the HL storage option. Hewitt and Leman lie south of the saline aquifers and are the most southerly fields. Additional storage requirements will need to be met by extending the route north and east.

Indefatigable lies slightly further away than Viking and Leman and has an earlier gas decommissioning date. Given the size of Leman and dates they are less likely to be attractive as an extension of the HL storage option, but is an attractive area to route a trunk pipeline to as an alternative to Viking in the first instance. If Viking is used first, then Indefatigable, including the depleted Shell area, would be a valuable extension area once Viking is full. Viking represents the other major target area for trunk pipelines.

Firstly, like Leman, there are closer fields lying on the route to Viking that offer a phased development of the pipeline. It is also overlain by a significant, and potentially most likely aquifer storage of 1114mt capacity which could be proven whilst Viking is used for CO_2 storage. The problem with this option is the uncertainty about the use of saline aquifers, so a routing that picks up other stores is needed. Beyond Viking the Indefatigable field offers an excellent store as an alternative to an aquifer, and would extend the network to near the UK eastern limits.

The intermediate storages that could be cheaply served by a pipeline to Viking include Amethyst E & W then Pickerill, Barque & Barque South, Galleon and Audrey, all lying on a line from the Dimlington /Easington terminal, and similarly from Theddlethorpe (maybe without Amethyst). As noted before some of these fields have low injectivity and would not be attractive unless easily served, have low flow rates and some re-use of facilities occur. This alignment also opens up future cost effective pipe options for the aquifers 2/48 and 3/48, and Clipper. We label this Viking by increments route VI.

The residual fields include Victor and Vulcan, possibly accessed from Leman or a Viking pipe route and making use of some existing pipelines, Sean as an eastern outlier and Schooner well to the north east. Ravenspurn North may be a special case as it deserves consideration as a possible step in a link to the northern North Sea or Schooner and saline aquifers, or as an opportunity for a pipeline from Dimlington.

Table 7.3 Summary of core routes

Route		Total distance km	Note
Easington	VI	191	Includes Indefatigable
	HL	210	Pre 2030 only
Theddlethorpe	VI	195	Includes Indefatigable
	HL	190	Pre 2030 only
Dimlington	Ravenspurn	70	

7.9 SUMMARY OF CORE ROUTES

On the basis of simplicity the HL option is best, particularly if high flow rates occur quickly and high well and field development costs mitigate against smaller storage sites.

For uncertain timings of CO_2 flows and a reasonable build up of flow the VI option appears best. It is possible to see that both routes would be developed if there is distinct phasing of the onshore system.

The following lengths include allowances for infield pipelines.

The modelling of the filling schemes was done for both the HL and VI routes. Of particular note was the constraint of injectivity, meaning that all fields are found to be in use for at least 10 years with more than one field storing CO_2 at all times after the start, thus mitigating the risk of a problem with a single field. It may be better for some fields to be further investigated to see what actual injectivity can be achieved as in general the timing of pipeline investment is driven by injection rates, not the storage capacity of the stores.

7.10 OFFSHORE ROUTE CHOICE

The onshore design has led to a preference for a route from Theddlethorp. The choice between the VI and HL routes was determined by the relative costs, with VI not requiring early extension to Indefatigable if the adjacent aquifer is proven the HL being on average more costly. The major uncertainty, which affects both, is the potential use of saline aquifers. If no aquifer on the VI route is proven then VI would also be extended to Leman to provide secure storage. Conversely if the HL route was chosen the line extensions would be northwards to Indefatigable, Viking (including the aquifer), and Barque in order to meet possible scenarios.

7.11 DECOMMISSIONING OF OFFSHORE PIPELINES

The lives of the assets included in this study extend beyond 2050. We assume that decommissioning would be as is done for existing large diameter pipelines, which is that they are filled with inhibited seawater and left in-situ as the best current practice solution.

8.0 DEPLOYMENT SCENARIOS

8.1 DEVELOPMENT OF THE NETWORK

This transport study is focused on the period 2013 to 2030 to reflect the period in which key investment decisions in capture plants and local depleted gas reservoirs will most strongly interact. It is only focused on the needs of the Yorkshire and Humber area. This is in order to obtain a realistic estimate of the transport cost component of a decision to invest in carbon capture and storage.

In the bigger picture, such as considered by the North Sea Task Force, enhanced oil recovery (EOR) in the northern North Sea, large scale saline aquifer storage, longer pipelines, and international trade in storing CO_2 are important considerations. We assume that on balance these are positive opportunities for the further use of CCS in the Yorkshire and Humber area, and that additional and longer term use of CCS will be possible by extension of the network in the longer term. Too much speculation on the exact shape of that, beyond the asset life of the initial capture and storage decisions, seems unnecessary. However to be safe we have modelled the assumption that all the Tier 0 (over 1mt/year) and much of the smaller emitters up to 2050 do use CCS and shown that there is sufficient local storage to accommodate that amount of CO_2.

This study does take the simple premise that the amount of CO_2 emissions are as current emissions plus publicly known proposals, such as new IGCC plants, plus correction for known short term reduced emissions due to low plant utilisation. This means that old plant, destined to be decommissioned in the study period, is assumed to be replaced with plant with the same emissions, and CCS choices are made at that time. It does not attempt to model plant outputs or for example the area's grid export capacity. However factors such as increased electricity demand are reflected in the scenarios because plant replacements are brought forward by prices and use of CCS with the new plant is evaluated. Whereas the old gas turbine or sub critical coal plants would not be retrofitted for CCS.

The presence of oil refinery skills and the opportunity to build IGCCs means that not only CO_2 but also H_2 are more readily available. The inclusion of the possibility of H_2 pipelines in the routing considerations is not important to the volume of CO_2 transported, but is done to enable alternative investment decisions in base and peak power matching, chemical plants, and transport energy planning.

Enhanced oil recovery is perhaps the best driver for CCS, relying as it does more on oil prices than political decisions about CO_2. The density of sources in the study area makes it an excellent and secure source for a commercial use of CO_2. The disadvantage is the distance from the area to the oil fields. The proximity of depleted gas reservoirs is a significant risk reduction for sources wanting a low cost and secure sink for their CO_2, against an EOR contract with shorter term and more onerous supply conditions which, if transport costs were lower, may offer lower unit costs. Given that there are other large sources closer to EOR opportunities that suffer from more expensive storage costs we considered that for the study period the area may not be competitive, and could not rely on, EOR as a sink for CO_2.

Shipping and long pipes for CO_2 for EOR will be a potential boost for CCS in the region. Any such reduction in use of the offshore pipelines in the network scenarios is as likely to be offset by additional opportunities to transport CO_2 from regions around the study area and in offering a secure sink for CO_2 as an alternative to EOR.

With the above in mind the following three scenarios were developed to bound and stress the timing and size of the CO_2 transport network.

The general path of the network is depicted in figure 8.1.

8.2 CENTRAL SCENARIO

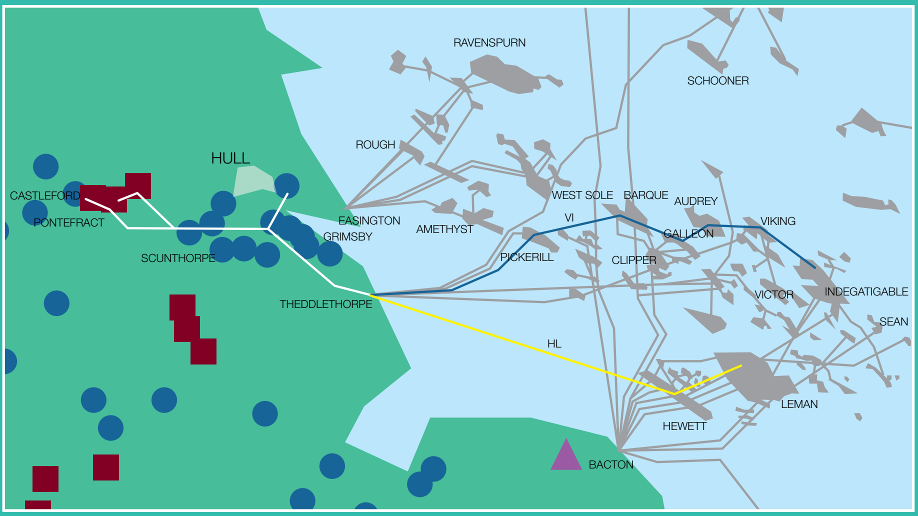
Broadly this describes there being no CO_2 transported until 2016, with by 2030 10 of 15 Tier 0 sources connected to the network. This reflects a very substantial level of activity deploying CCS in response to real drivers.

8.2.1 Scenario concept

Principal influences are assumed to drive initial investment because of:

- Phase 3 and 4 of the ETS look as though CO_2 values are in the €30-40/tonne range.
- The outlook for coal prices is for 10 to 15 years to remain systematically cheaper than gas and that Australia has invested in more capacity.
- EU proposals covering CCS have EU Parliamentary and majority member state support, and this is being reflected in UK legislation both in implementing EU policy to reduce greenhouse gases and in implementing the UK Climate Change Act target. Planning changes to include CO_2 pipeline classification to be as strategic as high pressure gas lines.

Figure 8.1 General network route showing alternative offshore routes



- ETS auctioned revenues from 2012 are used to enable 3, 450MW scale IGCC demonstration CCS plants and associated infrastructure in the area operational by 2020.
- The competing uses for generation investment of nuclear, CCGTs and wind are not compellingly more attractive in company portfolios.
- The Yorkshire and Humber area has a low cost base for transport and storage of CO_2 from capture sources.

To maintain a steady growth in CO_2 reductions beyond the initial government encouraged demonstrations and maintaining the above international market drivers through the 2020s will be moderated by factors such as

- Good progress in significantly reducing the technical risks around capture, transport and storage. This includes secure storage, acceptable transport parameters, and operating up times and costs for the capture technologies.
- Reasonable ability of industry to man up as nuclear builds match about present fleet. Sufficient knowledge and skill development to rank the UK as an important CCS country. This does assumes a redirection of effort from Olympic Games type work to power coal and nuclear power station construction from 2011 on.
- There is a definite shift away from oil for transport points to additional power generation for electric/fuel cell cars, but biofuels and improved efficiency are helping meet targets.
- Predictable growth in the local network size to maintain good utilisation of pipes and storage to maintain the Yorkshire and Humber area as a low cost base for transport and storage.
- Good public understanding of the CCS principles and support for the concept.

The long term investment decisions towards the end of the 2020s will have sufficient confidence in the following issues:

- The long term energy sources for the UK, including long HVDC links, H_2 corridors, energy for transport, and the potential for fusion, are understood enough to maintain changing the existing coal emitters to CCS.
- However efficient use of coal is becoming an issue but natural gas CO_2 capture is becoming viable.
- Smaller, varied emitters, such as biomass CHP plants, and industrial processes have access to capture technology, and can benefit from CO_2 trading and incentive schemes, to enable them to capture CO_2 and inject into the low cost regional infrastructure.

8.3 LOW GROWTH SCENARIO

This describes CO_2 flow beginning in 2017, with 8 of 15 Tier 0 sources transporting by 2030. This illustrates a scale of activity for an extensive network. It is not a low level of CCS activity- in the worse case nothing may be built before the mid 2020s and there is therefore no need for a network solution. It achieves some useful impact by 2030.

8.3.1 Scenario concept

Principle influences are assumed to drive initial investment because of:

- Phase 3 and 4 of the ETS look as though CO_2 values are in the €15-25/tonne range because of pressure to relax the National Allocations because of trade fears and energy intensive industry lobbying and low cost post Kyoto CDM type certificates.
- The outlook for coal prices is for 10 to 15 years to remain cheaper than gas but with increased volatility.
- EU policies covering CCS are not mandatory and energy security as the priority is reflected in UK legislation both in implementing EU policy to reduce greenhouse gases and in implementing the UK Climate Change Act target. No allowances for testing storage integrity or changes to present planning rules for CO_2 pipelines.
- ETS auctioned revenues from 2012 may be used for demonstration CCS plants and associated infrastructure by bidding in “rounds” of capacity.
- The competing uses for generation investment of nuclear, CCGTs and wind are more attractive, though companies want CCS in their portfolios.
- The Yorkshire and Humber area may have a low cost base for transport and storage of CO_2 from capture sources.

To maintain any growth in CO_2 reductions beyond the initial government encouraged demonstrations and maintaining the above international market drivers through the 2020s will be moderated by factors such as:

- Progress is made in reducing the technical risks around capture, transport and storage by pilot plants. This includes secure storage, acceptable transport parameters, but there remains uncertainty over operating up times and costs for the full scale capture technologies.
- There is a focus on nuclear builds and internationally the UK is not seen as a knowledge or skill centre for CCS.
- Policy, efficiency and oil price moderation means there is no additional demand for electricity, or hydrogen, for transport use.
- Growth in the local network size is entirely driven by specific projects and there is little networking benefit or capacity to for new CCS projects to use.
- Public uncertainty of the CCS principles and support for the concept.

The long-term investment decisions towards the end of the 2020s will have sufficient confidence in the following issues:

- The long term energy sources for the UK, including long HVDC links, H_2 corridors, energy for transport, and the potential for fusion, are understood enough to discourage investment in coal CCS.
- Natural gas CO_2 capture remains unviable.
- Some smaller, varied emitters, such as biomass CHP plants and industrial processes have access to capture technology and benefits from ETS and incentive schemes to enable them to capture CO_2, but transport and storage costs are high.

8.4 HIGH SCENARIO

In this case the network starts to work in 2014, with 12 of the 15 Tier 0 sources using it by 2030. It illustrates what might be possible given a very large drive to address climate change as soon as possible knowing the positive impact of early action.

8.4.1 Scenario concept

Principal influences are assumed to drive initial investment because of:

- Phase 3 and 4 of the ETS look as though CO_2 values are in the €45-60/ tonne range.
- The outlook for coal prices is for 10 to 15 years to remain systematically cheaper than gas and China's demand growth is well matched by supply.
- EU proposals covering CCS have strong EU Parliamentary and majority member state support, and are part matched by China and others. This is reflected in UK legislation both in implementing EU policy to reduce greenhouse gases and in implementing the UK Climate Change Act and meet energy diversity goals with specific plans to for CCS implementation. Planning changes to include CO_2 pipelines as strategic and EU cooperation to develop North Sea storage and EOR.
- UK takes a lead by 2010 to commit to use ETS auctioned revenues from 2012 to enable 4, 900MW scale IGCC demonstration CCS plants, 1 oxy fuel and a second post combustion demonstrator with associated infrastructures oversized to encourage more capture projects.
- The competing uses for generation investment of nuclear, CCGTs and wind are less attractive in company portfolios.
- The Yorkshire and Humber area has a low cost base for transport and storage of CO_2 from capture sources with a strong cluster of four large demonstration plants and additional CCS capacity operational between 2014 and 2020.

To maintain a growth in CO_2 reductions beyond the initial government encouraged demonstrations and continuing the above international commodity market drivers through the 2020s will be moderated by factors such as:

- Good progress in significantly reducing the technical risks around capture, transport and storage. This includes secure storage, acceptable transport parameters, and operating up times and costs for the capture technologies.
- Private-public focus on training skills ability of industry to man up for new coal and nuclear rebuilds. Sufficient knowledge and skill development to rank the UK a leading CCS country. Clear redirection of effort from Olympic Games type work to power coal and nuclear power station construction from 2011 on.
- Low carbon power demand increases the demand for CCS to meet increased energy replacement of oil for transport by use of hydrogen and electricity.
- Attractive growth in the local network size allows early investment in pipe capacity and storage and maintains the Yorkshire and Humber area as a low cost base for transport and storage.
- Good public understanding of the CCS principles and support for the concept.

The long-term investment decisions towards the end of the 2020s will have sufficient confidence in the following issues:

- The long-term energy sources for the UK, including long HVDC links, H_2 corridors, energy for transport, and the potential for fusion, are understood enough to make it easy to decide to invest in CCS.
- Steady improvement in CCS technology makes better use of coal and natural gas CO_2 capture is viable.
- Smaller, varied emitters, such as biomass CHP plants, and industrial processes have access to a range of capture technologies and are driven by allocation of allowances and some demonstrator schemes to enable them to capture CO_2 and inject into the low cost regional infrastructure.

8.5 STAND-ALONE COMPARISON

The alternative to a network approach, particularly initially when driven by individual projects, is the standalone solution of one source, transport, and a storage site.

Reviewing the Tier 0 sources, which emit over 1mt/year, the obviously ideal location for a standalone scheme is the Saltend site. This has the benefit of being close to the coast and a gas terminal, with a number of storage sites as noted in the section on storage. It is also isolated by the cost of an estuary crossing to join up with the cluster of emitters at Immingham. These factors make it a good test case when compared to say testing Ferrybridge with a standalone CCS system.

Saltend was therefore used as comparison case. It is to be stressed that this was done without any alignment with whatever plans that site may have, but only to illustrate the impact of a network solution.

An analysis was done for the central case with the three discount rates using the same cost data. It so happens that in this case the Tier 0 emissions at Saltend are assumed to start to be captured in 2023, as well as the Tier 1 emissions from a foreseen development at the site, both capturing and storing 90% of the foreseen CO_2 emissions, and is assumed to continue at the same rate to 2050. This gives an ideal case of a significant flow rate from an ideal site of 3.1 mt/year. The target storage site is Ravenspurn which has the required injectivity for the source flows. Note that Amethyst, West Sole and small depleted fields are also potential targets. There is also potential reuse, at least for some years, of existing pipelines and use of offshore compression. These potentials also apply to the network solution, and to make the point for comparative evaluation both the standalone and network use the same assumptions of new pipelines and minimal offshore facilities. Please note that this is not a statement about any plans that in fact asset owners in this local area may have.

8.6 SCENARIO QUANTITIES

The flow rates for these scenarios is illustrated in figure 8.2.

As discussed above the flows are primarily from Tier 0 emitters because their volumes are the determinant of any sizing of a large scale transport solution, which in turn will enable smaller emitters to be connected. There demonstration and initial plant will bring learning and cost reduction which will gradually make the capture of smaller scale emissions more economic. No scenario includes Tier 2 flows before 2030. The “Low” scenario does not have Tier 1 before 2030. “Central” and “High” have 0.3mt/year from 2023 and 2020 respectively, and “High” has increased Tier 1 flow to 1 mt/year by 2030.

The cumulative total volumes are as shown in the table overleaf. Note that flows are extended through to 2050 based on continuing the trend in the scenario. This was done to stress test the network capacity and indicates the potential to store CO_2 in the context of the UK targets to address climate change.

Figure 8.2 Stored carbon dioxide per year for scenarios

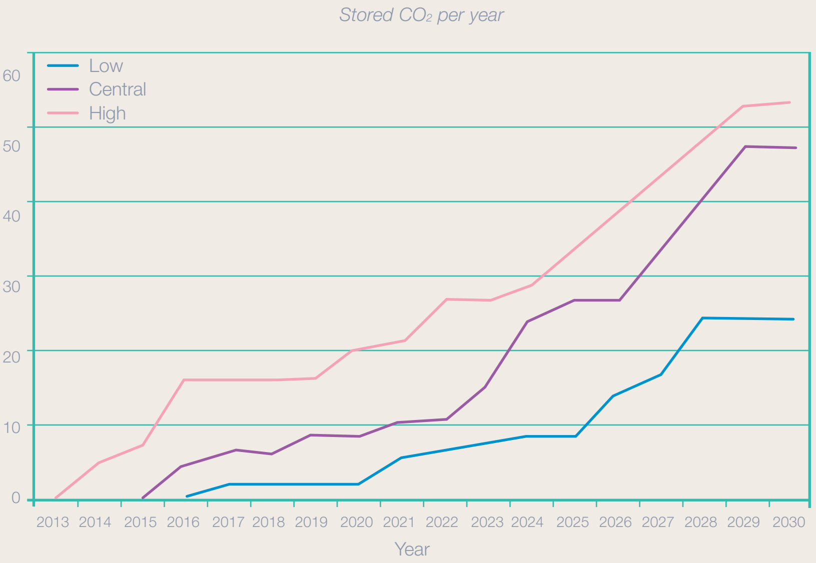


Table 8.1 Cumulative carbon dioxide stored for scenarios

Network scenarios – cumulative flows million tonnes

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
“Low”				2	4	7	9	15	21	28
“Central”	3	9	16	23	29	38	47	57	68	85
“High”	5	12	28	44	60	76	96	118	144	171

Scenarios – cumulative flow without Saltend

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
“Low”				2	4	7	9	15	21	28
“Central”	3	9	16	23	29	38	47	57	68	82
“High”	5	12	28	44	60	76	93	112	135	159

Network scenarios – cumulative flows million tonnes

	2024	2025	2026	2027	2028	2029	2030	2040	2050
“Low”	37	45	59	76	100	125	149	661	1241
“Central”	109	136	163	194	233	281	328	917	1537
“High”	200	234	273	317	365	418	471	1090	1737

Scenarios – cumulative flow without Saltend

	2024	2025	2026	2027	2028	2029	2030	2040	2050
“Low”	37	45	56	71	92	113	135	641	1216
“Central”	103	127	150	179	215	259	303	889	1506
“High”	184	215	251	292	337	387	437	1052	1697

9.0 ECONOMICS

9.1 INTRODUCTION

The transport and storage network for the capture of carbon is focused on the period 2013 to 2030, which is most likely to host key investment decisions around capture plants and local depleted gas reservoirs. The objective of the economic analysis is to find a realistic estimate of the transport cost components (onshore and offshore) of a decision to invest in carbon capture and storage. At this stage of the project, the main emphasis is focused on costs rather than a comparison between costs, revenues, financing and benefits. Decision makers will be left with the issue of evaluating potential outcomes and choosing policies to achieve these outcomes in the presence of the intense complexity of the CCS network. These complexities will not be captured at this stage, but hope to be considered in a later stage. Management options can be developed comparing the three scenarios (low, central and high) described here, to cover the range of timing and scale uncertainty in the development of a transport system in the study period.

This study refers to the volumes of transported and stored CO_2. Please note that this is not the same as abated CO_2, the measure of CO_2 used in climate change analysis and national allocation plans which under pin revenue values of CO_2. Abated CO_2 is the net savings in CO_2 emissions from a plant capturing or not capturing CO_2. The difference is the additional energy used to capture, transport and store the CO_2. This varies substantially between capture processes, but as it all has to be transported all figures here refer to stored, not abated volumes. To a small extent contaminants will also make the actual greenhouse gases stored a different amount than the volumes transported.

A context in which to consider the costs in this study is to look at the general market forecasts for CO_2 and CCS. European Union Allowances (CO_2 prices) are foreseen in the 2008 to 2020 period to be €35/tonne (Deutsche Bank, Global Markets Research 23rd July 2007 and repeated since). In another analysis by McKinsey for Vattenfall the merit order of abatement costs is plotted [10] which shows CCS as a large and necessary component in abating CO_2 in the €25 - €34 tonne CO_2 range. Scenario work by Shell [11] highlights the role of CCS but suggests needing €50 to €100/tonne to be commercial.

Looking towards about 2030 under the Central scenario, with €50/tonne CO_2 and volumes adjusted by a factor of 0.7 for abated capture revenues, the economic activity added by the carbon capture and storage users of this network may amount to £1.2bn per year.

9.2 COST BENEFIT ANALYSIS

The ideal method of analysis with a project of this nature is to compare the costs and benefits of the economic, environmental and social aspects. The capture, transport and storage of CO_2 is a complex activity and if the full benefits of the project are not considered the real value of the scheme will be undermined. Led by the Stern Review, there has been an increasing call from many quarters to subject all government programs to better cost benefit analysis, (CBA), because it provides a means of comparing complex projects, even when benefits and costs occur during different time periods. The steering group discussed this and considered that the wider impact of CCS on the area needed further study. Yorkshire Forward therefore commissioned a sustainable development study which will use input from this transport study.

9.3 UNCERTAINTY IN INPUTS

As noted earlier there are several cost data uncertainties that may affect this project, such as the price of steel and the market for lay-barges. These may have large uncertainties, for example +/- 50%, for doing work in the near term, let alone in 20 years time. For this study this uncertainty is mitigated in three ways:

- Firstly there are multiple phases over the period, with many different components, so that a distribution of results arises when combined. This ensures that the overall cost will be more accurate than the individual component accuracy.
- Secondly in order to be robust we have used current technology and new build infrastructure, and assumed that there will be no offshore compression which simplifies the interface to storage sites. Agreement to enable incremental investment does require more than one major emitter to commit, but routes and especially the onshore pipeline network does not require many emitters to commit in the early stages of the network.
- Thirdly the choices made in arriving at the presented results have been done in a consistent and comparative way. This means that it is possible to rework the IEA Mersey-Dee [14] study to compare with these figures, though the output analysis is not immediately comparable without applying the same assumptions. Within this study the comparison between the network and standalone figures are valid, but in doing a business case for a standalone or a project in the network different details and timings will give different actual costs.

9.4 DISCOUNT RATE

The decision to use an appropriate discount rate to evaluate the cost of CCS is highly important. There are a variety of discount rates that could be used in this study. Choosing the correct rate for a cost analysis or CBA is important because society wishes, in principle, to undertake a mix of public and private investments that can maximize social well-being. To undertake an investment, the expected return on that investment must cover all costs (investment, operation and maintenance costs), including the rate of interest. Under fairly restrictive assumptions, one can argue that the investment will continue until returns across alternatives are the same and just balance the returns required by savers. Under these conditions, one can argue that a single interest rate and a single rate of return on capital will prevail throughout the economy. In reality, however, there are a number of reasons that multiple rates prevail. The choice facing the decision maker is which of these many rates may apply in a CBA.

There are several important points that need to be considered when we make a decision on the discount rate:

Higher interest rate verses lower interest rates – although it is possible to define the reasons that differentiate interest rates, it does not mean that choosing a rate for analysis is a simple task. On the contrary, in the final analysis the choice of a rate is fairly arbitrary. For this reason, it is typically the case that individuals who are in favour of larger government investments to protect the environment can make arguments for low rates, whereas those who would prefer less government involvement in the economy can make equally plausible arguments for higher rates. It is clearly the case that higher interest rates will lead to fewer projects presenting positive net present values than lower ones. Unfortunately, the arguments used to support both these positions are complicated and fail to lead to a definitive solution. Undertaking an additional public project will be possible through displacing private consumption, private investment or some fraction of both. If one displaces consumption by undertaking the public investment, then the appropriate discount rate is the consumer's after tax time preference, a relatively low rate of return. If one displaces private investment the investment displaced is at a higher, before tax rate of return. Because the purpose of CBA is to increase public well-being, it does not want to use parameter variables that lower the effective national rate of return on investment or variables that displace consumption by consumers inappropriately. There are several approaches that have been suggested to cope with this problem. If one knew the proportion at which the public investment displaced private investment and private consumption he/she could weigh the two and form an average discount rate accordingly. Taking the above into consideration, perhaps, more appropriately one could apply a more complicated model to take into account the fact that the costs and benefits specifically related to the displaced private consumption and displaced private investment occur at different points in time. In practice, information needed for either approach is generally unavailable. Thus, the debate appears to return to personal preference for public investment.

Inflation – It is difficult to model the range of expectations, but, unless specifically defined and modelled, there is implicit rate within a total discount rate that reduces a series of numbers over time to a present value. We currently have a period of low inflation that sees 1.5 to 3% inflation as normal. For the purposes of time adjustment to input costs, and including implicitly within discount rates a single figure has been used for this study.

Impact of taxes – Conflict in choosing a rate generally arises over the role that taxes play in determining interest rates. Because of corporate income taxes and personal income taxes, the rate of return on a private investment is greater than the after tax return. It is also true that the consumer after tax rate of return time preference is lower than the before tax rate of return. This means that consumers make the decision of how much to save based on the after tax rate of return, while business investors make the decision of how much to invest based on before tax rates of return.

Climate change issues – Debates over long-term environmental issues such as global climate change (control of CO_2 release) tend to focus on inter-generational equity, rather than intra-generational efficiency. The choice of an interest rate is largely a pursuit to help the public sector choose investments that will improve the over-all level of national economic well-being for a given set of consumers and investors. Many investments take place over long time-spans, some of which are long enough to be inter-generational. A decision to undertake CO_2 abatement to reduce the probability of global warming is a decision to forgo the increment of consumption or retirement forever. Moreover, because most benefits will occur long into the future, almost any reasonable discount rate, even one reflecting consumption time preference, rather than private rate of return, will suggest that the project is inefficient. For these reasons, attention turns from efficiency concerns, getting the right rate of private and public rates of return, to equity concerns, taking into account the rights of future generations. Economists argue generally a social rate of time preference is appropriate for inter-generational discounting, which would be composed of two components.

The first is a "pure" time preference that is arguably zero, in the sense that a significant positive rate would preclude intergenerational investments. A zero rate means that the well-being of future generations is given equal weight to the well-being of the current generation. However, due to a second component, that rate need not be negative. The second component reflects the fact that future generations will likely be much better off economically than the present generation, even at modest rates of economic growth. Hence, policies to sacrifice current consumption in favour of future consumption essentially transfer wealth from the poorer current generation to the wealthier future generation. Thus, a small, but positive social rate of time preference is justified. This rate combines the fact that economic growth will occur, adjusted for the fact that marginal increases in wealth will yield increasingly smaller increases in economic satisfaction.

Considering these factors a decision was made to use fairly straightforward discount rates to compare cost of three different scenarios which may be visualised as based on a Bank of England rate of 5%, as:

- A lower, wider economic rate, bearing in mind the impact that this investment has on most other future investments (effective government support).
- A likely rate for a transport company well integrated by ownership and contracts with the source and sink companies for whom this is just a part of an overall investment in CCS (80% debt).
- A standalone company without any other interests (70% debt).

However this is only one perspective; the range of rates is given so that they can be interpreted from whichever rate is necessary.

The chosen discount rates are 6.5%, 11% and 14%. If not stated reported figures are based on an 11% rate.

9.5 METHOD AND INTERPRETATION OF COST CALCULATIONS

The discounting of costs over time is a way of reconciling expenditures that occur over a number of years where you are making decisions between the attractiveness of different investments. To do so, all options are calculated relative to the same year.

Starting with the cost information for the network we can say that if it was all built in 2008, that is all the pipelines, pumps and plant, it would cost about £2.0bn. If you built it in the future we expect some inflation of those costs, say a long-term average of 2% per year, so in 2013 the same plant would cost £2.2bn and for the network "Central" example with different timing of parts over the period out to 2040 the cost is £2.6bn allowing for inflation.

However not everything needs to be built today, so if as a organisation you could invest some money at the same risk as spending on the network, at say for example 11%, until you needed to actually spend it on the network. This return on investment more than offsets the inflation of costs.

The same applies to the operating costs. Between 2008 and 2040 these are £6.3bn at 2008 costs, but obviously most of this expenditure is many years ahead.

Adding the capital and operating spends for each year, adjusted for inflation, the total cost in 2008 is £8.9bn. But given the opportunity to invest between now and when the expenditure actually occurs, at a rate of 11%, we can discount the future expenditure by 11% per year. This gets all the costs of making the decision to invest in the network back to 2008 values which allows comparison of the concept of a network with alternative ways of transporting CO_2. It also provides data for adding to a business case for a full carbon capture and storage scheme which can then include revenue, taxation and other issues not included in this analysis.

Doing this reduces the amount the decision costs in 2008 to £1.44bn, made up of £0.75bn capital spend and £0.69bn of operating costs. The £2bn costing of the plant if all built now is reduced to £0.75bn due to time effects. Once you decide what your discount rate is, in this example 11%, a cost of £1.44bn, combining capital costs and operating costs, is therefore the correct way to look at the decision to invest in the network.

To further illustrate this say that no choice about the whole system was made until 2015 and the system started transporting the first CO_2 in 2016. In that case all comparisons are recalculated and referenced to 2015 pounds and there is less time for the effect of deferred expenditure to reduce the apparent costs of the decision in that year. The period considered is still out to 2040. This is an arbitrary choice of a 25 year evaluation. Because inflation and discounting is a rate per year it compounds so that the present cost of £100 in 2015 but spent in 2040 is only £12 in 2015 value.

The cost in 2015 can be said to be £2.8bn expressed in 2015 pounds.

The amount of CO_2 transported by the system can indicate the network cost. Care must be taken in use of this as it depends on how long the system is operational as the design life of most of the capital cost is greater than 25 years the average cost is reduced by more years of operation. In the "Central" scenario the amount transported by 2040 is 846 million tonnes, or 0.85bn t/CO_2.

For a 2008 decision the present cost per tonne is £1.44bn/0.85btCO_2, or £1.7/tonne.

For a 2015 decision the 2015 cost is £2.8bn/0.85btCO_2, or £3.3/tonne in 2015 costs.

The UK is relatively expensive for transport due to the high cost base and the need to transport offshore. Route lengths are at least 100km to 400km. This compares with some US examples where storage can be adjacent to the site or sold to an existing EOR pipe network. The Yorkshire and Humber area is however, in UK terms, attractive for the distances required, especially given the large volumes.

We stress that the revenue to recover this cost is much greater. A £100 today, with the same inflation and investment value as above, is the same present value as receiving £828 in 25 years. The bulk of revenue occurs much later than the capital expenditure, so the effect of its benefit in present value is also lessened. To illustrate this for the case of 2% inflation and 2% discount the cost per tonne expressed in terms of capital and operating cost may be £1/tonne, but expressed in terms of revenue timing maybe £5/tonne.

A number of other issues affect revenue requirements and without a commercial structure for the network it is premature to advise the minimum revenue to recover the transport costs, but is certainly greater than the above due to the time difference between expenditure and revenue. Similarly a full economic analysis requires the wider economic benefits to be calculated over time. The costs in this study can be used as input costs to those financial and economic evaluations.

9.6 RESULTS

Simple analysis of the cost comparison of high, central and low scenarios of onshore and offshore CCS is given below.

The capital expenditure, expressed in 2008 terms and shown by cumulative amounts up to the date given is shown in the table overleaf.

Table 9.1 Cumulative capital cost

Cumulative capital cost £ million						Cost to accommodate only pre 2030 sources
Discount	Year	2020	2030	2040	2050	2050
6.5%	Low		725	908	961	725
	Central	825	1,205	1,205	1,205	1,073
	High	1,007	1,304	1,304	1,304	1,132
11%	Low	297	434	499	514	434
	Central	579	763	763	763	708
	High	763	899	899	899	827
14%	Low	230	316	349	356	316
	Central	465	579	579	579	550
	High	640	723	723	723	682

The variability of timing in line with growth of inputs and filling of storage sites gives rise to some steps in the data. In addition if only the sources connected to the network before 2030 are served by the network through to 2050 then some expenditure just before 2030 is not necessary, as well as capital spend after 2030. The effect of this reduced capital expenditure is illustrated in the right hand column of table 9.1.

For all scenarios the spend to 2050 if all the network was built today is £2bn, but if the capacity was limited to 2030 flow rates the costs would vary from £1.3bn to £1.7bn.

Table 9.2 Cumulative carbon dioxide stored

Cumulative CO_2, million tonnes to date					With capital to only accommodate pre 2030 flow rates
Year	2020	2030	2040	2050	2050
Low	9	149	526	1,072	632
Central	35	314	846	1,450	1,263
High	96	471	1,048	1,681	1,543

The cost per tonne stored is based on capital costs and operating costs, expressed as 2008 costs, divided by the cumulative amount of CO_2 stored. The initial flows start between 2014 and 2018, and for a 25 year project analysis the 2040 figures are the most relevant, but the 2050 figures are most relevant for climate change targets. The costs per tonne are shown in the table opposite.

Table 9.3 Cumulative average cost £/tonne

Cumulative average cost £/tonne CO_2 stored

Discount	Year	2040	2050	2050 only for 2030 sources
6.5%	Low	3.34	1.98	2.85
	Central	3.28	2.21	2.27
	High	2.76	1.92	2.02
11%	Low	1.57	0.88	1.30
	Central	1.71	1.06	1.12
	High	1.57	1.01	1.09
14%	Low	1.02	0.53	0.84
	Central	1.18	0.71	0.76
	High	1.16	0.73	0.79

The conclusion is that for the central case by 2040 846 million tonnes would be transported for an average cost of £1.71/tonne. Due to timing of investments and design differences the other cases in this instance have a lower cost per tonne, but the table shows that different discount rates have more influence on costs per tonne than do the differences between scenarios.

If not otherwise noted the costs per tonne refer to the 2040 volumes and cumulative costs at 11% discount using £1.70/tonne.

Analysis of the most favourable standalone case of a near coastal source using just Ravenspurn North for storage from the same date as the central scenario shows the following comparison:

Table 9.4 Cumulative average cost £/tonne best stand-alone comparison

Cumulative average cost £/tonne CO_2 stored

Year	2040	2050
Ideal standalone	1.83	1.33
Central	1.71	1.06

An inland site has additional pipeline costs and future business case analysis may show revenue requirement differences which make the standalone case less attractive, but the first emitter to commit to CO_2 capture and storage does face higher costs whether or not their pipeline becomes part of an evolving network. There is therefore a need to address the problem of network initiation.

10.0 CONCLUSION

The first step in meeting the aims of the Carbon Capture and Storage Partnership for Yorkshire and Humber was to focus work on the economic costs of the transport component, excluding capture and storage costs, of a carbon capture and storage (CCS) area network solution serving multiple sources and offshore geological storage.

The major commercial concern regarding CCS is uncertainty of the value of CO_2. For a particular plant the major cost decision faced by an individual plant operator is that required to capture their CO_2, as the capture largest cost component of CCS. This study does not address the value or revenue or accounting aspects of CCS.

This study provides a regional level transport feasibility study. It shows that a network decision at an economic level is relatively cost attractive, which is important in terms of choices regarding what the UK should do to reduce CO_2 emissions.

The inputs for individual investments cascade down from a global level, well beyond local concerns, but what can be achieved at regional level is the provision of a route and storage option for a local emitter considering capture of their CO_2.

The amount of storage near to Yorkshire and Humber is large, but not much larger than the potential maximum supply from the region to 2050, or if emitters from outside the region decide to store CO_2 in the same area of the southern North Sea. Even though the potential for use of depleted gas fields is very good, access, injectivity and volumes require to be confirmed. Furthermore, there is a definite need to establish the availability or otherwise of saline aquifer storage. The preferred offshore routing reduces access costs to the larger aquifers, or routes to enough depleted gas fields to accommodate output from emitters starting to capture before 2030 and continuing to store until 2050. To have the most security of choice for local storage, including post 2050 storage, without use of deep saline aquifers, all the large depleted gas fields are needed to meet the CO_2 capture scenarios.

To develop a CCS network to service more than one plant, the additional issues of transport and storage of CO_2 need to be in place to support an investment decision on CO_2 capture at multiple sites.
The next steps to do this are described in the recommendations section.

Considering what commitment is required to create a network some of the choices within the scenarios suggests that a general aim to deploy CCS at large scale is important as it enables economies of scale. However, the detailed timing and level of emissions from a single source are only important over a shorter term, i.e. within about a 5 to 7 year window. In other words in the short term the sizing and routing decisions are affected by significant (>200,000t/year) volumes. Thus long-term commitments enables pipelines, generic way leave planning and agreements on storage sites, short term commitments enables incremental pipe sizing and offshore well developments.

The initiation of a network remains a particularly difficult problem as the first user takes a much higher risk and greater costs than someone joining after it is well established.

A key recommendation is to address how to provide the first parts of the network. The main thrust is to aim to re-use existing infrastructure when the first commitment is relatively small. This must reduce costs and will also have value if it can defer costs. The uncertainties include timing, technical suitability, decommissioning and ownership transfers or agreement on asset costs, store licensing and liabilities

A second part of this initial phase, and for each large capacity increase, will be the aggregation of commitments. For this we see the Carbon Capture and Storage Partnership for Yorkshire and Humber as the starting point.

Looking to the local community, communication and engagement will have to develop so that the benefits are understood and people have the facts available when particular questions and consultations arise so that timely and appropriate decisions are made.

Outward communication and awareness will also be important. Firstly to attract a cluster of early CCS projects, secondly to ensure national political support and thirdly, because of the excellent potential to do so, to materially contribute to meeting the UK's climate change targets.

Stern states that a disproportionately large share of the burden for achieving the required cuts will have to be borne by the power-generation sector (Reference 1 pxiii):"Large-scale uptake of a range of clean power, heat, and transport technologies is required for radical emission cuts in the medium to long term. The power sector around the world will have to be at least 60%, and perhaps as much as 75%, decarbonised by 2050 to stabilise at or below 550ppm CO_2e." Given the substantial power sector in the Yorkshire and Humber region the scale of the transport network covered by this study will support this requirement.

The range of scenarios for the network covers transport of, in total, between 150 and 470 million tonnes carbon dioxide by 2030 and by 2050 between 630 million tonnes (with no further sources added after 2030) to 1700 million tonnes (with high and continuing CCS after 2030).

The capital cost spend is about £2.0 billion if it was all built today, but spreading expenditure over time and adjusting for inflation, the present cost of a decision to build a network depends on the discount rate you choose to apply, but for a 6.5% discount the capital costs vary by scenario from £0.7bn to £1.0bn, and with a 14% discount rate the present cost of the decision is to spend £0.3bn to £0.6bn. The "Central" scenario and 11% discount gives a £0.7bn present cost.

Operating costs are also modelled and the combined capital and operating spend divided by the amount of carbon dioxide transported is used to calculate the present value using a range of discount rates to reflect the time and risk value of the expenditure. These costs, as explained previously, are not the revenues required.

The cost per tonne transported is therefore dependent on how long the system operates and under what financial assumptions, but for a fixed asset maximising volumes per year means lower costs per tonne and a longer period are cheaper per tonne. However cutting the period of consideration to from about 2015 to 2040, about 25 years of operation, the unit costs are more representative, though we are still only in 2008. The different scenarios, for a given discount rate, show very little difference in unit costs. For example for an 11% discount rate the cost per tonne varies from £1.5 to £1.7/tonne. Due to investment timing the "Central" scenario has the higher rate, and that cost of £1.70/tonne has been used as the illustrated result. The conclusion is that the discount rate is more important than the scenarios when looking at transport costs per tonne.

Given a range of discount rates of 6.5% to 14% the costs per tonne of £1.2/tonne ($2.1, €1.6/tonne) to £3.4/tonne ($6, €4.7/tonne), with a mid point of 11% of a round £1.7/tonne ($3.1, €2.4/tonne) CO_2 transported as at 2008 for the period 2015 to 2040.

11.0 RECOMMENDATIONS

The recommendations following this study are detailed and specific to the aims of the Carbon Capture and Storage Partnership for Yorkshire and Humber. Though this report shows the benefits of large scale co-operation in addressing climate change using CCS, it rests on effective initiation to the ability to transport CO_2. This will best be enabled by a cluster of projects, driven by UK government policy and other mechanisms, to quickly reduce both capture costs, transport and storage costs. Strategic leadership at the highest level is required to ensure that this project develops at the necessary pace and scale to contribute to the draft Climate Change bill target to cut CO_2 emissions compared to 1990 by 26% to 32% by 2020. Potentially, it could capture a significant proportion of those emissions by 2020. The recommendations are grouped as follows:

11.1 GOVERNMENT

Yorkshire Forward promote a cluster of CCS projects to be an early material action in addressing climate change and justify an efficient CO_2 transport and storage system driven by the co-operation by the capture site organisations and public bodies.

The UK government, through whatever process including zero emissions power projects, funding support, provision of infrastructure or other means, designate a cluster approach apply to the first phase of CCS projects in the UK demonstrating CCS at least at the scale of the current demonstration proposal. This should be in line with at least the time scales of the "Central" scenario with operation in 2016 in order to materially address the cumulative emissions of CO_2 from this country.

An early decision is needed to establish a long-term, secure funding stream from UK revenues derived from the EU Emissions Trading Scheme, both in phase II and phase III of the ETS to deploy CCS.

Provide further evidence of regional CCS benefits.

Enable regulation to secure way leaves in the same way as for natural gas pipelines.

Progress the ability to transport and store CO_2 from non-UK sources.

11.2 ECONOMIC WORK

Cost benefit analysis on the sustainable development of CCS; this has already been initiated by Yorkshire Forward.

Adopt or develop example business cases for the complete CCS activity including capture and storage to illustrate public discussions for a number of Tier 0 (Over 1m tonne/year) emitters with CO_2 value and various financial assumptions using the network transport costs as an input.

Evaluate the potential to reduce the initial costs of establishing the network by re-use of existing infrastructure.

Develop the value added aspects of CCS including enhanced oil recovery, shared use of way leaves, synergy of decommissioning gas fields, importation of CO_2 for storage, physical offsetting between sources on the network, and impacts for smaller emitters.

More detailed scenarios to understand the possible scope and benefits for the local supply of H_2 via pipeline to conveniently located smaller power and combined heat and power installations to demonstrate the possibilities.

Linear programming and sensitivity analysis to show the most effective project scenario, fundamental variables and incremental benefits or impacts from manipulating project variables.

11.3 TECHNICAL

Research into offshore storage site availability: viability of depleted gas fields, current decommissioning details, dates of use, possibility of using existing pipelines, wells and structures, and likely monitoring issues and approaches.

Research into southern North Sea saline aquifers; identify uncertainties associated with them and the methods, timescales and costs to prove them as stores for CO_2.

Further investigation of selected fields to model what actual injectivity can be achieved to determine the costs and benefits of field investment and timing of transport links.

11.4 CARBON

Research into carbon footprint of whole CCS network from each plant to storage: calculate how much carbon will be used in the whole process i.e. including converting plants/capture/transport/storage. Abated value analysis compared to stored costs.

Evaluate CCS compared to improved demand side/efficiencies, nuclear, CHP and renewable energy as a low carbon energy source.

11.5 SOCIAL

Research into public and industry perceptions of CCS; how current population feels/how to increase knowledge/how to improve perception etc.

More detailed research into environmental impacts of CO_2 transport, both pipelines and shipping.

Further research into detailed benefits both social/environmental it will bring to region as a whole.

11.6 SAFETY

Continue support for the health and safety work of the CCSA and UKCCSC.

Detailed safety case of CO_2 transportation onshore including consultation with the HSE.

The issues of a shared way-leave between CO_2, natural gas and H_2 pipes be understood and, for certain routes, way-leaves are designed with this option in mind.

12.0 CCS GLOSSARY

Anthropogenic source	Source which is man-made as opposed to natural.
Aquifer	Geological structure containing water and with significant permeability to allow flow; it is bound by seals.
BAT	Best available technology
Carbon Capture	A process by which CO_2 is extracted from flue gases for the purposes of sequestering the carbon rather than releasing into the atmosphere.
Carbon Dioxide (CO_2)	A colourless, odourless gas that is produced by respiration or the combustion and decomposition of carbon-containing materials. Carbon dioxide is essential to the photosynthesis process that sustains plant and animal life, however, it can accumulate in the air and trap heat near the Earth’s surface (the “greenhouse effect”).
CCGT	Combined Cycle Gas Turbine.
CCS	Carbon Capture and Storage, sometimes referred to as Carbon Capture and Sequestration.
COMAH	Control Of Major Accident Hazards. Major UK legislation governing chemical plants, refineries and power plants.
Depleted Reservoir	Refers to a hydrocarbon reservoir oil or gas that has had the economically recoverable hydrocarbon removed.
HVDC	High Voltage Direct Current. Means of connecting power stations to the national grid.
EOR	Enhanced Oil Recovery. In EOR fluids such as water and carbon dioxide are injected in to hydrocarbon reservoirs to enable the hydrocarbon to be extracted.
EU-ETS	European Union Emissions Trading Scheme. Process by which the allocation of carbon dioxide emission allowances for an emitter can be traded for users with excess allowable emissions to those with who require higher allowances.
GHG	Greenhouse Gas.
H_2S	Hydrogen sulphide, a pungent gas produced when sulphur containing material such as coal is burnt. The gas exists in small volumes in flue gases from combustion processes.
IEA GHG	International Energy Agency Greenhouse Gas Programme.
IGCC	Integrated Combined Cycle. A pre-combustion process for the use of coal for power generation encompassing carbon capture.
IPCC	Intergovernmental Panel on Climate Change.
kWh	Kilo Watt Hour.
NOx	The group of chemicals nitrogen oxides including nitrogen dioxide, common contaminant found in flue gases of combustions processes.
OEM	Operational Engineering Manager.
OSPAR	Oslo Paris Convention. 1992 agreement guiding international co-operation on the protection of the marine environment of the north east Atlantic.
Post-Combustion Capture	A system for CO_2 capture from a fossil fuel conversion/combustion where the fuel is combusted in air and resulting CO_2 is scrubbed, absorbed, or otherwise captured from the flue gas, which is primarly CO_2 and nitrogen.

Pre-Combustion Capture	A system for CO_2 capture from a fossil fuel conversion where the fuel is decarbonised via gasification, pyrolysis, or reforming prior to combustion. The synthesis gas from de-carbonatisation is primarily a mixture of CO_2 and hydrogen. The CO_2 is captured from the hydrogen before the hydrogen is combusted.
PSR	Pipeline Safety Regulations.
Reservoir	A subsurface, porous, permeable rock body surrounded by impermeable rock and containing oil, gas, or water. Most reservoir rocks consist individually or collectively of limestone, dolomites, or sandstone.
Saline	Also referred to as Brine. A solution of water and sodium chloride, common salt, other metal salts may also be present. Saline/brine requires extensive desalination treatment before it could be consumed as drinking water.
Saline Aquifer	Geologic formation of porous rock that is filled with saline/brine.
SOx	The group of chemicals sulphur oxides including sulphur dioxide, sulphur trioxide, common contaminants found in flue gases from sulphur bearing fuels.
Stern Review	Titled “The Economics of Climate Change”, the Stern Review, commissioned by the UK Government and led by renown economists Sir Nicholas Stern. The report examined the economic impact of climate change based on projections up to 2006, predicting cost of predicted changes to the global economy in addition to cost comparisons for abatement options.
ZEP	Zero Emissions Platform. EU programme to enable European fossil fuel power plants to have zero CO_2 emissions by 2020.

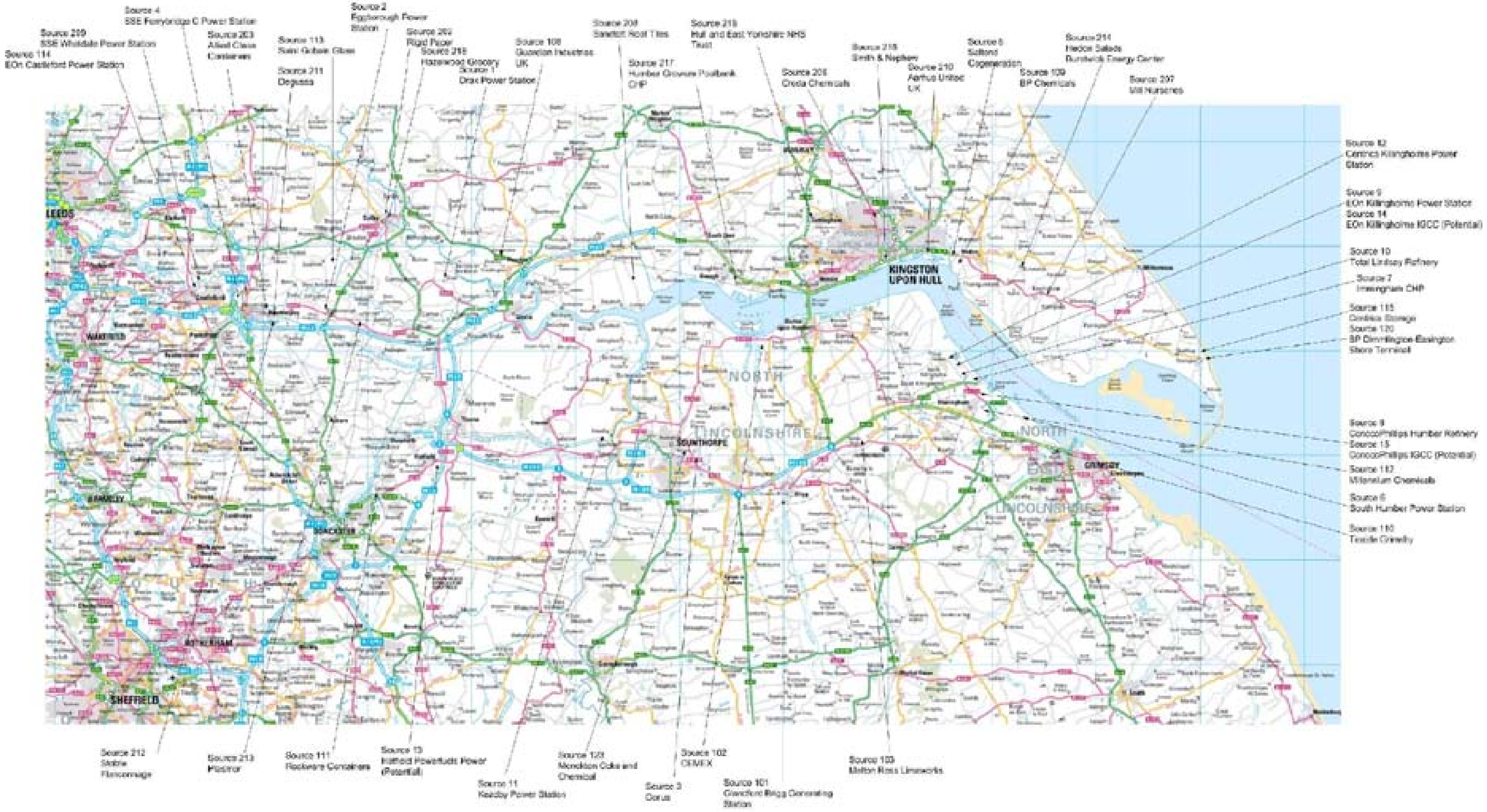
REFERENCES & APPENDICES

1. STERN REVIEW: The Economics of Climate Change **www.sternreview.org.uk**. HM Treasury 30 Oct 2006
2. Report on Infrastructure, Availability and Costs for CO_2 Transportation and Storage Offshore – Southern North Sea, East of England Energy Group (EEEGR), Feb 2006
3. An assessment of carbon sequestration potential in the UK – Southern North Sea case study. By Michelle Bentham, Tyndall Centre for Climate Change Research and British Geological Survey. Tyndall Centre Working Paper No. 85, January 2006
4. Storing CO_2 under the North Sea Basin, A key solution for combating climate change. A report by the North Sea Basin Task Force, June 2007. By the Norwegian Ministry of Petroleum and Energy and the UK Department of Trade and Industry, June 2007
5. Development of a CO_2 transport and storage network in the North Sea. A report to the North Sea Basin Task Force. In association with Element Energy Limited, Pöyry Energy, British Geological Survey, UK Department for Business Enterprise & Regulatory Reform, November 2007
6. IPCC Specail Report on carbon dioxide Capture and Storage, IPCC, Cambridge University Press, Cambridge, 2005
7. 4th Assessment Report: Climate Change 2007, IPCC, Cambridge University Press, 2007
8. **http://www.encoreoil.co.uk/pages/news/index asp?NewsID=107**
9. EU research on use of hydrogen, quote from press release and HyWays report **http://ec.europa.eu/research/energy/nn/nn_pu/hyways/article_0001_en.htm and at http://www.hyways.de/**
10. Vattenfall AS at **http://www.vattenfall.com/www/ccc/ccc/569876nextx/573533globa/index.jsp and in McKinsey Quarterly 2007 No1. mckinseyquarterly.com**
11. Shell scenarios 2005 at **www.shell.com** and presentation at the Society of Petroleum Engineers in London, January 2008
12. **http://www.encoreoil.co.uk/pages/news/index.asp?NewsID=107**
13. Meeting the Energy Challenge – A white paper on energy – DTI – May 2007
14. Feasibility Study on the distributed collection and transmission of CO_2 – Gastec at Cre – Oct 2006
15. The EU flagship programme – ZEP – Oct 2007
16. Capturing CO_2 – IEA Greenhouse gas R & D programme – May 07
17. Dynamis CO_2 Qulaity recommendations, de Visser, E et al. Ecofys, Dynamis Consortium 2006-2009, 2008

APPENDICES

Appendix A

Regional map



Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k	Included in Study /Notes
1	328	Drax Power Ltd	Drax Power Station PO Box 3 Selby North Yorkshire YO8 8PQ	Large Electricity Producers	**22,369,953**			Yes Volume adjusted by +7mt due to low power in NATS data year
2	332	British Energy	Eggborough Power Station Eggborough Goole East Yorkshire DN14 0BS	Large Electricity Producers	**7,675,086**			Yes
3	1	Corus UK Ltd	Scunthorpe Integrated Iron & Steel Works Scunthorpe Works PO Box 1 Brigg Road Scunthorpe North Lincolnshire DN16 1BP	Iron & Steel	**7,586,309**			Yes
4	325	Scottish and Southern Energy Ltd	Ferrybridge "C" Power Station P.O Box 39 Stranglands Lane Knottingley West Yorkshire WF11 8SQ	Large Electricity Producers	**6,200,279**			Yes
5	369	International Power	Saltend Cogeneration Company Limited Saltend Hedon Road Hull HU12 8GA	Large Electricity Producers	**3,122,732**			Yes
6	348	CENTRICA SHB Ltd	Centrica SHB Ltd South Humber Bank Power Station SOUTH MARSH ROAD STALLINGBOROUGH NORTH EAST LINCOLNSHIRE DN41 8BZ	Large Electricity Producers	**2,893,024**			Yes
7	2254	Immingham CHP Limited Liability Partnership	Immingham CHP Power Station Immingham CHP Immingham CHP Rosper Road Immingham North Lincolnshire DN40 3DZ	Large Electricity Producers	**2,833,392**			Yes
8	4077	ConocoPhillips Limited	Humber Refinery Eastfield Road South Killingholme IMMINGHAM North Lincolnshire DN40 3DW	Refineries	**2,399,605**			Yes
9	360	E.ON UK plc	Killingholme power station Killingholme power station PO Box 11 Immingham Grimsby NE Lincolnshire DN40 3NG	Large Electricity Producers	**2,026,243**			Yes
10	2960	Total UK Limited	Lindsey Oil Refinery Eastfield Road North Killingholme Immingham North Lincolnshire DN40 3LW	Refineries	**2,011,622**			Yes
11	357	Scottish and Southern Energy Ltd	Keadby Power Station Keadby Power Station Trentside Keadby Scunthorpe North Lincolnshire DN17 3EF	Large Electricity Producers	**1,654,765**			Yes

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa	Tier 1 tpa	Tier 2 tpa	Included in Study /Notes
					>1M	50k - 1M	<50k	
12	358	Centrica Generation Limited	Centrica Energy Killingholme Power Station Chase Hill Road North Killingholme Immingham North Lincolnshire Dn40 3eh	Large Electricity Producers	**1,497,168**			Yes
101	366	Centrica Brigg Ltd	Glanford Brigg Generating Station Scawby Brook Brigg North Lincolnshire DN20 9LT	Large Electricity Producers		**603,370**		Yes
102	640	CEMEX UK Cement Limited	South Ferriby Works South Ferriby Cement Plant South Ferriby Barton-Upon-Humber North Lincolnshire DN18 6JL	Cement		**569,251**		Yes
103	662	Singleton Birch Limited	Melton Ross Limeworks Melton Ross Quarries Melton Ross Quarries Barnetby North Lincolnshire DN38 6AE	Lime		**316,063**		Yes
104	93	Humber Energy Limited	Humber Energy Limited Grimsby Power Station PO Box 24 Great Coates Grimsby North East Lincolnshire DN31 2SS	Chemicals		**286,564**		Yes
105	691	Redfearn Glass Ltd	Redfearn Glass Ltd Burton Road Monk Bretton Barnsley South Yorkshire S71 2QG	Glass		**171,063**		No Not in study area
106	23	CORUS UK LIMITED	CORUS ENGINEERING STEELS - ROTHERHAM ROTHERHAM WORKS ROTHERHAM WORKS PO BOX 5 ALDWARKE LANE ROTHERHAM SOUTH YORKSHIRE S60 1DW	Iron & Steel		**159,043**		No Not in study area
107	2454	Guardian Industries UK Ltd	Guardian Industries UK Ltd Goole Rawcliffe Road Goole East Riding of Yorkshire DN14 8GA	Glass		**145,830**		Yes
108	127	BP Chemicals Ltd	BP Chemicals Ltd, Hull Saltend Hull East Yorkshire HU12 8DS	Chemicals		**138,127**		Yes
109	2522	NPOWER COGEN LIMITED	TIOXIDE GRIMSBY CHP PLANT HUNTSMAN TIOXIDE GRIMSBY MOODY LANE GRIMSBY NORTH EAST LINCOLNSHIRE DN31 2SW	Chemicals		**133,225**		Yes
110	2788	Rockware Glass	Rockware Glass - Wheatley Wheatley Rockware Glass Barnby Dunn Road Doncaster South Yorkshire DN2 4RH	Glass		**130,595**		Yes

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa	Tier 1 tpa	Tier 2 tpa	Included in Study /Notes
					>1M	**50k - 1M**	**<50k**	
111	283	Millennium Inorganic Chemicals Ltd.	CHP Plant Millennium Inorganic Chemicals Ltd. Laporte Road Stallingborough Grimsby NE Lincs DN40 2PR	Chemicals		**129,426**		Yes
112	249	E.ON UK Cogeneration Ltd	Thornhill power station Calder Road Ravensthorpe Dewsbury West Yorkshire WF12 9EA	Other Electricity Producers		**119,921**		No Not in study area
113	2811	Saint-Gobain Glass UK Ltd.	Saint-Gobain Glass UK Ltd. Eggborough Plant Weeland Road Eggborough East Riding of Yorkshire DN14 0FD	Glass		**113,507**		Yes
114	2748	E.ON UK Cogeneration Ltd	Castleford Power Station Castleford Power Station Wheldon Road Castleford West Yorkshire WF10 2JT	Other Electricity Producers		**112,754**		Yes
115	2216	Centrica Storage Ltd	Centrica Storage Ltd Easington Terminal Dimlington Road Easington, Nr. Hull East Yorkshire HU12 0SX	Downstream Gas		**110,965**		Yes
116	2840	Viking UK Gas Limited	Knapton Generating Station Knapton Generating Station Knapton Generating Station East Knapton Malton North Yorkshire YO17 8JF	Other Electricity Producers		**88,187**		No Not in study area
117	148	Ciba Specialty Chemicals Water Treatments Ltd	Ciba Specialty Chemicals Ltd - Bradford Bradford P. O. Box 38 Low Moor Bradford West Yorkshire BD12 OJZ	Chemicals		**79,540**		No Not in study area
118	703	Rockware Glass	Rockware Glass - Headlands Headlands Headlands Lane Knottingley West Yorkshire WF11 0HP	Glass		**79,035**		No Not in Study area
119	142	British Sugar Plc	York Sugar Factory P.O. Box 17 Boroughbridge Road York North Yorkshire YO26 6XF	Food and Drink		**75,630**		No Not in Study area
120	129	BP Exploration Operating Company Ltd	Dimlington-Easington Shore Terminal Dimlington-Easington Shore Terminal Easington Kingston upon Hull East Riding of Yorkshire HU12 0ST	Offshore		**75,004**		Yes

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k	Included in Study /Notes
121	289	Syngenta Limited	Syngenta Limited Huddersfield PO Box A38 Leeds Road HUDDERSFIELD West Yorkshire HD2 1FF	Chemicals		**73,334**		No Not in study area
122	683	Allied Glass Containers Ltd	Allied Glass Containers Ltd - Leeds Leeds Works South Accomodation Road Leeds West Yorkshire LS10 1NQ	Glass		**70,464**		No Not in study area
123	182	Georgia Pacific GB Ltd	Oughtibridge Mill Georgia-Pacific GB Ltd, Oughtibridge Mill Main Road, Wharncliffeside, Oughtibridge SHEFFIELD South Yorkshire S35 0DN	Pulp & Paper		**66,327**		No Not in study area
124	2614	Dalkia Utilities Services	Leeds Infirmary Generating Station Complex Leeds Infirmary Clarendon Way Leeds West Yorkshire LS1 3EX	Services		**57,511**		No Not in study area
125	8	The Monckton Coke and Chemical Company Ltd	The Monckton Coke and Chemical Company Ltd Lundhil Lane Royston Barnsley South Yorkshire S71 4BE	Chemicals		**55,805**		No Not in study area
126	2831	Scottish Courage Ltd	John Smith's Brewery, Tadcaster The Brewery Tadcaster North Yorkshire LS24 9SA	Food and Drink		**54,322**		No Not in study area
127	2381	Elyo UK Industrial	Nestlé York CHP Nestlé York Nestle Rowntree 61 Wigginton Road York YO1 1XY	Food and Drink		**53,187**		No Not in Study area
128	1642	Glazteknology (Glaztek) UK Limited	Harworth Snape Lane Harworth Doncaster South Yorkshire DN11 8NF	Glass		**52,726**		No Not in Study area
129	2061	Outokumpu Stainless Ltd	SMACC Site Outokumpu Stainless Ltd (Formerly AvestaPolarit Ltd) PO Box 161 Shepcote Lane Sheffield South Yorkshire S9 1TR	Iron & Steel		**52,466**		No Not in Study area
201	707	Hepworth Building Products Ltd	Hazlehead Hepworth Building Products Ltd Hazlehead Crow Edge Sheffield South Yorkshire S36 4HG	Ceramics		**49,343**		No Not in Study area

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa	Tier 1 tpa	Tier 2 tpa	Included in Study /Notes
					>1M	**50k - 1M**	**<50k**	
202	705	Beatson Clark plc	Beatson Clark plc - Rotherham Rotherham Container Glass Works Greasbrough Road Rotherham South Yorkshire S60 1TZ	Glass			**47,976**	No Not in Study area
203	240	Novartis Grimsby Ltd	Novartis Grimsby Ltd Novartis Grimsby Ltd Pyewipe Grimsby N E Lincolnshire DN31 2SR	Chemicals			**45,108**	Yes
204	2781	Rigid Paper Limited	Selby Paper Mill Rigid Paper Ltd Denison Road Selby North Yorkshire YO8 8DB	Pulp & Paper			**44,833**	Yes
205	702	Allied Glass Containers Ltd.	Allied Glass Containers Ltd. - Knottingley Knottingley Works Fernley Green Road Knottingley West Yorkshire WF11 8DJ	Glass			**44,772**	Yes
206	302	Nationa Grid Gas Plc	Scunthorpe Compressor Station Butterwick Road Messingham Scunthorpe Lincolshire DN17 3PN	Downstream Gas			**44,180**	No Not in study area
207	2985	UK COAL Mining Ltd.	Harworth Colliery Harworth Colliery Scrooby Road Bircotes, Harworth Doncaster South Yorkshire DN11 8AB	Other Electricity Producers			**41,162**	No Not in study area
208	157	Croda Chemicals Europe Ltd	Croda Chemicals Europe - Hull Oak Road Site Oak Road Hull East Yorkshire	Chemicals			**41,035**	Yes
209	2330	Mill Nurseries Ltd.	Mill CHP Mill Nurseries Ottringham Road Keyingham Kingston-Upon-Hull East Yorkshire HU12 9RX	Food and Drink			**40,013**	Yes
210	3108	Tate & Lyle Industries Limited	Tate & Lyle Citric Acid Selby Denison Road Selby North Yorkshire YO8 8EF	Chemicals			**39,372**	Yes
211	2747	E.ON UK Cogeneration Ltd	Bradford CHP plant (AH Marks) AH Marks Wyke Bradford West Yorkshire BD12 9EJ	Chemicals			**37,732**	No Not in study area

Appendix B

Study ID No.	**NAP ID**	**Operator Name**	**Installation Address**	**EU-ETS Sector**	**Tier 0 tpa**	**Tier 1 tpa**	**Tier 2 tpa**	**Included in Study /Notes**
					>1M	**50k - 1M**	**<50k**	
212	720	Sandtoft Roof Tiles Limited	Broomfleet Works Broomfleet Tileries Broomfleet Works Broomfleet, Brough East Yorkshire HU15 1RS	Ceramics			**36,036**	Yes
213	3134	SSE Generation Ltd	Wheldale Power Station Wheldale Green Energy Park Wheldon Road Castleford West Yorkshire WF10 2RR	Other Electricity Producers			**35,845**	Yes
214	2658	McCain Foods (GB) Ltd	McCain Steam Boilers - Scarborough McCain Foods (GB) Ltd - Scarborough Havers Hill Eastfield Scarborough North Yorkshire YO11 3BS	Food and Drink			**35,283**	No Not in study area
215	3478	Total Solutions For Industry (Power Resources 1) Limited	Sonoco CHP Plant Sonoco Board Mills Dog Lane Stainland Halifax West Yorkshire HX4 9PY	Pulp & Paper			**30,500**	No Not in study area
216	3125	Warwick Energy Exploration and Production Limited	Caythorpe Generating Plant Caythorpe Wellsite Rudston Near Driffield East Yorkshire YO25 4JD	Other Electricity Producers 28,080			**28,080**	No Not in study area
217	5014	Aarhus United UK Ltd	Aarhus United UK Ltd King George Dock Hull Yorkshire HU9 5PX	Food and Drink			**27,838**	Yes
218	2302	Degussa Knottingley Ltd	Degussa Knottingley Ltd Common Lane Knottingley West yorkshire WF11 8BN	Chemicals			**27,435**	Yes
219	3175	E.ON UK CoGeneration Ltd	St James Hospital CHP Plant (St. James University Hospital) St James University Hospital Beckett Street Leeds Yorkshire LS9 7TF	Services			**26,810**	No Not in study area
220	5013	T G Power Limited	Power House Complex RAF Fylngdales RAF Fylingdales Pickering North Yorkshire YO18 7NT	Services			**23,997**	No Not in study area
221	690	Beatson Clark plc	Beatson Clark plc - Barnsley Barnsley Container Glass Works Hoyle Mill Road Stairfoot Barnsley South Yorkshire S70 3EU	Glass			**23,605**	No Not in study area
222	2645	Hanson Clay Products Ltd.	Howley Park Factory Howley Park Quarry Lane Howley Park Dewsbury West Yorkshire WF12 7JJ	Ceramics			**23,083**	No Not in study area

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k	Included in Study /Notes
223	704	Stolzle Flaconnage Limited	Stolzle Flaconnage Limited Weeland Road Knottingley West Yorkshire WF11 8AP	Glass			**23,017**	Yes
224	753	Plasmor Limited	Plasmor Limited Great Heck Green Lane Great Heck Goole East Yorkshire DN14 0BZ	Ceramics			**22,448**	Yes
225	3480	SSE Generation Ltd	Hedon Salads Burstwick Energy Centre Hedon Salads Burstwick Main Road Burstwick East Yorkshire HU12 9DZ	Food and Drink			**21,667**	Yes
226	709	Naylor Drainage	Naylor Drainage Cawthorne Clough Green Cawthorne Barnsley South Yorkshire S75 4AD	Ceramics			**18,934**	No Not in study area
227	706	Carlton Main Brickworks Ltd	Carlton Main Brickworks Ltd Grimethorpe Clay Burn Road Grimethorpe Barnsley South Yorkshire S72 7BG	Ceramics			**18,672**	No Not in study area
228	3223	Muntons plc	Muntons plc Flamborough Maltings Jewison Lane Bridlington East Yorkshire YO15 1DY	Food and Drink			**16,082**	No Not in study area
229	2187	Carlsberg UK Limited	Joshua Tetley Brewery Leeds Hunslet Road PO Box Leeds West Yorkshire LS1 1QG	Food and Drink			**16,019**	No Not in study area
230	3497	Sheffield Teaching Hospitals NHS Trust	Northern General Hospital - Boiler House Northern General Hospital Sheffield Teaching Hsopitals NHS Trust Herries Road Sheffield Teaching Hosp NHS South Yorkshire S5 7AU	Services			**15,475**	No Not in study area
231	3498	Sheffield teaching Hospitals NHS Trust	Royal Hallamshire Hospital Boiler House Sheffield Teaching Hospitals NHS Trust Glossop Road Sheffield Teaching Hosp NHS South Yorkshire S10 2JF	Services			**14,494**	No Not in study area
232	759	Ibstock Brick Ltd.	Ibstock Brick Ltd - Nostell Nostell Factory Ibstock Brick Ltd. Swine Lane, Nostell Wakefield West Yorkshire WF4 1QH	Ceramics			**14,059**	No Not in study area

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa	Tier 1 tpa	Tier 2 tpa	Included in Study /Notes
					>1M	50k - 1M	<50k	
233	155	Croda Chemicals International Ltd	Croda Chemical Europe - Goole Rawcliffe Bridge Rawcliffe Bridge Station Road Goole East Yorkshire DN14 8PN	Chemicals			**13,830**	Yes
234	8091	British Gypsum Ltd	Sherburn Gypsum Works Sherburn Fenton Lane Sherburn In Elmet Nr Leeds Yorkshire LS25 6EZ	Others A			**12,736**	NoNot in study area
235	2647	Hanson Clay Products Ltd.	Swillington Factory Swillington Wakefield Road Swillington Leeds West Yorkshire LS26 8BT	Ceramics			**12,239**	No Not in study area
236	3547	DONCASTER & BASSETLAW HOSPITALS NHS TRUST	Doncaster Royal Infirmary Boiler House Doncaster Royal Infirmary Armthorpe Road Doncaster South Yorkshire DN2 5LT	Services			**11,843**	No Not in study area
237	2175	Cadbury Trebor Bassett	Energy Centre - Sheffield Cadbury Trebor Bassett Sheffield PO Box 8 Livesey Street Sheffield Yorkshire S6 2AP	Food and Drink			**11,791**	No Not in study area
238	2646	Hanson Clay Products Ltd.	Stairfoot Factory Stairfoot Wombwell Lane Stairfoot Barnsley South Yorkshire S70 3NS	Ceramics			**11,240**	No Not in study area
239	2709	P Garnett & Son Ltd	P Garnett and Son Ltd Otley Paper Mill Mill Lane Wharfeside Otley West Yorkshire LS21 1QJ	Pulp & Paper			**10,988**	No Not in study area
241	6027	Smith & Nephew Medical Ltd	Smith & Nephew Medical Ltd PO Box 81 Hessle Road Hull HU3 2BN	Chemicals			**10,558**	Yes
242	8075	Hazlewood Grocery Ltd	Selby Sauces and Pickles Greencore Grocery, Selby Barlby Road Selby North Yorkshire YO8 5BJ	Food and Drink			**10,091**	Yes
243	2377	Elyo UK Industrial	Nestlé Halifax Boiler House Nestlé Halifax Nestlé Rowntree Albion Mills Halifax West Yorkshire HX3 9XT	*Food and Drink*			**9,790**	No Not in study area

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k	Included in Study /Notes
244	4036	Humber Growers Ltd	Poolbank CHP Poolbank Salads (Humber VHB) Common Lane Welton Brough East Yorkshire HU15 1UT	Food and Drink			**9,629**	Yes
245	2557	John Roberts Holdings Ltd.	Langcliffe Paper Mill Langcliffe Settle North Yorkshire BD24 9NX	Pulp & Paper			**8,846**	No Not in study area
246	38	Sheffield Forgemasters Engineering Limited	Sheffield Forgemasters Steel Melting Shop River Don Works P.O. Box 286 Brightside Lane Sheffield South Yorkshire S9 2RW	Iron & Steel			**8,711**	No Not in study area
247	2258	Coors Brewers Limited	Tower Brewery Coors Brewers Ltd Wetherby Road Tadcaster North Yorkshire LS24 9SD	Food and Drink			**8,457**	No Not in study area
248	3549	Hull & East Yorkshire Hospitals NHS Trust	Hull & East Yorkshire Hospitals NHS Trust Castle Hill Hospital Castle Road Cottingham East Yorkshire HU16 5JQ	Services			**8,091**	Yes
249	2461	Hanson Building Products	Hanson Building Products - Calder Works Calder Works Lower Edge Road Elland West Yorkshire HZ5 9PY	Ceramics			**7,696**	No Not in study area
250	4027	Bardmilne Ltd	University of York Heslington York North Yorkshire YO10 5DD	Services			**7,448**	No Not in study area
251	8058	YORK HOSPITALS NHS TRUST	YORK HOSPITAL BOILERHOUSE YORK HOSPITAL WIGGINTON ROAD YORK HOSPITAL NORTH YORKSHIRE YO31 8HE	Services			**6,401**	No Not in study area
252	3504	Barnsley Hospital NHS Foundation Trust	Barnsley Hospital NHS Foundation Trust Barnsley Hospital NHS Foundation Trust Gawber Road Barnsley South Yorkshire S75 2EP	Services			**5,980**	No Not in study area
253	3035	Whiteley Ltd	Whiteley Ltd Whiteley Ltd Pool Paper Mills Pool-in-Wharfedale West Yorkshire LS21 1RP	Pulp & Paper			**5,676**	No Not in study area
254	3116	Dyson Industries Ltd	Dyson Industries Limited - Totley Dyson Refractories, Totley Works Owler Bar Sheffield South Yorkshire S17 3BJ	Ceramics			**5,587**	No Not in study area

Appendix B

Study ID No.	NAP ID	Operator Name	Installation Address	EU-ETS Sector	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k	Included in Study /Notes
			Total for Tier		**62270178**	**4173242**	**1172533**	67615953
			Total included in Study		**62270178**	**2864681**	**501618**	74597775
			Total Proposed Emitters in Study		**71231476**	**3164681**	**501618**	74676810
			% of Region Total (not including future emitters)		**92.09%**	**6.17%**	**1.73%**	
			% of Study Area Total		**95.10%**	**4.23%**	**0.67%**	

Known Proposed Future Emitters

Operator Name	Installation Address	Tier 0 tpa >1M	Tier 1 tpa 50k - 1M	Tier 2 tpa <50k
ConocoPhillips	Immingham IGCC	1,761,298		
EON Killingholme	EON Killinghome IGCC Power Station	2,400,000		
Powerfuel Power Ltd	Hatfield IGCC Power Station	4,800,000		
BP Bioethanol			300,000	
		8,961,298	**300,000**	

Disclaimer

The information, analysis, scenario and discussion within this report are the result of an independent review and report for Yorkshire Forward. Whilst potential emitters and stakeholders have been engaged with the project the information presented here does not represent any stakeholder's policy towards carbon capture and storage in the Yorkshire and Humber region. Scenarios presented within are based on publicly available information, stake holder and project discussions and should not be taken as stating or implying regional or a specific entity's policy.

Authors

AMEC
AMEC House
Yarm Road
Darlington
County Durham DL1 4JN
United Kingdom
Telephone: +44(0)1325 744400
Fax: +44(0)1325 744404
Email: alastair.rennie@amec.com
Website: www.amec.com

Acknowledgements

The authors and Yorkshire Forward are grateful for the Steering Group inputs but any errors are our own.

The steering group comprised:

Mike Smith, Chairman, Yorkshire Forward

Dr Stephen Brown, Project Manager, Yorkshire Forward

Tim Hill, Eon UK

John Mitchell, Scottish and Southern Energy

Nigel Burdett, Drax Power Ltd

Ishfaq Ahmed, Conoco Phillips

Phillip Pearson, TUC

Michael Gibbons, Powerfuel Power Ltd

Chris Treadgold, Corus

Stefan Cousquer, Hydrogen Energy

Malcolm Stephenson, Shell

Alastair Rennie, AMEC

Important notice

This report was prepared exclusively for Yorkshire Forward by AMEC plc, (AMEC), Industrial division, Darlington. The quality of information, conclusions and estimates contained herein is consistent with the level of effort involved in AMEC's services and based on:

i) information available at the time of preparation,

ii) data supplied by outside sources and

iii) the assumptions, conditions and qualifications set forth in this report. This report is intended to be used by Yorkshire Forward and consortium partners only, subject to the terms and conditions of its contract with AMEC. Any other use of, or reliance on, this report by any third party is at that party's sole risk.

CONTACT US

If you want more information about the carbon capture and storage network for Yorkshire and Humber, contact our sustainable development team on **0113 394 5672** or visit **www.yorkshire-forward.com**

Yorkshire Forward
Victoria House
2 Victoria Place
Leeds LS11 5AE

www.yorkshire-forward.com

Printed in the region on recycled paper (75% post consumer waste and totally chlorine-free (TCF))

05_08 100203