DISTRIBUTED COLLECTION OF CO_2

Technical Study

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DISTRIBUTED COLLECTION OF CO_2

Background

Large CO_2 sources such as power stations and large industrial plants are expected to provide the main opportunities for CO_2 capture and storage. Small and medium scale fixed sources account for a smaller but nevertheless substantial proportion of total global emissions of CO_2. In order to achieve the large reductions in CO_2 emissions that are expected to be necessary to avoid major climate change, major reductions in emissions from these sources will be required. Emissions from these sources could potentially be reduced by energy efficiency improvements, use of low-CO_2 energy carriers, particularly electricity and hydrogen, and by capture and storage of CO_2. Few studies have so far been carried out to assess capture and storage of CO_2 from medium scale sources and this was identified as a knowledge gap in the IPCC Special Report on CO_2 Capture and Storage, published in 2005. Although the costs of capture and storage of CO_2 are expected in general to be higher for medium scale sources than for large scale sources, the costs may be lower than those of alternative CO_2 abatement options.

IEA GHG has commissioned two studies to assess the feasibility and costs of capture and storage of CO_2 from medium scale fixed sources. This study focuses on collection of CO_2 from an array of smaller sources using a network of pipelines and compressors. Once the CO_2 from medium scale sources has been collected and combined into large capacity pipelines, further transportation and storage of the CO_2 will be same as for large scale sources. A companion study focuses on CO_2 capture from medium scale sources.

This study was carried out for IEA GHG by Gastec UK and AMEC both based in the UK with some input from Gastec in the Netherlands.

Study Approach

The study was based on the costings for a real situation rather than a theoretical network because the results would be more realistic. However the costing routines were developed in the form of a spreadsheet based program so that they could be applied universally to any distributed CO_2 collection situation. This would simply require adjustment of the units cost tabulations in the program.

Initial thoughts were to consider distributed collection right down to domestic level but this was felt to be unrealistic because the maintenance of capture systems at this small size would result in the need for impractical amounts of manpower. Sources of emissions down to a cut off of 5,000 tpa were considered in the study.

The Merseyside and Deeside basin in the north west of England was chosen as the region to be analysed. This area hosts a diverse set of industries which collectively emit about 20 million tpa of CO_2. It is typical of industrial agglomerations around the world centred around good transport access by water. The sources of emission were identified and plotted on a map. A plan of the required network was developed and a number of optional designs for pressure levels and network layout considered. A detailed spreadsheet was then constructed which allowed all of the elements of the required pipeline gathering network and compression facilities to be entered with additional details on the route lengths, types of crossing, valve and metering stations etc. This information was coupled with cost information to enable an aggregated cost for the network to be calculated.

The sources were divide into three tiers >1MMtpa, >50Ktpa, >5ktpa of CO_2 (designated tier 0, 1 and 2 respectively) and costs for networks incorporating first the top tier and then the lower tiers were developed. This enabled marginal costs for connecting smaller emitters to be estimated.

During the study all of the main emitters were contacted and invited to a seminar in which the study was explained and the opportunity taken to ask participants to fill in a questionnaire about their awareness and plans for emission management. A follow up seminar was held to explain the results. Valuable feedback on the practicality and other issues were obtained from these contacts.

Results and Discussion

The study revealed that the bulk of emissions in the region came from 5 major sources with a relatively small amount from a much larger number of small sources. This is probably typical of other industrial zones. Collecting CO_2 from these main sources alone would thus establish a simple backbone trunk line system to which other sources might be added. The tier zero sources amounted to 14.5 Mtpa. The preferred design of collection network for the larger number of smaller sources is a tree type system in contrast to the ring main system commonly used for gas distribution. This leads to shorter lengths of line but leaves no redundancy in the system which is a key reason for using ring mains when distributing gas. There were 24 tier 1 sources amounting to about 4.5Mtpa of CO_2. Finally there were 49 tier 2 sources amounting to just 0.7 Mtpa. This distribution of capacities is illustrated in Figure 1.

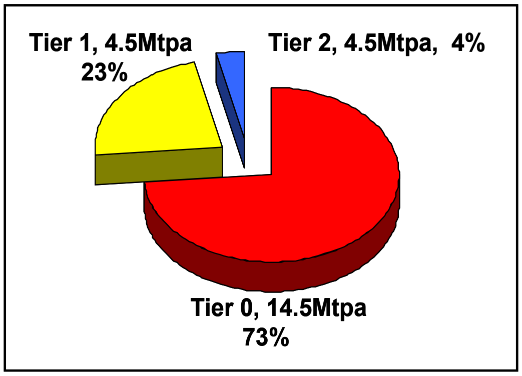

Figure 1 Distribution of source sizes

Pressure of Operation

The sister report on distributed CO_2 capture examined and proposed a number of technologies and all these generally deliver CO_2 water wet at atmospheric pressure. It was concluded that the outermost branches of the collection network could be designed either to blow or suck CO_2 to intermediate collection nodes. The collection network was divided nominally into high medium and low pressure sections. Examination of the economics revealed high fixed cost for compression stations so that having a central suction station serving several small sources appeared cheaper than equipping each source with its own compressor or blower. Even though a suction system would involve lines operating under partial vacuum and hence with significantly larger diameter it was concluded that the suction system was more attractive cost-wise and for operational reasons. The capture systems become simpler as they have no compressor and safety is improved as there is reduced tendency to leak. This vacuum LP system was adopted for the tier 2 sources.

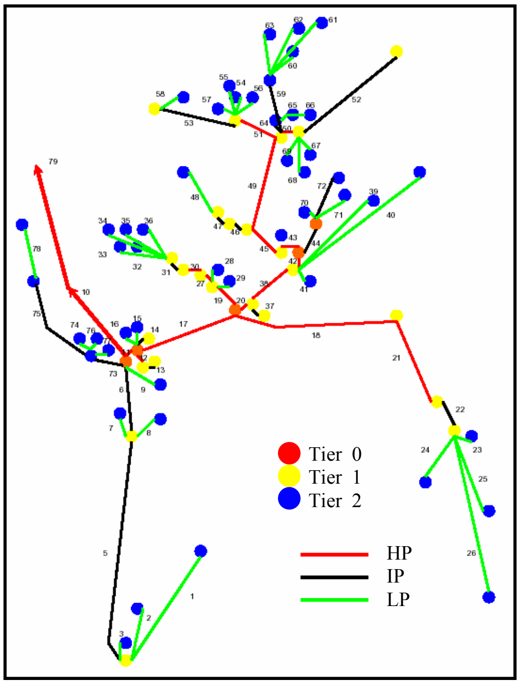

Figure 2 Network structure

The intermediate pressure (IP) systems were nominally set at 10 barg as this allows selection of the corrosion resistant plastic HDPE material. The diameter of the system reaches the limit for available line sizes at a flow rate of about 170Ktpa so above this flow a high pressure system with nominal pressure of 100 barg is selected. However for safety reasons it was considered inappropriate to run such high pressure supercritical lines through heavily populated areas. In these areas pressure was limited to 10 barg and multiple IP lines were used. It became clear when laying out the network in this region that it was very difficult to avoid populated areas and the safety issues which this raises would need more detailed investigation. The basic structure of the network is indicated in Figure 2.

The main trunk-line system was nominally set to operate at 100bar. For this exercise the trunk line was taken as running out through North Wales to the gas/oil fields in the southern part of Liverpool Bay

Materials of construction

High pressure CO_2 lines are normally constructed of carbon steel and the CO_2 is dried to avoid corrosion. For intermediate and low pressure lines HDPE could also be used and this would be resistant to wet CO_2 corrosion. HDPE was chosen for the LP system as this eliminates the need for drying. However it was considered that water build up in the system could cause problems of flow restriction and blockage, so drying units were specified at every location anyway. Whilst this in principle would allow selection of carbon steel the risk of one of many small drying units failing and causing corrosion was considered too high.

Overall costs

The cost for collecting from the tier 0 sources was calculated at $8.5per ton. When the tier 1 sources are added the overall unit cost increases slightly to $8.8per ton but the marginal cost for extending the system to collect these sources is somewhat higher at $9.7/ton. Further extension to capture the tier 2 sources is expensive. Although the average unit cost increases only slightly to $9.7 per ton the extra quantity collected is very small and the marginal cost of the extension is about $34/ton. These costs are specific to the particular example chosen and are also based on construction in the UK which is high compared to most other regions. They are shown graphically in figure 3.

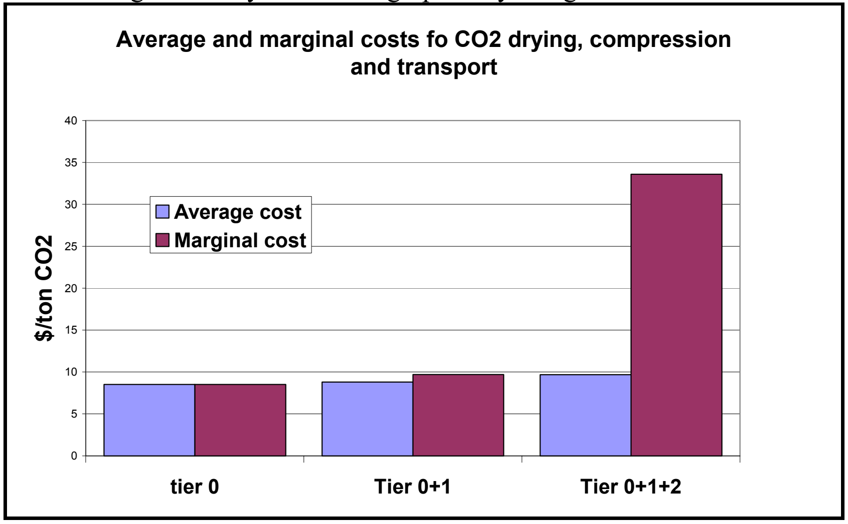

Figure 3 Average and marginal costs of CO_2 collection

Sensitivities were run to estimate the effects of decreasing and increasing the distance between the sources. This was done simply by multiplying the length of all lines by a constant factor. The estimating spreadsheet than recalculates lines sizes and compression requirements and reallocates pressure levels if necessary. The costs are sensitive to increases/decreases of 25% although the corresponding percentage cost changes are significantly less than this. The results of this simple analysis are shown in figure 4.

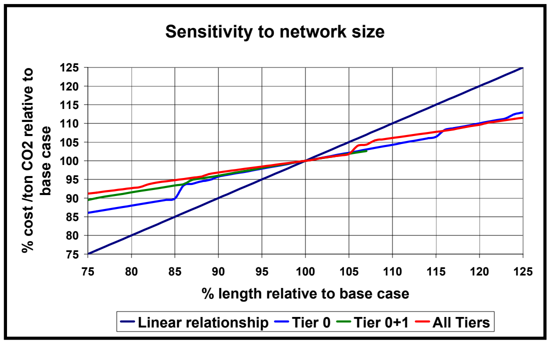

Figure 4 Cost sensitivity to network size

Cost breakdown

Estimates were developed in significant detail by considering not only the lengths of line to be laid but also other features which add to cost. For each segment of line a count of the following "extras" was made following which standard unit prices are applied:

- Crossings of roads, motorways, railways, rivers and canals.
- Block valves
- Drainage points
- Metering stations

In addition to these features the cost of compressors and drying facilities was also estimated. The overall estimates show that the costs of drying and compression are a significant element of the total system cost. Furthermore these increase as the smaller sources are included in the collection network. The cost of compressors has been based on building stand alone compression stations and it is likely that costs of compression if integrated into a capture site would be somewhat less. Figure 5 illustrates the distribution of the costs between

- Pipelines and fittings,
- Compression
- Drying

for networks collecting down to different tier levels. The overall cost ranges for a complete CCS system is indicated in figure 6.

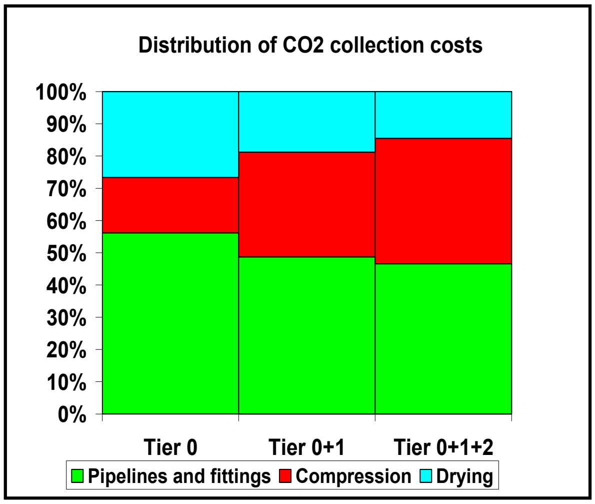

Figure 5 Distribution of CO_2 collection costs

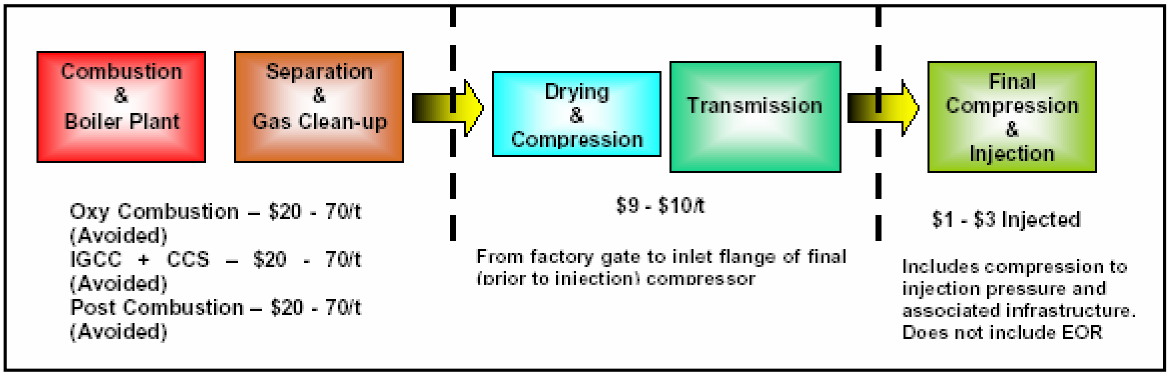

Figure 6 Costs for complete CCS chain

Expert Reviewers' Comments

Reviewers felt that the marginal costs of progressively including smaller sources should be calculated and emphasised to put costs in better perspective. It was also commented that the costs for distributed capture and the costs for storage mentioned in the report seemed low. The ranges were adjusted and widened although the data from other reports on which the figures were based do indicate that with new technologies smaller scale capture could be at similar costs to that for large scale capture today. Some reviewers felt that the estimates of compression cost were rather high and some downwards adjustments were made to the fixed costs assumed for setting up compression sites. It was further commented that more specific information about the safety aspects of laying CO_2 lines in inhabited areas should have been included. However this level of detail is beyond the scope of this study. Because of the issues identified during discussions with the local HSE executive the design principle of limiting pressure to 10barg in inhabited areas was adopted. Also a relatively short distance between block valves (1000m) in such areas was assumed. This choice was made as a best endeavour engineering judgement purely for the purposes of obtaining a realistic cost estimate. In practice a detailed risk assessment would have to be made and the design assumptions should not be considered to imply that the required levels of safety for a real project would necessarily be met. Safe distances, pressures and inventories will need to be established on a line by line basis until general standards and guidelines can be established.

Major Conclusions

The costs of collecting CO_2 from moderate sized industries are not excessive and should be considered when planning CO_2 pipeline and storage infrastructure. However alternatives such as centralizing CO_2 capture using pre-combustion and distributing hydrogen as fuel to nearby industries may offer a more economic solution. Extending the collection network to encompass smaller sources will increase the need to lay pipelines near places where the public live, work and travel and this has safety implications particularly if supercritical conditions are used.

Much of extended networks could be constructed using plastic materials thus eliminating any exposure to corrosion risks.

It was apparent from the two seminars conducted during preparation of this report that collaboration and information exchange will be needed between those operating in heavy industrial zones if optimum choices to reduce GHG emissions are to be made and appropriate shared infrastructure and facilities built.

Recommendations

The findings of this study further support the recommendation from the sister report on medium scale capture technologies that a study be carried out to compare the alternative ways of reducing CO_2 emissions from medium scale energy users, including energy efficiency improvements and use of energy carriers (hydrogen and electricity) from renewable energy sources and large scale fossil fuel plants with CO_2 capture and storage.

An additional recommendation is that a road map be prepared to assist zones with a high concentration of industry to collaborate, exchange information and plan infrastructure development with a view to effectively cutting greenhouse gas emissions.

The study encountered the safety issue of what standards to apply when running CO_2 lines through inhabited areas. It is recommended that this issue is included in the scope of the planned study on safety in CCS projects.

A final recommendation is that the spreadsheet based calculator for CO_2 pipeline networks be upgraded to cover the cost profiles other main regions in the world and a more user friendly interface be provided possibly at the same time incorporating the program into the IEAGHG,s general “Energy distribution and CO_2 capture cost estimation model”.

Distributed Collection and Transmission of CO_2

Prepared for:	IEA Greenhouse Gas R&D Programme
Prepared By:	GASTEC AT CRE Ltd
Report No:	GaC3484 (IEA/CON/06/125)

March 2007

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Abbreviations and Symbols

ASME	American Society of Mechanical Engineers
BGS	British Geological Survey
CAPEX	Capital Expenditure
CCS	Carbon Capture & Storage
CHP	Combined Heat & Power
CO_2	Carbon dioxide
DCLG	Department for Communities and Local Government
DTI	Department of Trade and Industry
ECBM	Enhanced Coal Bed Methane
EOR	Enhanced Oil Recovery
EU ETS	European Union Emissions Trading Scheme
GaC	GASTEC at CRE Limited
HDPE	High Density Polyethylene
H_2S	Hydrogen sulphide
HSE	Health and Safety Executive
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined Cycle
IPPC	Integrated Pollution Prevention Control
ktpa	Thousands of tonnes per annum
Mtpa	Millions of tonnes per annum
MW	Megawatt
NO_x	Oxides of nitrogen
OPEX	Operational Expenditure
SC	Supercritical
SO_2	Sulphur dioxide
tpa	Tonnes per annum
tph	Tonnes per hour
UK ETS	United Kingdom Emissions Trading Scheme

1 Particulars

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2 Executive Summary

GASTEC at CRE Limited (GaC) was commissioned by The IEA Greenhouse Gas R&D Programme (IEAGHG) to undertake a feasibility study to assess the economic and practical viability of a distributed carbon dioxide collection and transmission network. This study has concentrated on estimation of the drying and transmission costs. For completeness estimates of collection and disposal costs have also been included from literature sources, with reference to how they have been derived as appropriate.

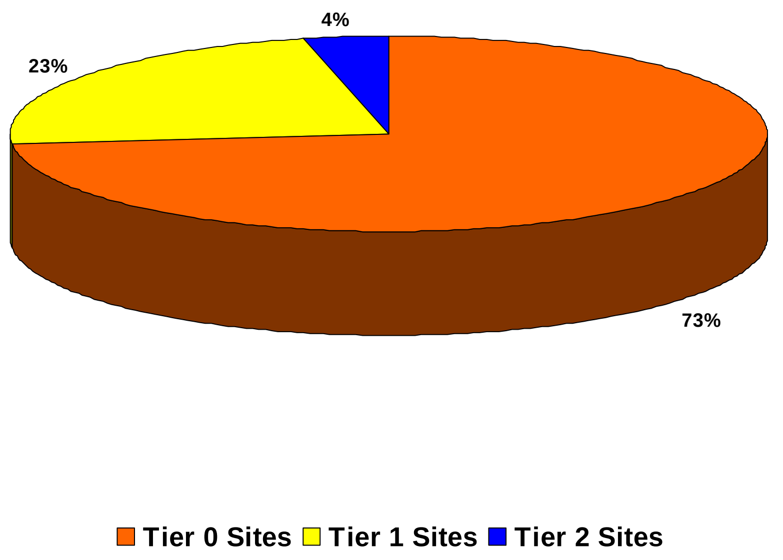
It has been well documented that the capture and storage of CO_2 from fossil fuel power plant and other major industrial processes offers one route to major reductions in greenhouse gas emissions. Collection of CO_2 from large point sources is attractive because of the large economies of scale that can be achieved, and the relative simplicity of the transmission system. However, there remain a significant proportion of CO_2 emissions which derive from the industrial and commercial sectors which is distributed. Most recent studies have concentrated on centralised CO_2 collection and disposal, possibly coupled with distribution of ‘clean’ energy in the form of electricity or hydrogen to the smaller, decentralised sources. However, such a strategy would still require an extensive distribution network and has not been compared to the alternative of decarbonisation at the point of consumption combined with distributed collection and transmission of CO_2.

In order to formulate designs for the distributed collection system, three distinct levels of collection were considered.

- The top level (Tier 0) is made up of installations producing over 1Mtpa CO_2, these typically comprise power stations and very large refineries.
- The middle level (Tier 1) comprises major industrial sites such as small refineries, chemical works, CHP installations and other major industrial complexes that produce 50ktpa – 1Mtpa CO_2. Collection from Tiers 0 and 1 is considered to be the most feasible as considerable economies of scale still apply even when considering installations emitting 50ktpa CO_2.
- The lowest level considered (Tier 2) is made up of smaller scale light industrial and commercial enterprise such as very large offices, hospitals, industrial estates, manufacturing complexes and research facilities. At this scale of collection, individual emissions of the order of 5ktpa CO_2 were considered. This is equivalent to a continuous electrical load of 1+MW.

Although it would have been possible to base the study on a theoretical region with a statistically derived distribution and dispersion of sources, it was decided to base the study on a real geographical area. The North West of England, specifically the River Dee and River Mersey basins was chosen to be the subject area. This area was chosen as there is a very high concentration of heavy industry, producing large quantities of CO_2 across a sizeable geographical area. Furthermore, viable storage options were shown to be within close proximity to the subject area.

Suitable point sources (Tier 0, 1 & 2) were identified from the publicly available emissions information on the Defra website (installations-list.xls spreadsheet) and separated into their respective Tiers. The figure below presents the percentage emissions represented by each Tier.



Prior to preliminary network design and development of the design spreadsheet, basic build and operational parameters had to be established for the network:

- **Shape of Network: Ring Main Vs Tree**
  Two main shapes of network were considered; A ring main, such as the current natural gas distribution network in the UK with each source or node feeding into a high pressure main; or a tree type network with each source or node feeding into the next until a common ‘trunk line’ is reached. A tree type network was used on the grounds of simplicity.

- **CO_2 Dryness**
  A crucial factor of the design was the specification for the dryness of CO_2 to be accepted by the collection network. As Tier 0 and Tier 1 sites were to be connected to medium and high pressure lines, a reasonable degree of drying would be required anyway. It was decided that full drying (to -5°C dew point) would be carried out at these points to prevent condensation build-up within the network and the negative effects of this such as condensate ‘slugs’ and corrosion.

- **Impurities**
  An initial concern was the effect of gaseous impurities such as SO_2 and NO_x on the phase envelope of CO_2 and on the network as a whole (corrosion etc). It was assumed that no H_2S would be present. For this study, it was established that the introduction of impurities could be limited via careful selection of CO_2 capture plant or via enhanced gas clean up prior to network injection.

- **Compression**
  The compression of CO_2 is likely to be the largest operational cost of the scheme due to the high usage of energy. It is therefore proposed that CO_2 compression is achieved using electrically driven 4 stage compressors. Although this would result in a CO_2 emission elsewhere through the generation of electricity, it removes the problem of actual CO_2 release within the envelope of the network itself.

- **Materials of Construction**
  Polyethylene plastic piping is cheaper to purchase and easier to lay than the steel equivalent and therefore is to be used wherever possible in the proposed network. Standard piping sizes have been assumed.

- **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.

- **Valves**
  In order to reduce the inventory released in the event of a pipeline failure, valves would be installed at regular intervals of 1000m for high pressure line and 2000m for medium to low pressure lines. These valves would automatically slam shut on pipeline rupture (detected by a loss of pressure), thus limiting the escape of CO_2 to the amount contained in the pipeline between the valves.

- **Leak Detection**
  Leak detection equipment is essential to a network of this scale. Stringent monitoring and inventory accounting would be required by the pipeline operator. Leak detection is likely to be in the form of temperature sensing outer sleeves for major pipelines and routine pressure testing for smaller pipelines.

- **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. HDPE pipelines would not need protection from corrosion.

A spreadsheet model was developed to allow evaluation of the feasibility of the proposed scheme. The spreadsheet calculates pipeline sizes, compression duties, and capital and operating costs from the various inputs from the user.

The spreadsheet is designed to be applicable to any geographical area. However, due to the large price variance between different countries for most factors (such as cost of labour, materials etc) the costs derived from the spreadsheet in its current form apply to pipelines solely within the UK. However, the spreadsheet still proves to be a useful tool for other countries, as with some manipulation of the data sources within the spreadsheet; it could be quickly adapted for use elsewhere.

Although this study is primarily to determine a cost per tonne to deliver the CO_2 to a storage point and not to include the cost of final disposal/storage it was considered necessary to determine the most viable storage option for the study region. The most viable storage option would then be used to calculate items such as pipeline costs (onshore or offshore etc) assess skills requirements of the scheme and determine whether a viable storage option actually exists for the region.

The main storage technologies for consideration within the study area are the various types of sub-surface storage, these being Enhanced Coal Bed Methane (ECBM), storage in depleted oil and gas wells (including Enhanced Oil Recovery (EOR)), storage in deep saline aquifers (on and off shore) and temporary storage in deep underground salt cavities. For the purposes of this study it is to be assumed that disposal will take place in the East Irish Sea gas and oil fields.

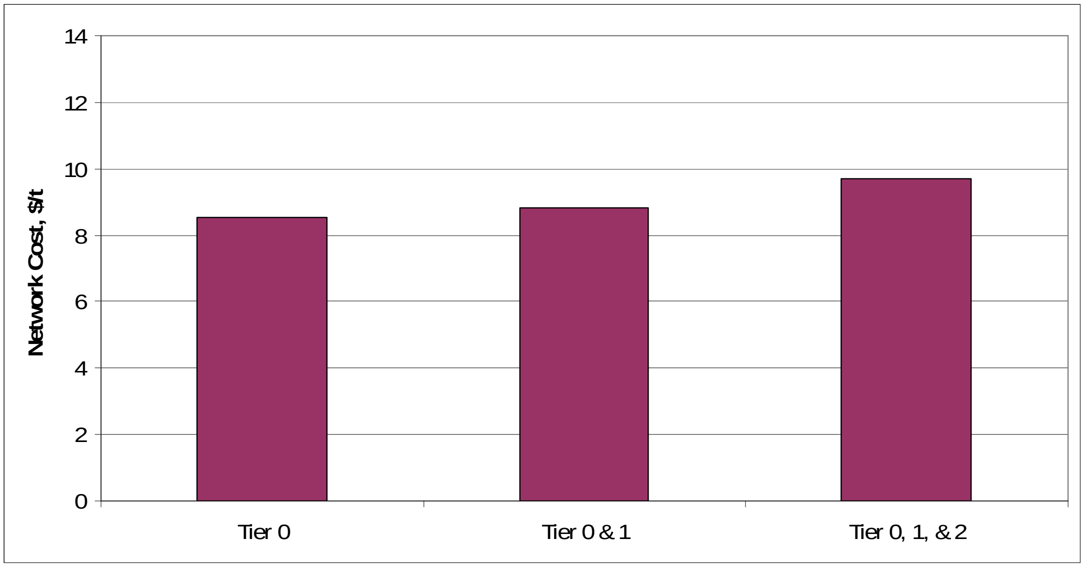
Carbon dioxide is an odourless, colourless gas under atmospheric conditions. It is not flammable or explosive, but it can act as an asphyxiant at concentrations above about 10% v/v. At concentrations between 5% and 10%, CO_2 impairs physical and mental ability, and even at concentrations around 3%, it can have physiological effects on humans such as shortness of breath. CO_2 has a molecular weight of 44 which is considerably heavier than air. This means that any release of CO_2 is likely to lead to a potentially dangerous accumulation in low lying areas/spaces.

The lack of definitive information about the effects of a pipeline rupture suggests that a conservative design approach should be adopted. The fact that the study area is densely populated and that much of the area is urban supports this philosophy. Therefore, a number of safety features were built into the design, such as block valves every 1km, and the use of medium pressure pipelines in urban areas.

The practicalities of separating and collecting CO_2 from industrial sources are complex. Most CO_2 collection studies have been based on separation at large power station sites where it is assumed that the capacity to operate the plant and equipment exists or could easily be brought in. For smaller industrial plant, this may not be the case. In order to ascertain whether the practicalities would present a barrier to the introduction of the technology, a seminar was held in the study region to which local industrialists were invited. The participants were asked to complete a questionnaire, and the results suggested that most companies would have the capacity to operate such separation and collection systems.

The cost of CO_2 transportation was calculated for three different collection networks. The first network included all sources; in the second network the smaller Tier 2 sources were removed; in the third network, only the five large Tier 0 sources were modelled.

The results are shown in the figure below.



From this figure it can be seen that increasing the size and complexity of the network increases the costs of CO_2 transport significantly.

The cost of CO_2 collection and transmission for the whole network (all tiers) was calculated to be $9.70/t. Trimming the network to remove sources which were geographically remote and which could not be connected to the suction system reduced the collection and transmission cost to $9.20/t. Removing all sources below about 800 000 tonnes per year (i.e. only leaving the five largest emitters) reduced the collection and transmission cost to $8.50t.

In order to put these collection costs into perspective an assessment of the costs for a complete capture and disposal system is needed. Based on studies carried out for the IEAGHG it is to be expected that new build capture options in the range $20-$40 will be available. However for retrofits in which the full costs are borne by the CO2 capture this figure can be considerably higher. A report on potential new capture technologies applicable to distributed sources will shortly be available from IEAGHG and will indicate indicative costs for innnovative technologies which could be deployed as replacements for many existing Smaller scale CO2 emitting industrial applications.
Studies of the cumulative costs curves for CO2 geological storage in the USA and Europe undertaken for the IEAGHG suggest large volumes to be available at net costs below $10/ton

The alternatives to carbon capture and storage for these distributed sources would be to provide them with “green” electricity or hydrogen. Overall there are many technical obstacles to hydrogen distribution, however if subscription to such a network was high, the costs could be reduced significantly. Although ‘green’ electricity is becoming more competitive, the cost of production is still substantially higher than electricity from traditional fossil fuel routes. The costs of electricity transmission are also high when compared with natural gas transmission.

When taking into consideration the marginal costs of introducing each emission band (Tier 0, Tier 1 etc) it becomes apparent that it may be more economical to deliver clean energy in the form of green electricity or piped hydrogen to Tier 2 sources instead of collecting their CO_2. Marginal costs for Tier 1 were higher than those for Tier 0 however, they were of the same order of magnitude and were likely to be skewed upwards by remote smaller sources within the emission band. Taking this into account, it is concluded that distributed CO_2 collection networks can be economical for smaller industrial sources (<1Mtpa CO_2) however, great care must be taken when deciding upon suitability and estimating costs. It is also apparent from this study that, despite the costs associated with hydrogen distribution, it may be cheaper than distributed CO_2 collection from very small (<50ktpa CO_2) sources. The table below presents the marginal costs associated with each Tier.

Element	Tonnes CO_2	Tier Network Cost ($)	Marginal Tier Cost ($/tonne)
Tier 0	14,000,000	119,000,000	8.50
Tier 1	4,600,000	44,680,000	9.70
Tier 2	700,000	23,530,000	33.60

These costs are representative of a one particular industrial area and the typical construction costs of the chosen region. The more densely sources are concentrated the lower will be the collection costs and for more widely dispersed sources the converse. Sensitivities show that the costs do not rise and fall linearly with transport distances because of relatively high fixed elements especially for compression. It is expected that similar results would be found for other heavily industrialised areas but case by case analysis using the same spreadsheet costing tool is probably the best way to compare costs in other locations. IEAGHG are planning to enhance the tool by having cost data for other regions added.

3 Introduction

GASTEC at CRE Limited (GaC) was commissioned by The IEA Greenhouse Gas R&D Programme (IEAGHG) to undertake a study to assess the economic and practical viability of a distributed carbon dioxide collection and transmission network.

It has been well documented that the capture and storage of CO_2 from fossil fuel power plant and other major industrial processes offers one route to major reductions in greenhouse gas emissions. Several studies have been conducted by IEAGHG and other organisations into the feasibility of such collection and storage systems[1 - 5]. Collection of CO_2 from large point sources is attractive because of the large economies of scale that can be achieved, and the relative simplicity of the transmission system. However, there remain a significant proportion of CO_2 emissions which derive from the industrial and commercial sectors which is distributed (as evident from figures generated for this report). Previously, the capture and collection of CO_2 from this sector has been considered as too complex and expensive to offer a viable solution for carbon abatement. Most recent studies have concentrated on centralised CO_2 collection and disposal, possibly coupled with distribution of ‘clean’ energy in the form of electricity or hydrogen to the smaller, decentralised sources. However, such a strategy would still require an extensive distribution network and has not been compared to the alternative of decarbonisation at the point of consumption combined with distributed collection and transmission of CO_2.

This study considers the distributed collection and transmission (to a viable disposal point) of CO_2 from point sources within the Mersey and Dee Basins in the North West of England. Over 70 installations were identified as having the potential to provide CO_2 for the suggested network, totalling nearly 20Mtpa or 5% of UK point source emissions[6, 7] (Including domestic emissions – or 7.6% of all industrial CO_2). These sources are located in an area of approximately 4100 square kilometres (1.7% UK land area - effectively within a 30-40 km radius). This gives an emission of CO_2 per square kilometre of 4826 t/km^2. A result of this concentration of point sources is a wide variety of large, medium, and small CO_2 emitters dispersed across a densely populated area. The study aims to assess the viability of including medium and small CO_2 sources with large emitters into a collection and transmission network.

The report details specific criteria for collection and transmission that were derived during the study from critical analysis of CO_2 behaviour and the economics of pipeline and transmission system design.

The network design elements of this project were conducted in association with the Industrial Division of AMEC and Kiwa GASTEC NL.

4 Scenario Definition

In order to formulate designs for the distributed collection system, three distinct levels of collection were considered.

- The top level (Tier 0) is made up of installations producing over 1Mtpa CO_2, these typically comprise power stations and very large refineries.
- The middle level (Tier 1) comprises major industrial sites such as small refineries, chemical works, CHP installations and other major industrial complexes that produce 50ktpa – 1Mtpa CO_2. Collection from Tiers 0 and 1 is considered to be the most feasible as considerable economies of scale still apply even when considering installations emitting 50ktpa CO_2.
- The lowest level considered (Tier 2) is made up of smaller scale light industrial and commercial enterprises such as very large offices, hospitals, industrial estates, manufacturing complexes and research facilities. At this scale of collection, individual emissions of the order of 5ktpa CO_2 were considered. This is equivalent to a continuous electrical load of 1+MW.

It is most likely that any collection system would proceed at the highest level first before incorporation of the smaller sources. For this reason, designs are presented which consider the following scenarios;

- Tier 0 sources only
- Tier 0 and Tier 1 sources
- Tier 0, 1 and 2 sources
- A trimmed network comprising viable sources only from all levels

Once suitable CO_2 sources are identified, further consideration is then required into detailed network design parameters such as inter-source connections, pipeline routes, materials of construction, compression and drying and finally network costs and economics.

One of the main outputs from the study is a spreadsheet which considers all of the parameters required to design a network and manipulates them to detail pipeline pressures, materials and capital and operating costs. This spreadsheet could be employed in other geographical locations to assess the viability of carbon capture and transmission networks.

Some discussion is also presented that explores the possibility of piped hydrogen, safety aspects of carbon and hydrogen transmission and other considerations such as the ability of emitters to operate capture plant etc.

5 Study Area & CO_2 Sources

Although it would have been possible to base the study on a theoretical region with a statistically derived distribution and dispersion of sources, it was decided to base the study on a real geographical area. The basis for this was two-fold:

- Due to the geographical complexity of industrial areas (often coastal, high density of roads, railways, canals and often rivers, high population density, clusters of densely populated conurbations) where distributed CO_2 could be a viable option, it was considered that a statistically derived study area would be of little value, and that it would be very difficult to justify all the assumptions that such an approach would require.
- Furthermore it was considered that basing the study on a real region of the UK could be of true benefit to any future studies or pilot projects relating to carbon capture and disposal in the subject area.

Three UK candidate locations were considered:

- Bristol including Avonmouth. This area has a large fertiliser plant producing compressed CO_2, a carbon black plant, a 600MW power plant and several other large industrial point sources including substantial docklands. The gas could be collected and piped across the Severn to the Corus steel plants in S Wales. The only real option for large scale disposal from this location would be deep saline aquifer storage in the Celtic Sea. There would be no option for use in enhanced oil recovery.
- The North West of England, particularly the area around Runcorn and environs, including Stanlow. This has a host of chemical plant, refineries, heavy industry and several large power plants. Storage in offshore oil and gas wells would be possible as well as enhanced oil recovery and deep saline aquifer storage.
- Teesside. This area has one of the highest concentrations of heavy industry in the UK. Being on the East Coast of England, Teesside is convenient for CO_2 storage in disused oil wells in the North Sea or enhanced oil recovery. Research carried out for the Statoil Sliepner project also indicated that deep saline aquifers suitable for CO_2 storage are also within reasonable proximity[13].

After discussions with the project team and the IEA GHG programme, the North West of England, specifically the River Dee and River Mersey basins was chosen to be the subject area. This area was chosen as there is a very high concentration of heavy industry, producing large quantities of CO_2 across a sizeable geographical area. Furthermore, viable storage options were shown to be within close proximity to the subject area. A diagram of the study area is presented in Figure 1.

Figure 1: Study Area

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This area was selected due to the high concentration of large industrial point sources of CO_2, complemented by a large commercial and light industrial sector. Information gathered from the Department for Communities and Local Government (DCLG) and the Department for Trade and Industry (DTI) indicates that CO_2 point source emissions in this region totals 20Mtpa or 5% of UK point source emissions[6, 7] (This figure includes emissions from domestic sources, 20Mtpa is equivalent to 7.6% of all industrial CO_2 emissions) The land area covered by the study is approximately 4100 square kilometres (1.7% UK land area).

Another important factor for the selection of this region was the proximity of final disposal options for the captured CO_2. The study area is very close to the Eastern Irish Sea oil and gas fields, which may be suitable for Enhanced Oil Recovery (EOR) or disposal into depleted wells. In addition, geological studies conducted by the BGS[8] suggest that disposal within structural and stratigraphic geological traps also has potential beneath the Eastern Irish Sea. The region also has deep, unminable coal seams and salt deposits which may be suitable for further gas storage. These options will be discussed in greater detail in Section 7.

5.1 Point Sources of CO_2 within the region

Suitable point sources (Tier 0, 1 & 2) were identified from the publicly available emissions information on the Defra website (installations-list.xls spreadsheet) and separated into their respective Tiers. Emissions figures were derived from each installation's allocation under Phase 1 of the UK Emissions Trading Scheme (ETS) and those identified under the National Allocation Plan for the EU ETS[6, 7]. The emissions identified for this study represent each site's emission during 2005. It should be noted that these emissions may be subject to change and may not be fixed. However, for the purposes of this report the figures also presented real values that give a good picture of the possible size and spread of emissions sources from an industrialised region. The UK ETS is a voluntary scheme at present for all industrial CO_2 sources except those that produce electricity for use off site. The scheme offers financial incentives for participants that reduce their carbon emissions. The EU ETS covers industrial CO_2 resulting from energy activities, production and processing of ferrous metals, mineral industries and pulp and paper industries (all sites covered by IPPC). It is likely that sources included within either scheme would be most interested in CCS due to the possible financial gain from trading credits. In theory sites operating under either scheme should be able use the collection network provided that the cost of emission and the reward for reduction/sequestration is kept the same under each scheme.

5.1.1 Tier 0 Sources

In total, 5 Tier 0 sources were identified comprising four power generation facilities and one large oil refinery. A list of Tier 0 sites for the study area is presented in the table below;

Table 1: Tier 0 Sites

Site No.	Site name	Activity	CO_2 Emission (tpa)
1	AEP ENERGY SERVICES UK GENERATION LTD.	Power Generation	4,957,707
2	SHELL U.K. OIL PRODUCTS LIMITED	Refinery	3,968,712
3	POWERGEN UK PLC	Power Generation	3,189,160
4	DEESIDE POWER DEVELOPMENT CO. LTD	Power Generation	1,092,247
5	INTERGEN LTD	Power Generation	1,307,490
		TOTAL	14,515,316

As can be seen in the table above, the Tier 0 sites represent 14.5Mtpa CO_2 or 73% of the total emissions that are proposed to be collected by the scheme.

The Tier 0 sites were found to be in relative proximity to each other and conveniently are 'strung-out' across the study area allowing a high pressure trunk-line pipe to connect them together.

Figure 2 displays the approximate locations of the Tier 0 sites. The locations of all sites are also shown more precisely in Appendix 1.

Figure 2: Tier 0 site locations

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5.1.2 Tier 1 Sources

In total, 24 Tier 1 sites were identified within the study area. Various industries are represented within this group including large CHP plant, cement production, chemicals, paper manufacturing, glass, food and drinks industries and smaller scale refineries. The majority of these sites were found to be within reasonable proximity to the Tier 0 sites. Some sites with emissions of just below 50ktpa (within 10%) were included into the Tier 1 bracket. Although the study brief declared a lower end cut off for Tier 1 at 50ktpa, a natural break was found in the source data at 46ktpa after which there weren't any sources greater than 38ktpa. It therefore appeared logical to include these smaller sites (50 – 46ktpa) within the Tier 1 bracket and use the natural break between 38ktpa and 46ktpa to define the Tier 2 sites. A list of Tier 1 sites is presented over the page;

Table 2: Tier 1 sites

Site No.	Site name	Activity	CO_2 Emission (tpa)
1	CASTLE CEMENT	Cement	422,136
2	INEOS CHLOR LIMITED	Chemicals	374,546
3	SHOTTON CHP LTD.	Pulp & Paper	300,150
4	INNOGY COGEN LTD	Pulp & Paper	226,054
5	PILKINGTON GLASS	Glass	223,669
6	BRIDGEWATER PAPER CO LTD	Pulp & Paper	212,860
7	SCOTTISH AND SOUTHERN ENERGY	Food & Drink	179,748
8	PILKINGTON GLASS	Glass	77,386
9	UPM-KYMMENE (UK) PLC	Pulp & Paper	72,499
10	POWERGEN CHP LTD	Chemicals	56,758
11	JAGUAR CARS LTD	Other Combustion Activities	53,547
12	JAGUAR CARS LTD	Other Combustion Activities	50,719
13	EASTHAM REFINERY LIMITED	Refineries	50,470
14	POWERGEN CHP LTD	Other Combustion Activities	597,679
15	KRONOSPAN LTD	Pulp & Paper	114,738
16	BRITISH SALT LTD	Food & Drink	70,283
17	PPG INDUSTRIES (UK) LTD	Glass	48,881
18	KEMIRA GROWHOW UK LIMITED	Chemicals	46,909
19	SONAE UK LTD	Pulp & Paper	47,625
20	POWERGEN CHP LTD	Other Combustion Activities	180,000
21	QUINN GLASS LIMITED	Glass	140,000
22	EASTHAM REFINERY LIMITED	Refineries	342,610
23	POWERGEN CHP LTD	Other Combustion Activities	137,000
24	GAZ DE FRANCE GENERATION	Other Combustion Activities	550,000
		TOTAL	4,576,267

The 24 Tier 1 sites represent a total of just under 4.6Mtpa CO_2 or 23% of the total point source emissions identified within the proposed scheme. As expected the majority of sites were also found to be within relatively close proximity to the Tier 0 sites.

Figure 3 shows the locations of the Tier 1 sites. All sites are also shown more precisely in Appendix 1.

Figure 3: Tier 1 site locations

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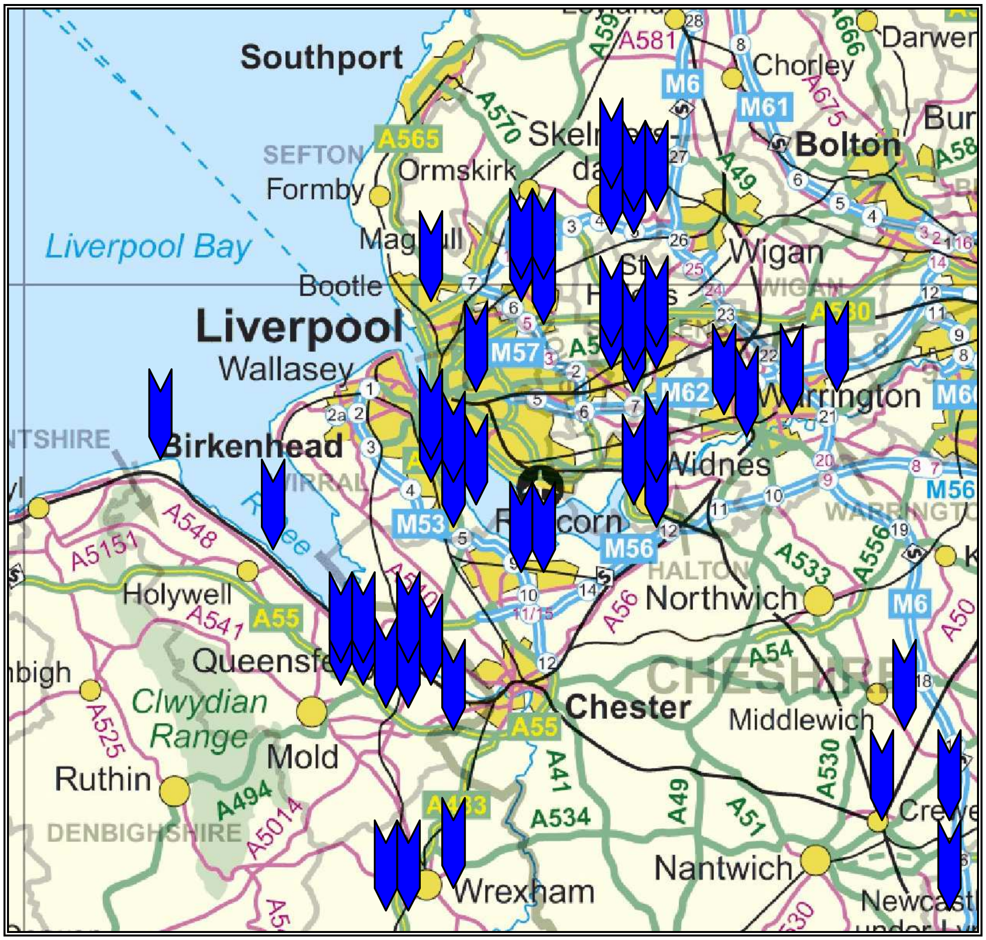
5.1.3 Tier 2 Sources

A total of 49 Tier 2 sites were identified within the proposed scheme area. The Tier 2 sites represent a total of 0.7Mtpa CO_2 or 4% of the total point source emissions identified within the proposed scheme.

Figure 4 shows the approximate locations of the Tier 2 sites. All sites are also shown more precisely in Appendix 1.

Figure 4: Tier 2 site locations



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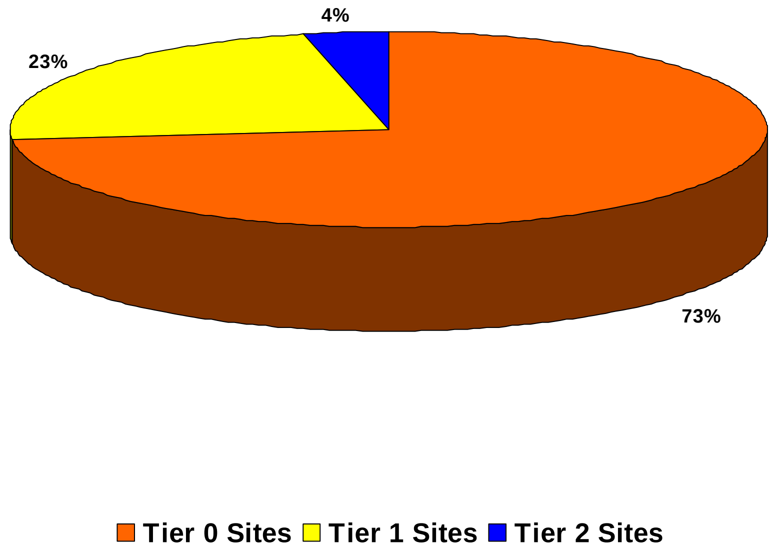
5.1.4 All Sources

A summary of all sites identified as suitable for the proposed scheme, detailing CO_2 emissions (Tier), industry, address and company is presented in Appendix 2.

Figure 5 shows a summary of the proportions of point source CO_2 emissions for each Tier within the scheme;

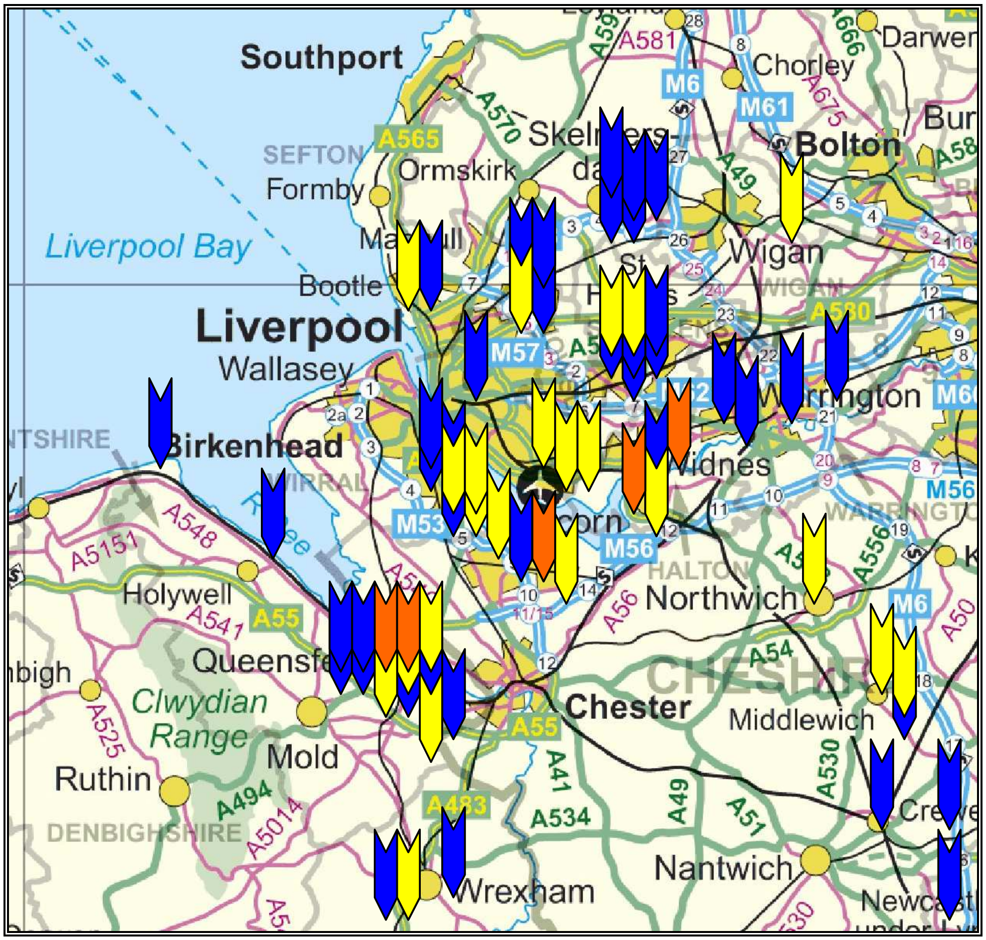
Figure 5: Proportion of emissions represented by each Tier



As one would expect, sites from all Tiers were found to be situated in clusters across the study area with only a handful of remote, isolated sources.

Figure 6 shows the approximate locations of sites from all Tiers. Note that some site locations are covered by other markers. All sites are also shown more precisely in Appendix 1.

Figure 6: All Tiers, site locations



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As can be seen from Figure 6, the Tier 0 and a large proportion of Tier 1 sites are in reasonably close proximity to each other. This should result in favourable conditions for a collection and transmission network. It is also apparent that the high density of population and associated transport infrastructure is likely to have a large impact upon the cost of any capture and transmission scheme. Due to the region's long history of heavy industry, a high density of canals, railways and roads cross the region, particularly in the areas close to the identified sources. This will inevitably add complications to the proposed network and also affect cost.

6 Collection Network Design

6.1 Operational parameters

Prior to preliminary network design and development of the design spreadsheet, basic build and operational parameters had to be established for the network. These parameters were established in conjunction with AMEC and Kiwa GASTEC NL. The following outlines each specific area of consideration that had to be established prior to preliminary design. It should be noted that the design of most distributed gas networks is undertaken on a safety risk assessment basis. As this was not possible for this study it should be noted that some assumptions had to be made by AMEC and Kiwa NL in order to design and derive costs for the network. In most cases these elements have been incorporated into the network design tool (discussed later) and are presented in the following sections.

- **Shape of Network: Ring Main Vs Tree**
  Two main shapes of network were considered; A ring main, such as the current natural gas distribution network in the UK with each source or node feeding into a high pressure main; or a tree type network with each source or node feeding into the next until a common ‘trunk line’ is reached.

  In gas distribution there are several advantages of using a ring-main, however these do not apply when considering a network which essentially removes CO_2 from sources as opposed to delivering natural gas. Furthermore, it was considered uneconomic to lay the additional high pressure pipeline required for a ring-main as opposed to a trunk-line which only operates at high pressure where required. It was also decided that due to the possible safety implications of supercritical CO_2 pipelines, the high pressure pipeline should be limited to rural areas, thus, the pipelines in urban areas would be transporting sub-critical CO_2 gas. These issues are discussed in further detail in Section 8.

  It was also decided that clusters of Tier 2 sites would not be inter-connected but each have an individual line to a common node. In this way, outages caused by problems at one site would have a minimal impact on the operation of sites closer to the end of the branch.

- **Operating Pressures**

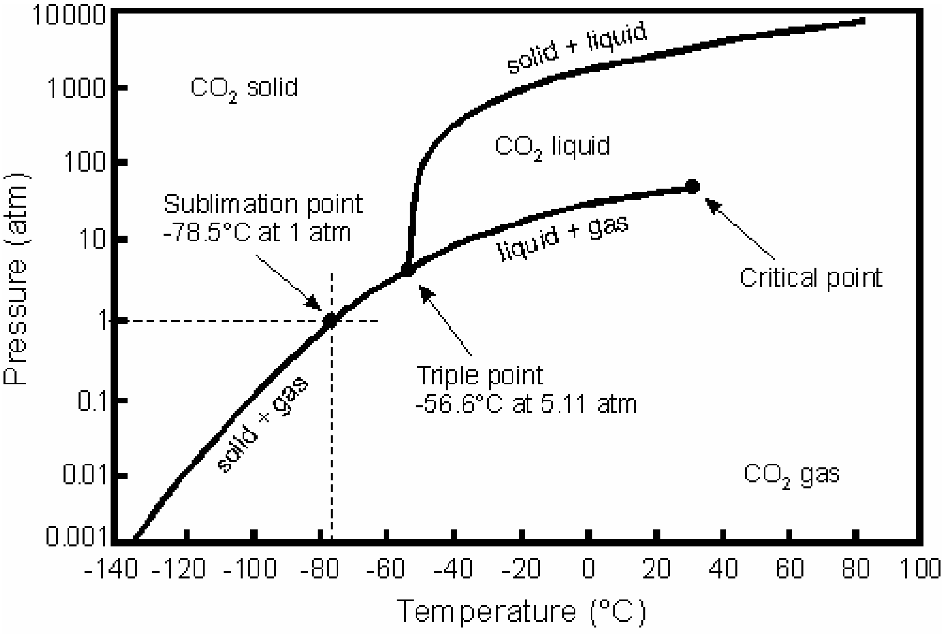
  In order to reduce costs for pipeline installation and operation, Tier 2 sites would be connected to the network via a negative pressure system up to the interconnecting node. This would allow relatively cheap small scale ‘blowers’ to be used instead of more expensive compressors.

  From the node onwards, the CO_2 would be transported at a pressure of 10bar. This pressure would allow the use of relatively low cost High Density Polyethylene (HDPE) pipe.

  Once the total flow in a pipeline exceeds about 5.4 kg/s (170ktpa), the required pipeline diameter becomes greater than that available in HDPE pipe.

At this point, the CO_2 would normally be compressed to between 80 and 100 bar and steel pipe of a much smaller diameter becomes more economic. At pressures above 60 bar CO_2 becomes a supercritical fluid (that undergoes no phase change with temperature) which is the most economic way to transport the material by pipeline. A phase diagram for CO_2 is presented in Figure 7 below. Note that at pressures above 80bar CO_2 is in the supercritical phase at ambient temperature.

Figure 7: CO_2 Phase Diagram



The high pressure line restriction imposed by safety considerations (Section 8) dictates that pipelines in urban areas should operate with sub-critical gas meaning that, in some areas, multiple medium pressure lines must be used. This condition was derived following several meetings with the UK Health and Safety Executive (HSE). Although the HSE has not made a final decision regarding supercritical CO_2 pipelines, it was suggested that tighter safety controls may be put in place than exist for natural gas. It was also implied that supercritical pipelines may not be permitted in urban areas. For the purposes of this study the authors decided to err on the side of caution and exclude high pressure/supercritical CO_2 lines from urban areas. This condition may not be the case in all countries. It is the opinion of the consultant that it is external risks such as groundworks that pose the most danger to the integrity of the pipeline and therefore pipelines in dense urban areas are at greater risk. An option was incorporated into the network design sheet that allows the user to dictate whether supercritical flow is permitted or not. If it is decided that supercritical flow is not permitted, all preceding lines are also prevented from being high pressure. This prevents large amounts of energy being wasted by pressurising to 80 bar only to de-pressurise at a later point.

- **CO_2 Dryness**

  A crucial factor of the design was the specification for the dryness of CO_2 to be accepted by the collection network. As Tier 0 and Tier 1 sites were to be connected to medium and high pressure lines, a reasonable degree of drying would be required anyway. It was decided that full drying (to -5°C dew point) would be carried out at these points to prevent condensation build-up within the network and the negative effects of this (condensate 'slugs)' and for steel pipelines, corrosion. It was considered whether it would be feasible to accept saturated CO_2 from Tier 2 sites for centralised drying at a central node (to reduce costs) however it was decided that the negative effects of condensate build-up within the low-pressure network outweighed the benefits of centralised drying; and therefore full drying (to -5°C dew point) was to be conducted at all sources. The -5°C dew point was established through consideration of the sub-soil temperature range within the subject region.

  Despite the high level of drying it is inevitable that some condensate will form within the network, due to drying plant failure and the subsequent introduction of sub specification gases. In order to deal with this scenario, condensate removal points have to be included in the network design at low points in the piping system and prior to compression stations. A further consideration relating to condensate build-up is discharge of the liquid to sewer or river. Discussions with local water authorities and consideration of legislation[12] revealed that each site would require a discharge consent to release condensate produced during drying to foul sewer. It is not likely that discharge to local watercourses would be permitted. Furthermore the network operator would also require many discharge consents for the release of condensate collected at the traps dispersed across the transmission network. Depending upon the nature of the condensate, this could add considerable cost to the operation of the network and an additional financial burden to businesses wishing to inject CO_2 into the system.

- **Impurities**

  An initial concern was the effect of gaseous impurities such as SO_2 and NO_x on the phase envelope of CO_2 and on the network as a whole (corrosion etc).

  For the purposes of this study, it is was assumed that all toxic impurities (eg H_2S, SO_2, NO_x) have been removed from the CO_2 during the separation process. Thus, the introduction of impurities would be limited via careful selection of CO_2 capture plant or via enhanced gas clean up prior to network injection. This is justified because the levels of impurities are likely to be very low. The pipelines are sized based on the properties of pure CO_2, and it is not expected that the small concentrations of impurities will materially alter the calculations.

- **Compression**

  The compression of CO_2 is likely to be the largest operational cost of the scheme due to the high usage of energy. It is therefore proposed that CO_2 compression is achieved using electrically driven 4 stage compressors. Although this would result in a CO_2 emission elsewhere through the generation of electricity, it removes the problem of actual CO_2 release within the envelope of the network itself. It could also be argued that any release outside of the envelope of the scheme could also be captured and sequestered or that the electrical energy itself may come from low or zero carbon energy sources.

Furthermore, electrically driven compressors offer better control of compression and can be powered up or down relatively easily in comparison to gas turbine compression units. This will allow the network to react quickly to peak and low flows and minimise energy wastage.

- **Materials of Construction**
  Polyethylene plastic piping is cheaper to purchase and easier to lay than the steel equivalent and therefore would be used wherever possible in the proposed network. The network design tool incorporates this rule and only uses steel for higher pressures. Standard piping sizes have been assumed. High pressure lines have been assumed to be Steel although it is understood that new, multi layered polymer pipes are coming onto the market which can withstand high operating pressures. As these are relatively unproven and robust cost data is not available, they have not been incorporated into the network tool but could be at a later date.

- **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. The cost of metering has bee incorporated into the network tool and is based upon data obtained from natural gas metering.

- **Valves**
  In order to reduce the inventory released in the event of a pipeline failure, valves would be installed at regular intervals of 1000m for high pressure lines and 2000m for medium to low pressure lines. These valves would automatically slam shut on pipeline rupture (detected by a loss of pressure), thus limiting the escape of CO_2 to the amount contained in the pipeline between the valves. The implications of this for the operation of upstream CO_2 separation and compression plant would need to be carefully considered. These distances were derived through discussion with the HSE.

- **Leak Detection**
  Leak detection equipment is essential to a network of this scale. Stringent monitoring and inventory accounting would be required by the pipeline operator. Leak detection is likely to be in the form of temperature sensing outer sleeves for major pipelines and routine pressure testing for smaller pipelines.

- **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. HDPE pipelines would not need protection from corrosion.

- **System Peak Flow Capacity**
  The overall annual emission for the region is 20mtpa CO_2 which translates into ~2290 tph. This flow rate would be subject to hourly, daily and seasonal variations. Given that around 60% of the system emissions are from power stations, it is likely that the system flow rate would fluctuate due to grid electrical demand. It should be noted that the vast majority of other processes within the study are continuous and are likely to produce near constant emissions. However, as stated there will still be variation in flow from the major power stations and inevitably some fluctuation from other sources that must be dealt with by the system. The possibility of using salt caverns for peak storage and low flow balancing is discussed later in Section 7 of this report. A system of this kind would undoubtedly be designed to handle the anticipated peak flow plus some kind of allowance (peak flow +X%). In this report the network has been designed to handle the average flow, as the determination of peak flow and daily/annual flow profiles for the system would be an additional study beyond the scope of this report. It is expected that over sizing the network to cope with peak flow is likely to only add around 5-10% to the overall costs of the transmission network or less than \$0.5 - \$1 per tonne (OR less than 2.5% of estimated complete network costs). This has been determined given that the only major cost increase when adjusting the capacity of the network is the cost of compression which individually accounts for 20% of overall transmission system cost. Costs such as way-leave and groundwork would not change significantly for a slightly larger pipe although it should be noted that some additional costs may also be incurred for larger drying plant.

6.2 Collection System Design Spreadsheet

A spreadsheet design tool was developed to allow evaluation of the feasibility of the scheme. The spreadsheet calculates pipeline sizes, compression duties, and capital and operating costs from the various inputs from the user.

The spreadsheet is designed to be applicable to any geographical area. However, due to the large price variance between different countries for most factors (such as cost of labour, materials etc), the costs derived from the spreadsheet in its current form apply to pipelines solely within the UK. Originally it was assumed that a model designed for the UK would largely hold in price terms for most of the EU. However; it has been established over the course of this study using data from AMEC (who have global experience of pipeline construction) and Kiwa GASTEC NL (who have excellent experience of mainland EU pipelines) that the UK is significantly more expensive than the rest of Europe.

However, the spreadsheet still proves to be a useful tool for other countries, as with some manipulation of the data sources within the spreadsheet; it could be quickly adapted for use elsewhere.

6.2.1 Inputs

The sources to be included within the scheme were input into the spreadsheet along with their emission of CO_2 in tonnes per annum. Each source is attributed an individual ID number.

The pipelines and their routes required to link the various sources were established using traditional mapping. A schematic of the network (not to scale or actual pipeline routes) is shown in Appendix 7.

For each pipe within the system, the following was then input into the spreadsheet;

- Which plant the pipeline flows from
- Any previous pipeline to be added (connected) to the subject pipe
- Which pipe the subject pipe connects to (downstream)
- Terrain through which the pipeline is routed:
    - Flat open countryside
    - Urban
    - Mountainous
    - Desert
    - Forest
    - Offshore
- Pipeline length (m)
- Number of crossings of:
    - River
    - Canal
    - Railway
    - Motorway
    - Major road
    - Minor road
    - Sub-minor road

- Whether a supercritical pipeline is allowed or not. This is established by the spreadsheet but should be checked. For this study, supercritical pipelines are not permitted in areas classed as urban.
- Pipes can also be designated as being part of a suction system (Most Tier 2 sites). Note the tool will not allow low pressure connections (even if specified) when the pipeline required would be too large.
- Whether a condensate removal point is required for each pipe section.
- The desired distance for slam-shut valves on high pressure lines

All of these criteria affect the cost of the network and therefore the network tool factors in each variable and adjusts the cost of each pipeline accordingly. The cost information required to do this was provided by AMEC who have extensive experience of pipeline construction in the UK and worldwide. It is recommended that interested parties should consult the network tool to establish the basis for the cost calculation.

6.2.2 Outputs

Based on the input data, the model decides on the operating pressure of each pipeline, and then calculates the pipeline diameter, material and costs. These calculations finally result in a cost per tonne of CO_2 disposal.

The model outputs for each pipeline and the overall scheme are:

- Pipeline diameter
- Pipeline material
- Start and end points
- Capital cost (CAPEX)
- Operating cost (OPEX)
- Cost per tonne of CO_2 transported ($/tonne)

Note that OPEX is calculated using the standard IEAGHG procedure;

2% of overall pipeline investment
5% of overall compressor investment
Cost of energy of 6$/GJ

This is explained in full detail in section 11.

7 Storage Options

Although this study is primarily to determine a cost per tonne to deliver the CO_2 to a storage point and not to include the cost of final disposal/storage it was deemed necessary to determine the most viable storage option for the study region. The most viable storage option would then be used to calculate items such as pipeline costs (onshore or offshore etc) assess skills requirements of the scheme and determine whether a viable storage option actually exists for the region.

The main storage technologies for consideration within this study area are the various types of sub-surface storage, these being Enhanced Coal Bed Methane (ECBM), storage in depleted oil and gas wells (including Enhanced Oil Recovery (EOR)), storage in deep saline aquifers (on and off shore) and temporary storage in deep underground salt cavities.

Other storage technologies that are often discussed with regard to CCS are mineral disposal and deep ocean storage. These have both been discounted from this study due to environmental and legislative concerns with regard to deep ocean storage and cost and timescale limitations of mineralisation.

The study area is particularly fortunate in that it is within close proximity to several economically and technologically proven final disposal/storage options. As previously mentioned, within the subject area possible disposal routes include;

- **Enhanced Oil Recovery (EOR) & Storage in Depleted Oil and Gas fields**
  EOR is a well established technique that is used widely in the United States and other countries with ‘end of-life’ oil producing wells. Oil and gas production from the East Irish Sea first began in 1995 (Hamilton North Field) and there are currently 8 active fields operating within the East Irish Sea Basin. The majority of East Irish Sea Fields are gas producing with the exception of the Douglas Field which only produces oil and the Lennox field which produces oil and gas. Taking into consideration the sites that are included within the study any pipeline to the Irish Sea Fields would pass from the Connah’s Quay area, along the River Dee estuary to the Point of Ayr gas terminal (27km) for final compression before being pumped out to a platform at the Douglas and Lennox fields (33.5km).

  Although the storage of SC CO_2 in depleted oil and gas wells is not widely practiced, the principles and some of the technology would not be too dissimilar to that which is used for EOR and acid gas disposal (widely practiced in North America) which are both feasible, proven technologies.

  Due to the large amount of infrastructure already in place in the East Irish Sea Basin it is likely that some of this would be available for use in any CCS scheme. Furthermore, the expertise that would be required to undertake such a project will involve skilled workers that are already in place due to the offshore oil and gas industry. These factors greatly increase the feasibility of this disposal option.

A recent study undertaken by the British Geological Society[8] (BGS) estimates that the total storage capacity of the oil and gas fields within the East Irish Sea Basin at 1047Mt SC CO_2. This equates to approximately 50 years emission from the sources identified within this study. Figure 8 below shows the proximity of the Eastern Irish Sea gas fields. The various stratigraphic traps highlighted in a recent BGS report are also in this area. Also shown are the southern Irish Gas Fields however it is considered that these are too distant to be a viable storage option for the study area.

Figure 8: Location of Eastern Irish Gas Fields

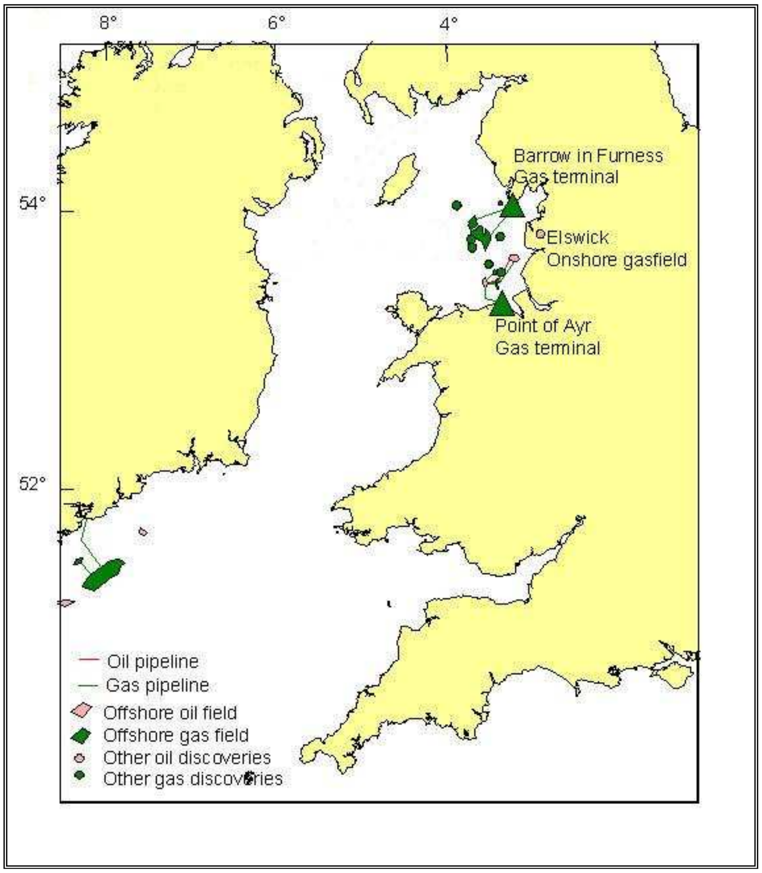


Image edited from http://www.defra.gov.uk

- **Geological Storage in Deep Saline Aquifers**

  Storage of SC CO_2 within deep saline aquifers is a method which has received steadily growing support over the years. Several projects around the world now undertake this practice and to date have proved very successful at containing the SC CO_2. The most widely known of these projects is the Sleipner project which has pumped around 1Mtpa SC CO_2 beneath the Norwegian Sea since 1996.

  A recent study undertaken by the British Geological Society[8] (BGS) has identified suitable closed structures beneath the East Irish Sea, that are potentially capable of storing SC CO_2 in a similar manner to the Sleipner Project. Estimates by the BGS put the storage potential of closed structures within the East Irish Sea Basin at a further 630 Mt SC CO_2. It should be noted however that the integrity of these structures should be examined further, especially given that they are scattered between hydrocarbon bearing structures but do not bear any oil or gas themselves. This could be an indication that they are not suitable for CO_2 storage.

- **Enhanced Coal Bed Methane**

  The study region further benefits from being directly over deep unminable coal seams. Projects in the United States have successfully injected SC CO_2 into deep coal seams. The CO_2 displaces methane and binds to the coal thus sequestering the CO_2 whilst also producing methane gas, the sale of which reduces the cost of disposal.

  Little assessment has been made as to the suitability of the coal in the study region for ECBM CO_2 disposal. Should the coal type prove suitable it should be noted that this would not provide a long term storage solution for the study area but could provide an economic means of CCS for isolated sources in the study area that may not be able to economically connect to any distributed collection network. Furthermore some studies[9, 10] suggest that ECBM should only be undertaken in coal seams that are not directly below populated areas because of safety concerns over the collection of displaced methane or escaped CO_2 in confined spaces such as basements or service ducts.

  Increased capacity could be reached via offshore ECBM the potential of which is unknown for this study area and therefore should be investigated further. There is also some suggestion that without sufficient subsidy from the government Coal Bed Methane would not be competitive with natural gas (a subsidy exists within the United States[9]).

- **Deep Salt Cavities**

  Beneath the eastern portion of the study area lie large salt deposits which could also provide a storage solution for isolated sources within the study area. Another more beneficial use for salt cavities would be use in balancing the CO_2 collection network. Cavities could be formed in key areas along the distributed collection network via solution mining. These cavities could then be filled with SC CO_2 during peak or excess demand periods and then emptied during low demand periods thus a relatively constant volume of SC CO_2 would be transmitted to the storage facility.

For the purposes of this study it is to be assumed that disposal will take place in the East Irish Sea gas and oil fields. Although, as discussed earlier, other disposal routes are available for the study region, many of these require a great deal of further investigation before they can be verified as having CO_2 storage potential. In contrast EOR and storage of gases other than CO_2 within depleted wells are established technologies with relatively well defined costs and requirements. It should be noted that the other potential options mentioned should not be discarded completely and that options such as network balancing using salt cavities is not without merit.

8 Safety Considerations of CO_2 Transportation Network

Carbon dioxide is an odourless, colourless gas under atmospheric conditions. It is not flammable or explosive, but it can act as an asphyxiant at concentrations above about 10% v/v. At concentrations between 5% and 10%, CO_2 impairs physical and mental ability, and even at concentrations around 3%, it can have physiological effects on humans such as shortness of breath. CO_2 has a molecular weight of 44 which is considerably heavier than air. This means that any release of CO_2 is likely to lead to a potentially dangerous accumulation in low lying areas/spaces.

In some places, volcanic activity results in naturally high concentrations of CO_2, notably near Lake Nyos in Cameroon where a sudden release of CO_2 led to approximately 1800 fatalities.

Supercritical CO_2 is transported by pipeline in a number of places worldwide. In particular, there are several enhanced oil recovery (EOR) projects in the United States. Most EOR projects use naturally occurring CO_2, and the CO_2 is transported in steel pipes at pressures high enough to ensure that it remains a supercritical fluid. These oilfield areas generally have low population densities, and pipeline routes are generally away from urban areas.

CO_2 is generally classified as non-toxic but is considered to be hazardous due to its asphyxiant properties.

A recent report commissioned by the IEA GHG R&D Programme suggests that the safety issues surrounding CO_2 transport by pipeline can be covered by existing standards and guidance The report suggested that greater issues surrounded the standards and norms required for geological storage of CO_2, compared with the pipeline. Some limited dispersion modelling of the effects of failure of a supercritical CO_2 pipeline was carried out, indicating that even in the event of a full bore fracture of the pipeline, the affected area would be quite limited. It was noted that these dispersion model studies were not adequate to provide generic guidance as site-specific conditions will affect the actual dispersion.

In order to properly model the release of supercritical CO2 from a pipeline rupture, physical parameters that define the release at source are of particular importance. For example, it is usual to include an air dilution factor of around a factor of 2 for many dense gas releases, however for high pressure releases there is a large amount of turbulence at the release site resulting in a much greater dilution of the released gas at source. The subsequent hazard profile will be greatly affected by the amount of dilution at source. The appropriate set of source terms for supercritical CO_2 releases has not yet been developed, although experiments are underway to measure dilution effects etc.

The lack of definitive information about the effects of a pipeline rupture suggests that a conservative design approach should be adopted. The fact that the study area is densely populated and that much of the area is urban supports this philosophy. Therefore, a number of safety features were built into the design, such as block valves every 1km, and the use of medium pressure pipelines in urban areas.

9 Costs of CO_2 Transportation Network

9.1 Capital Costs

Capital costs for each type of pipeline were estimated using in-house data from AMEC, who have a long track record of installing natural gas transmission and distribution pipework in the UK and worldwide. Capital costs for instrumentation, valves, compressors, blowers etc were also estimated from AMEC's in-house databases, and selected budget quotations from suppliers.

Overall capital cost estimates are expected to be better than ±30%.

The capital costs were compared with published data for natural gas transmission and distribution systems from around the world. Figure 9 shows the comparison for a range of steel pipe sizes.

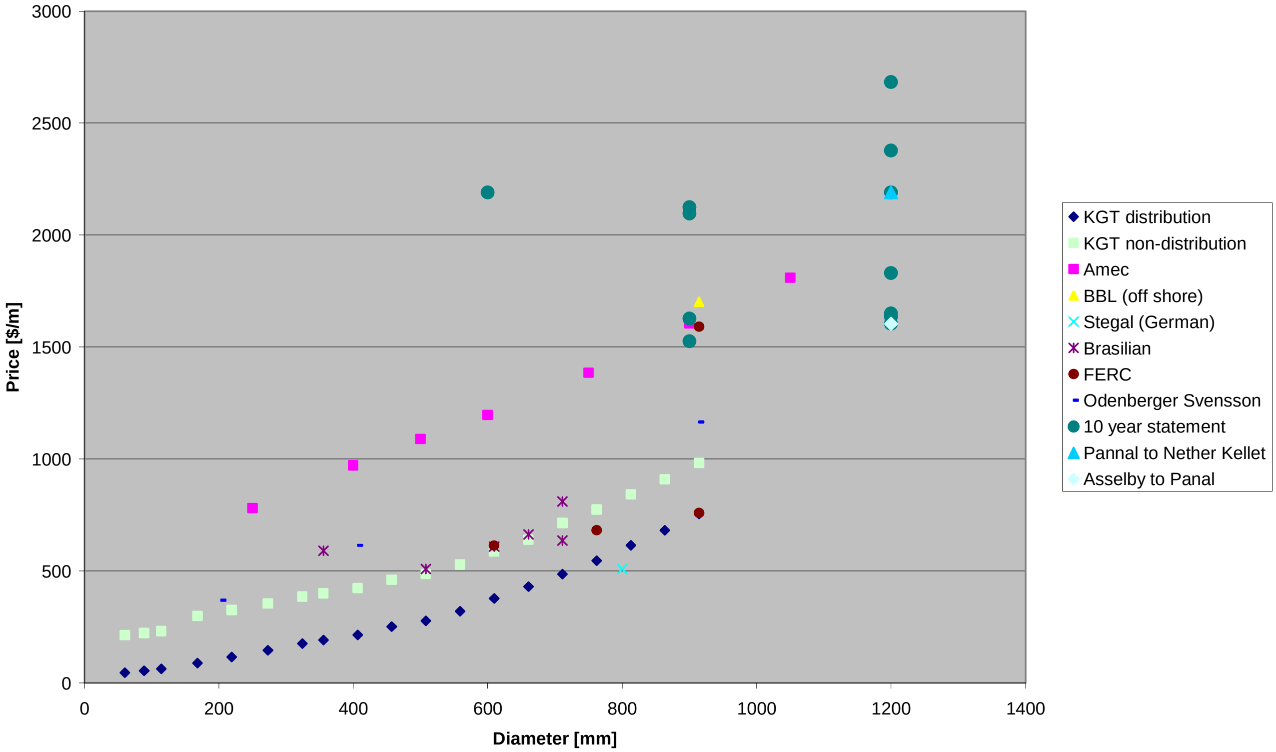


Figure 9: Comparison of pipeline costs with published data

From this figure, it is clear that costs vary quite considerably around the world, and that UK costs tend to be higher than other parts of Europe. It is also clear that the AMEC costs used in this report are in line with published information from the UK.

The following equipment lifetimes were used to annualise the capital costs:

Compressors and blowers	25 years
Pipeline	30 years

Furthermore AMEC provided cost factors to be applied to different terrains types and crossings etc. The network design tool incorporates these factors and uses them to calculate CAPEX and OPEX. It should be noted that these factors are derived directly from AMEC's own experience and are therefore thought to be extremely reliable. Table 7 below gives examples of the cost differences between different terrains and crossings for various diameters of medium pressure steel pipe ($/m);

Table 3: Example of MP Steel Pipe Cost Data

Area Type	60 mm	89 mm	114 mm	168 mm	219 mm	273 mm	324 mm	356 mm	406 mm
Flat open countryside	$303	$318	$331	$422	$459	$504	$547	$569	$603
Urban	$485	$509	$530	$675	$735	$806	$875	$910	$966
Mountainous	$425	$445	$463	$590	$643	$655	$711	$739	$784
Desert	$607	$636	$662	$843	$919	$1,008	$1,094	$1,138	$1,207
Forest	$425	$445	$463	$590	$643	$655	$711	$739	$784
Offshore	$607	$636	$662	$843	$919	$1,008	$1,094	$1,138	$1,207
Drainage	$25	$25	$25	$25	$25	$25	$25	$28	$28
Trench dust	$5	$5	$6	$6	$8	$8	$10	$10	$14
River	$13,800	$14,300	$14,700	$15,600	$16,500	$17,400	$18,200	$18,800	$19,600
Canal	$28,700	$29,700	$30,500	$32,300	$34,000	$35,800	$37,500	$38,600	$40,300
Railway	$11,000	$11,400	$11,700	$12,400	$13,100	$13,800	$14,500	$14,900	$15,600
Motorway	$22,600	$23,400	$24,100	$25,500	$26,900	$28,300	$29,700	$30,500	$31,900
Major road	$11,000	$11,400	$11,700	$12,400	$13,100	$13,800	$14,500	$14,900	$15,600
Minor road	$6,800	$7,000	$7,200	$7,700	$8,100	$8,600	$9,000	$9,200	$9,700
Sub-minor road	$5,400	$5,600	$5,800	$6,100	$6,500	$6,800	$7,200	$7,400	$7,700
Valves	$621	$879	$1,552	$2,121	$4,708	$5,910	$7,113	$8,135	$9,156

9.2 Operating Costs

Operating and maintenance costs (OPEX) were estimated using internal databases in use by Kiwa Gastec and AMEC. The main operating costs for a pipeline are the energy costs for compression. These costs were determined based on the energy required to compress the CO_2 at each compression station, typical compressor efficiencies, and an energy cost of $6 per GJ.

Maintenance costs were based on typical engineering factors applied to the capital costs of pipeline and equipment. The factors applied were:

Compressors and blowers	5% of capital cost annually
Pipeline	2% of capital cost annually

9.3 Costs of CO_2 Collection and Transport to Disposal Site

Obviously the real cost of collection, transmission and disposal for CO_2 can only be derived from site specific assessment of every site within the study. This would be required to assess which capture technology would be best suited to each site and to determine any site specific complications/advantages etc which may affect the overall price of CO_2 abatement.

For the purposes of costing the entire network from boiler to borehole it was realised that the boundaries of what this study can confidently assess must be well defined. For the avoidance of doubt it is emphasised that this study can only accurately (within engineering cost tolerances) estimate the cost of the transmission network; effectively from the flange at the factory gate to the flange before the final compressor (prior to injection) at the platform in the Irish Sea.

The costs of CO_2 transmission to the disposal site from the factory gate were calculated by taking the annualised capital costs, plus operating and maintenance costs, divided by the assumed amount of CO_2 sent for disposal (~20Mtpa), using the standard IEA GHG economic evaluation parameters, with adjustments to equipment lifetimes as per section 9.6.

In the base case network (all tiers not trimmed) described in Section 5, the costs of collection were calculated as $9.69/tonne.

In this instance, upon consultation with IEA GHG it has been decided to derive costs for collection and disposal from literature review. These costs and their boundaries are described in Section 9.4 and graphically in Schematic 1.

9.4 Overall Costs of CO_2 Separation, Collection, Transport and Disposal

To examine the overall costs of CO_2 separation, collection, transport and disposal, figures for the cost of separation and disposal must be added to the costs of the network.

9.4.1 Disposal Costs

For this study it has been proposed to dispose of CO_2 collected within depleted gas and oil wells in the East Irish Sea. To date little research has been conducted (that is available in the public domain) into the general costs for disposal of CO_2 in offshore oil and gas wells. It is thought that some recent studies must have been commissioned by companies such as Statoil and BP for their respective Sleipner and Miller projects, however these reports have not been published.

IEA GHG have commissioned two such studies, one for northern America and one for Europe, which investigate the costs of storage in depleted oil and gas wells, EOR and deep saline aquifer storage, there is also some mention of Enhanced Coal Bed Methane (ECBM).

The North American study (*A CO2 sequestration supply curve for North America and its implications for the deployment of sequestration systems* – Dahowski et al, 2004) suggests figures of around $12.5/tonne for storage in depleted oil and gas wells (without EOR) whilst the European study (*Cost Curve for CO_2 storage: European Sector* – T. Wildenborg et al, 2004) suggests figures of $2 - $3 per tonne of CO_2 (without EOR). Clearly there is considerable difference between these values. Closer examination of the North American data reveals that; as the majority of fields in America have been injecting CO_2 (mainly for EOR) since the 1980's, many have near 20 year old vertical wells. This is significant because, in the American oilfields (which are older than their European counterparts) difficult to produce fields were simply drilled a multitude of times to increase the number of wells and thus production. This greatly increases the capital costs of any project and therefore skews the data. By the time oil was found in the North Sea, drilling technology had advanced significantly with the advent of horizontal drilling. In this case, a poorly producing well was simply extended horizontally through the producing strata therefore increasing the surface area (and ingress of oil) within the bore. By comparison, the European report requires a single well for every 5 American wells, this significantly reduces costs in the European case.

As there is great experience within Europe (and the study area in particular) of horizontal drilling, especially offshore, it may be that the figures expressed by the European report should be used as the basis for this study. Indeed as there may be some opportunity for EOR at the Lennox and Douglas fields it is very possible that these estimates of cost may prove to be too high given the sometimes negative costs experienced in EOR (from sales of produced oil).

As there remains some uncertainty over these costs, a range of $1 to $10/tonne of CO_2 is used in the subsequent analysis.

9.4.2 Capture Costs

The cost of capture is a very complex issue and as expressed earlier can only really be defined by site specific studies for each plant on the network in order to truly understand all of the potential issues and costs involved. For the purposes of this study the project team has studied several reports, again published by the IEA GHG Program. The most recent report, *"Performance and costs of power plants with capture and storage of CO_2"* John Davidson Feb. 2006 discusses in sufficient detail the costs of various different new build power plant with CO_2 capture. The report considers established capture technologies and the additional cost of pollution control plant required by modern power plant such as FGD etc. It should be noted that it is generally accepted that FGD would be a prerequisite to CO_2 capture due to the low contaminant requirements of the CO_2 transmission network.

The Davidson study gives values for capture in the mid $30/t range, however it should be noted that the figures discussed by the study are for $/tonne avoided not overall captured and introduced to the network. Actual CO_2 captured costs would be of the order of 20% lower i.e. high $20/t range.

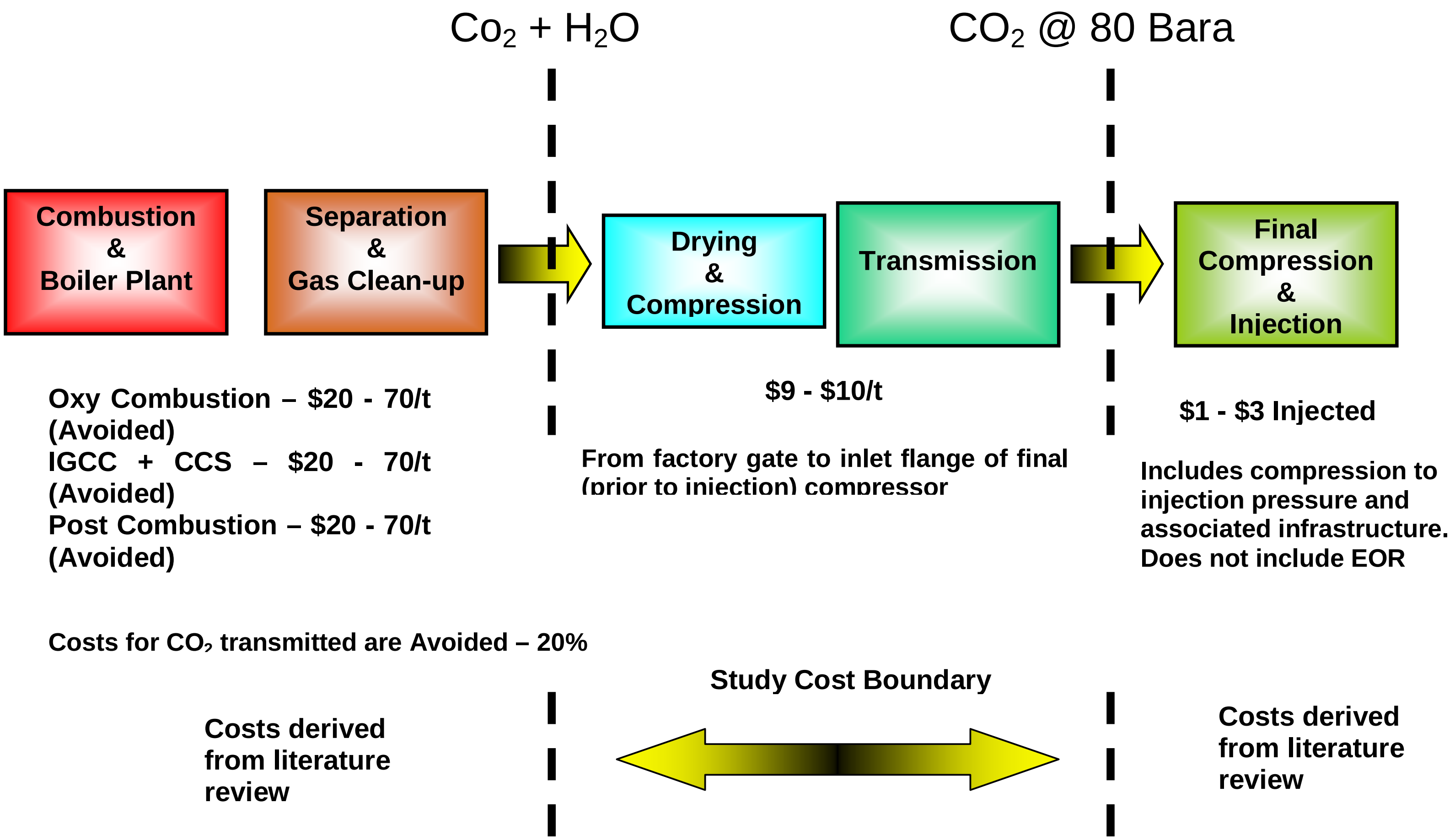
Studies from some years ago by IEA GHG suggest that retro-fitting existing plant can be very expensive (of the order $70 - $90). However, any decision to install CO_2 capture plant would form part of a major refit/repowering exercise and would not be undertaken as a stand-alone project. It is for this reason that GaC and IEA GHG feel that costs in this instance would be close to (if not lower than) costs for new plant as major costs such as sub-stations, land, cooling towers etc would already be paid for.

A draft report by the IEA Greenhouse Gas Project has estimated the cost of CO_2 capture for smaller installations using several potential capture technologies. Of the five technologies assessed by the study three are applicable to this study, these are;

- Small Gas Turbine with pre-combustion Pressure Swing Adsorption
- Coal fired Oxygen Conducting Membrane furnace
- Gas fired Oxygen Conducting Membrane furnace

Although the costs of capture depend heavily upon the type and scale of each installation it is likely that specific circumstances that are individual to each site will have a greater effect upon final capture costs. It should be noted that these technologies give costs for some plant at around $20 per tonne. However, it should also be recognised that these technologies are still largely in the development stage and may not be applicable to all plant and processes within the study. It is for this reason that a higher figure ($25 - $30/t region) has been used in this study. Although future discount opportunities may present themselves at a later date (in terms of capture costs), it is considered that this cannot be included or even quantified at this stage.

Schematic 1: Scheme Boundary Definition



$Co_2 + H_2O$

CO_2 @ 80 Bara

Combustion & Boiler Plant

Separation & Gas Clean-up

Drying & Compression

Transmission

Final Compression & Injection

Oxy Combustion – $20 - 70/t (Avoided)
IGCC + CCS – $20 - 70/t (Avoided)
Post Combustion – $20 - 70/t (Avoided)

$9 - $10/t

From factory gate to inlet flange of final (prior to injection) compressor

$1 - $3 Injected

Includes compression to injection pressure and associated infrastructure. Does not include EOR

Costs for CO_2 transmitted are Avoided – 20%

Study Cost Boundary

Costs derived from literature review

Costs derived from literature review

9.4.3 Overall Costs

The total costs for capture, and transmission from all sources are therefore:

Cost of separation	\$20 – 40/tonne (Avoided – 20%)
Cost of collection network	\$10/tonne
Cost of disposal	\$1 – 10/tonne
Total Costs	\$31 - \$60/tonne

It should be noted that this cost is for all of the sites identified within the study area and can be reduced by removing or changing some aspects of the proposed network as will be discussed in later sections.

9.5 Marginal Costs

It is apparent from inspection of the cost data that the cost of collection raises as lower Tiers are introduced to the network. This is due to increased number and lengths of pipe for a comparably low amount of additional $CO_{2.}$ The table below displays the marginal costs of introducing each additional Tier to the network. It should be noted that these costs are applicable to this network only and are not indicative of costs of connecting to sources of these Tier sizes generally.

Table 4: Marginal Costs

Element	Tonnes CO_2	Tier Network Cost (\$)	Marginal Tier Cost (\$/tonne)
Tier 0	14,000,000	119,000,000	8.50
Tier 1	4,600,000	44,680,000	9.70
Tier 2	700,000	23,530,000	33.60

It is evident from the data presented in Table 8 that; although the suction network gives substantial gains in terms of overall costs, the marginal costs for inclusion of Tier 2 sources into the network are still too great and therefore, in this instance (and overall), Tier 2 sources should not be collected from. It should be noted that this is a generalisation and that reasonably sized Tier 2 sites that are very close to Tier 0 or 1 sites (i.e. the main pipelines) could still prove economic to include in a collection network and should not therefore be overlooked as a matter of course.

In this instance it appears that centralised hydrogen production and distribution with CO_2 capture may be more economic than distributed CO_2 collection. This option should be investigated further.

It is the opinion of the consultant the marginal costs for Tier 1 are not prohibitive. Furthermore it is very likely that these costs are distorted by some uneconomic small, distant sources and that the network could be trimmed to reduce the marginal cost further.

9.6 Sensitivity Analysis

The spreadsheet model was used to carry out a sensitivity analysis of the effects of making changes to some of the model parameters.

9.6.1 Sensitivity to network size

The cost of CO_2 transportation was calculated for three different collection networks. The first network included all sources; in the second network the smaller Tier 2 sources were removed; in the third network, only the five large Tier 0 sources were modelled.

The results are shown below in Figure 10.

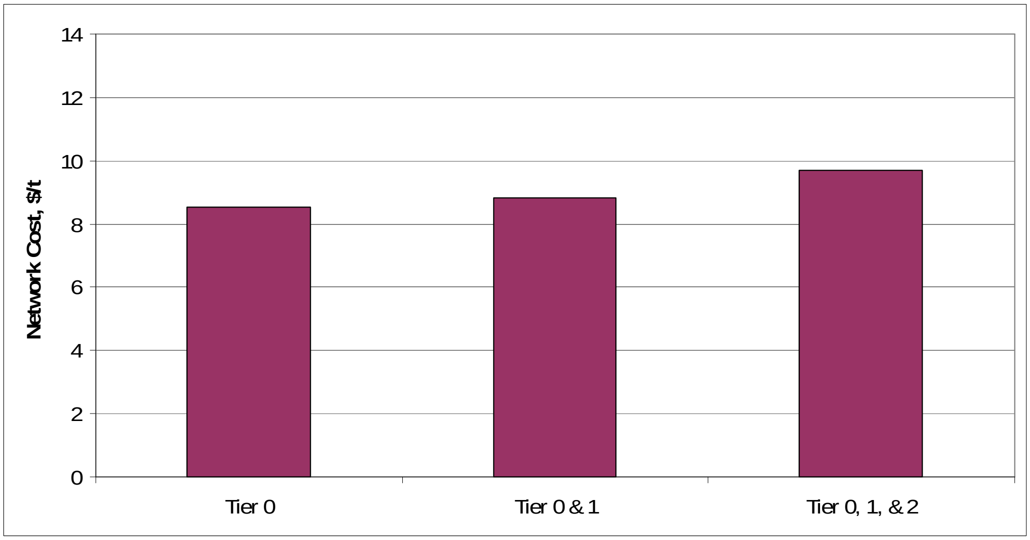


Figure 10: Effect of network Catchment on cost

From this figure it can be seen that increasing the size and complexity of the network increases the costs of CO_2 transport significantly. It should be noted however that this is also due to the decreasing CO_2 output of each source as you move down the Tiers. For example a larger network of Tier 0 sites would still give better economies of scale (and overall cost per tonne) than a large network of Tier 0 and 1 sites.

9.6.2 Sensitivity to discount rate

The cost of CO_2 transportation was calculated for three different discount rates for each of the networks described above, and the results are shown in Figure 11.

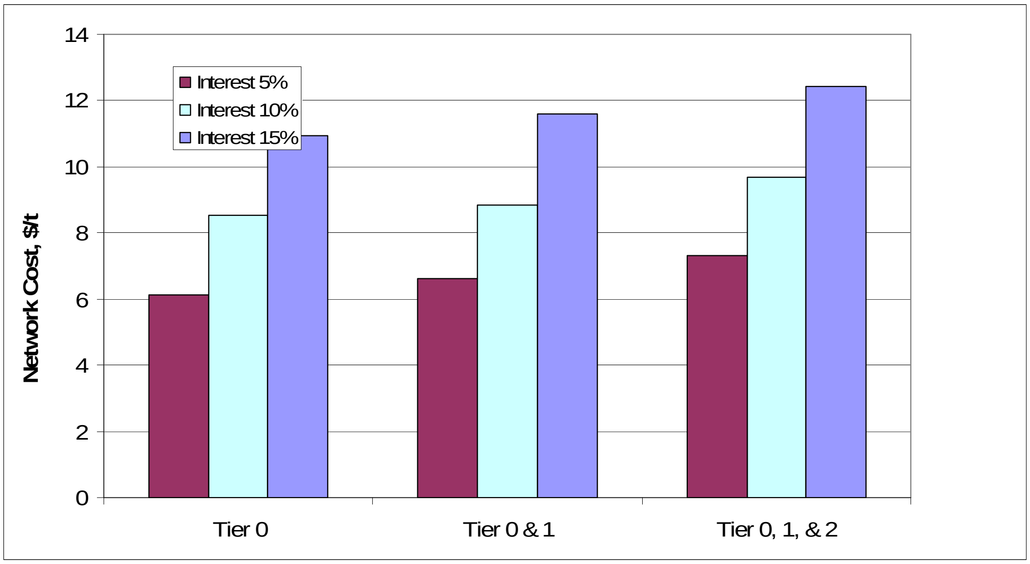


Figure 11: Effect of discount rate

As expected, increasing the discount rate leads to increased network costs.

9.6.3 Sensitivity to construction time

In practice, a network would be built up in phases. The following assumptions have been compared with a network that is all built in year 0.

Tier 0 network built in year 1, operational in year 2.
Tier 1 network added in year 4, operational in year 5
Tier 2 network added in year 9, operational in year 10.

Figure 12 shows the effect of this on transport costs.

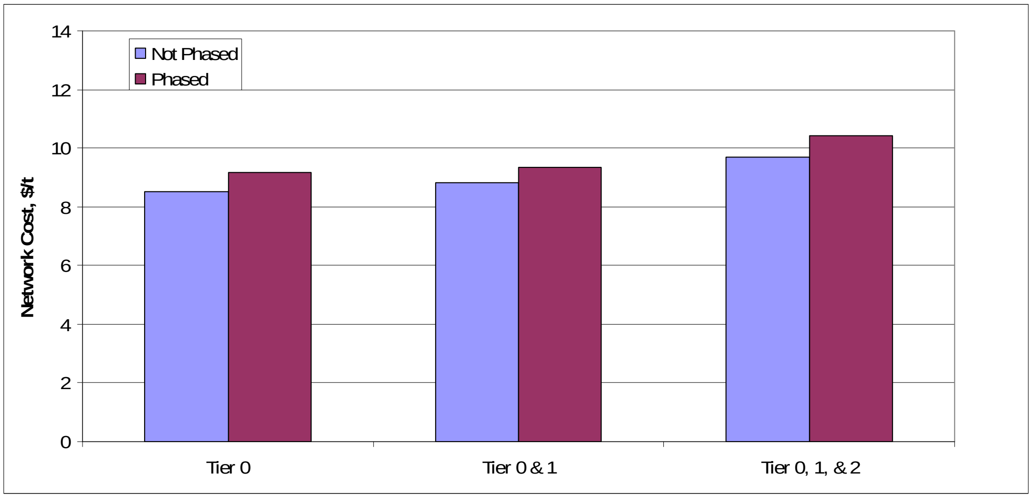


Figure 12: Effect of construction time

9.6.4 Sensitivity to plant lifetime

Plant lifetimes can have a significant effect on project costs. The cost of CO_2 transportation was calculated using the following equipment lifetimes:

Pipelines	30 years
Crossings	30 years
Separators	30 years
Compressors	25 years
Suction system	30 years
Meters	25 years
Valves	30 years
Drying plant	25 years

Some of these lifetimes were adjusted as detailed below and the model was run again.

Pipelines	25 years
Crossings	25 years
Separators	25 years
Compressors	15 years
Suction system	25 years
Meters	15 years
Valves	25 years
Drying plant	15 years

The results are shown below in Figure 13.

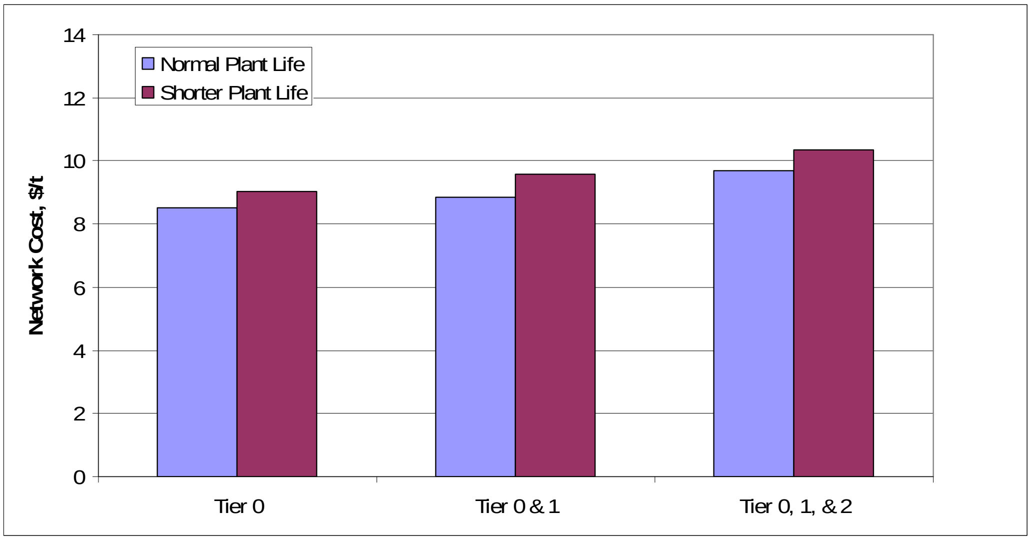


Figure 13: Effect of plant lifetimes

As expected, shorter plant lifetimes lead to increased network costs, particularly the compressor lifetime as these bear the largest operational and capital cost.

9.6.5 Sensitivity to network length

The spreadsheet is designed to be used in a real region, with numbers of road crossings, terrain etc entered following pipeline routing using the actual geographical features that exist in the region. However, it can be used to examine the effect of building a more distributed or more concentrated network. Figure 14 shows the effect of increasing network length by 25% and reducing network length by 25%. The terrain and numbers of crossings were unchanged.

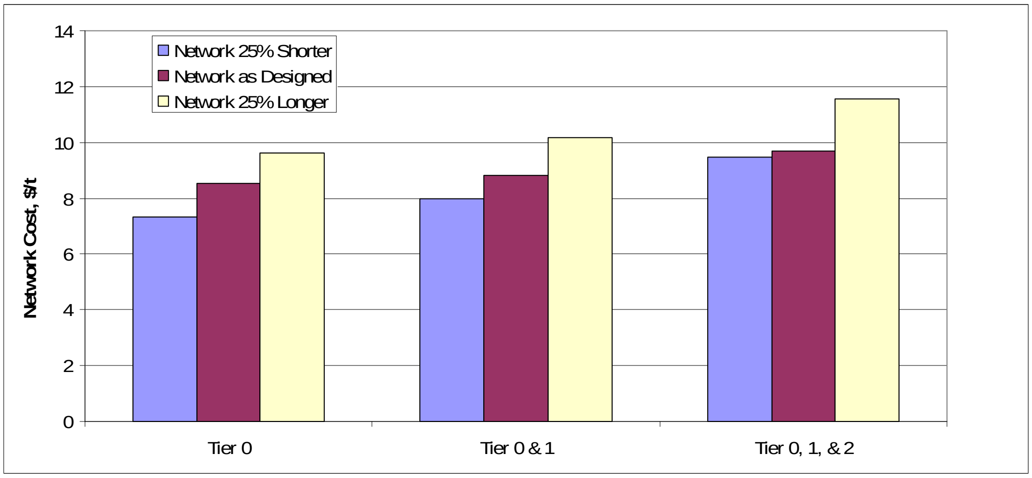


Figure 14: Effect of network length

It can be seen that increasing the network length increases costs quite significantly. This is mainly due to the requirement for extra compressor booster stations to ensure that the CO_2 is transported through the new longer network. This translates into higher costs for lower densities of emission sources.

9.6.6 Sensitivity to use of suction network

As many of the Tier 2 sites as possible have been connected to the network using a low pressure suction system. This was included to keep costs down for low yield sites to make low level collection more feasible. Figure 15 below demonstrates the effectiveness of employing such a technology to the network. The applicability depends upon a factor of emission size and transmission distance to the closest medium pressure node and therefore not every Tier 2 site is suitable for the system. It should be noted that the network in its current form could be trimmed to remove Tier 2 sites where a suction system is not possible. This would reduce the overall network costs further to \$9.20 per tonne CO_2.

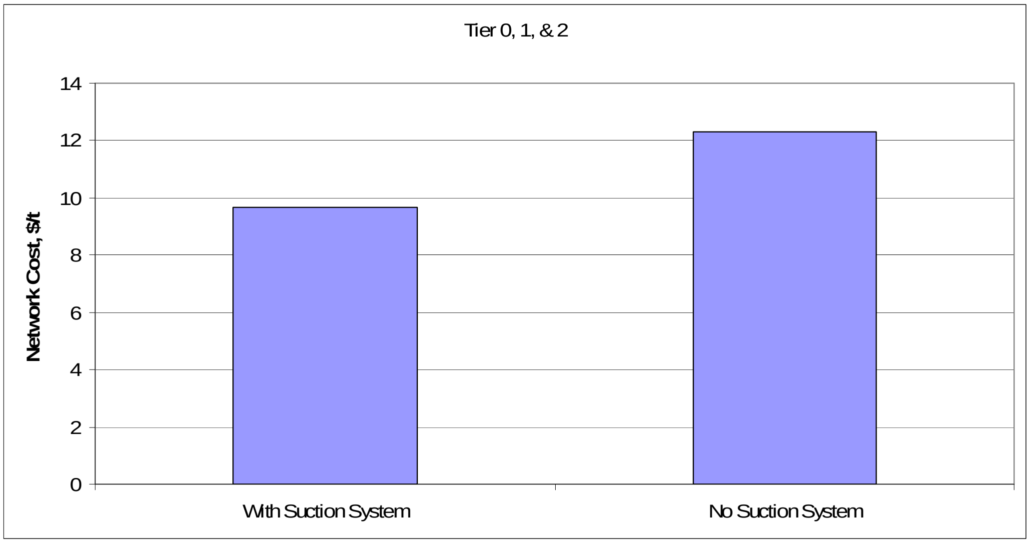


Figure 15: Effect of suction network upon cost

10 Capacity of CO_2 Producers to Operate Separation and Disposal Infrastructure

The practicalities of separating and collecting CO_2 from industrial sources are complex. Most CO_2 collection studies have been based on separation at large power station sites where it is assumed that the capacity to operate the plant and equipment exists or could easily be brought in. For smaller industrial plant, this may not be the case. In order to ascertain whether the practicalities would present a barrier to the introduction of the technology, a seminar was held (12 June 2006) in the study region to which local industrialists were invited.

The seminar took the form of a series of presentations on the concept of collecting CO_2 from local industry and transporting it in a pipeline network to a final disposal point in the Irish Sea. The presentations were followed by a general discussion of the points made. A questionnaire was handed to delegates, and the results were analysed. The questionnaire appears in Appendix 3, and the presentations are shown in Appendix 4. The delegate list is shown in Appendix 5, and a detailed analysis of their responses in shown in Appendix 6.

Over half of respondents considered that they could or probably could operate CO_2 capture plant. It should be noted however that these responses were predominantly from large emitters who already host complex or large process plant. The remainder of respondents were smaller emitters who unsurprisingly either felt they would require outside help, were unsure if they would have the technical capacity, or in one case would not have the capacity to operate CO_2 capture plant.

11 Alternatives to CO_2 Collection – Hydrogen and Electricity Distribution

The direct alternative to collecting CO_2 from sources which are consuming fossil fuel is to provide carbon free energy in the form of hydrogen or electricity which has been produced centrally with CO_2 capture. There are many possibilities to consider when establishing alternatives to carbon capture such as widespread implementation of CHP however, it should be noted that this technology may not always be compatible and it is therefore the consideration of the author that the supply of green electricity or distributed hydrogen are the only options that have universal applicability.

The simplest system would entail centralised production of hydrogen and a pipeline distribution system to supply the hydrogen to end users. This idea has been critically considered, and a number of issues arise:

- **Pressure of transmission and distribution system.** Industrially, hydrogen is transported within plant boundaries at medium pressures (up to about 20bar). Hydrogen production plant generally produce hydrogen at pressures up to 20bar.

  Some small hydrogen distribution networks do exist around the world, for example in Teesside, UK and Rotterdam, Holland. These have been constructed using draft codes and standards and operate over relatively small distances (~30km) and at low pressures (up to 20bar). A selection of draft standards are currently under review for large scale hydrogen distribution and storage. Some bulk hydrogen pipelines are also in operation around the world however, these are mostly constructed using existing (often oil) infrastructure and are rarely constructed from new.

  A trans-European pipeline also exists between Holland and France that uses old oil infrastructure. This pipeline operates at reasonably high pressure (~100bar) and to date has had few problems with pipeline durability.

  Gas transmission systems usually operate at high pressures in order to reduce pipeline diameter and hence costs. One problem of high pressure hydrogen distribution is embrittlement of steel which has caused failures of some long distance hydrogen pipelines. High pressure hydrogen pipelines are known to lose 30% in toughness and 15% of burst strength. Again, as few pipelines exist (~2000km compared to many millions of km for natural gas) design codes and best practice standards are few and far between at present. Design codes are expected to be finalised in the third quarter of 2007 after several years of research by the ASME.

- **Design velocity of transmission system.** The density of hydrogen is much lower than natural gas, and although the calorific value of hydrogen is higher, to get the same energy flow with hydrogen, the design velocity would need to be increased by a factor of 3 compared with methane. High velocity pipelines could suffer from erosion problems caused by entrained particulates or liquid droplets. There are also likely to be noise problems associated with high velocity pipelines. Therefore design velocities are limited, and the pipeline diameter would have to be increased. Thus the cost of a hydrogen pipeline will be higher than for a natural gas pipeline.

Table 5: Physical Properties of Hydrogen and Methane

	Calorific Value MJ/m^3	**Density kg/m^3**	**Calorific Value MJ/kg**
H_2	13	0.09	144
CH_4	39	0.71	55

- **Materials of construction**. For medium pressure pipelines, it is believed that HDPE would be an adequate material, probably better and cheaper than steel, but this is not known with certainty. As mentioned previously, the majority of hydrogen pipelines are made in steel and often use old infrastructure. Research is being undertaken into the applicability of polymer lined steels for hydrogen pipelines however little data is available on their performance.

- **Customers for hydrogen.** It is not clear that all industries would be able to convert their processes to use hydrogen as a fuel. This may mean that some producers would still need to separate and dispose of CO_2. It is also likely that the construction of a hydrogen infrastructure would result in a greater demand. Furthermore, the customers for hydrogen would not be limited to the larger consumers considered in this study, other, smaller users would want to be connected to the network which would make demand predictions very important for network design. However, it is the opinion of the consultant that large users would be most likely to adopt (and develop) hydrogen use first due to the already increasing pressures of the EU ETS capping system.

- **Costs of transmission and distribution.** It is clear that transmission of hydrogen to end users would be more expensive than natural gas, even without the costs of hydrogen production, which are also higher than the costs of natural gas production.

- **Odorisation.** Traditionally mains distributed natural gas has been odorised at medium to low pressures using various mercaptans. This may not be possible for distributed hydrogen as mercaptans would grossly affect the function of hydrogen fuel cells, a likely recipient technology for any distributed hydrogen gas. The sensitivity of fuel cells makes odorisation very difficult. Research[11] conducted by the Japan Automobile Research Institute suggests that 2,3-butanedione or 5-ethylidene-2-norbornene may be suitable in terms of compatibility with fuel cells, vapour pressure and offensive odour, however further research is needed to establish how effective these chemicals would be for odorising a hydrogen transmission system.

Overall there are many obstacles to hydrogen distribution however if subscription to such a network was high, the costs could be reduced significantly. As previously mentioned, it is estimated that many users would want to connect to a hydrogen distribution network and this would also not be limited to industrial users. It is likely that any such network would resemble the Towns Gas networks of the past with localised production plants connected to small distribution networks. No benefit would be obtained from a national transmission network given the production pressure of hydrogen (~20 bar) and the energy required (and infrastructure) to elevate the pressure to 60+ bar for long distance transmission.

An alternative of providing “green electricity” to plants has also been suggested in previous studies however this too has a large cost implication. Although ‘green’ electricity is becoming more competitive, the cost of production is still substantially higher than electricity from traditional fossil fuel routes, especially when considering next generation high efficiency coal plant. The costs of electricity transmission are also high when compared with natural gas transmission. A rule of thumb for energy transmission and distribution costs are that if it costs $x/km to distribute a kWh of natural gas, it costs $7x/km to distribute a kWh of electricity and $49x/km to distribute a kWh in the form of hot water.

12 Conclusions

A study was carried out to assess the economic and practical viability of a distributed carbon dioxide collection and transmission network. The feasibility study was based on the distributed collection and transmission of CO_2 from point sources within the Mersey and Dee Basins in the North West of England to a disposal point in the Irish Sea oil and gas fields. In total, 77 sources of CO_2 emission were identified in the study area. Sources ranged in size from 1000 to 4.96 million tonnes of CO_2 per year. The total emissions from these sources were 20 million tonnes of CO_2 per year. The five largest sources accounted for 73% of the annual emissions.

A network was designed which operated at 3 pressures – a negative pressure collection system (-0.5bar) which fed to a medium pressure system (10bar), which fed on to a high pressure (100bar) supercritical CO_2 transmission pipeline. A spreadsheet model was developed to calculate pipeline sizes, compression duties, and capital and operating costs of the network.

Based on the above, the following conclusions can be drawn.

1. The cost of CO_2 collection and transmission for the whole network was calculated to be $9.70/t. When the cost of CO_2 separation at each plant and costs for disposal in depleted oil or gas fields were added, the overall cost of CO_2 separation, collection, transmission and disposal was calculated to be $30 - $50/t.

2. Trimming the network to remove sources which were geographically remote and which could not be connected to the suction system reduced the collection and transmission cost to $9.20/t.

3. Removing all sources below about 600 000 tonnes per year (i.e. only leaving the five largest emitters) reduced the collection and transmission cost to $8.50/t.

4. When taking marginal costs into consideration it becomes apparent that in this instance distributed CO_2 collection is not viable for very small sites, even using low cost suction networks. It should be noted however that this may not be the case in every network and sites should be considered on an individual basis.

5. Safety aspects of the collection and transmission network were considered, this led to the limitation that supercritical CO_2 pipelines would not be permitted in urban areas. This was a requirement imposed by the HSE which comes from a conservative standpoint. It should be noted that at the time of writing no research into supercritical pipeline rupture or indeed design of urban CO_2 transport networks had been undertaken in the UK.

6. The alternatives to carbon capture and storage for these distributed sources would be to provide them with “green” electricity or hydrogen. Overall there are many obstacles to hydrogen distribution, however if subscription to such a network was high, the costs could be reduced significantly. Although ‘green’

electricity is becoming more competitive, the cost of production is still substantially higher than electricity from traditional fossil fuel routes. The costs of electricity transmission are also high when compared with natural gas transmission. What is needed is for industry to work together to assess the options properly and decide upon what shared infrastructure they require.

7. A seminar was held in the study region to which local industrialists were invited. This seminar was used to gauge whether the industries would have the capacity to operate complex CO_2 separation and collection systems. Over half of respondents considered that they would or probably would have the technical capacity to operate such plant.

8. The seminar was also used to gauge industrialists' opinions on when CCS would be deployed in the UK. Although around half of respondents were unwilling to predict a date when CCS would be deployed, very few thought it would never be deployed.

13 Recommendations

As part of this study, further work was identified which would enable the concept of distributed CO_2 collection and disposal to be realised at reasonable cost. This further work includes:

1. A more detailed study to review the best options for each individual plant in the study should be undertaken. These options would include “green” electricity, hydrogen, and carbon capture and storage. Should CCS be identified as feasible, the precise capture technology and how it could be employed should be established for each plant.

2. An alternative to CO_2 collection would be the distribution of hydrogen for use in small – medium industrial and commercial applications. The cost of this is very network specific. It is the recommendation of the consultant that a similar network tool be designed for distributed hydrogen so that costs can be more easily obtained.

3. Further consultation with industry to gauge the reaction of companies to the threat of climate change would be useful.

4. The network design and costing spreadsheet should be adapted to apply to other world regions. (It is understood that the IEA GHG Programme has already started to pursue this.)

5. Further geological studies of the storage options need to be carried out to enable a disposal option to be chosen with more confidence.

6. The effect of impurities such as NO_x and SO_2 in the CO_2 stream are not well characterised and further experimental studies would enable limits to be set.

7. The safety implications of medium and high pressure pipelines carrying carbon dioxide have not been fully addressed. The effects of leaks or pipeline ruptures are not well characterised, and safe distances for planning purposes need to be developed.

14 References

1. IEA Greenhouse Gas Project July 2003 – PH4/21: *Saline Aquifer* CO_2 *Storage Project (SACS): Best Practice Manual*
2. IEA Greenhouse Gas Project November 2004 – PH4/29: *Overview of Monitoring Requirements for Geologic Storage Projects*
3. IEA Greenhouse Gas Project December 2004 – PH4/37: *Modelling of* CO_2 *– The GOSAC Study*
4. IEA Greenhouse Gas Project September 2005 – 2005/11: CO_2 *Storage by Mineral Carbonation*
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6. DEFRA – 2005: *National Allocation Plan Figures (xls)*
7. DEFRA – 2003: *Local and Regional Estimates of* CO_2 *Emissions (xls)*
8. Karen Kirk – British Geological Survey 2006: *Storing* CO_2 *in the Rocks Beneath the East Irish Sea*
9. M. Vendrig Et Al – DNV Consulting 2003: *Risk Analysis of the Geological Sequestration of* CO_2
10. Comments from the American Public Power Association to the National Commission on Energy Policy November 2005: *The Challenge of Carbon Sequestration for the Utility Sector*
11. D. Imamura Et Al – Japanese Automotive Research Institute 2004: *Hydrogen Odorants for Fuel Cell Vehicles*
12. Environmental Protection Act 2000
13. Parliamentary Office of Science and Technology – March 1005, Postnote 238: *Carbon Capture and Storage*

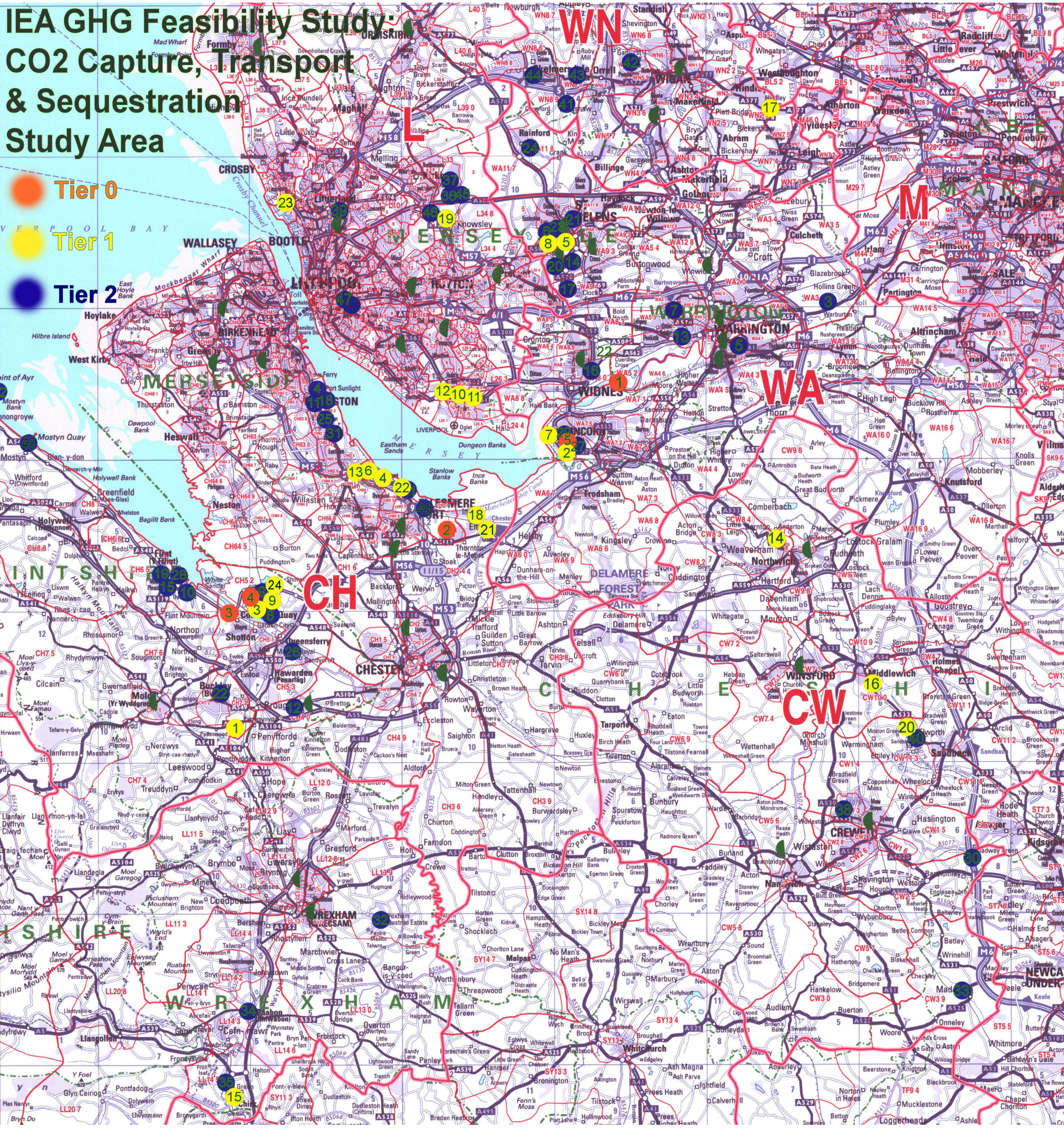
Appendix 1 – Detailed Site Locations Map

IEA GHG Feasibility Study: CO2 Capture, Transport & Sequestration Study Area

● Tier 0

● Tier 1

● Tier 2



Appendix 2 – Site Summary Details

MAP ID	CO2 Emissions (tpa)	Main activity	Installation	Operator
1	4,957,707	Power Stations	FIDDLER'S FERRY POWER STATIONWIDNES ROAD, CUERDLEYWARRINGTON, CHESHIRE, WA5 2UT	AEP ENERGY SERVICES UK GENERATION LTD.
2	3,968,712	Refineries	STANLOW MANUFACTURING COMPLEX, PO BOX 3, ELLESMERE PORT, SOUTH WIRRAL CH65 4HB	SHELL U.K. OIL PRODUCTS LIMITED
3	3,189,160	Power Stations	CONNAHS QUAY POWER STATIONKELSTERTON RDCONNAHS QUAYDEESIDENORTH WALESCH5 4BP	POWERGEN UK PLC
4	1,092,247	Power Stations	DEESIDE POWER STATIONZONE 4, DEESIDE INDUSTRIAL PARK, FLINTSHIRE, CH5 2UL	DEESIDE POWER DEVELOPMENT CO. LTD
5	1,307,490	Power Stations	ROCKSAVAGE POWER STATION, RUNCORN	INTERGEN LTD
1	422,136	Cement	CASTLE CEMENT LTDPADESWOODMOLDFLINTSHIRECH7 4HB	CASTLE CEMENT PADESWOOD
2	374,546	Chemicals	RUNCORN SITEP O BOX 9RUNCORNCHESHIRE WA7 4JE	INEOS CHLOR LIMITED
3	300,150	Pulp & Paper	WEIGHBRIDGE ROAD DEESIDE INDUSTRIAL PARK SHOTTON FLINTSHIRE. CH5 2LF	SHOTTON CHP LTD.
4	226,054	Pulp & Paper	C/O BRIDGEWATER PAPER COMPANY LTD, NORTH ROAD, ELLESMERE PORT, SOUTH WIRRAL. CH65 1AF	INNOGY COGEN LTD
5	223,669	Glass	GREENGATE SITE, SHERDLEY ROAD, ST HELENS, WA9 5DZ	PILKINGTON UNITED KINGDOM LTD
6	212,860	Pulp & Paper	BRIDGEWATER PAPER MILL, NORTH ROAD, ELLESMERE PORT, SOUTH WIRRAL, CH65 1AF	BRIDGEWATER PAPER CO LTD
7	179,748	Food & Drink	SALT UNION CHP, C/O SALT UNION LTD, MERSEY VIEW ROAD, RUNCORN, CHESHIRE, WA7 4HB	SCOTTISH AND SOUTHERN ENERGY GENERATION LTD
8	77,386	Glass	WATSON ST SITE, CANAL STREET, ST HELENS, WA10 3JY	PILKINGTON UNITED KINGDOM LTD
9	72,499	Pulp & Paper	SHOTTON PAPER MILL, WEIGHBRIDGE ROAD, SHOTTON, FLINTSHIRE, NORTH WALES, CH5 2LL	UPM-KYMMENE (UK) PLC
10	56,758	Chemicals	C/O ELI LILLY LTDFLEMING ROADSPEKELIVERPOOL L24 9LN	POWERGEN CHP LTD
11	53,547	Other Combustion Activities	SPEKE BOULEVARD HALEWOOD LIVERPOOL L24 9BJ	JAGUAR CARS LTD
12	50,719	Other Combustion Activities	HALEWOOD, LIVERPOOL, MERSEYSIDE, L24 9LE	JAGUAR CARS LTD
13	50,470	Refineries	NORTH ROAD, ELLESMERE PORT, SOUTH WIRRAL, CH65 1AJ	EASTHAM REFINERY LIMITED
14	597,679	Other Combustion Activities	WINNINGTON LANEWINNINGTON, NORTHWICH, CHESHIRECW8 4EE	POWERGEN CHP LTD
15	114,738	Pulp & Paper	CHIRK, WREXHAM, LL14 5NT	KRONOSPAN LTD
16	70,283	Food & Drink	CLEDFORD LANEMIDDLEWICHCHESHIRECW10 0JP	BRITISH SALT LTD
17	48,881	Glass	LEIGH RD, HINDLEY GREEN, WIGAN, LANCS, WN2 4XZ	PPG INDUSTRIES (UK) LTD
18	46,909	Chemicals	INCE, CHESTER, CH2 4LB	KEMIRA GROWHOW UK LIMITED
19	47,625	Pulp & Paper	KNOWSLEY INDUSTRIAL PARK, MOSS LANE, KNOWSLEY, MERSEYSIDE, LL33 7XQ	SONAE UK LTD
20	180,000	Other Combustion Activities	SANDBACH CHP	POWERGEN CHP LTD
21	140,000	Glass	INCE, CHESHIRE	QUINN GLASS LIMITED
22	342,610	Refineries	EASTHAM REFINERY, ELLESMERE PORT, CH65 1AJ	EASTHAM REFINERY LIMITED
23	137,000	Other Combustion Activities	PORT OF LIVERPOOL CHP	POWERGEN CHP LTD
24	550,000	Other Combustion Activities	SHOTTON CHP, WEIGHBRIDGE ROAD, SHOTTON, FLINTSHIRE, NORTH WALES, CH5 2LF	GAZ DE FRANCE GENERATION LIMITED
1	38,865	Other Combustion Activities	ELLESMERE PORT PLANT, NORTH ROAD INDUSTRIAL ESTATE, ELLESMERE PORTCH65 1AL	VAUXHALL MOTORS LTD
2	38,040	Offshore Including Gas Production Own Use	POINT OF AYR TERMINAL, TULARE, HOLY WELL, FLINT SHIRE CH8 9RD	BHP BILLITON PETROLEUM LTD.
3	37,099	Offshore Including Gas Production Own Use	WARRINGTON COMPRESSOR STATIONMOAT LANE, RIXTON, WARRINGTONCHESHIRE WA3 6EY	TRANSCO PLC
4	36,171	Chemicals	UNIQEMA CHEMICALS LTD, POOLE LANEBEBINGTONWIRRALCH62 4UF	DALKIA UTILITIES SERVICES PLC
5	30,462	Non-ferrous	LATCHFORD LOCKS WORKS, WARRINGTON, CHESHIRE, WA4 1NP	ALCAN RECYCLING
6	27,870	Glass	PO BOX 10 STAFFORD ROAD ST HELENS, MERSEYSIDE WA10 3NS	KNAUF INSULATION
7	26,759	Chemicals	LIVERPOOL ROADWARRINGTONWA5 1AB	INEOS SILICAS
8	19,789	Glass	CHEMISTRY LANE, QUEENSFERRY, FLINTSHIRE, CH5 2DB	KNAUF INSULATION
9	16,792	Iron & Steel	CORUS COLORS SHOTTON WORKSDEESIDEFLINTSHIRECH5 2NH	CORUS UK LTD
10	16,209	Pulp & Paper	OAKENHOLT MILL, OAKENHOLT, FLINT, CLWYD, NORTH WALES, CH6 5PU	SCA HYGIENE PRODUCTS LTD
11	13,274	Chemicals	DOCK ROAD SOUTHBROMBOROUGH WIRRALCH62 4SH	LUBRIZOL LTD.
12	12,994	Other Combustion Activities	CHESTER ROADBROUGHTONCHESTERFLINTSHIRECH4 0DR	AIRBUS UK LIMITED
13	12,944	Chemicals	MOORFIELD ROAD, WIDNES, CHESHIRE, WA8 0JU	ROCKWOOD ADDITIVES LIMITED.
14	12,288	Power Stations	SCOTTISHPOWER GREENGATE POWER STATIONBURTONHEAD RDST HELENSMERSEYSIDEWA9 5EA	SCOTTISHPOWER GENERATION LTD
15	12,169	Pulp & Paper	COLESHILL MILL, ABER ROAD, FLINT, FLINTSHIRE, NORTH WALES	KIMBERLY CLARK LTD
16	11,516	Chemicals	FOUNDRY LANE, DITTON, WIDNES, CHESHIRE, WA8 8UB	CRODA CHEMICALS EUROPE LTD
17	10,743	Bricks/Ceramics	ROUGHDALES FACTORY, CHESTER LANE, ST.HELENS, MERSEYSIDE, WA9 4EN	IBSTOCK BRICK LTD.
18	9,351	Food & Drink	PORT CAUSEWAY BROMBOROUGHWIRRAL CH62 4TH	CEREAL PARTNERS UK
19	8,303	Pulp & Paper	DELYN MILL, ABER ROAD, FLINT, FLINTSHIRE, NOTH WALES	KIMBERLY CLARK LTD
20	6,918	Other Combustion Activities	SCOTTISHPOWER WATSON STREET POWER STATIONBURTONHEAD RDST HELENSMERSEYSIDEWA9 5EA	SCOTTISHPOWER GENERATION LTD
21	6,234	Power Stations	SCOTTISHPOWER RAVENHEAD POWER STATIONRAVENHEAD WORKS NUTTAL STST HELENSMERSEYSIDEWA10 3LP	SCOTTISHPOWER GENERATION LTD
22	5,824	Bricks/Ceramics	LANE END WORKSBUCKLEYCLWYDCH7 3AD	HANSON BRICK LIMITED
23	5,425	Power Stations	SCOTTISHPOWER COWLEY HILL POWER STATIONCOLLEGE STST HELENSMERSEYSIDEWA10 2RZ	SCOTTISHPOWER GENERATION LTD
24	3,946	Bricks/Ceramics	MILL LANE, RAINFORD, ST. HELENS, MERSEYSIDEWA11 8LP	SAINT-GOBAIN INDUSTRIAL CERAMICS LTD.
25	2,119	Bricks/Ceramics	THERMAL CERAMICS U.K. LTD. TEBAY ROAD, BROM BOROUGH WIRRAL CH62 3PH	THERMAL CERAMICS U.K. LTD.BROMBOROUGH SITE
26	2,083	Other Combustion Activities	DEESIDE INDUSTRIAL ESTATEFLINTSHIREWALESCH5 2QJ	TOYOTA MOTOR MANUFACTURING (UK) LTD
27	2,033	Chemicals	INEOS FLUOR LIMITED, PO BOX 9, RUNCORN SITE, RUNCORN, CHESHIRE WA7 4JE	INEOS FLUOR LIMITED
28	808	Pulp & Paper	FLINT MILL, ABER ROAD, FLINT, FLINTSHIRE, NORTH WALES	KIMBERLY CLARK LTD
29	N/A	Chemicals	PO BOX 9, RUNCORN, CHESHIRE, WA7 4JE	EUROPEAN VINYLS CORP (NOW INEOS CHLOR)
30	17,616	Other Combustion Activities	RADWAY GREEN - SAANR CREWECHESHIRECW2 5PJ	ROYAL ORDNANCE PLC
31	17,343	Chemicals	LEVER BROTHERS, PO BOX. 69PORT SUNLIGHT, WIRRALL62 4ZD	DALKIA UTILITIES SERVICES PLC
32	13,659	Food & Drink	BRYN LANE WREXHAM INDUSTRIAL ESTATE, WREXHAM LL13 9UTNORTH WALES	KELLOGG COMPANY OF GREAT BRITAIN LTD (WREXHAM)
33	12,361	Bricks/Ceramics	KEELE WORKSRIDGE HILL DRIVE, MADELEY HEATH, CREWE, CHESHIRECW3 9LY	ETERNIT CLAY TILES LIMITED
34	10,679	Chemicals	RUABON WORKS, CEFN MAWR, WREXHAM, N. WALESLL14 3SL	FLEXSYS RUBBER CHEMICALS LTD
35	7,810	Food & Drink	STATION AVENUECHIRKWREXHAMLL14 5LT	CADBURY TREBOR BASSETT
36	7,076	Chemicals	CHEMICAL MANUFACTURING DIVISION. ACORNFIELD ROAD, KIRBY. LIVERPOOL. L33 7UF	KODAK LTD
37	4,909	Food & Drink	MOORGATE ROAD, KIRKBY, LIVERPOOL. L33 7XJ	DAIRY CREST LTD
38	3,574	Other Combustion Activities	PYM'S LANECREWECHESHIRECW1 3PL	BENTLEY MOTORS LIMITED
39	2,813	Other Combustion Activities	68 HORNBY ROADLIVERPOOLL9 3DF	HMP LIVERPOOL
40	171	Chemicals	ALBION CHEMICALS CHP PLANT MIDDLEWICH ROADSANDBACHCHESHIRECW11 3PZ	POWERGEN COGENERATION LTD
41	32,379	Pulp & Paper	C/O SCA HYGIENE PRODUCTS, TAWD PAPER MILL, PADDOCK ROAD, SKELMERSDALE, LANCASHIRE. WN8 9PL	INNOGY COGEN LTD
42	14,906	Food & Drink	SPRINGS ROAD KITT GREEN WIGAN LANCASHIRE WN 5 0 JL	H. J HEINZ
43	14,205	Bricks/Ceramics	RAVENHEAD FACTORY, CHEQUER LANE, UPHOLLAND, SKELMERSDALE, LANCASHIRE, WN8 0DD	IBSTOCK BRICK LTD.
44	9,587	Pulp & Paper	TAWD MILL, PADDOCK ROAD, WEST PIMBO, SKELMERSDALE, LANCASHIRE, WN8 9PL	SCA HYGIENE PRODUCTS LTD
45	4,909	Food & Drink	MOORGATE ROAD, KIRKBY, LIVERPOOL. L33 7XJ	DAIRY CREST LTD
46	23,695	Chemicals	PENRHYN ROAD, KNOWSLEY BUSINESS PARK, LIVERPOOL, L34 9HY	CP KELCO UK LIMITED
47	22,440	Other Combustion Activities	ROYAL LIVERPOOL HOSPITAL, ENERGY CENTREPRESCOTT STREETLIVERPOOLL7 8XP	DALKIA UTILITIES SERVICES PLC
48	30,000	Chemicals	MOSTYN, HOLYWELL, FLINTSHIRE, CH8 9HE	WARWICK INTERNATIONAL LIMITED
49	25,000	Chemicals	INNOSPEC, MANUFACTURING PARK, OIL SITE ROAD, ELLESMERE PORT, CH65 4EY	INNOSPEC INC
TOTAL				
76	19,768,743			

Appendix 3 – Industry Questionnaire

Carbon Dioxide Capture and Sequestration from Industrial and Commercial Sources

14 June 2006
Hulme Hall, Port Sunlight

Questionnaire

Name				
Organisation				
Site				
Process				
Operating Regime?	Continuous	Batch	Heating Season	Other please specify
Annual CO_2 emissions, tonne				
Employees at site				
Engineers/scientists at site				
What plans does your organisation have in place to look at CO_2 capture?				
What are your concerns regarding CO_2 capture and disposal?				
Do you have the technical capacity to operate CO_2 capture plant? Would you recruit / sub-contract / do nothing / other?				
When do you think CO_2 capture may be deployed in the UK at the following scales?				
Level 0 >1million tpa				
Level 1 50k – 1m tpa				
Level 2 <50k tpa				

Please Leave your Completed Questionnaire at the Seminar Reception Desk

GASTEC at CRE	IEA GREENHOUSE GAS R&D PROGRAMME	amec

Appendix 4 – Seminar Presentations

Carbon Capture and Storage

Studies on distributed carbon dioxide capture and collection

About the IEA Green house Gas R&D Programme

- Started in 1991
- One of many IEA implementing agreements
- Supported by interested countries as well as interested industrial organisations
- Main aim is to provide consistent information on Greenhouse Gas mitigation technologies
- Guardian of the GHGT international conferences

About the IEA Green house Gas R&D Programme

- Fosters international networks on topics of current interest
- Provides information on research and demonstration projects
- Actively supports a selection of key demonstration projects
  - E.g Sleipner, Weyburn, CO2Sink, Recopol……

Current Membership

OPEC Organization of the Petroleum Exporting Countries

ALSTOM B&W BG GROUP bp Chevron EniTecnologie e·on EPRI

ExxonMobil REPSOL YPF RWE Schlumberger STATOIL TOTAL VATTENFALL

Distributed collection of CO2

- Most focus has been on centralised capture of CO2 and comparison with other mitigation technologies such as renewables and energy efficiency improvement.
- Option of more distributed capture is under study for comparison purposes.
- Alternative to provision of “Green” energy to distributed users in form of electricity or hydrogen

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Studies underway

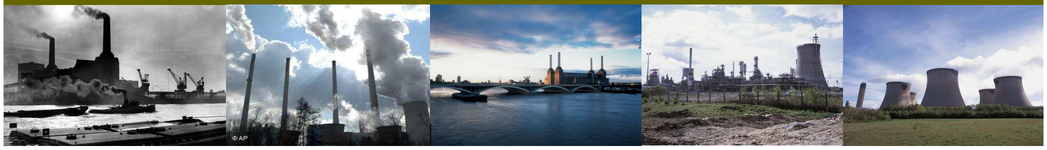
- 1) Future technology for distributed capture
  - Technologies and indicative costs
- 2) Costs for distributed collection.

Distributed collection study

- Restricted to relatively large sources
- Probably unattractive and impractical at small commercial / domestic level (<50,000tpa CO_2)
- Costs to be based on realistic regional scenario
- Key parameters to be derived so that results can be factored to other regions.
- Study lead by Gastec UK in consortium with AMEC.

EU Emissions Trading Scheme

Carbon Dioxide Capture and Sequestration from Industrial and Commercial Sources
Hulme Hall 15 June 2006



Iain Summerfield

Gastec at CRE Ltd

What is the EU ETS ?

- The EU ETS is one of the policies being introduced across Europe to tackle emissions of carbon dioxide and other greenhouse gases and combat the serious threat of climate change.

Why emissions trading ?

- Way of reducing emissions at ***least cost*** to industry – offers industry more flexibility than ‘traditional’ regulation
- Offers incentives for industry to go beyond what is expected of them
- Overall environmental impact the same

defra
Department for Environment
Food and Rural Affairs

How does the EU ETS work ?

- “Cap and trade” system
- First phase runs until December 31st 2007
- 2nd phase in line with 1st Kyoto Protocol commitment period
- Carbon dioxide only in first phase
- Mandatory for certain activities (energy activities, ferrous metals, mineral industry and pulp and paper)

defra
Department for Environment
Food and Rural Affairs

How does the EU ETS work ? continued…

- Allowances freely tradable throughout EU
- One allowance = one tonne of CO2
- Calendar year reporting of emissions
- 28th February each year - each participant receives number of allowances

defra
Department for Environment Food and Rural Affairs

How does the EU ETS work ? continued…

- By end of April following year- each participant must surrender number of allowances equal to annual reportable emissions
- These allowances then cancelled
- Operator needs sufficient allowances in account to cover emissions
- Penalty per tonne of excess emissions
  - €40 (2005-2007)

defra
Department for Environment Food and Rural Affairs

Options for Participants

- Annual emissions exactly equal to the number of allowances given each year.
- Decrease emissions and sell surplus.
- Let emissions remain high and buy extra allowances needed to cover the gap.

defra
Department for Environment Food and Rural Affairs

For further information

Website
http://defraweb/environment/climatechange/trading/eu/index.htm

defra
Department for Environment Food and Rural Affairs

Carbon Dioxide Capture and Sequestration
from Industrial and Commercial Sources
Hulme Hall
15 June 2006

Capture Technologies

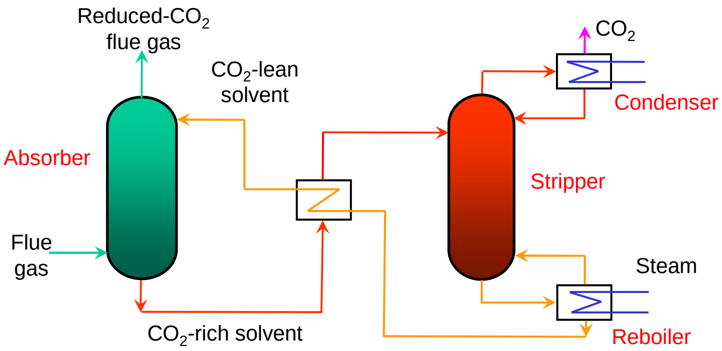
Iain Summerfield
Gastec at CRE Ltd

Capture Technologies

3 Routes:

- Post combustion
- Pre Combustion
- Oxy-Fuel

Post-Combustion - Solvent Capture


Reduced-CO_2 flue gas

CO_2-lean solvent

CO_2

Condenser

Absorber

Stripper

Flue gas

Steam

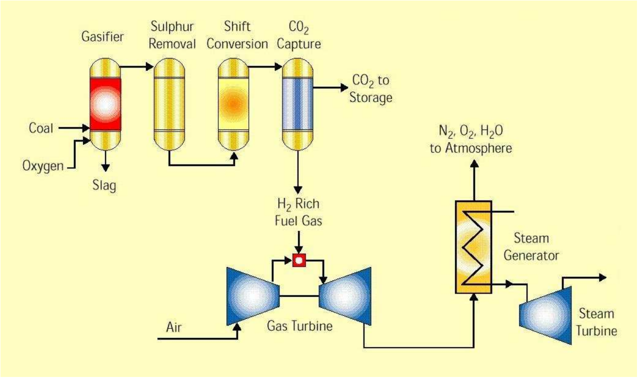
CO_2-rich solvent

Reboiler

Solvent Capture

- **Advantages**
  - **Existing combustion technology can be used**
  - **Retrofit to existing plants is possible**
    - **But retrofit to old inefficient plants is not attractive**
  - **Demonstrated at some small power plants**
- **Disadvantages**
  - **Energy penalty has been relatively high**
    - **Penalty is being reduced by process developments**
  - **Solvents are degraded by oxygen and impurities**
    - **Need to dispose of degraded solvent**
    - **Less widely used for oxidising flue gases**

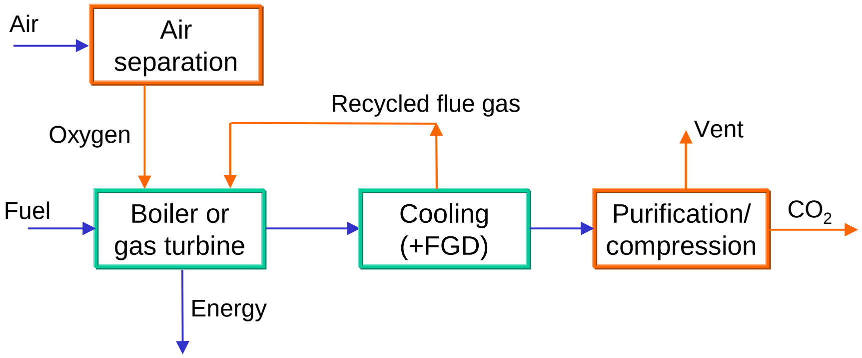
Pre-Combustion - IGCC with CO_2 Capture



IGCC with CO_2 Capture

- **Advantages**
  - High CO_2 concentration and high overall pressure
    - Lower energy consumption for CO_2 separation
    - Compact equipment
  - Proven CO_2 separation technology can be used
  - Possibility of co-production of hydrogen
- **Disadvantages**
  - IGCC is unfamiliar technology for power generators
  - Existing coal fired plants have low availability
  - IGCC without CO_2 capture has generally higher costs than pf combustion

Oxy-Fuel Combustion



Oxy-Fuel Combustion

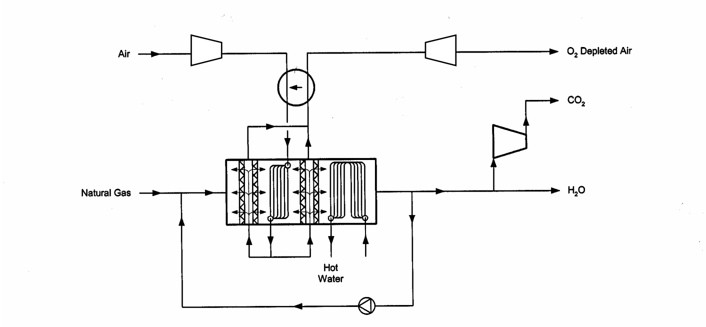
- **Advantages**
  - **Combustors could be fairly conventional**
  - **Possibility of compact boilers with lower quantities of flue gas recycle**
  - **Possibility of avoiding FGD**
- **Disadvantages**
  - **Only tested at a small scale**
  - **High cost of oxygen production**
    - **Advanced O_2 membranes with lower energy consumptions are at pilot scale**
  - **New gas turbines designs are needed**
    - **Will only be developed if there is a large market**

Capture Technologies for Small-Scale Operation

IEA GHG Report by ECOFYS (Draft)

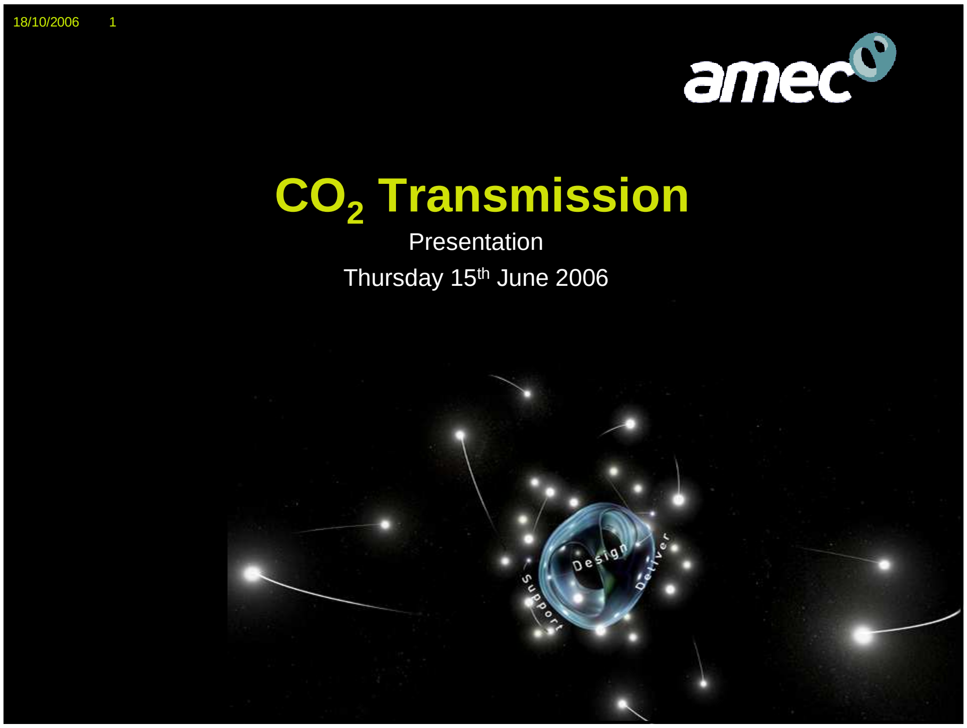
- IC Engine with Post Combustion Solvent
- NG Turbine with Pre Combustion PSA
- Oxy Fuel Coal Boiler with O_2 Membrane
- Oxy Fuel NG Boiler with O_2 Membrane
- SOFC with O_2 Membrane

NG Boiler with O_2 Permeable Membrane



Summary

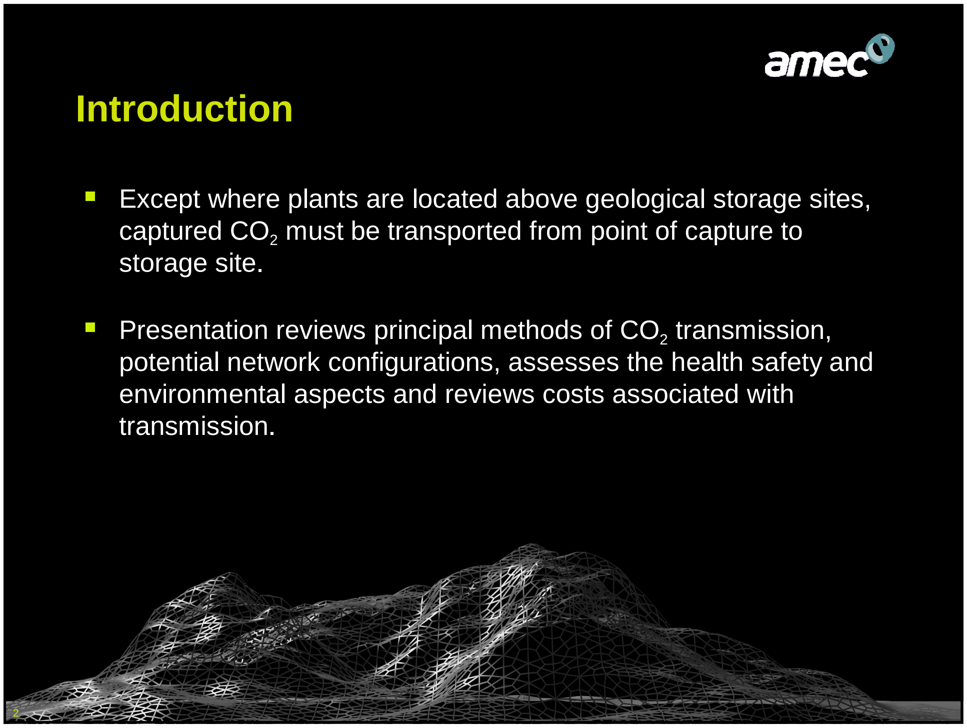
- CO_2 can be captured using existing technology
- Technology needs to be demonstrated at larger scales
- CO_2 capture reduces plant efficiency significantly
- Cost of capture is about 1-3 USc/kWh, excluding storage
  - \$20-60/t CO_2-avoided
- CCS can have a role in a mix of CO_2 abatement options



CO_2 Transmission

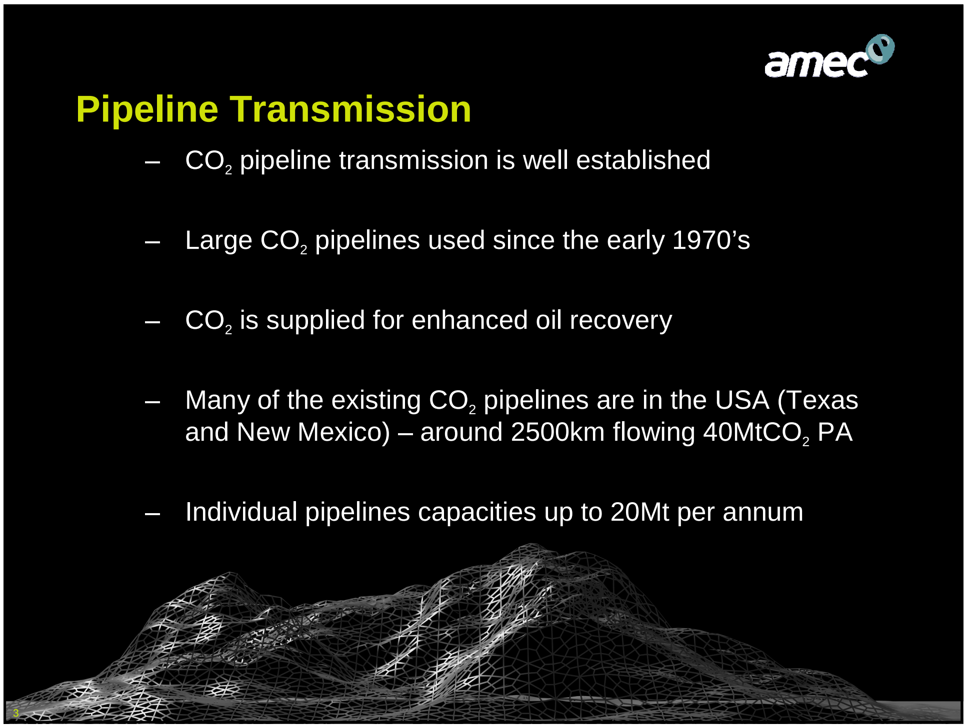
Presentation

Thursday 15th June 2006



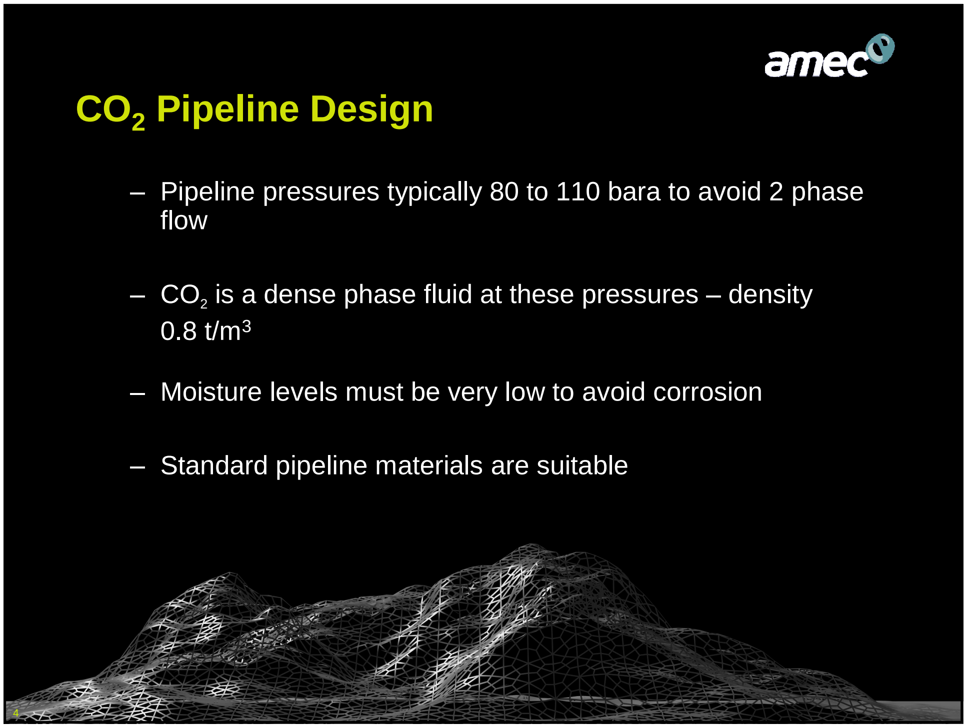
Introduction

- Except where plants are located above geological storage sites, captured CO_2 must be transported from point of capture to storage site.
- Presentation reviews principal methods of CO_2 transmission, potential network configurations, assesses the health safety and environmental aspects and reviews costs associated with transmission.



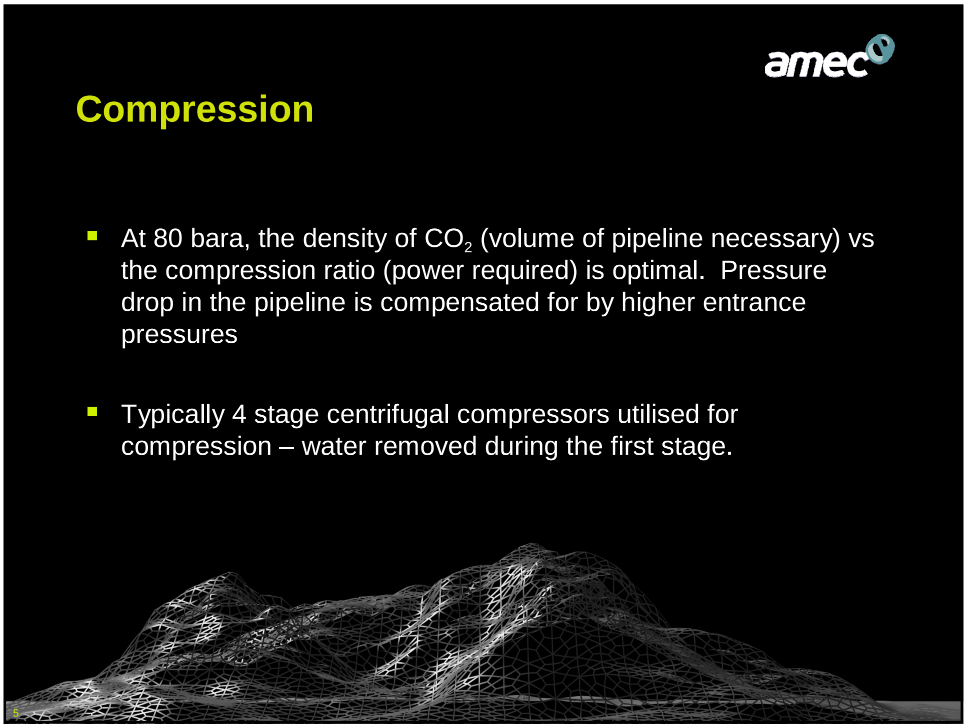
Pipeline Transmission

- CO_2 pipeline transmission is well established
- Large CO_2 pipelines used since the early 1970's
- CO_2 is supplied for enhanced oil recovery
- Many of the existing CO_2 pipelines are in the USA (Texas and New Mexico) – around 2500km flowing 40MtCO_2 PA
- Individual pipelines capacities up to 20Mt per annum



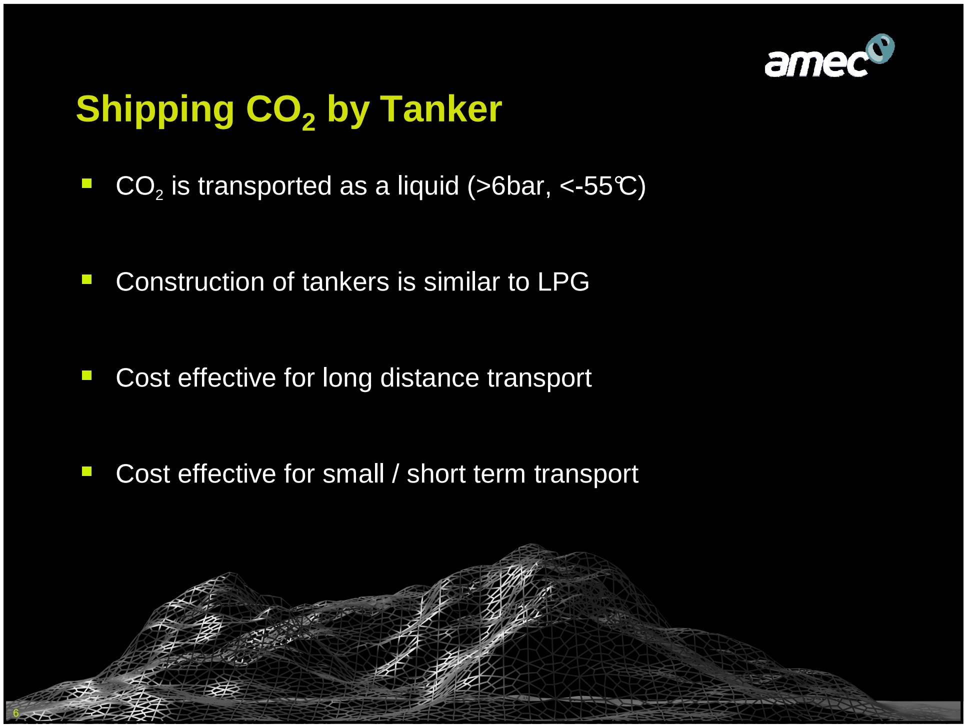
CO_2 Pipeline Design

- Pipeline pressures typically 80 to 110 bara to avoid 2 phase flow
- CO_2 is a dense phase fluid at these pressures – density 0.8 t/m^3
- Moisture levels must be very low to avoid corrosion
- Standard pipeline materials are suitable



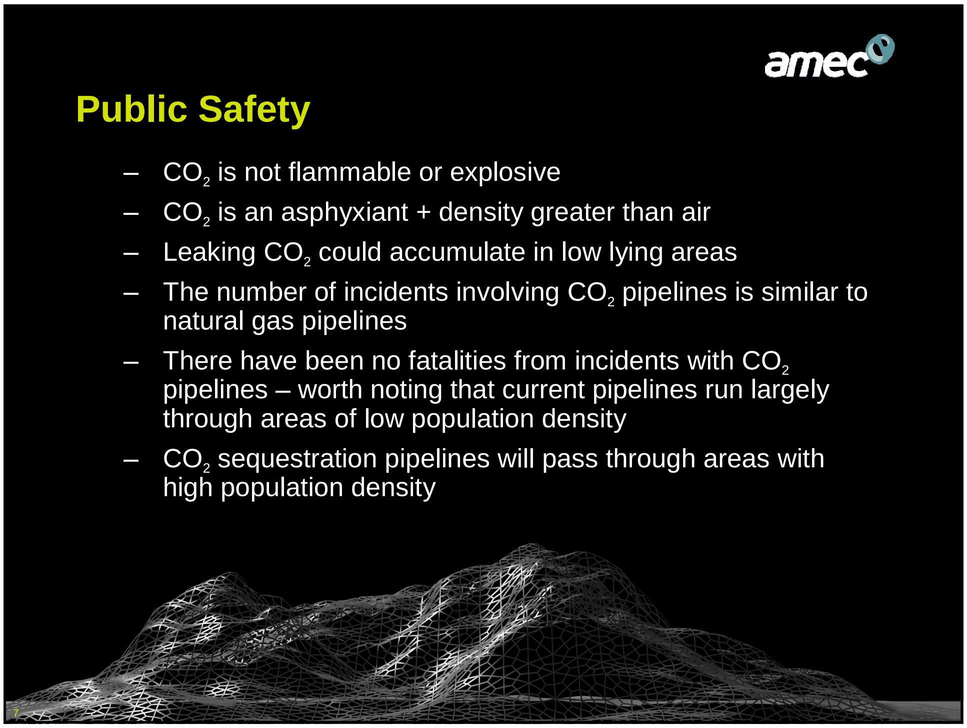
Compression

- At 80 bara, the density of CO_2 (volume of pipeline necessary) vs the compression ratio (power required) is optimal. Pressure drop in the pipeline is compensated for by higher entrance pressures
- Typically 4 stage centrifugal compressors utilised for compression – water removed during the first stage.



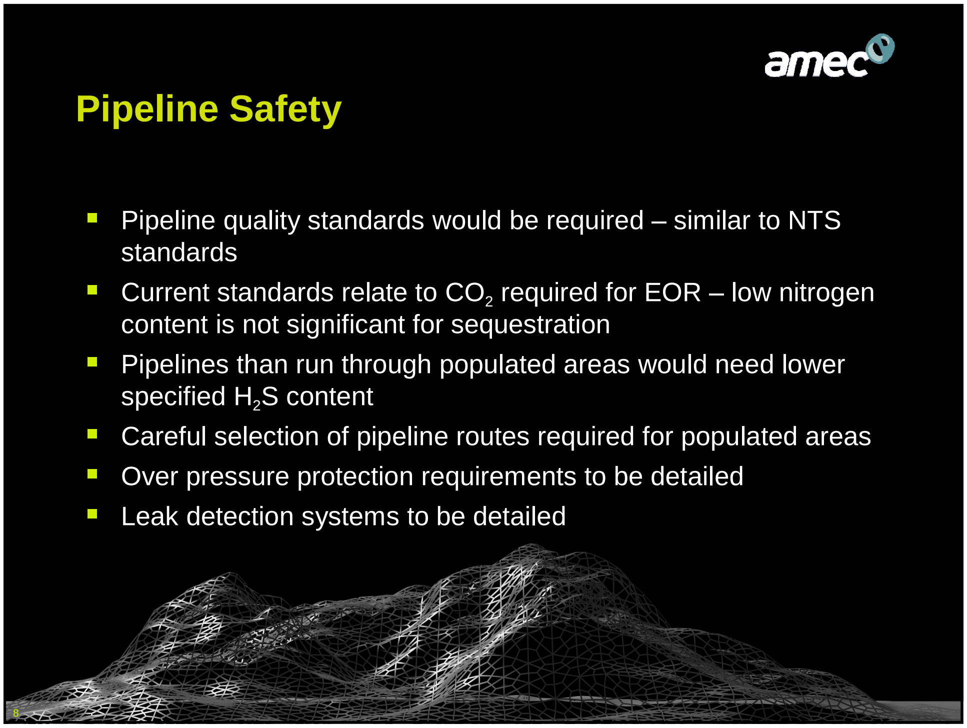
Shipping CO_2 by Tanker

- CO_2 is transported as a liquid (>6bar, <-55°C)
- Construction of tankers is similar to LPG
- Cost effective for long distance transport
- Cost effective for small / short term transport



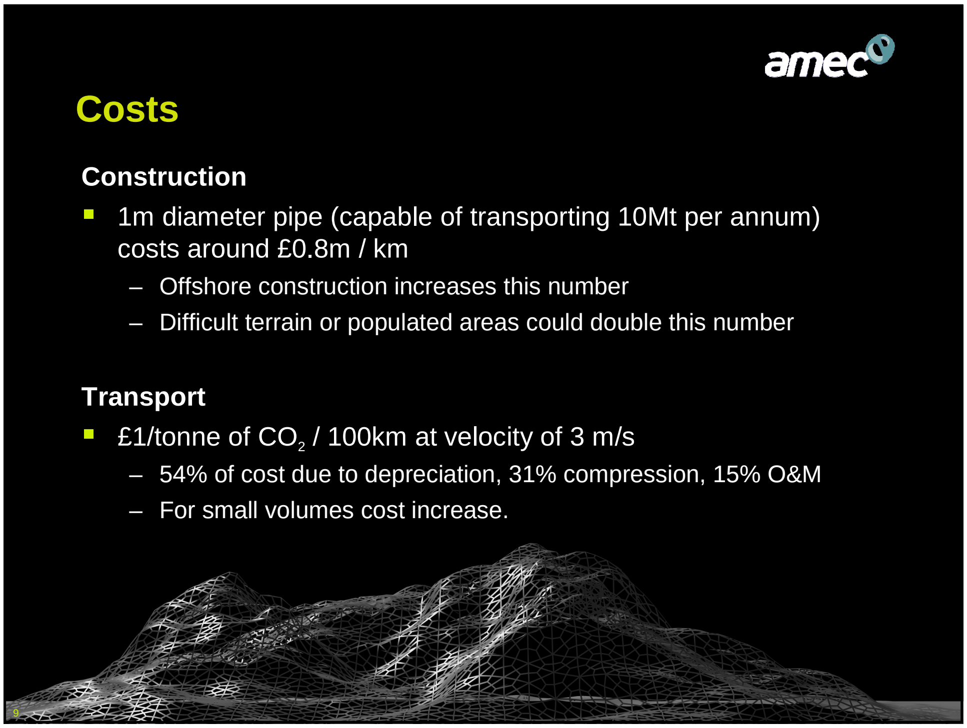
Public Safety

- CO_2 is not flammable or explosive
- CO_2 is an asphyxiant + density greater than air
- Leaking CO_2 could accumulate in low lying areas
- The number of incidents involving CO_2 pipelines is similar to natural gas pipelines
- There have been no fatalities from incidents with CO_2 pipelines – worth noting that current pipelines run largely through areas of low population density
- CO_2 sequestration pipelines will pass through areas with high population density



Pipeline Safety

- Pipeline quality standards would be required – similar to NTS standards
- Current standards relate to CO_2 required for EOR – low nitrogen content is not significant for sequestration
- Pipelines than run through populated areas would need lower specified H_2S content
- Careful selection of pipeline routes required for populated areas
- Over pressure protection requirements to be detailed
- Leak detection systems to be detailed



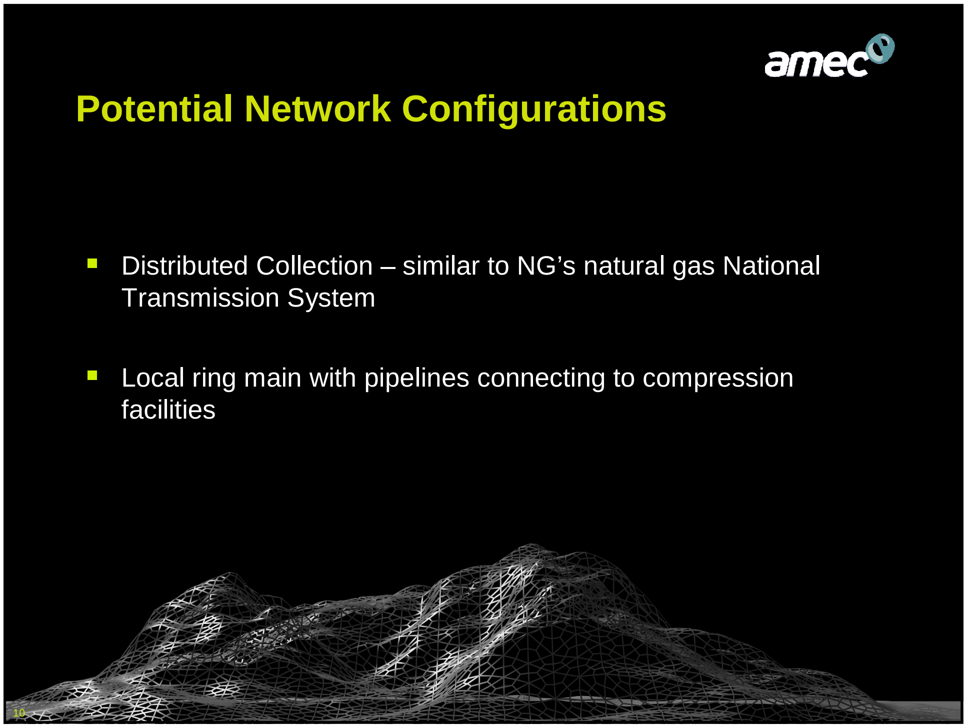
Costs

Construction

- 1m diameter pipe (capable of transporting 10Mt per annum) costs around £0.8m / km
  - Offshore construction increases this number
  - Difficult terrain or populated areas could double this number

Transport

- £1/tonne of CO_2 / 100km at velocity of 3 m/s
  - 54% of cost due to depreciation, 31% compression, 15% O&M
  - For small volumes cost increase.



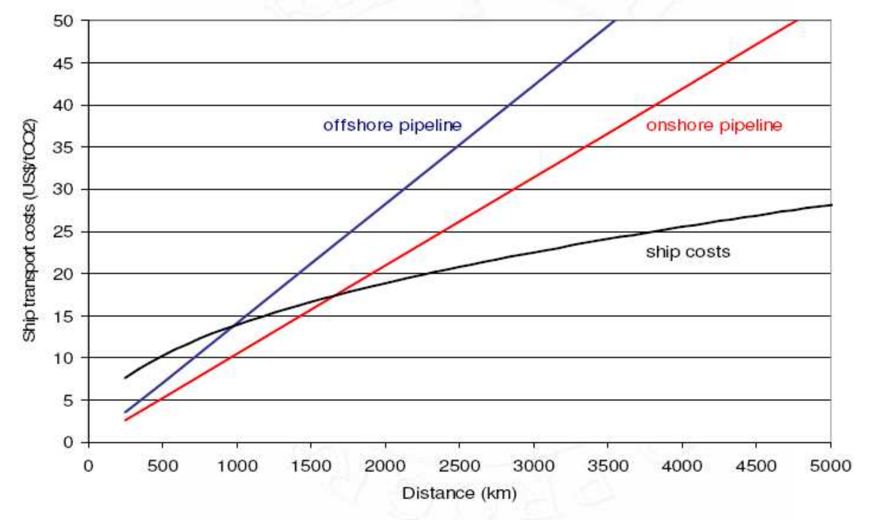
Potential Network Configurations

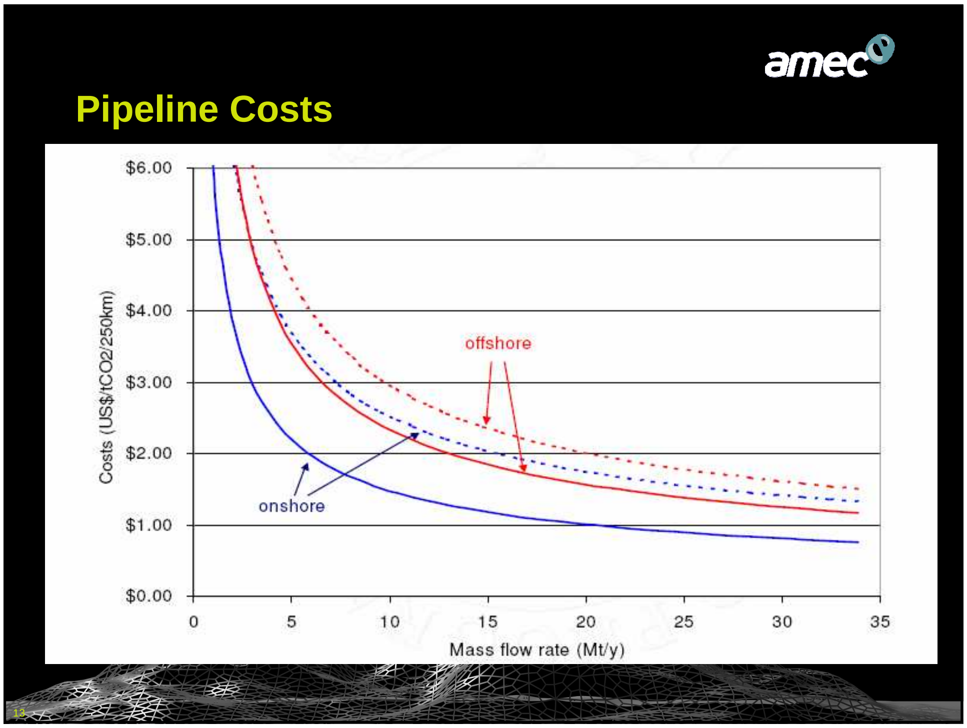
- Distributed Collection – similar to NG’s natural gas National Transmission System
- Local ring main with pipelines connecting to compression facilities

Liabilities

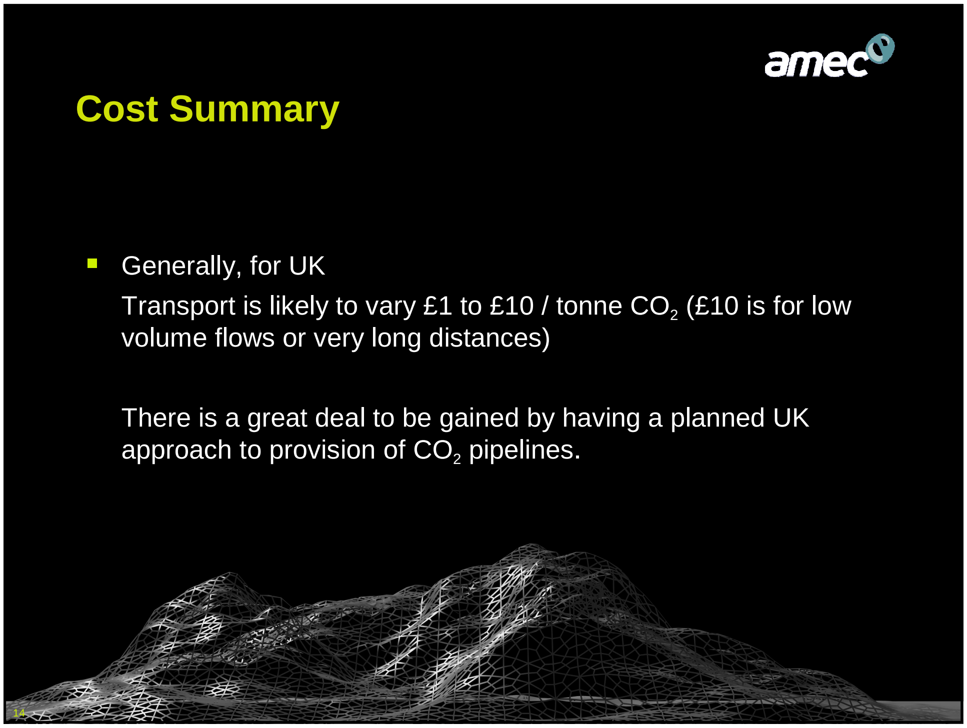
- Liability for CO_2 during transportation not clearly defined at this stage
- CCSA are promoting long term liabilities for CO2 storage in geological formations should be transferred to public body following cessation of injection and installation of appropriate measures for monitoring.

Transmission Costs





Pipeline Costs

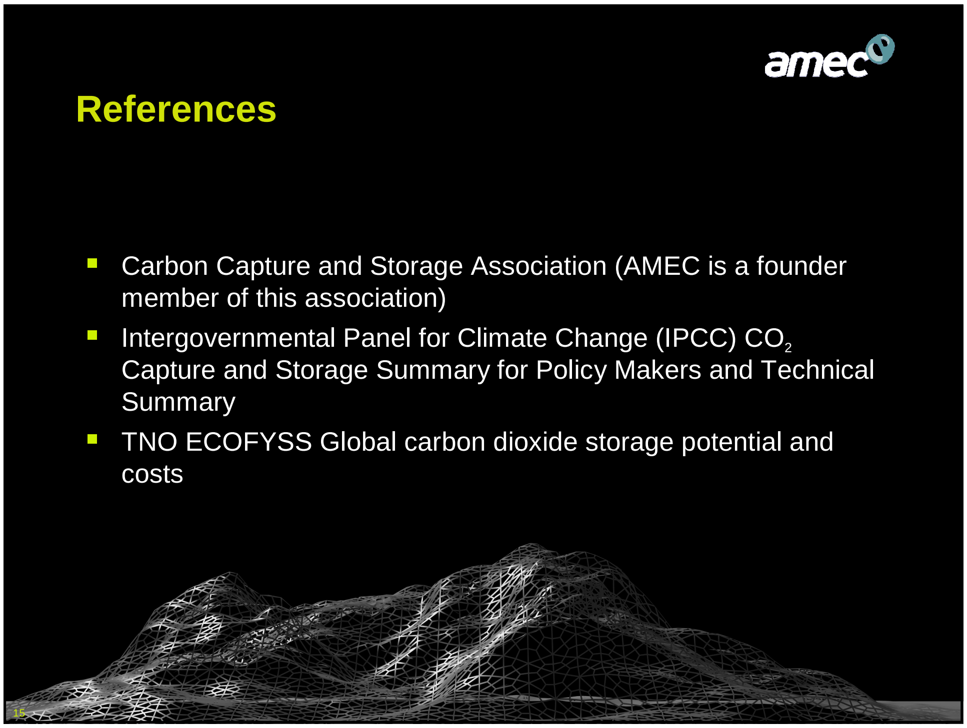


Cost Summary

- Generally, for UK

  Transport is likely to vary £1 to £10 / tonne CO_2 (£10 is for low volume flows or very long distances)

  There is a great deal to be gained by having a planned UK approach to provision of CO_2 pipelines.



References

- Carbon Capture and Storage Association (AMEC is a founder member of this association)
- Intergovernmental Panel for Climate Change (IPCC) CO_2 Capture and Storage Summary for Policy Makers and Technical Summary
- TNO ECOFYSS Global carbon dioxide storage potential and costs

CO$_2$ Capture & Sequestration

Options for Disposal

Presented By

Ben Rouncefield

Gastec at CRE

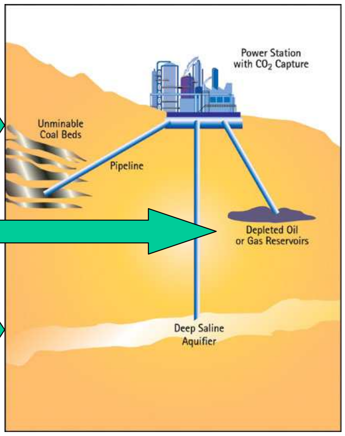
Main Technologies

- Sub Surface Storage
  - Enhanced Oil Recovery with CO$_2$ (EOR)
  - Enhanced Coal Bed Methane recovery (ECBM)
  - Storage in depleted oil and gas reservoirs
  - Storage in deep saline aquifers
  - Temporary Storage in deep underground salt cavities
- Mineral Sequestration
  - Not commercially viable
- Deep Ocean Sequestration
  - Uncertainties & Environmentally Unacceptable

Unminable Coal Seams
30 Gt CO_2
Able to store <2 Years of 2030 Emissions

Depleted Oil & Gas Fields
930 Gt CO_2
Able to Store 50 Years of 2030 Emissions

Deep Saline Aquifers
400-10 000 Gt CO_2
Able to store 20 - 530 Years of 2030 Emissions

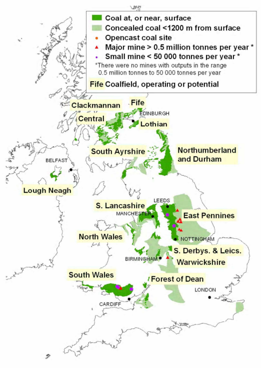


Most Viable Options for Region

- Sub Surface Storage
  - Enhanced Coal Bed Methane recovery (ECBM)
  - Storage in depleted oil and gas reservoirs
  - Storage in deep saline aquifers
  - Temporary Storage in deep underground salt cavities

Enhanced Coal Bed Methane recovery (ECBM)

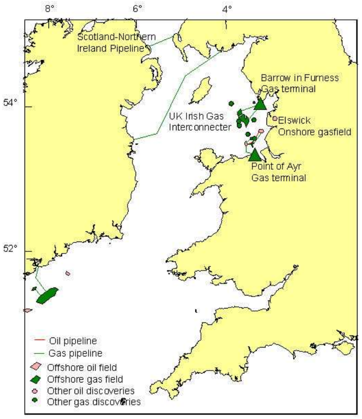
- Deep uneconomic to mine coal measures
- CO_2 displaces CH_4 and binds with coal
- Sale of CH_4 displaces costs
- Potential for offshore CBM recovery
- Low storage volume



Source: BGS and the Coal Authority

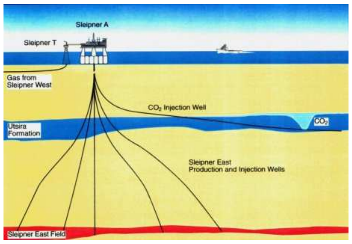
Storage in depleted oil and gas reservoirs

- Irish Sea gas fields
- Relatively low storage costs
- Infrastructure already in place
- High storage volume
- Established industry base and skills



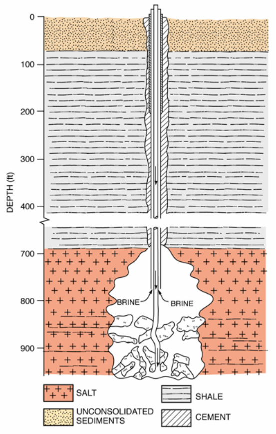
Storage in deep saline aquifers

- Non-potable saline aquifers >1km below ground
- Slightly higher cost than depleted gas fields
- Uncertainty regarding long term fate of CO_2 and impurities
- Sleipner pilot scheme currently being monitored



Storage in deep underground salt cavities

- Cavities must be >800m below ground
- Onshore storage raises safety concerns
- Low storage volume
- Interim storage prior to offshore disposal



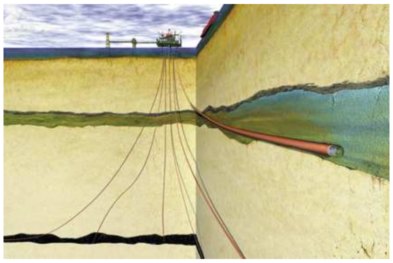
Best Potential for Study Area

Offshore

- Depleted Oil and Gas Fields
- Deep saline aquifers

To a lesser Extent

- ECBM
- Deep Salt Cavities



Questions & Discussion

Hosted by

Mark Crowther

Gastec at CRE Limited

Appendix 5 – Seminar Delegate List

		CANDIDATE NAME	COMPANY	PROCESS	SITE
1		Matthew Demmon	Quinn Glass Limited	Glass	Ince
2		Les Waymont	Warwick International Ltd	Chemicals	Mostyn
3		Martin Gledhill	Eastham Refinery Limited	Refineries	Ellesmere Port
4		Melanie Smythe	Ineos Silicas	Chemicals	Warrington
5		Paul Sharp	Kemira GrowHow UK Ltd	Chemicals	Ince
6		Richard Holden	Shell UK	Refineries	Stanlow
7		Paul McGeehin	Mowlem Engineering	Consulatnts	Various
8		Peter Shields	Innospec Inc	Chemicals	Ellesmere Port
9		Ron Barber	British Salt Limited	Food & Drink	Middlewich
10		Nigel Brooker	Jaguar	Automotive	Halewood
11		Adele Aubry	University of Manchester	Academic	manchester uni
12		Simon Slade	Pilkington Glass	Glass	Various
13		Gordon Newsholme	HSE	Government	Bootle
14		Mike Hancock	Dee Associates	Consulatnts	Chester
15		Tony Foster	Energy Wholesale	Other Combustion Activities	Winnington
16		Richard Wood	Air Products	Chemicals	Ellesmere Port
17		Dave Morris	Flexsys Rubber Chemicals Ltd	Chemicals	Rhuabon
18		Dave Shepard	Flexsys Rubber Chemicals Ltd	Chemicals	Rhuabon
19		Jim Morris	Environment Agency	Government	EA N. Wales
20		Colin Brooks	Gaz de France Generation Limited	Other Combustion Activities	Shotton
21		Martin Bookbinder	Abitibi Consolidated	Pulp and Paper	Ellesmere Port
22		Allan Morgans	Knauf Insulation	Glass	St Helens
23		John O'Callaghan	Cereal Partners UK Bromborough	Food & Drink	Bromborough
24		Jill Wilday	Health & Safety Laboratory	Government	Buxton
25		Richard Long	Entec UK	Consulatnts	NW
26		Andrew Needham	Cheshire County Council	Government	Cheshire
27		Prof Reginald Mann	University of Manchester	Academic	manchester uni
28		Dr Tim Hill	E.ON UK	Power Generation	Various
29		Mike Bilio	HSE	Government	Bootle
30		Clive Gaskell	Environment Agency	Government	Chester
31		Martyn Gilbert	Intergen	Power Generation	Runcorn
32		Simon Quarmby	Ineos Silicas	Chemicals	Warrington
33		Peter Richmond	Invensys Systems Limited	Systems Technology	Manchester
34		Steve Graville	BOC Gases	Chemicals	Guilford
35		Kester Boardman	RSKENSR	Consulatnts	Helsby

Appendix 6 – Spreadsheet Instructions

Appendix 6: Spreadsheet Instructions

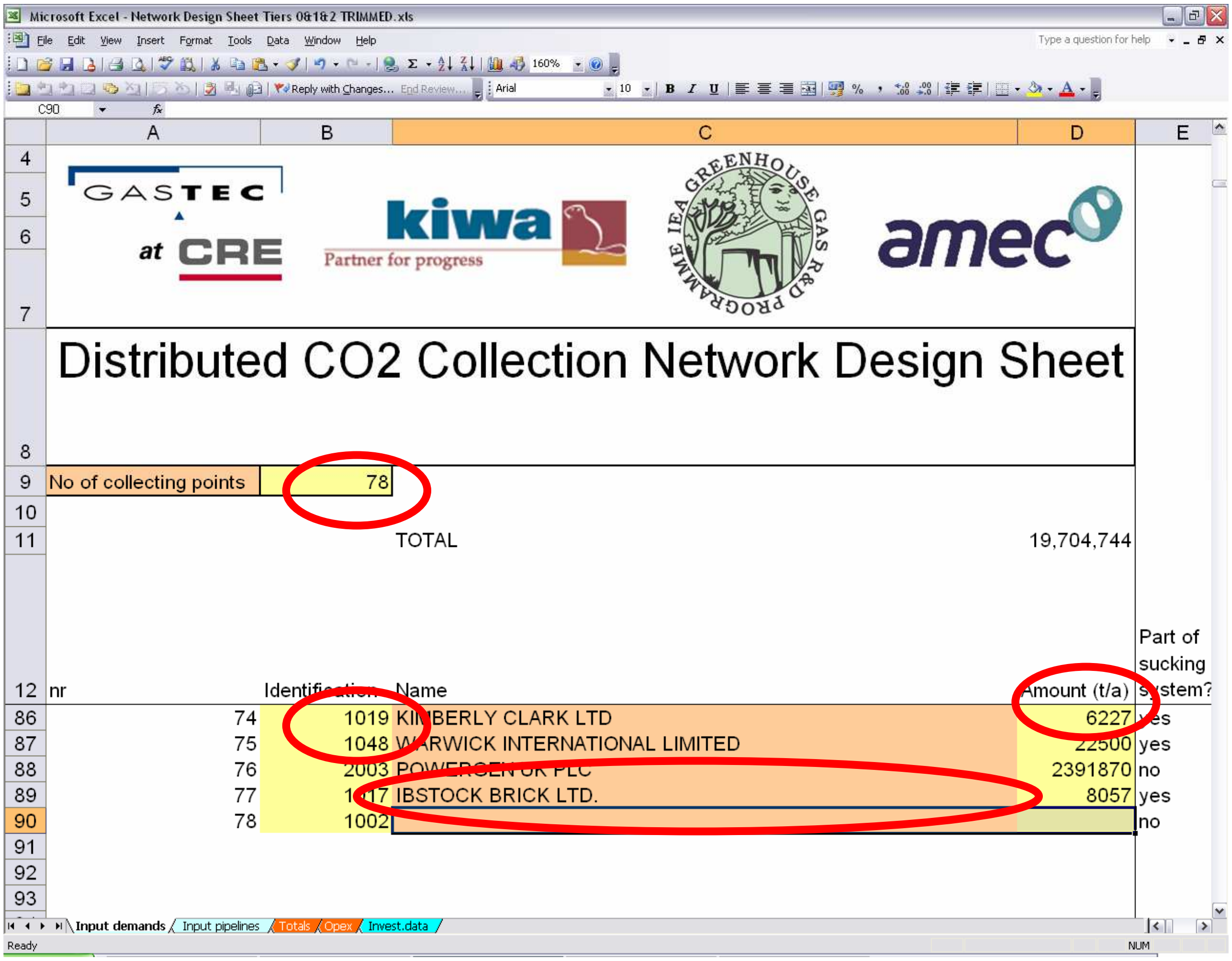
The following section is a simple step by step guide intended to aid network designers who wish to use the design spreadsheet.

The spreadsheet will only tell a designer what size/material of pipe is required, pressures and costs, however a number of design decisions still need to be made. Prior to using the spreadsheet, the shape of the network to be designed should be determined and pipeline connections and distances should be established in the usual manner.

First of all, open a copy of the spreadsheet and save it under a new name e.g. Network1.xls. Now follow Steps 1 – X carefully to design your network.

Step 1: Input Emission Sources

Ensure that the **"Input Demands"** tab is open.



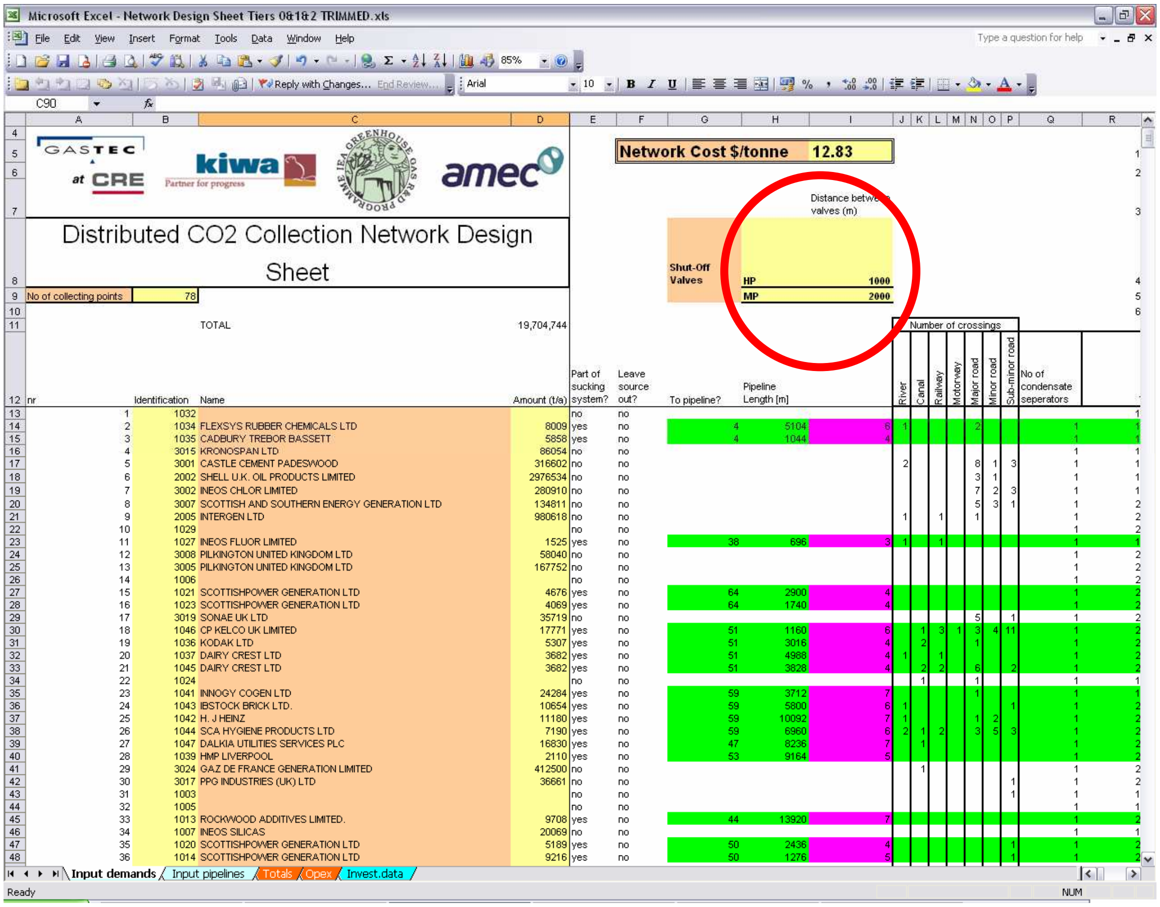
Distributed CO2 Collection Network Design Sheet

	A	B	C	D	E
9	No of collecting points	78			
10					
11			TOTAL	19,704,744	
12	nr	Identification	Name	Amount (t/a)	Part of sucking system?
86	74	1019	KIMBERLY CLARK LTD	6227	yes
87	75	1048	WARWICK INTERNATIONAL LIMITED	22500	yes
88	76	2003	POWERGEN UK PLC	2391870	no
89	77	1[illegible]17	IBSTOCK BRICK LTD.	8057	yes
90	78	1002			no
91					
92					
93					

Input the total number of sources to be included within your scheme in the yellow box next to "No of collecting points". Next input the name of each source and give it a unique identification number e.g.

1001, 1002 etc. Input the emission (total to be collected) from the source in the column to the right of the name.

The distance required between shut-off valves can also be entered on this tab. Default values applicable to the United Kingdom are already set, but these can be altered.



Distributed CO2 Collection Network Design Sheet

No of collecting points 78

Network Cost $/tonne **12.83**

Distance betwe valves (m)

Shut-Off Valves	
HP	**1000**
MP	**2000**

TOTAL 19,704,744

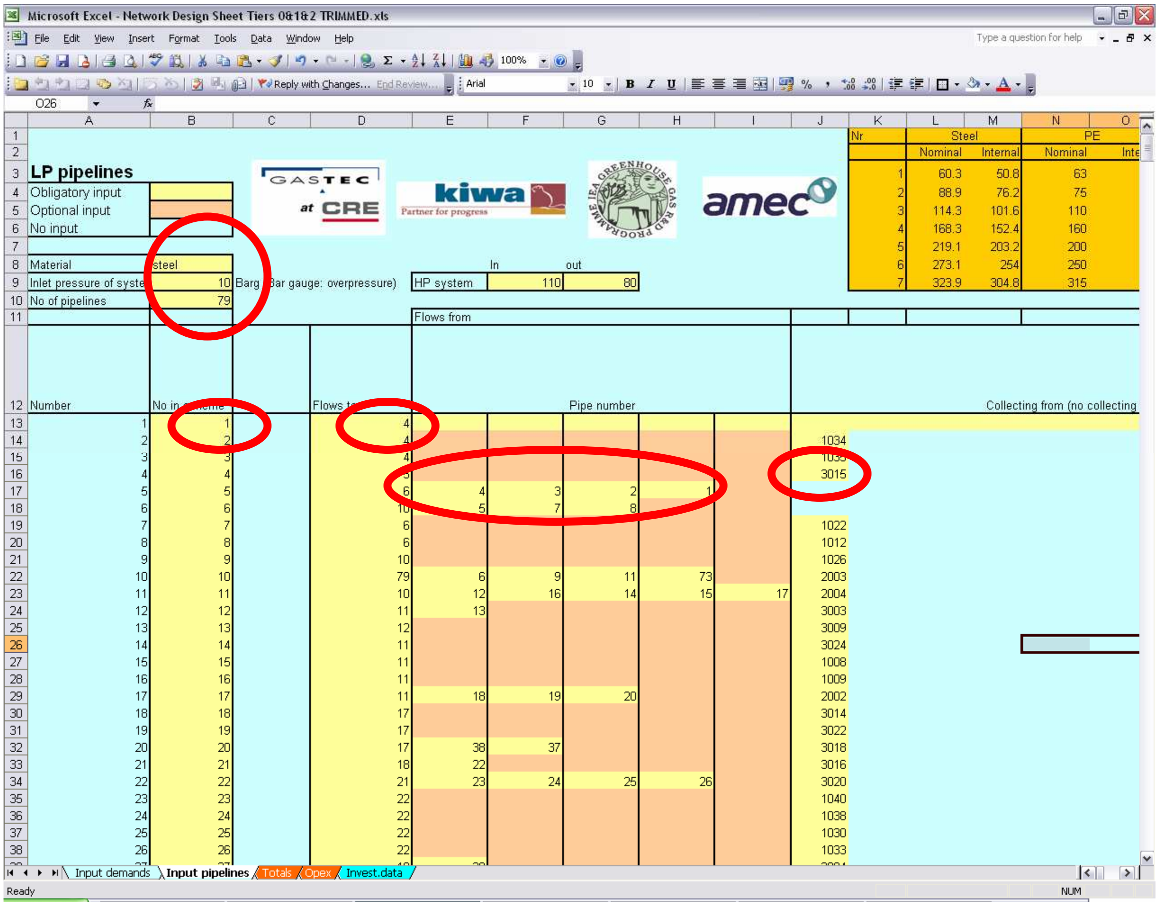
nr	Identification	Name	Amount (t/a)	Part of sucking system?	Leave source out?	To pipeline?	Pipeline Length [m]		Number of crossings							No of condensate seperators	
									River	Canal	Railway	Motorway	Major road	Minor road	Sub-minor road		
1	1032			no	no												1
2	1034	FLEXSYS RUBBER CHEMICALS LTD	8009	yes	no	4	5104	6	1				2			1	1
3	1035	CADBURY TREBOR BASSETT	5858	yes	no	4	1044	4								1	1
4	3015	KRONOSPAN LTD	86054	no	no											1	1
5	3001	CASTLE CEMENT PADESWOOD	316602	no	no				2				8	1	3	1	1
6	2002	SHELL U.K. OIL PRODUCTS LIMITED	2976534	no	no								3	1		1	1
7	3002	INEOS CHLOR LIMITED	280910	no	no								7	2	3	1	1
8	3007	SCOTTISH AND SOUTHERN ENERGY GENERATION LTD	134811	no	no								5	3	1	1	2
9	2005	INTERGEN LTD	980618	no	no				1		1		1			1	2
10	1029			no	no											1	2
11	1027	INEOS FLUOR LIMITED	1525	yes	no	38	696	3	1		1					1	1
12	3008	PILKINGTON UNITED KINGDOM LTD	58040	no	no											1	2
13	3005	PILKINGTON UNITED KINGDOM LTD	167752	no	no											1	2
14	1006			no	no											1	2
15	1021	SCOTTISHPOWER GENERATION LTD	4676	yes	no	64	2900	4								1	2
16	1023	SCOTTISHPOWER GENERATION LTD	4069	yes	no	64	1740	4								1	2
17	3019	SONAE UK LTD	35719	no	no								5		1	1	2
18	1046	CP KELCO UK LIMITED	17771	yes	no	51	1160	6		1	3	1	3	4	11	1	2
19	1036	KODAK LTD	5307	yes	no	51	3016	4		2			1			1	2
20	1037	DAIRY CREST LTD	3682	yes	no	51	4988	4	1		1					1	2
21	1045	DAIRY CREST LTD	3682	yes	no	51	3828	4		2	2		6		2	1	2
22	1024			no	no					1			1			1	1
23	1041	INNOGY COGEN LTD	24284	yes	no	59	3712	7					1			1	1
24	1043	IBSTOCK BRICK LTD.	10654	yes	no	59	5800	6	1						1	1	2
25	1042	H. J HEINZ	11180	yes	no	59	10092	7	1				1	2		1	2
26	1044	SCA HYGIENE PRODUCTS LTD	7190	yes	no	59	6960	6	2	1	2		3	5	3	1	2
27	1047	DALKIA UTILITIES SERVICES PLC	16830	yes	no	47	8236	7		1						1	2
28	1039	HMP LIVERPOOL	2110	yes	no	53	9164	5								1	2
29	3024	GAZ DE FRANCE GENERATION LIMITED	412500	no	no					1						1	2
30	3017	PPG INDUSTRIES (UK) LTD	36661	no	no										1	1	2
31	1003			no	no										1	1	1
32	1005			no	no											1	1
33	1013	ROCKWOOD ADDITIVES LIMITED.	9708	yes	no	44	13920	7								1	2
34	1007	INEOS SILICAS	20069	no	no											1	1
35	1020	SCOTTISHPOWER GENERATION LTD	5189	yes	no	50	2436	4							1	1	2
36	1014	SCOTTISHPOWER GENERATION LTD	9216	yes	no	50	1276	5							1	1	2

You will notice that there are further columns to the right of those that have been filled in, ignore these for the time being and proceed to the next step.

Step 2: Input Pipe Distances and Connections

Ensure that the **"Input Pipelines"** tab is open.

Input the number of pipelines within the proposed network, the inlet pressure of the system and the materials of construction; this will open up the appropriate number of lines on the sheet for pipes.



Microsoft Excel - Network Design Sheet Tiers 0&1&2 TRIMMED.xls

LP pipelines

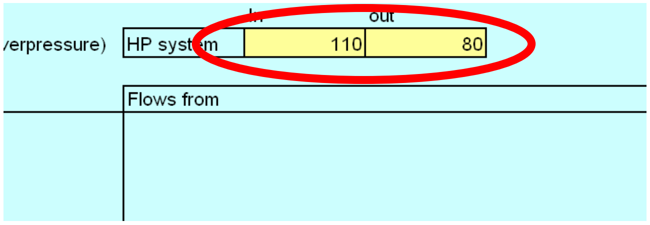
Obligatory input	
Optional input	
No input	
Material	steel
Inlet pressure of syste	10 Barg (Bar gauge: overpressure)
No of pipelines	79

	In	out
HP system	110	80

Nr	Steel		PE	
	Nominal	Internal	Nominal	Inte
1	60.3	50.8	63	
2	88.9	76.2	75	
3	114.3	101.6	110	
4	168.3	152.4	160	
5	219.1	203.2	200	
6	273.1	254	250	
7	323.9	304.8	315	

Number	No in scheme	Flows to	Flows from Pipe number					Collecting from (no collecting
1	1	4						
2	2	4						1034
3	3	4						1035
4	4	5						3015
5	5	6	4	3	2	1		
6	6	10	5	7	8			
7	7	6						1022
8	8	6						1012
9	9	10						1026
10	10	79	6	9	11	73		2003
11	11	10	12	16	14	15	17	2004
12	12	11	13					3003
13	13	12						3009
14	14	11						3024
15	15	11						1008
16	16	11						1009
17	17	11	18	19	20			2002
18	18	17						3014
19	19	17						3022
20	20	17	38	37				3018
21	21	18	22					3016
22	22	21	23	24	25	26		3020
23	23	22						1040
24	24	22						1038
25	25	22						1030
26	26	22						1033

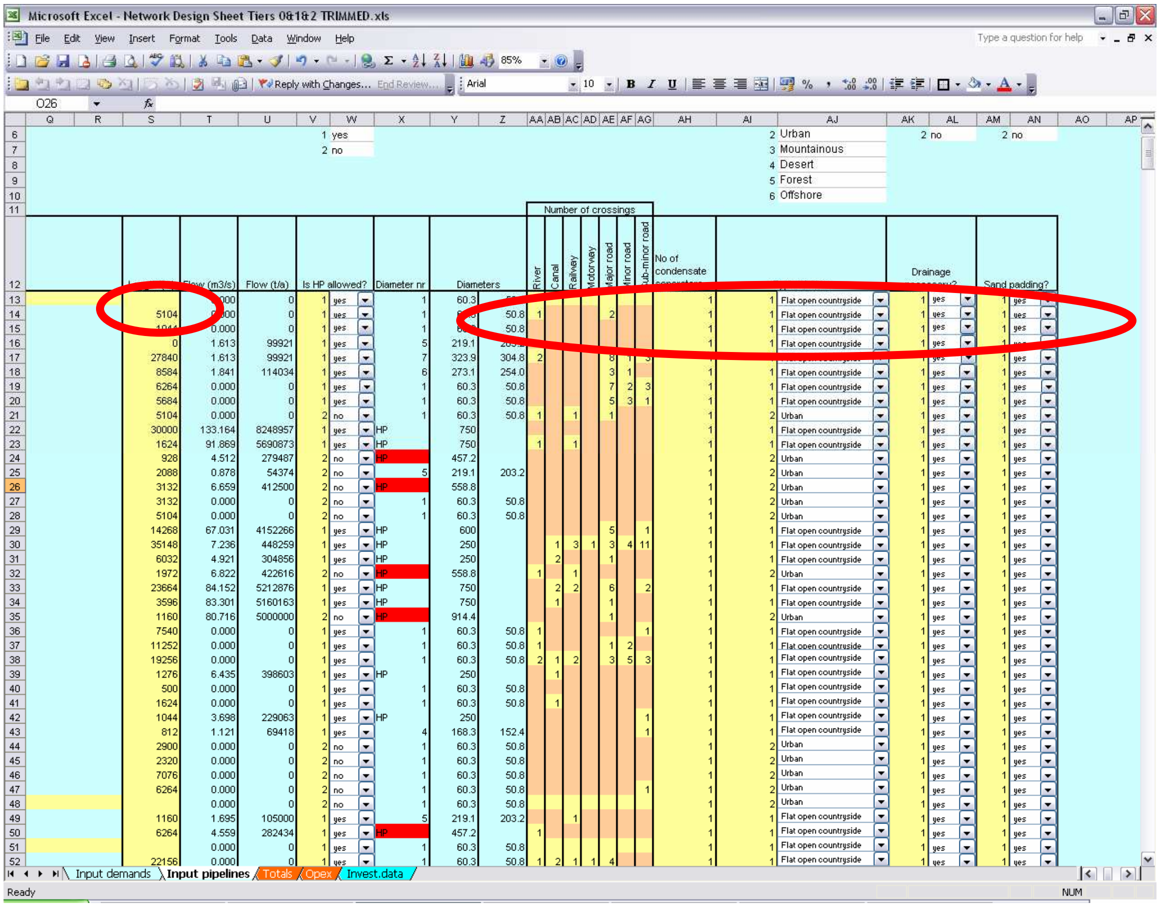
For each pipeline input it's allocated number in the scheme, any pipes that the pipe flows to (for pipes that flow out of the network input "0") and pipes that flow into that particular pipe. If a particular pipeline collects CO_2 from a source in the network, input the source ID (e.g. 1001, 1002) into the "Collecting from (no collecting point)" column. The inlet and outlet pressure of the high pressure system can also be input. The default values ensure that the CO_2 is in the supercritical phase.



verpressure)		In	out
	HP system	110	80

Flows from

Next input the length of the pipeline, the predominant terrain that it crosses, any major crossings (e.g motorways etc) the number of condensate separators, and whether drainage or sand padding is required for the pipeline.



	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN
6						1	yes												2	Urban	2	no	2	no
7						2	no												3	Mountainous				
8																			4	Desert				
9																			5	Forest				
10																			6	Offshore				
11											Number of crossings													
12			[illegible]	Flow (m3/s)	Flow (t/a)	Is HP allowed?		Diameter nr	Diameters		River	Canal	Railway	Motorway	Major road	Minor road	Sub-minor road	No of condensate separators	[illegible]		Drainage [illegible]		Sand padding?	
13				[illegible]	0	1	yes	1	60.3	[illegible]								1	1	Flat open countryside	1	yes	1	yes
14			5104	[illegible]	0	1	yes	1	[illegible]	50.8	1				2			1	1	Flat open countryside	1	yes	1	yes
15			[illegible]	0.000	0	1	yes	1	[illegible]	50.8								1	1	Flat open countryside	1	yes	1	yes
16			0	1.613	99921	1	yes	5	219.1	[illegible]								1	1	Flat open countryside	1	yes	1	[illegible]
17			27840	1.613	99921	1	yes	7	323.9	304.8	2				8	1	3	[illegible]	[illegible]	[illegible]	[illegible]	yes	1	yes
18			8584	1.841	114034	1	yes	6	273.1	254.0					3	1		1	1	Flat open countryside	1	yes	1	yes
19			6264	0.000	0	1	yes	1	60.3	50.8					7	2	3	1	1	Flat open countryside	1	yes	1	yes
20			5684	0.000	0	1	yes	1	60.3	50.8					5	3	1	1	1	Flat open countryside	1	yes	1	yes
21			5104	0.000	0	2	no	1	60.3	50.8	1		1		1			1	2	Urban	1	yes	1	yes
22			30000	133.164	8248957	1	yes	HP	750									1	1	Flat open countryside	1	yes	1	yes
23			1624	91.869	5690873	1	yes	HP	750		1		1					1	1	Flat open countryside	1	yes	1	yes
24			928	4.512	279487	2	no	HP	457.2									1	2	Urban	1	yes	1	yes
25			2088	0.878	54374	2	no	5	219.1	203.2								1	2	Urban	1	yes	1	yes
26			3132	6.659	412500	2	no	HP	558.8									1	2	Urban	1	yes	1	yes
27			3132	0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
28			5104	0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
29			14268	67.031	4152266	1	yes	HP	600						5		1	1	1	Flat open countryside	1	yes	1	yes
30			35148	7.236	448259	1	yes	HP	250			1	3	1	3	4	11	1	1	Flat open countryside	1	yes	1	yes
31			6032	4.921	304856	1	yes	HP	250			2			1			1	1	Flat open countryside	1	yes	1	yes
32			1972	6.822	422616	2	no	HP	558.8		1		1					1	2	Urban	1	yes	1	yes
33			23664	84.152	5212876	1	yes	HP	750			2	2		6		2	1	1	Flat open countryside	1	yes	1	yes
34			3596	83.301	5160163	1	yes	HP	750			1			1			1	1	Flat open countryside	1	yes	1	yes
35			1160	80.716	5000000	2	no	HP	914.4						1			1	2	Urban	1	yes	1	yes
36			7540	0.000	0	1	yes	1	60.3	50.8	1						1	1	1	Flat open countryside	1	yes	1	yes
37			11252	0.000	0	1	yes	1	60.3	50.8	1				1	2		1	1	Flat open countryside	1	yes	1	yes
38			19256	0.000	0	1	yes	1	60.3	50.8	2	1	2		3	5	3	1	1	Flat open countryside	1	yes	1	yes
39			1276	6.435	398603	1	yes	HP	250			1						1	1	Flat open countryside	1	yes	1	yes
40			500	0.000	0	1	yes	1	60.3	50.8								1	1	Flat open countryside	1	yes	1	yes
41			1624	0.000	0	1	yes	1	60.3	50.8		1						1	1	Flat open countryside	1	yes	1	yes
42			1044	3.698	229063	1	yes	HP	250								1	1	1	Flat open countryside	1	yes	1	yes
43			812	1.121	69418	1	yes	4	168.3	152.4							1	1	1	Flat open countryside	1	yes	1	yes
44			2900	0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
45			2320	0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
46			7076	0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
47			6264	0.000	0	2	no	1	60.3	50.8							1	1	2	Urban	1	yes	1	yes
48				0.000	0	2	no	1	60.3	50.8								1	2	Urban	1	yes	1	yes
49			1160	1.695	105000	1	yes	5	219.1	203.2			1					1	1	Flat open countryside	1	yes	1	yes
50			6264	4.559	282434	1	yes	HP	457.2		1							1	1	Flat open countryside	1	yes	1	yes
51				0.000	0	1	yes	1	60.3	50.8								1	1	Flat open countryside	1	yes	1	yes
52			22156	0.000	0	1	yes	1	60.3	50.8	1	2	1	1	4			1	1	Flat open countryside	1	yes	1	yes

Note that if a pipeline crosses several different types of difficult terrain it is advisable to split it into several smaller pipes to gain an accurate cost for that section.

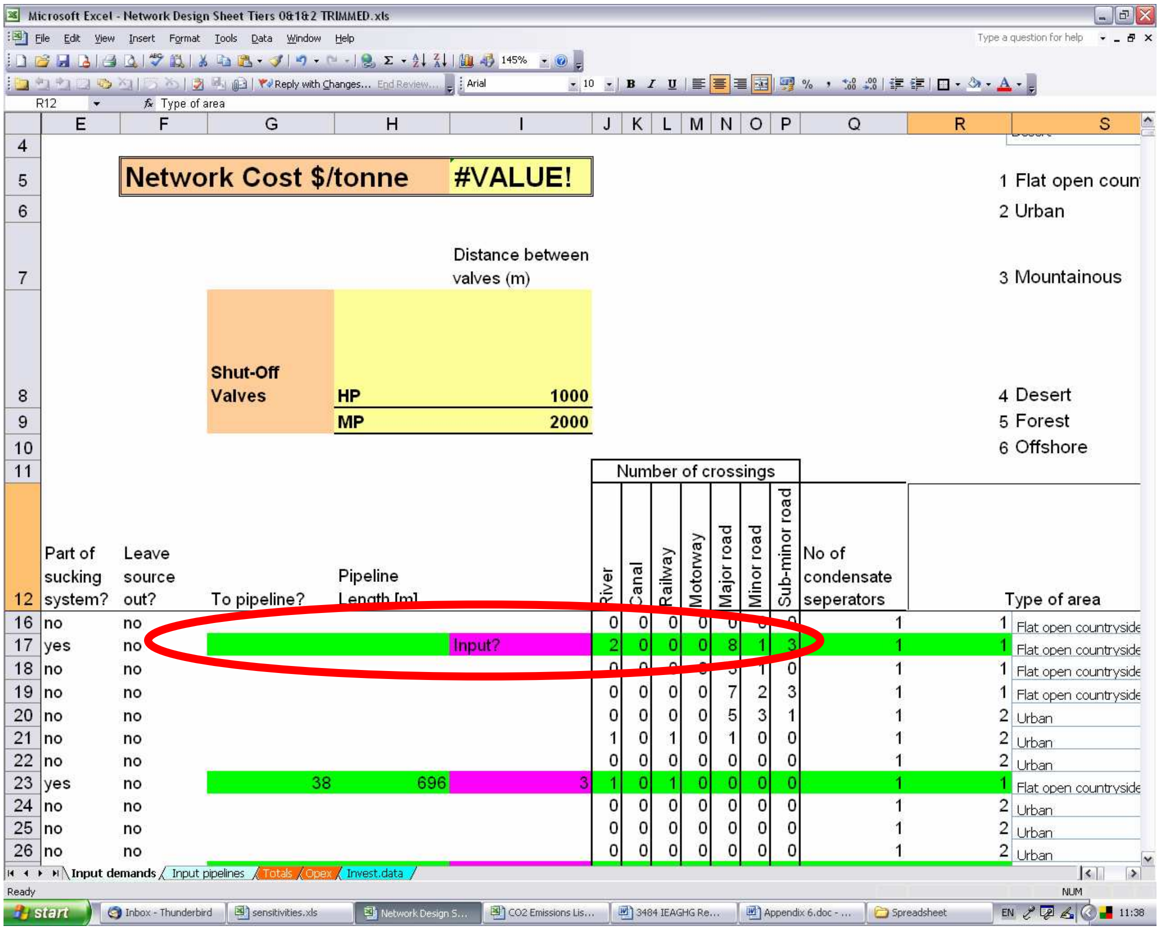
The default setting for the spreadsheet is to not allow high pressure lines in urban areas. This setting can be changed just above that column by setting all lines to yes (allow HP).

Care should be taken to ensure that all lines are entered correctly. Any mistakes in the data will affect the spreadsheet output. Once all data has been entered proceed to the next step.

Step 3: Input Suction Network

Ensure that the **"Input Demands"** tab is open.

You will notice that the information relating to crossings etc has been transposed to this sheet. You can now select parts of the network to operate under a suction system. Choose a source to be included in the suction network and select "yes" in the "Part of Sucking System?" column. Some of the columns to the right of the source will change colour.



Network Cost $/tonne #VALUE!

Distance between valves (m)

Shut-Off Valves		
	HP	1000
	MP	2000

1 Flat open countryside
2 Urban
3 Mountainous
4 Desert
5 Forest
6 Offshore

	Part of sucking system?	Leave source out?	To pipeline?	Pipeline Length [m]		Number of crossings: River	Canal	Railway	Motorway	Major road	Minor road	Sub-minor road	No of condensate seperators	Type of area	
16	no	no				0	0	0	0	0	[illegible]	0	1	1	Flat open countryside
17	yes	no			Input?	2	0	0	0	8	1	3	1	1	Flat open countryside
18	no	no				0	0	0	[illegible]	[illegible]	1	0	1	1	Flat open countryside
19	no	no				0	0	0	0	7	2	3	1	1	Flat open countryside
20	no	no				0	0	0	0	5	3	1	1	2	Urban
21	no	no				1	0	1	0	1	0	0	1	2	Urban
22	no	no				0	0	0	0	0	0	0	1	2	Urban
23	yes	no	38	696	3	1	0	1	0	0	0	0	1	1	Flat open countryside
24	no	no				0	0	0	0	0	0	0	1	2	Urban
25	no	no				0	0	0	0	0	0	0	1	2	Urban
26	no	no				0	0	0	0	0	0	0	1	2	Urban

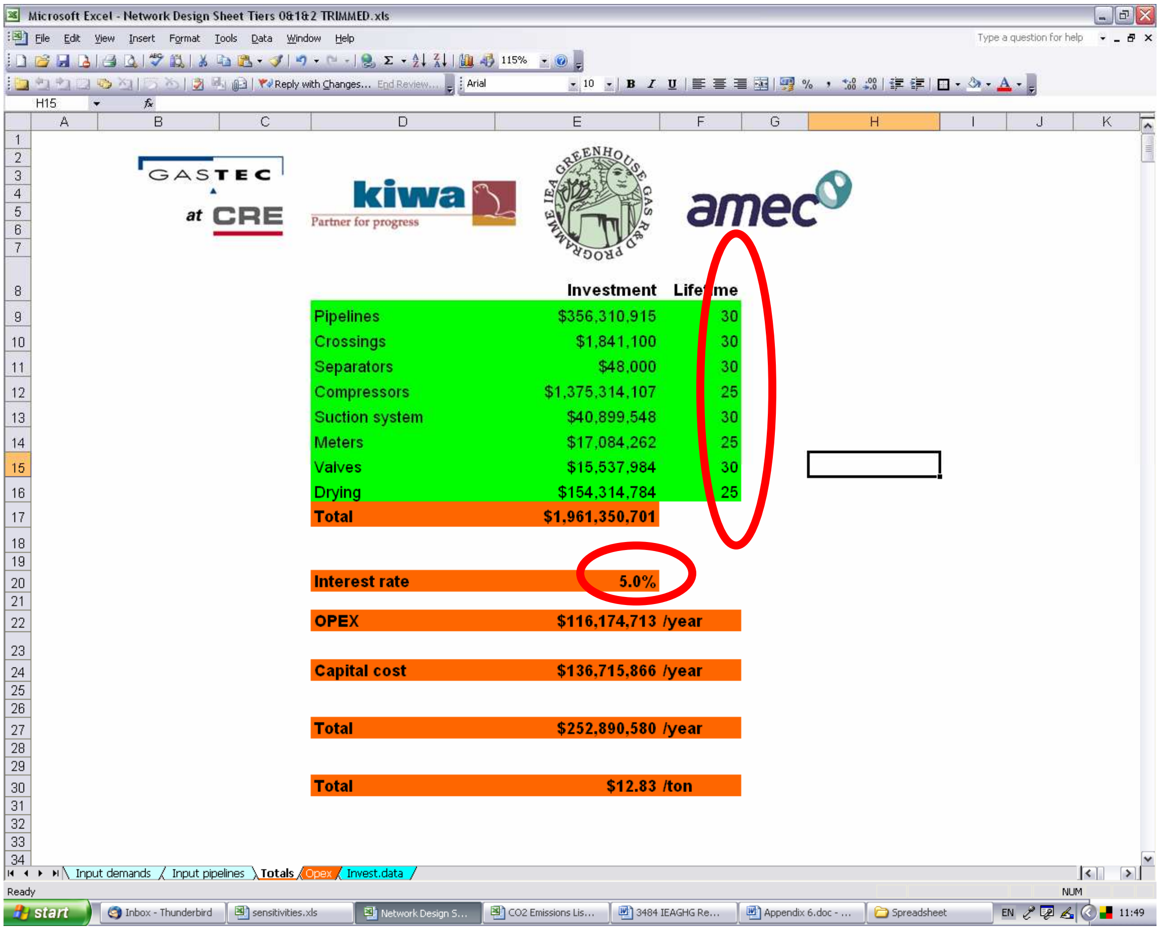
Input which pipeline the suction system is connected to for example if pipeline 1 is to be under suction and is connected to pipeline 2 you would enter a 2 in the "To pipeline?" column. Enter the length of the pipeline in the adjacent column. The purple column should now change; if it reads "n.a", then a suction pipeline is not possible for this source either because of the size of emission or the distance to be travelled means that the pipe required is too large. If a suction pipe is not feasible for a particular source ensure that the "Part of sucking system" column is returned to "no".

Once this stage is completed all information relating to sources and pipelines should have been entered into the spreadsheet.

Step 4: Interest, Plant Lifetimes and Operational Costs

Ensure that the **"Totals"** tab is open.

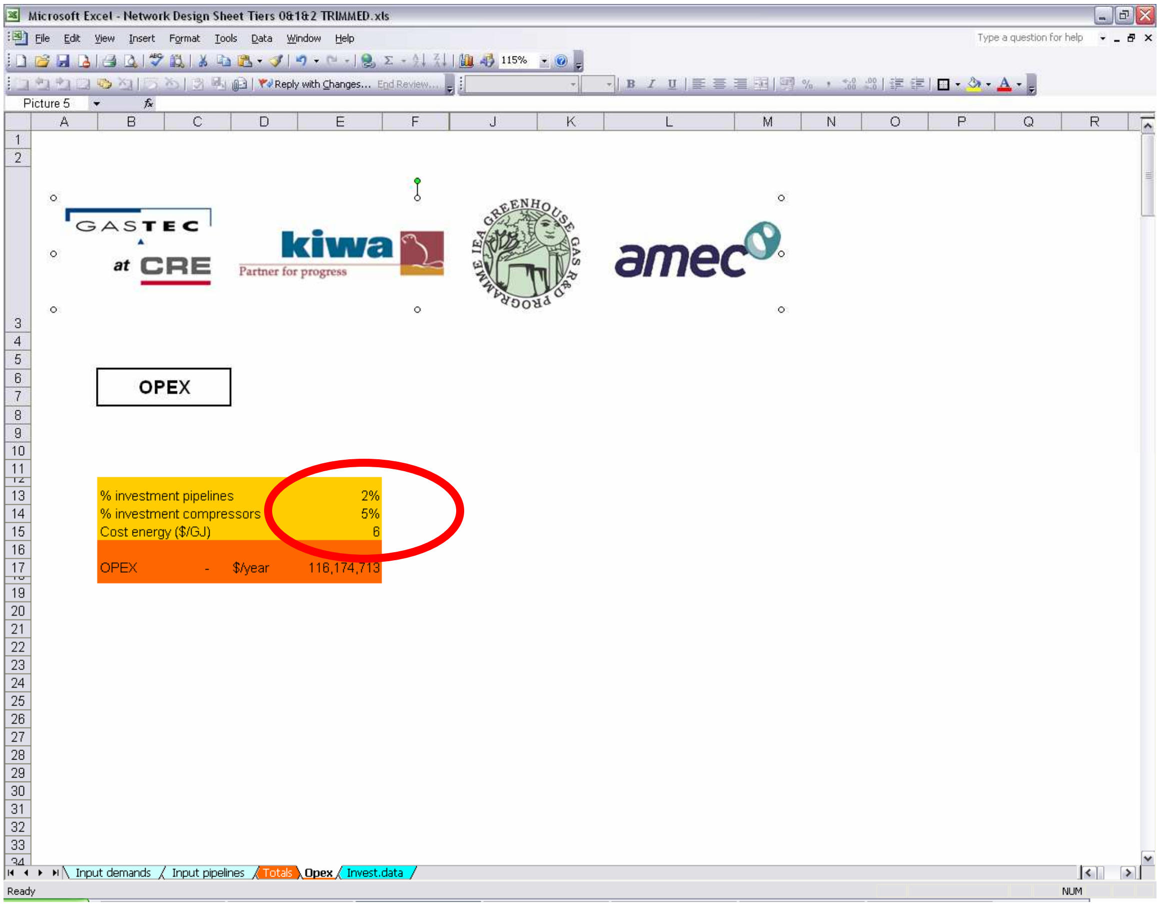
From this tab the plant lifetimes and interest rate can be changed depending upon the particular circumstances applicable to the network being designed.



	Investment	Lifetime
Pipelines	$356,310,915	30
Crossings	$1,841,100	30
Separators	$48,000	30
Compressors	$1,375,314,107	25
Suction system	$40,899,548	30
Meters	$17,084,262	25
Valves	$15,537,984	30
Drying	$154,314,784	25
Total	**$1,961,350,701**	
Interest rate	**5.0%**	
OPEX	**$116,174,713 /year**	
Capital cost	**$136,715,866 /year**	
Total	**$252,890,580 /year**	
Total	**$12.83 /ton**	

Next ensure that the **“Opex”** tab is open.

From this tab the operational costs can be estimated. It is possible to change the percentage operational cost from capital cost and the cost of energy for compression.

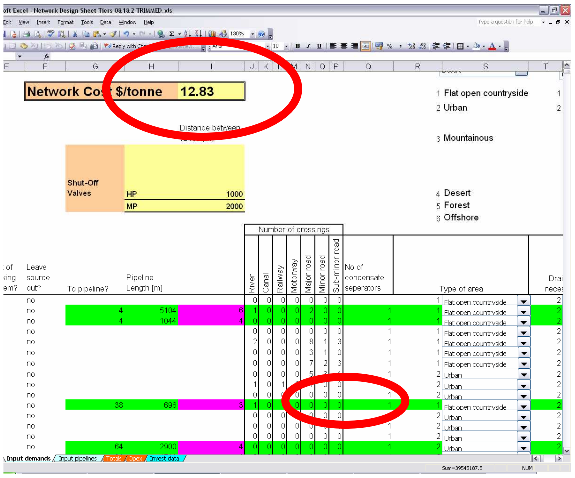


OPEX

% investment pipelines			2%
% investment compressors			5%
Cost energy ($/GJ)			6
OPEX	-	$/year	116,174,713

Your network should now be complete.

The total cost of transportation for the network per tonne of CO_2 is displayed on the **"Totals"** tab and the **"Input Demands"** tab.

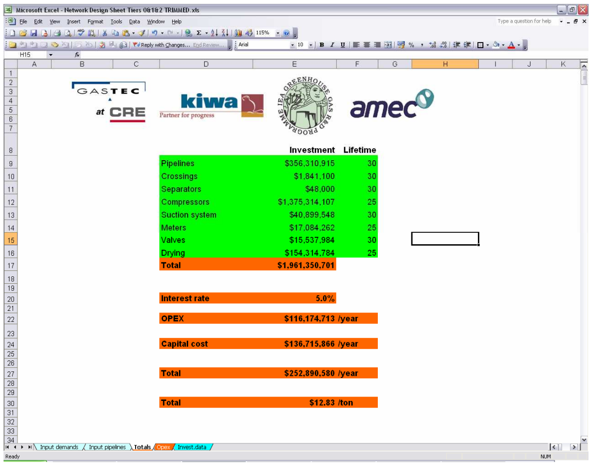


Network Cost $/tonne 12.83

Shut-Off Valves

HP	1000
MP	2000

1 Flat open countryside
2 Urban
3 Mountainous
4 Desert
5 Forest
6 Offshore



	Investment	Lifetime
Pipelines	$356,310,915	30
Crossings	$1,841,100	30
Separators	$48,000	30
Compressors	$1,375,314,107	25
Suction system	$40,899,548	30
Meters	$17,084,262	25
Valves	$15,537,984	30
Drying	$154,314,784	25
Total	**$1,961,350,701**	

Interest rate **5.0%**

OPEX **$116,174,713 /year**

Capital cost **$136,715,866 /year**

Total **$252,890,580 /year**

Total **$12.83 /ton**

Appendix 7 – Network Schematic

Appendix 7: Network Schematic