CARBON CAPTURE AND STORAGE CLUSTER PROJECTS: REVIEW AND FUTURE OPPORTUNITIES

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ACKNOWLEDGEMENTS AND CITATIONS

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Key messages

- The most successful clusters remain those based on the use of CO_2 for EOR application.
- A major obstacle in early years is maintaining a core organisation which is able to carry a CCS cluster project forwards.
- Pre-investment in pipelines and storage may be essential to generate the confidence needed for investment decisions on capture facilities to be made.
- New methods to attract international investment in CCS capacity are needed to exploit the full low cost potential of the best cluster locations.
- Workshops are proposed to explore more systematic development of business plans for CCS clusters with emphasis on customers and revenues.

Introduction

The main objectives of the study are to identify the gaps, risks and challenges faced by regions developing a carbon capture and storage (CCS) cluster, to compare business models with the aim of revealing factors for success and to consider the characteristics which would make new locations suitable for a CCS cluster.
IEAGHG commissioned this analysis to Mike Haines, Cofree Technology Ltd (UK).

Approach

The study was in the form of a literature review and is thus based on publicly available information. A CCS cluster was taken to mean any development which has been proposed or implemented in which multiple sources of captured CO_2 share infrastructure, usually the transport system but also capture and storage facilities. Although this definition would classify as few as two sources sharing as being a cluster, most cluster plans involve a much greater number of sources.

The approach to collecting data for comparison was to construct a database which included fields for technical, cost and business planning information. A preliminary collection of literature was made jointly with IEAGHG staff on the basis of which the most significant clusters for in depth study were identified. A further check was made in four global CCS project databases to identify any other integrated CCS projects which might qualify as being a cluster.

The database was developed essentially as a questionnaire for internal use to aid the search for relevant information. Particular attention was paid to business planning as this is seen as a key element in the eventual success of CCS cluster proposals. To facilitate discovery and collection of information on business plans a modern business planning method was chosen and used to generate the lists of data to be sought for the analysis. The reader is referred to the main report for details of the business planning template which was used. Sources of technical and commercial information were a mixture of scientific papers, published studies, presentations and news articles.

The information collected was used to generate a narrative description of the main technical characteristics of each significant cluster and the status of its business plan. For less developed initiatives relating to CCS clusters more general narratives were prepared. The key references containing the information used are given. Based on this information the technological and commercial gaps, barriers and challenges which stand in the way of development of successful CCS businesses using a cluster approach are explored. Finally the information on development of existing clusters is used to define the attributes of sites and regions most favourable for the development of new CCS cluster businesses.

Results and discussion

Detailed descriptions of the following 12 cluster projects, see also Fig 1, were prepared:

- Rotterdam (ROAD and RCP), The Netherlands
- Skagerrak/Kattegat, Scandinavia
- Alberta (ACTL), Canada
- Yorkshire & Humber, UK
- Teesside, UK
- Collie, Australia
- Denver City, USA
- Gulf Coast, USA
- Rocky Mountain, USA
- Shenzhen City, China
- Marseille (VASCO), France
- Le Havre (COCATE), France

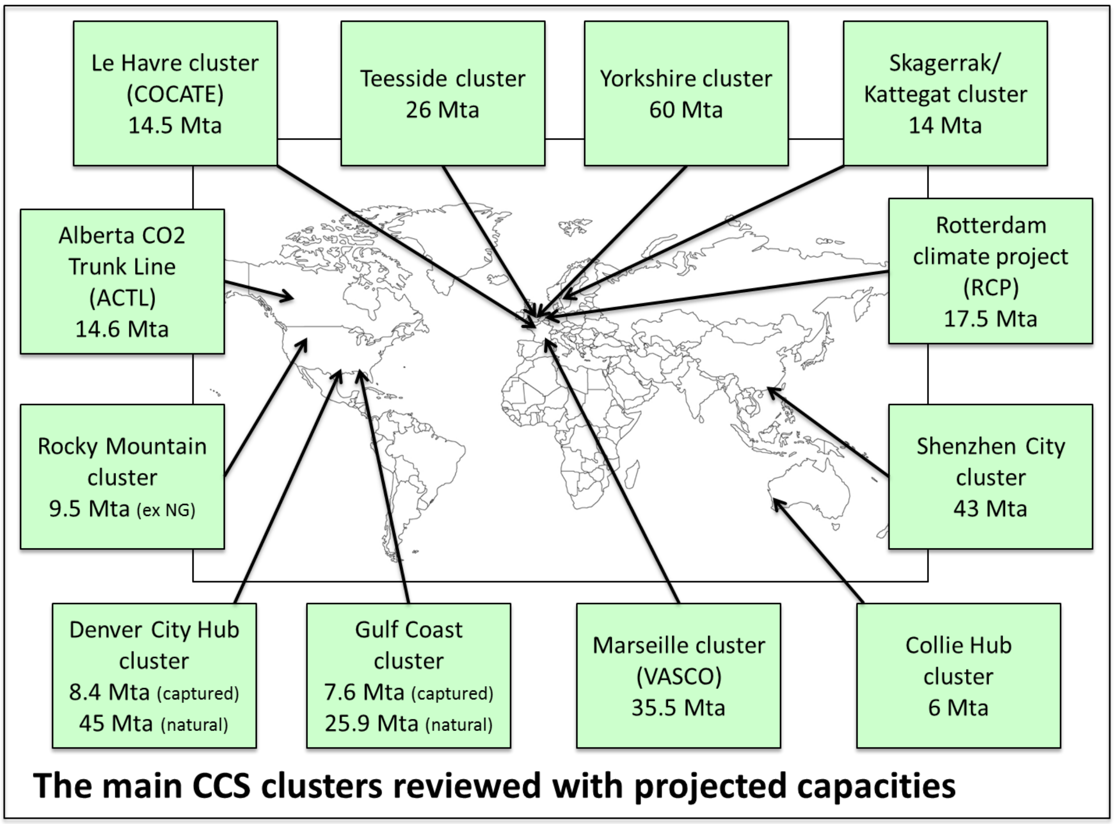


Fig 1 Map of clusters reviewed

The maximum projected CO_2 capture capacity of these twelve clusters amounts to about 272 million tonnes per year. Of this about 17 million tonnes is separated during natural gas production. In addition, approximately 51 million tonnes of natural CO_2 are produced in the two largest USA clusters.
More general information was found on proposals for other clusters in the USA and the Iberian Peninsula and also on the prospects for clustering in Germany.
The individual project details are outlined in the executive summary of the report and will not be discussed further in this overview.

Gaps, risks and challenges

The most important results of this study are the information and insights which can be derived from the analysis and comparison of the cluster projects. These projects range from the mature systems in the USA to projects which are moving through design towards implementation of initial phases to proposals at the early concept stage. This analysis revealed both technical and commercial gaps, risks and challenge which are briefly summarized below.

Gaps

Revenue gap – 50% or more Government support is likely to be needed to implement first stages of cluster projects.
Possible remedies are:

- Use of Contracts for difference (CfD)

- Higher levels of direct State funding
- Coupling CCS with future enhanced oil recovery (EOR) benefits to satisfy World Trade Organisation (WTO) and other State aid rules
- Sell cluster's long term reduction capacity benefits globally (New financial instruments needed and recognized long term international certificate trade.)

Monetizing CO_2 stored through EOR – Whilst technically the monitoring technologies needed are well developed, the measurement, monitoring and verification protocols for CO_2-EOR need to be established so that tradable emission reduction certificates can be generated and monetized when CO_2 is stored during an EOR operation.

CO_2 shipping – Shipping forms a part of several cluster plans mainly to aid incremental expansion and to access remote sources and sinks. Also shipping may play a role in offshore EOR. Some development is needed to deploy large dedicated CO_2 ships.

Offshore EOR – Cheaper and more flexible methods for implementing offshore EOR to tap revenues from this resource.
Possible solutions are to:

- Develop floating EOR systems
- Develop rapid CO_2 ship to EOR unloading and CO_2 reheating systems

CO_2 pipeline safety – Larger inventories of cluster transport networks will increase risks. Cost effective methods to model and minimize releases and to monitor integrity need to be developed although these are already issues for smaller point to point projects.

Risks
The main risks for clusters are commercial. The following were identified and options to reduce them are discussed in the main report:

- Collapse of CO_2 reduction certificate prices
- Major CO_2 pipeline accident in the industry
- Loss of customers and/or withdrawal of a key partner
- Loss of a storage site
- Extensive delays in implementation
- Failure to gain key permissions
- Alternative EOR methods become more cost effective

Challenges
The following commercial challenges were identified and are discussed in the report:

- Business organisation – Finding the best way to organise diverse partners with different interests and expertise.
- Business globalisation – Finding ways to market the low cost advantages which clusters have to a wider clientele than that of the local businesses. Finding ways to deploy cluster expertise in multiple cluster locations.

- Maintaining momentum – Funding the core organisations for the extended period needed to proceed to implementation and retaining high calibre staff.
- Enabling incremental expansion – Finding ways to allow sources to commit to emission reductions incrementally to reduce their risks.
- Setting up specialist services – Providing more efficient specialist services on a global scale rather than having them in house.
- Managing confidential data – Finding ways to collect key but commercially sensitive data about emission sources.
- Identifying and connecting with "customers" – Broadening the customer base from those with emission sources to all stakeholders with interests in emission reduction.
- Developing EOR and storage businesses together – Tackling the diverse interests of those engaged in emission reduction and EOR activities including the widest definition of stakeholders.

Business cases

The key elements of the 12 cluster project business cases are discussed and assessments made of the maturity of each element. A dashboard representation of maturity is also presented for each cluster similar to the example in Fig 2. This enables a high level overview of each cluster's business plan maturity to be seen at a glance. Details of the categories and scoring are in the main report. In general it was found that the customer/revenue plans are less developed than plans for resources and costs. This is understandable because of the technical complexity and novelty of the CCS industry and because the elements are more difficult to address.

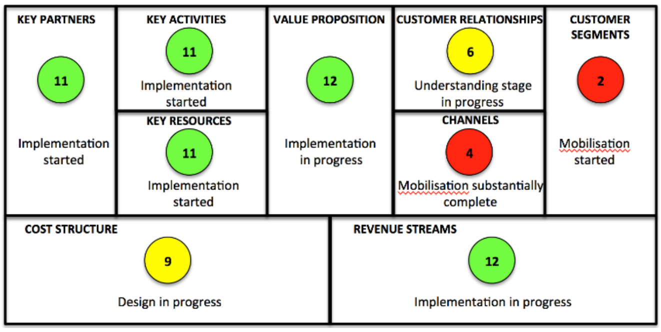


Fig 2 Example business plan dashboard

New CCS cluster locations

The report describes positive and negative factors which influence where new CCS clusters may develop. Amongst these are existence of opportunities for CO_2-EOR and countries amenable to provision of substantial State funding. Availability of CO_2 from gasification and a general low cost CCS chain arrangement of sources and sinks are other positive factors. Negative factors include regions where heavy industry is tending to migrate and where discovery of shale gas offers an alternative method of emission reduction. Mexico, Indonesia, oil producing regions of Russia and the countries of the Former Soviet Union and certain locations in China appear to best fit the criteria for new CCS clusters.

Expert reviewers' comments

The draft report was reviewed by five experts. Their impressions of the report, particularly the insights into business plans, were positive. They also provided useful additional information about some of the clusters which was incorporated into the report. Some reviewers commented that they felt that the report underestimated the value of underlying Government fiscal support through regulation and taxation rules which underpinned the development of CO_2-EOR clusters in the USA more than might be apparent at first sight. A number of other points were raised. It was suggested that use of a discount rate of 10% for evaluating pre-investment in pipeline infrastructure was too high and that a lower rate should be used for such strategic investments. It was also suggested that there is a significant but less tangible value in the pre-investment in pipelines and storage, as bringing these into existence generates the confidence needed for investment decisions on capture facilities to be made. Reviewers felt that a number of the issues covered in the report applied equally to point to point projects and that it was not entirely clear which were related to cluster projects alone. The text was modified to make this clearer. As a result of comments, reference to the recently published work by the Zero Emissions Platform (ZEP) on business models for transport and storage was added.

Several reviewers were concerned about how the emergency response zone proposed for the Alberta CO_2 Trunk Line was described in the draft text. The text was modified to make the purpose of the zone clearer. This raises the important issue of public confidence and information in relation to pipeline safety. In particular that the size of the area within which it would be responsible to publicise emergency plans will be much larger than that in which significant risks are present.

One reviewer felt that more specific recommendations could be made in relation to Government policy to provide more balanced support for CCS in the context of the integrated energy system and for extension of such mechanisms as feed in tariffs to cover CCS. However this is beyond the remit of this report.

Conclusions

The most successful clusters remain those based on the use of CO_2 for EOR application. Whilst clustering may slightly reduce costs, the savings are insufficient to fill the cost - revenue gap so that substantial Government support in one form or another will be required.

The cost savings which a CCS cluster can make from sharing pipelines and storage are relatively small but there is potentially a much larger value in this pre-investment as it will generate the confidence needed for multiple sources to plan and implement CO_2 capture. Savings from sharing are much greater where pipelines are offshore or long but locations which have to use such routes are less attractive because of the extra transport costs. Further savings may accrue from sharing organisational costs, gaining public acceptance and providing specialist services. Clustering does not appear to offer direct reductions in the cost of capture particularly for the major sources in a cluster. There may be some potential for reductions for smaller sources if these can be aggregated into larger capture facilities or if these can utilize hydrogen as fuel from a centralized pre-combustion capture facility.

A major obstacle in early years is maintaining a core organisation which is able to carry a CCS cluster project forwards. This can only be overcome if long term funding is committed so that key staff can be engaged and retained. In the long term the costs of this will be minor compared to the total investment in a CCS cluster.

Promising CCS cluster locations should be in a position to attract international funding and not just rely on providing the CO_2 capture service on a local basis. Mechanisms and structures to allow this widening of support are absent and need to be put in place for CCS clusters to succeed. The prospect of buying-in long term to the lowest cost emission reduction opportunities should be very attractive to some organisations with long term vision and financial capacity. Instruments to facilitate such cross border investment in low emissions need to be developed. Not only would these promote such long term investment, they would also allow much smaller tranches of capacity to be shared and risks to be spread.

Recommendations

The results and conclusions of this study lead to the following recommendations regarding future activities that IEAGHG can initiate:

1) Commission a study with a leading specialist financial institution to propose and develop financial instruments and forms of contract which would allow long term investments in CCS clusters and their lifetime benefits to be traded and exchanged internationally.
2) Promote more systematic development of business plans for CCS with emphasis on customers and revenues to complement efforts being made on technical, environmental, safety and public acceptance issues. Workshops and webinars are suggested as the most effective means of initiating this collaboration.

Carbon Capture and Storage Cluster Projects: Review and Future Opportunities

Executive summary

Information on carbon capture and storage (CCS) cluster projects has been collected and reviewed with a focus on the maturity of their business plans. The study was based largely on literature in the public domain and a few enquiries to ascertain current status. Some valuable additional material was also obtained from expert reviewers of the study. Sufficient information was found to review 12 clusters in depth and a number of other less developed clusters at a more general level. Based on the results the gaps, risks and challenges faced by those developing CCS cluster projects are described. Some criteria for selecting additional cluster locations are developed and recommendations for increasing the likelihood of success are put forwards. The data and references were gathered in a working database to facilitate comparisons. A CCS cluster is taken to mean a location where the opportunity to cluster sources and/or sinks for CCS has been identified in published literature.

Cluster locations

Clusters centred on 12 locations were reviewed in depth in so far as information was available and are described in detail. They are shown in the Table 1 below. Capacities are of CO_2 captured per annum. Several other clusters were identified but as less detail was available these are given summary descriptions.

Table 1 Clusters investigated in depth ** In brackets natural CO_2 capacity*

CLUSTER	COUNTRY	CAPACITY Mta of CO_2	INCEPTION DATE	MATURITY
Rotterdam (RCP)	Netherlands	17.5	2006	Concept
Skagerrak/Kattegat	Sweden/Denmark/Norway	14	2009	Study
Alberta (ACTL)	Canada	14.6	2006	Construction
Yorkshire & Humber	UK	60	2010	Study (FEED)
Teesside	UK	26	2010	Study
Collie	Australia	6	2011	Concept
Denver City	USA	8.4(45)*	1985	Operating
Gulf Coast	USA	7.6(25.9)*	1999	Operating
Rocky Mountain	USA	9.5	1986	Operating
Shenzhen City	China	43	2011	Identified
Marseille (VASCO)	France	35.5	2010	Study
Le Havre	France	14.5	2010	Study

Time lines were created where enough information was found and are shown for 8 of these clusters in Figure 1.

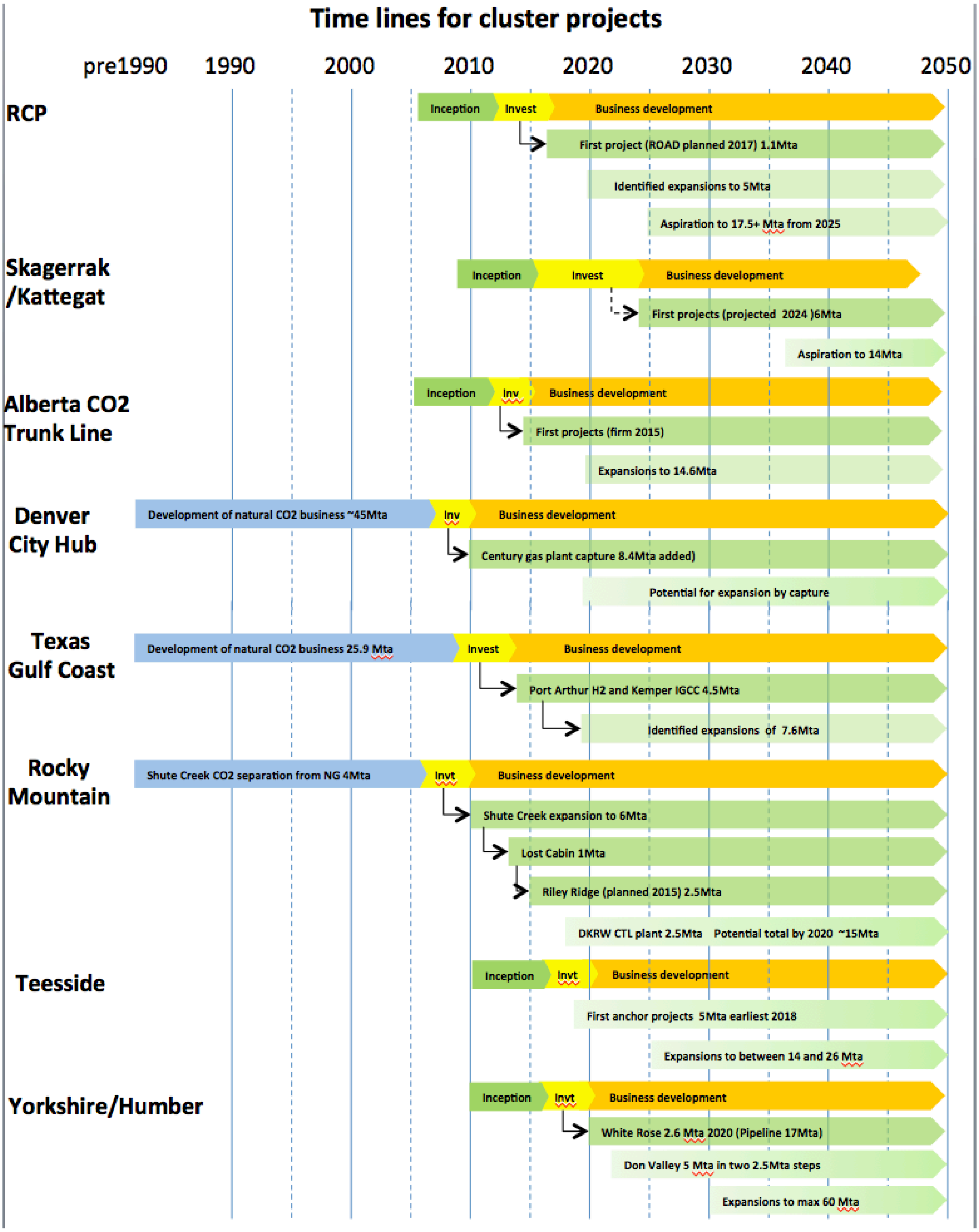


Figure 1 Time lines of 8 cluster projects

The most mature clusters are those based around natural CO_2 networks in the USA established for CO_2 enhanced oil recovery (CO_2-EOR). These are now starting to expand with some additions of anthropogenic captured CO_2 and most started as small systems which expanded as more EOR projects were implemented. Alberta is close to starting up the Alberta CO_2 Trunk Line (ACTL) system which is planned to become a major cluster again based on CO_2-EOR. All the other projects are at a much earlier stage and rely for the most part on emission reduction credits. They have all started as cluster concepts although initial implementation often involves a point to point anchor project. A number of other clusters have been identified at high level in the literature.

Cluster capacity build-up

The capacities shown in Table 1 are indicative of projected system capacity but are not strictly comparable. For the less mature projects these are indicative of what might be available to capture whilst, for the mature systems in the USA, they indicate the current or near term expectation. The three systems in the USA are under-pinned by transport of very large amounts of naturally occurring CO_2 and some CO_2 separated from natural gas. This latter could be regarded as being naturally occurring as it is not produced by combustion or through chemical reactions in other industrial processes. The published material on CCS clusters often shows phased build-up or presents several scenarios where increasing fractions of CO_2 emissions in the cluster region are captured. Most clusters include a mix of industrial and power plant sources with the industrial sources smaller and more expensive to capture. The quantities are displayed in the Figure 2 below and occur in the assessed order of maturity.

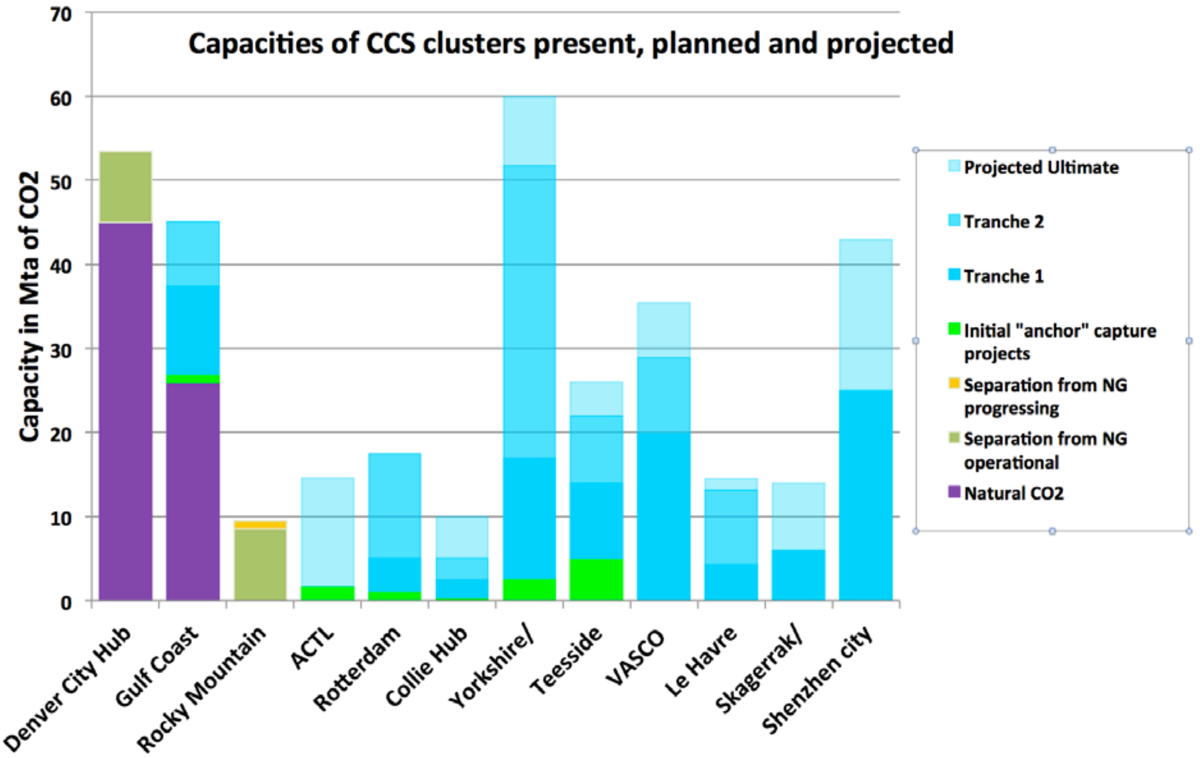


Figure 2 Capacity build-up of 12 clusters

Clusters which are closer to realisation have often identified a first anchor project phase and these projects are shown in bright green in the chart. The naturally occurring CO_2 is indicated by purple bars and CO_2 separated from natural gas by dark green bars. Progressively lighter shades of blue bars indicate tranches of proposed capacity based on figures from the scenarios. The expectation is that the likelihood of implementation of larger capacity scenarios is progressively lower.

It is difficult to draw any firm conclusions from the pattern. Clearly the financial risks are such that most clusters appear to plan for a small start with an anchor project with the potential large longer term capacity a spur to making the initial steps. Additions of captured CO_2 capacity to the US clusters are also relatively small compared to current throughputs. Some studies have evaluated projected capital costs savings for shared pipelines and have also considered the economics associated with underutilization of capacity in early years. Indications are that reaping the rewards of economies of scale often mentioned in the context of CCS clusters may prove to be difficult to achieve in practice.

Gaps in CCS technology

There are a few gaps in the technology required to implement CCS clusters. Effective and accepted safety measures for large supercritical pipelines, particularly in more populated areas, need to be developed. This is particularly important for clusters as these will have much higher capacities than point to point projects. Shipping appears to be an important element of many clusters as it helps to overcome the problem of underused pipeline capacity during expansion. Development not only of refrigerated, pressurised CO_2 ships but also cost effective ways for these ships to discharge and condition their cargoes into storage reservoirs is required. EOR is likely to be an important element of clusters because of the revenue it contributes. Methods for metering and verifying CO_2 stored during EOR need to be developed in order to be able to be able to bank emission reduction credits. Cost effective technology to take CO_2-EOR offshore, perhaps through use of floating production systems which can be redeployed, is needed in order to take advantage of the revenues which this can generate for cluster projects.

Gaps in commercial viability

The main gap is in the revenue which emission reduction generates. Traded carbon price alone seems insufficient to support CCS whether as clusters or point to point projects. A major factor remains the high cost of capture but this is largely a technical issue and one which is only likely to see incremental improvements. Two ways in which this gap could be bridged commercially identified by the clusters are through long term Contracts for Difference (CfD) with Governments and through much greater State funding. A major obstacle to either of these is competition regulation in the form of World Trade Organisation (WTO) rules and State aid regulations such as those applied by the EU. The report suggests that in the case of CCS, especially if coupled with long term benefits from EOR royalty revenue to the State, much larger contributions from Governments could be forthcoming without running into State subsidy issues. This need for stronger Government support is in line with conclusions reached in a report on business models for commercial CO_2 transport and storage recently issued by the EU Zero Emissions Platform (ZEP).

A further gap is the lack of a market for long term options. At present CO_2 reduction certificates in the EU emissions trading system (EU ETS) can be traded up to 2020 and most trades are for dates much closer to the present with the main driver being fulfilling the current year's emission obligations. The benefits of a CCS investment will be available for up to 40 years by which time the value of reductions could far outweigh the costs. Mechanisms to make these long term options available to a much larger investment community would greatly help in raising the finance needed to implement CCS cluster projects. Large cluster projects may be in a stronger position to bring influence to bear to close the commercial gap.

Risks

The main risks for clusters are commercial. The following were identified and are discussed in the main report.

- Collapse of CO_2 reduction certificate prices,
- Major CO_2 pipeline accident in the industry,
- Loss of customers,
- Loss of a storage site,
- Withdrawal of a key partner,
- Extensive delays in implementation,
- Failure to gain key permissions,
- Alternative EOR methods become more cost effective.

Each of these could seriously threaten the viability of the ongoing business. Measures can be put in place to ameliorate the results of most of these events and are discussed in the main report.

During the review process the commercial risk of pre-investment in oversize pipelines was highlighted. It was pointed out that whilst such pre-investment is a risk to the commerciality of a pipeline system if capacity is not taken up within a few years, the potential value of the confidence generated by pre-installing the capacity and assuring the availability of storage also needs to be considered. Without this confidence investment in the capture elements of the cluster may not progress. The pre-investment may thus be a critical precursor. It is a significant part of the transport and storage costs but is a much smaller proportion of the total cluster cost.

Challenges

Based on the literature reviewed the following, largely technical, challenges were identified:

- System optimisation
- Waste heat utilisation

- CO_2 specifications
- Project management

It will be important to be able to optimise the costs of a CCS cluster over the full range of timescales. Methods for optimisation are available but the challenge will be to apply them successfully to the CCS cluster system. Waste heat utilisation from industries (not power plants) was identified in the Scandinavian cluster as having considerable potential to reduce operating costs. Taking advantage of this opportunity will be an engineering challenge because of the deeper integration of capture plant with the industry which this will require. CO_2 specifications which are technically sound, not unduly onerous and accepted by both capture plants and storage have to be established. It will be a challenge to do this at minimum cost especially where a range of capture processes are employed and there is a range of storage destinations.

Finally the management of a complete cluster project will be complex and the technology is quite diverse. Different parties may have different standards. Setting up an appropriate organisation with the correct choice between centralisation and dispersion of the project management tasks will be a challenge.

There are also commercial challenges which are greater than the technical ones:-

- Business organisation
- Business globalisation
- Maintaining momentum
- Enabling incremental expansion
- Setting up specialist services
- Managing confidential data
- Identifying and connecting with “customers”
- Developing EOR and storage businesses together

If the project management task is a challenge then setting up the interlocking businesses which will run a cluster is a greater one as this extends into the operational phase. There is a whole spectrum of possible organisations from a central business running the entire chain to specialist businesses for each part of the chain and support requirements. Business organisation of CCS has been discussed and compared with approaches in related industries in a number of publications.

Many of the services required in a CCS cluster project could be provided on a global basis to a number of clusters. The provision of CO_2 shipping is one example where the possibility of an international rather than a localised business has been suggested. Such globalisation would bring considerable benefits in the form of access to expertise and in economies of scale. It remains a challenge to set up such globalised businesses to serve CCS clusters and point to point projects because the industry is in its infancy, is thinly spread and thus tends to be served by locally based enterprises. One of the key lessons from the Rotterdam clusters is that momentum will have to be maintained over a long period in order to realise a CCS cluster project. How to attract the funding and people needed for this continuity remains a challenge.

Of the other commercial challenges, that of successfully identifying and connecting with all the "customers" is perhaps the most important. Because a cluster may involve interlocking businesses many elements will be both customer and supplier. However, the problem is wider because the ultimate customers for CO_2 reduction services are also National Governments (they are negotiating reduction commitments through the UN process), individual citizens and organisations of all sizes within countries. Additionally, those who might provide funding should also be considered as customers when analysing and setting up the business. As CO_2 can be traded the customer base for a particular cluster could also be considered as global. To be able to identify, classify and tap in to all customers should greatly enhance the chances of success.

Future cluster locations

The final part of the scope of this study was to consider how to identify other locations where CCS clusters could be set up. Several studies have given indications of those locations where the juxtaposition of sources and sinks makes clustering interesting. This can be the starting point but much more than this juxtaposition is needed for a cluster to be viable as a business. Table 2 summarises positive and negative factors relevant to development of CCS clusters.

Table 2 Factors for and against development of CCS clusters

FACTOR	EXPLANATION
POSITIVE	
Mature oil fields onshore.	Is a major revenue source
Competitive CCS situation.	Basic costs need to be competitive
Gasification opportunities	Where needed for other operations gives low cost capture
State controlled industrial sector	Easier to implement large centrally planned projects
Relaxed attitude to State funding	Easier to close the funding gap
Affordability of state funding	More likely that State can afford to contribute
Receptive to foreign funding	Widens scope for obtaining funding
Ability to attract capture sources	Strong local trade organisations should make this task easier
Cheap coal due to shale gas	Emission increase due to fuel switching/retaining coal plants
NEGATIVE	
Shale gas etc. changes fuel mix	Introduces great uncertainty into long term emission sources
Migration of heavy industries	Existence of this trend leads to loss of emission sources
Increasing power intermittency	High renewables reduces fossil power plant stream factors

Several attributes have been identified which can be used to further filter out those places where clusters could be developed. Shale gas has made coal cheaper making it more attractive for some locations to switch to coal increasing pressure on them to decarbonise.

The study notes that Mexico, Indonesia, oil producing regions of Russia and the countries of the Former Soviet Union and perhaps other locations in China could be locations which fit the criteria in favour of developing CCS clusters.

Conclusions and recommendations

The most successful clusters remain those based on use of CO_2 for EOR. The funding/cost gap for CCS purely for emission reduction is currently an insurmountable obstacle to large scale CCS deployment, whether as clusters or point to point projects. The cost reduction benefits of combining infrastructure are mainly in reducing the cost of transport by pipeline because of economies of scale. However, the reductions are small compared to the overall CCS chain cost. Furthermore a failure to utilise capacity within a few years would negate any economic advantage. At the same time it may be that pre-investment is essential to generate the confidence needed for the emission sources in the cluster to progress their plans for capture. Other significant benefits could result from sharing organisational costs, arranging permits, gaining public acceptance and pooling specialist services but are difficult to quantify. The cost reductions are greater for offshore pipelines because of the high mobilisation and laying costs and are also greater when there are long distances from source to store. However, both offshore and long distance routes make cluster locations less attractive. In Europe onshore storage may prove to be unacceptable so that the advantages of clustering will be greater.

A major obstacle in early years is maintaining a core organisation able to carry a cluster project forwards. This can only be overcome if long term funding is committed so that key staff can be engaged and retained. In the long term the costs of this will be minor compared to the total investment in a CCS cluster. Those countries which clearly have a long term competitive cluster location should consider setting up and funding the necessary core organisation for as long as the project takes to come to fruition.

The more mature clusters all rely on CO_2-EOR and do not yet derive revenues from emission reduction. The newer clusters can learn from the technology deployed in the more mature systems but need to develop their own business models. Some knowledge on how to monetize emission reductions may be transferable to the more mature clusters in due course. As clusters based on emission reduction progress it is clear that their layout often differs significantly from that set out in earlier plans and maintaining the long term master plan becomes less important to the project partners than implementing the critical initial phase. This reinforces the case for ensuring that a core organisation able to manage the long term vision is adequately funded.

Good cluster locations should be in a position to attract international funding and not just rely on providing the capture service on a local basis. Mechanisms and structures to allow this widening of support are absent and need to be put in place for clusters to succeed. These could include financial instruments to allow shares in future capture capacity and the associated emission reduction benefits to be purchased.

1 Contents

List of figures and tables

2 Introduction

CO_2 capture and storage (CCS) has the potential to contribute significantly to reductions in greenhouse gas emissions. The IEA 450 ppmv scenario suggests as much as 17% of required emission reductions could be through application of CCS. The obvious advantages of sharing the infrastructure, particularly for transport and storage, have been recognised. A number of initiatives have already been started in locations around the world to explore clustering of CCS facilities and to bring CCS to commercial reality in these places. Worldwide there are more than 200 CCS projects ranging from small scale R&D to larger scale demonstration. These projects cover capture, storage and in some cases the complete CCS chain. These CO_2 projects are extensively summarized in several databases maintained by leading institutions. This review looks at the literature and development plans for CCS projects where formation into a cluster format is envisaged. A CCS cluster is "A location where the opportunity to cluster sources and or sinks for CCS has been identified in published literature". Such plans usually envisage connecting up multiple CO_2 sources and maybe multiple sinks from the start or may plan for an initial point to point project, often referred to as an "anchor" project, designed to evolve into a CCS cluster later.

There are several reasons for adopting a cluster. The main one is the perception that the cost of transport pipelines or shipping systems will be significantly reduced. Similarly, but less recognised, is the potential reduction in costs for organisation, permitting and public engagement. Another is to promote locations as low carbon dioxide emissions centres to attract and retain industry. In some cases the reasoning is subtly different, e.g. that reductions of emissions are necessary to retain the licence to operate in a region. A further reason is that setting up the CO_2 collection infrastructure will allow smaller emitters to join initially or later at acceptable cost. Finally a compelling reason is the unlocking of depleted oil reserves through CO_2 EOR which boosts the regional economy. EOR projects do not have a long term steady off-take. Clustering of multiple sources, EOR projects and the presence of non-EOR sinks will help to smooth out imbalances between supply and demand.

The main objectives of the study are to identify the gaps, risks and challenges faced by regions developing a CCS cluster, to compare business models with the aim of revealing factors for success and to consider the characteristics which would make new locations suitable for a CCS cluster.

3 Approach

3.1 General

This review identifies all locations where formation of a CCS cluster has been documented in literature. Information on each cluster is collected into a comprehensive template which has been developed not only to capture the key technical details but also to consider the extent to which a viable business plan has been developed. Preliminary investigation of the literature did not reveal any publications of fully integrated business plans for clusters. This is not surprising and is due to the fact that no clusters are in commercial operation as businesses apart from the EOR-based systems in the USA which do provide some information for investors. Also it is likely that when this stage is reached the business plans for the cluster may be largely confidential. Thus the information about what the cluster business plan is likely to include has to be extracted from the literature.

For information relating to the business plan the template includes all those elements which would be necessary for a strong commercial business to be operating. This will expose not only what is in place but also what would still be required to go commercial on a sustainable basis. The business plan data set is based on the work of Osterwalder (1) which defines a business model canvas of 9 key complementary areas. These are broadly divided into those concerned with providing the business offering and those concerned with establishing customer relationships and creating revenue. In the business offering category are defining:-

Partners, Activities, Resources and Cost structures.

In the customer and revenue category are defining the:-

Value proposition, Customer Relationships, Communication channels, Customer segments and Revenue streams.

The analysis also includes an assessment of the maturity of the business case development using the five stages: - Mobilisation, Understanding, Design, Implementation, and Management as proposed by this author. The maturity of each of the nine elements is assessed individually. An overall maturity assessment is also made based on these individual element assessments. The technical details for each cluster cover all of the key parameters relating to size, location, routing, technology choices, engineering and operation. In addition information on overall and unit costs is collected where available.

The information is reported in narrative form for each potential cluster location and has been collected as entries in a comprehensive database. As early analysis revealed that cluster projects are being started by smaller semi-commercial systems which appear to rely on substantial Government financial support, the review analyses literature on both the initial system proposals and the full cluster proposals separately where appropriate. The business case for the initial system is thus a subset of that for the much larger cluster. Also the maturity of the initial enterprise is naturally far greater than that of the proposed cluster. This is because there will be many more opportunities for strategic alliances, supply of specialised support services etc. for a CCS cluster than for the initial enterprise. These aspects will likely not figure in the business plans for the initiating projects.

Many potential CCS cluster projects have yet to be developed beyond the stage of initial identification of possibilities. The detailed analysis of such cluster projects is not appropriate and thus a much reduced set of data on these is collected. This included identification of the best options in the regions considered and collection of basic data on capture capacity, transport distance and potential storage capacity. Where available data on costs is also collected.

3.2 Business case analysis

The first stage of the analysis is to extract as much data as possible from the literature about the 9 individual components of the business plans. The entries for each component are essentially a list and the expectation is that every cluster will have similar entries. For example common value propositions and revenue streams are to be expected. The database thus includes a set of standard fields based partly on preliminary examination of the more advanced projects but also on Osterwalder et al's own suggestions as to what types of value proposition could be offered. For each field the simplest is to record a Yes or No as to whether the item is included. This method has the advantage that comparisons and analysis across all clusters is then easy to carry out. However simply recording a "Yes" or "No" does not accurately describe the state of play. For example one motivation mentioned in official documentation for building a capture plant is the "wish to be in the forefront of the technology". This falls under the general heading of "Newness" which is one of Osterwalder's proposed types of value proposition. Simply recording a Yes does not give enough detail to appreciate what aspect of "newness" is being valued. Thus a second parallel field is often included into which a short narrative text can be included in the database.

As data collection proceeds it is inevitable that additional common elements will be found and when this happens additional fields are created in the list.

The narrative explains what, according to the literature available, has been planned or implemented in each of the 9 elements of the business plan. A general discussion on the completeness or otherwise given the overall maturity of the cluster is then given. Below are the main items which would be expected are summarised for each element.

3.2.1 Key Partners

In a successful business plan all the necessary key partners should be identified and the nature of their relationships and responsibilities clearly formulated. The degree of detail will depend on the maturity of the plan. Some elements of the relationships are of particular importance and include the governance of the overall enterprise, whether partners are horizontally or vertically integrated and who is responsible for financial and operational risks.

3.2.2 Key Activities

There should be clarity in the plan on all of the activities which need to be undertaken. In a mature plan there will be a host of supporting activities which some organisation has to perform. Certainly in the more advanced cluster projects a host of detail was found of less obvious activities such as obtaining permits, insurance, rights of way etc. all of which are essential for the CCS chain to function as an effective business. The discussion for each cluster will include a general review of items which may have been overlooked.

An activity which can be key is the acquisition of funding and the setting up of the cost and revenue structures which are separate elements described below. A distinction should be made between the key activities and resources (see following) needed to do this, which could be significant, and the definitions of the cost structure and revenues.

3.2.3 Key Resources

This is closely related to the Key Activities but covers the physical resources which have to be acquired in order to operate. For example a pipeline and compressors may be part of the resource whilst the task of operating and maintaining the pipeline is part of the necessary activities. Resources can also be in the form of services. The discussion on the resources defined as needed for the cluster will also include a general review of any which have so far been overlooked.

3.2.4 Cost structure

The cost structure should define all of the capital and operating costs which the venture will incur and as such it is essential that all of these are recognised and quantified by the time the business is up and running. Anything missed out can seriously affect the bottom line especially if it is found to be difficult to recover such costs via revenues. Some cluster projects have already identified and estimated such things as long term liability provisions even though these may only be incurred very late in the life of the enterprise. Because costs for the full CCS chain are high, any structures which reduce them are of particular interest. Anything which is mentioned in the literature in this respect will be included in the narrative. The discussion will thus include an assessment of how well the cost structures cover the full spectrum, note any novel or valuable cost reducing methods and where novel methods from other clusters might be usefully applied.

Many of the individual cost elements which will arise are known to the emerging industry. Abandonment, MMV (Monitoring, Measurement and Verification) of storage sites, provision of emergency response capabilities, CO_2 fiscal metering, CO_2 injection conditioning, well work-overs, ROW (Right of Way)and land acquisition etc. all add to the cost and will need to be understood in order to create a viable business plan.

3.2.5 Value propositions

The very basic proposition for CCS is that it will provide an emission reduction at a lower price than emitters will have to pay to comply with whatever regulations, taxes, emission certificate purchases etc. apply. However there are potentially many other supplements to this basic proposition. In the case of CO_2 supplied for EOR the emission reduction value proposition may be far exceeded by the value of extra oil production. This may however detract from the perceived value of accompanying emission reductions due to anthropogenic CO_2 storage because of the different positions of potential customers. Within the CCS chain there are expected to be opportunities to provide many other things which can be perceived by customers as having value. So far the clusters have tended not to explore this to any great extent but some examples are emerging. Being able to provide seamless transport and storage services is a common theme. Freeing emitters from having to fund and organise this is put forwards as something into which they may well want to buy. Under this heading any "values" which the literature on the clusters appear to put forwards will be described. In the discussion any opportunities which exist in a particular location but which do not appear to have been recognised will be noted.

3.2.6 Customer relationships

This covers the type of relationship which is established with customers. As CCS will involve relatively few large customers these are likely to be in the form of close bilateral contractual relationships once contracts are in place. The relationship in the lead up to a commercial arrangement is also important. The study will consider customers in a wider context than the narrow confines of major emitters seeking to store CO_2 as a means of reducing their emissions. Governments both regional and central have become major contributors and are hence very significant early "customers". Furthermore the consumers of "green products" such as renewable energy can also be classed as "customers". Also within the CCS chain there may be a host of "internal" customers, for example those requiring specialist operational, maintenance or monitoring services for capture plant or storage sites, solvent reclamation services, chemical and utility supply services. These will be covered in the narrative when they are in some way recognised in the literature. The discussion will cover the extent to which the full range of customers and relationships with them have been recognised in business plans.

3.2.7 Customer communication channels

It is critical that organisations involved in the CCS business of a cluster communicate with both active and potential customers. The method and channels by which this is done complement the relationships which are sought with them. This section will thus describe what methods of communication are planned or established. The discussion will review the extent to which these are likely to be adequate.

3.2.8 Customer segments

The fact that there may be different types of customer has already been touched on in the foregoing. Where there are distinct classes of customer it is important that these are recognised and the relationships and communications established accordingly. The extent to which such segmentation has been done will be summarised for each cluster. Discussion will centre on the extent to which segmentation has been carried out and further segmentation might be useful.

3.2.9 Revenue streams

This is the last but possible the most critical element of the whole business plan. This is not only because every business must have revenues to cover its costs but for CCS clusters is even more important because at present there is perceived to be a large gap between what customers might be willing to pay and what provision of the services would cost. Mirroring the need to find structures which reduce costs, any ways of enhancing revenue streams which are mentioned in the literature will be highlighted. Any particularly interesting novel methods will be covered in the discussion. Also the scope for enhancing revenue streams by adopting methods from other clusters will be covered. Revenue is treated in the widest context and does not necessarily have to be regular. Thus grants and one-off payments are considered and may be a significant element of the overall revenue needed to cover costs.

3.2.10 Overall maturity

The second stage of the analysis is to assess the maturity of the business plan. To some extent this will be evident from the assessment of the forgoing elements. However to make this of greater transparency the maturity of each of the 9 elements is assessed separately based on the stage of development which has been identified. Based on these assessments an overall assessment is made. The report aims to provide both a good overview of the results as well as in depth analysis. The levels of maturity have thus been further subdivided into "started, in progress and substantially complete". This has resulted in the following standard scale.

Table 1 Business plan maturity levels

0	Not considered
1	Blue sky idea
2	Mobilisation started
3	Mobilisation in progress
4	Mobilisation substantially complete
5	Understanding stage started
6	Understanding stage in progress
7	Understanding stage substantially complete
8	Design started
9	Design in progress
10	Design substantially complete
11	Implementation started
12	Implementation in progress
13	Implementation substantially complete
14	Initial plan in early management
15	Mature managed plan

The maturity has been represented graphically on the business canvas using symbols coloured as shown to give a quick overview of the assessment of the status.

When reading documentation this approach has proved useful to help question and ascertain the true state of development of the business plans. In order to interpret how these categories apply to each element of the business plan in a consistent way a short description of how each of the 5 main elements apply was developed. This and the full approach to collection and analysis of business case information is explained in full detail in Appendix A.

3.2.11 Technical details

The collection of technical details is comparatively straight forward compared to assessing the business plans. In part this is because such technical data is shared and published more openly. Also much of the basic technical data is in the public domain helped by the extensive support which research organisations, companies and governments have given to development of CCS technology. The basic organisation of the data collection was described above. The level of detail collected about the transport system is given the greatest attention as this is the part of the cluster system most intensively shared. It is also the part where greatest financial savings compared to point to point projects are perceived to be possible. The data set is divided into 4 sections. The first logs general technical information about each cluster and includes a list of which if any of 4 key publically internet accessible project databases maintained by ZeroCO_2Norway, the Global CCS Institute (GCCSI), NETL and IEAGHG the cluster projects are reported in. The other three sections list technical information on capture, transport and storage respectively. A separate list of references which were consulted is also assembled with a brief description of the main contents and sort fields for geographic location, date, key subjects and scope. References on clusters were found at various scope levels, those dealing with clusters on a worldwide level, those looking regionally, those looking at specific clusters and those addressing specific parts of cluster development.

The technical details on capture record as far as possible information about the capture capacity of the cluster. Of interest are aspects of capacity such as variability, build up profile, phasing, all of which are addressed in slightly different ways in the literature. Thus fairly general headings have been created for these items and a range of methods used for displaying the data such as charts, tables using links to documents where appropriate. A few key parameters are developed for expressing the form of the capture capacity portfolio. The mix of source types is another piece of key information which many cluster studies report. This has been recorded as a brief narrative with cross reference to source documents.

No great detail was sought on the detailed choice or design of capture technologies. Some choices are however quite relevant to cluster development for example some clusters are promoting hydrogen or syngas systems as well as CO_2 collection systems to extend the reach of decarbonisation. Oxygen distribution for oxy-combustion is another possibility although no firm proposals for including this in clusters were found. Capture technology choices such as this which help support the viability of the overall cluster have been extracted and documented in the database where they have been found.

Cost and efficiency data is also entered into the database where found. Cost estimates per unit captured along with capture efficiency and the ratio captured to avoid are also recorded if available either as central estimates or ranges depending on what is reported. The date of costs estimates is reported to aid in comparisons and any caveats on the estimating methodology is recorded in narrative form. Costs are also collected for transport and storage with cost per actual tonne as the preferred measure.

The approach to collection and analysis of technical information is explained in more detail in Appendix B.

3.3 References

Information on cluster projects is available from a wide range of sources. The results of initial screening are often reported in scientific literature. However the clusters are commercial enterprises and many studies have had shared funding from governments and large companies and for IP reasons not all of the reports which have been generated are in the public domain. Some clusters present their information on websites. In the more commercialised developments significant events are often reported in business news. The approach taken in referencing is to provide the main reference describing the cluster where this exists and then to identify the other key documents from which information is available, cluster by cluster. The text in this report is intended to give an overview of what this body of literature contains. Readers who wish to know more about a particular cluster and how it has developed over time will need to study these key documents. Many items of information such as capacities, storage locations, and pipeline designs are to be found in several documents and are often changed and refined as the projects develop. Citations are thus not provided for every piece of information as it was felt that this could make the report cumbersome to read. However citations are provided selectively where the source of the information is outside that to be found in the key project documents.

The key document and website is included as a footnote within the text for each cluster for ease of reference. All other references are numbered and listed at the end of the report.

4 Discrete Cluster projects

4.1 Rotterdam CCS Cluster Project (RCP)

4.1.1 Outline

This opportunity is supported principally through the Rotterdam Climate Initiative which is a partnership between the City of Rotterdam, the Port of Rotterdam, DCMR Environmental Protection Agency Rijnmond, and Deltalinqs. (Deltalinqs is an association of industrial enterprises in the Rotterdam area). The initiative started with the objective of reducing CO_2 emissions by 50% and climate proofing the city. Their vision includes a full CO_2 network capturing CO_2 from the power plants and industries in the Rotterdam area and transporting this for storage offshore on the Dutch continental shelf. The vision extends ultimately to beyond the Rotterdam region also to neighbouring countries and beyond the Dutch continental shelf. Within the concept is a first integrated CCS project ROAD (**R**otterdam **O**pslag en **A**fvang **D**emonstratie, *translation: Rotterdam Storage and Capture Demonstration*). This project effectively kicks off the overall cluster initiative and is thus currently the key element. It will be described and analysed separately after information on the full cluster has been discussed.

4.1.1.1 Key information sources

The initiative maintains a website (3) http://www.rotterdamclimateinitiative.nl/en. A series of reports have been published the most recent being entitled “Rotterdam CCS Cluster Project Case study on lessons learnt” (4). Other references for this cluster project are:- (5), (6), (7), (8), (9).

4.1.2 RCP technical description

4.1.2.1 Capture

The proposals fall into several phases. Firstly the anchor project ROAD of 1.1Mta capacity which is a single plant capturing from 25% of the flue gas from a newly built coal fired power station. Secondly a small group of specific projects with loose agreements on co-operation which could capture an estimated further 3.8Mta. Beyond that the Rotterdam area aspires to be reducing emissions using CCS by 17.5Mta in total by 2025. Thereafter it aspires to become a regional hub through which additional CO_2 from other parts of the Netherlands but also Germany and Belgium could be routed. At this stage the full details of what these sources would be is based on available regional emission data. Economic analysis of the longer term development within the Netherlands has been made using a MARKAL model which indicates that by 2050 up to 62Mta might be economically captured assuming free use of available reservoirs onshore and offshore. If restrictions apply this is reduced considerably to a peak of 40Mta or less and declining mainly because of the cost of transport to more distant offshore storage sites. The first project will use MEA post combustion capture. The next tranche of projects include capture from two hydrogen plants using pre-combustion technology and a coal fired oxy-combustion unit. A small addition will be made by connecting up to the existing supply system which distributes captured CO_2 from the Pernis refinery and Abengoa bioethanol plant for seasonal use in greenhouses. The capture technologies which would be used for the later phases are not yet defined.

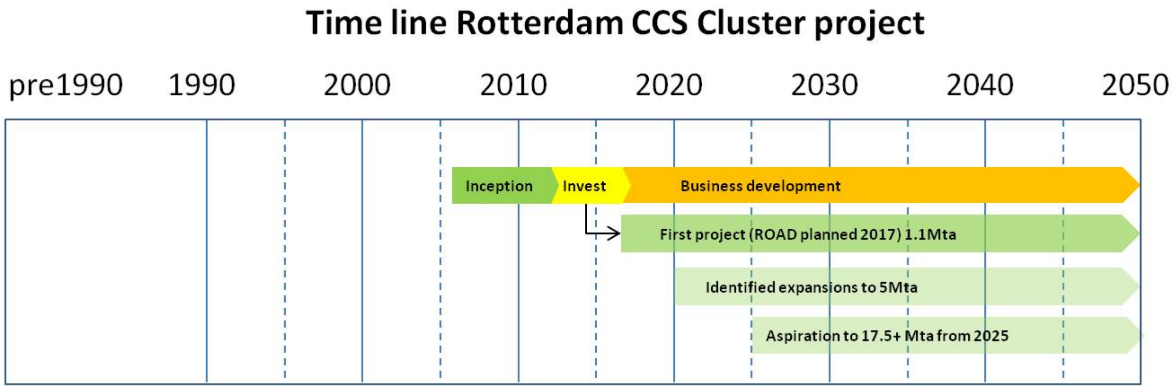


Fig 1 Timeline Rotterdam cluster

4.1.2.2 Transport

The initial transport will be by dedicated pipeline to a depleted gas field about 25km offshore. The pipeline will be insulated along its whole length to ensure the CO_2 is warm enough for injection into the low pressure depleted reservoir. In the next phase the other sources would be connected and use the offshore section of line which will be sized so that it can transport up to 5Mta. There will also be an extension of the reach of the network in this phase and this is expected to be provided by a newly formed consortium of companies trading under the name CINTRA. Some relatively firm plans on the further phased extension of the network to connect to more sources and sinks are published. Analysis of alternative ways to further expand capacity over time has also been performed. This work includes studies of how other potential CO_2 hub locations might evolve and share the transport infrastructure.

4.1.2.3 Storage

Storage capacity has been subject of independent studies conducted by TNO. Initial storage for the anchor project would be in the P18 field reservoirs 6, 5 and 2 with identified capacity of up to 42.4Mt (although 35Mt is more commonly quoted). This field would also suffice for the second tranche of projects.

TNO reported in three separate phases. The first report identified near term opportunities in depleted oil/gas fields available by 2020. The fields P18, K12-B, Q01 + Q01 oil, Q08-A, P06-AB, P06-MP, P15-9, P15-11, P15-13 were studied and found to have an estimated capacity of 254.8Mt. (8). A second report evaluated these fields in more detail. The phase 3 report (5) looks more widely for potential high capacity storage opportunities and identified potential capacity in the Dutch offshore sector over the longer term. It listed a maximum potential of 2160Mta at distances ranging from 40 to 200Km from Den Helder. It estimated minimum development times of 5-7 years for each of the opportunities.

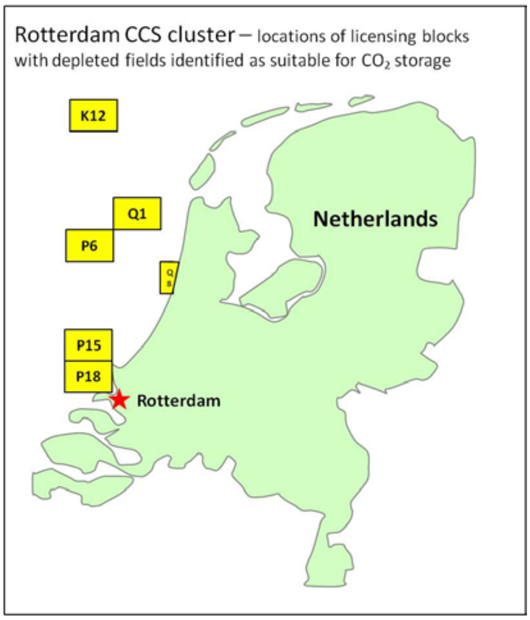


Fig 2 Rotterdam cluster map

4.1.3 RCP business plan

4.1.3.1 General

At this early stage there is no detailed commercial business plan for the various elements of the proposed system. However very clear vision and goals have been formulated and so far there has been ongoing and consistent communication of these.

4.1.3.2 Key partners

The most significant development in business partnership is the creation of the CINTRA consortium of 4 partners to provide "one stop" CO_2 transport services. The other significant partnership relationship is the use of letters of co-operation which have been signed by 9 organisations promising to undertake key studies in exchange for funding of independent assessment of the study results. Apart from GDF SUEZ and E.ON working together to fund the anchor project (ROAD) no other commercial partnerships have been mooted. It is presumed that a relationship will be established with the OCAP system partners feeding greenhouses when this is connected to the new CO_2 transport system. Expectations appear to be that each source would handle its own capture as evidenced by the capture projects which have been announced as potential parts of the second phase. Each of these is in the sole hands of the company with the emission source. The other key co-operation which was instrumental in the initial phase of researching the cluster opportunity is that between the Port of Rotterdam, the City of Rotterdam, the environmental agency and the Rotterdam area employers' organisation Deltalinqs. However the funding for this is now drawing to an end and it is unclear what size and form any central organisation to take the cluster forwards would have and where the funding to keep it going would come from.

Looking to the future it is evident that further co-operations and deeper agreements will be needed for the necessary commercial businesses which will eventually form the cluster to come into being. Potential partners in the CCS cluster enterprise will probably need to commit further ongoing funding for some years to ensure that a core set of organisations can continue in a co-ordinated manner.

4.1.3.3 Key activities

The plans so far simply identify the three main activities of capture, transport and storage. Intermediate storage of liquefied CO_2 at a hub located somewhere in the Rotterdam port area is also envisioned. Details of the many supporting services required have still to be developed.

4.1.3.4 Key resources

Again the plans identify at high level the main physical resources of capture, transport and storage equipment which will be needed but do not go into detail at this stage. Access to funding is a key resource for start-up of such large infrastructure projects and as yet these have not been acquired. Expertise and the capacity to deploy it at the necessary scale is also a vital resource. The CINTRA consortium outlines how the 4 participants bring all the key expert resources required to build and operate the transport system. The consortium members consider that they have in house all of the expertise built up over many years and substantial capacity to undertake the design, construction and operation of the cluster transport system.

Resources in capture and storage on the full cluster scale have yet to be developed and built up. A portfolio of existing depleting hydrocarbon fields has been identified but commercial arrangements to acquire these for use by the cluster have yet to be made. There are plans for several capture plants using different processes to be built and if these come to fruition they will form a part of the clusters resource.

At present it is only the transport element which the RCP is aiming to develop as on integrated business. Both capture and storage would appear to be left for individual parties to develop largely in response to market forces. The exact role of the transportation business in co-ordinating these other elements is not yet clear. The "one stop" principle is described on the basis that the transporters would be responsible for acquiring the storage capacity which their business would demand thus relieving those running capture plants from this responsibility. Business models are possible in which capture services and storage services are integrated but do not yet appear to have been explored.

4.1.3.5 Cost structure

Various studies have evaluated unit and capital costs for the three main elements of the CCS chain. Costs are known in considerable detail for the ROAD anchor project. Further detailing will be required for the next phases.

4.1.3.6 Value propositions

The main value proposition appears to be that Rotterdam is well placed to deliver emission reductions through CCS at a lower cost than elsewhere in the world. Part of this is due to the favourable geography placing sources and offshore sinks close together with relatively easy pipeline routes. Part is based on economy of scale and part on the capacity flexibility which use of CO_2 shipping would provide thus avoiding long periods of underutilised capacity. The cluster also considers that it can contribute substantially to the aspirations of the City and Port of Rotterdam by offering a route to obtaining "low carbon" credentials for the region. This is promoted as something which would be attractive to businesses. Other values which the documentation mentions are acquisition of capture expertise from the early projects and gaining acceptance of coal for power generation. CINTRA in particular places value on offering the "one stop" shop arrangement because this greatly simplifies business for those with emission sources. They also consider that the good reputations of the consortium members in related activities will be valued by potential customers.

Further out in time the use of barge shipping from Germany instead of other solutions is offered as providing better value. This value will be dependent on whether and to what extent restrictions are applied to onshore storage and large onshore CO_2 pipelines. Finally the possibility of deriving value form CO_2-EOR is mentioned both in general terms and also with reference to a first emerging opportunity in a MAERSK oil field.

The literature for this cluster recognises the need for a high enough value to be placed on emission reductions in the not too far distant future to underpin the basic value proposition. A number of other "values" have been mentioned in the documentation but have not yet been quantified. So far values have only been considered from the perspective of major emitters and to some extent from that of the regional authorities. Value creation for individual customers and SME's could also be explored. Many of these will be clients of the main emitters and thus may ultimately be the ones paying. Also the National Government is ultimately the body which agrees GHG emission restrictions in the international forum and as such could also be considered a key client. Values for the Government such as unlocking EOR potential and hence petroleum revenues, royalties and taxes could also be explored. Providing value to external investors such as banks does not yet appear to have been explored.

4.1.3.7 Customer relationships

The main relationships with potential customers are through the local trade association DELTALINQS and through co-operation on a number of specific projects under letters of co-operation. These are all directed at emitters. So far these relationships have been developed under the umbrella of the Rotterdam Climate Initiative. It is not clear how CINTRA intends to progress relationships with potential customers. Because the economic viability of CCS is poor because of the low value placed on emission reduction in the near term relationships with potential investors either private or Governmental have not been explored.

4.1.3.8 Customer communication channels

This section considers 5 phases in the communications process. The first is raising awareness of the customer. Given that designing the appropriate relationships is in an early phase this element of the business plan is inevitably less developed. The primary methods of communication have been through publishing and presentation of papers at conferences and meetings, provision of information through international organisations such as GCCSI which are promoting CCS and through the trade association Deltalinqs. The overall profile has also been raised by engaging well recognised political figures (Including ex-Prime Minister Lubbers) to spread a general message about the value of CCS and that government is supportive.

The next stage is helping customers to evaluate the value propositions. Essentially the same methods have been employed. Notable in this category is the provision of independent assessments of studies undertaken by potential partners some of whom could become clients.

The next stage is to communicate to customers how they may actually purchase. It has been indicated that this is likely to be through a tariff for transport and storage but exact details of how this would be constructed have not been developed. Thus potential customers of the transport system have been made aware through the foregoing communication channels that this is likely to be the method of charging.

Thereafter the method of delivery of the service needs to be communicated. In the case of a tariff this could be through a contract for which the duration and terms for variation would need to be explained. This level of definition has not yet been developed.

The final item to communicate is how after sales service or support will be delivered. It is too early to consider this as the earlier stages have not been developed.

The range of customers within a CCS system has not yet been much developed for this cluster. The focus is very much on providing CO_2 transport services for large emitters who have installed capture facilities. These may not be the only clients and it is certainly not the only service required. Considerable attention will need to be given to this aspect of the business before a well-functioning integrated CCS chain can be set up.

4.1.3.9 Customer segments

Several studies have been done to obtain a better overview of potential clients with CO_2 emissions but little has been done to define customer segments in a business plan. The focus is very much on larger emitters but the range of internal and external customers is far greater.

It is important to identify all the types of customer for an integrated CCS cluster. Potential investors could be clients as could end users of decarbonised products. Bringing these into consideration would greatly extend the business possibilities. It is by no means a foregone conclusion that emitters are the main clients. Capture plant operators could for example make a business of purchasing flue gas and the accompanying emission certificates to make a profit by capturing and storing most of the CO_2, selling the certificates on. Companies wanting CO_2 for EOR will tend to be clients of the transporters whereas companies just storing CO_2 will tend to regard the transporters as clients purchasing storage capacity. Alternatively the transport and storage could be a single business. The way in which the CCS chain is divided up into commercial businesses could define customers in many different ways.

4.1.3.10 Revenue streams

Two main revenue streams are evident in the literature on this cluster so far. The largest will be the tariff for the CO_2 transport. The other is loans or investments from government to support early development. These are substantial and form the bulk of revenues secured so far. A considerable amount of work has gone into securing these, partly because they fall under EU subsidy regulations, and this is evidenced by the decision documents published by the EU commission. This money may not have been considered as a revenue stream in the business model planning process. There is discussion in the literature of Governments investing in the CO_2 infrastructure to enable CO_2-EOR which would ultimately return far greater sums to Governments through royalties and taxes on production. Studies undertaken on storage potential in the Dutch continental shelf by TNO have identified a small potential for CO_2-EOR and this possibility is also mentioned in the RCI documentation. There is scope for a much wider consideration of where revenues into the business could come from and this should include all possible sources of early investment capital. The Alberta CO_2 Trunk line cluster described later in this report is a good example of this as it has attracted very large investments from the Government as well as from a very large investment bank.

4.1.3.11 Overall maturity

A few elements of the business plan are in process of mobilisation and already some understanding of cost structure has been gained. Mobilisation still needed to tackle the other areas and hence gain a proper understanding. This needs to happen for all elements of the CCS chain. The most developed is the transport element but even here much has to be done to fully understand how this business will work before a business plan design can be made. Given that storage and capture business also have to be in place the assessment is that overall the cluster is only at the stage of “starting to mobilise”. This will be contrasted with the maturity of the ROAD project which is addressed in the next section.

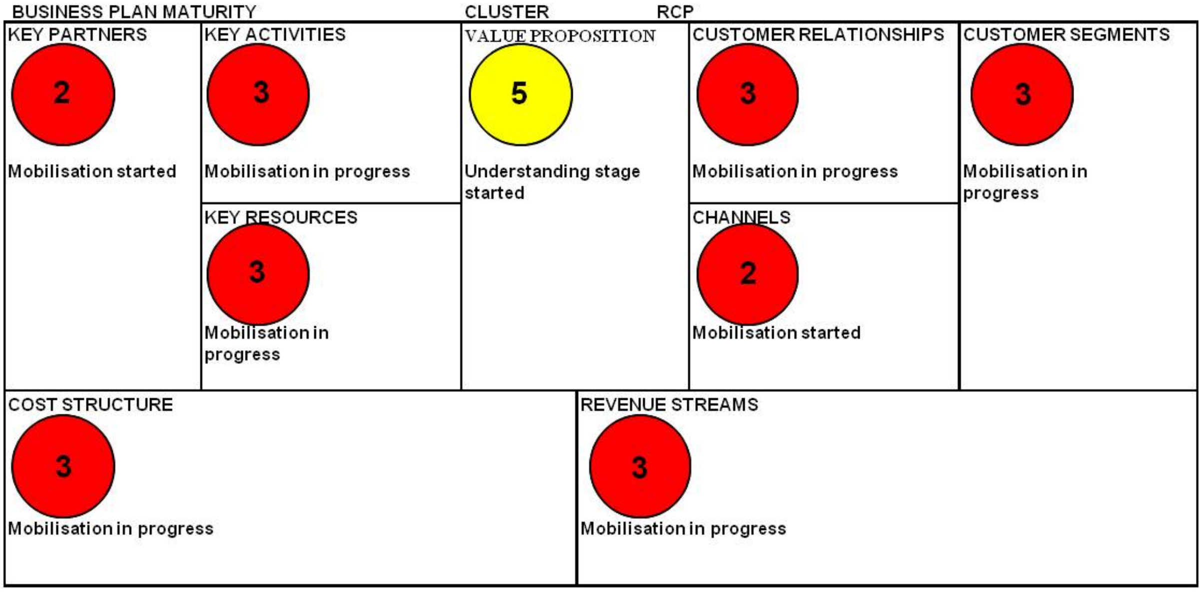


Fig 3 Rotterdam cluster business plan maturity

4.2 Rotterdam opslag en afvang demonstratie project (ROAD)

4.2.1 General information

This project is the first “anchor project for the Rotterdam cluster.

4.2.2 Key information sources

There are general descriptions of the ROAD project in the main cluster documentation. More specific details are given at the project website http://road2020.nl/en/ (10). The project is described in a technical paper “CCS project development in Rotterdam”, (11). Other references for this project are :- (12), (13).

4.2.3 ROAD project technical details

4.2.3.1 General

The Rotterdam Opslag en Afvang Demonstratie project is the first concrete step in the cluster CCS opportunity at Rotterdam. Although the scale is commercial at 1.1 million tons per annum it is small in comparison with the projected scale of the full cluster. The initial pipeline will have higher capacity at 5 million tons per annum allowing significant expansion providing more storage is connected since the selected P18 field can only hold an estimated 35 Million tons or a nominal 7 years at full pipeline capacity. This is reported separately to the main cluster in order to reveal useful details about the early stages of setting up an integrated CCS business in a location where a large cluster is envisaged.

4.2.3.2 Capture

The proposed capture plant will use post combustion technology and will be located on the site of E.ON Benelux behind the new coal-fired unit Maasvlakte Power Plant 3 (MPP3) of

1100 MW_e. The plant will burn coal and biomass and the unit will capture CO_2 at 90% efficiency from a constant stream of 25% of the normal flue-gas output. One advantage of this scale is that the plant will run at full capacity as long as the coal plant is not idle. The MPP3 plant has been constructed and after some delays attributed to problems with high temperature boiler materials is in hot commissioning (As of March 2014, private communication). The capture plant has not been built but some provisions for its construction have been made. The investment will be made jointly by E.ON Benelux and GDF Suez.

The tie-ins for the flue gas have been made as have those for steam extraction for regeneration and reclaimer operation. LP steam can be extracted without upsetting the steam turbine operation as the MPP3 plant was designed for a similar amount of steam extraction for local district heating but this will not be used. No foundations for the main equipment have been made but space is reserved and the design allows most of the construction to take place with the main plant in operation. The absorption solvent will be MEA. The power plant can be considered as capture ready as defined by the EU.

4.2.3.3 Transport

An insulated pipeline of approximately 25Km will be built partly over industrial terrain at Maasvlakte and then subsea to the storage location. The line will be sized for 5Mta and is intended to form part of a larger and expanding network. However this initial line will be part of the ROAD project and will be owned by the two partners in ROAD. In this case the CINTRA consortium will not be involved.

4.2.3.4 Storage

The CO_2 will be injected into and stored in reservoirs 6, 4 and 2 of the depleted gas field P18 at a depth of around 3500m. The injection will be managed by the operators of the field, TAQA. Estimated capacity is 35Mt and a maximum of 5 wells can be provided each with a capacity of 0.5-1.5Mtpa. The field will become available between 2015 and 2017 and is very well characterised. The storage permit was issued in 2013 and is the first to be awarded under the EU CCS Directive.

4.2.4 ROAD project business plan

4.2.4.1 General

The project is relatively small in comparison with the full cluster and there are just two executing/operating organizations. These are the joint venture between E.ON and GDF Suez for the capture plant and pipeline and the operator of the storage facility TAQA.

4.2.4.2 Key partners

There are three key partners. E.ON and GDF working together as a joint venture to build and operate the capture plant and transport pipeline and TAQA to revamp the P18 field for injection and to run the injection and storage operation.

4.2.4.3 Key activities

The key activities to be undertaken are well defined. The main activities still to be done are completion of the detailed design of the capture plant, design and construction of this along with the pipeline, conversion of the P18 platform to provide injection and monitoring facilities. Thereafter to operate the system for a period of 5 years. A critical activity is to raise the remaining funding. €330 million has been obtained from the EU commission and the Dutch Government but a further sum of around €130 million is needed to be able to proceed. Recently some additional funding has been promised by Norway. Although the funding issue is part of the cost structure, the effort needed to obtain it is noted here as a key activity because of its considerable significance. Also important will be obtaining all the relevant planning permissions. As the onshore section of line is in an industrial area no serious obstacles are foreseen.

4.2.4.4 Key resources

Apart from the CCS facilities the key resources needed are the continuous supply of 25% of the full capacity flue gas from MPP3, resources to operate the facilities which will be provided by E.ON and sufficient funds to cover all costs as well as contingencies. Part of the resources are the provision of essential utilities of power, steam and cooling water from the main MPP3 plant. As the ongoing operation will not generate nearly enough revenue to continue in operation the availability of funds is key to how long the project will be able to run. Further key resources will be skilled labour to run the capture facilities, the insulated transport pipeline and the storage facility.

4.2.4.5 Cost structure

The capture plant and pipeline Capex and Opex are the main costs. Storage is expected to be paid for as a contract with TAQA for the storage services but no details of exactly how this would be structured are given.

4.2.4.6 Value propositions

The main value propositions are deduced from the applications for funding. One is knowledge acquisition about the CCS process particularly operation of the capture plant. Another is gaining acceptability for use of coal in the longer term is mentioned as of key value.

4.2.4.7 Customer relationships

The main relationships are between the capture consortium and the power plant, and the funders. Also between TAQA and the consortium who will initially be the sole customer for their storage service. In the next phase beyond ROAD when others also use the line to P18 additional relationships will have to be established but no details have yet been published.

These relationships are presumed to be on the basis of one to one negotiation.

4.2.4.8 Customer communication channels

General information about ROAD has been widely communicated through publishing of studies, participation of some organisations in the studies and through conferences and technical meetings. The RCI has also been used to facilitate general communication. However the main channel is expected to become one to one negotiation and dialogue between the parties once the project moves into constructional and operational phases.

4.2.4.9 Customer segments

Not relevant due to the limited number of customers.

4.2.4.10 Revenue streams

The main revenue streams are the funds of €180 million from the EU and €150 million from the Dutch government. Part of this revenue will be paid to support operating expenses on a per tonne basis, the rest will be drawn down as procurement and construction proceeds. Additional revenue has to be found and at present is unlikely to derive from the two partners but could come from other governments or EU Horizon 2020 funding. Norway has recently indicated that it is willing to provide some additional support. As E.ON is one of the partners, the payment arrangements for transfer of utilities and use of common facilities from MPP3 will be significant. No information has been found on the fiscal arrangements. TAQA's revenue breakdown is also not known.

4.2.4.11 Overall maturity

The ROAD project business plan is relatively simple as it involves very few "customers". In all categories both understanding and design of the business plan elements appear to be more or less complete.

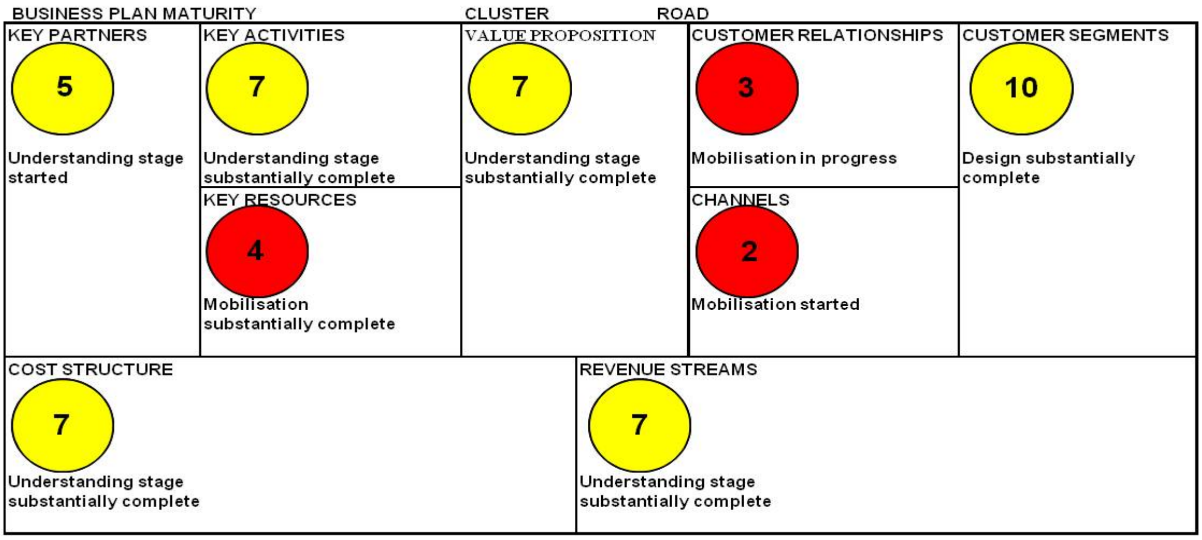


Fig 4 ROAD project business plan maturity

The key partnerships have been implemented and in the critical area of revenues for the capture and transport about 2/3 could be regarded as implemented but the "design" of a plan to close this well understood gap remains. Little information is available on TAQA's own business plan so it can only be assumed that it is more or less at the same stage of maturity, i.e. designed but awaiting implementation. It is interesting to reflect that the value propositions and revenue streams for ROAD are quite different to those of the full cluster development. Also the learning and demonstration of coals' acceptance if delivered once at Rotterdam will be of far less value if repeated elsewhere in the world. Thus being first could be considered as greatly enhancing the value proposition of ROAD. Experience gained when for example the Canadian Boundary Dam capture project starts up could diminish some of the value proposition of knowledge acquisition. However learning related to local regulation and public perception remains of significant value. It also raises the question of whether some this value will inevitably be acquired for free by other clusters and whether there is any way of deriving revenue from elsewhere.

4.3 Skagerrak/Kattegat cluster

4.3.1 General

The Skagerrak/Kattegat area lies between Southern Norway and Sweden and Northern Denmark. There are a number of emission sources at industrial sites along these coasts and sedimentary basins exist subsea and in Northern Denmark. There are a number of geological CO_2 storage prospects within these basins which are thus relatively close to these sources. A CCS cluster based on this juxtaposition has been explored through studies funded mainly by EU, National and Regional authorities supported by local Universities, Research Institutions and some of the local industries.

4.3.2 Key information sources

The main report on this cluster, published in 2012, is entitled "CCS in the Skagerrak/Kattegat region" (14). Information about the project can be obtained from the website http://www.ccs-skagerrakkattegat.eu (15). Some of the information generated during the project has been published in technical papers -: (16), (17), (18). More general information on CCS in the Scandinavian area some of which was used for study of this cluster is found in (19).

4.3.3 Skagerrak/Kattegat cluster technical details

4.3.3.1 Capture

The studies have analysed data on the emissions from sources >0.1Mta in the region and formulated two cases involving capture of 6Mta from 7 of the largest sources and 14Mta from 15 plants consisting of 29 point sources. The costs of capture from each of these 7 plants have been investigated. Two post combustion capture technologies have been considered, MEA and Chilled Ammonia. The overall unit costs for the chilled ammonia process are estimated to be lower mainly because of lower heat requirements for regeneration of solvent. However the report acknowledges that the costs for the chilled ammonia process are based on design and performance assumptions which are not yet certain.

Capture using MEA has been investigated for each of the 5 industrial sites selected for the smaller 6Mta scheme. A detailed review of sources of low grade waste heat has been done for each site and designs are based on utilising this. Where the heat is at too low a temperature heat pumps are used. Costs are estimated for a lower and a higher price fuel case.

The two other sources in the 6Mta scheme are a coal fired plant and a gas fired plant. The costs using either MEA or Chilled Ammonia as solvent have been estimated also for high and low fuel costs.

Costs per tonne captured range from €33 for a coal plant using chilled ammonia, €44 with MEA, €46-65 for the industrial sites and €118-174 for the gas fired power plant. The last is high mainly because the plant has a very low stream factor.

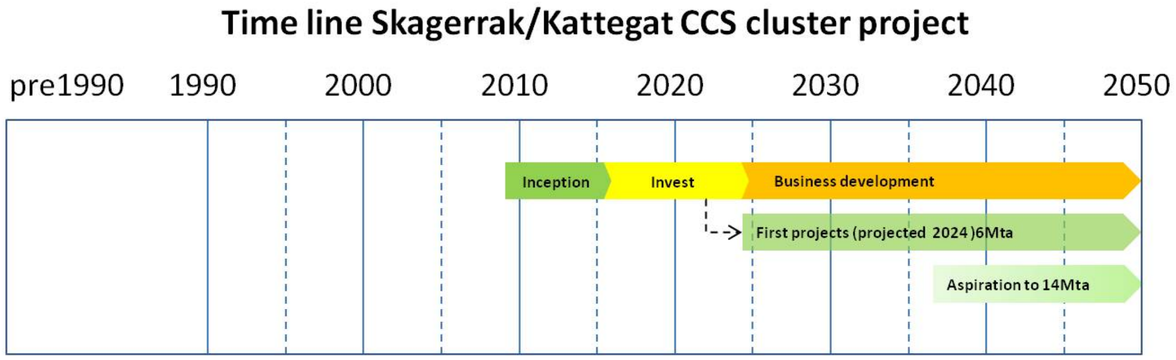


Fig 6 Time line Skagerrak/Kattegat cluster

4.3.3.2 Transport

Outline designs and costs for transport of 6Mta and 14Mta were investigated. Options for pipelines only, shipping with a few lines and an optimal mix of lines and shipping were explored. The cheapest and most flexible option was found to be a combination of pipelines and shipping. Designs were based on pipeline transport in the dense phase with a delivery pressure of 75bar to the Gassum formation 60 km offshore. In the shipping cases 7-8 ships of max 40,000m^3 were required. Exact line sizes were not shown in the report. The lowest costs for the 6Mta case worked out at €12.1 per tonne with the main hub at Grenland in Norway. Two alternative locations for the main hub were also investigated and were slightly more expensive. An option for direct offloading offshore was also studied but proved significantly more expensive mainly because of the time for which ships would be tied up for the unloading.

Fig 5 Skaggerak/Kattegat Cluster map

Costs ranged between the lowest of €12.1 to €16 per tonne. Costs for the 14Mta case were slightly higher ranging from the cheapest option at €14.1/tonne again for the hybrid shipping/pipeline system with a hub at Grenland to €20.9/tonne for shipping with offshore unloading. These costs are based on reaching full capacity from the start. Cases in which capacity was ramped up in 25% tranches over 10, 25 and 50 years were costed for the 14Mta

system. Ramping up in 10 years in a fully sized system raises the cost to €26/tonne. If instead the system capacity was increased in stages the costs would be much higher at €46/tonne although this difference reduces when the ramp up is slower.

The main reason is that offshore pipeline laying costs are high and overall costs do not increase greatly with diameter.

The hybrid system for 6Mta would consist of a central backbone line running subsea between Varo in Sweden and Grenland in Norway. CO_2 from sites at Goteborg (S) and Aalborg (DE) would feed in through side branches. Ships would be used to transport CO_2 from 4 other locations on the Swedish/Norwegian coast to a hub at Grenland. A branch would run from the trunk line westwards under the Skagerrak to the Gassum field storage location which is south of Kristiansand (N). It was noted that the pipelines may be more expensive as there are some Natura 2000 areas (i.e. nature protection areas established under the 1992 EU Habitats Directive) in the region and it is uncertain to what extent routes and designs might have to deviate to protect these.

4.3.3.3 Storage

Onshore Norway and Sweden in this area consist of crystalline basement rocks with no storage potential. There are sediments offshore but these have not been opened for oil and gas exploration and knowledge of their geology and reservoir characteristics is limited. GEUS together with SINTEF performed studies to identify potential storage sites and to simulate performance of the more promising candidates. The Gassum, Skagerrak, Haldager Sand and Byrne formations were investigated as promising storage locations. The Gassum formation 60km offshore in 200m of water was selected for more detailed reservoir simulation. Storage would be in an open slightly dipping reservoir and the simulations indicated a potential capacity of 200Mt. Several simulations were performed with some showing limited migration out of the store after 4000 years. Well capacity was estimated to be 3.3Mta and hence 5 injection wells would be required for the 14Mta case. In addition 2 exploration and 1 observation well were assumed for cost estimation purposes. Overall costs for 14Mta were estimated to be €6.9/tonne and €11.4/tonne for 6Mta.

4.3.3.4 Overall

The study reported unit costs of capture not the costs of net emission reduction but also reported the plant efficiencies and fractions captured allowing the avoided or abated costs to be determined. The results indicate a minimum capture cost for a coal fired power plant operating as part of the larger 14Mta scheme of €54/tonne captured. Abatement efficiency is only 81.9% so that for every tonne captured the actual reduction in emissions is only 0.819tonnes. Thus the minimum abatement cost is €54/0.819tonnes which is approximately €66/tonne. For industrial plants the costs are from €67-86/tonne with abatement efficiency close to 85% due to use of waste heat for regeneration. Abatement costs are thus ranging from €70-101/tonne. For the small 6Mta scheme costs would be about €3/tonne higher across the board. If capacity has to be ramped up, which is likely to be a more realistic scenario, the costs rise further by around €12/tonne capture or about €15 per tonne abated. It is clear that without other sources of revenue emission costs would have to be in the region of €100/tonne for this cluster to be financially viable.

4.3.4 Skagerrak/Kattegat cluster business plan

4.3.4.1 General

Various organisations have co-operated to produce a comprehensive study focussed largely on feasibility, basic technical requirements and costs as well as legal regulatory implications. The suite of studies carried out were supported by a range of universities, regional and central governments, EU and a few industrial companies. These included-: Gassnova, Tel-Tek, Statoil ASA, Skagerrak Kraft AS, Yara Norge AS, Esso Norge AS, Preem AB, Vattenfall AB, Borealis AB, Goteborg Energi, plus University of Oslo, and SINTEF.

A few simple alternatives for division of the overall business are also explored. However there has not yet been any significant mobilisation of partners to form commercial businesses for this cluster. While the study work gives useful pointers to costs and the scope of activities and resources required, less information has been generated on value propositions, how customers will be served and what revenue streams could be tapped. At this stage there is no central organisation set up or leading person championing further development.

4.3.4.2 Key partners

Significant study work has been carried out under co-operation of several universities, regional and national governments and some industrial companies. At this stage the identity of some of the potential key players are known. However no formal business partnership arrangements appear yet to have been discussed or made.

4.3.4.3 Key activities

The required activities are recognised at high level only as a result of the study.

4.3.4.4 Key resources

The required technical resources are recognised at high level in the studies and the importance of capabilities in planning and permitting are noted. These as well as the time to characterise storage reservoirs are estimated to add a lead time of around 10 years to start-up of the cluster.

4.3.4.5 Cost structure

This has been identified at high level and segmented into overall costs for capture, transport and storage. However the detailed identification of all the costs of all the services which a CCS cluster will require has not yet been done.

4.3.4.6 Value propositions

The main proposition is that costs for CCS could eventually be lower than for buying emission certificates. Economy of scale and lower costs through use of heat integration and the more efficient chilled ammonia process are mentioned as effectively adding to value. However there is no real formulation of a value proposition at the development stage which has been reached.

4.3.4.7 Customer relationships

Nothing is described but it is clear that there has been close involvement with some potential customers to evaluate their useable low grade heat potential.

4.3.4.8 Customer communication channels

The main channels of communication have been through conferences, and publishing of studies and technical papers. There is no definition at this stage of how communications with customers would be organised.

4.3.4.9 Customer segments

Some basic segmentation of customers with different types of emission sources has been done.

4.3.4.10 Revenue streams

The study considers that the main income will be the value of emission certificate which do not have to be purchased. Several options for the business ranging from a take or pay tariff to various levels of ownership of the transport and storage network have been explored. Sources appear to be responsible for capturing their own CO_2 and no possibilities for a business with revenues in the capture area have been considered. The estimated abatement costs are likely to be in the region of €100 per tonne. The highest certificate price discussed in the study is only €45 per tonne so that there is a significant gap which has to be filled to make a viable business case.

4.3.4.11 Overall maturity

Business planning is at a very early stage for this cluster. Some of the groundwork for mobilisation of partners is a potential spin off of the co-operation required during the studies. Some understanding of costs has been gained but the required resources and activities are defined at high level only.

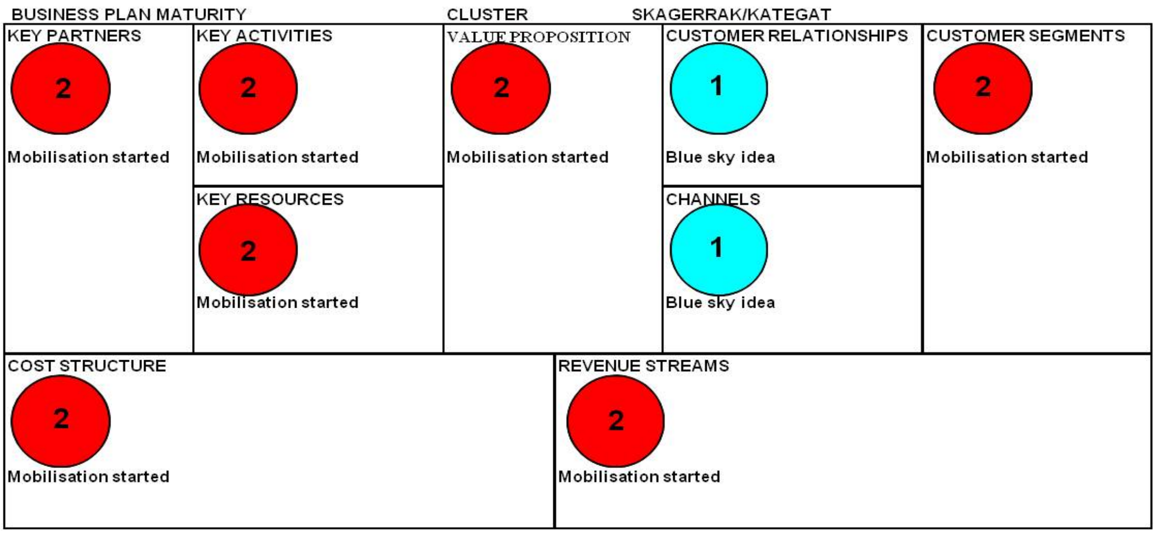


Fig 7 Business plan maturity Skaggerak/Kattegat cluster

4.4 *The Alberta Carbon Dioxide Trunk Line (ACTL)*

4.4.1 General

This project is based on the perceived synergy between oil producers who can benefit from CO_2-EOR and emitters particularly from the oil upgrading industry who have a strong interest in limiting CO_2 emissions from their operations. The concept of a central CO_2 pipeline infrastructure is seen as mirroring the highly successful development of oil and gas trunk lines which opened up that industry some decades earlier. This project is possibly the most advanced of any of the proposed cluster projects around the world.

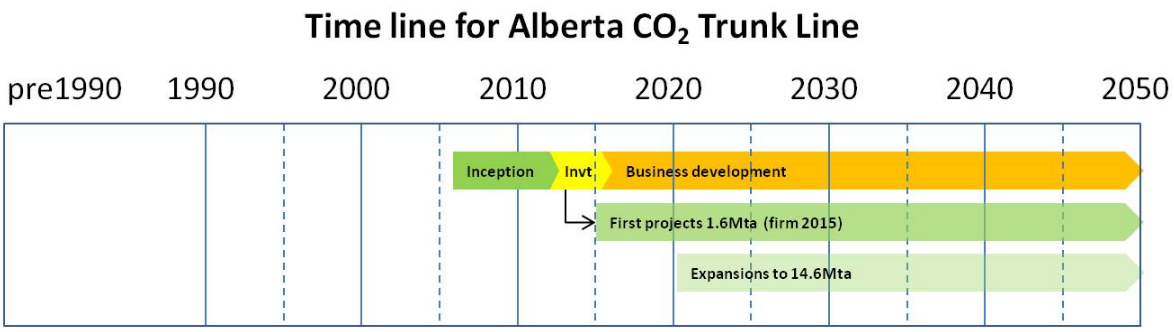
4.4.2 Key information sources

Enhance Energy Inc. is the company running this project and details of the project and its progress can be found on their website at www.enhanceenergy.com (20). Extensive details of the plans for the project are in a report entitled “Enhance Energy Inc. and North Redwater partnership, Detailed report 2011” (21). This key report is summarised in (22), a paper on the project has been published (23) and the most up to date progress in (24).

4.4.3 ACTL technical details

4.4.3.1 Capture

The project is being initiated with two CO_2 sources, one a fertilizer plant owned by Agrium and the second the Sturgeon heavy oil upgrading refinery. The CO_2 from the fertiliser plant is already pure although it is heavily water saturated. Processing thus consists of compression



water condensation and final drying using triethylene glycol (TEG). Sturgeon is a new facility and uses gasification of asphaltenes, a bottom product of the refinery, to generate the hydrogen needed for upgrading.

Fig 8 Time line Alberta CO_2 Trunk Line

The CO_2 is removed from the syngas stream from the gasifier after shift and sulphur removal using the Rectisol process. It is pure enough to meet the specifications and simply requires to be compressed. The main contaminant from both sources is hydrogen. The costs of capture are estimated at CAD21/tonne at Agrium and CAD12/tonne at Sturgeon for 1.2Mta and 0.4Mta respectively. In the longer term the trunk line is envisaged to have an ultimate capacity of 14.6Mta which leaves considerable scope for additional capture.

4.4.3.2 Transport

The CO_2 is transported over a 242km long pipeline, of which 12km is 12” and 220km 16”. It runs from the industrial area northeast of Edmonton to the Clive oil field south of Edmonton. Where the 12” section crosses the Saskatchewan river a spare 12” line will be installed. The line is buried to a minimum depth of 1.2m and has a maximum allowable working pressure (MAWP) of 179bar. Delivery pressure is 137bar (2000psi). For the initial phase there is no intermediate pumping but one and eventually 2 pumping stations are envisaged to reach maximum capacity of 14.6Mta. The main line will be constructed of 14.3mm thick welded carbon steel and with this thickness does not need crack arrestors. Block valves are installed every 15km and the safety zone around the pipeline established for emergency response purposes is 700m either side. The line is equipped with state of the art leak detection monitoring in accordance with the state regulations. Total transport costs are estimated at CAD6.4/tonne of which CAD0.4/tonne is Opex and CAD1/tonne is for maintenance. The line is expected to cost CAD245 million.

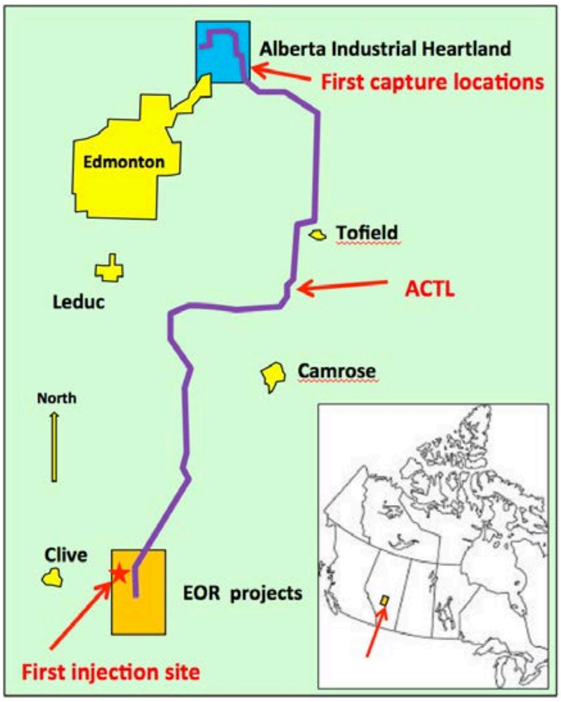


Fig 9 Alberta CO_2 Trunk Line map

4.4.3.3 Storage

The first storage site is the Clive oil field where the CO_2 will be injected into the Nisku and Leduc horizons for enhanced oil recovery. The estimated CO_2 capacity is 18.8Mt based on re-pressurizing the fields to the initial discovery pressure of 2407psig from the current depleted pressure of about 125bar (1800psig). Without re-pressurisation capacity is estimated at 12.2Mt. The regional potential for storage is however much larger estimated at 2000Mt.

Based on previous water injectivity, wells are expected to have a capacity of an average of 240t/day so that approximately 18 injection wells will be required. Cost for provision of facilities at Clive are estimated to be CAD100 million and unit cost for injection will be CAD3/tonne of which CAD2/tonne is for MMV and CAD1/tonne for well maintenance.

4.4.4 ACTL Cluster business plan

4.4.4.1 General

4.4.4.2 Key partners

The key operational partners are Enhance Energy a company set up specifically to build and operate the Alberta CO_2 trunk line and to attract CO_2 suppliers and CO_2-EOR users to the system. In the initial phase there are two CO_2 suppliers, Agrium a fertiliser company and

North West Redwater, a heavy oil upgrading company. There is one CO_2-EOR company the operator of the Clive oil field, Fairborne Energy Ltd.

4.4.4.3 Key activities

The main activities in the first phase are construction and operation at the two capture locations. These consist of drying and compression of a concentrated stream of CO_2 which is a by-product of fertiliser production at Agrium. At NWR the CO_2 is produced in a hydrogen plant supplying the upgrading unit. It is extracted from a syngas stream using the Rectisol process and is then compressed. Enhance energy will organise the construction of the CO_2 pipeline and will be the operator. Fairborne will operate the CO_2-EOR at Clive. This includes implementation of MMV of the stored CO_2 as well as design of the well locations, injection programme and reservoir management. In addition to these basic activities Enhance Energy is engaged in attracting new clients to both supply and use CO_2 for EOR. They also provide technical advice on EOR opportunities. Another key activity has been raising funds for the initial phase of the project and also for further expansion.

4.4.4.4 Key resources

These comprise the capture facilities, the pipeline, the storage reservoirs as well as expert staff for their operation. In addition venture capital for investment in both the pipeline and elements of the capture facilities.

4.4.4.5 Cost structure

The costs for operation of the main transport business are a unit cost for purchase of the CO_2, and a transport tariff. These are based on estimates of capital and operating elements reported in a detailed report to the main investors.

4.4.4.6 Value propositions

The main value proposition is delivery of CO_2 at an affordable price to CO_2-EOR projects. Another is the ability to reduce the local Alberta state “tax” on CO_2 emissions. In addition the sources are able to benefit from facilitated access to government and private funding.

4.4.4.7 Customer relationships

Enhance Energy uses one to one relationships with both CO_2 sources and users. In addition relations are maintained with government and private investors. The extent of the latter is not known, only that relations with one key investor, Barclays Capital, have been successful in raising capital. (25), (26).

4.4.4.8 Customer communication channels

Enhance energy undertakes general communications through its website, and the release of newsletters. Details of one to one communications with clients are not available. Early in the project use was made of lobbying to assist in obtaining government investment. These have to be made public under the Lobbying Act and this reveals that the CEO of Enhance Energy had approaches made on 9 occasions. (27), (28), (29). More recently Enhance energy has joined in a newly formed group “Alberta plus” which is supported by a small number of key industries with the vision of making Alberta a leading petrochemical producer thus enhancing the economic value of its energy resources. One of its aims is to reduce greenhouse gas emissions. The group currently consists of North West Redwater, Agrium, Enhance Energy, Nova Chemicals, Williams and Alberta Industrial Heartland, itself an association of 5 local municipalities.

4.4.4.9 Customer segments

Potential future customers do not yet appear to have been formally segmented. At present they naturally fall into three categories, companies wanting CO_2 for EOR, companies who have a source of CO_2 and organisations wishing to invest in infrastructure.

4.4.4.10 Revenue streams

Investments in infrastructure from Government and private venture capital are by far the largest sources of revenue at present. Once the first part of the trunk line is built this can be expected to change although assistance with the cost of adding capture facilities may still be required. The main revenue stream will be payments for CO_2 delivered for EOR. Avoidance of the Alberta CO_2 emission levy is part of the value proposition but is not specifically listed as a revenue stream. The detailed accounting for stored CO_2 is not defined although the assumption appears to be that due to full recycling of CO_2 as soon as it breaks through in the EOR process only small fugitive emissions to atmosphere will need to be accounted for.

4.4.4.11 Overall maturity

The first phase of the ACTL is relatively mature. Agreements are in place for substantial government and private venture capital. Commercial agreements have been made with two CO_2 suppliers and with one CO_2 user although details of these are not published. Construction of the capture facilities and the pipeline is underway and relationships with the first partners and customers have been established. Several parts of the business plan for the first phase are thus already in the implementations stage. However the development of customer relations, segmentation and communications, particularly for later phases of development, are far less advanced. It is also not clear how the revenue streams will develop once government funding used to kick start set up of the infrastructure becomes less important.

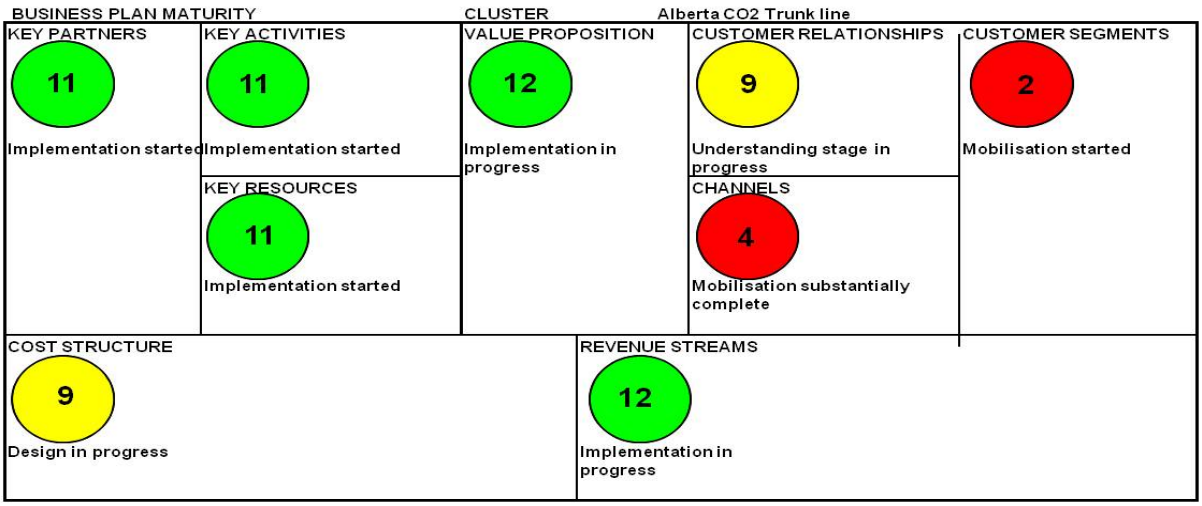


Fig 10 ACTL business maturity

4.5 Yorkshire and Humber Cluster (UK)

4.5.1 General

A major study was undertaken by AMEC for the regional development agency known as "Yorkshire Forwards". This resulted in a report identifying sources, possible storage sites in the North Sea, an outline network design and estimates of costs for the transport network and a comparison with a point to point project. The Agency was abolished in 2012 but the National Grid Plc has continued to be active in promoting the cluster concept. And there are now firm plans to implement an anchor project by 2020.

4.5.2 Yorkshire and Humber Cluster technical details

4.5.2.1 Capture

Sources were grouped into tier 0, 1 and 2 capacities being >1Mta, 0.05-1.0Mta and 0.001-.05 Mta. 92% of the emissions were found to come from 15 tier 0 sources. A general study was performed which defined three scenarios (Low, Central and High), in which capacities were estimated based on low, medium and high projections of CO_2 price. The cases captured CO_2 from 8, 10 and 12 of the tier 0 sources respectively. Build up profiles of capacity were generated which indicated capacities rising by 2050 to about 24Mta, 47Mta and 53Mta respectively. Since the general report further work has been done by National Grid Plc working with two potential sources which would constitute the first phase of a CCS cluster. Much of the Yorkshire & Humber Cluster development has been funded by the EU EEPR scheme in conjunction with the Don Valley Project. However, due its selection ahead of Don Valley in the UK Government Commercialisation Programme funding competition, the key anchor project would be a new capture plant at the Drax power station (known as the White Rose project) which would have a capacity of 2.6Mta. The initial system would be sized to take 17Mta including a further 5Mta from the Don Valley CCS project which is a proposed coal fired integrated gasification combined cycle (IGCC) plant (formerly Hatfield). The White Rose project would be coal fired and would utilise oxy-combustion technology. UK Government funding for a FEED study has been awarded. Construction is currently expected to start around 2016 with first operation in 2020.

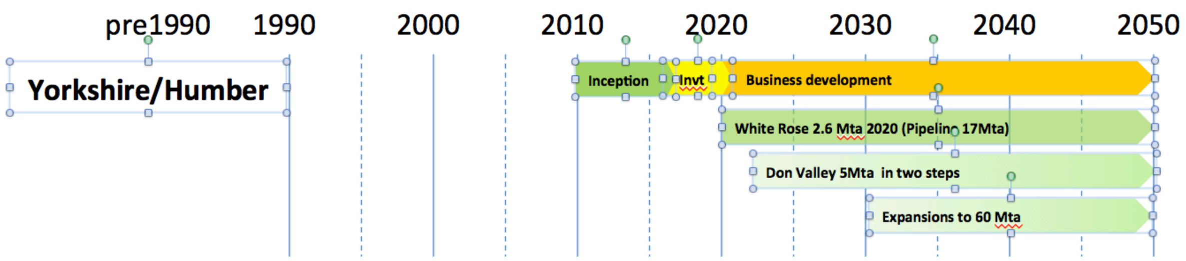


Fig 11 Yorkshire/Humber cluster current time line

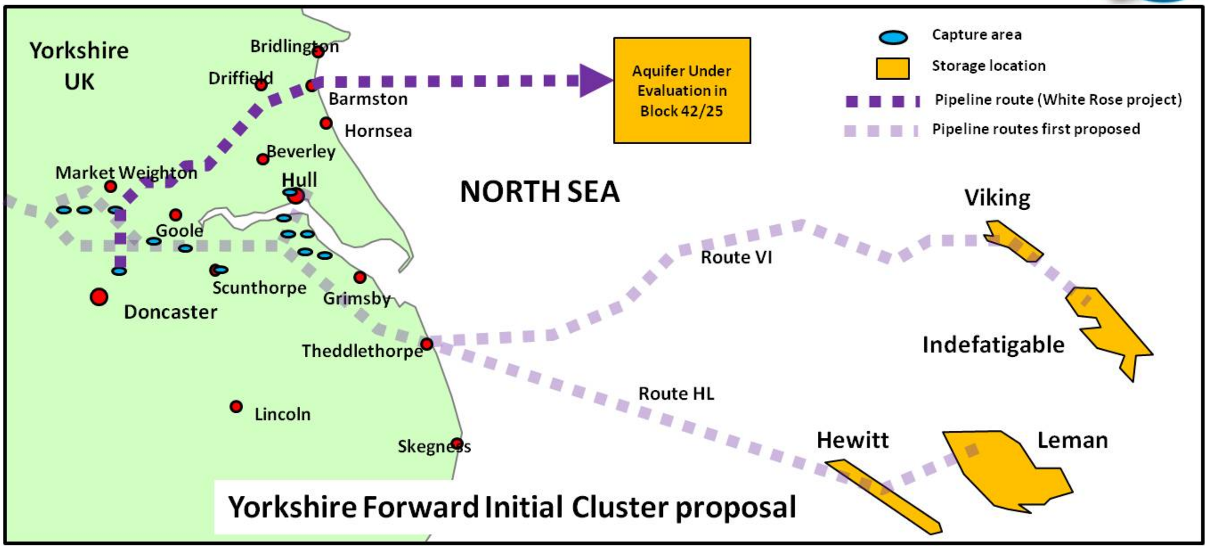


Fig 12 Yorkshire Forward initial cluster concept map

4.5.2.2 Transport

The Yorkshire Forward's (YF) study outlined the onshore pipeline networks which would be required to gather CO_2 for the three scenarios. It also identified two offshore routes one to Hewett/Leman area and one to Viking/Indefatigable area each of about 190km. The published report did not detail the sizes of the lines. Expansion of the trunk line system would be predominantly by line looping. Pressure on shore was limited to 125bar in the initial study. It was also concluded that the maximum delivery pressure needed to avoid offshore compression/pumping was 170bar. The National Grid Plc is currently proposing a pressure of 150bar onshore and up to 200bar offshore. The final delivery pressure has now been defined in the FEED study but has yet to be published.

The YF study looked at the stepwise expansion of the system. The costs reported show only a single step increase in the investment for the Central and High cases in 2030 and for the Low case steps also on 2040 and 2050. The report makes a comparison between the costs of the integrated network and a point to point project and shows a reduction varying between 6.5% and 20% depending on selection of discount rates. Examination of the cost per tonne estimates suggests that these have been derived without applying the discount rate to the CO_2 volumes which results in rather low values especially at higher discount rates.

The initial study suggested a shore station at Theddlethorpe south of the Humber. The current plant is for a line running some way north of the Humber to a shore pumping station just north of Barmston. The planning application was submitted in mid-2014. The capacity of the initial pipeline is planned to be 17Mta leaving plenty of scope to add additional sources of CO_2 after the first two planned projects with 7.6Mta capacity are on stream.

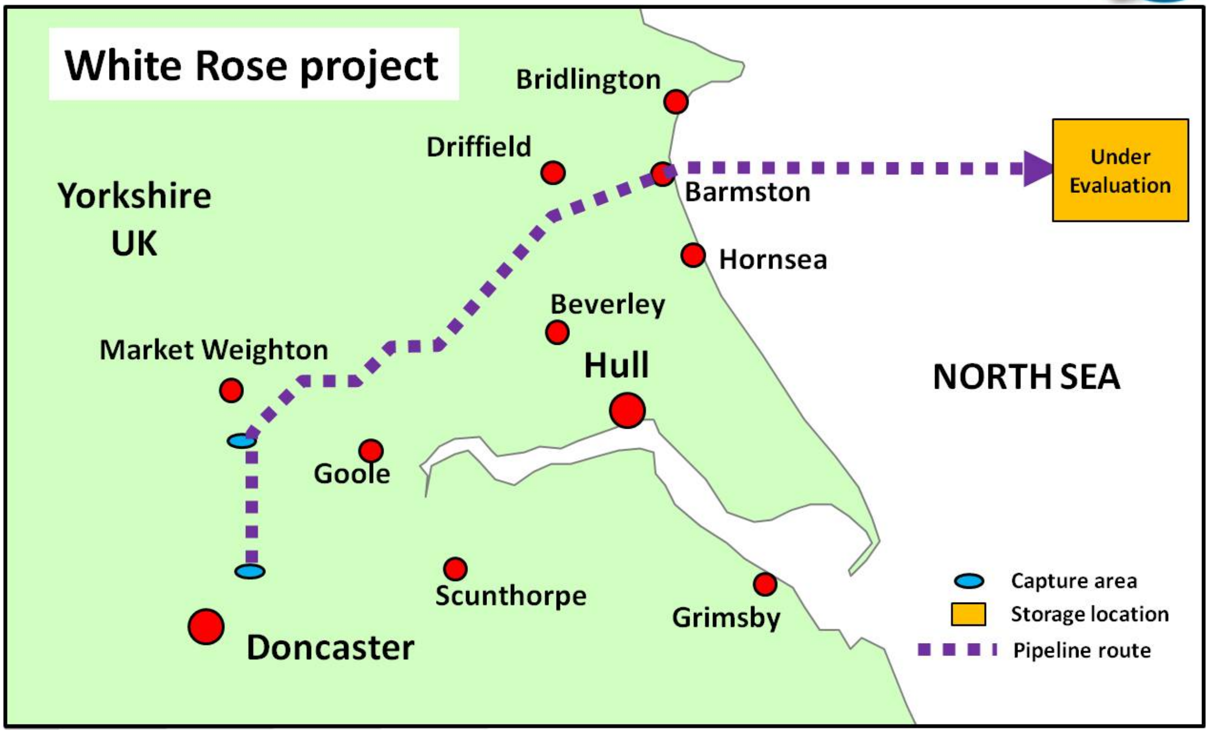


Fig 13 White Rose project anchor project for Yorkshire/Humber Cluster map

4.5.2.3 Storage

The YF study identified 17 depleted gas fields with potential storage capacity of >40Mt. Of these 4 were considered the best candidates being:- Leman 870Mt, Hewett (216Mt), Indefatigable (333Mt) and Viking (214Mt). Total potential storage identified was 2,437Mt. In addition three saline aquifers near West Sole, Barque/Clipper N and Viking were identified with potential capacity of 6585Mt. Depths are in the range 1100-1400m. However each of these opportunities suffer from potential sealing issues due to the presence of known faults.

The current plans are somewhat changed in part because the depleted gas fields identified in the earlier study are not yet accessible. The storage site now selected is about 70km offshore of Barmston and has recently been test drilled. Indications are that the aquifer unit, known as 5/42, with a depth of approximately 1000m can store up to 200Mt of CO_2.

4.5.3 Yorkshire and Humber Cluster business plan

4.5.3.1 General

The initial study was funded by the regional development agency aiming to identify the scope, scale and approximate costs as well as key issues. The agency was abolished in 2012 leaving industry to advance CCS plans in the region. Some support is still available from Government sources in the form of funding for demonstration projects to be won by competition. The focus is thus less on developing the cluster and more on bringing anchor projects into existence against the backdrop created by the YF report that the region was favourably placed in terms of concentration of CO_2 sources with access to plentiful and not too distant storage.

4.5.3.2 Key partners

A few companies are now working together to develop initial projects. The key anchor project for which funding for a FEED study has been granted has collaboration of Alstom, Drax Power and British Oxygen Company (BOC, now part of the Linde Group) in Capture Power Ltd. working with National Grid Plc who will provide the pipeline for both projects. National Grid Carbon will also undertake the storage element of the project. They have been characterising a new storage site 70km offshore and recently reported successful results of test drilling. The Don Valley Project is being developed by 2CO Energy to use the same shared information.

4.5.3.3 Key activities

The key activities are design, construction and operation of the first anchor project, White Rose. The design and construction and operation of the CO_2 pipeline and a pumping station on the coast and an offshore pipeline together with proving up of a storage site by test drilling and further characterisation was undertaken as part of the Don Valley project supported by EU EEPR funding. The design, construction and operation of the offshore injection facility which is likely to include a single offshore platform and some wells, is being progressed as part of the White Rose project supported by UK Government funding.

4.5.3.4 Key resources

Key resources include expertise in oxygen plant (BOC-Linde), power plant construction, carbon capture using oxy-combustion (Alstom), power plant operations (Drax) and pipeline (National Grid Plc). In addition expertise is needed in CO_2 storage and this will be provided by a subsidiary of National Grid Plc, National Grid Carbon. Storage capacity and a suitable site is a necessary key resource and National Grid Plc recently announce preliminary success in developing a claimed 200Mt of storage following a successful appraisal well. However it is unclear what the source of storage and reservoir expertise is but National Grid Plc has worked with Petrofac, Fairfield energy and Premier Oil on storage for CCS. To address this issue they have developed an internal team of informed buyer's to manage the activity and are outsourcing to established oil and gas industry contractors (e.g. Genesis, AGR TRACS, ADTI)

4.5.3.5 Cost structure

The costs outlined in the YF report were at very high level. The cost structure of more recent projects has not been reported publicly but can be expected to be reasonably well understood.

4.5.3.6 Value propositions

The UK Government, in providing support to the first UK CCS projects, is seeking to achieve its legally binding EU and UK carbon emission reductions in a way which has the lowest cost. For the project partners part of the value proposition is avoidance of having to purchase CO_2 emission certificates. However this is recognised as falling far short of the necessary funding.

The main proposition is that the anchor projects will establish a leading position for the UK in CCS and that this is an element in achieving reductions at lowest cost. Reasons that a leading position in CCS has value are described in other documents for example the joint CCSA TUC study on CCS which concluded that the industry would promote employment. The proposition is that the project will be made viable by concluding Contracts for Difference (CfDs) with the UK Government to cover the extra costs of capture beyond the value of certificates. The UK Government has established a Levy Control Framework to manage the total cost of support schemes. For 2020-21 the cap covering Renewables Obligations, Feed-in tariffs and contracts for difference is £7.6bn with forecast of £2.534bn for contracts for difference with low carbon generators. The partners are also actively seeking external investors to provide loans. The value proposition for these will be interest payments and security of the loan.

4.5.3.7 Customer relationships

Very limited details of the relationships between the parties in the CCS chain are published. The main relationships are one to one between major industrial companies. Relationships between the enterprise and Government and potential investors are also important. The only information found was through news releases indicating agreements for example to take equity in the Don Valley project. (Samsung C&L and BOC). For White Rose the UK Government Department of Energy and Climate Change (DECC) contracts with Capture Power Ltd. (CPL). In turn CPL contracts with National Grid Carbon for the transport and storage services.

4.5.3.8 Customer communication channels

The main communications within the CCS chain and other “Customers” appear to be one to one negotiation. The various companies also communicate general information through websites, brochures and public consultations.

4.5.3.9 Customer segments

There are different types of “customer” identified but no information on systematic segmentation.

4.5.3.10 Revenue streams

The main revenue streams identified in the documentation are, emission certificates, Contract for Difference payments on electricity price, Government funding, equity from investors and loans from investors. Also very recently (August 2014) €300 million has been awarded from EU NER300 funding. Public details of how these will be structured contractually were not found. It is anticipated that National Grid Plc. will gain revenue for the transport and storage by some form of tariff agreement similar to its other transport business although nothing explicit about how this would be structured was found.

4.5.3.11 Overall maturity

The partnerships necessary to implement the first anchor projects are in process of being formed. At this stage it is unclear how well the required formal partnership arrangements have been understood and designed. The other key elements of the plan are the value proposition and revenue streams. Getting to grips with these is still in the mobilisation phase as the understanding of what contribution each should make has not yet been developed. The extent to which Contract for Difference can be used to create a sound business plan has yet to be explored and may come under scrutiny by the EU commission in the same way as has the recent deal for the new Hinckley Point nuclear plant. The issues surrounding use of State funding and support with respect to the EU and the WTO are of importance in this respect and are well summarised in (30).

4.6 Teesside UK Cluster, (UK)

4.6.1 General

A number of heavy industries with substantial greenhouse gas emissions are situated near the NE coast of England near the mouth of the river Tees. Investigation of the opportunity for development of a CCS cluster was promoted through an industry grouping, the North East Process Industry Cluster (NEPIC). A number of studies have been carried out and proposals made for early investment in a demonstration project. The cluster continues to be promoted by NEPIC as the Process Industries Carbon capture and Storage Initiative (PICCSI). It is promoted also because of the relative proximity to depleted oil and gas fields which will become available for storage in the North Sea.

4.6.1.1 Key information sources

This cluster opportunity is summarised in a report prepared by Element energy for NEPIC (30). The cluster was maintaining a website (31) at http://www.teessidelowcarbon.com/ . Other references are -: (32), (33).

4.6.2 Teesside UK Cluster technical details

4.6.2.1 Capture

Studies so far have proposed four tranches of development involving an initial anchor project with 1 source and, Small, Medium and Large options with 5, 8 and 35 sources respectively. These would enable capture of an initial anchor 5Mta with capacities later of: - Small 14, Medium 22 and Large 26 Mta.

Capture would be from a range of industries including power plants (7), iron and steel plants (2), chemical plants (13) petroleum refining (5), biomass and other large sources (7). In addition potential for a new IGCC plant using underground coal gasification has been identified. The study was based on most of the capture being by retrofit.

The analysis further assumed that emission reduction would be 84% of the total amount captured.

Further study is to be undertaken by Tees Valley Unlimited using part of a further £1 million which has been granted under the Tees Valley City Deal. A pre-FEED study of capture from the steelworks, BOC Linde hydrogen plant, the ammonia plant (GrowHow) and some other smaller industries will be carried out.

4.6.2.2 Transport

So far analysis has been based on providing a notional 200km offshore line which would be able to reach a number of potential storage sites. Diameters for the 3 sizes of project were estimated to be 500mm, 600mm, 900mm respectively. No allowances for seasonal variations in capacity were considered. The possibility of using some shipping during build-up of capacity was identified. The maximum operating pressure would be less than 250bar but exact values were not specified in the reports. Delivery pressure would be 110bar.

There would be some onshore sections which would be buried and because of the hazardous classification for supercritical CO_2 could not be run near residential areas.

4.6.2.3 Storage

The studies carried out so far have not made any selection of storage reservoirs and have only ascertained that Teesside has access to a number of potential offshore storage sites within a radius of 200km. One of the main report recommendations is that further work to select and characterise the reservoirs which would be used needs to be carried out. High level costs for storage were estimated at £14, 13, 12 and 12 per tonne stored for the 4 sizes of project.

4.6.3 Teesside UK Cluster business plan

4.6.3.1 General

Development of a business plan for the Teesside cluster is at a very early stage. The initiative is kept in progress by the NEPIC organisation. A consortium, Teesside Low Carbon was formed to bid for funding in the UK competition. They were unsuccessful but were placed on a reserve list. Their project would essentially be point to point but could be regarded as the first anchor project for the cluster. Part of a recently granted £1 million will be spent on developing a business case.

4.6.3.2 Key partners

The project is at an early stage of mobilisation. No commercial partnerships have been formed but the industries in the region are working together under the umbrella of the NEPIC organisation. Some of the study work has been undertaken by international contractor AMEC through their regional office. At this stage it is unclear which organisations would be interested in taking a significant stake in the development.

A consortium was formed for the UK competition with the following members:-BOC (Linde), International Power, National Grid, Fairfield, Energy, Premier Oil, Progressive Energy and GDF Suez.

4.6.3.3 Key activities

The only activities undertaken to date have been the early studies on feasibility and costs.

4.6.3.4 Key resources

Also at an early stage of development. The studies have identified that the site is favourably located for routing of an offshore line and also that viable onshore pipeline routes are available to connect all of the major emission sources. The industries in the region have already developed shared infrastructure for various utilities and this capability to share industrial infrastructure could be considered a valuable resources.

4.6.3.5 Cost structure

The costs have been developed at high level and do not yet include details of all of the elements which will be required.

4.6.3.6 Value propositions

The overarching value proposition for the UK Government has already been outlined for the Yorkshire/Humber cluster. The main value proposition is the avoidance of payment for emission certificates on the basis that by pooling the infrastructure for transport and storage will be cheaper. Also that Teesside is favourably located with regard to distance to storage. The cost analysis does show slight reductions in storage and transport cost as capacity increases but overall costs including capture increase substantially as total capacity rises. Thus the main value proposition is that favourable distance to storage makes Teesside a low cost location to employ CCS in the UK.

A further element of the proposition is that businesses will be able to claim low carbon credentials, it being suggested that their major customers are increasingly considering carbon footprint of their suppliers when making purchases. This effect is however not quantified.

4.6.3.7 Customer relationships

The main relationships so far are incidental through co-operation with the studies which have been and are about to be undertaken. However with no commercial organisations yet being set up to progress development of the cluster this element of the business planning has yet to be started.

4.6.3.8 Customer communication channels

At present the main communications with potential customers are thorough the NEPIC and PICCSI organisations and through publication of the study reports and a few scientific papers. This element can only be developed once the customers for the various parts of the CCS chain business are identified.

4.6.3.9 Customer segments

Some segmentation of customers has been done by classifying these into types of industry and into which phase of the development they would naturally fall based mainly on expected cost for capture. Potential customers in the wider definition have not yet been explored.

4.6.3.10 Revenue streams

The main premise is that emitters would pay for transport and storage. Details of how this could be done have been explored in the studies with both tariff and equity/cost recovery arrangements proposed. The possibility of Government guarantees to cover some of the business risks is also put forwards. Government support in the form of CO_2 floor prices, CCS levies and support for demonstration projects are also suggested but details of the mechanisms by which these would provide revenues need to be worked out. In the interim some general funding has been obtained from the UK Government to progress further study (34).

4.6.3.11 Overall maturity

The business plan for the elements of the CSS chain has still to be developed and the significant players have yet to mobilise. The consortium formed for the UK competition could become a platform for developing the cluster in the future.

4.7 The Collie hub cluster, Australia

4.7.1 General

Amongst the many CCS initiatives in Australia the plan for the Collie hub in South Western Australia is the only one which is being promoted as a full cluster. The plans stemmed from an initiative by the coal industry through the Coal Futures association. The plans fall into 4 phases, with capture and storage starting in the second "enabling" phase when a first smallish "anchor project would be set up. Thereafter a base case would be established in which a second much larger emitter joins. This is followed by the last "extended phase in which further sources are captured. Beyond this further growth is foreseen but not yet planned.

4.7.2 Key information sources

The GCCSI published a report on the development of the Collie hub (35). Additional information is available in a brochure (36). Early information on storage in the region is presented in (37).

4.7.3 Collie hub Cluster technical details

4.7.3.1 Capture

The first phase will be capture of 0.35Mta which may be available from a chemical plant at Kwinana. The nature of the plant is not reported. In the base case phase the CO_2 from a fertiliser plant will be captured bring the total to 2.45Mta. This initial phase will thus be using mainly the pre-combustion technology which is used in the production of ammonia so that the extra costs for capture will be relatively low. Finally CO_2 from other plants which may include a new power plant as well as CO_2 from new or retrofitted chemical plants will bring the total capacity to 5-6Mta. Thereafter the capacity may rise to around

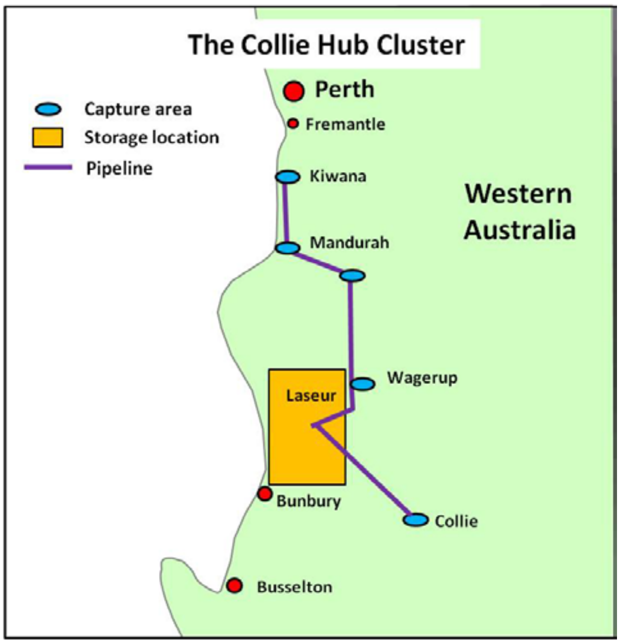


Fig 14 Collie Cluster, Australia map

10Mta. No specific details of the expected costs or capture efficiencies were reported.

4.7.3.2 Transport
Transport would be by a single line, working above critical pressure, which would be approximately 75km in length but this assumes that the proposed storage site is found to be acceptable.

4.7.3.3 Storage
The plans are currently based on proving up storage in the Leseur formation which is a sandstone reservoir at a depth of approximately 2000m. It is known to have a good permeability but does not appear to have a continuous cap rock. The sealing would thus have to rely on the baffling effect of overlying non-continuous sealing strata. Initial reservoir simulations have indicated that storage could be secure but would rely to considerable extent on residual trapping mechanisms. Simulations suggest a capacity of 200-260Mta and a well injectivity between 0.9 and 1.7Mta. First studies assume that 6 wells would be required.

4.7.4 Collie hub Cluster business plan

4.7.4.1 General
The Collie hub initiative is currently lead by the Australian Department of Mines and Petroleum. However a transition to management by a consortium of private companies is envisaged.

4.7.4.2 Key partners
There are currently 6 key partners from private industry who have signed Memoranda of Understanding and are also co-operating to set up an Unincorporated Joint Venture (UJV) to manage the project. The mobilisation of key partners is thus complete but full understanding of how the partnership will operate and design of the business relationships has still to be undertaken

4.7.4.3 Key activities
The key activities have not yet been defined in full detail. At present they are concentrated on characterising the potential storage reservoir and assessing the pipeline route. Another key activity is securing funding of which 1/3 is expected to come from the Flagship programme. In principle the rest is expected to come from the private sector but whether this is restricted to just the UJV partners is not known.

4.7.4.4 Key resources
Details of resources are limited but the cluster does appear to have access to concentrated streams of CO_2 from some industrial processes such as fertiliser production. It is also reported that small amounts of CO_2 (0.07Mta) are already being used by some of the partners to react with alkaline waste products from bauxite production. This activity will be expanded to 0.25Mta in the proposed anchor project. This alternative destination for CO_2 sequestration is a valuable resource. The CO_2 for the next phase is specified as coming from a new fertiliser plant and hence much of the capture process will already be available. Access to a

pipeline route and a storage location are other key resources which have been identified as critical but have yet to be acquired.

On the financial front a grant of AUD52million has been given from the flagship programme. A total of about AUD330 may become available. The UJV has still to mobilise to understand where the balance of the projected financial resource of AUD1billion cost can be acquired.

Some of the key resources are thus already in process of being mobilised but most have yet to be acquired and the UJV has to mobilise sufficiently to be able to understand all of the items which will be needed and design a business plan to acquire them.

4.7.4.5 Cost structure

The overall costs have been estimated but much work still has to be done to understand all of the cost elements.

4.7.4.6 Value propositions

Three general value propositions have been mentioned which are enabling : -

- companies to meet new Government emission regulations which are expected to require reductions,
- companies to satisfy their own corporate emission reduction goals,
- sources of CO_2 to manage their emission costs.

One quite specific value proposition is enabling Bauxite residues to be converted so that they may be re-used in the future.

These are rather general propositions and as yet their full value is difficult to know.

4.7.4.7 Customer relationships

The main relationship appears to be that between the partners of the UJV. No details of how this will be managed are published. Nor is the relationship between the operator of the storage reservoir and the UJV established. An important relationship is that between the DMP and later the UJV and the Government Flagship programme.

At this early stage only some of the major relationships with “customers” within the overall CCS cluster have been mentioned. It is not clear whether the UJV will undertake all or just some of the activities and whether parts of the system will be run by independent businesses. This structure and hence the definition of all customers and their relationships have yet to be understood and designed.

4.7.4.8 Customer communication channels

The main channel of communication appears to be via the UJV but there are no details yet of how this will be designed and managed.

4.7.4.9 Customer segments

No customer segmentation has been done yet.

4.7.4.10 Revenue streams

The nature of the revenue streams which will be based on the current value propositions has yet to be understood and defined.

4.7.4.11 Overall maturity

The business plan is at a very early stage of development. Mobilisation is started for some elements but has yet to occur for most. The full scope of the UJV has yet to be defined, in particular which of the various key services it will undertake and which will be subcontracted or provided by other specialist organisations or perhaps by the individual partners.

4.8 Denver City hub cluster, USA

4.8.1 General

The existing CO_2 trunk line systems in the USA already provides a backbone transport system for CO_2, mainly from naturally occurring underground CO_2 reservoirs, destined for EOR projects. At the centre of the largest system is the Denver City hub in Texas which has evolved from the start of CO_2-EOR operations in the 1980’s based mainly on use of natural underground stores of CO_2. This will be examined in more detail along with two other locations where pipelines are supplying natural CO_2 for EOR. These all have the potential to become CCS clusters if substantial sources of captured CO_2 are added. These systems have undergone and continue to undergo considerable expansion. Denver City in Texas is a point at which several long distance CO_2 pipelines converge and from which CO_2 is distributed to over 40 oilfields for EOR. It is linked by pipeline to another smaller hub, the McCamey hub.

4.8.2 Denver City cluster technical details

4.8.2.1 Capture

The bulk of the CO_2 entering the system is derived from natural CO_2 reservoirs. However some of the CO_2 is derived from natural gas processing, the most recent example being the Century plant which will bring an additional 8.4Mta into the system. This compares with the total capacity of the system based on the capacities of the 4 main pipelines (Cortez, Sheep Mountain, Bravo and the planned Lobos pipelines) and natural CO_2 reservoirs (McElmo, Doe Canyon, Bravo and Sheep Mountain domes and the planned St John’s) described in the Kinder Morgan website. This amounts to around 45Mta.

News reports indicate a cost of around $1.1 billion for the capture facilities at Century which consists of two processing trains of 5 and 3.4Mta CO_2 each. The plant uses Honeywell UOP's Selexol process. The cost of capture at Century can be roughly estimated but depends greatly on project lifespan and required rate of return. For 10% return over 20 years with capital expenditure split 50/50 over 2 years and no operating costs price would be $16.9/tonne but at 20% return rises to $29.9/tonne. It should also be noted that a substantial part of the cost may be borne by natural gas sales as the process plant will be required to bring the high content CO_2 gas to sales specification.

The above compares with the cost of production of CO_2 from Bravo Dome reported in Oil and Gas Journal range from \$0.6/mscf to \$1/mscf, the latter being for much high recovery from the reservoir entailing more wells and gathering lines. (That is \$11.3 to 18.8 \$/tonne). Assumptions made in a 2010 white paper on CO_2-EOR potential a price of \$15 was assumed.

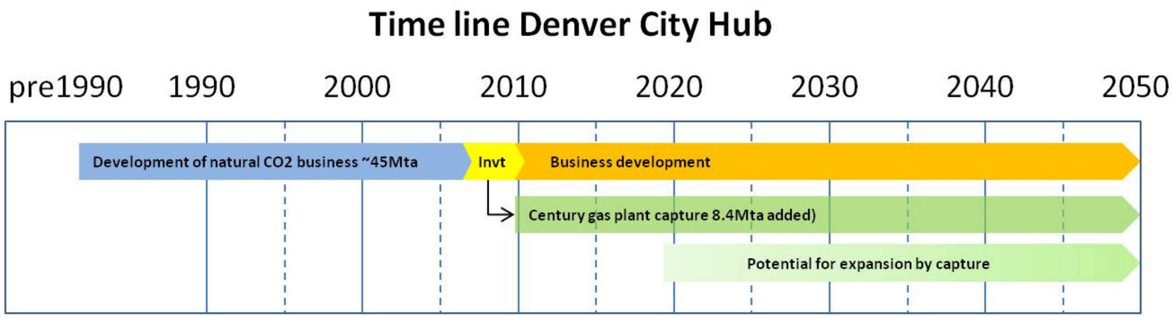


Fig 15 Time line Denver City Hub

4.8.2.2 Transport

Transportation is by pipeline at supercritical pressure and additions are routine in design and operation. In the case of the Century project a 160km pipeline has been constructed from the plant to the Denver City hub.

4.8.2.3 Storage

At present all of the CO_2 is destined for EOR projects and no projects purely for storage are projected. Commercial pressures continue to dictate that CO_2 consumption in the EOR process is optimised to the minimum per barrel of additional oil.

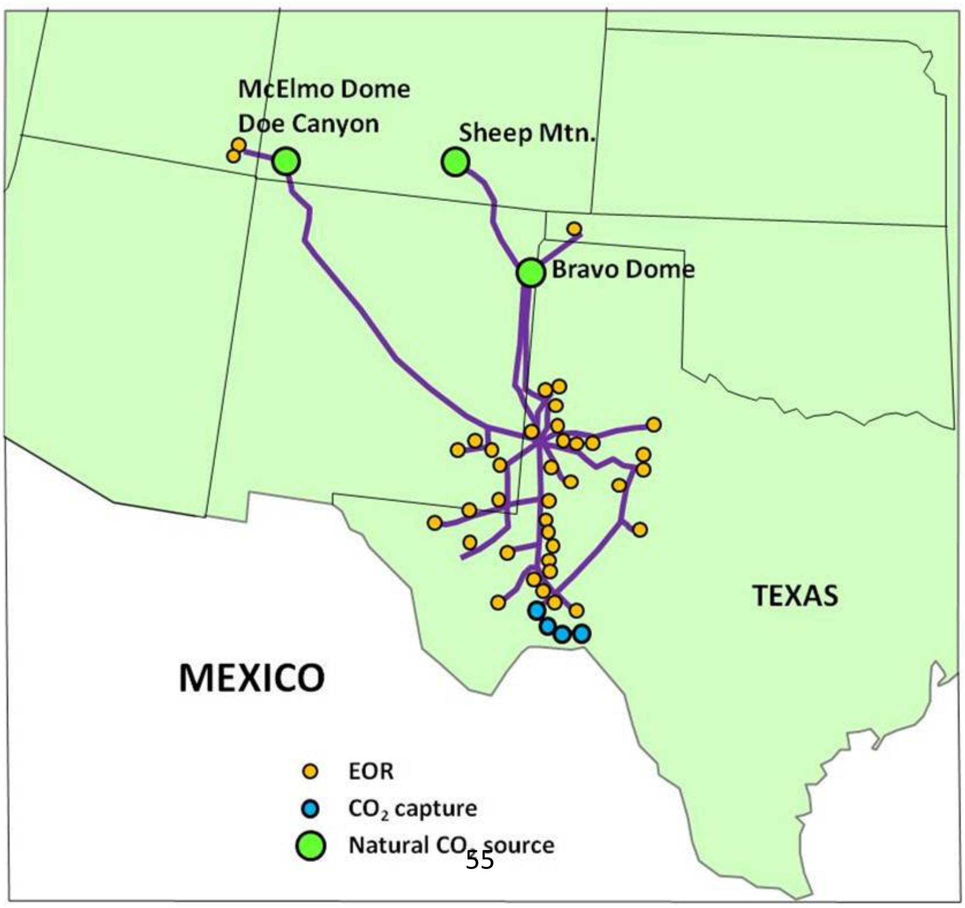


Fig 16 Map of Denver City hub CO_2 system

4.8.3 Denver City hub business plan

4.8.3.1 General

The extensive network of natural CO_2 sources, transport pipelines and EOR projects is owned and operated by a number of large companies. The sources and transport are dominated by Kinder Morgan but other consortia usually of 2 or 3 members own different parts of the supply and transport system. Most of the EOR operations are in effect the customers of the system. However the system participants also own/operate many properties engaged in EOR. The transport system makes use of publicly traded master limited partnerships. These have the advantage that they do not pay tax on profits directly. Taxes are only paid by unit holders when payments are distributed which can enhances the liquidity of the partnership.

4.8.3.2 Key partners

The main partner in the Denver City hub is Kinder Morgan. They operate not only the CO_2 business but also a range of oil and gas production and distribution facilities. Thus whilst their CO_2 operations are large they are underpinned by a much larger business portfolio. Parts of the system are co-owned and operated by other major companies involved in oil and gas and include Occidental, BP, Amerada Hess and Exxon Mobil. Some information on the various partnerships is available at the company's corporate websites and in their publications and also in news releases particularly those reporting new developments.

The mechanisms for forming the necessary partnerships to expand the network are mature.

4.8.3.3 Key activities

The key activities are operation of natural CO_2 reservoirs to supply CO_2, some operations of natural gas plants to remove and recover CO_2 to meet NG specifications, design construction and operation of CO_2 pipelines and more recently addition of booster pumping stations as well as operation of some EOR facilities. Operation of gas processing plants to recover CO_2 from the associated gas produced in the floods is also an activity which is undertaken on a contract basis.

The CO_2-EOR business which underpins the activities commercial success started in the mid 1980's and is now mature.

4.8.3.4 Key resources

The key resources are the large natural CO_2 reservoirs and their production wells and now starting to become more prominent, natural gas with higher than specification CO_2 content. The other key resource is depleted oil fields amenable to CO_2 flooding. Finally but not least the now extensive interconnected network of high pressure CO_2 pipelines

4.8.3.5 Cost structure

Commercial details of the detailed costs of the business are not generally published. However the main costs of well drilling and completion, pipeline construction and operation are well known to the industry partners. The costs of CO_2 capture from natural gas production and perhaps fertiliser production and gasification which are expected to become more prominent in the next phase of the business are less transparent. This is because the split of costs between the CO_2 business and the natural gas, synthetic gas or fertiliser businesses could be done in various ways.

4.8.3.6 Value propositions

The current CO_2 business is based on the profitability of extracting addition oil using the tertiary recovery method of miscible CO_2 flood. The sole proposition is that the costs per tonne of CO_2 is substantially less than the value of the extra oil recovery. No data was found on how the long term contract price was set. One interesting reference was found to a possible differential pricing mechanism which would supply CO_2 for the early part of a new flood at a lower price thus reducing the economic risk for the project. Continuation of a successful flood would then be at a higher price.

Data on contracts is sparse but one example quoted in O&G Journal suggest long term agreements – a contract between Occidental and Kinder Morgan for CO_2 supply to a flood at the Cogdell Canyon Reef unit is for 10 years. Thus continuity of supply can be part of the value proposition. No details of price escalation clauses was given but presumably these will also give long term assurance as part of the value proposition. Interestingly a further contract for processing the recycle gas from the field for 20 years was and returning the extracted CO_2 for a fee was also put in place.

The value proposition is relatively simple and mature in this region. No direct information was found on possible value of carbon emission credits but it seems likely that this will be added at some stage. This is based on the general contract clauses which are included in published specimen contracts for CO_2 supply which have a section covering carbon credits. Recently in the new point to point project in which CO_2 is sent from the Coffeyville fertiliser plant to Chaparral's EOR project in Osage county specific carbon credit clauses are included in the contract. Their terms are interesting in that they allow for transfer of credits or their monetary value only for deviations in offtake up to an amount which is less than the minimum yearly contractual amount of later years. The parties agree to transfer credits to compensate the source if less than the agreed offtake but only up to a maximum offtake of 640,000tpa. Interestingly if there is a failure to supply (but again limited to the 640,000tpa level) the source will transfer credits to the EOR project presumably on the basis that the source is now enjoying reduced emission charges but the EOR project is suffering from lack of supply.

However at present the value of such a clause is debatable. The Waxman Markey bill would have established a trading system and through other requirements a price for CO_2 in the

USA. However the bill was defeated in the Senate in 2010 and until Carbon Credits come into existence such clauses are essentially dormant.

A further interesting inclusion in this particular contract is a volume banking system which allows over/undersupply to be banked for up to 5 years which has the effect of greatly reducing the costs of failure of the EOR project to take contractual volumes in any one year.

4.8.3.7 Customer relationships

Few details of how customers are approached are published, usually only news bulletins and articles announce significant contracts and agreements between parties. The relationship is thus typical of that existing between the commercial departments of large oil and gas companies since the CO_2 transporters and suppliers are generally also engaged in this business.

The relationships existing are mature but as more anthropogenic sources become commercially viable they will need to be adapted particularly if the new CO_2 sources are not engaged in the oil and gas industry.

4.8.3.8 Customer communication channels

Again there are few details about how the communications are managed. There are general communications through articles, conferences and studies. There is also an organisation set up by the Centre for Climate and Energy Solutions in conjunction with the Great Plains Institute entitled NEORI (National Enhanced Oil Recovery Initiative). However the 32 members and observers do not include representative from Kinder Morgan (and neither from Denbury, one of the other major CO_2 suppliers).

The main communications with prospective clients and partners are presumably managed in the main on a one to one basis by the supplier’s commercial organisation.

4.8.3.9 Customer segments

The main segment is for customers engaged in EOR. The other identified segment is customers requiring gas processing involving CO_2 which may be for extraction from natural gas or from the recycle gas stream in an EOR operation.

This segmentation of the business is mature and it is not clear whether any other significant segments requiring different approaches are likely to emerge.

4.8.3.10 Revenue streams

The main revenue streams are transportation tariffs and sale of CO_2. Some revenue is also derived from processing CO_2 containing gas. No revenues from carbon Credits exist yet. It is not clear whether any revenues are being derived from specialist services related to design and operation of CO_2-EOR projects. In general these appear to be developed and run by the owners/operators of the units in which they are set up.

This is a mature industry with mature revenues. There is some evidence in news reports of adjustments to the tariff regime for example to supply initial tranches of CO_2 to a new EOR project at reduced price so that the customers risk from poor performance is reduced. EOR projects are often carried out in phases with the experience and performance of earlier phases influencing both the design and the extent of later phases.

4.8.3.11 Overall maturity

Overall the Denver City hub consist of a set of mature commercial operations underpinned by the centralised supply of natural CO_2 from a few very large sources. The business model is changing slightly as sources of captured CO_2 start to be exploited. Further changes may occur if and when carbon credits or emission taxes or restrictions are introduced by the either national or regional authorities.

4.9 The Gulf Coast cluster USA.

4.9.1 General

The Denver City hub described above is by far the largest CO_2 distribution pipeline cluster in the United States. Other similar clusters exist or are emerging and the most notable are described below. Of these the business of Denbury resources appears to be the next largest after the Denver City Hub. Unlike the Denver City hub their growing business is based in two main locations, the Gulf Coast and Wyoming with the intention of extending into the Rocky Mountain region where CO_2 from the Labarge field separated at the Shute Creek gas plant operated by ExxonMobil has been utilised for EOR since the mid 1980's mainly in the Rangely field. There was a major expansion in capacity at Shute Creek in 2010.

4.9.2 Gulf coast cluster technical details

4.9.2.1 Capture

Denbury Resources has completed one project to bring in captured CO_2 into its systems. Two Air Products hydrogen plants at Port Arthur have been equipped with capture facilities and supply approximately 1Mta of CO_2 in the Denbury Green Pipeline. This compares with a capacity of natural CO_2 of around 25.9Mta. The plant and spur line cost $431 million of which $284 million was funded by the DOE. The economics of this compare poorly with those for the Century gas plant. For 10% return over 20 years with the full capital expenditure split 50/50 over 2 years and no operating costs price would be $55/tonne. If the private capital is taken as only 1/3 of the total the costs are then $18/tonne which is more in line with actual CO_2 costs from the competing natural sources.

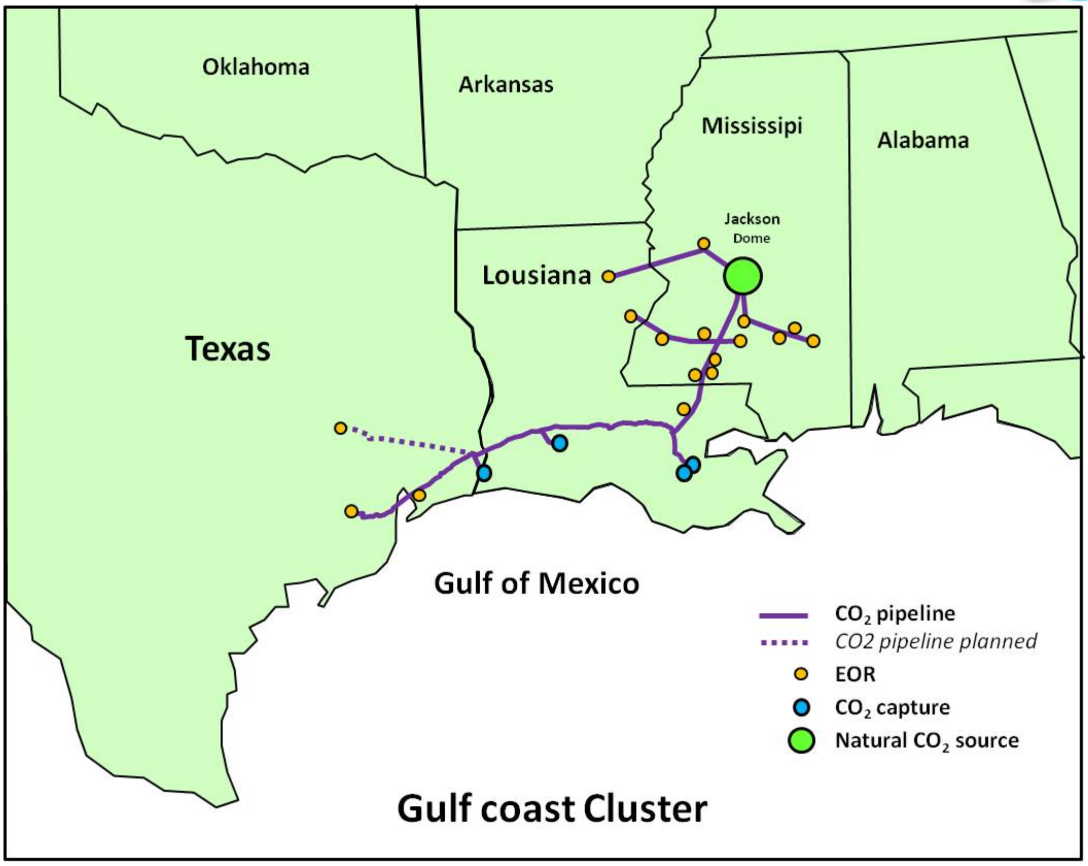


Fig 17 Gulf Coast USA cluster map

On a wider front Denbury has claimed to have identified potential for contracts to acquire captured CO_2 amounting to 48Mta (1500mscfd) in the regions where it is planning to operate. Some of these are in the Gulf Coast region. An up to date description of these opportunities is given in their 2013 investor presentation. (38)

4.9.2.2 Transport

The backbone of the Gulf Coast system is a single 24inch 320km pipeline (known as The Green Pipeline) running from the Jackson Dome to the Hastings oil field. It is also linked to some other EOR sites. The Port Arthur facility is linked into this pipeline by a 23km feederline. There is nothing particularly special about the line but one fact has important implications for the industry in general and that relates to the status of the main line as being in the "eminent domain". This means that it has common carrier status which confers certain rights of access. This status was successfully challenged in the Texas courts on the basis that whilst the CO_2 from Port Arthur along with plans to bring in CO_2 from other third parties fulfilled required conditions of public access, Denbury were only supplying to their own EOR projects. To qualify both CO_2 inputs and outputs from the system would thus need to include some from and to third parties.

4.9.2.3 Storage

The sole destination for CO_2 whether natural or captured is EOR and for the time being in units operated by Denbury. It may be expected that as the supply and transport systems develop more third parties will be drawn is as customers. For the time being there is a very large EOR potential which has been identified so that storage purely for carbon emission reduction is unlikely to compete.

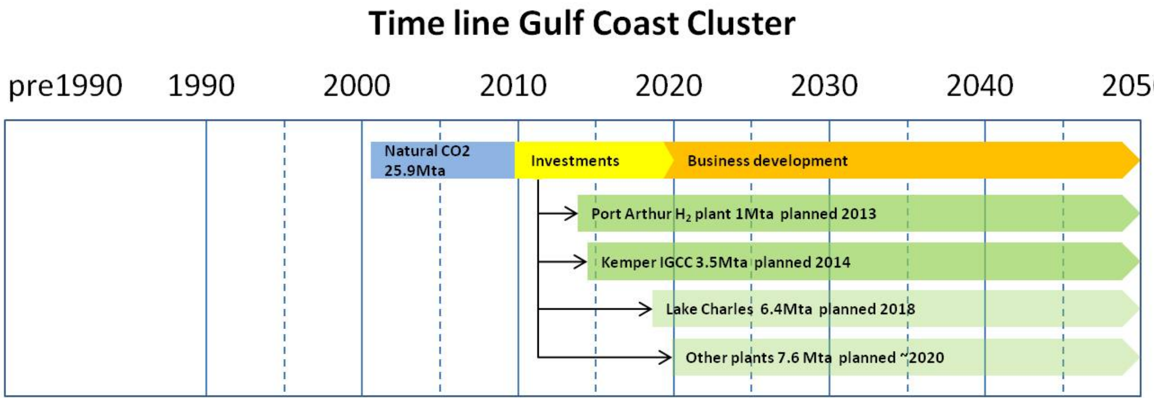


Fig 18 Time line Gulf Coast Cluster

4.9.3 Gulf Coast system business Plan

4.9.3.1 General

The business plan is driven by Denbury who seek to expand their EOR operations supported by bringing in new sources of CO_2 supply and transport. Although the Gulf Coast region is most advanced in this similar aspirations are held for the other regions in particular the Rocky Mountain region.

4.9.3.2 Key partners

Denbury Resources is working on its own to expand its CO_2 supply and transport system to support an increasing holding of EOR projects and are using acquisitions as the main method for growth. However the supply of anthropogenic CO_2 will be by bilateral agreements with the sources. In the gulf coast region bringing in partners for the transport operation by forming Master Limited Partnerships has been investigated but rejected as not in the best interests of shareholders.

4.9.3.3 Key activities

The key activities are identifying acquiring and developing suitable mature oilfields suitable for EOR using CO_2 flood. In addition the firming up of contracts to obtain additional supplies of CO_2 from industrial sources. The literature would suggest that the capture would be performed by the companies who own these sources. Another key activity is working on obtaining government financial support for early capture projects.

4.9.3.4 Key resources

The key resources are the backbone of natural CO_2 reservoir and distribution pipeline. In addition the ability to assess fields for EOR and acquire these. Acquisition of additional CO_2 supply from anthropogenic sources is seen as an important resource for the future if this can be acquired at acceptable cost. The identified potential amounts to about 19Mta over and above the 25.9Mta existing reported capacity of Jackson Dome.

4.9.3.5 Cost structure

The costs for production of natural CO_2, transport and injection for EOR are well understood. The costs for bringing captured CO_2 into the system from sources other than natural gas processing are less well understood and particularly the assignment of costs between CO_2 captured and the other products an issue which probably also applies to separation in gas plants. Although total costs for the Port Arthur and Kemper IGCC plants are reported the allocation of costs to capture was not.

4.9.3.6 Value propositions

The key value proposition is incremental oil production from EOR and the value of the reserves which EOR unlocks. This is the key proposition which is put to investors in the company's literature and is also extensively researched in more general studies. (ref e.g. NEORI reports). Denbury's particular proposal is that it can finance expansion of EOR operations through careful selection of the best performing floods and disinvestment from poorer elements in its portfolio. A minor proposition was the purchase of CO_2 and transport through a pipeline system with "Eminent Domain" status. This status has been challenged and was recently withdrawn. It is possible that in future, supply of CO_2 through a common hub system may be offered, especially if this enables easier extension of the distribution system be re-acquiring eminent domain status.

4.9.3.7 Customer relationships

The relationships are similar to those for the Denver City hub.

4.9.3.8 Customer communication channels

The channels are similar to those for the Denver City hub. The lobbying activities of Denbury (and also Kinder Morgan) were checked but do not seem to be particularly directed towards obtaining Government support as was the case for the ACTL in Canada.

4.9.3.9 Customer segments

At present Denbury has a policy of keeping or acquiring ownership of the destination EOR fields so that this is not a customer segment in the way that it is for the Denver City hub. Within the system Denbury will itself be the main customer for captured CO_2. As this entails bilateral agreements with a relatively small number of potential suppliers there is also no segmentation as such. The other key "customers" are Denbury's investors and the Government for grants towards capture plants but again the concept of segmentation does not appear to be helpful in the current business structure.

4.9.3.10 Revenue streams

The main revenue stream is from sales of incremental oil since the CO_2 at present is not being supplied to third parties. Suppliers of CO_2 will derive revenue from the system operator which together with government grants constitute the revenue stream for their participation. At present there is no revenue stream from carbon credits.

4.9.3.11 Overall maturity

This business is relatively new and its adaptation to encompass a significant proportion of captured CO_2 has only just started. Issues such as continuity of supply and off-take are recognised and will need to be addressed in supply contracts and also in off-take contracts to third parties if these materialise in the future. It is also not yet adapted to third party sale of CO_2.

4.10 Rocky Mountain cluster, USA

4.10.1.1 General

This cluster is the third most prominent in the USA and its development is similar to that of the Denver city hub in that different companies are owning and operating parts of the system. It is however much more dependent on captured CO_2. The main source is a very high (65%) CO_2 content natural gas from the LaBarge field. Thus part-way to being a natural CO_2 reservoir. The gas from this field is processed at ExxonMobil's Shute Creek facility and historically (since 1986) some of this CO_2 was captured for supply to Chevron's Rangley field EOR operation. Recently Denbury has added capture from a similar field at Riley Ridge and plans to co-operate with ConocoPhillips to capture gas from the Lost Cabin gas plant. Other sources are also identified.

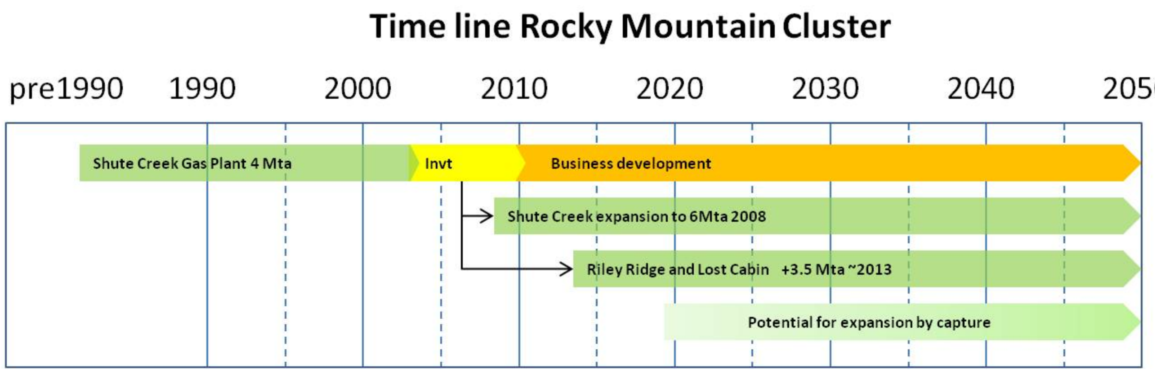


Fig 19 Time line Rocky Mountain cluster

4.10.2 Rocky Mountain cluster technical details

4.10.2.1 Capture

The main capture plant is Shute Creek processing gas from the LaBarge field. This plant was upgraded in 2010 to a capacity of 7Mta using ExxonMobil's Controlled Freeze Zone technology. To this has been added 1Mta of CO_2 as from the Lost Cabin gas plant owned and operated by Denbury Resources. Denbury has acquired a 1/3 royalty interest in the Labarge field and will purchase up to 3.7Mta for Shute Creek for its own expanding operations. Denbury has also acquired Riley Ridge (an extension of the Labarge field) and the Riley Ridge gas plant which it intends to bring on stream in 2017 to supply 2.5Mta of CO_2. The plant will also extract Helium (Note Helium content is owned by the US Government but Denbury has the right to extract and sell the helium for a fee) There are further less defined plans to capture CO_2 from additional sources in the area.

4.10.2.2 Transport

An interconnected transport system is developing in the region. An existing system with a total length of over 300km connects Shute Creek to Rangely (SSE) and to Monell, Beaver Creek, Werz, Lost Soldier and Grieve to the North East. Denbury has recently built a 232km 20” line (the Glencore line) from Lost Cabin to Bell Creek effectively extending the system by about 200km further to the North East. Further expansion to connect more sources and more EOR fields is in planning.

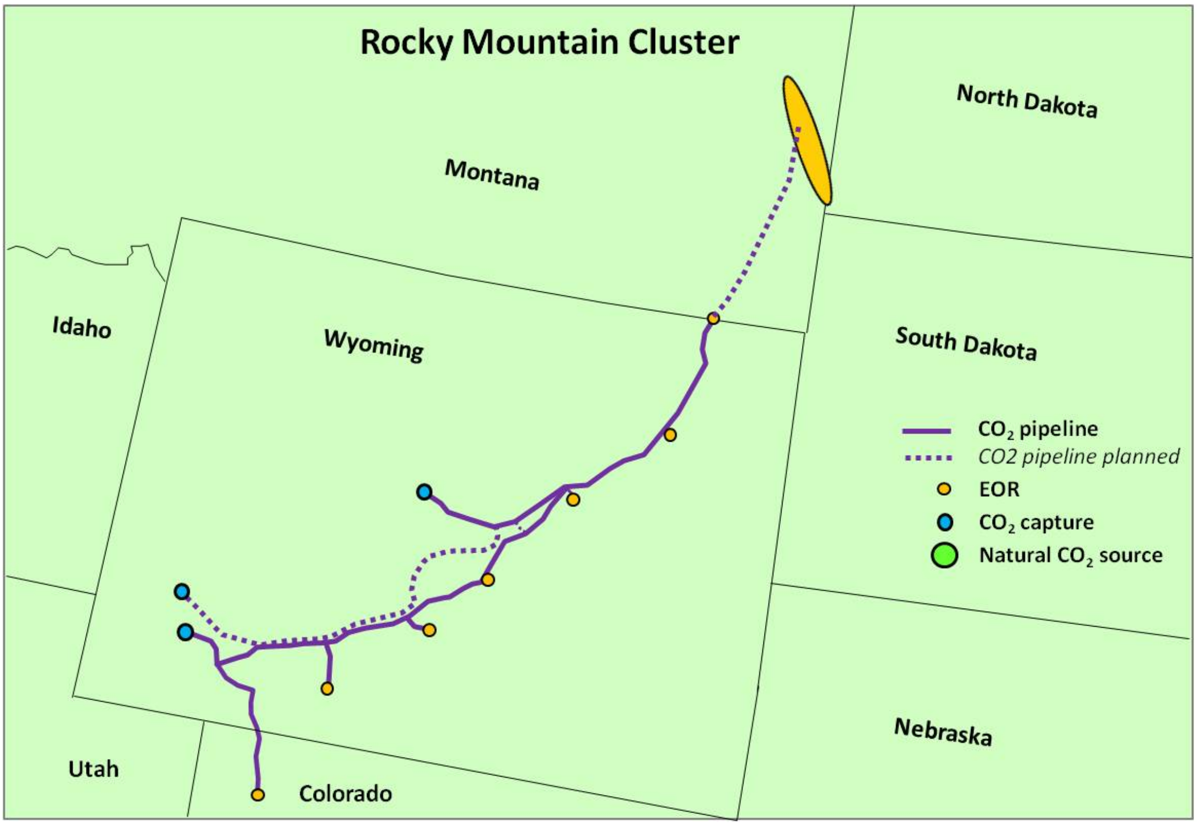


Fig 20 Rocky Mountain region cluster, Wyoming, USA

4.10.2.3 Storage

Again the sole destination for the CO_2 is EOR. The EOR fields are operated by several different companies including Anadarko, Chevron, Devon Energy, Merit Energy, ConocoPhillips and Denbury Resources.

4.10.3 Rocky Mountain cluster business plan

4.10.3.1 General

The business is a mixture of very mature Capture and EOR operations and a recent expansion with Denbury Resources apparently leading through acquisitions and expansion. Unlike the Gulf coast system and more akin to the Denver City hub there several owners/operators of the various parts of the system.

4.10.3.2 Key partners

ExxonMobil Anadarko, Chevron, Devon Energy, Merit Energy and Denbury Resources are currently all active in various parts of the system. New partners may become involved either as suppliers or as users of CO_2 and acquisitions of interests are considered likely.

4.10.3.3 Key activities

The key activities are CO_2 capture currently by extraction from high CO_2 gas, CO_2 transport and EOR. An additional and new activity is capture and sale of Helium although this can only be a minor part of the business. A critical activity is identification of new CO_2 sources and EOR prospects as these are the basis of further growth. In this region there is less need for Government funding for the capture. Some DOE funds have been awarded through the PCOR partnership aimed at improving understanding of the EOR potential, CO_2 storage potential and the measurement, monitoring and verification of storage of the injected CO_2.

4.10.3.4 Key resources

The key resources are access to sources of CO_2 at affordable cost and depleted oil fields amenable to CO_2 flood. Also the distribution system for the CO_2. Access to funds for the developments is also important and these are resourced from the profits from ongoing operations of the various oil and gas companies involved.

4.10.3.5 Cost structure

The costs for separation of CO_2 from high CO_2 content natural gas are well understood especially since the key plant has been in operation since the mid 1980's. The allocation of costs between CO_2 and natural gas is not revealed. It could be argued on the basis of the following that most of the costs should be allocated to the natural gas production. This because in June 2008, ExxonMobil was ordered by the Wyoming Oil and Gas Conservation Commission to curb carbon dioxide emissions at Shute Creek and redirect the greenhouse gas into pipelines for enhanced oil recovery. The commission also passed a resolution requiring the company to submit progress reports to the commission detailing its progress in marketing much of the CO_2 it vents.

4.10.3.6 Value propositions

The main value proposition is production of incremental oil through EOR. Also the delivery of CO_2 at an affordable price. An additional proposition following the Conservation Commission ruling is the ability to produce and sell gas from high CO_2 reservoirs.

4.10.3.7 Customer relationships
The relationships are similar to those for the other US hubs.

4.10.3.8 Customer communication channels
The channels are similar to those for the other USA hubs.

4.10.3.9 Customer segments
Similar to other USA hubs.

4.10.3.10 Revenue streams
The main revenue stream is from sales of incremental oil. Also in this system there are sales of CO_2 between the parties and these will include transport tariffs. There is an additional minor source of income from Helium sales reduced by the US Government royalty fee. An indirect source of revenue for CO_2 suppliers using high CO_2 content gas reservoirs is the revenue from gas sales which otherwise might not be possible due to withholding of operating permissions.

4.10.3.11 Overall maturity
The Rocky Mountain system is a development of a very mature business. Although employing captured CO_2 this is an established practice unlike that in the Gulf Coast region. If the source of capture changes the business plan will need to be adapted. As the system is already quite large the issues of continuity of off-take may be less although if significant CO_2 venting is not allowed the production of CO_2 will become closely linked to gas production. It is not reported whether this is at all seasonal but if it is then the issue of variable production will need to be addressed. It is not known whether Helium production would impose similar continuity of supply constraints.

4.11 Shenzhen City cluster China

4.11.1 General
This cluster has only been explored at the academic level and is reported in a scientific paper. Shenzhen is situated at the mouth of the Pearl River and is a city which has grown rapidly in the last decades. A CO_2 hub located here could ultimately collect also from Hong Kong. It was selected from several other potential clusters in Guangdong province for a more detailed economic assessment. Two other potential clusters were identified feeding into hub locations at Zhanjiang to the South West and Shantou to the North East of Shenzhen.

4.11.1.1 Key information sources
The main source of information is academic papers (39) “Getting ready for carbon capture and storage through a ‘CCS (Carbon Capture and Storage) Ready Hub’: A case study of Shenzhen city in Guangdong province, China” and (40) “Financing New Power Plants ‘CCS Ready’ in China – a case study of Shenzhen city”.

4.11.2 Shenzhen City cluster technical details

4.11.2.1 Capture

Few technical details are given on how capture would be carried out. Two main cases are considered. In one the capture of emissions from a new 4GW coal fired power plant are considered. This would form an anchor plant for the system. In the other this along with capture of emissions from a number of other sources in Shenzhen city are evaluated. The capacity of the smaller option would be 25Mta and that of the larger option 43Mta. The study suggests that new power plants should be made capture ready and estimates the cost of adding capture in a retrofit as 60% of the capital cost of the main plants. As total capacity goes beyond 18Mta the study indicates that capture from gas fired units would be required which it notes is considerably more expensive. Also capture would be required from existing plants with progressively shorter remaining economic life which also pushes up the unit costs for the overall system.

4.11.2.2 Transport

The main assumption is that a 250km offshore line would be required and that this would enable a number of potential storage reservoirs to be reached. For the higher capacity option an additional onshore network extending for a total of 292km would be required. Part of this would be a Y shaped trunk line of about 69km into which other gathering lines would join. Overall Capex and Opex cost estimates are given but no technical details of line sizing or operating conditions are given.

4.11.2.3 Storage

The study references potential storage capacity in 3 offshore basins totalling over 93,000Mt. Most of the storage is in saline aquifers with just 60Mt potential in depleted oil and 12Mt in depleted gas reservoirs. Significant work on characterisation would be required in order to prove up sufficient of this large potential capacity. Capital costs are estimated as CNY57 Million for 25Mta case and only slightly higher at CNY62 million for the 43Mta case. Operating costs for storage were estimated at CNY25/tonne (1US$ =6.5CNY).

4.11.3 Shenzhen City cluster business plan

4.11.3.1 General

The study work so far only outlines the potential scope and rough costs. There is insufficient detail to be able to analyse the business plan elements at this early stage. Hence only key points raised will be reported here. The main value proposition is that investment in making any new plant capture ready will ultimately reduce overall abatement costs by 15-20%. The economic study suggests some unit cost reductions for the transport and storage elements as capacity increases but this appears to be more than offset by increasing capture costs as more difficult to process sources are added to the network.

4.12 Marseille and area cluster (VASCO study)

4.12.1 General

This study entitled Valuation and storage of CO_2 was carried out between 2010 and 2012. The study was led by GeoGreen and supported by several other research institutions. It was sponsored by about 8 other organisations including major industrial companies and regional authorities. The study was at high level and identified 3 scenarios, high, medium and low. Initial characterisation of nearby storage sites was done and a tentative capture and pipeline transport network proposed. Opportunities for shipping of some CO_2 to North Africa for EOR were also proposed. Since the project was finished there does not yet appear to have been any commercial take up.

4.12.2 Key information sources

The results of the VASCO study are held by GeoGreen and other organisations who took part in the study. The results of the project are outlined in a presentation given at TCCS7 in Trondheim available at GeoGreen's website (41).

4.12.3 Marseille area cluster technical details

4.12.3.1 Capture

The study identified 4 concentrations of sources in the South of France near Marseille at Berre, Beaucaire, Gardanne and Fos-Lavera. Capture from sources amounting to between 19.9, 28.9 and 35.5Mta for the 3 cases was projected. A capture efficiency of 79% was assumed but because of the energy requirements for capture these base emissions would rise slightly so that CO_2 avoided would be about 74%. The report showed that capture would use a mix of the three main processes, post combustion pre-combustion and oxy-combustion. Some locations where capture by absorption and regeneration of rich solvent would be aggregated were identified.

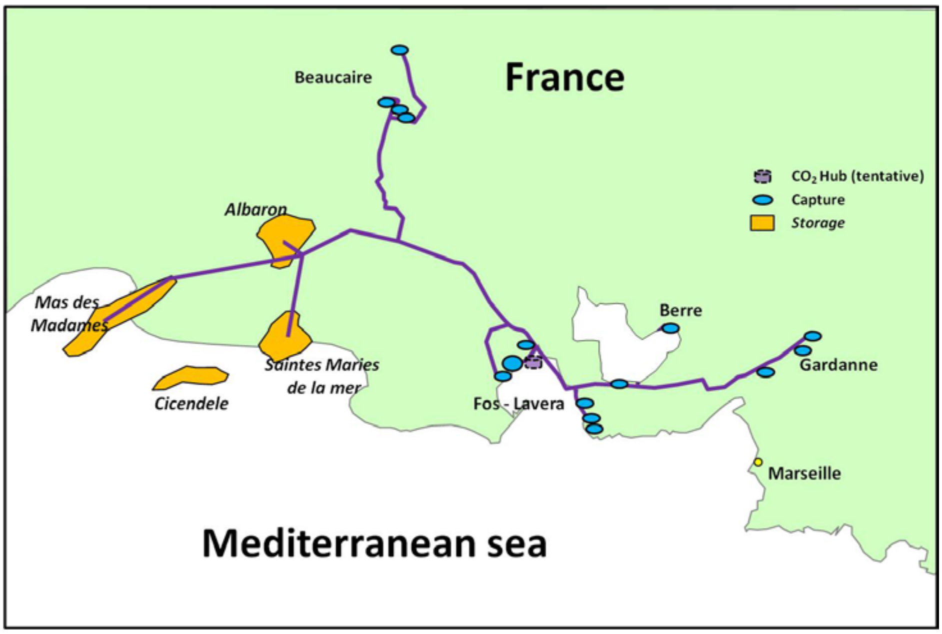


Fig 21 VASCO project Marseille, France, Cluster Map

4.12.3.2 Transport

The bulk of the transport would be by high pressure pipeline to storage locations located about 40 - 60km due west of Fos. The network would comprise around 200km of lines with sizes in the range 14 to 30inch. Low pressure local networks are also envisaged for aggregating CO_2 from nearby sources but no details of the pressure of operation were found.

4.12.3.3 Storage

Storage would be in up to 4 potential storage sites to the West of Fos. These have been identified only from interpretation of available geological data and would need to be proven. Reservoirs of >800m with favourable structures and effective caprock are present at Albaron which is onshore, Cicendele which is close offshore, Stes Maries de la Mer, Mas des Madames both of which straddle the coastline. All of these prospects would require extensive investigation in order to fully characterise them.

The other option noted in the study was export of CO_2 by ship to clusters of oilfields in North Africa. The key target would be Libya but Egypt is also considered a possibility. Fields in Algeria were considered but do not seem to be a part of the plan.

4.12.4 Marseille area cluster business plan

4.12.4.1 General

The VASCO study is the first co-ordinated investigation of the cluster around Marseille. It was supported by some large industrial concerns and the local regional authorities. It also brought several leading French research and development organisations together to work on the various aspects of the study. However at this stage there is no evidence that industrial consortia are forming to take the project further.

4.12.4.2 Key partners

The study identified the main sources of CO_2 and dialogues and meetings were held in order to help in preparing the regions emission database. The study was also well supported by the local regional authorities. However at this stage it does not appear that any more enduring partnerships have been set up.

4.12.4.3 Key activities

Key activities were only identified at high level and include the usual main elements of the CCS chain. Shipping is identified as one potential activity with the port of Fos as the export location. However no information on the destination ports or onward distribution were found in the presentation material. The project focussed to some extent on possible industrial use of CO_2 and concluded that there was some scope for algae production which would thus be one of the projected activities.

4.12.4.4 Key resources

A key resource would be the nearby storage. This is very close to the site and mostly on land which would have a considerable cost advantage. However this storage resource would need to be proven. Apart from the usual CCS chain resources a local aggregation network and shared capture and solvent regeneration facilities were proposed as part of the resources. Also a possible CO_2 shipping terminal at Fos although details of intermediate storage requirements and exact location of the berths were not indicated.

4.12.4.5 Cost structure

No details of the costs structure were given.

4.12.4.6 Value propositions

The value proposition was only described at high level and no discussion of carbon credit *per se* was included although this could be presumed to be part of the proposition. Meeting national targets is mentioned and also giving the industrial region a low carbon footprint which if not implemented might ultimately threaten as much as 85% of the employment in a carbon constrained society. On the positive side an increase of as much as 7% in local employment could result if the cluster plans were implemented. Expansion of the port bulk capacity of between 4 and 6% is also mentioned as a possible benefit. A small percentage of the CO_2 would go to value creating activities namely 10% to EOR and 2% to algae production. In addition a negligible but still growing amount would go to other small scale industrial uses.

4.12.4.7 Customer relationships

No details found.

4.12.4.8 Customer communication channels

No details found.

4.12.4.9 Customer segments

The only segmentation is that of the different types of sources although it is not clear of this would lead to different approaches for these customers.

4.12.4.10 Revenue streams

Although the various value propositions are mentioned exactly what revenue streams would result and how large these might be was not addressed at this early stage.

4.12.4.11 Overall maturity

This cluster is at a very early stage of development. The opportunity has been identified and shown to be of considerable scale. Also the possibility of a storage site close by has been identified. Some additional revenue generating options have been identified although the economics of these are uncertain. Although several organisations have co-operated to perform and support the study mobilisation of partners to develop elements of the business has yet to occur.

4.13 The Le Havre cluster, France – COCATE project

4.13.1 General

The COCATE project was an EU funded study which examined amongst other things the technology and economics of collecting raw flue gases from large emitters for capture of CO_2 at near atmospheric pressure at centralised locations. It also examined options for further collection of the captured CO_2 to a hub location by pipelines operating at low or high pressure and with or without refrigeration. In this project insulated refrigerated pipeline transport was evaluated within the Le Havre area for transport to a central hub for comparison and not specifically to enable shipping. In order to provide realistic figures and concepts the study was based around collection of CO_2 from large emitters in the Le Havre area. Thus many of the issues relating to a CCS cluster based at Le Havre were explored. However further development of a business plan for the cluster has yet to occur.

4.13.2 Key information sources

Most of the publications produced by the COCATE project are proprietary to the partners and are not publically available. The main information source is the publishable summary of the project results (42). Additional details were presented at a workshop held in Johannesburg (43) and a conference in Pittsburgh (44).

4.13.3 Le Havre cluster technical details

4.13.3.1 Capture

The characteristics of a system whereby the stacks of major emitters were fitted with booster fans to transport the flue gases to five central locations for post combustion capture were evaluated. Key design issues such as pressure drop, gas velocity, selection of materials were addressed in the study. Pooling flue gases to central locations was found not always to be the best solution and alternatives in which solvent was distributed to absorbers closer to installations were also studied. The local collection of CO_2 from the pooled capture locations was also investigated. Collection using high pressure, low pressure and refrigerated liquid conditions were compared with the conclusion that high pressure or refrigerated liquid based collection systems were cheaper. The total capacity of the system which was studied

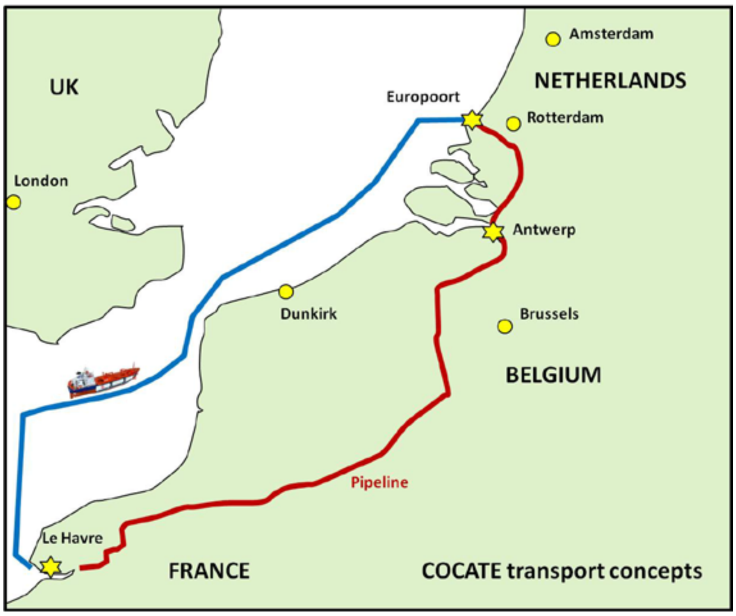


Fig 22 Le Havre France, project cluster project map

was 13.1Mta and a two-step option in which an initial tranche of 4.3Mta was collected followed by an expansion to 13.1Mta after 7 years.

4.13.3.2 Transport

The study compared onshore offshore and shipping options for onwards transport of CO_2 from Le Havre to a hub at Rotterdam. The onshore route of some 616km via Antwerp was the cheapest option but not by a large amount. This route required booster pumping stations. Some safety issues would need to be resolved for the overland route. The study also evaluated shipping on a 60 day cycle using 3 sizes of ship namely 20,000, 30,000 and 40,000 m^3. This was found to be slightly more expensive and was not particularly sensitive to ship size as long as the number of ships was selected so that the cycle did not involve excessive waiting.

The offshore line would be 28" and operate at 200bar whilst the onshore line would run at a lower pressure of 150bar and be between 24 and 28" with booster stations roughly every 100-150km.

Unit costs were estimated for pipeline, ship and some ship/pipeline combinations in a 2 step development. Costs ranged from €20-23 per tonne for the two step options compared to €17 per tonne for a single stage onshore pipeline running at full capacity from the start of operations. Estimates were based on steady flows over 30 years with the step up after 7 years and a discount rate of 8%.

4.13.3.3 Storage

Storage was not investigated as it was assumed that this would be provided by the destination hub at Rotterdam.

4.13.4 Le Havre cluster business plan

The study looked at options for setting tariffs and assessed barriers to commercial implementation. There is insufficient detail published to address the 9 business plan elements separately thus only general information from the published material will be covered. The partners who undertook the study would not necessarily be those who would form the consortia to implement the cluster. The study was very focussed on the transport element including that needed for local aggregation of emission sources. A reasonable understanding of the relative costs for a range shipping, pipeline and hybrid shipping pipeline systems was obtained and a proprietary economic model was developed. The major costs for an integrated cluster will be for capture and storage and these would thus also need to be understood. For a real cluster project much more detail would be required to develop a full cost structure and to ensure that all cost elements were covered. The resource requirements have been defined at high level and a good understanding of the local site and routing issues gained. The value proposition and associated revenue streams are not developed in any detail. The main proposition appears to be that costs can be lower through pooling. The study explored a number of generic options for interlocking businesses which would run the key parts of the system. It concluded that if possible the number of separate system operators should be kept to a minimum with a few operators offering several of the required elements, otherwise setting up would be very complex. The study made a start at recognising the various customer segments in particular identifying that large and small emitters may need to be treated differently. The rough segmentation into emission source industry types was also made although whether these segments would need different treatment was not explored. A start on understanding and setting up channels of communication with potential customers has yet to be made.

The COCATE study was a technical and economic study which used a specific potential cluster location to make the results realistic. It provides useful groundwork and information which could be used in developing a business plan for any new cluster development but did not set out to produce a business plan as such.

5 Less developed cluster opportunities

5.1 General

The CCS clusters described in section 4 are those which from the literature appear to have evolved to the point that they have a distinct identity and for which some insight into their business plan is available. There is also a considerable body of literature which looks at CCS clustering in a more general context at regional and global level, suggesting regions where clustering might be possible. This section 5 provides an overview of a selection of these less developed clustering possibilities.

5.2 Iberian Peninsula Clusters

5.2.1 General

Studies have identified a number of potential clusters in this region but plans are at a high level and further development of planning for discrete source sink clusters has still to occur (45), (46), (47). Under the EU COMET project an economic analysis of the potential for CCS in Spain, Portugal and Morocco was done. By applying least cost algorithms the general sequence in which storage and sources were expected to be developed was thus explored. This suggested that only a limited number of 8 sinks would be utilised and also a limited number of regions connected. Of these two have capture total emissions above 10Mta, 8 above 5Mta and three above 3Mta. The potential for clustering has also been examined specifically for Portugal.

5.2.1.1 Capture

The study collected information on major point sources and grouped these into clusters. Only general economic assumptions were made about capture costs. The study narrowed down those clusters of sources most likely to be captured.

5.2.1.2 Transport

The main output of the study was the mapping of routes with application of the constraints of no cross border transport and use of existing pipeline corridors. As such the results indicated the most favoured corridors for pipelines but did not delineate specific discrete source/transport/sink CCS clusters. It did however identify a few possible combinations based on inspection of the mapping of the overall results.

5.2.1.3 Storage

The economic constraints applied by the model meant that of 40 potential clusters of storage only 8 were likely to be utilised.

5.2.1.4 Potential CCS clusters

Based on the forgoing the following "complete" source/storage clusters were noted. Navarra/Logroño in the north east of Spain, Barcelona/Alcañiz in the east of Spain, Huelva & Gibraltar/Úbeda, in the south of Spain, and Sines & Coimbra/Lusitanian onshore basin in Portugal (see more details for Portugal below). The level of detail on potential Spanish clusters is insufficient for further analysis as their components have only been considered as part of a regional optimisation model.

5.2.2 Portuguese clusters

5.2.2.1 Sources of information

A number of more detailed papers on Portuguese CCS opportunities have been published some under the MIT Portugal programme. These give some insight into where sources are clustered and where the most prospective storage locations are to be found. (48), (49), (50), (51), (52).

5.2.2.2 Capture

The main sources are clustered into three areas, Lisboa/Setuba/Sines, Coimbra/Leira/Pego, and Porto. These have emissions of around 16.7 Mta, 5.8Mta and 2.6Mta respectively

5.2.2.3 Transport

There are already well established pipeline routes between these source clusters which have been identified as potentially of use to provide ROW for CO_2 transport. The disposition of potential storage sites and the small size of two of the clusters suggests that an interconnected system with a backbone serving the Sines area should be adopted. The smaller source areas are less likely to be able to form economically viable CCS clusters on their own.

5.2.2.4 Storage

Storage opportunities close to the emission sources are limited and not yet characterised. The most promising in terms of potential and location appear to be in the onshore and offshore Lusitanian basin and the Porto basin. These are some distance from the largest source cluster which is in a high seismicity area and has no obvious storage opportunities. Several papers provide information on the geology of possible storage sites in Portugal but much work needs to be done to find and characterise suitable reservoirs.

5.3 Other CCS clusters in the USA

Three clusters based on existing EOR operations have already been described. Inspection of the NETL and GCCSI databases reveals about 24 integrated CCS projects in the USA at various stages of development. However these are all classed as point to point projects. In the general study of sink source matching carried out for IEAGHG by Element Energy (53) found relatively short distances for many of the CCS opportunities in the USA. This may explain why cluster projects where CO_2 captured from multiple sources are collected do not yet appear to be in development in the USA. The advantage of pooling capacity investigated in a number of studies does not reduce overall costs of the CCS chain by much especially if the transport distances are short. It also requires commitment of multiple sources early on to avoid underutilised capacity. Such underutilisation has been shown to significantly increase costs. The other reason may be that in the competitive environment of the USA such co-operation would be difficult.

5.4 CCS clusters in Germany

There are a number of regions with clusters of emitters with the largest and most concentrated being in the state of North Rhine-Westphalia. However no cluster projects are under consideration and even the point to point CCS projects which have been proposed are either shelved or not progressing. A recent paper on the role of CCS in Germany (54) suggests that this could be very primarily because renewable electricity generation will be more competitive in most cases by the time large scale commercial CCS can come to the market. There is limited onshore storage and there are public concerns about its use. CCS may still have a role in other industries such as cement and steel where some of the emissions are not energy related and thus cannot be eliminated by using renewable energy technologies. It should be noted that the Rotterdam Climate Initiative (RCI) has identified emission sources in Germany as having the potential to be included in an expanded Rotterdam CCS cluster.

The FP7 CO_2Europipe project reported on the feasibility of large scale transport in Germany (55). It identified transport corridors and the main emission clusters. It showed that there was significant capacity for barge transport through to Rotterdam and that this could form an important part of a CO_2 transport network. It also examined scenarios where onshore storage, which is controversial in Germany, was not allowed. This would greatly reduce the scope for economic application of CCS.

The work on CCS clusters in Germany has not yet progressed to the stage of developing business plans for a complete CCS cluster system. The report did consider the financing of the CO_2 transport pipelines. The performance of several major gas pipeline companies was analysed and this revealed a heavy reliance on low cost loans and limited amounts of equity. It concluded that key factors would be access to low interest loans, long term contracts and having political risks being covered by Governments. The companies would have to be able to charge a tariff similar to that which covers their costs for natural gas transport.

5.5 Global and regional clustering studies

5.5.1 General

There is some literature on global opportunities for clustering sources and sinks. These identify interesting locations but do not go into the same depth as that found for the clusters which are (or have been) actively developed as described in the foregoing sections. The following sections identify and discuss some these wider ranging and higher level studies.

5.5.2 Development of a global CO_2 pipeline infrastructure

This is an IEAGHG report (53) prepared by Element Energy building on earlier work on source sink matching by Pöyry. It identified likely clusters of sources connected to sinks or clusters of sinks. It estimated the percentage saving in pipeline length which might be made by such sharing of pipeline infrastructure. Although considerable length and cost savings could be made in some locations, the report concluded that these could be lost through delays in filling capacity or through delays caused by longer construction periods.

5.5.3 One North Sea

This study was carried out by Element Energy and others on behalf of the North Sea Basin Task Force (56). For the Norwegian Ministry of Petroleum and Energy and the UK Foreign and Commonwealth Office in 2010. It examined scenarios for CCS in countries surrounding the North Sea ranging from a "Very High" case in which 273Mta would be stored by 2030 down to a "Medium" case in which only 46Mta would be stored largely in point to point projects. Five intermediate cases were developed in which various types of restriction applied to the Very High case. Restrictions were lack of cross border transport agreement, exclusion of hydrocarbon fields, no onshore storage, poor aquifer capacity and low investment in capture. Clustering would be considerable in the very high capacity cases but far less important in the others.

5.5.4 UNIDO study

UNIDO commissioned a global study (57) relating to clustering of CCS from industrial sources in non OECD countries. The study performed by GeoGreen considered 5 categories of industrial sources:- iron and steel production, cement production, downstream oil and gas (refineries), biomass/bio-energy-related and a group of technologies considered high CO_2 purity sources (including gas processing). These were matched with sinks and potential capacities identified. The study established "hotspots" in each region being places where a number of sources existed in a cluster with matched sinks.

5.5.5 FP7 projects relating to CCS clustering

5.5.5.1 General

The EU commission FP7 programme funded several projects which studied aspects of CCS systems in Europe. These have looked at characterising emission sources and sinks and also the development of infrastructure. The most relevant to clustering are those which have studied integrated transport systems either as part or all of the scope. These were

CO_2Europipe which looked at transport infrastructure in Europe, COMET which looked specifically at South West Europe and COCATE which studied a case in France. Possible clusters based on information from these projects has been described above. CO_2Pipehaz was a fourth project which looked specifically at safety issues in CO_2 transport.

5.5.5.2 CO_2Europipe

This was an EU funded research project which investigated the development of a Europe wide CO_2 pipeline transport system. In addition to review of possible clustering and transport in Germany the project also looked at cases in the Czech Republic, Karsto in Norway and Belchatow power station in Poland. These were used mainly to generate information on all aspects of CO_2 pipeline development. Only in the case of the Czech Republic was there significant consideration of clustering to share the pipeline capacity. However this was all at high level and did not go as far as detailing business plans for specific clusters.

5.5.6 Other regional or country literature

5.5.6.1 Saudi Arabia

Saudi Arabia because of its vast oil reserves has potential for CO_2 capture for use in EOR. Interest has been shown in CCS and the country has supported inclusion of CCS in the Clean Development Mechanism (CDM). At present the literature has identified some potential for CCS but no specific cluster projects have yet been proposed. Saudi Aramco is active in supporting and developing carbon management. The first steps in CO_2-EOR are at small scale (http://www.slideshare.net/globalccs/saudi-aramco-cmeffort-may-2013). 40mmscfd will be captured at the Hawiya gas plant and injected into test area in the Ghawar field (the world's largest).

5.5.6.2 Indonesia

Indonesia has significant potential for CCS and an abundance of depleting oil and gas fields. A paper (58) discussing the overall potential was presented at GHGT-10. The paper noted that many of the sources of CO_2 are distributed thus limiting opportunities for clustering.

5.5.6.3 China

China has very large potential for CCS and has an active research, development and demonstration programme. The overall potential is described in a paper (59) presented at GHGT-11. It concludes that there is adequate onshore storage for many decades for all but the Southern area. The development of specific CCS clusters rather than point to point projects has yet to be addressed. The potential for a cluster in the Northern Shaanxi area where there are a number of fields amenable to CO_2-EOR and potential for CO_2 capture from a number of sources was presented at the recent IEAGHG Post Combustion Capture Conference (PCCC2) in 2013, Bergen, Norway (60).

5.5.6.4 India

Studies on CCS in India are at an early stage. A paper (61) was presented at GHGT-10 outlined long term prospects and highlighted the lack of information on storage capacity. A more recent overview (62) analyses potential for capture from the power sector. It is does not appear that any specific CCS clusters are being considered in India at present.

5.5.6.5 Malaysia

It is too early to consider CCS clusters in Malaysia although as a rapidly industrialising country potential has been identified for CCS (63).

5.5.6.6 Baltic Sea

Studies have been carried out to characterise emissions sources and storage sites around the Baltic Sea. This work largely supported by the Swedish Energy Agency has focussed on characterising storage sites under the Baltic. The recent BASTOR (64) and ongoing BASTOR-2 projects have collected geophysical data and identified some prospects on which reservoir simulations have been carried out. However until there is more certainty on location, capacity and integrity of potential storage sites it is too early to be considering specific CCS cluster projects.

5.5.6.7 UAE

Abu Dhabi National Oil Company ADNOC has plans for a point to point CCS project which would capture a high purity CO_2 stream from a steel works and transport it for use in CO_2-EOR in an onshore oil reservoir. The Masdar Institute (UAE) has supported study of a more extensive network by researchers at Imperial College (UK) (65). Plans for such a cluster are thus still at a very early stage.

5.5.6.8 Scotland

Element Energy recently completed a report for Scottish Enterprise examining the long term potential for CCS systems in Scotland and the Central North Sea (CNS) area (66). The possibilities of shared infrastructure and clustering are covered in the report and St Fergus was identified as well placed to become a CO_2 hub. However organic growth of the transport network rather than a centrally planned cluster approach is identified as a significant competing option. Development of storage reservoirs can benefit from a step out approach due to the layout of the more centrally planned cluster concept. Long term policy and price support is identified as a key to making the latter viable. In addition to sharing the pipeline infrastructure also some of the reservoirs in the CNS are amenable to integrated development.

5.5.6.9 Saskatchewan, Canada

A first step has been taken to identify integrated opportunities to capture CO_2 and utilise it for CO_2-EOR in Saskatchewan through a study undertaken by ICO2N (67). The study was supported by IPAC CO_2 and the Saskatchewan Government. The study identified two locations, Lloydminster and Weyburn, with the most potential for an integrated capture and CO_2 utilisation system. Lloydminster has potential for capture and use of up to 17Mta to unlock 100,000bl/day of oil whilst Weyburn could expand by up to 4.5Mta limited by supply rather than demand. Weyburn is already a pioneer in CO_2-EOR using 1.7Mta of captured CO_2 piped from North Dakota. The report analyses the economics based on a proprietary model but concludes that whilst the overall economics for the State, oil companies and CO_2

providers appears favourable a significant redistribution of rewards towards the CO_2 suppliers would be needed to make such enterprises viable.

5.6 Learning from clusters of different maturity.

The clusters which have been reviewed in depth fall into several categories of overall maturity. By comparing clusters in different stages of development some observations are made which may be helpful for clusters in earlier stages of development.

The well-developed clusters were all founded on EOR and largely but not exclusively on naturally occurring CO_2. Where anthropogenic sources have been incorporated into the supply these were generally produced as by-products of other industrial processes and involve relatively cheap separation of the CO_2.

These clusters have not yet monetized CO_2 emission reductions even though the possibility of doing so in the future has been recognized. Thus although there is considerable technical learning from these projects they do much less on the business side to assist projects which are primarily intended to reduce emissions. They may in fact be able to learn more from CCS clusters aiming at emission reduction on how to monetize these.

Other lessons can be distilled by examining the history of development of the few clusters aiming primarily at emission reduction.

It is noticeable that those which are moving towards implementation of their first phase appear, not surprisingly, to be adopting systems which are not the same as the initial large scale concepts. The first movers in capture are dictating the location and scale of the first elements and seem ready to accept that long term plans have to be flexible and adaptable. Because of the inevitable focus on getting the anchor project underway there is less activity in adapting and updating the details of the long term plans. There could be a case for expending more effort on maintaining master plans, although funding for this will be difficult to obtain as it will not necessarily be seen as part of the immediate CCS project. This could pay off in the longer term as it could ensure more informed decision making and engage future participants more effectively.

6 Gaps, Risks and Challenges

In this chapter the information collected on clusters is used to help identify the gaps, risks and challenges which clusters face during their development and implementation. Each of these is considered in turn. Some of the issues faced by clusters are the same as those applying to point to point projects or demonstrations of parts of the CCS chain. An indication of which are specific to clusters is given.

6.1 Gaps in technology hindering commercial deployment

6.1.1 General

There is some degree of overlap between technical and commercial gaps, risks and challenges. To distinguish clearly between these the technical gaps are taken as meaning those which are not purely about marginal cost reduction to create an economic case. The technical gaps are thus things which have to be developed in order for the technology to be deployed even if investors might otherwise reasonably be able to afford to do so.

6.1.2 Safety of large diameter pipelines in populated areas

Evidence is emerging which suggests that the zone in which serious injury or fatality could occur around the point of a major leak or rupture of a large supercritical CO_2 pipeline could be large. The severity of an incident is likely to be greater for the pipelines used in clusters simply because their inventory is larger. On the other hand historical pipeline incident statistics typically show that the frequency is less for bigger diameter lines.

The emergency response zone for the Canadian ACTL is projected in their information (23) to be 700m, this being the distance within which comprehensive emergency response procedures will apply. All residents and public land users of the zone will be contacted during formulation of the response plan which will include a communication plan. The pipeline runs in an area of low population density, has automatic block valves every 15km and leak monitoring system to reduce risks thus consequences for emergency response in the event of a leak are low (20).

More sophisticated methods for assessing the dispersion of the CO_2 plume in the event of a leak could give more accurate and potentially shorter distances. The results of computational fluid dynamics (CFD) modelling of releases in the COCATE project showed this to be particularly useful method in undulating terrain where it can also aid in safer route selection. In order to be able to obtain the necessary permits and to assure that risks are acceptable further development of reliable predictive methods such as CFD is needed. Solutions which are noted in several of the projects are to install automatic isolation valves at short intervals and install leak detection systems. Because CO_2 is not hazardous at moderate concentrations and only has life-threatening metabolic effects above quite sharply defined threshold levels, such valves need not be tight shut off and there could be scope for developing a low cost, non-leak tight valve for the service. CO_2 is a significant component of both fresh air (390ppm) and exhaled air (about 4%vol). It is generally classified as non-toxic and unlike other toxic or flammable substances an automatic blow-down of inventory in a safe location or maybe several locations should be acceptable. The safe concentration of most toxic gases reduces considerably as exposure time increases (an effect described by their Probit function). CO_2 is unusual as there is a very sharp boundary between dangerous concentrations and those which can be tolerated for an extended period. Other approaches to the safety issue could be enhanced methods of detecting and dealing with a major release. Emergency vehicles which do not rely on the internal combustion engine might be required. Overall a concerted development of these various potential technical contributions to dense phase or supercritical CO_2 pipeline safety in populated areas will be required if large scale CCS is to be applied in some areas.

Improved methods of communication within emergency response zones especially in more populated areas where much larger numbers of people might need to be contacted is another need where technical advances would be useful.

A number of research projects in Europe, such as COOLTRANS, are addressing the various aspects of CO_2 pipeline safety.

6.1.3 Metering to verify CO_2 storage in EOR projects

Historically the value of emission certificates has not been a component of the business case for CO_2-EOR projects. General emission reductions have already influenced operations such as Shute Creek in the USA in terms of continuing licence to operate. However the value of certificates is emerging as a potential revenue source which can only be realised if full measurement around the EOR operation is implemented. There are a number of streams containing CO_2 which emerge from the production facilities and in principle all of these would have to be properly accounted for and measured to fiscal standards in order to be able to claim carbon credits. Doing this constitutes a challenge and possibly also some technical gaps in CO_2 stream analysis and metering technology will need to be closed. This issue is not specific to cluster projects although most CO_2-EOR projects form part of a cluster system.

6.1.4 Shipping of CO_2

Several clusters have identified shipping of CO_2 as a viable alternative to pipelines. The ships would be similar but not the same as semi-refrigerated LNG/LPG (liquefied natural gas / liquefied petroleum gas) carriers using pressurised tanks. Advantages identified in the cluster context are ability to adapt to demand, ability to mobilise and de-mobilise quickly, ability to deploy ships/barges to alternative sites or alternative liquid cargoes. Use of shipping also enables easier incremental expansion of the system. Point to point systems using shipping are expected to be costly so that this issue may be more applicable to clusters. Purpose built CO_2 ships still need to be developed.

6.1.5 Offshore unloading and conditioning of shipped CO_2

A key part of a CCS chain using shipping for the final transport to the storage site is the ship unloading operation. This is not specific to clusters although as noted above shipping may have more application in clusters than in point to point projects. There are two issues which need to be addressed. The first is how to minimise the cost of demurrage whilst the ship unloads. High but intermittent injection rates could be used to limit waiting time. Alternatively some form of floating storage could be provided which would be cheaper than keeping a seagoing vessel on station.

The other issue is how to condition the liquid CO_2 from its low shipping temperature, which could be as a liquid as low as -50°C, to one suitable for injection. A considerable amount of heat is required and generating this offshore will be expensive if fuel is used and will also create significant emissions. Some reheating using seawater or air could be provided and even geothermal heat from saline aquifer water could be considered.

6.1.6 Offshore CO_2-EOR

Revenues generated by CO_2-EOR is key to the success and expansion of the most successful clusters found in the USA. Several other cluster projects have identified CO_2-EOR as having a role but often in offshore locations. The required offshore facilities, particularly the oil stabilisation and gas recycling systems, are expensive to build and operate offshore. Furthermore, this type of operation has not yet been conducted offshore. Delivery systems for the CO_2 if it arrives by ship would also need to be developed. The possibility of using a floating system for storage of CO_2, production and export of oil is an option which might be considered to reduce the overall costs and increase flexibility. Such a system could be reused at another field. The experience from the first floating LNG (FLNG) project which will soon start up could be helpful in analysing the potential for floating CO_2-EOR. Significant development is needed to enable CO_2-EOR to be taken offshore at a competitive cost. The technology would have more application in clusters than in point to point systems.

6.2 Gaps in commercial viability

6.2.1 General

There are in fact few real gaps in technical capability to implement cluster CCS projects. The main gaps are found in the commercial viability which can be broadly divided into economic and regulatory. The primary incentive to capture and store CO_2 for emission reduction is largely arising because governments are making commitments at the international level to reduce country emissions. Policies and associated regulation which flows from these commitments is inevitably tied up with the economic issues. Thus, regulatory issues which are economic at root because they have significant economic consequences will be addressed along with those which are purely economic. Obligations and performance standards are examples of regulations which might take the place of more direct systems of taxes and trading systems to create a framework in which emission reduction is commercial.

6.2.2 Gaps in economic viability

6.2.2.1 Cost of capture

A common theme in virtually every CCS project is the need to reduce the cost of CO_2 capture which often dominates the economics of the CCS chain. Projects where CO_2 is separated from natural gas or from the products of a gasification process do not suffer in the same way and can allocate some of these costs to the other products. The real gap is for capture from power plant and other industries. Both the Capex and the ongoing Opex are seen as too high. The Capex gap is the most difficult to bridge and huge efforts have been put into process and equipment development in the search for a technical solution. On the premise that commercially useable technologies do exist the main cost gap could be viewed as now being a commercial one. The search should perhaps focus on finding new ways of being able to “sell” the product. The same can be said for the Opex and in particular the cost of additional energy needed for the capture process. The Opex gap could be closed by finding cheaper sources of the low grade heat needed for solvent regeneration or for the base-load electrical demand of air separation units required for oxy-combustion. The studies undertaken for the Skagerrak cluster showed that industrial sites could provide most if not all of the required low grade heat especially if heat pumping was used. High Capex could be addressed by limiting the size of the capture unit so that higher stream factors are obtained. Again the Skagerrak cluster study analysis of capture from a gas fired plant showed how low stream factors drive up unit costs.

In summary it is suggested that part of the economic gap in capture costs might be filled by innovative commercial arrangements. This is equally applicable to clusters and point to point projects.

6.2.2.2 Price of "green" products

The other side of the high cost issue is the "inadequate price" issue. Feed-in tariffs have been used extensively to support renewable energy but with the objective of doing so only until they become competitive. This addresses the issue indirectly as the tariff is paid centrally and passed on to all consumers via taxation or through a general increase in price. The feed-in tariff mechanism suffers from some inflexibility because the rate is set in advance and over time may become inappropriate. To counter this, the rates are open to change, generally downwards with the prime goal being to stimulate development of the renewable energy industry. The use of Contracts for Difference (CfD) for electricity price with Government is gaining favour as a support mechanism and as has been done recently for nuclear power from the proposed Hinckley Point station (68). The advantage of CfD is that the support is no longer a fixed amount but is based on the difference between a target price and the actual price. The target price can be fixed or subject to general and fuel escalation adjustment. A review of the risks and opportunities of CfD contracts in the UK is given in ref. (69).

The feed –in tariff and CfD mechanisms do not give the ability to directly contract higher prices with consumers, both private and industrial for low emission energy. The Renewable Obligation (RO) has been used to do this. Under this system power companies are obliged to generate as specified fraction of power from renewable sources. A trading system allows surpluses and deficits to be exchanged between companies. In effect consumers are forced to accept higher prices for electricity. There have been examples of consumers signing up voluntarily for higher prices for guaranteed portions of "green" electricity but this value proposition is not attractive. Research suggests that a maximum price premium of around 15% is the most which is likely to be taken up by domestic consumers of electricity (70), (71). The issue is somewhat circular in nature. While it is for the most part National Governments that actually make treaty commitments for emission reduction, they do so on behalf of their citizens and other institutions and businesses. The costs of the commitments have to be passed on in so far as the bulk of Governments' income is derived from its citizens and the organisations in which they are engaged. Some income is of course derived from international trade but this is two way and in long term balance.

While the above considerations apply to all CCS projects the larger capacity of CCS clusters give them greater influence with Government and in the marketplace to make progress on this issue.

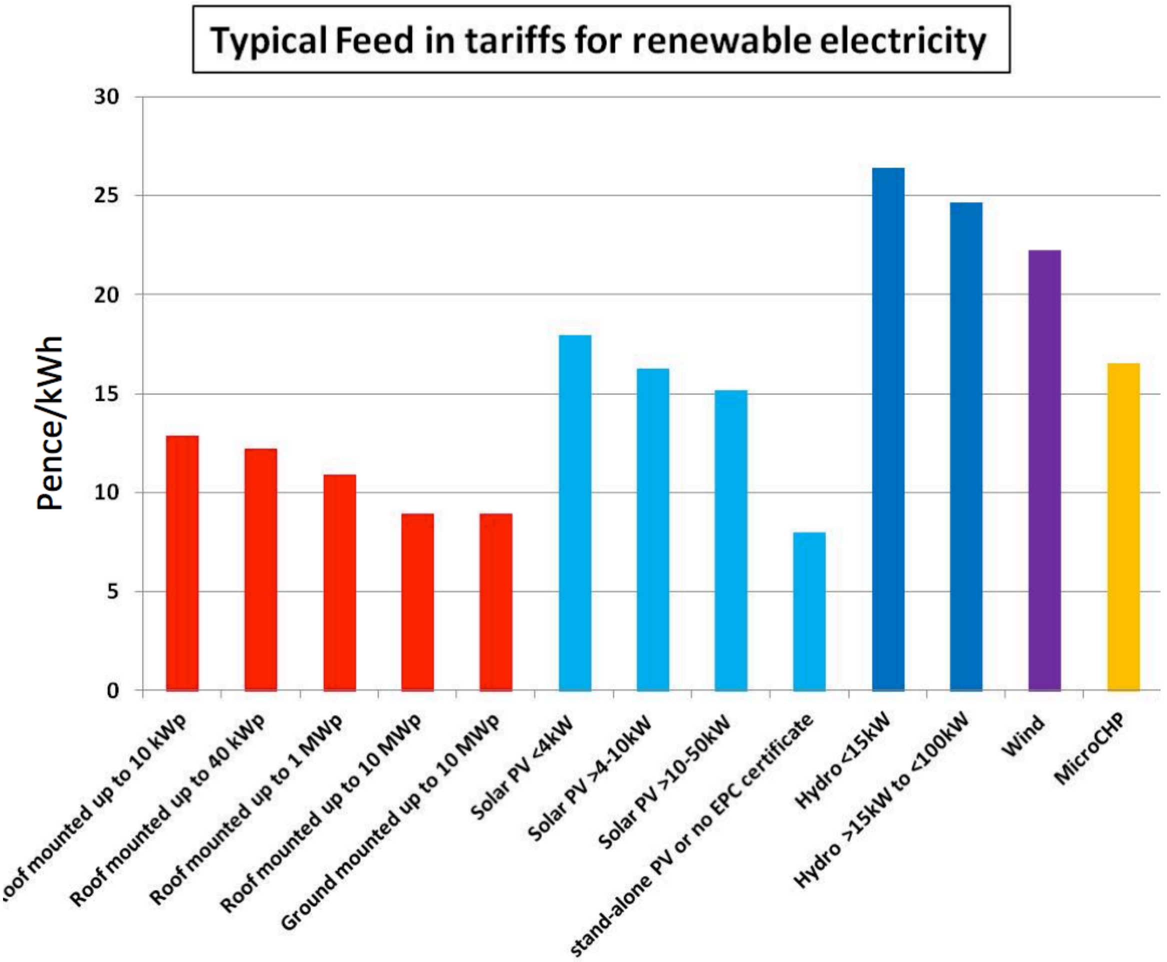


Fig 23 Typical feed-in tariffs for renewable electricity

A carbon trading system is seen as the main mechanism for bridging the cost/price gap but suffers from a number of well recognised disadvantages. The long term price is uncertain, CO_2 is only traded by a limited number of countries and in limited quantities, future trades in the EU ETS are restricted to no further out that 2020. Some attempts to address these problems such as by setting floor prices, manipulating the supply of allowances are in discussion but do not seem to offer a full solution. A search for other novel but legitimate ways of passing on the costs of green products is warranted.

6.2.2.3 Lack of tradable long term CO_2 emission reduction options

As mentioned in the previous section it is not possible to trade emissions certificates out beyond 2020. However investments in CCS are for lifetimes of up to 40 years and would secure access to emission reductions for long time periods. Clusters are likely to be planned over longer time scale than point to point projects making long term financing and stability more important to them. The few examples of investors taking stakes in CCS clusters, mainly those involving EOR, do show that there is some appetite for buying in. The investments are mainly by taking equity in parts of the business without any direct link to quantities of CO_2 abated. Investors are rewarded purely on the financial performance usually as dividends, share value or interest payments. It should however be possible for shares in future benefits specifically linked to CO_2 quantities to be formulated. Organisations which need to acquire future reduction in emissions would fall into this category. The ability to easily buy in to the best CCS locations which in time should prove to be cheaper than traded certificates, rather than having to pursue more expensive options at home should be attractive. It is thus suggested that the commercial community investigate novel ways in which products linked to specific CO_2 quantities of abatement, transport and storage might be marketed to a range of investors from individuals to institutions and industrial enterprises and preferably in a way which is globally tradable.

6.2.2.4 Limits to amount of State aid which is legally permitted

Another approach which is being exploited for early projects is to acquire very substantial amounts of State aid. Given that it is the State making reduction commitments it could be argued that it is not unreasonable for the State to pay the costs. However doing this may constitute State subsidy. The World Trade Organisation (WTO) has as signatories most of the countries of the world. As such they have signed up to a system which can identify when State subsidy is being given, identify whether a “benefit” is being conferred and then allows for two types of remedy if other countries believe that their trade is affected. The countries may either seek a ruling to have the subsidy stopped or take countervailing measurers in the form of import taxes and restrictions. Because the time required to prepare and present a case and achieve a ruling is long countries often simply apply countervailing measures.

The subsidy and benefit are regarded as legally separate issues. In other word proof of a subsidy does not automatically mean there is a benefit and vice versa. Both have to exist for a successful claim.

The EU Commission has rules which run alongside those of the WTO and these are in some areas more onerous and in others less so (72). There is an obligation to report possible subsidies which does not exist under WTO rules. The Commission will then determine if there is a subsidy and if so whether it can be allowed. This is based on whether competition in the single market is distorted. An important example where effective subsidy has been allowed is in high feed in tariffs for renewable energy. The EU rules are however more relaxed than those of the WTO in that a subsidy only exists if there is a net cost to the exchequer. This is interesting in the context of EOR where the combination of a subsidy for CCS and extra revenues from oil production royalties could be shown to be at no cost and indeed a profit to the Government. This strong positive balance is recognised for land based CO_2-EOR by both US and Canadian Governments and appears to be behind the large percentage contributions to some capture projects in these countries.

Another twist in the interpretation of when subsidies exist is that failure to collect applicable taxes is seen as a subsidy even though there is no direct monetary payment from Government to the subsidised enterprise. In future it could thus be argued that failure by a country to meet its treaty obligations on emissions could be a failure to collect adequate taxes from the sector which would allow legitimate countervailing measures to be put in place. A danger of proceeding down this path is that it could result in re-erection of trade barriers.

It is thus suggested that the extent to which State aid might be legitimate to provide CCS services under WTO and EU Commission rules should be explored and that it may be possible to justify much larger State subsidies. National Governments are of course concerned that incurring such costs could make their countries uncompetitive particularly with those that do not de-carbonise in line with their obligations. Thus it is suggested that the possible legitimate remedies under WTO rules should be explored at the same time.

Several of the more advanced cluster projects have attracted substantial amounts of Government funding for their initial phases. The ACTL project is promised up to CAD495 million towards the total costs of the first phase reported to be around CAD1 billion. The ROAD project has been granted a total of €330 million and currently has a shortfall of around €130 million to close its funding gap. The amount of private funding is not published. The expansion of the Gulf Coast system is promised government funding including an element of tax breaks amounting to US$687 million to support the Port Arthur hydrogen plant and Kemper IGCC capture projects. The contribution for Port Arthur amounts to about 66% of the costs. The Collie hub has the potential to receive AUD333 million Government funding towards the estimated AUD1 billion for the full project but contingent on a successful first phase. These figures indicate that 30-50% subsidy may be required in the current economic and regulatory climate to bring the first phase of CCS cluster projects to fruition.

Very recently the EU Zero Emissions Platform (ZEP) published a report (1) on commercial models for CO_2 transport and storage. Amongst its key conclusions was that business models should proceed through three phases with progressively reducing State support. In the first phase, support is directed at specific projects, followed by a period of selective market support after which a fully liberalised market without need for support develops.

Element Energy recently published a more specific report than the ZEP report which analyses the potential of tax incentives for CO_2-EOR in the UK to kick-start the CCS industry (73). It concludes that overall Government revenues could be increased and that CO_2-EOR is unlikely to be implemented without some form of Government fiscal incentive.

6.3 Commercial Risks

6.3.1 General

Commercial risks are analysed on the basis that an economically sound business plan is being followed and that certain events or trends significantly affect the business in a worst case scenario. Each will be described and discussed in a separate subsection

6.3.2 Collapse of CO_2 emission certificate price

The presumption is that the price of emission certificates has appeared adequate to justify starting the CCS business. This would imply either that there is some form of guarantee or certainty that the long term price will remain above a certain level or that other revenue streams can replace it.

The level of risk will change as time passes because the capital expended for building the facilities will be progressively recovered. The level of risk which remains to continuation of the business will depend on how the capital was raised. If it is purely equity than the shareholders will lose value but if prices are still sufficient to cover ongoing costs the business will be able to continue. If on the other hand the capital is loaned, the business will be more vulnerable to a price reduction because of interest payments and eventual maturing of the loans.

The extent will depend on what provision were made or can be made to defer interest payments and/or write off the loans. Thus the methods by which initial capital is raised and the terms attached need to be considered carefully in order to provide some protection for the business in the event of a significant and prolonged CO_2 price fall. It could be argued that given the lifespan of the projects and the inevitable long term need to continue reducing emissions that profitability is bound to return in the end.

The early history of traded prices in the EU ETS has not been encouraging as is illustrated by the above chart of historical prices which indicate both a downward initial trend and considerable volatility. As the price is controlled to a large extent by the way the capacity cap is managed it is to be hoped that learning from experience with the early years of CO_2 trading systems will lead to a more stable long term price regime.

6.3.3 Serious pipeline accident

A serious pipeline accident could be seen as a technological risk but in reality repairing a pipeline and compensating those affected will be a minor cost compared to the damage which the industry might suffer if CO_2 transport was subsequently restricted. The risk is foreseeable but not predictable. If proper insurance is in place there should be little effect on the bottom line. Thus such an event will be treated as a commercial risk. The likelihood is that normal operations would eventually resume following repair and implementation of improvements, should investigations reveal that these are necessary. It is unusual for existing operations to be stopped permanently even after a disastrous event unless the entire facility has been destroyed. Even then if there is continuing value in the business it is likely to be replaced as for example happened when the Piper Bravo platform started up just 4 years after the Piper Alpha disaster.

The main effects are thus likely to be on the further development of the industry and possibly on the way operations are conducted in the rest of the industry. Thus a significant risk that after a pipeline disaster or storage problem all other CCS businesses will be faced with the costs of upgrading their operations. To date there have been no disasters of serious failures so the fledgling industry has a clean record. It is perhaps inevitable at some stage that a disaster will happen or else a very stringent safety regime needs to be established for the entire industry so that it does not. A good example of success in this respect is the refrigerated transport of LNG in ships which has to date over many decades demonstrated it is able to effectively manage the risks. The risk of severe consequences would be reduced if careful attention was paid to global safety standards and if organisations were prepared already for the types of upgrade which might be required in the aftermath of an incident. Full exploration of the consequences of worst case incidents and understanding of what extra protective measures could be put in place is suggested even if all they are not adopted because the likelihood is low.

6.3.4 Loss of customers

The key customers of the business are the sources of CO_2. The value of managing the volumes and fully utilising capacity is well recognised. However companies capturing CO_2 could cease their operations unexpectedly for a range of reasons unconnected with the CCS business. Loss of anticipated future customers where there has been pre-investment in transport and storage capacity presents a similar but smaller risk. Even the existence of long term contracts would not protect against this eventuality. Loss of a major source in this way would leave the rest of the system exposed to loss of revenues. The risk could be reduced if capacity is not allowed to get ahead of demand as then new sources could be brought in albeit with some delay whilst new facilities were constructed. This raises interesting differences between the types of capture facilities. Post-combustion capture plant has to be close to the flue gas source which it treats as it is difficult to transport over any distance. Oxy-combustion systems have less limitation in that the air separation unit (ASU) can deliver oxygen over a pipeline and may not even be built next to the capture facility. A pre-combustion unit has some flexibility in that the gasification section could still produce hydrogen for combustion elsewhere. If the combined cycle gas turbine (CCGT) power plant using the hydrogen ceased operation it might be possible to market the fuel to other industries.

6.3.5 Loss of a storage site

If problems develop with a storage site it may be necessary to cease injection. Fortunately the on-going reservoir management should give long early warning of such an event. This could be seen as a technical risk although the final capacity of a new storage site cannot be predicted with certainty. Reliance on one site or for that matter one well would constitute a risk to continuation of the business. In this category can also be placed failures to agree or prove up the new storage sites needed to continue operation. The risk can be reduced by careful long range planning and contracting of multiple sites. The short term capacity of alternative sites can be increased by drilling extra wells and temporary increases in injectivity of existing wells may also be possible. It is thus suggested that contingency plans for additional storage capacity through extra wells, or reservoirs are made. New wells can be drilled and completed very quickly as long as a rig and the necessary well materials are available. However if for some reason a store has to be abandoned there is a very long lead time to characterise and approve a new one. The contingency plans could thus include rapid access to drilling rather than keeping spare wells and having more than one storage location appraised and developed.

6.3.6 Withdrawal of a key partner

The basis of many of the clusters examined is one or more a consortia often with several key partners each with essential expertise. Withdrawal of a partner could undermine the commercial viability of the system. To some extent the eventuality can be prevented by the nature of the contracts which bind the partners into the consortia. Provisions could be included in contractual terms and conditions should there be changes of ownership or divestments. However this would not protect against withdrawal because of a bankruptcy or other severe form of failure of a partner's business. The services which support the business can all be acquired competitively on the open market and the key asset of a consortium will be the central staff and facilities. Thus it is suggested that one solution would be for the core management of the activities to be run by a dedicated well-funded organisation rather than relying on parts of partners' organisations to carry out this function. If any of these were suddenly lost it could severely disrupt the business and be difficult to replace.

Another related issue is the lack of key partners in Europe willing to undertake CO_2 storage. To protect against loss of partners with this essential expertise it might be advisable to ensure that risks are spread amongst several companies.

6.3.7 Extensive delays

A full CCS system has many interdependent parts all of which have to operate to generate revenue. The effect of delays in any part is thus compounded. In a cluster having multiple sources or multiple sinks will alleviate the risk which is thus most evident in the early "anchor" stages. Where fixed amounts of funding have been obtained delays increase the overall cost due to inflation whilst the grants are often not inflation linked. In addition other costs can mount when there are delays. The risk can be tackled from two sides. In the first case careful planning and attention to the critical paths in the development will help. Also careful control of commitments so that funds are not expended on one part of the system when other parts are likely to be delayed. Good co-ordination is needed in addition to good planning. On the other side realistic provisions should be made for additional funding to cover the contingency of delays.

6.3.8 Failure to gain key permissions

When a CCS system is first set up it is essential that the full chain can be implemented. Many of the studies on CCS systems and clusters have identified planning consents and permissions as being time consuming and potentially difficult to obtain. The particular issue encountered by Denbury Resources in the Texas Coast in obtaining eminent rights for its pipeline is a small example of what can hold things up. All the investments made in other parts of the system are at risk if one part cannot be completed. The risk can be mitigated by ensuring that major investment decisions are in step even if this delays the overall project. This in itself can introduce the risks associated with delays. It may be prudent to have a number of alternatives for pipe routings and storage locations to reduce the risk of a complete impasse.

6.3.9 Alternative EOR methods become more cost effective

Future business projections for clusters where the bulk if not all of the CO_2 is destined for EOR could be overoptimistic if other methods of tertiary recovery are deemed by the field operators to be more cost effective or are more readily available when required. At present the performance of other existing methods is understood so that the comparison can be made. Some competing tertiary extraction methods are nitrogen injection, polymer injection, steam injection, natural gas injection and use of foaming agents. Even so projections could easily be overoptimistic if this competition is not adequately evaluated. What is less certain is whether new developments in EOR methods might change the competitive environment. Some of the innovations which are being made for example in use of foams or other chemical to enhance sweep efficiency might be equally applicable to CO_2. It is of course not possible to predict what new technologies may emerge. However the example of the advances in horizontal drilling, fracking and reservoir management have dramatically changed the natural gas production industry. It is also possible that as new more difficult hydrocarbon resources are developed that CO_2 might be able to play a bigger role. In order to mitigate this risk the business needs to be alert to developments in tertiary recovery techniques and to regularly benchmark the performance of these against CO_2. It is not only the techniques which may change but also availability of other materials for flooding. For example if oxy-combustion were applied on a large scale, the availability of cheap nitrogen for either miscible or non-miscible flooding could displace CO_2 miscible flooding in some reservoirs.

Unlike point to point projects, clusters can protect against this risk to some extent by diversifying their customers. This should include maintaining awareness of the characteristics of customers EOR projects and aiming to have a balance between EOR and CO_2 storage off-takes.

6.4 Technological Risks

6.4.1 General

Technological risks encompass any element of the system which the long term plan expects to implement which for technical reasons may not be possible to build or operate for anywhere near the projected costs in the business plan.

6.4.2 Reservoirs unsuitable for CO_2 flood

To some extent this is similar to item “alternative EOR methods proving more attractive”. However until initial CO_2 flood tests have been made in a new reservoir it is not possible to accurately assess what CO_2 flood performance will be. This risk can be mitigated by improved reservoir simulation techniques. It can be mitigated commercially by careful management of the financial commitments to capacity expansions based on future off-takes.

6.4.3 Emitting industries changing basic process or products

This risk applies specifically to industries such as iron and steel or cement where the nature of the process used has a significant effect on CO_2 emissions. Radical changes such as to use of electric reduction or hydrogen reduction would change the amount and nature of emissions which might be captured. Furthermore the industries might relocate if an alternative resource needs to be in proximity. Even the power industry is not immune to this type of change for example base-load plant might switch to peaking operation drastically reducing the amount to CO_2 which could be captured.

To guard against this risk the cluster business should make sure that there is a reasonable understanding of the industrial processes from which capture is intended and what the nature of technological advances is likely to be in these industries. This should be extended to consider also their products and what alternatives might replace them. For example steel by aluminium, concrete structures by steels etc.

6.5 Main challenges

6.5.1 General

Challenges can be divided into those relating to technology and engineering and those related to business.

6.5.2 Technical challenges

6.5.2.1 Scale up

At first sight scale up might seem to be a prominent issue. However the challenge of scale up is shared by point to point CCS projects. Only those areas where clustering means that scale up issues are increased are addressed. In a cluster there may be more capture plants but the sizes will not usually be affected by clustering. There may be cases where centralised plants might be preferred over separate units because of economies of scale and this would tend to increase the need for scale up to larger unit sizes. It is in the collection and transport system that larger components may be needed. The main elements which may be considerably larger are central compression, central drying/conditioning, pumping and pipelines. Central compression will be to boost to trunk pipeline pressure and the size of machines needed are widely available for natural gas and other services. Some minor modifications may be needed to account for the slightly different properties of CO_2. For drying conditioning and pumping the size of units which might be required is well within current industry practice. Likewise for pipelines there are minimal constructional scale up issues. However somewhat thicker walls are needed because of the relatively high operating pressures and to prevent running fractures. Thus there may be some limitations when using the largest available diameters because of weldability of very thick steels. Qualifying the use of higher strength steels in supercritical CO_2 service could potentially ease any wall thickness limitations. Of far greater concern is the massive inventory of very large supercritical CO_2 pipelines in the event of a major release and the larger safety distances which this may require. Technical solutions could be utilising smaller pipelines in parallel, extensive use of automatic emergency block valves, increased wall thickness and additional protection against third party interventions and natural events. Developing design methods and codes of practice in this area is a challenge. Work on fracture mechanics, transient conditions and safety in the event of major leaks in very high pressure CO_2 pipelines may result in a need to modify current the codes for very large diameter high pressure systems. At present these are mainly employed for natural gas systems.

Clusters handling large volumes will put pressure on the filling rate of the available storage sites. Especially as volumes increase there will be a need for systems to maximise the rate at which reservoirs can be filled without compromising safety or final storage capacity.

Scale up will also tend to introduce a wider range of CO_2 compositions as more and more diverse sources are added. It will be a challenge to manage this so that costs are minimised across the CCS chain.

6.5.2.2 Project management

CCS cluster projects are by their nature large and both geographically and technically diverse. Thus the issues which management of very large projects bring to the fore are likely to be important and will be challenging. The design of the project management and decision making systems will be a challenge. The right balance between centralised and decentralised management will need to be developed. It will be important to allow sufficient flexibility to respond to altering circumstances while at the same time maintaining adequate scope, budgetary and schedule control. A solution in which individual parts of the overall system are managed by independent managers may provide better overall control than a highly centralised management structure. The lack of centralisation will then need to be compensated by good co-ordination between the independently managed parts of the enterprise. A good overview of this general issue is given in reference (74) which also contains extensive further references to literature in this field.

6.5.2.3 Process and system control and optimisation

The need to be able to cater for capacity variations is noted in some cluster documentation. The ability to optimise the operation of the entire system would have a commercial advantage and developing this capability is a thus a technical challenge.

6.5.2.4 Waste heat utilisation

The use of waste heat supplemented by heat pumping was identified in the Skagerrak cluster as having potential to greatly reduce extra energy costs. The principles and equipment needed to use waste heat are well developed and understood. It does however represent a technical challenge to apply this technology effectively in the context of CO_2 capture in a wide range of industries and situations. Five industrial sites were analysed including three refineries, an ethylene cracker and an ammonia plant. The waste heat was distributed between residual heat in flue gas stacks and many process streams. To collect the heat will thus require installation of a significant number of heat exchangers. In four of the five plants there was insufficient heat above 129°C to satisfy demand and three designs included use of heat pumps to raise the temperature of low grade waste heat. In the final site an additional biomass boiler was needed as a heat pump was not appropriate. The table below summarises the amounts of heat available, the number of process sources and chimneys from which heat could be recovered as well as the estimate of the shortfall to be provided by heat pump or supplementary boiler. This gives an impression of both the potential and the degree of complication.

Table 2 Waste heat availability at typical locations in Skaggerak/Katttegat study

Waste heat availability in 5 typical industrial sources

Name of installation	MW >150C	MW >129C	MW >90C	MW Total waste heat	Gross CO2 kTa emission	CO2 captured	Number of process sources	Number of chimneys	Shortfall in heat above above 129C	How supplemented
Preem, Lysekil - Refinery	40	82	225	450	1740	1,479	55	4	18	Heat pump
Preem, Gothenburg - Refinery	30	54	107	218	484	411	65	2	0	No shortfall
Esso, Slagentangen - Refinery	4	18	56	82	365	310	10	9	4.5	Heat pump
Borealis, Stenungsund – Ethylene cracker	20	23	30	252	566	481	32	13	7.7	Heat pump
Yara, Porsgrunn - Ammonia plant	4	5	19	25	744	638	2	1	1.5	Biomass boiler

6.5.2.5 CO_2 specifications

Most clusters address the choice of CO_2 specifications. The key requirement identified is adequate water drying. Thereafter the specification for other components tends to be dependent on the type of source and capture process. The issue of mixing streams which are captured in reducing pre-combustion environment and those captured in an oxygen containing environment does not seem to have arisen. When these different types of capture process are combined, and if for example stringent oxygen specifications are mandated for an EOR application, an optimum technical solution for clean-up of raw captured CO_2 will be required. The chance of mixing issues is greater the more diverse the sources in the cluster. The other main effect is that of significant amounts of non-condensable impurities such as nitrogen and argon which may have a disproportionate effect on pipeline and reservoir capacity.

6.5.3 Commercial challenges

6.5.3.1 Business organisation

A wide choice of business structures is available for cluster projects. The scope is also not limited to a particular cluster as many of the services and activities are amenable to provision by businesses serving a number of clusters. There is also likely to be an evolution as has occurred in many industries whereby core functions initially carried out by the central business become “commoditised” and can be better provided by specialist companies serving the whole industry. Thus there is a significant challenge in setting up the most effective structure of possibly interlocking businesses and also adapting this as the industry grows.

To understand the issues better it is worthwhile to compare the approaches of several of the more advanced projects to the core of the cluster business, the pipeline transport system. The approach in Rotterdam has been to use a consortium which includes the major operator of gas pipelines Gasunie. By comparison, in the UK National Grid Plc is taking a sole lead in developing the pipeline business which it sees as complementary to its gas and electricity transport activities. Nevertheless National Grid Plc is also including the storage business in its portfolio of activities but probably with a commercial arrangement with a company or companies more specialised in this aspect of the business. In Alberta, by contrast, a new dedicated company, Enhance Energy, has been set up to build and manage the central pipeline. This is in contrast to the USA where two companies in particular Denbury resources and Kinder Morgan play a central role in managing some but not all of the pipelines. However these companies both have a much larger portfolio of activities in the oil and gas business.

A further consideration will be the maturity of the energy and emission reduction markets. For CO_2 emissions these are expected to move from a regulated to a liberalised environment with time. This will affect the way in which players engage with a far greater role for independent specialist services in a liberalised market.

The foregoing shows that there is quite a variety in the way the pipeline element of a cluster CCS project can be set up. Factors which are clearly affecting the choice are:

1) Financial capacity
2) Expertise in running a transmission pipelining business
3) Availability of mature subcontracted resources
4) Strategic fit with other core activities
5) Regulatory environment for the market
6) Legal constraints on scope of operations of central transmission pipeline companies

In the case of the USA clusters factors 1, 2 and 4 appear to be key and also design and construction of CO_2 pipelines is a mature activity which is easily subcontracted. The businesses have substantial assets and income from their operations and the ability to finance new projects from own resources or by raising capital. In the case of Canada, Enhance Energy is reliant on item 3, the ability to subcontract resources to build the pipeline. The company has to build its own expertise in management of the pipeline. It is also heavily reliant on Government funding and venture capital as it has no other assets on which it can draw. In Europe for both Gasunie and National Grid Plc all of the factors apply but some are not so strong. They do not hold oil and gas assets but only engage in the energy transport business. They do have a high level of expertise in running pipeline networks but may have legal constraints as to the businesses in which they are allowed to engage. The extension into CO_2 is not such a strong strategic fit as it is for the US companies engaged in oil production. Cross financing is less justified and may even be subject to regulation. Also design and construction of CO_2 pipelines is a new activity in Europe and is thus less mature than in the US and Canada. This will place some limitations on how this activity is subcontracted and too much of an arm's length approach may not be possible because of the potential for public resistance and the importance of establishing a clean safety record.

The foregoing is illustrated in the following four figures which show some examples of the scope which individual business could have. The diagrams indicate five main business areas of industrial activities with emissions, capture, transport, storage and oil and gas production.

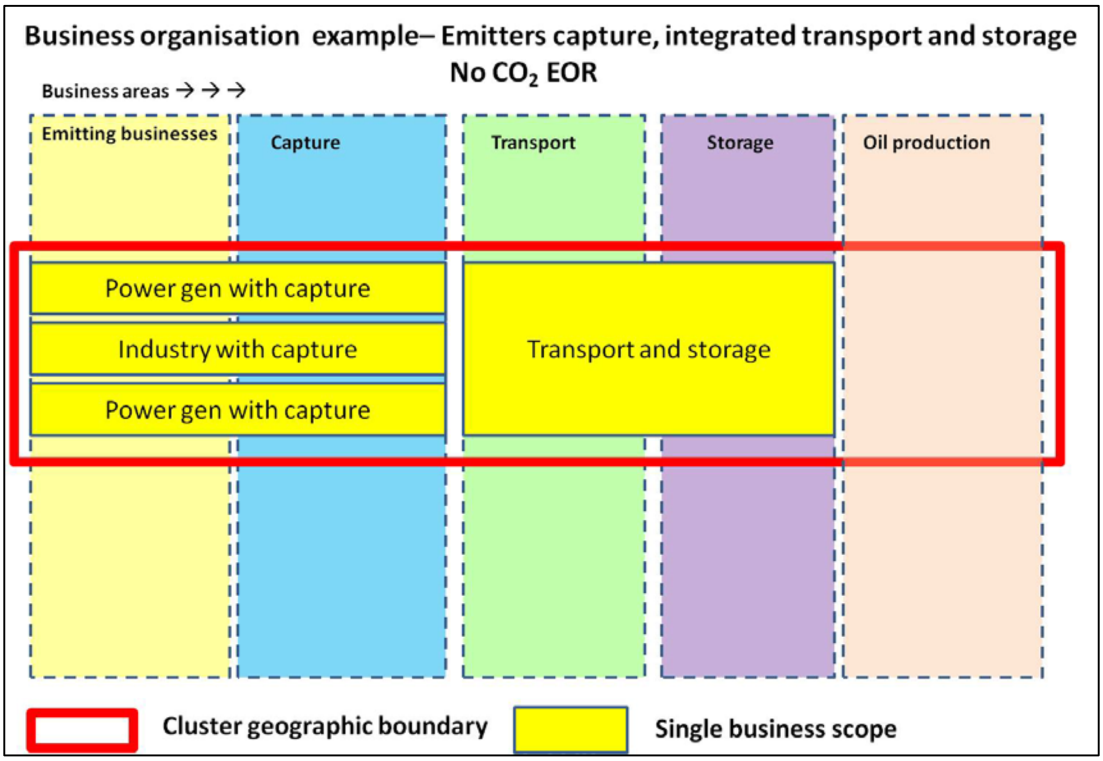


Fig 25 Example of CCS business organisation with emitters providing capture and a single business providing transport and storage.

The red outline represents the boundary of a cluster region and a yellow box indicates an individual business. In the first figure 25 a typical approach to a cluster business is shown. Individual emitters will operate capture plant and a single business will collect transport and store the CO_2.

In the next figure 26 the typical arrangement of a business in the USA which delivers mainly natural CO_2 for EOR operations is shown. Captured CO_2 is being added by separate businesses who conduct their own capture. The storage of CO_2 is solely through EOR by the same business as transports the CO_2. Storage alone is shown only as a possible future activity carried out by the same controlling business entity.

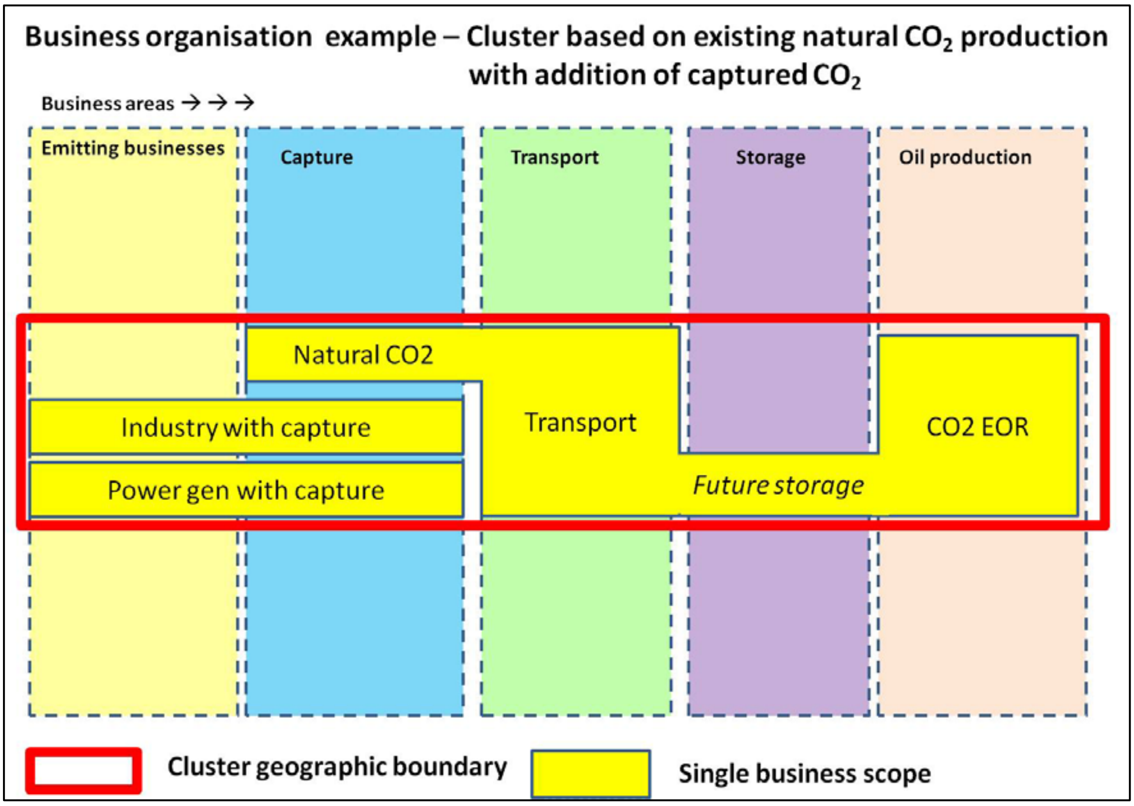


Fig 26 Example of typical existing US CCS cluster based on existing natural CO_2 for EOR business

In the next figure 27 a similar arrangement is shown but now one business is operating transport and EOR operations in more than one cluster.

The final figure 28 shows how business expertise might be deployed across multiple clusters. Here one business is providing shipping services in two cluster projects, another is providing pipeline transport in three clusters and a third is providing capture services across all three clusters.

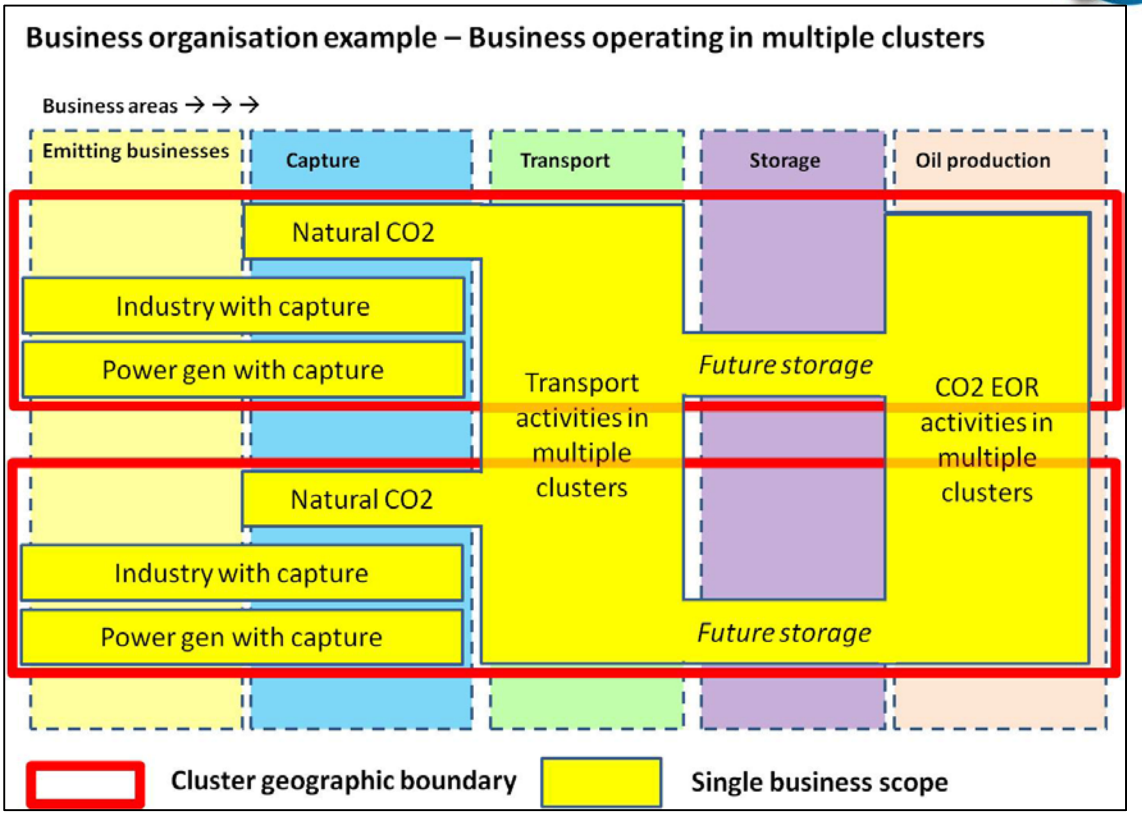


Fig 27 Example showing operation in multiple clusters based on existing CO_2-EOR systems

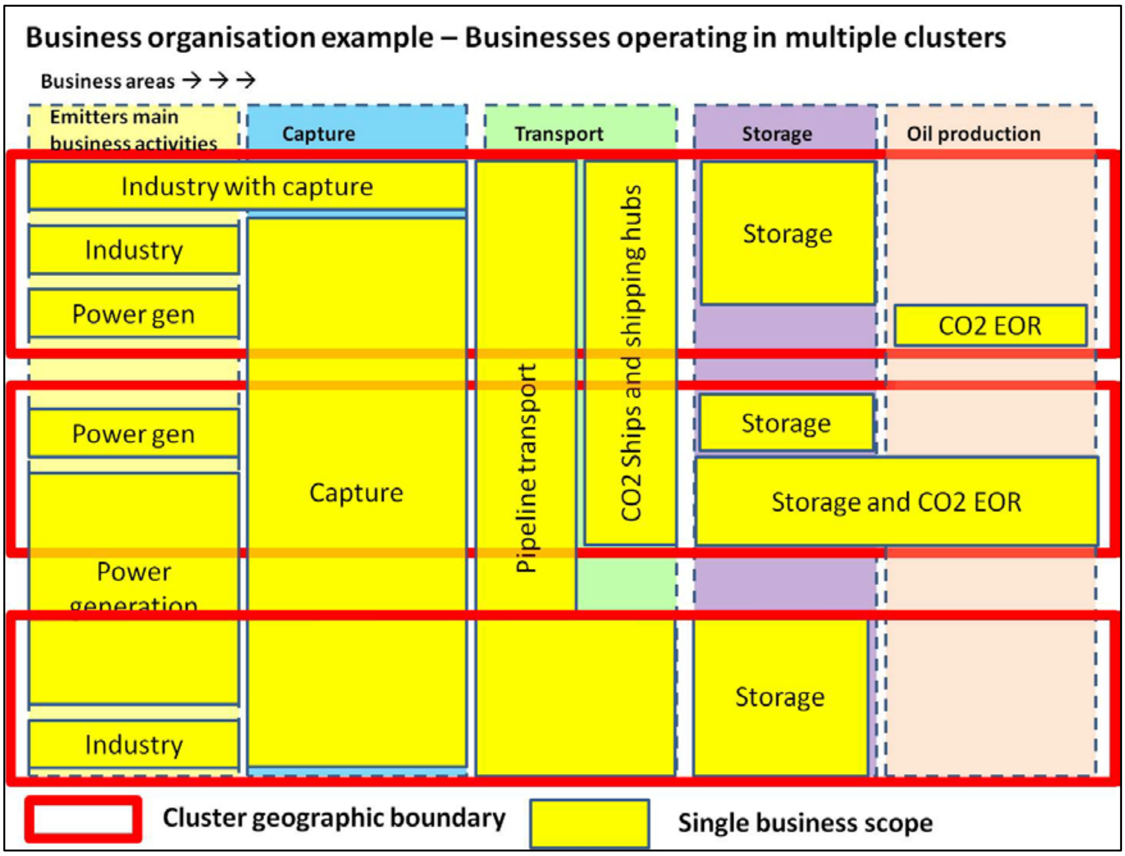


Fig 28 Example showing potential for cross cluster CCS businesses

6.5.3.2 Business globalisation

Another aspect of the business organisation is the degree of globalisation which might be possible. All of the existing projects apart for those in which Denbury Resources is involved tend to have businesses built around a single cluster or hub location. However this is not necessarily the only way to organise. There would be scope for example for CO_2 pipelines for clusters in several locations to be run by one organisation.

A far bigger element of the CCS system, the capture facilities, could also be run on a more global basis. At present all of the cluster and point to point projects are based on the expectation that the capture plants will form an integral part of the source facilities and that these will be operated by the organisation running the main facility or one closely associated with it. However there are potentially other models which could be adopted with the source flue gas or other CO_2 containing stream being seen simply as a feedstock for an independent capture operation. This concept has to some extent been explored in the COCATE and VASCO projects where the collection of flue gases for more central processing is proposed.

Such a model could offer a very different type of value proposition in the longer term. It would be based on being able to capture and store CO_2 at a lower cost than that of emission certificates in favourable locations. And as clusters could be expected to be the most favourable locations to do this they should be able to attract the necessary investment. A business challenge is to be able to exploit this opportunity to the full. A key to this could be expanding the customer base to include any industry which would like to invest in CCS to reduce the cost of CO_2 emissions. The conventional approach presumes that the main customers are the owners of the emission sources within the cluster. If there is a free market to trade certificates, which are earned by capturing and storing CO_2, it follows that at least in theory anyone could invest in the facilities and thus gain title to the benefits. The CCS cluster enterprise would have to agree to take emitters sources of CO_2 for the consideration of the equivalent number of certificates with a discount to make it worthwhile for the supplier of the stream containing the un-captured CO_2. If the enterprise was indeed able to capture and store the CO_2 for less than the price of certificates it would end up generating certificates with a higher value than its costs. The owners of the enterprise could then either sell these if they did not need them, but more interestingly if an investor needed the certificates for its own emissions elsewhere in the world it could use its share of those that had been earned to satisfy this need. The value proposition would be that companies operating in a place which was unfavourable for low cost CCS could nevertheless invest in CCS in a place where it was cost effective. The CCS cluster would then be able to obtain funding from a much wider pool of potential investors than those with sources within the cluster.

6.5.3.3 Maintaining momentum

One of the challenges noted particularly by the some of the projects such as Rotterdam Cluster project, is that of maintaining the momentum of the project. It is essential to have in place a team who can maintain commitment to the long term goals of the project and yet be flexible to changing circumstances. Underlying this challenge is that of getting funding to keep a core organisation going possibly for many years. Equally it will be a challenge to find champions who are prepared and enthusiastic enough to work on setting up the cluster and provide staff continuity over the many years which this may span.

6.5.3.4 Enabling incremental expansion

Another challenge to structuring the business is that customers wishing to reduce their emission by capturing CO_2 are generally faced with an all or nothing decision on the capacity to install. Economies of scale dictate that capture of at least the full base-load emission should be installed. The ability to purchase the reduction incrementally if it were available could prove more attractive. This is the along the same lines as that of sharing the investment with third parties which is discussed above but making use of a physical increments rather than financial ones. The three main technologies differ in their ability to deliver such a proposition. Pre-combustion capture technology is best placed as a central plant could deliver hydrogen allowing in principle existing carbon containing fuels to be gradually switched to carbon free (i.e. hydrogen). Some modifications to burners and NO_x controls may be needed when this is done because of the higher flame temperatures and velocity and changed Wobbe index. Oxy-combustion is less flexible since each fuel consuming unit must switch entirely from air to oxygen firing. However there could be considerable economies of scale if ASU's were built on a large scale and centralised. Least flexible is post-combustion capture technology. Some degree of centralisation is possible where separate sources are close together since either flue gases can be ducted to a central unit or solvent can be piped from a central regeneration unit to individual absorbers. These issues are illustrated in figure 29.

The possibilities of distributing hydrogen and syngas from centrally located plants fitted with capture to nearby industries is noted in the documentation for some clusters but does not form part of any immediate plans. Commercialising this form of de-carbonisation for smaller industries with high individual capture costs is a challenge for clusters as they mature.

A particular challenge associated with the foregoing type of business model would be to be able to arrange for a separate organisation to run capture facilities within the site of the emitter. It would be somewhat easier if the facilities were on a separate site, even if enclosed within the main site. Another part of this challenge would be the ability to share utilities and other energy and material flows between the capture plant and the source facility. Some industrial sites have developed so that multiple separate businesses are able to share key utilities. One such example is Teesside, UK.

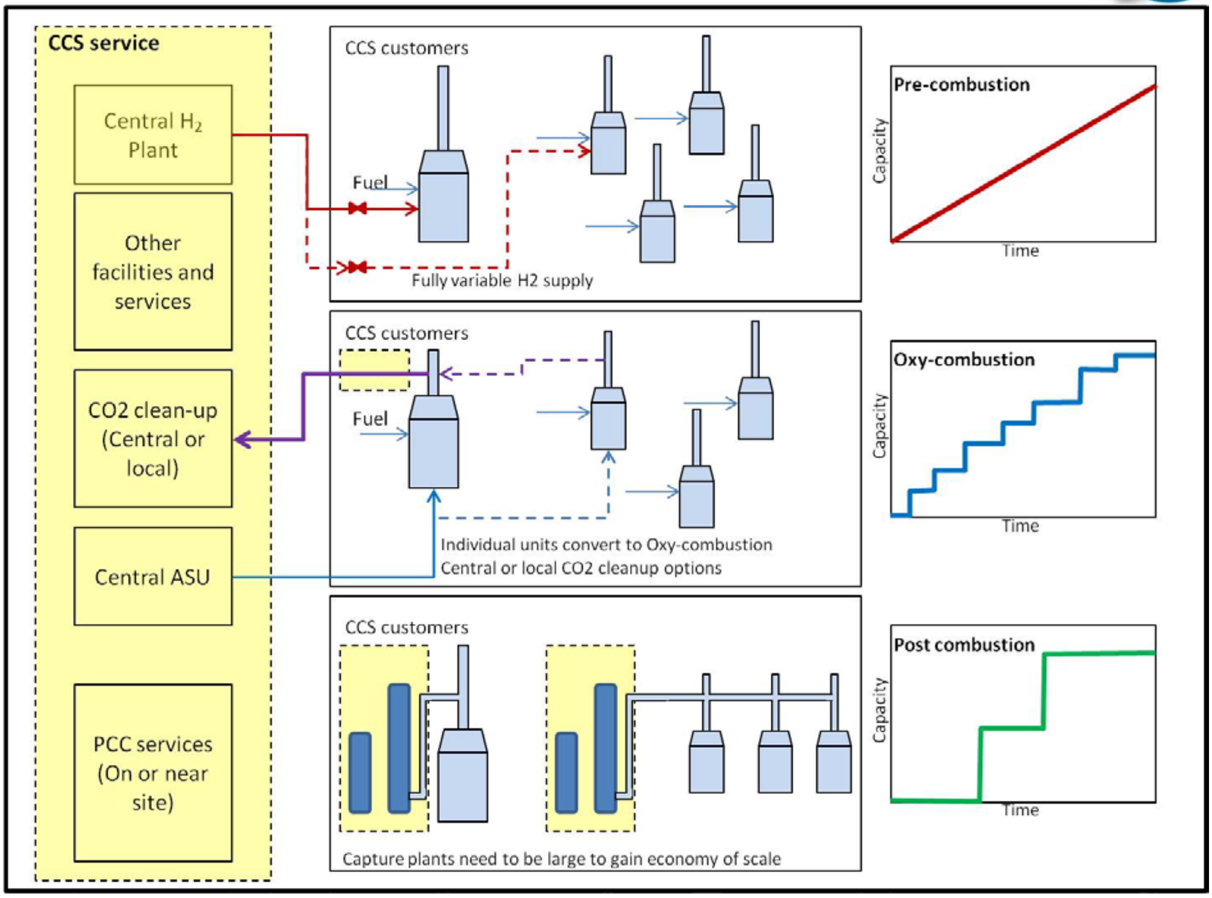


Fig 29 Illustration of incremental capacity increase options for main capture technologies

Another approach to incremental expansion would be to arrange this on a commercial rather than a physical basis. The benefits of running a capture plant on a flue-gas stream could then be shared amongst a number of clients who would receive a share of the emission reduction certificates to cover their own emissions. This would allow individual clients to buy capacity incrementally leaving the CCS service provider to manage the financing and construction of large steps in capacity. Setting up such a commercial structure would be a significant challenge but would have the advantage of opening up to a much wider client base as discussed further below. This concept is illustrated in Fig 30 where four client companies A, B, C and D provide funds to the capture service provider in exchange for their required emission certificates. A major emitter who prefers to surrender certificates rather than invest in CCS provides the flue gases to the service provider's capture plant in exchange for the value of a small percentage of the required certificates for their emissions. The value of the rest or actual certificates are handed over with the flue gas. The major emitter could be one of the client companies and thus contract to deal with only a part of their emissions using CCS.

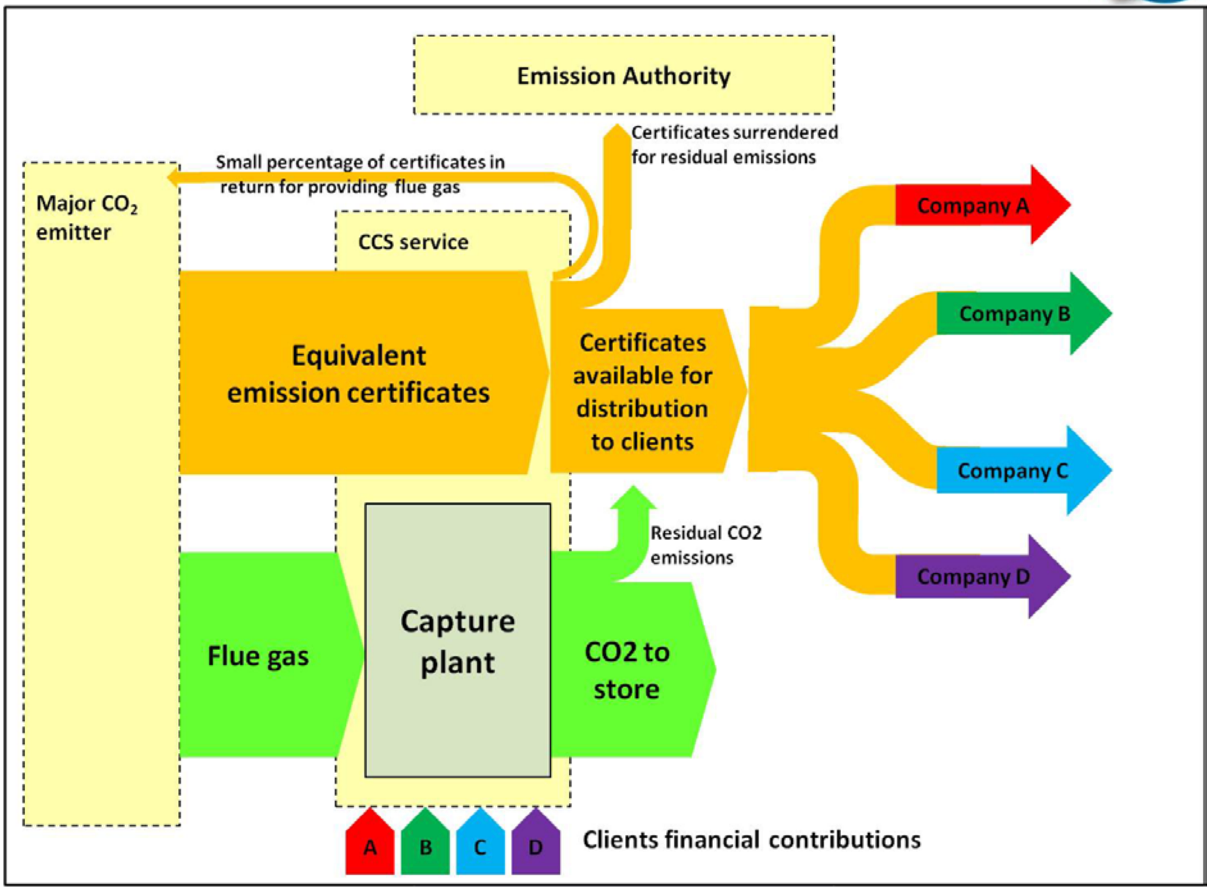


Fig 30 Commercial scheme for sharing increments of emission reductions from a CCS system

6.5.3.5 Setting up specialist services

There are a number of specialist services associated with large scale CCS operations which could form either local or global businesses. For example the reclamation and processing of waste solvent, monitoring of storage sites, metering and accounting services. If these could be undertaken more efficiently by service organisations then the overall costs of the CCS system would be lower. It is a significant challenge to organise and develop the business so that these types of economies can be made. It may not be possible to subcontract such specialist services in the early phases but the business plan could set up to seek out and recognise such opportunities.

6.5.3.6 Managing confidential data

An issue which has been noted in development of some clusters is the sensitivity of information on emissions expressed by some companies. Information about the performance of a competing company in terms of its energy and materials efficiency and emissions profile could be commercially sensitive. It is thus a challenge for a cluster CCS business to obtain the data necessary to make offers to potential customers and plan regulation and expansion of the system in a confidential way. An example of this sensitivity is paralleled in organisation of the shared district heating system in Copenhagen where the heating companies set up the separate company VLE to carry out the optimisation. This item is included here as a challenge although it could also be considered to be a gap.

6.5.3.7 Identifying and connecting with customers

The issue related to the customer identification is that there is a range of groups who may be considered as customers and therefore need to be identified, have the value proposition of CCS explained and then be convinced that they should contribute to the revenue needed to provide the service. The three broad groups are:- The organisations which emit CO_2, the Governments which make commitments to reduce CO_2 emissions and the consumers of products produced using CCS as part of their creation process. The consumers can range from individual persons, to organisations and intermediate industries which use the output of CO_2 emitting industry.

Most of the cluster projects are based on the main customers being emitters with a need or wish to reduce emissions. Several of the projects actually appear to have governments as major customers for their initial phase in that by far the largest financial contribution is coming from this source. However it is also evident that these government payments are not without scrutiny. Both the public and various organisations express views about the validity and effectiveness of such contributions.

If a CCS cluster is to set up as a business case then it will need to identify and connect with all of the potential customers of its service. The challenge is to recognise the diverse range of "customers" and apply the necessary effort to research and market to them. Revenue streams from one segment may rely heavily on support from another.

This broadening of the customer base is illustrated in Fig 31 below. The conventional view is that the CCS is business with just the power industry and heavy industry involved with some initial support from Government funding. The stars indicate where additional "clients" prepared or required to contribute to the funding base might be sought. Expanding the customer base to many contributors outside big industry and Government in this way would have similarities with "crowd" financing in other businesses but is undoubtedly a major challenge.

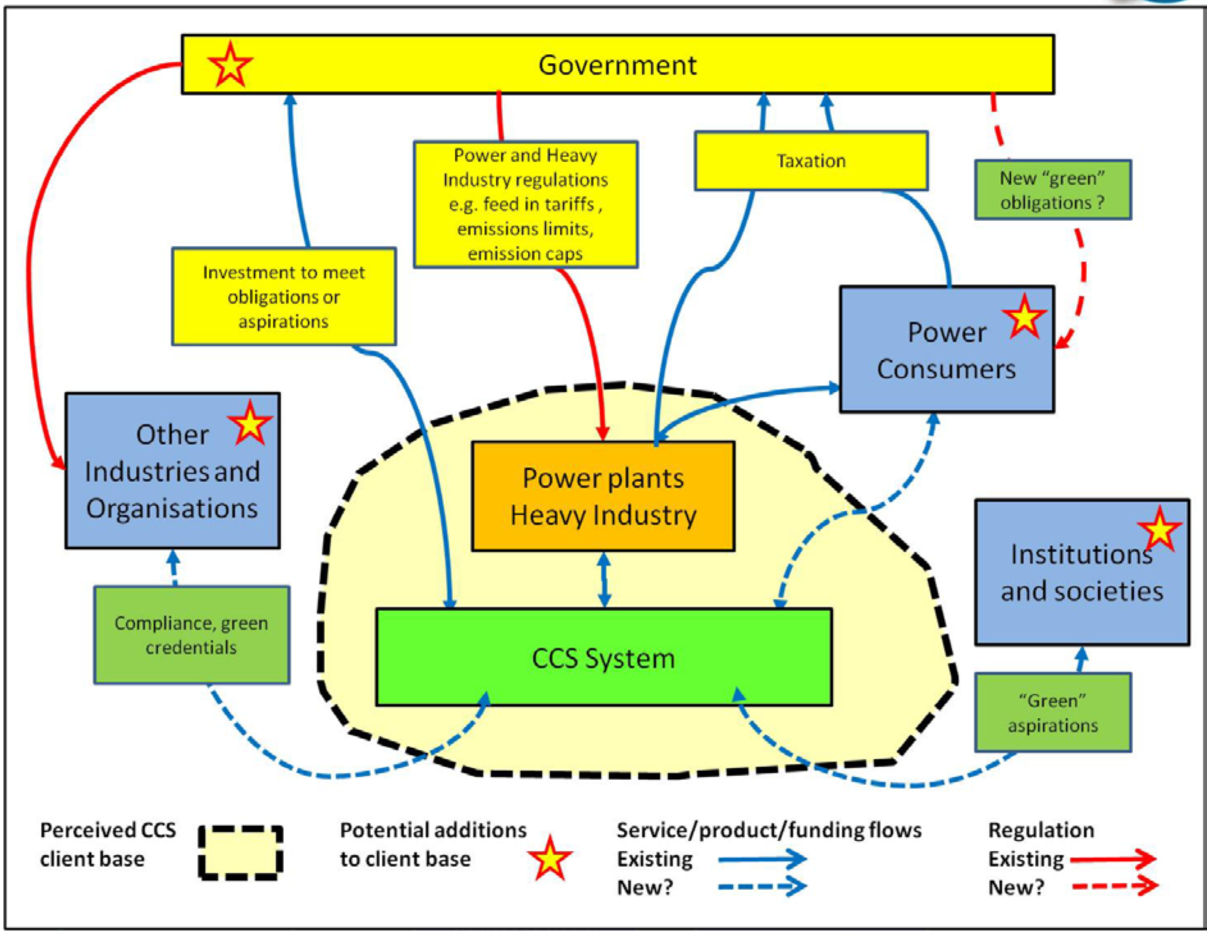


Fig 31 Potential for expanding client base for CCS clusters

6.5.3.8 Developing EOR and CO_2 storage businesses together

The value propositions of extra oil from CO_2-EOR and earning of carbon credits through geological storage are separate. If the geological storage is being carried out in separate reservoir they could be commercially separate even if common infrastructure is used. Once credits can be earned in EOR projects the two will be physically and commercially bound together. However the customers interested in carbon credits are not necessarily the same as those interested in EOR and hence it is possible to envisage different sets of customers for each. It will be a challenge to market to these two sets of customers at the same time especially as EOR projects might take in extra CO_2 for storage above and beyond the optimum amount for CO_2-EOR. Operators of EOR projects will probably not need all of the carbon credits generated by storing anthropogenic CO_2 for their own operations and could thus sell these on to emitters who need them. Some of the revenues would need to be retained to pay for the measurement, monitoring and verification and to cover any increased liabilities for the long term security of the storage. It would also be possible for emitters to take shares in the EOR project in return for the carbon certificates but not the incremental oil. This could thus provide an additional source of project funding and also alleviate any ethical issues which emitters may have in enabling additional oil production. Another challenge in this type of system will be accounting for CO_2 emission reductions when large quantities of natural

CO_2 are also flowing through the system including that captured from production of high CO_2 containing natural gas.

This challenge is illustrated in Fig 32 which shows on the right hand side the same clients/CCS service interdependencies as in Fig 31 whilst on the left hand side is the oil industry equivalent but needing to share the oil production/CO_2 storage reservoirs. Until the market for emission reductions is liberalised there will be an issue of cross subsidy. Government incentives for the emerging CCS industry may need to be transparently ring fenced so that do not appear to be subsidising oil production.

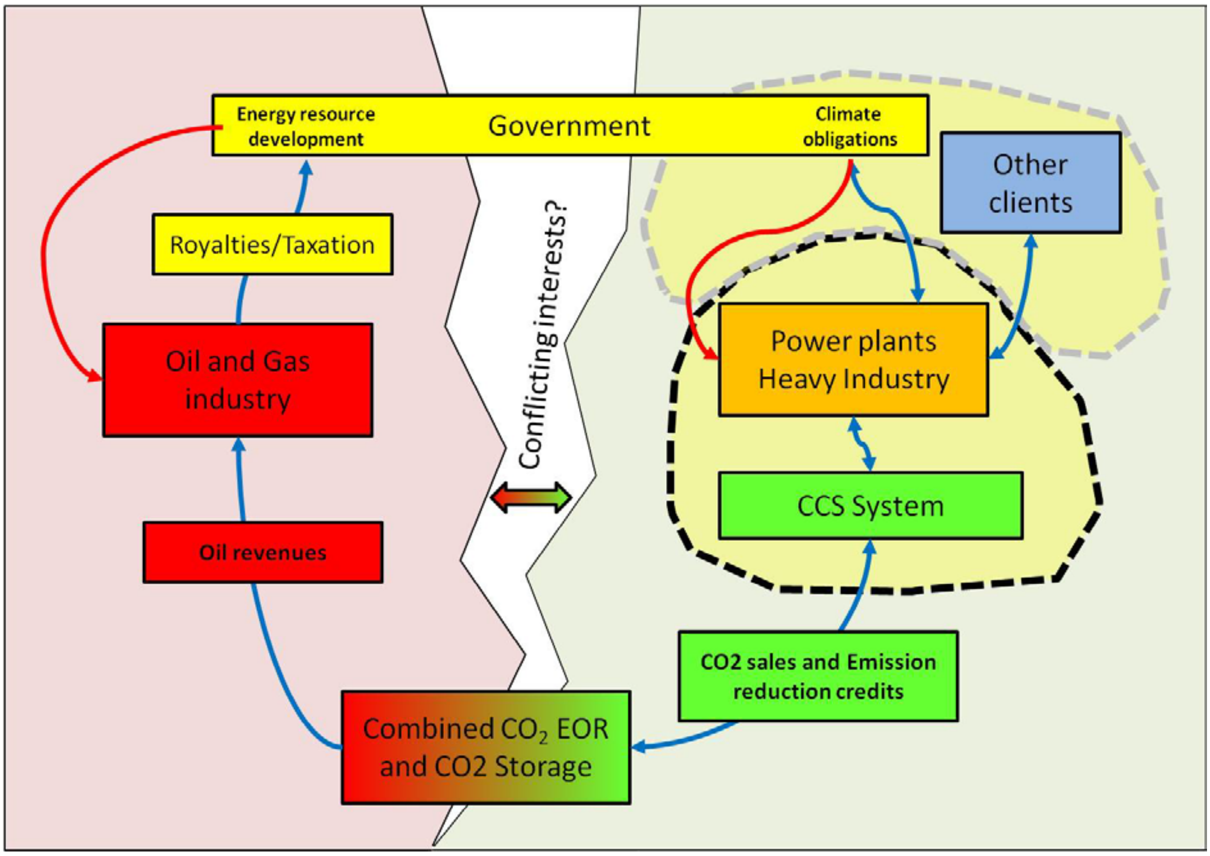


Fig 32 Reconciling CO_2-EOR and CO_2 storage businesses and their customers

7 Future cluster locations

7.1 Criteria for viable cluster locations

Examination of the plans and progress made by the clusters identified in this report indicates several key and obvious criteria for success. Overriding is an economic case and the only clusters which are becoming reality have two important advantages, 1) they are using the CO_2 for EOR, which gives it a clear long term value linked to energy prices, and 2) they are able to exploit very low cost capture opportunities. This can be qualified further in that the EOR opportunities are exclusively onshore where costs are much lower. They are also occurring in situations where the CO_2 capture is largely linked to hydrocarbon production operations such as natural gas processing and heavy oil upgrading. These clusters look set to enjoy growth in the absence of any carbon emission reduction credits. An additional driver for employing CCS is obtaining or retaining the licence to operate. Expansions in capacity or even continued operation may only be permitted if CO_2 emissions to atmosphere are reduced..

This does little to promote the image of CCS as a carbon emission reducing prospect but it may have to be accepted that it is a powerful commercial route to spreading the use of the technology. A number of projects both point to point and cluster have reviewed reuse of existing oil and gas facilities, particularly the pipeline infrastructure, and have concluded that there is little or no cost advantage. However clusters which build up a system based on EOR will be much more suitable for transition to capture purely for storage in the future.

Key criteria for early clusters are thus:

- Countries with mature oil producing provinces
- Countries with significant CO_2 containing gas reserves either in operation or available for development
- Countries with significant access to cheap feed stocks for gasification and industrial reasons for carrying out gasification operations such as chemicals and fertiliser production and heavy oil upgrading which require large scale hydrogen production

7.1.1 Sharing resources

Clustering is to a large extent about a value proposition of sharing resources. Several studies have attempted to quantify the cost reductions which result from use of larger capacity shared pipelines. The savings compared to single point to point projects are at best in the low tens of percent but only apply to the transport element of the chain. As this is itself a small fraction of the total cost the economic advantage overall is quite small and thus does not appear to be an overriding reason for forming a cluster. An exception to this is in the early phases of projects where some CO_2 sources are available with low capture cost so that the costs of pipelines and storage are substantial. Depending on the size of the storage reservoirs and the capacity of injection wells, sharing of storage may also offer substantial savings during initial phases when flows are low. Larger savings might be available from more organisational sharing of elements of the CCS system such as management of capture and storage elements and all of the attendant specialist services which a full CCS operation will require. This is unfortunately an area which has not been greatly explored.

It is nevertheless true that for long and thus expensive pipelines, there is a case for installing a large capacity system in anticipation of increasing capacity. A consideration in this is for offshore pipelines where the incremental costs of higher capacity is less because of the high mobilisation costs for laying. To illustrate this some simple comparisons were made between two example pipelines, one with double the capacity but only 1.5 times more expensive. This ratio is in line with typical figures in the literature for pipeline costs. Basic economic parameters used were discount rate of 10% and a 20 year project lifetime. A notional unit cost of the smaller pipeline was calculated assuming it operated at full capacity from the start. For the large pipeline it was assumed that capacity would start at 50% and ramp up to 100% over time. Four different ramp up profiles were generated (see fig 33) -: a step increase, a linear increase, a fast initial increase tapering off and a slow initial increase increasing later. Parameters for the shape were adjusted so that each gave the same discounted unit cost as the baseline project of 50% capacity. The profiles show that costs would be similar as long as the time to fill the pipeline capacity has a median of around 6 years. This period would be extended if lower discount rates (6% was mentioned by one of the expert reviewers as being more suitable) and longer lifetimes sometimes used for infrastructure projects were applicable. This analysis reinforces the conclusions found in many studies that the case for over-sizing transport pipelines is not strong and that if this is done considerable efforts would need to be made to negotiate contracts to use the additional capacity.

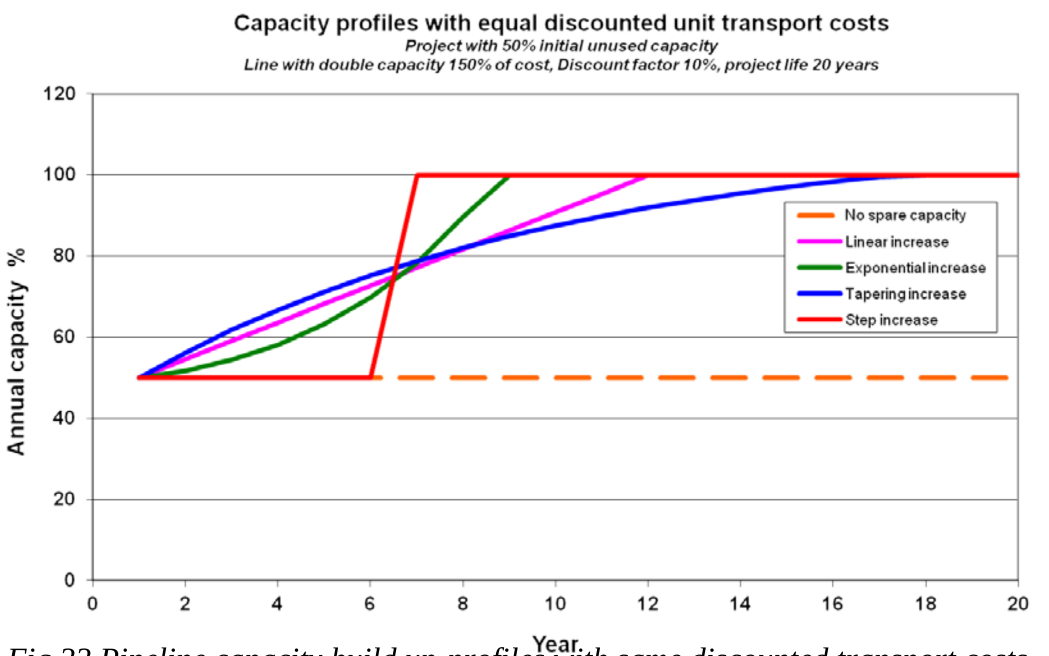


Fig 33 Pipeline capacity build up-profiles with same discounted transport costs

Considering the lead time for new capture capacity the economic window of opportunity is quite short. Future customers would need to be “in the pipeline” long before start of operations. A major value in having the transport capacity installed and waiting is that lead time associated with developing a new pipeline is eliminated thus removing what can be a significant barrier to an integrated CCS project. Another important factor to which it is less easy to assign a value is the confidence which is created if the pipeline infrastructure and storage reservoir are known to be available. Such confidence can be the catalyst which spurs emission sources within a cluster to progress plans for capture. The pre-investment, whilst a large risk for the pipeline and storage elements of the cluster, is relatively small in the context of the total investment for the complete CCS system.

In summary a location where there is a ready chain of new customers and significant planning hurdles for new pipeline infrastructure would be favourable for hosting a CCS cluster rather than point to point developments. The high cost of mobilising to lay offshore pipelines would favour laying of a larger line to serve a cluster of emitters. The options for increasing capacity offshore are limited to line looping whereas onshore adding additional booster pumping stations are a cheap option for increasing capacity. Also looping sections of line is much easier and cheaper onshore. The economics of pre-investment in transport alone are not enough to justify clustering.

7.1.2 Organisational disposition

Another important cluster criterion is the appetite and capability which a region has for organising a CCS cluster business opportunity. A common theme is many studies is that significant funding is likely to be needed from Government. Thus the organisational capability will need to include the ability to mobilise substantial funding and support from Government. The COCATE study suggested a range of options for the structure of the industry from a “sewage model” in which the Government provides the full service and charges the users to the other extreme which is, a fully privatised free and competitive market. An important lesson from development of the LNG industry is that State owned oil companies played a major role in setting up this industry in the early years.

Parallels are drawn between the oil and gas and power industries and the emerging CCS industry. However these industries have evolved in many countries into a far more privatised, unbundled and international business which is no longer so conducive to setting up infrastructure businesses. Indeed this parallel could be seen as quite unhelpful in the context of setting up CCS clusters. Thus countries which still host strong State industries with expertise relevant to CCS could be in a stronger position to initiate cluster developments. Other countries may be better identifying and developing the best point to point projects as these will likely be easier to set up, more economic and may ultimately form the anchors for later cluster development.

7.1.3 International cross investment

A key principle of international CO_2 trading is that this will help enable the world to seek out the lowest cost for CO_2 emission reduction opportunities. Given that successful clusters should be able to offer low costs it would make sense for international investment to be directed towards them. However the recipient regions would need to be amenable to this type of inwards capital flow for investment, the investors would need to be confident that their long term interests were secure. Thus another key factor in selecting where to set up CCS clusters will be the ease with which international investment funds could be attracted, accepted and applied.

7.1.4 Stability of future emission quantities

Mentioned in a number of studies is uncertainty about future emissions and the risk that plants partway through their lives might shut down or relocate. Thus the age and stability of the industries from which CO_2 would be captured is an important factor. Trends which may have a significant effect are:-

a) Discovery and development of shale gas which could lead to phase out of existing coal plants in some areas and increased use of freed up coal production in others.
b) Migration of high emitting heavy industries such as chemicals, iron and steel and cement to regions where costs are lower.
c) Developing intermittency in fossil fuelled power generation due to high renewables penetration.

7.1.5 Long term funding for core organisation

A key learning from the Rotterdam cluster is that it is essential to maintain a long term vision but one adaptable to changing circumstances. In order to provide the continuity this will require a core organisation to exist with secure long term funding so that a central team of at least a few well qualified and dedicated staff can be maintained. Although the costs of this are substantial, maybe several million dollars per year, the amount is trivial compared to the overall costs of a large CCS cluster. Based on the experience of clusters so far it is likely that the core organisation would have to be supported for at least 10-15 years before a viable self-financing cluster business is established. Keeping such a core organisation alive has proved difficult in some cases. For example the agency which promoted the Yorkshire Forwards cluster in the UK was abolished and not replaced and it is also understood that the initial tranches of funding for support of the Rotterdam project is also running out. In Canada the ACTL project relies heavily on the continued existence of Enhance Energy Inc. Thus another indicator of where clusters are likely to flourish is the whether long term, secure funding for a core organisation can be forthcoming. GCCSI, Governments and large companies have all been very helpful in funding core activities for clusters but all such funding is relatively short term. Examination of locations where guaranteed funding of this long term nature could be provided is a thus a useful filter. In many instances funding of such long term open ended commitments is not favoured by those in a position to provide the funding.

7.1.6 Future cluster locations

The time required to research and develop a CCS project is considerable and even more so for a cluster of CCS projects. This study has discussed a range of CCS clusters projects from those which are well established on the basis of business case with possibility of supplying natural CO_2 for EOR, to those cluster projects which have only started to study the disposition of sources and potential storage sites. The development of CCS projects has so far followed a path of research and demonstration leading to the first commercial scale point to point projects, some of which are envisaged as seeding a CCS cluster. The existence of a CCS project cluster opportunity is a factor when selecting first CCS projects in a region but not necessarily a decisive one. The most likely places for new clusters to develop is in locations with a significant CO_2 emitting industry in reasonable proximity to a mature onshore oil production province. A key advantage could be the availability of proven reserves of high CO_2 content natural gas. Separating CO_2 from these reserves will unlock substantial revenues for the natural gas and the CO_2 could be used to generate additional oil revenues. Production of such reserves with release of the CO_2 is likely to become increasingly unacceptable potentially stranding the gas. This CO_2 could provide the backbone of initial supply to which CO_2 captured from industrial sources could be added step by step.

Countries not mentioned which could consider CCS clusters could thus be Mexico, Indonesia oil producing regions of Russia and the countries of the Former Soviet Union and perhaps other locations in China. A study of the juxtaposition of places high CO_2 content natural gas, mature onshore oil and industrial emissions sources would be needed to identify such cluster CCS prospects.

8 Conclusions and recommendations

The most successful clusters remain those based on the use of CO_2 for EOR application. The funding/cost gap for CCS projects purely for emission reduction is currently an insurmountable obstacle to large scale CCS deployment, whether as clusters or point to point projects. The required revenue drivers are virtually fully reliant on Government policies of one form or another. The cost reduction benefits of combining infrastructure are mainly in reducing the cost of transport by pipeline because of economies of scale. However the reductions are small compared to the overall cost of the CCS chain. Furthermore a failure to utilise CO_2 pipeline and storage capacity within a few years would negate any economic advantage. At the same time pre-investment will potentially be essential to generate the confidence needed for the emission sources in the cluster to progress their plans. Other significant benefits could result from sharing organisational costs, arranging permits, gaining public acceptance and pooling specialist services but are difficult to quantify. Such services could be in the field of maintenance and operation of capture facilities, supply of chemicals and waste disposal or CO_2 measurement and accounting. The cost reductions for CCS cluster projects are greater for offshore pipelines because of the high mobilisation and laying costs and are also greater for long distances from source to store. However both offshore and long distance routes make cluster locations less attractive in terms of overall cost.

A major obstacle in early years is maintaining a core organisation which is able to carry a CCS cluster project forwards. This can only be overcome if long term funding is committed so that key staff can be engaged and retained. In the long term the costs of this will be minor compared to the total investment in a CCS cluster. Those countries which clearly have a long term competitive cluster location should consider setting up and funding the necessary core organisation for as long as the project takes to come to fruition.

Promising CCS cluster locations should be in a position to attract international funding and not just rely on providing the CO_2 capture service on a local basis. Mechanisms and structures to allow this widening of support are absent and need to be put in place for CCS clusters to succeed.

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APPENDIX A: Technical and Business data collection checklists

This checklist was used as an aid to gathering information from the literature sources. The fields are set up to reflect what should be available from a CCS cluster which has been well developed on both the technical and business fronts. Many fields will thus not be applicable to less well developed clusters. Where specific items were found in one cluster these were added to the list to prompt checking for similar items in other clusters. The final spreadsheet is available as a supplement to the written study report.

CCS CLUSTER PROJECT DATABASE CHECKLIST	
Types of information sought	**Background**
Title/location/organisation	
Official name of project if available	Gives focus to the CCS cluster opportunity
Main country or region	Identifies lead country
List of countries if multiple	Indicates where international co-operation and cross-border trade and issue
Main organisation	Identifies whether a central responsible and co-ordinating organisation exists
Person(s) leading the enterprise	Identifies whether the project has a single person leading it
Leader(s) credentials	Indicates weight and experience of the person leading the project (if any)
Business/Commercial Contact	Helps indicate whether the project has a strong business presence
Names and roles of other key personnel	Indicates strength of core team if there is one.
Identities of other supporting organisations	Indicates depth and breadth of support
Main website	Key source of project information
Key document(s)	Key source of technical and business information
Influential supporters	Gives indication of how high the profile of the project is.
Project status and information sources	
Inception date	Indicates how long co-ordinated work has been done on the cluster
Proposed start-up date	Indication of maturity and for existing projects

	length of experience base
Maturity level	An assessment to allow different clusters to be compared on a 0-7 scale
Maturity description	Taken from a standard list based on the numerical scale
Project Website(s)	Sometimes there is more than one website relating to the project
Databases on which registered (specifically as a cluster)	A useful check on whether the project is recognised in these main databases.
Zero CO2 Norway	
GCCSI	
NETL	
IEAGHG	
Other Key references (Numbers from list)	To help identify data sources
Technical details "General"	
Quantity available to be captured	Allows relative size of clusters to be compared
Capacity build up profile	Indicates how project envisages build up and extension of the system
Anchor project(s)	Important in many clusters as this can be a key to getting started
Technical details "Capture"	
Number of sources	Gives indication of spread of the cluster
Types of source – tabulate/chart – use standard classifications	Indicates range of processes which are expected to be deployed and spread of industries which have to be engaged
Capacities – Values in Mta	Summary of expected capacities at various stages in project. Broken down into elements where this is available
Capacities graphical	To allow collection of graphical representation of capacity profile where available
Capacity variation characteristics – e.g. steady, diurnal, seasonal etc.	To record what issues, if any, the project has identified in relation to capacity variations on daily or seasonal basis
Capture processes proposed	More details of capture processes to be deployed and whether these have been identified

New or retrofit	Information on balance between new and existing sources
Capture efficiency (i.e. of actual capture process)	For comparison if quantified and published
Abatement efficiency (i.e. % of initial emissions avoided)	For comparison if quantified and published
Purity specifications (at export to transport)	Indicates whether this issues has been addressed
Costs CAPEX	Fields here are to prompt collection of information on main cost elements
Capture cost per tonne estimates Central	Sometimes a typical figure is published
Range	Often a range is given due to uncertainty or because of the variations between capture units
Date of estimate	Useful for comparison of estimates made at different times
Estimating methodology	Helps identify quality of estimate
Technical details "Transport"	
Principle method (s)– ship, pipeline	Important for comparison as several projects include hybrid systems
Principle transport condition(s) – gas, dense phase, liquid, refrigerated etc.	For basic comparison
Capacity	Similar to capture values but may differ due to phasing and installation of speculative capacity
Distances	Key parameter for comparison
Sizes – diameters, ship tonnages	Key parameters for comparison
Booster pumping	Useful to know whether this is part of system or of capacity upgrade plans
Intermediate storage	Usually only associated with project when shipping is part of the transport system
Operating pressures	For comparison between clusters
Delivery pressure	For comparison between clusters
Design pressure	For comparison between clusters
Pre-conditioning requirements – e.g. supply pressure, minimum purity, water dryness	Important to understand whether this has been considered and if so in what detail
Pre-transport conditioning – i.e. if centrally applied	Indicates whether central conditioning is necessary

Flow measurement	An indicator of the level of detail in the project design and for comparison
Pigging/inspection	An indicator of the level of detail in the project design and for comparison
Key pipeline design features – buried, insulated, lined etc.	An indicator of the level of detail in the project design and for comparison
Safety provisions – e.g. block valves, low pressure,	An indicator of the level of detail in the project design and for comparison
Route selection – new ROW, existing ROW (pipeline, road, rail)	Any information on the route which helps show how for implementation plans have been developed
Delivery conditioning – e.g. heating, pressure reduction, recompression	An indication not only of whether necessary but also whether this issue has been identified and addressed.
Costs Capital	Fields here are to prompt collection of information on main cost elements
Operating	Fields here are to prompt collection of information on main cost elements
Overall	Fields here are to prompt collection of information on main cost elements
Method	Helps identify quality of estimate
Technical details "Storage"	
Types of storage – saline aquifer, depleted oil and gas fields, EOR, basalt, Farced shale etc.	Helps identify how well characterised storage is
Identity of storage sites	Helps further to identify how well characterised storage is
Type(s) of trapping	Helps further to identify how well characterised storage is
Number of storage sites	Helps identify how well characterised storage and whether there are fall-backs
Estimated capacity	Important to understand potential. Also quality of estimate recorded here
Estimated injection rates	For comparison and also to indicate maturity of characterisation
No of wells	If known an indicator of maturity
Capacity range	Captures any uncertainty in injection rates if reported.

Depth	For comparisons
Pressure	For comparisons
Availability timeline	Important as this can be a serious restriction. Record any issues noted
Maturity of characterisation	A narrative assessment based on what is published
Costs	On a per tonne basis if available. Useful for comparisons
Estimating basis	Helps identify quality of estimate
Legal/regulatory/social issues	
Significant Enablers	A catch all field to prompt recording of anything significant which project has identified
Significant Barriers	
BUSINESS PLAN	
Overall structure (interlocking business etc.)	A field for a narrative summary of the business plan into far as it exists
Business plan details (Based on business model canvas)	
SUMMARY	Fields available for short narrative summary based on detailed information which is extracted
Key partners	Partners can be investors, sources, system operators
Key activities	Indication of the understanding of the full range of activities which have to be undertaken
Key resources	Indication of what resources the cluster already has ore intends to acquire
Cost structure	Indication of how well all the cost elements are understood
Value proposition	The range of value propositions which the cluster has identified and how firm they are.
Customer relationships	The type of interaction which the business have or intend to have with all classes of customer and how well developed design of this is
Channels	The ways in which the businesses communicate or intend to communicate with all classes of

	customer
Customer segments	The extent to which the businesses have identified the various types of customer and hence the varying needs
Revenue streams	Indication of which main sources of income will be tapped by the businesses, particularly those beyond CO_2 reduction certificate values
Key partners	
Investors (identified)	Important to guage strength of business
No of investors	For comparison and to indicate breadth of support
CO_2 sources	Whether CO_2 sources are partners
CO_2 transporters	Whether any companies engaged in transport are partners
CO_2 users	Whether an companies who use CO_2 (principally EOR) are partners
Other partners	Nature of any other partners who may be supporting the business
Relationship other partners	The basis on which any other partners are engaged.
Joint ventures – for sections of the system	Look for information on any JV's which are formed or proposed
Business scope of joint venture	Extract information on scope of any joint ventures
Strategic alliances	Look for information on any alliances (which fall short of full JV's) which are formed or proposed
Business scope of strategic alliances	Extract information on scope of any Alliances (which fall short of full JV's) which are formed or proposed
Competition - Strategic alliances between competitors	Look to see if any alliances are actually between competitors.
Motivations – economy of scale	Check list of things likely to motivate partners to take part where specifically mentioned or implied
Motivations – risk reduction	Look for indications that working together is seen as reducing risks

Motivations – resource acquisition	Look for indications that partners seek to acquire key resources or access. Usually storage and rights of way in the case of CCS
Motivations - learning	Is mentioned by some so look to see if others are quoting this as a motivation
Motivations - other	Catch all for anything else implied as motivating the partners to work together
Key activities	The following is a check list of activities which a cluster will have to carry out as part of some entity's business. Aim is to explore how much is covered by the plans. Specialised items have been picked up during data collection from some of the clusters
Capturing CO_2	
Transporting CO_2	
Storing CO_2	
CO_2 Accounting services	
Liability insurance	
Confidential data handling	
System operational management	
Capture related specialist services	
CO_2-EOR specialist services	
Emission control specialist services	
Matching suppliers and consumers (EOR)	
Other	Any other key activities which cluster specifically mentions as something they will do
Key resources	The following is a check list of resources which businesses in a cluster will probably need. Aim is to explore how much is covered by the plans. Specialised items have been picked up during data collection from some of the clusters
Access to funds	UP front funding is a key requirement regardless of any gap between costs and revenue
Capture facilities	Are these part of consortia or are sources expected to make have their own facilities?
Transport facilities	Particularly anything beyond the trunk pipeline

	systems such as shipping facilities
Storage facilities	
Storage exploration capability	Do any partners bring this capability which is essential for the full CCS chain
Technical expertise in diverse CCS related fields	Look for any specialised resources such as capture technology, financing expertise
Access to low grade waste heat	Mentioned in one cluster and may thus be important for others
Helium co-production	Mentioned in one cluster and may thus be important for others
Value proposition	This is check list of things which the plans may mention as being of value. List built up from what is reported by individual clusters. First items are CCS specific. Others are generic items suggested by Osterwalder.
Deliver affordable CO_2 for CO_2 EOR	Mainstay of existing clusters
Licence to operate for fossil fuel suppliers	
License to operate for fossil fuel users	
CO_2 emission reduction credits	
Meeting Country international emission reduction obligations	
Meeting Country emission reduction targets	
"Getting job done" in any of the foregoing	To what extent do plans propose to take the burden of making CO2 reductions away from emitters
Newness – solving an essentially new issue	Is there an element of novelty in the proposed solutions
Performance – Could this win over price?	Do the cluster businesses purport to be able to deal with the CO_2 in a better performing way because of their capabilities
Customisation – Capture expertise?	Are the businesses offering a customised service to emitters
Brand – Being in "good hands"?	Are the businesses exploiting their brand names to customers

Design – unlikely but worth exploring	Are the businesses offering specialist design e.g. of capture facilities or other features of the system which could be attractive to customers
Price – can it be shown to be best if via a cluster	Are the businesses offering a direct price advantage
Cost reduction – could this be a long term attraction of being in a cluster	Is future lower cost (or price) a stated proposition
Risk reduction	Do the businesses offer to reduce any of the risks associated with emission reduction by whatever means
Accessibility – is there any way that businesses could gain access to reduction technology	Are the businesses offering any form of exclusive access to emission reduction solutions
Convenience – getting someone else to do the necessary	Similar to getting job done but more directed to being able to unload the responsibility for emission reduction
Favourable terms for the extra fuel needed to run CCS	Item picked up from literature
Knowledge generation and sharing	Item picked up from literature
Using high CO_2 content gases	Item picked up from literature
Low carbon credentials needed to promote or retain business	Item picked up from literature
Other	
Customer relationships	These general classifications are the main types of customer relationship which can be established. Some are more relevant to markets but are listed for a complete check
Personal	
Industry associations	
Regional development agencies	
Dedicated personal	
User community	
Co-creation	
Automated services	
Self service	
Site studies	
Project studies	

Other	
Channels	This list is largely generic from the business plan canvas but has a few specific additions relating specifically to a CCS cluster business
1. Awareness How do we raise awareness about our company's products and services	
Form associations	
Global institutions	
Conferences and events	
Publications	
News	
Direct contacts	
2. Evaluation How do we help customers evaluate our organization's Value Proposition?	
Specialised Consultancy services	
Confidential surveys and evaluations	
Loan of specialist staff	
Courses for clients specialist staff	
3. Purchase How do we allow customers to purchase specific products and services?	
Bilateral deals	
Take and dispose	
Transport tariff	
Co-ownership	
Capture fees	
Sell access and/or capacity	
Sales of CO_2 for EOR	
CO_2-EOR design	
CO_2-EOR project implementation	
CO_2 – EOR operational services	

Sale of options	
Through mass market sales – power customers sign up for a “green supply” using CCS	
4. Delivery How do we deliver a Value Proposition to customers?	
Service contract	
Reserve access to capacity	
EPCO of capture process for clients	Engineer, procure construct and operate complete service
5. After sales How do we provide post-purchase customer support?	
Capture plant maintenance	
Capture plant monitoring	
Capture plant improvements	
Storage monitoring services	
Customer segments	This is a check list to see to what extent clusters have identified particular segments and intend to treat them separately
Emitters	
Oil and gas producers – depleted fields no CO_2-EOR option	
Oil and gas refiners and upgraders	
Chemical industry	
Biomass consumers	
Underground coal gasification	
National Government	
Regional Government	
Enterprise zone	
CO_2-EOR producers	
Large emitters	
Small emitters	
Decarbonised energy amenable emitters	

Carbon fuel dependent emitters	
Mass market energy consumers	
Diversified – (other customers with completely different needs)	
Multi-sided- (Customers with complementary needs)	
Cost structure	This is a check list to gain an overview of the extent to which most of the various cost elements found in publications have been recognised and how well they are understood.
Project management	
Capital for facilities	
Capture	
Transport	
Storage	
Direct Opex for facilities-manpower, utilities, chemicals, spares, maintenance	
Capture	
Transport	
Storage	
Well work overs	
Mothballing storage facilities	
Abandonment of storage facilities	
Abandonment Wells	
Abandonment Platforms offshore	
Abandonment storage site onshore	
System administration	
Exploration and appraisal	
Monitoring	
Insurance	
Liability transfer	
Uninsured damage liabilities	

Licences and permits for storage and Pipeline (ROW etc.)	
Land acquisition	
Emission certificates	Cluster operations may incur emissions of its own
Increased cost of fuel	
Revenue streams	This is a check list of possible revenue streams some of which relate to how the value of emission reductions is recovered and others which are payments for services within the cluster. Various forms of funding have been included as "revenue" on the basis that they are the balance for the costs
Sale of CO_2	
Sale of storage capacity	
Sale of transport capacity	
Payment for removing CO_2	
Sale of system assets - shares	
Sale of by-products	
Sale of green energy vectors (H_2 or electricity)	
Value of emission reduction credits	
License fees for capture process	
Fees for operation and maintenance of capture process	
Fees for storage reservoir management	
Loans from users or potential users	
Loans from investors	
Loans or payments from government bodies	
Loans or payments from private investors or charities.	
Loans or payments from international bodies – World bank, EBRD, UNEP, EIB	
Climate levies or taxes on customers	
Increased sales of fuel for CCS	

Miscellaneous	
Business plan maturity assessment	In this section an assessment of the maturity of each business plan element and an overall maturity is given using a 16 point scale withy standard narrative descriptions
Maturity index (Overall)	
Maturity description (standard phrase)	
Maturity description Narrative	
Individual elements maturity	
Key Partners score	
Descriptor	
Key Activities score	
Descriptor	
Key Resources score	
Descriptor	
Value proposition score	
Descriptor	
Cost Structure score	
Descriptor	
Customer Relationships score	
Descriptor	
Channels of Communication score	
Descriptor	
Customer segments score	
Descriptor	
Revenue streams score	
Descriptor	

APPENDIX B: Approach to technical data collection.

The technical data available from the literature on each cluster project varies so that it is not always possible to collect a full set of information in the same format and units across all projects. The data base entries were constructed sequentially by adding new fields as additional cluster literature was explored. Some data items are characterised by single numbers or statements but in more complex areas, such as capacity build up, there is often a long list of items to be extracted from the data. In these cases the fields in the spreadsheet were simply populated with a text containing the information. This was then used as a source of numerical information for construction of charts where a single numbers was needed for comparison purposes. Values used and timings were based on judgement.

Where possible data was collected in Mta of gross CO_2 captured or transported. Cost were collected by preference in US dollars but otherwise in other currencies. Initially it was hoped that sufficient cost data might be collected to allow direct comparisons. However the times, currencies, discounting and financing assumptions and scopes were found to be too diverse to allow meaningful comparisons to be made.

The more advanced projects had, by their nature, considered and designed in much more detail. Basic decisions had been made on detailed items such as CO_2 specifications, design pressures, metering provisions etc. As this key information was found additional fields were thus added to record the information but also to act as a prompt to search for the same information from subsequent projects as their literature was consulted.

It is inevitable in such large projects that slightly different values are mentioned in the literature depending on the author and also often the time of publication. Here judgement had to be exercised as to which set of data to record with a preference for more up to date information or that from a source closest to the core development team.

Some of the data sought relates to the technical performance in terms of such things as capture efficiency and where necessary numbers are derived from other published data.

Information was gathered from a range of sources from peer reviewed technical papers to presentations aimed at both technical staff and to business analysts. Information was also obtained from popular journal articles, news reports and company websites.