Department for
Business, Energy
& Industrial Strategy

CCS deployment at dispersed industrial sites

Element Energy for the Department for Business Energy and Industrial Strategy (BEIS)

BEIS research paper number 2020/030

August 2020

Acknowledgements

We gratefully acknowledge the following stakeholders for the support and input they provided:

- Tata Steel
- Mineral Products Association
- Breedon Cement
- BOC
- Air Liquide
- Chemical Industries Association

Any enquiries regarding this publication should be sent to us at:
Emrah.Durusut@element-energy.co.uk

Contents

Executive Summary

Summary of context and objectives

The Department for Business Energy and Industrial Strategy commissioned Element Energy in 2019 to identify and assess the range of high-level deployment options for Industrial Carbon Capture (ICC) technology on sites isolated from CO2 transport and storage infrastructure in the United Kingdom. This area is of particular relevance because most of the existing Carbon Capture and Storage (CCS) reports in the UK focus on how shoreline CCS clusters can be developed. Isolated or inland emitters and clusters are generally excluded in these reports, or high-level onshore pipelines routes are presented in the longer term once the shoreline hubs are developed; the level of thinking and evidence are therefore limited in this area.

In this work we identify key dispersed sites in the UK as well as their unique challenges and barriers to CCS deployment. Next, we appraise a range of high-level options for CCS deployment and the risks associated with each challenge and finally we assess the most promising options based on their cost, risk and emission reduction potential. We also include a comparison of CCS against alternatives such as carbon utilisation and hydrogen fuel switching based on the same metrics.

This work has been supported by a period of stakeholder engagement during which organisations involved across a wide range of the CCS value chain were consulted.

Identification and categorisation of industrial emitters

Our analysis suggests that there are 36 ‘dispersed’ industrial sites in the UK that would be potentially suitable for CCS. The method applied to identify these sites consists of the following three-stage process of all UK industrial sites and is described in further detail on page 13:

- Only large sites emitting 50 ktCO2/annum or more considered
- CCS suitable industries only
- Exclusion of sites already located in CCS industrial clusters

Once the above process is applied, the remaining sites emit an estimated 20.7 MtCO2 with the majority (87%) of emissions arising from the following sectors: Iron & Steel, Cement and Refining.

In the context of CCS, we find that there are certain synergies/similarities between these 36 sites, and that they can be grouped into four categories according to these:

- Group 1: Industries located inside the South Wales industrial cluster, which has been included in this study due to limited storage opportunities nearby.
- Group 2: Industries that are not in Group 1 and that are within 30km of a major port.
- Group 3: Five high emitting sites that are located either inside enclosed by the Peak District National Park were identified. All located within 20km of one another.
- Group 4: All remaining sites – these can be considered as truly dispersed.

Risks and challenges of CCS for dispersed industrial sites

Through a series of stakeholder interviews and in-house expertise, we re-analyse the traditional risks and challenges of CCS (i.e. those for sites located inside industrial clusters) for dispersed industrial sites. We find that the dispersed location of a site can be a significant challenge towards CCS deployment, but not necessarily a showstopper. Our research suggests that some challenges are valid for all sites considered whereas others are more relevant to certain groups (defined above) than others. The main risks are categorised into the following: cross chain, policy and technical.

Cross chain risks - For all sites considered there is uncertain availability of transport & storage (T&S), which leads to risk of stranded assets with no alternative use. Due to the singular nature of sites in Groups 2 & 4, certain segments of the CO2 transport infrastructure would only serve one site. As a result, these cannot benefit from economies of scale so bear higher cost of abatement and are more at risk of low utilisation of transport assets due to e.g. industry down time. For some locations (e.g. those located in a National Park), CO2 transport challenges would be so high that the preferred option may be to consider alternative technologies or relocate sites entirely.

Policy risks, with knock-on effect as economic & market risk - For all sites not located in industrial clusters (i.e. all sites apart from those in Group 1), there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process. Obtaining the required implementation and operating consent, permits and licenses for all aspects of the Industrial Carbon Capture and Storage (ICCS) chain may lead to delays in the Final Investment Decision (FID), construction etc. This is especially true of sites located in and around restricted areas (Group 3). The high risks associated with permitting provides significant deterrent to investors.

Technical risks - Many dispersed industrial sites (Groups 2,3,4) may have issues with energy (for CO2 compression / liquefaction), feedstock, oxygen (O2) e.g. for O2 separation for oxyfuel combustion in the cement sector, and water use of capture plant.

The analysis of risks and challenges highlighted that **the transport of CO2** has a high perceived risk for dispersed industrial sites. As a result, we considered in more detail the risks and constraints of the three possible **CO2 transport options** for CCS, including pipeline, ship and road/rail. The results of the analysis are summarised in Table 1.

Table 1: Principal risks and constraints CO2 transport options for CCS.

Onshore pipeline	Shipping	Road/rail transport
Regulatory: several permitting requirements for the construction of onshore pipelines that vary by pipeline length, however, White Rose project proved that, in theory, CO2 pipeline transport can be done safely. CO2 will continue to be classified as though it were a dangerous substance until specific legislation is introduced. **Disturbance**: local impact to population from its construction (one time)	**Regulatory**: exposure to different international regulatory frameworks including EU-ETSD, EU CCS Directive, UNCLOS, SOLAS IGC Code; these have an influence on the development and requirements for CO2 shipping. **Port constraints**: certain ports unable to accommodate CO2 ships Limited experience in CO2 shipping and lack of business models	**Safety**: route choice constraints because CO2 is a dangerous substance, explosion hazard **Capacity**: CO2 trucks currently operate with 20 tonne capacity. Less and less available rail capacity due to increased passenger traffic **Disturbance**: local impact to population from operation (constant) **Storage**: potential impact on feasibility and transport cost due to additional storage capacity required at capture site

Options appraisal based on cost-effectiveness and carbon reduction potential

The analyses of the different transport options shown above revealed that different options are better suited than others to each group based on the risks and challenges involved. The other main considerations when comparing decarbonisation options are the costs and the carbon reduction potential, which was modelled during the course of this project.

The transport of CO2 is segmented into two for the purposes of our modelling. In segment 1, we assume that CO2 is transported from each site to the nearest port terminal. In segment 2, CO2 is transported from the terminal to the nearest offshore storage site via pipeline.

In segment 1, the various transport options are considered: pipeline, shipping, road, rail and their combinations. The applicability of these options to the previously investigated groups of dispersed industrial sites is illustrated in Table 2.

Table 2: Applicability of transport options to the dispersed site groups.

Transport options	Group 1: South Wales	Group 2: Close to ports	Group 3: Peak District	Group 4: Truly dispersed
Pipeline (site - terminal)	Yes	-	Yes	Yes
Pipeline + Shipping (site - port - terminal)	Yes	Yes	-	Yes
Road (site - terminal)	-	-	Yes	Yes
Road + Shipping (site - port - terminal)	-	Yes	-	Yes
Rail (site - terminal)	-	-	Yes	Yes
Rail + Shipping (site - port - terminal)	-	Yes	-	Yes

In segment 2, four locations were chosen as port terminals: Peterhead, Teesside, Humberside and Liverpool. Transport costs from terminal to storage site were assumed to be £12/tCO2[1].

Summary of findings from our modelling estimates:

We modelled the costs in £/tCO2 associated with the transport of CO2 from the emission site to the offshore storage site for each of the 36 sites considered. We also estimated the carbon intensity as a percentage in terms of tCO2 emitted per tCO2 transported. A summary of the results by group is shown below.

- Group 1 (South Wales): We find that both pipeline and pipeline + shipping options may be optimal. Cost-effectiveness is estimated at £18/tCO2 to £21/tCO2.
- Group 2 (Close to major ports): The cheapest transport option is pipeline + shipping for all considered sites. However, if the Fawley refinery is excluded from calculations, the average transport cost increases from £23/tCO2 to £40/tCO2 and CO2 emissions from

[1] Results are based on Element Energy's CO2 shipping model for BEIS (2018) and further assumptions on onshore pipeline cost and road and rail fuel consumption reported in the appendix. Costs refer to 2018 and are undiscounted.

the transport activity will increase from 1.0% to 2.8% as a proportion of the amount of transported CO_2.

- Group 3 (Peak District): The cheapest and least carbon intensive option is pipeline; with costs of £15/tCO_2 and transport emissions of 0.1% of the transported CO_2, it is significantly cheaper and less carbon intensive than road and rail, which are estimated to cost between £33/tCO_2 and £36/tCO_2 and emit between 1.5% to 1.8% as a proportion of the amount of transported CO_2.
- Group 4 (Truly dispersed): In this group we find that in general the costs are higher with the most cost-effective ranging from £31/tCO_2 to £44/tCO_2. This owes largely to isolation of these sites from CCS infrastructure (ports, terminals etc.) relative to other groups as well as smaller infrastructure capacity that is often not mutualised with other users, which is especially true for pipeline transport (i.e. a singular user in this group may have to pay for a long pipeline with a relatively low capacity, which is more costly than a pipeline with a higher capacity shared by several users in the same group). We also find that the optimal pathway is less clear and more site specific rather than group specific. The cheapest transport options are pipeline or rail, and for one site pipeline + shipping. Carbon intensity is lowest for pipeline.

Comparison against alternative options

A comparison between different transport options is relevant in the context of CCS; however, alternative options to CCS exist, such as hydrogen fuel switching and Carbon Capture and Utilisation (CCU). We compared these two alternatives to the transport options over the same metrics (principal risks, costs and carbon abatement potential) and found more similarities by sector, rather than location.

For sectors with a large portion of process emissions (cement, glass, lime), CCS achieves a significantly higher level of abatement than hydrogen (H_2) fuel switching (or electrification).

As explained, one of the main technical considerations of CCS at dispersed sites is the availability and cost of transport infrastructure for CO_2. Hydrogen fuel switching would also encounter many of these challenges until the gas network is converted into hydrogen, as would CCU unless emitters and users are collocated, which for dispersed sites is more unlikely than for clusters.

Conclusion

The transition to net-zero in the UK will require deep decarbonisation of all industrial sites, including dispersed ones; this study shows there are various solutions available to them, ranging from CCS, CCU and fuel switching. This work shows that there are similarities and potential synergies between dispersed sites based on their location or sector. These should be leveraged to develop a common decarbonisation strategy for such sites. However, this work also shows that some sites are truly dispersed and for those a tailored decarbonisation solution is necessary.

We find that emissions from dispersed industrial sites represent a significant proportion of the UK's industrial emissions. Future funding and business models in the UK should include a strategy for such sites, ensuring viable technology and infrastructure solutions can be made available to them.

List of acronyms

AONB	Area of Outstanding Natural Beauty
CO2	Carbon dioxide
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation & Storage
FID	Final Investment Decision
H2	Hydrogen
ICC	Industrial Carbon Capture
ICCS	Industrial Carbon Capture & Storage
O2	Oxygen
MtCO2	Mega tonnes of CO2
tCO2	Metric tonnes of CO2
T&S	Transport & Storage (of CO2)

Introduction

The Department for Business Energy and Industrial Strategy commissioned Element Energy in 2019 to identify and assess the range of high-level deployment options for Industrial Carbon Capture (ICC) technology on sites isolated from CO2 transport infrastructure. This area is of particular relevance because most of the existing CCS reports in the UK focus on how shoreline CCS clusters can be developed. Isolated or inland emitters are generally excluded in these reports, or high-level onshore pipelines routes are presented in the longer term once the shoreline hubs are developed; the level of thinking and evidence are therefore limited in this area. In addition, industrial organisations/ stakeholders who are in natural CCS clusters (e.g. Teesside, Humber, etc.) are more engaged with CCS developments, so dispersed emitters may not be interested in discussing CCS solutions.

Meeting the UK’s legally-binding, long-term emissions reductions goals will require deep decarbonisation of all sectors of energy use, including energy-intensive industries. CCS has been recognised, both internationally, and in the UK, as a key technology in reducing CO2 emissions in the energy-intensive industry. To achieve deep decarbonisation, industrial CCS needs to be deployed beyond the simpler cluster-based strategies, into dispersed industrial sites far from a potential CO2 transport and storage network.

Most of the previous studies on CCS in the UK focus on how shoreline CCS clusters can be developed. Inland emitters are generally excluded in these reports or high-level onshore pipelines routes are presented in the longer-term once the shoreline hubs are developed. Further investigation around the opportunities, obstacles and costs of deployment of CCS at dispersed industrial sites is therefore required.

Objectives

The key aim of this study is to identify and assess the range of high-level deployment options for Industrial Carbon Capture (ICC) technology on sites isolated from CO2 transport infrastructure.

- Identification of the challenges and barriers to CCS deployment specifically at these dispersed sites
- Appraisal of the range of high-level options for CCS deployment and the risks associated with each challenge
- Assessment of the most promising options based on their cost, risk and emission reduction potential.

Review of dispersed industrial sites in the UK

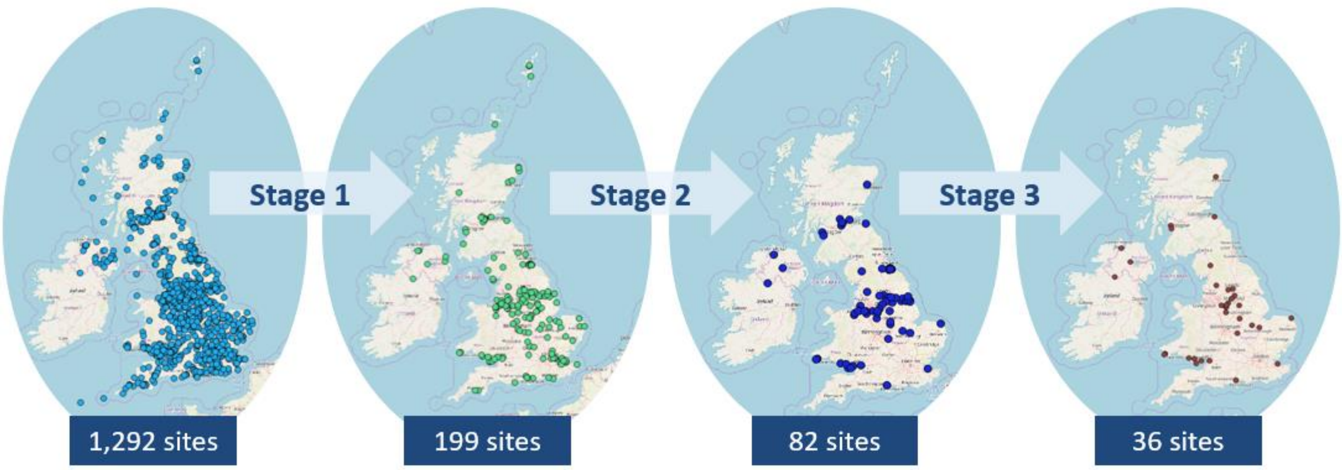
In this chapter we define the list of ‘dispersed’ industrial sites taken forward for analysis, i.e. the industrial sites in the UK that are located far away from existing industrial clusters and that would be potentially suitable for CCS. Next, we assess the emissions associated with these sites and identify the principal industry sub-sectors. Finally, we categorise them into subdivisions according to their location by identifying similarities between them and potential synergies in the context of CCS.

Definition and identification of ‘dispersed’ industrial sites

In this work ‘dispersed’ industrial sites are defined as those located far from major industrial clusters. Through a three-stage filtering process, **36 dispersed industrial sites** with CCS potential were identified, with **total emissions of 20.7 MtCO2** in 2016[2].

The methodology and results of the site identification process are outlined below and summarised in Appendix A: Assumptions.

Figure 1: Dispersed industrial sites were identified through a three-stage filtering process



An initial pool of 1,292 sites was considered based on the sites registered in the NAEI 2016 large point sources database, including all UK large industrial emitters.

Stage 1: Through the first filtering stage the group was reduced to 199 sites by removing all point sources with emissions smaller than 50 ktCO2/year, considered to be the minimum size of a CO2 stream for which carbon capture is economically advisable (see Appendix A1: Assumptions on CO2 emissions threshold on page 58).

Stage 2: Through the second filtering stage the group was further reduced to 82 sites by retaining only sites in industry sectors deemed as most suited for CCS, such as:

[2] Based on the National Atmospheric Emissions Inventory for point sources. Note that 2016 was the most recent available reporting year at the time of analysis.

- Cement, Ironmaking, Refining, Ethylene, Ammonia
- Ceramics / other mineral industries
- Glassmaking
- Processing & distribution of natural gas
- Other chemicals

The rationale behind the sector choice is outlined in Appendix A2: Assumptions on industries suitable for CCS on page 59.

Stage 3: In the third and last filtering stage all sites located at less than 30km from all UK's main **industrial clusters** (Grangemouth, Teesside, Humber, Wider Humber, Merseyside) or from St Fergus CO2 terminal were excluded from analysis, obtaining a final selection of 36 sites. The rationale behind the chosen distance of 30km to define a dispersed site is reported in Appendix A3: Assumptions on industrial cluster size on page 61.

We defined the UK's main industrial clusters based on the Industrial Strategy[3] (see table for estimated annual emissions). However, industrial sites located in the clusters of South Wales and Southampton were taken forward for analysis due to lack of carbon storage options in these locations.

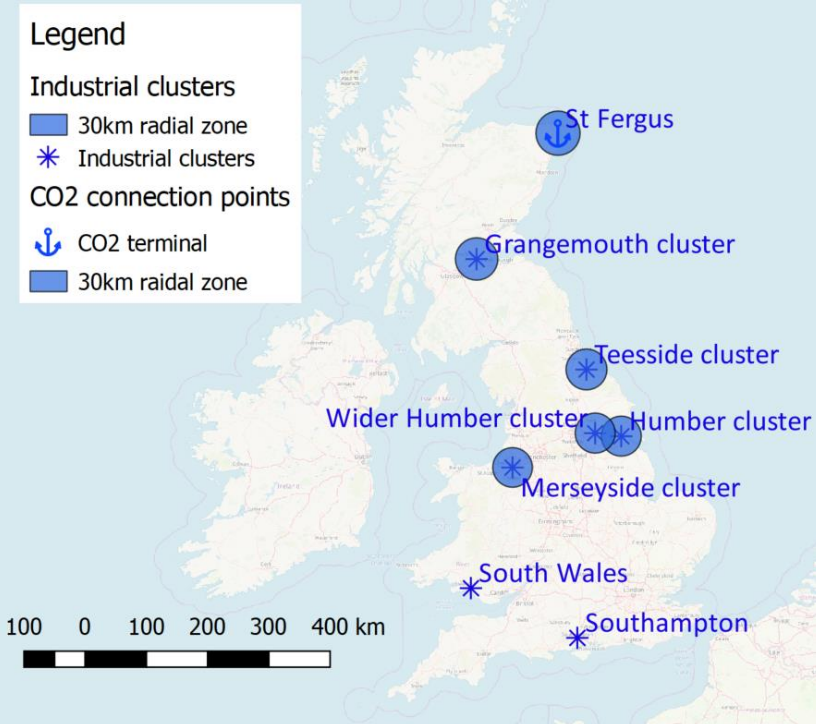
In addition to proximity to industrial clusters, certain sites were excluded due to proximity to CO2 terminals. The terminals at Liverpool port, Humberside and Teesside are inside the 30km industrial cluster exclusion zones and so have not been included in the map. However, the terminal close to Peterhead port is not and so is shown separately. A map is shown in Figure 2.

Table 3: Largest industrial clusters by emissions

Industrial clusters	Emissions (MtCO2)
Humber	12.4
South Wales	8.2
Grangemouth	4.3
Teesside	3.1
Merseyside	2.6
Southampton	2.6

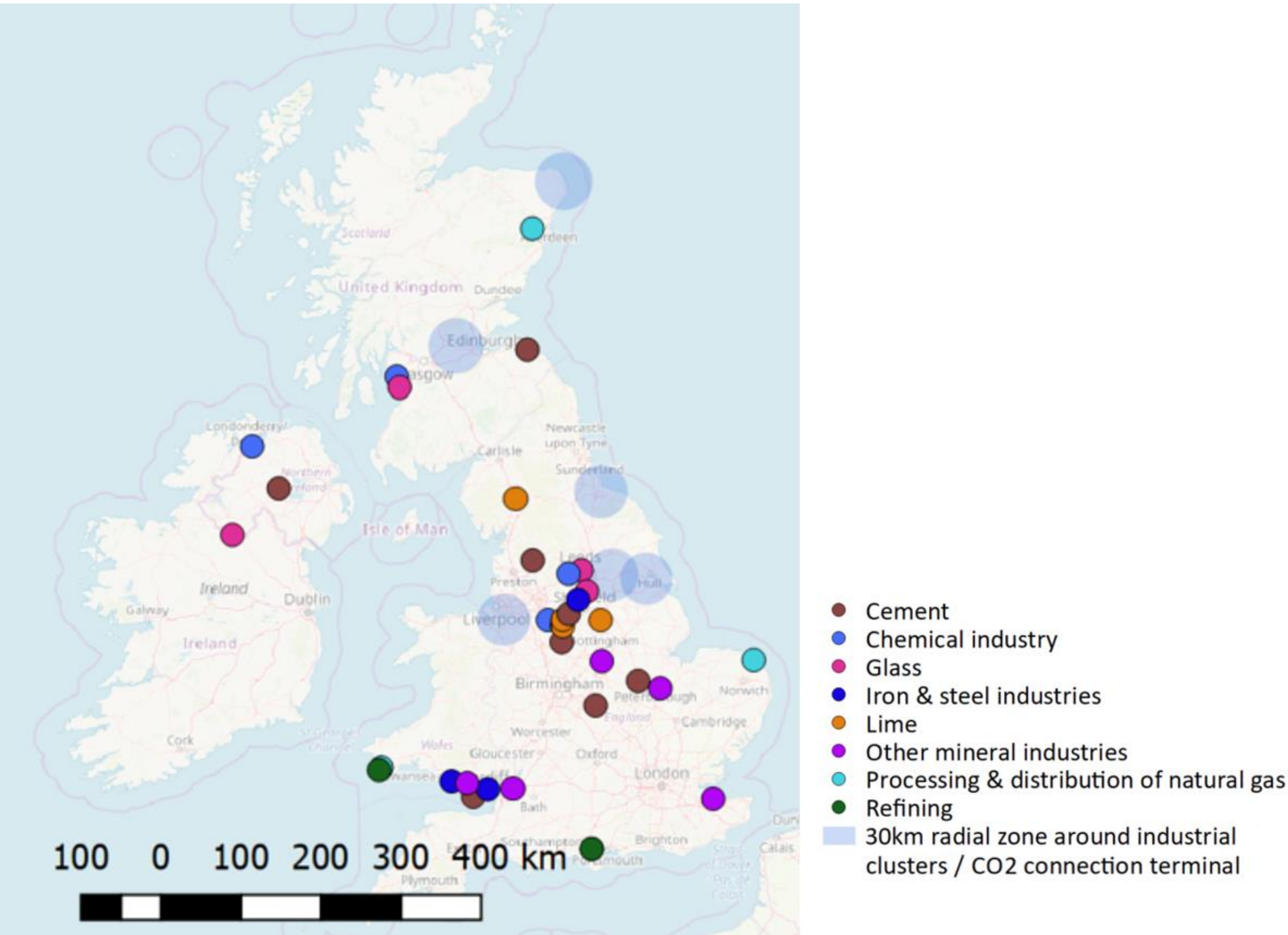
[3] Industrial Strategy, Industrial Clusters mission

Figure 2: Industrial clusters in the UK



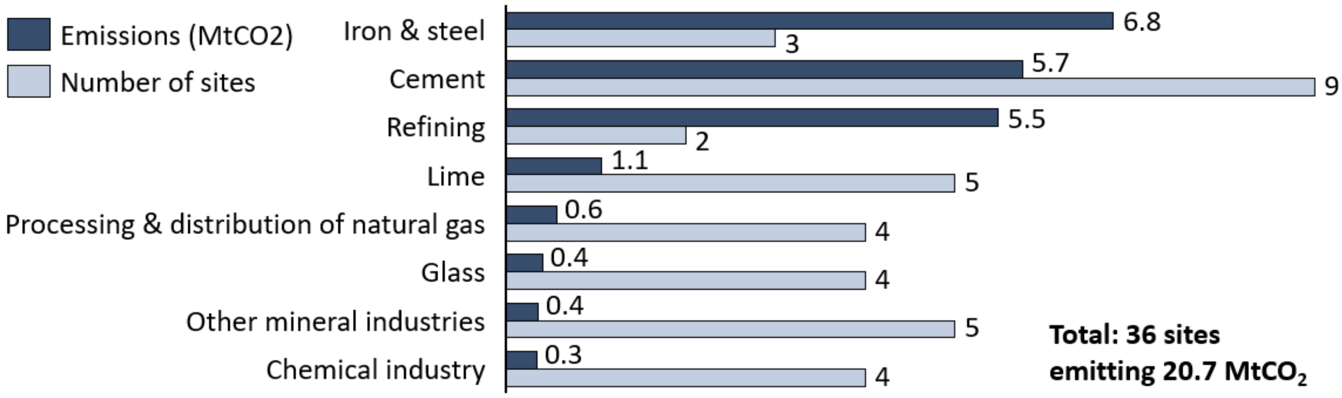
Having applied this filtering process, we end up with 36 dispersed industrial sites with CCS potential; they are shown schematically in Figure 3.

Figure 3: Identified dispersed industrial sites with CCS potential



The identified 36 dispersed industrial sites with CCS potential emit between them 20.7 MtCO2 (2016 emissions). Within this group, 80% of total emissions derive from the 10 largest emitters, each producing annual emissions >500ktCO2/annum.

Figure 4: Breakdown of dispersed industrial sites by sector[4], emissions (MtCO2 emitted in 2016) and number of sites



The majority (87%) of emissions come from the following sectors: Iron & Steel, Cement and Refining, see Figure 4.

A more in depth analysis of the 36 sites and their emissions shows that one third of emissions are made up by three Iron & Steel sites (two of which are located in South Wales, one of which is located in between Leeds and Liverpool). The next highest emitting sector is Cement, with nine sites identified. These are dispersed around the country, generally close to quarries with some located in national parks. Refining, another sector which is considered to be well suited to CCS, represents one quarter of emissions spread over two sites. These are the Fawley refinery in Southampton, and the Pembroke refinery in South Wales. The remaining sectors (Lime, Other mineral industries, Processing & distribution of natural gas, Glass and Chemical industry) make up 22 of the 36 sites considered (59%), but only represent 2.8 of the 20.7 MtCO2 emitted (14%).

[4] NB: the sites included in “other mineral industries” includes ceramics, gypsum, and other construction materials. “Chemical industry” includes manufacture of pharmaceuticals, manufacture of chemicals for textiles, manufacture of dispersions and additives.

Categorisation of UK dispersed sites

The 36 identified dispersed sites were segmented into four subdivisions based on geographical similarities in the context of CCS:

- **Group 1 – South Wales cluster (limited storage nearby)**: industries located inside the South Wales industrial cluster[5].
- **Group 2 – Close to a major port but not a major cluster**: industries that are not in Group 1 and that are within 30km of a major port[6].
- **Group 3 – Peak District inland cluster**: five high emitting sites that are located either inside or enclosed by the Peak District National Park were identified. All located within 20km of one another.
- **Group 4 – Dispersed sites**: all remaining sites.

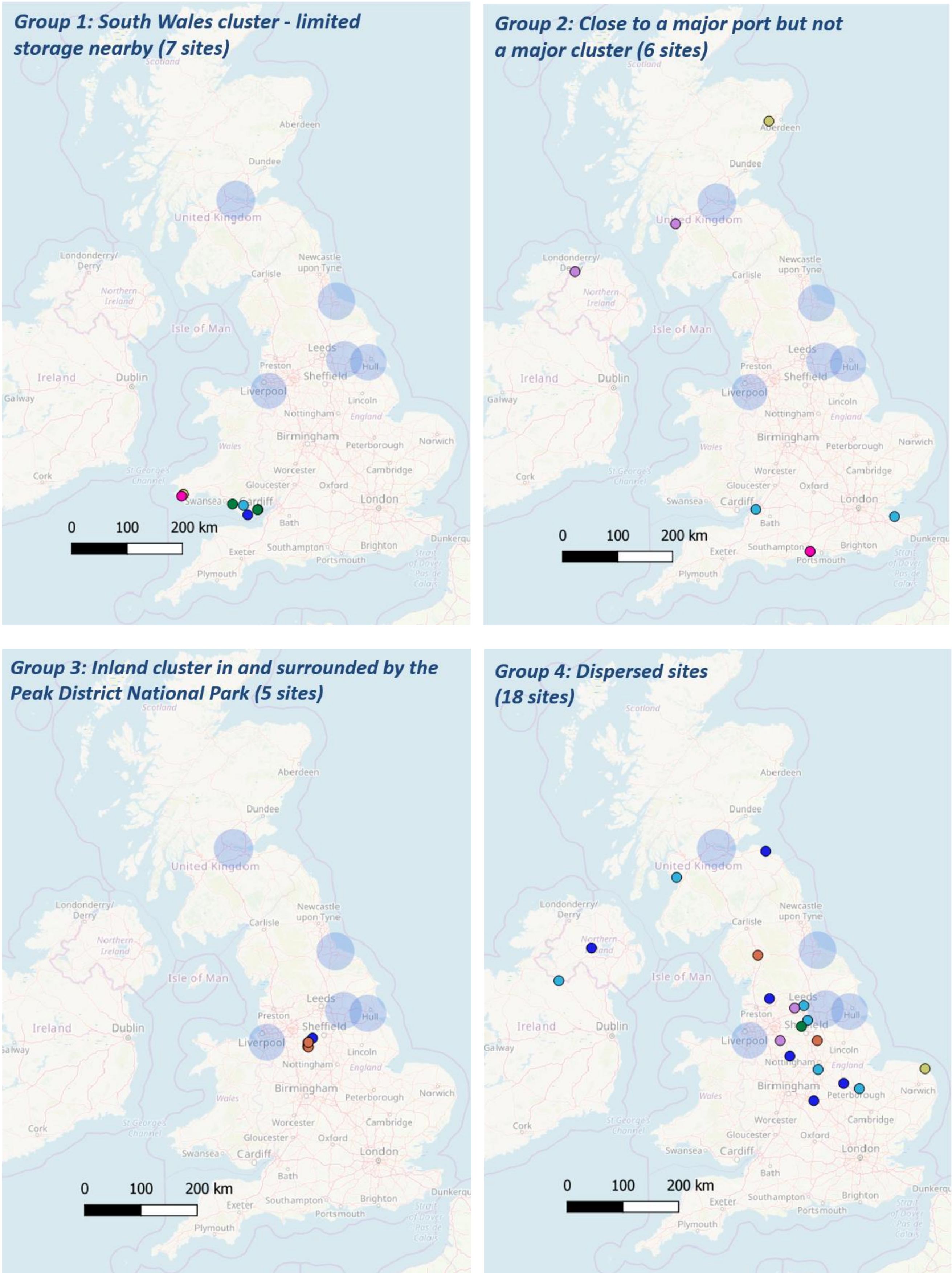
The location of the identified sites in each group and their industrial sector are displayed in Figure 5.

Legend to Figure 5:

- Cement
- Chemical industry
- Iron & steel industries
- Lime
- Other mineral industries
- Processing & distribution of natural gas
- Refining
- 30km radial zone around industrial cluster centre

[5] South Wales cluster as defined here: https://ukccsrc.ac.uk/sites/default/files/documents/event/chris-williams.pdf
[6] Major port, as defined in: DfT UK Port Freight Statistics 2017. Major ports are here defined as ports that handled over 2 million tonnes of freight in 2017.

Figure 5: Geographical location of sites within each group



Group 1: South Wales cluster (limited storage nearby)

The sites in this group are located within the South Wales shoreline cluster, characterised by limited CO2 storage opportunities nearby. The group includes 7 sites, producing in total **9.9 MtCO2** emissions in 2016.

Figure 6: Location of sites within Group 1

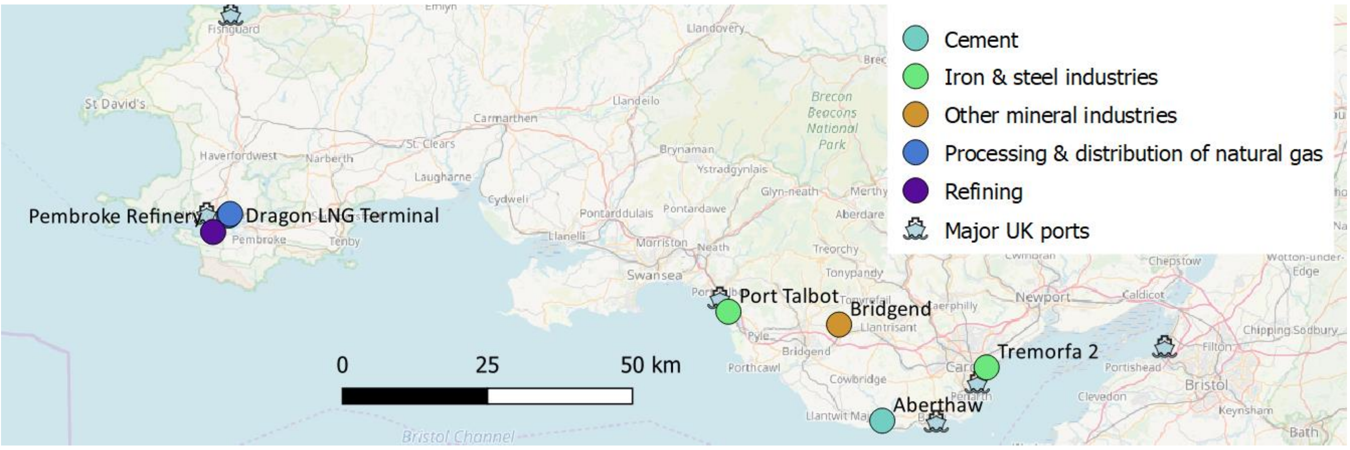


Table 4: List of sites within Group 1

Plant ID	Site	Sector	2016 emissions (ktCO2)
7018	Port Talbot	Iron & steel industries	6,648
14182	Pembroke Refinery	Refining	2,354
8684	Aberthaw	Cement	323
11065	South Hook LNG Terminal	Processing & distribution of natural gas	223
11077	Dragon LNG Terminal	Processing & distribution of natural gas	166
8913, 14013	Tremorfa	Iron & steel industries	110
9596	Bridgend	Other mineral industries	51

It should be noted that the sites in this Group are not truly 'dispersed', and that several options for decarbonisation have already been identified[7] (including CO2 shipping) for the South Wales industrial cluster.

[7] https://ukccsrc.ac.uk/sites/default/files/documents/event/chris-williams.pdf

It is also noted that whilst the focus of this study has been on industry, potential power projects in this region could couple to the industrial sites listed here thereby reducing T&S costs and boosting the business case. For example, CCU can offer electricity storage options through the production of synthetic methane, either by the processing of CO2 with renewable hydrogen, or by the direct co-processing of CO2 and water using renewable electricity as an energy source. CCU can therefore also assist sector coupling, by enabling the integration of renewable energy into the gas grid[8].

Group 2 – Close to a major port but not a major cluster

Sites in this group are located close to a major port but not to a major cluster; they would have good access to CO2 transport via shipping. The group counts 6 sites, with **3.6 MtCO2** emissions in 2016.

Figure 7: Location of sites within Group 2

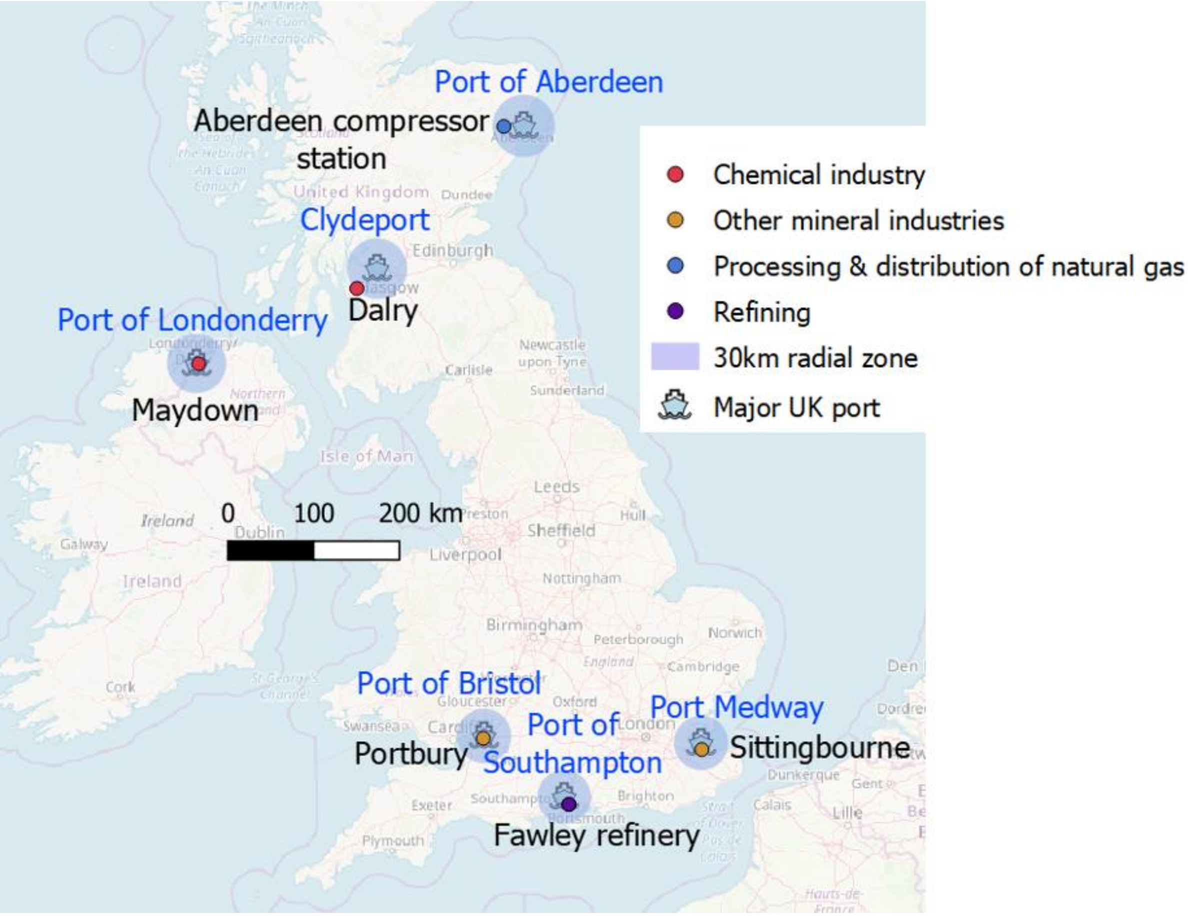


Table 5: List of sites within Group 2

Plant ID	Site	Sector	2016 emissions (ktCO2)
8051, 11971	Fawley	Refining	3,127
9075	Dalry	Chemical industry	119

[8] https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf

8979	Maydown	Chemical industry	102
9036	Aberdeen Compressor Station	Processing & distribution of natural gas	79
9594	Portbury	Other mineral industries	65
9595	Sittingbourne	Other mineral industries	57

Group 3 – Peak District inland cluster

The sites in this group form together an inland cluster surrounded by the Peak District National Park. The cluster is located far from CO2 storage opportunities. Additionally, transport of CO2 to storage is rendered more difficult by the surrounding National park, through which transport through pipeline, road and rail is hindered by a number of factors. The cluster counts five cement and lime sites with total emissions of **2.2 MtCO2** in 2016.

Figure 8: Location of sites within Group 3

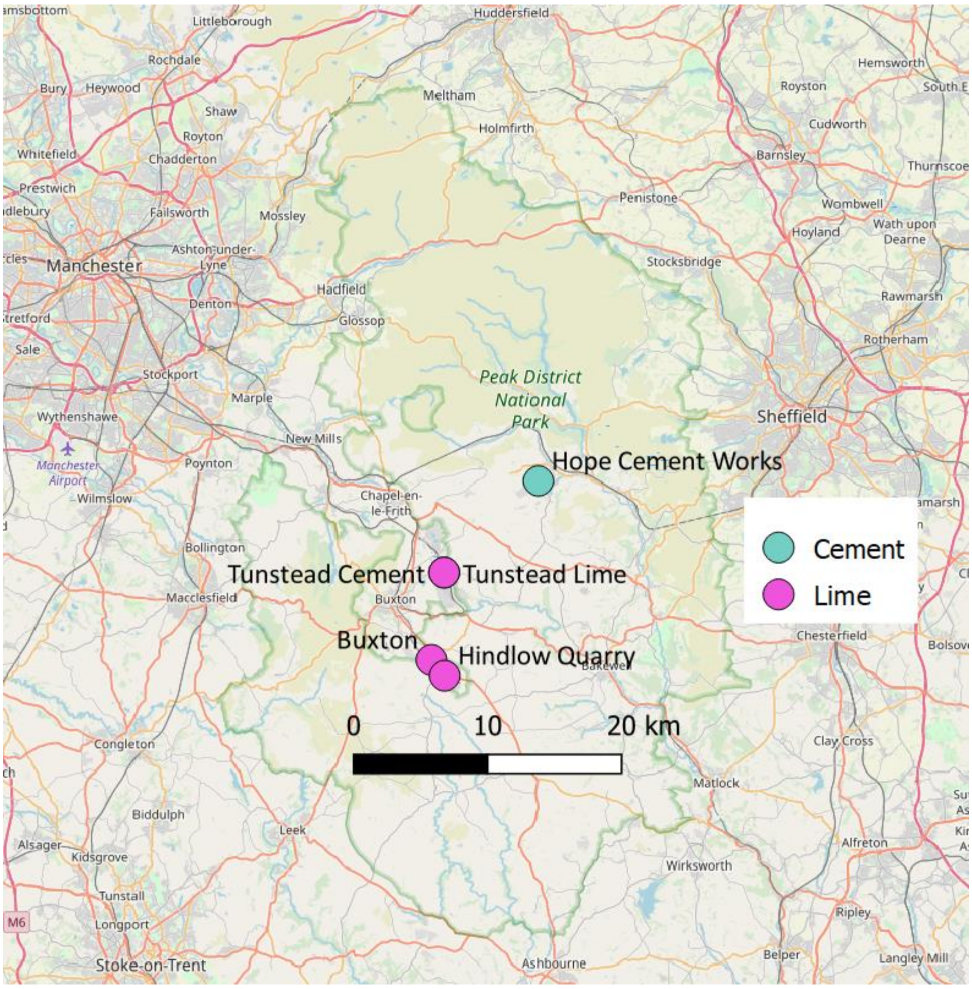


Table 6: List of sites within Group 3

Plant ID	Site	Sector	2016 emissions (ktCO2)
14245	Hope Cement Works	Cement	975
14686	Tunstead Cement	Cement	644
14688	Tunstead Lime	Lime	257
8218	Buxton	Lime	199
14687	Hindlow Quarry	Lime	142

Group 4 – Truly dispersed sites

The last group comprises truly dispersed sites, including all remaining sites that do not fit the description of the previous three groups. This group includes 18 sites with total emissions of **5.1 MtCO2** in 2016.

Figure 9: Location of sites within Group 4

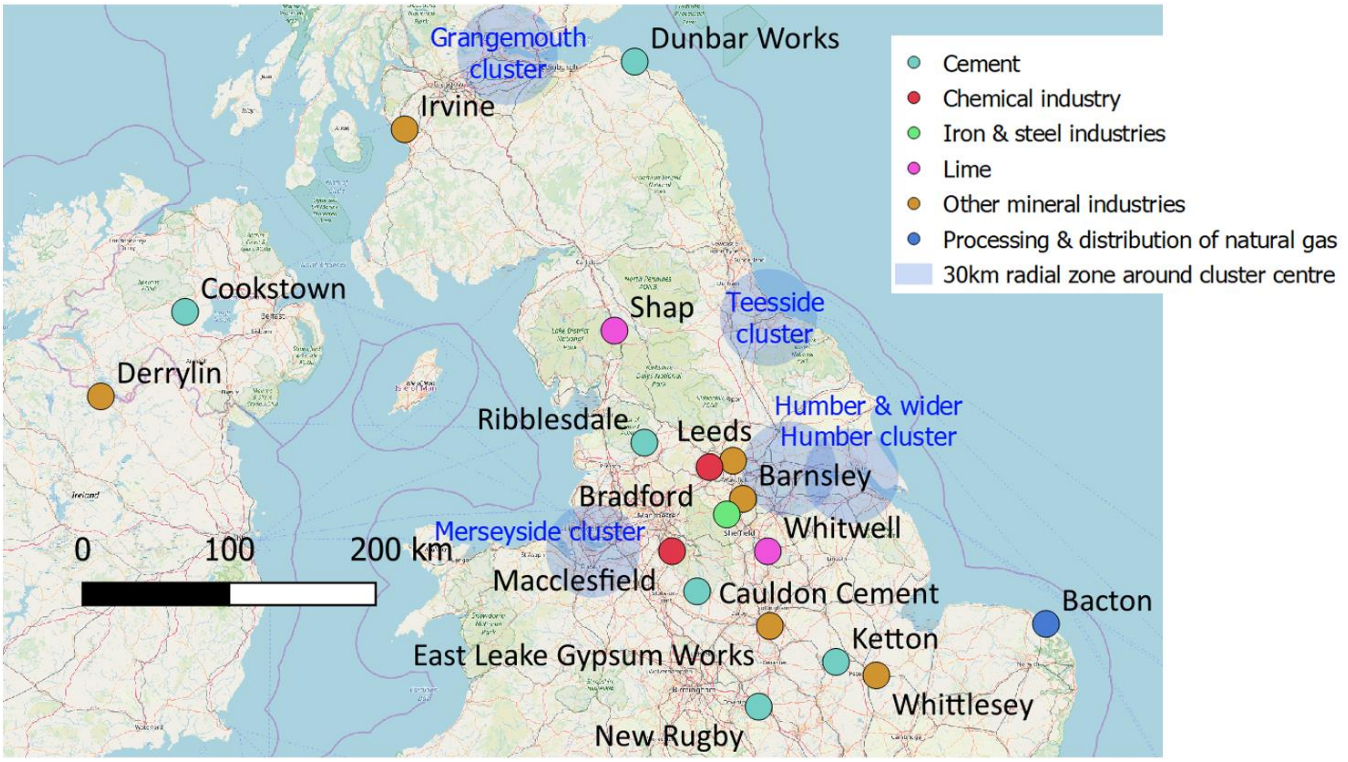


Table 7: List of sites within Group 4

Plant ID	Site	Sector	2016 emissions (ktCO2)
8059	New Rugby	Cement	1,090
8037	Ketton	Cement	683
14417	Cauldon	Cement	607
8015	Ribblesdale	Cement	574
11128	Dunbar Works	Cement	538
14454	Cookstown	Cement	311
8007	Whitwell	Lime	259
8322	Shap	Lime	208
9623	Barnsley	Other mineral industries	154
11478	Derrylin	Other mineral industries	118
14242	Whittlesey	Other mineral industries	99
8355	Bacton	Processing & distribution of natural gas	98
11750	East Leake	Other mineral industries	88
11387	Irvine	Other mineral industries	67
8263	Leeds	Other mineral industries	66
14415	Bradford	Chemical industry	63
8600	Macclesfield	Chemical industry	61
13756	Stocksbridge Works	Iron & steel industries	51

Challenges and risks of CCS at dispersed industrial sites

The starting point for this task was the recent work carried out by various organisations including the project team members on the risks and challenges of developing ICC infrastructure[9].

In this chapter, the traditional risks and challenges of CCS are re-analysed for the case of sites which are in dispersed locations. The re-analysis is carried out for each of the four groups that were identified in the previous chapter.

This chapter was also informed by stakeholder engagement. The tables in the following pages were presented to relevant organisations and feedback was noted. Through this iterative process, a comprehensive list of risks and challenges of CCS for dispersed sites was generated.

The aims of this chapter are to:

- Re-analyse the relevance and impact of traditional challenges to ICC on its deployment on dispersed industrial sites.
- Identify any novel challenges to deployment of ICC on dispersed industrial sites

Relevance of traditional challenges to industrial carbon capture for dispersed sites

The relevance and impact of traditional challenges to industrial carbon capture (ICC) was re-analysed for its deployment on dispersed sites. Traditional risks and challenges investigated are based on Element Energy's recent work for BEIS on Industrial carbon capture business models[10].

A list of the most relevant challenges and risks to ICC for conventional industrial clusters is reported in Table 8. The relevance of each challenge was assessed for each of the four identified groups of dispersed industrial sites. Where the group is considered to experience a particular risk due to its dispersed location (i.e. a risk that has arisen from being located outside of industrial clusters), the risk has been noted with its relevance to the group.

Note that, although the relevance of the risks and barriers within each group is generally valid across the sites for each group, there remain certain site-specific challenges that differ within groups. These are especially relevant to sites located in or around e.g. densely populated areas or AONBs.

[9] Element Energy 2018, Industrial carbon capture business models
[10] Element Energy 2018, Industrial carbon capture business models

Table 8: Impact of conventional cluster ICC challenges and risks on dispersed sites

Risk Category	Risk, barriers & market failures	Cluster	Group 1	Group 2	Group 3	Group 4
Technical	Technology maturity, performance, heterogeneity, first mover disadvantage	+	+	+	+	+
	Capture site challenges: ducting, energy, space, heterogeneity, multiple vents	+	+	++	+++	++
Industrial operations	Increased operational complexity, plant integration risks, product quality, familiarity	+	+	++	+	++
Economic & market	High capital investment, scale required	+	+	+	+	+
	Capital cost uncertainty and variability	+	+	+	+	+
	Poor finance terms due to risks of CCS, credit risk of industry, complexity, opaqueness	+	++	++	++	++
	Energy consumption: fuel price uncertainty	+	+	+	+	+
	Long investment timescales	+	+	+	+	+
	Insufficient value proposition – Availability of cheaper fuel switching options through co-located renewable generation	+	++	++	+	++
	Insufficient value proposition – Absence of revenue model (utilisation, CO2 product tax)	+	+	++	+	++

Risk Category	Risk, barriers & market failures	Cluster	Group 1	Group 2	Group 3	Group 4
	Less stability in industry and product demand uncertainty	+	+	+	+	+
	Reduced industry competitiveness	+	+	+	+	+
	Long-term operational cost uncertainties	+	+	+	+	+
Policy	Policy and regulatory uncertainty & lack of CCS framework	+	+++	+++	+++	+++
	Carbon leakage and employment loss risk	+	+	+	+	+
	CO2 price level and uncertainty	+	+	+	+	+
Cross chain	Integration risk, operational interface risk and risk allocation	+	+	+	+	+
	T&S fee uncertainty (monopoly)	+	+	+	+	+
	T&S uncertainty: availability, performance, capital investment and scale	+	++	+++	+++	+++
	Long term CO2 storage liability	+	+	+	+	+
	CO2 volume uncertainties across chain	+	++	+++	++	+++

Key:

+ risk relevant in general

++ risk more relevant for group

+++ risk highly relevant for group

Main ICC challenges for Group 1 – Within shoreline cluster with limited storage nearby

- **Policy and regulatory uncertainty & lack of CCS framework**

  South Wales, in particular the sites in Pembrokeshire have issues around AONB and National Parks. For sites located in restricted areas e.g. AONBs in coastal areas, there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process.

  Potential space restrictions if not located in an industrial park/cluster (more difficult to obtain planning permissions to expand if e.g. coastal)

  Obtaining the required implementation and operating consent, permits and licenses for all aspects of ICCS chain may lead to delays in FID, construction etc.

- **Poor finance terms due to risks of CCS, credit risk of industry, complexity, opaqueness**

  High risks associated with permitting provides significant deterrent to investors.

- **Insufficient value proposition – Availability of cheaper fuel switching options through co-located renewable generation**

  Competition with other decarbonisation options: some renewable energy generation provides a lower cost abatement option (fuel switching). Particularly relevant to sites located in close proximity to these resources.

  NB: in reality there would be significant variance of this risk across the group due to sectoral differences; fuel switching in industrial sites with high process emissions would have a lower abatement potential than CCS, see “Conclusions” section.

- **T&S uncertainty: availability, performance, capital investment and scale**

  Risk that storage capacity insufficient to meet commitments to capture plant.

  Uncertain availability of T&S leads to risk of stranded assets, with no alternative use.

  Shoreline cluster located in South Wales is fairly dispersed therefore intermediary transport would be necessary (to either port or offshore pipeline connection point), unless a CO2 onshore pipeline network is created. Risk that these costs are prohibitively high.

- **CO2 volume uncertainties across chain**

  Volume uncertainties of CO2 across the chain, potential low utilisation of assets. One part of chain unable to meet take or pay obligations. Lack of proven CO2 offtake arrangements to T&S companies.

Main ICC challenges for Group 2: close to a major port but not a major cluster

- **Capture site challenges: ducting, energy, space, heterogeneity, multiple vents**

  Potential issues with energy, feedstock and water use of capture plant if not located in an industrial cluster.

- **Increased operational complexity, plant integration risks, product quality, familiarity**

  Not located in an industrial cluster, therefore more difficult to source skilled labour.

  Exacerbated sense of unfamiliarity with capture technologies due to remoteness.

- **Poor finance terms due to risks of CCS, credit risk of industry, complexity, opaqueness**

  High risks associated with permitting provides significant deterrent to investors

- **Insufficient value proposition – Availability of cheaper fuel switching options through co-located renewable generation**

  Competition with other decarbonisation options: some renewable energy generation provides a lower cost abatement option. Particularly relevant to certain coastal sites with e.g. significant wind resource.

  NB: in reality there would be significant variance of this risk across the group due to sectoral differences; fuel switching in industrial sites with high process emissions would have a lower abatement potential than CCS, see “Conclusions” section.

- **Policy and regulatory uncertainty & lack of CCS framework**

  For sites located in restricted areas e.g. AONBs in coastal areas, there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process.

  Potential space restrictions if not located in an industrial park/cluster (more difficult to obtain planning permissions to expand if e.g. coastal)

  Obtaining the required implementation and operating consent, permits and licenses for all aspects of ICCS chain may lead to delays in FID, construction etc.

- **T&S uncertainty: availability, performance, capital investment and scale**

  Uncertain availability of T&S leads to risk of stranded assets, with no alternative use.

  Position relative to T&S infrastructure & intermediary transport risks. Some coastal sites located up to 30km from closest major port therefore intermediary transport may be necessary. Intermediary transport may be technically challenging, difficult to gain permitting for, and likely to have low utilisation if serving only one coastal site. Additionally, there may be limited options for transport (e.g. not close to railway, then only option is road or pipeline).

Since site is singular, it cannot benefit from economies of scale so bears higher cost of abatement, especially transport costs, which may be prohibitively high.

Although only major ports have been selected, port facilities may be inadequate for transport of liquefied compressed gas, or insufficient space to expand facilities for this use.

- **CO2 volume uncertainties across chain**

  Potential low utilisation of assets (especially transport) due to e.g. industry down time.

  Volume uncertainties of CO2 across the chain. One part of chain unable to meet take / pay obligations. Lack of proven CO2 offtake arrangements to T&S companies.

Main ICC challenges for Group 3: Inland cluster

- **Capture site challenges: ducting, energy, space, heterogeneity, multiple vents**

  Potential issues with energy, feedstock, oxygen and water use of capture plant if not located in an industrial cluster.

  Increased power demand for CO2 compression/liquefaction, exacerbated by additional power demand for O2 separation for oxyfuel combustion in the cement sector.

- **Poor finance terms due to risks of CCS, credit risk of industry, complexity, opaqueness**

  High risks associated with permitting provides significant deterrent to investors

- **Policy and regulatory uncertainty & lack of CCS framework**

  One of the sites is located in the Peak District National Park (and the rest are surrounded by it), there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process – a risk which is exacerbated if sites is located in a restricted area.

  Potential space restrictions if not located in an industrial park/cluster (more difficult to obtain planning permissions to expand)

  Obtaining the required implementation and operating consent, permits and licenses for all aspects of ICCS chain may lead to delays in FID, construction etc.

- **T&S uncertainty: availability, performance**

  Intermediary CO2 transport requirements. Sites located in inland ‘clusters’ would still need to transport CO2 to a central point from which CO2 transport would be share between sites. The intermediary transport leg would run very close to (and in one case inside) the National Park. It is uncertain as to whether this transport would be available, again due to permitting.

  Transport requirements from cluster to port/pipeline. Inland sites are located far from ports simply so do not have the option to ship CO2 directly. Certain sites with limited transport options may be restricted due to e.g. capacity constraints on the rail system.

- **CO2 volume uncertainties across chain**

Potential low utilisation of assets (especially transport) due to e.g. industry down time.

Volume uncertainties of CO2 across the chain. One part of chain unable to meet take / pay obligations. Lack of proven CO2 offtake arrangements to T&S companies

Main ICC challenges for Group 4: Dispersed sites

- **Capture site challenges: ducting, energy, space, heterogeneity, multiple vents**

  Potential issues with energy, feedstock, oxygen and water use of capture plant if not located in an industrial cluster.

- **Increased operational complexity, plant integration risks, product quality, familiarity**

  Not located in an industrial cluster therefore more difficult to source skilled labour

  Exacerbated sense of unfamiliarity with capture technologies due to remoteness

- **Poor finance terms due to: risks of CCS, credit risk of industry, complexity, opaqueness**

  High risks associated with permitting provides significant deterrent to investors

- **Insufficient value proposition – Availability of cheaper fuel switching options through co-located renewable generation**

  Competition with other decarbonisation options: some renewable energy generation provides a lower cost abatement option (i.e. fuel switching). Particularly relevant to remote sites that are not in AONBs

  In reality there would be significant variance of this risk across the group due to sectoral differences; fuel switching in industrial sites with high process emissions would have a lower abatement potential than CCS, see “Conclusions” section.

- **Policy and regulatory uncertainty & lack of CCS framework**

  For sites located in restricted areas e.g. AONBs, there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process.

  Potential space restrictions if not located in an industrial park/cluster (more difficult to obtain planning permissions to expand)

  Obtaining the required implementation and operating consent, permits and licenses for all aspects of ICCS chain may lead to delays in FID, construction etc.

- **T&S uncertainty: availability, performance, capital investment and scale**

  Uncertain availability of T&S leads to risk of stranded assets, with no alternative use. Certain sites with limited transport options may be restricted due to e.g. capacity constraints on the rail system.

  Position relative to T&S infrastructure & intermediary transport risks. Some dispersed sites located far from port/pipeline therefore intermediary transport necessary, which may be technically challenging (e.g. if located in a national park), and likely to have low utilisation. Additionally, there may be limited options for transport (e.g. not close to port or railway, then only option is road or pipeline).

Since site is singular, it cannot benefit from economies of scale so bears higher cost of abatement, especially transport costs, which may be prohibitively high.

- **CO2 volume uncertainties across chain**

  Potential low utilisation of assets (especially transport) due to e.g. industry down time.

  Volume uncertainties of CO2 across the chain. One part of chain unable to meet take / pay obligations. Lack of proven CO2 offtake arrangements to T&S companies.

Deployment options for CCS at dispersed industrial sites

In this chapter the relevant options for CCS deployment at dispersed sites are assessed, with specific relevance to the industry sub-sectors and Groups discussed earlier.

The following list of relevant options is considered:

- CO2 transport options including shipping, pipeline, road and rail transport
- Other options including hydrogen fuel switching and CCUS

Through a literature review and stakeholder engagement, we identified the key challenges, costs, technology readiness and case studies of past (& planned) deployments for each option.

Can be found in Appendix B: Options for CCS deployment at dispersed sites from page 68. The key challenges are synthesized in this chapter, and the remaining information was used to inform the next chapter (Transport costs estimates & Conclusions).

Finally, the different deployment options (1 & 2 as above) are assessed for each group and industry sub-sector.

Key challenges across CCS deployment options and alternatives

A summary of main challenges to CCS deployment options is reported below in relation to:

- Transport of captured CO2 via onshore pipeline, shipping, road or rail
- Utilisation of captured CO2 (CCU)
- Decarbonisation through hydrogen fuel switching

Onshore pipeline

- **Regulatory**: Although there is no precedent for CO_2 pipelines in the UK, the White Rose project went through the formal permitting process, which involved notification to the HSE, preparation of a MAPD, emergency procedures and arrangements, and provision of information for an Emergency Response Plan. The evidence base provided through the White Rose project proves that CO_2 pipeline transport can, in theory, be done safely. However, the planning application process is non-trivial and requires a strong evidence base. CO_2 will continue to be considered as though it were classified as a "dangerous substance" until specific legislation is introduced. Pipeline transport of explosive gases is commonplace in the UK, so if enough demand for CO_2 pipelines is created, one may expect specific legislation for CO_2 pipelines to be introduced. In addition, although there is precedent for the construction of CO_2 pipelines in the USA, these have been routed through sparsely populated lands. There is no precedent for CO_2 pipelines routed through settlements, which may be inevitable for CO_2 pipeline infrastructure connecting a network of industrial sites.

- **Disturbance**: Construction of a major pipeline is disruptive, especially if it runs through sensitive landscape.

Shipping

- **Regulatory**: exposure to different international regulatory frameworks including EU-ETSD, EU CCS Directive, UNCLOS, SOLAS IGC Code; these have an influence on the development and requirements for CO_2 shipping.

- **Port constraints**: The Port of Aberdeen and Londonderry /Foyle port are unable to accommodate the largest (30 kt) ships due to length and draft constraints, however, these ports would still be able to accept medium and small ships.

- **Limited experience**: Currently limited experience in CO_2 shipping at the scale needed, demonstration projects may be needed. The Norwegian CCS project plans to start with a small-scale shipping project but for the second phase an aim of a 1.5MtCO_2/yr flow rate has been set with the intention to scale this up to 4MtCO_2/yr relatively quickly. This should help reduce the risk premium for CO_2 shipping internationally.

- **Limited business models**: existing LPG/LNG business models and contracts are not expected to be replicable for CO_2 shipping

Road/rail

- **Safety**: There are route choice constraints because CO_2 is considered to be a dangerous substance, for example, trucks cannot pass through the Dartford tunnel with a full load.

- **Capacity**: CO_2 trucks currently operate with 20-26t capacity, and rail wagons are approximately 60t each. Considering that many industrial sites have emissions of 1MtCO_2/annum, capacity is a key consideration. In addition, there is less and less available rail capacity on certain parts of the network due to increased passenger traffic.

- **Disturbance**: Ongoing noise, visual and air pollution of trucks and trains.

- **Storage**: required additional storage capacity at the capture site may affect feasibility at space constrained sites and increase overall costs per ton, especially at sites with small CO_2 volumes.

Hydrogen fuel switching

- **Technical**: During stakeholder engagement, product quality and equipment compliancy concerns due to H_2 fuel switching was cited. There are technical constraints of H_2 fuel switching having a limited abatement potential due to process emissions.
- **Infrastructure**: As with CCS, infrastructure to transport the gas is necessary for H_2 fuel switching to be rolled out.
- **Insufficient value proposition** relative to e.g. CCS

Carbon Capture and Utilisation (CCU)

- **Technical**: CCU technologies are in general at a low technology readiness level. Additional technical constraints include high energy requirements, large land requirements.
- **Insufficient value proposition**: Potentially harmful environmental impacts of e.g. extensive mining*.
- **Co-location**: unless sites are co-located, CO_2 utilisation would have exactly same challenges as CCS regarding transport. Sites that emit are often not co-located with utilisation sites.
- **Market size**: CCU will not deliver projects at scale that CCS will – CCU projects are generally on the kt not Mt scale.

Suitability of options to various groups / sectors

Onshore pipeline, shipping, road/rail transport

The analysis of the different transport options revealed that different options are better suited than others to each group.

In Group 1, the CO_2 quantities are too large to be compatible with road and rail transport. However, onshore pipeline and shipping are both potential solutions, and the choice between the two would likely be driven by costs and regulation. Since Group 1 is the South Wales cluster, sites in this group are likely to make a communal decision about CCS.

Group 2 sites, which are close to major ports, would be most likely to utilise shipping, though intermediary transport options (pipeline to port, road to port or rail to port) would likely be driven by cost. Group 2 sites are individual, they are less dependent on decisions made by other industrial sites.

Group 3 sites would opt for a communal decision (as with Group 1) due to the sectoral, permitting and location synergies across the group. Since sites are located inside (or very close to) the Peak District National Park, regulatory constraints would probably be the principle driver for the decision. The choice of intermediary transport would be need to take into consideration the comparison between a one-time disruption (due to the construction of a pipeline), or ongoing disruption (due to ongoing road/rail traffic).

Being truly dispersed, Group 4 sites must consider all options.

H2 fuel switching

Hydrogen fuel switching is particularly suitable in the following sectors: refining, chemicals, glass and gas terminals and compressor stations. It is highly dependent on presence of local H2 grid, which is more likely to be available to sites located close to industrial clusters (i.e. Group 1).

H2 fuel switching is not effective if the industrial site has high process emissions

CCU

CCU is a viable alternative to CCS but it does not bypass the transport issues unless utilisation is directly on site (or by a very nearby site). CCU options include direct use in industry, chemical conversion of fuels, carbonisation of rocks and biofuel production. Much like H2 fuel switching, chemical conversion is only beneficial for sites with low process emissions.

CCU will not deliver projects at scale that CCS will – CCU projects are generally on the ktCO2 not MtCO2 scale.

Cost of CO2 transport for dispersed industrial sites

The information collected in the analysis described in the previous chapters is brought together to identify the most suitable transport options for each of the considered industrial groups/sites. The suitability of a range of transport options is assessed for each individual site on the basis of its cost and of the carbon intensity of the CO2 transport activity. A common transport strategy is identified for some of the groups where appropriate.

Costs are calculated in £/tCO2 and are associated with the transport of CO2 from the emission site to the offshore storage site. The carbon intensity is expressed in % as the proportion of CO2 emitted over the amount of CO2 transported.

Cost and carbon intensity results are based on Element Energy's CO2 shipping model for BEIS (2018)[11]. Further assumptions around onshore pipeline cost and road and rail fuel consumption utilised in our cost and emissions modelling can be found in Appendix A4: Assumptions and cost estimates for transport on page 63.

Transport and storage options

The transport of CO2 from the emission site to the offshore storage site is broken down into two steps. In the first step CO2 is transported from each emission site to the nearest port terminal. This step can be delivered by a range of transport options that will be evaluated in this chapter for all sites on a case-by-case basis. In the second step, CO2 is transported from the port terminal to the nearest offshore storage location via submarine pipeline.

In the **first step** (transport of CO2 from industrial site to port terminal), various options were considered: pipeline, shipping, road, rail and their combinations. Based on the characteristics of the location of the sites in the previously identified groups, the most promising options were investigated for each site. An overview of the options applicable to each group is provided in **Table 9**. The results of our analysis of the cost and carbon intensity of these options for all sites are illustrated in the next paragraphs.

Group 1 (South Wales Cluster) and Group 3 (Peak District Cluster) are both characterised by a potentially large CO2 capture volume from a relatively localised area. As transport costs per unit of CO2 transported tend to reduce with increased volumes, a sensible cost reduction in the implementation of CCS could be achieved if each cluster opts for a common transport option among its sites. Therefore, for both these groups a common transport strategy was investigated.

All sites in Group 2 and group 4 are too far from one another to benefit from a joint CO2 transport solution. Therefore, various transport options were investigated for each site within these two groups.

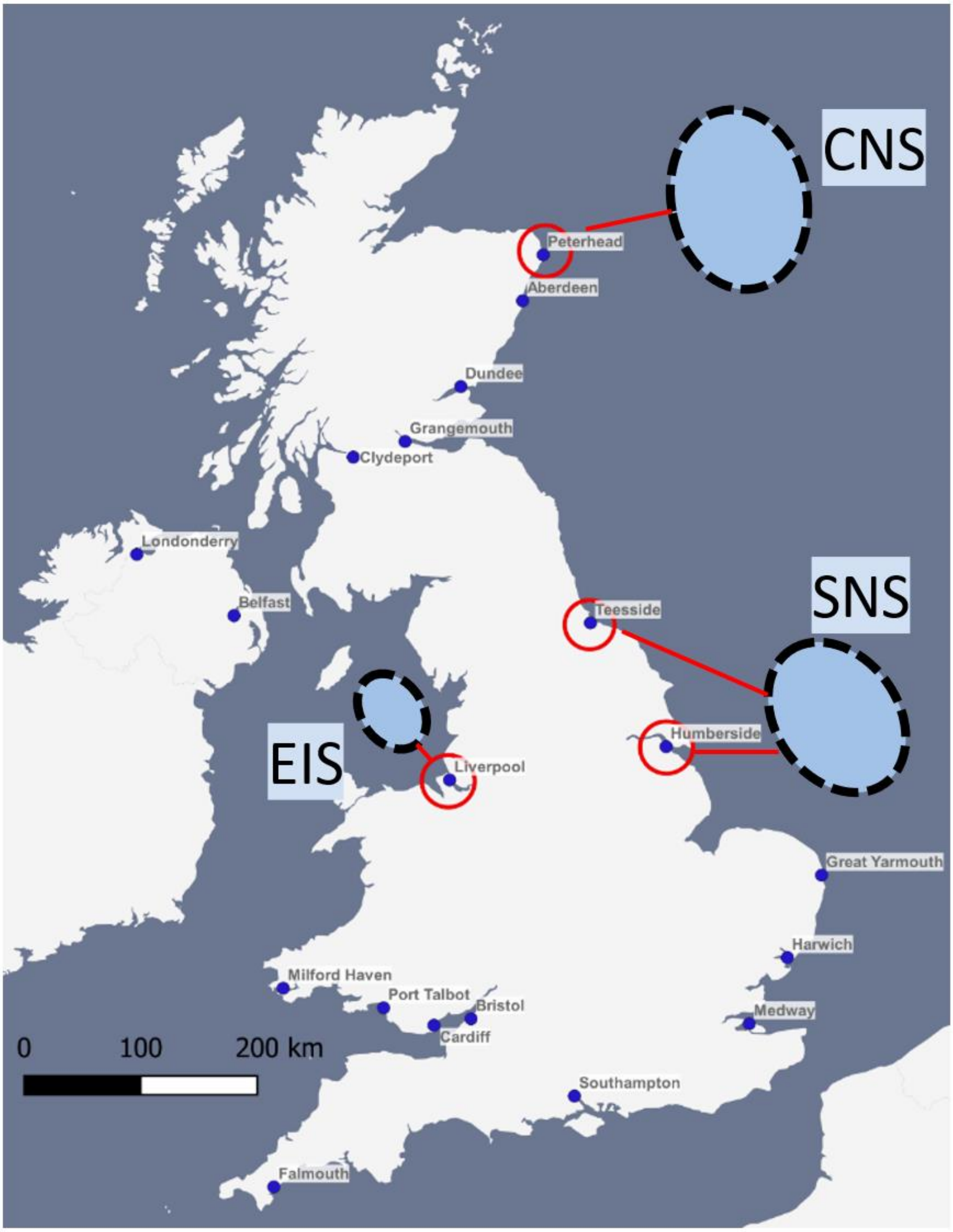
[11] Element Energy for BEIS 2018 Shipping CO2 – UK Cost Estimation Study

Table 9: Step 1 (from industrial site to port terminal) - Applicability of transport options

Transport options	Group 1: South Wales	Group 2: Close to ports	Group 3: Peak District	Group 4: Truly dispersed
Pipeline (site - terminal)	Yes	-	Yes	Yes
Pipeline + Shipping (site - port - terminal)	Yes	Yes	-	Yes
Road (site - terminal)	-	-	Yes	Yes
Road + Shipping (site - port - terminal)	-	Yes	-	Yes
Rail (site - terminal)	-	-	Yes	Yes
Rail + Shipping (site - port - terminal)	-	Yes	-	Yes

In the **second step** (transport of CO2 from port terminal to offshore CO2 storage), four locations were considered for the port terminals: Peterhead, Teesside, Humberside, and Liverpool. The location of the port terminals and of the offshore CO2 storage sites are displayed in Figure 10. The cost of transport from terminal to storage site was assumed to be £12/tCO2, the same for all options.

Figure 10: Step 2 (from port terminal to offshore CO2 storage) - Port terminals and storage



Legend:

CNS Central North Sea

SNS Southern North Sea

EIS East Irish Sea

Cost and carbon intensity of CO2 transport for group 1

For this group, a transport option common to all sites in the cluster is investigated, due to the colocation of the individual sites and the large amount of CO2 emitted by the group, amounting to ~6MtCO2/yr for the entire cluster. The location of the sites is shown in Figure 11 and individual emissions that could be captured from each site are reported in Table 10.

Figure 11: Location of sites withing group 1

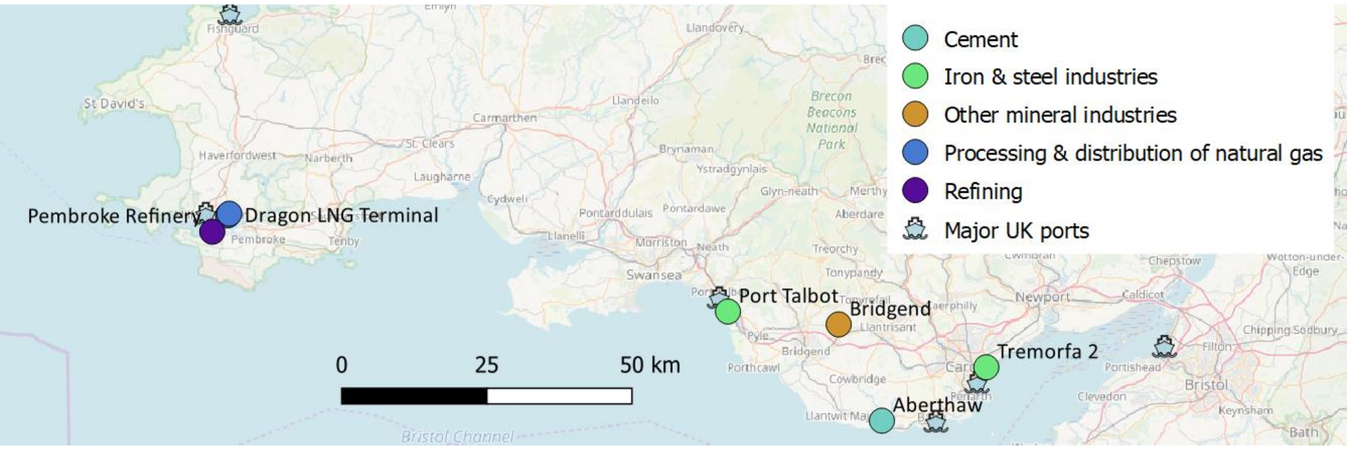


Table 10: Captured CO2 emissions from sites within group 1

Plant ID	Site	Sector	Captured volume (ktCO2)
7018	Port Talbot	Iron & steel	3,590
8684	Aberthaw	Cement	288
8913, 14013	Tremorfa	Iron & steel	60
9596	Bridgend	Other mineral industries	46
11065, 11077	South Hook and Dragon	Processing & distribution of NG	347
14182	Pembroke Refinery	Refining	1,907
7018	Port Talbot	Iron & steel	3,590

Transport options for group 1

The following two transport options were investigated, with all sites from the group choosing the same transport option:

- **Pipeline**: Transport via onshore pipeline from each site to Port Talbot. From there, transport via onshore pipeline from Port Talbot to the Liverpool port terminal. The infrastructure for this option involves:
    - 385 km local pipeline
    - 360 km transmission pipeline to Liverpool
- **Pipeline + Shipping**: Transport via onshore pipeline from each site to the nearest port (Milford Haven, Port Talbot or Cardiff). CO_2 at the port of Cardiff is shipped to Port Talbot. Finally, CO_2 at Port Talbot and Milford Haven is shipped individually to the Liverpool port terminal. The infrastructure for this option involves:
    - 150 km local pipeline to ports
    - 75 km shipping from Cardiff to Port Talbot
    - 460 km shipping from Port Talbot to Liverpool
    - 375 km shipping from Milford Haven to Liverpool

The transport options involving road or rail transport are not considered for this group, due to the large CO_2 stream volumes.

More information around our assumptions on pipeline and route length are found in Appendix A4: Assumptions and cost estimates for transport on page 63.

Optimal shipping route for the option pipeline + shipping

Three potential logistics for the option “Pipeline + Shipping” of Group 1 are investigated, see Figure 12, Figure 13 and Figure 14.

For each option, CO_2 is transported from each individual industrial site via pipeline to the nearest port, choosing among Milford Haven, Port Talbot or Cardiff. From there, CO_2 is subsequently transported via ship to the Liverpool terminal.

Our modelling identifies the cheapest transport option as the one including shipping from Cardiff to Port Talbot and 2 independent shipping routes from Milford Haven and Port Talbot to Liverpool. Shipping costs here include only shipping CAPEX and OPEX but exclude pipeline costs.

Two routes are in this case preferable to a single route, due to the large CO_2 volumes from both Milford Haven and Port Talbot. In fact, the additional logistic cost of maintaining 2 separate routes to Liverpool is estimated to be slightly smaller than the added cost of the larger storage required at the main port of the single route.

Figure 12: One route from Milford Haven – Shipping cost ~ 49.4 £m/yr

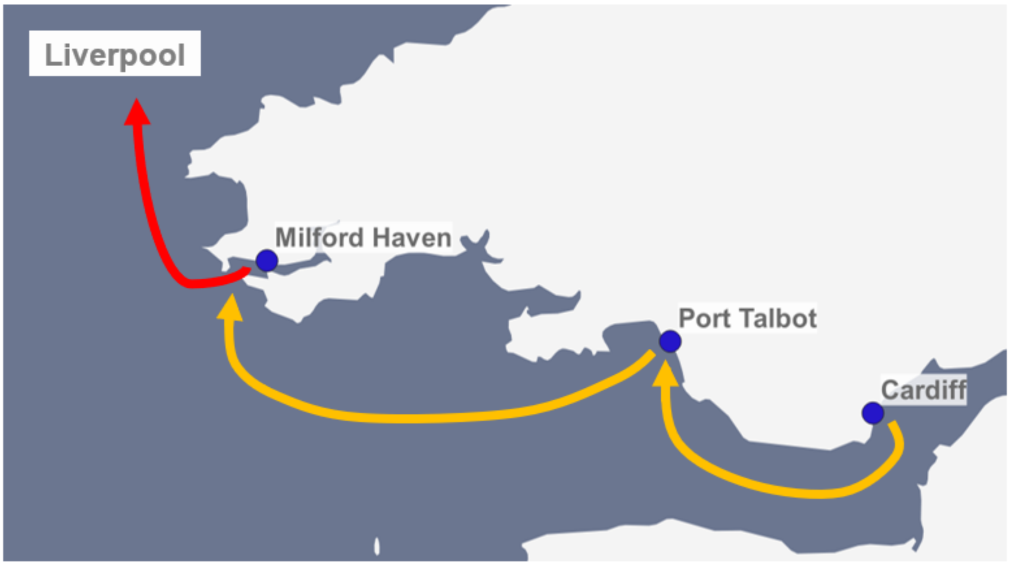


Figure 13: One route from Port Talbot – Shipping cost ~48.0 £m/yr

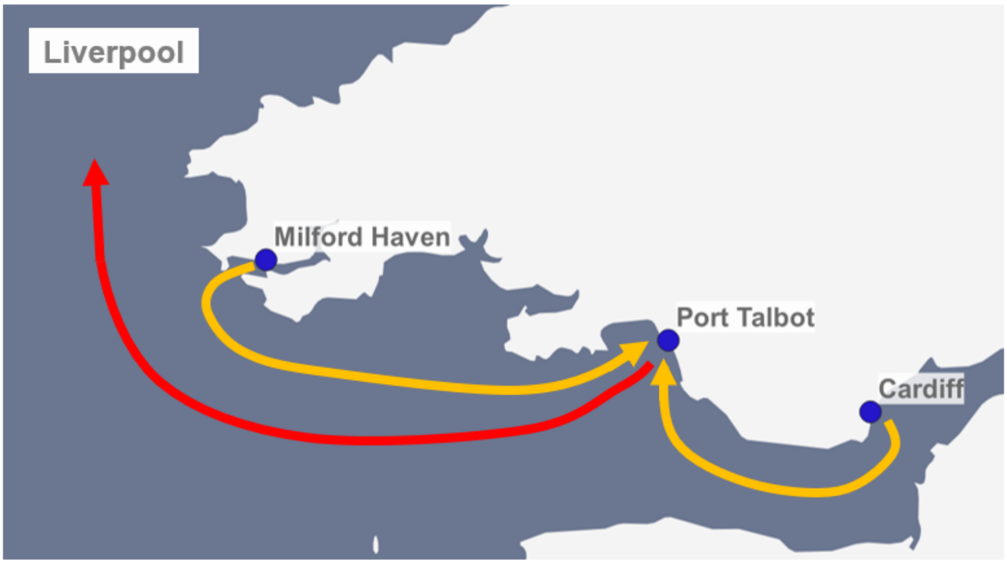
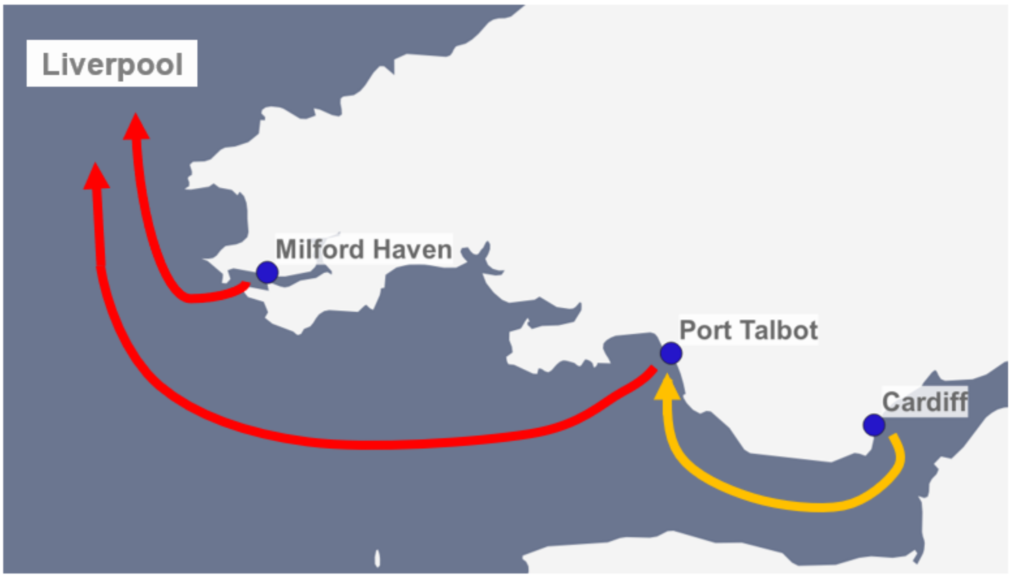


Figure 14: Two routes from Milford Haven and Port Talbot – Shipping cost ~47.1 £m/yr



Cost of CO2 transport for group 1

The results of our modelling on the cost of transport via pipeline or via pipeline + shipping for group 1 are reported in Figure 15. The carbon intensity of the transport options from the emissions site to the port terminal is shown in Figure 16, including direct and indirect carbon emissions produced by pipeline compressors, liquefaction units and ship fuel.

Figure 15: Transport cost (£/tCO2) for group 1

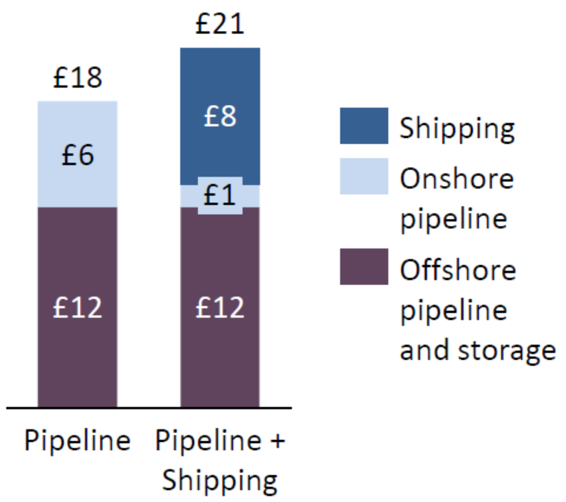
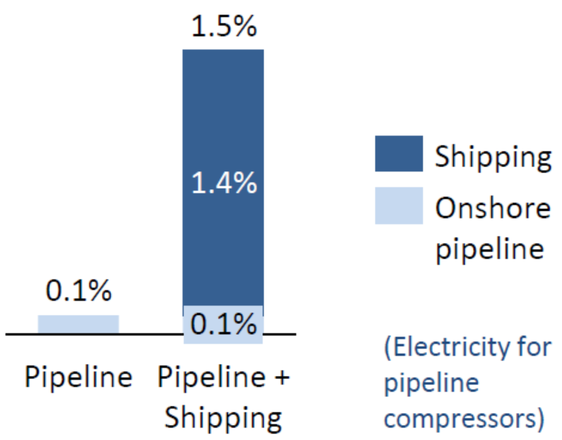


Figure 16: Carbon intensity of transport to port terminal (CO2 emitted per CO2 transported)



According to our modelling, the cheapest and least carbon intensive transport option for group 1 is pipeline, constituted by a local pipeline network in the cluster area and one single transmission pipeline connecting the cluster with the port terminal of Liverpool.

However, the choice of CO2 transport via pipeline from the cluster to Liverpool could be more problematic than transporting CO2 to Port Talbot and Milford Haven by pipeline and then shipping to Liverpool (pipeline + shipping option). The construction of a long pipeline presents risks related to potential permitting issues and delays in construction.

Our modelling suggests that the pipeline option is cost competitive due to the large volumes transported. If some of the industrial sites in the cluster were to discontinue their participation in the common transport scheme or not participate at all, the cost per unit of CO2 of the participants would increase and the pipeline + shipping option would be cheaper.

The high carbon intensity of the pipeline + shipping option is due to higher fuel consumption for the ship and the liquefaction of CO2, which is not required in the pipeline option.

Cost and carbon intensity of CO2 transport for group 2

As the sites in this group are located far from one another, transport options are investigated for each site individually. The location of the sites is shown in Figure 17, and individual emissions that could be captured from each site are reported in Table 11.

Figure 17: Location of sites withing Group 2

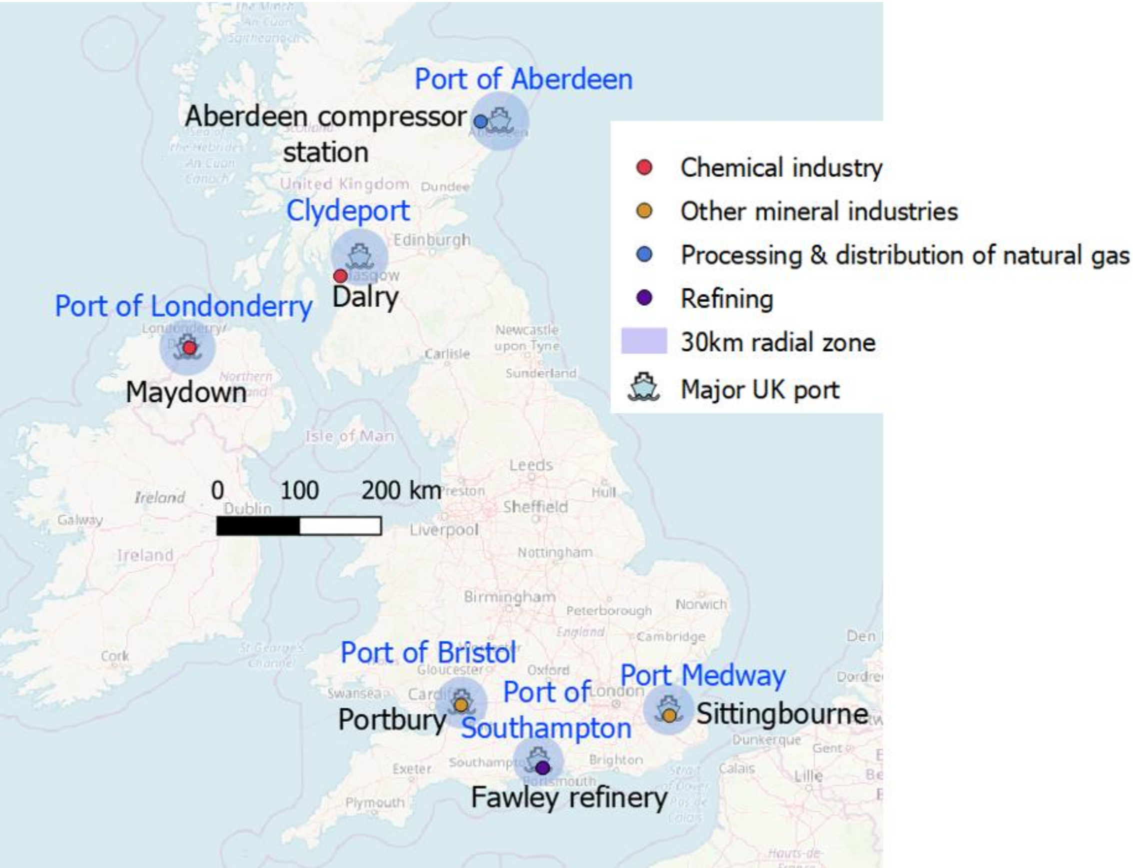


Table 11: Captured CO2 emissions from sites within group 2

Plant ID	Site	Sector	Captured volume (ktCO2)
8051	Fawley	Refining	2,533
8979	Maydown	Chemical industry	91
9036	Aberdeen	Processing & distribution of NG	71
9075	Dalry	Chemical industry	106
9594	Portbury	Other mineral industries	58
9595	Sittingbourne	Other mineral industries	51

Transport options for group 2

Three transport options are investigated, with each site choosing the most suitable option independently from other sites in the group:

- **Pipeline + Shipping**: Pipeline from the site to the nearest port and then shipping from the port to the nearest port terminal.
- **Road + Shipping**: Road transport from the site to the nearest port and then shipping from the port to the nearest port terminal.
- **Rail + Shipping**: Rail transport from the site to the nearest port and then shipping from the port to the nearest port terminal.

More information around our assumptions on pipeline and route length are found in Appendix A4: Assumptions and cost estimates for transport on page 63.

Cost of CO2 transport for group 2

The results of our modelling on the cost of transport for group 2 are shown in Figure 18. Costs and carbon intensity of the transport options from the emissions site to the port terminal are reported in Table 12, including direct and indirect carbon emissions produced by pipeline compressors, liquefaction units, truck, train and ship fuel.

Figure 18: Transport costs for each site and transport option

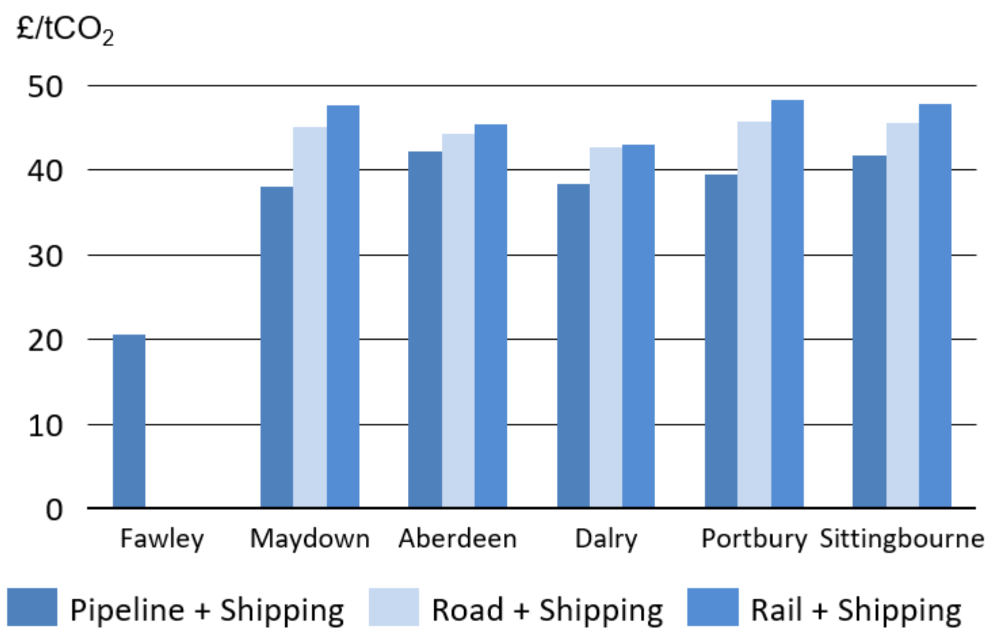


Table 12: Transport cost and carbon intensity for each site and transport option

	Cost (£/tCO2)			Carbon intensity to terminal (%)		
Site	**Pipeline + Shipping**	**Road + Shipping**	**Rail + Shipping**	**Pipeline + Shipping**	**Road + Shipping**	**Rail + Shipping**
Fawley	£21	-	-	0.7%	-	-
Maydown	£38	£45	£48	3.1%	4.1%	4.1%
Aberdeen	£42	£44	£45	1.5%	2.6%	2.5%
Dalry	£38	£43	£43	3.1%	4.2%	4.1%
Portbury	£39	£46	£48	3.7%	4.7%	4.7%
Sittingbourne	£42	£45	£48	2.8%	3.8%	3.8%
Average:	*£23/£40**	*£44*	*£46*	*1.0%/2.8%**	*3.9%*	*3.9%*

* Excluding Fawley Refinery

According to our modelling, the cheapest transport option is pipeline + shipping for all sites of group 2.

Although transport via pipeline is more expensive than road or rail transport for low CO2 volumes, the distance between the sites and their nearest port is short and the cost of the pipeline infrastructure does not have a large impact on the estimated final cost.

Rail transport is more expensive than road transport for the sites of group 2, due to the short distance to the nearest ports.

The average transport cost for all sites in group 2 is estimated to be £23/tCO2 but would be larger if the Fawley Refinery were not included in the average. The low cost of CO2 transport in £/t is significantly smaller for the Fawley Refinery than for other sites, due to the large CO2 volume and proximity to port.

Cost and carbon intensity of CO_2 transport for group 3

For this group, a transport option common to all sites in the cluster is investigated due to the colocation of the individual sites and the large amount of CO_2 emitted by the group, which in total amounts to ~2MtCO_2/yr for the entire cluster. The location of the sites is shown in Figure 19, and individual emissions that could be captured from each site are reported in Table 13.

Figure 19: Location of sites withing Group 3

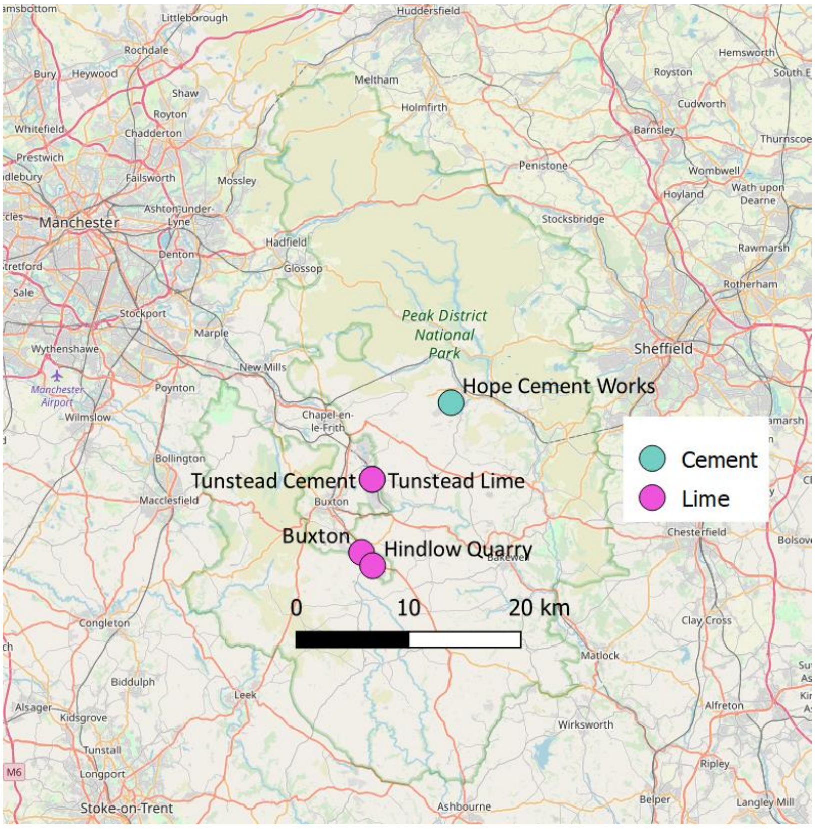


Table 13: Captured CO_2 emissions from sites within group 3

Plant ID	Site	Sector	Captured volume (ktCO_2)
8218	Buxton	Lime	178
14245	Hope	Cement	869
14686	Tunstead	Cement	574
14687	Hindlow	Lime	127
14688	Tunstead	Lime	229

Transport options for group 3

The three following transport options were investigated:

- **Pipeline**: Transport via onshore pipeline from the cluster to the Liverpool port terminal. The infrastructure for this option involves:
    - 40 km local pipeline
    - 140 km transmission pipeline to Liverpool
- **Road**: Transport via road from the cluster to the Liverpool port terminal. The infrastructure for this option involves:
    - 105 km road to Liverpool terminal (transport independent for each site)
- **Rail**: Transport via rail from the cluster to the Liverpool port terminal. The infrastructure for this option involves:
    - 105 km rail to Liverpool terminal (transport independent for each site)

More information around our assumptions on pipeline and route length are found in Appendix A4: Assumptions and cost estimates for transport on page 63.

Cost of CO2 transport for group 3

The results of our modelling on the cost of transport via pipeline, road or rail for group 3 are reported in Figure 20. The carbon intensity of the transport options from the emissions site to the port terminal is shown in Figure 21, including direct and indirect carbon emissions produced by pipeline compressors, liquefaction units, truck and train fuel.

Figure 20: Transport cost (£/tCO2) for group 3

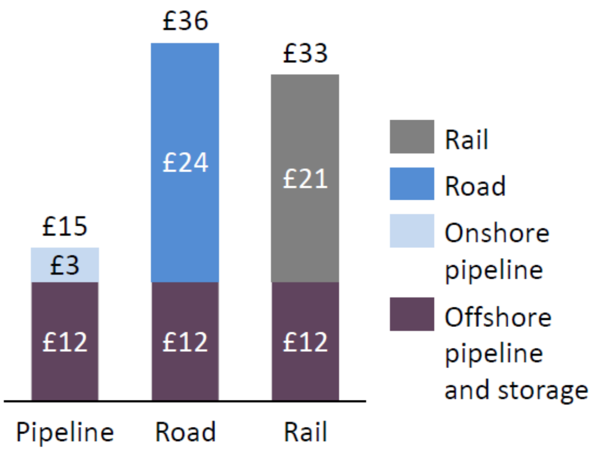
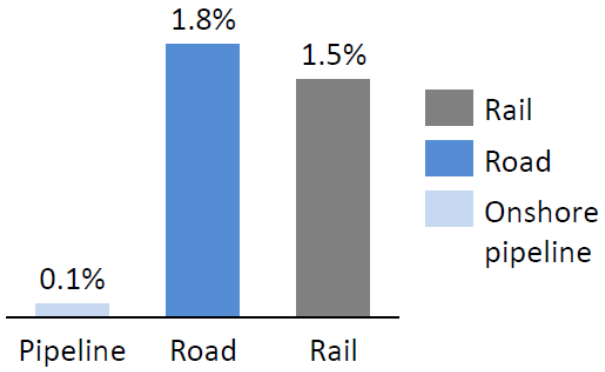


Figure 21: Carbon intensity of transport to port terminal (CO2 emitted per CO2 transported)



According to our modelling, the cheapest and least carbon intensive transport option for group 3 is pipeline, constituted by a small local pipeline network in the cluster area and one single transmission pipeline connecting the cluster with the Liverpool terminal.

The construction of a pipeline in the area presents large risks related to potential permitting issues and delays in construction. In particular, one site (Hope) is located inside the Peak District National Park grounds, where the construction of a new pipeline is subject to further regulatory restrictions.

The pipeline option is cost competitive due to the large volumes transported. If some of the industrial sites in the cluster were to discontinue their participation in the common transport scheme or not participate at all, the cost per unit of CO2 of the participants would increase and the pipeline + shipping option would be cheaper.

The carbon intensities of road and rail is high because of the fuel consumption for the truck or train as well as for the liquefaction of CO2, which is not required by the pipeline option. Comparing between road and rail, road is more expensive and carbon intensity due to the higher fuel consumption per unit of CO2 transported.

Cost and carbon intensity of CO2 transport for group 4

As the sites in this group are located far from one another, transport options are investigated for each site individually. The location of the sites is shown in Figure 22, and individual emissions that could be captured from each site are reported in Table 14.

Figure 22: Location of sites withing Group 4

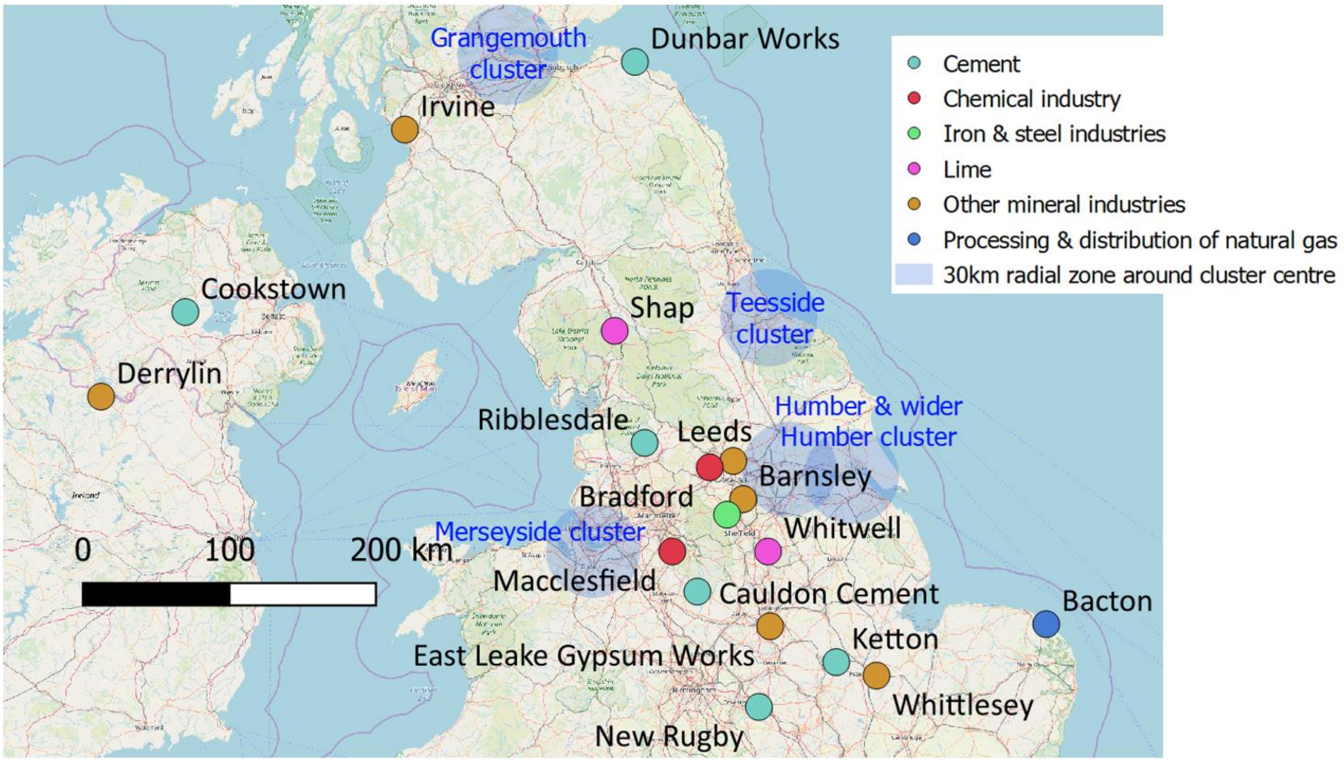


Table 14: Captured CO2 emissions from sites within group 4

Plant ID	Site	Sector	Captured volume (ktCO2)
8007	Whitwell	Lime	231
8015	Ribblesdale	Cement	512
8037	Ketton	Cement	608
8059	New Rugby	Cement	972
8263	Leeds	Glass	59
8322	Shap	Lime	186
8355	Bacton	Processing & distribution of NG	87

Plant ID	Site	Sector	Captured volume (ktCO2)
8600	Macclesfield	Chemical industry	55
9623	Barnsley	Glass	137
11128	Dunbar	Cement	479
11387	Irvine	Glass	60
11478	Derrylin	Glass	105
11750	East Leake	Other mineral industries	78
13756	Stocksbridge	Iron & steel	27
14242	Whittlesey	Other mineral industries	88
14415	Bradford	Chemical industry	56
14417	Cauldon	Cement	541
14454	Cookstown	Cement	277

Transport options for group 4

Six transport options were investigated, with each site choosing the most suitable option independently from other sites in the group:

- **Pipeline, Road or Rail**: Direct transport via onshore pipeline, road or rail to the nearest port terminal.
- **Pipeline, Road or Rail + Shipping**: Onshore pipeline, road or rail transport to the nearest port and shipping to the nearest port terminal.

More information around our assumptions on pipeline and route length are found in Appendix A4: Assumptions and cost estimates for transport on page 63.

Cost of CO2 transport for group 4

The results of our modelling on the cost of transport for group 4 are reported in Table 15. The carbon intensity of the transport options from the emissions site to the port terminal is shown in Table 16, including direct and indirect carbon emissions produced by pipeline compressors, liquefaction units, truck, train and ship fuel.

Table 15: Cost of transport (£/tCO2) for each site and transport option

Site	Pipeline	Pipeline + Shipping	Road	Road + Shipping	Rail	Rail + Shipping
Whitwell	**£25**	-	£39	-	£34	-
Ribblesdale	**£19**	-	£38	-	£33	-
Ketton	**£22**	-	£46	-	£38	-
New Rugby	**£22**	£30	£55	£57	£42	£46
Leeds	£50	-	£41	-	**£36**	-
Shap	**£26**	-	£43	-	£36	-
Bacton	£51	£48	£51	£49	**£41**	£49
Macclesfield	£43	-	£36	-	**£33**	-
Barnsley	**£28**	-	£40	-	£35	-
Dunbar	**£28**	£28	£58	£43	£44	£40
Irvine	£119	£55	£77	£51	£54	**£51**
Derrylin	£105	£53	£85	£57	£58	**£50**
East Leake	£47	-	£45	-	**£38**	-
Stocksbridge	£97	-	£42	-	**£36**	-
Whittlesey	£45	-	£47	-	**£39**	-
Bradford	£54	-	£42	-	**£36**	-

Cauldon	£20	-	£40	-	£35	-
Cookstown	£55	**£31**	£79	£42	£54	£39
Average:	*£31*	*£33*	*£50*	*£51*	*£40*	*£44*

According to our modelling, the cheapest transport option depends on CO2 volumes and location of each site but is generally pipeline or rail. Solutions including road transport are never the cheapest. Rail transport is less expensive than road transport for group 4, as this is more cost efficient over long distances.

Table 16: Carbon intensity to terminal (%) for each site and transport option

Site	Pipeline	Pipeline + Shipping	Road	Road + Shipping	Rail	Rail + Shipping
Whitwell	**0.1%**	-	1.8%	-	1.6%	-
Ribblesdale	**0.1%**	-	1.8%	-	1.5%	-
Ketton	**0.1%**	-	2.0%	-	1.6%	-
New Rugby	**0.1%**	1.2%	2.3%	2.9%	1.7%	2.4%
Leeds	**0.1%**	-	1.9%	-	1.6%	-
Shap	**0.1%**	-	1.9%	-	1.6%	-
Bacton	**0.1%**	3.2%	2.2%	4.4%	1.6%	4.3%
Macclesfield	**0.1%**	-	1.8%	-	1.5%	-
Barnsley	**0.1%**	-	1.9%	-	1.6%	-
Dunbar	**0.1%**	1.0%	2.3%	2.4%	1.7%	2.1%
Irvine	**0.1%**	3.1%	2.8%	4.3%	1.8%	4.1%
Derrylin	**0.1%**	3.1%	3.1%	4.6%	1.9%	4.3%

Site	Pipeline	Pipeline + Shipping	Road	Road + Shipping	Rail	Rail + Shipping
East Leake	**0.1%**	-	2.0%	-	1.6%	-
Stocksbridge	**0.1%**	-	1.9%	-	1.6%	-
Whittlesey	**0.1%**	-	2.1%	-	1.6%	-
Bradford	**0.1%**	-	1.9%	-	1.6%	-
Cauldon	**0.1%**	-	1.9%	-	1.6%	-
Cookstown	**0.1%**	1.4%	2.9%	2.7%	1.8%	2.5%

The carbon intensity of CO2 transport from all sites is estimated to be lowest for the pipeline option, as emissions from this option are linked only to fuel consumption of the compressors and thus mainly related to the transported volumes and not the location. Carbon intensity for the other options is estimated to be always lower than 2%.

Conclusions

Site assessment

Our analysis suggests that there are 36 'dispersed' industrial sites in the UK that would be potentially suitable for CCS; together they emit an estimated 20.7 MtCO2 and the majority (87%) of these emissions come from the following sectors: Iron & Steel, Cement and Refining. In the context of CCS, we find that there are certain synergies/similarities between these 36 sites, and that they can be grouped into four categories according to these:

- Group 1: Industries located inside the South Wales industrial cluster
- Group 2: Industries that are not in Group 1 and that are within 30km of a major port.
- Group 3: 5 high emitting sites that are located either inside enclosed by the Peak District National Park were identified. All located within 20km of one another.
- Group 4: All remaining sites – these can be considered as truly dispersed.

Risks and challenges of CCS for dispersed industrial sites

Through a series of stakeholder interviews and in-house expertise, we re-analyse the traditional risks and challenges of CCS (i.e. those for sites located inside industrial clusters) for dispersed industrial sites. We find that the dispersed location of a site can be a significant challenge towards CCS deployment, but not necessarily a showstopper. Our research suggests that some challenges are valid for all sites considered whereas others are more relevant to certain groups (defined above) than others. The main risks are categorised into the following: cross chain, policy and technical.

Cross chain risks - For all sites considered, there is uncertain availability of T&S, which leads to risk of stranded assets with no alternative use. In addition, due to the singular nature of sites in Groups 2 & 4, certain segments of the CO2 transport infrastructure would only serve 1 site. As a result, these cannot benefit from economies of scale so bear higher cost of abatement. For the same reason, Group 2 & 4 sites would also be at risk of low utilisation of transport assets due to e.g. industry down time. The stakeholder engagement part of the study suggested that, for some locations (e.g. those located in a National Park), CO2 transport challenges would be so high that the preferred option may be to relocate sites entirely.

Policy risks, with knock-on effect as economic & market risk - For all sites not located in industrial clusters (i.e. all sites apart from those in Group 1), there is currently no comprehensive plan, policy or regulatory framework to facilitate carbon capture, including formal permitting process. Obtaining the required implementation and operating consent, permits and licenses for all aspects of ICCS chain may lead to delays in FID, construction etc. This is especially true of sites located in and around restricted areas (Group 3). The high risks associated with permitting provides significant deterrent to investors.

Technical risks - Many dispersed industrial sites (Groups 2,3,4) may have issues with energy (for CO2 compression / liquefaction), feedstock, O2 (e.g. for O2 separation for oxyfuel combustion in the cement sector) and water use of capture plant.

The analysis of risks and challenges highlighted that **the transport of CO2** has a high perceived risk for dispersed industrial sites. As a result, we considered in more detail the three possible **CO_2 transport options** for CCS, including **pipeline**, **ship** and **road**/**rail**. For each of these three options, the key challenges were assessed and are summarised in the table below:

Table 17: Principal risks and constraints CO_2 transport options for CCS.

Onshore pipeline	Shipping	Road/rail transport
Regulatory: several permitting requirements for the construction of onshore pipelines that vary by pipeline length, however, White Rose project proved that, in theory, CO_2 pipeline transport can be done safely. CO_2 will continue to be classified as though it were a dangerous substance until specific legislation is introduced. **Disturbance**: local impact to population from its construction (one time)	**Regulatory**: exposure to different international regulatory frameworks including EU-ETSD, EU CCS Directive, UNCLOS, SOLAS IGC Code; these have an influence on the development and requirements for CO_2 shipping. **Port constraints**: certain ports unable to accommodate CO_2 ships Limited experience Limited business models	**Safety**: route choice constraints because CO_2 is a dangerous substance, explosion hazard **Capacity**: CO_2 trucks currently operate with 20t capacity. Less and less available rail capacity due to increased passenger traffic **Disturbance**: local impact to population from operation (constant) **Storage**: potential impact on feasibility and transport cost due to additional storage capacity required at capture site

Options appraisal based on cost-effectiveness and carbon reduction potential

The analyses of the different transport options shown above revealed that different options are better suited than others to each group based on the risks and challenges involved. The other main considerations when comparing decarbonisation options are the costs and the carbon reduction potential which we modelled. We modelled the costs in £/tCO_2 associated with the transport of CO_2 from the emission site to the offshore storage site for each of the 36 sites considered. We also estimated the carbon intensity as a percentage in terms of tCO_2 emitted per tCO_2 transported. The results are displayed in the table below. The most cost-effective and lowest carbon options are shown in **bold**. In Group 4, the most attractive option varies across the sites in the group therefore several options are highlighted.

Table 18: Cost and carbon abatement potential of transport options for each group.

Transport option	Group 1: South Wales	Group 2: Close to major ports	Group 3: Peak District	Group 4: Truly dispersed
Pipeline (site - terminal)	**£18/tCO2** **0.1%**	-	**£15/tCO2** **0.1%**	**£31/tCO2*** **0.1%***
Pipeline + Shipping (site - port - terminal)	**£21/tCO2** **1.5%**	**£23/tCO2*; £40/tCO2**** **1.0%*; 2.8%****	-	**£33/tCO2*** **1.4%***
Road (site - terminal)	-	-	£36/tCO2 1.8%	£50/tCO2* 2.1%*
Road + Shipping (site - port - terminal)	-	£44/tCO2* 3.9%*	-	£51/tCO2* 2.9%*
Rail (site - terminal)	-	-	£33/tCO2 1.5%	**£40/tCO2*** **1.6%***
Rail + Shipping (site - port - terminal)	-	£46/tCO2* 3.9%*	-	**£44/tCO2*** **2.6%***

* Average value for the group, values can vary significantly across sites in group (see detailed tables in previous section).

** Average value for Group excluding Fawley Refinery

Summary of findings from our modelling estimates:

Group 1 (S.Wales): We find that both pipeline and pipeline + shipping options may be optimal. Cost-effectiveness is estimated at £18/tCO2 to £21/tCO2.

Group 2 (Close to major ports): The cheapest transport option is pipeline + shipping for all considered sites. However, if the Fawley refinery is excluded from calculations, the average transport cost and carbon intensity increases from £23/tCO2 to £40/tCO2 and from 1.0% to 2.8%.

Group 3 (Peak District): The cheapest and least carbon intensive option is pipeline; it is significantly cheaper and less carbon intensive than road and rail.

Group 4 (Truly dispersed): In this group we find that in general the costs are higher but that the optimal pathway is less clear and more site specific rather than group specific. The cheapest transport options are pipeline or rail, and for one site pipeline + shipping. Carbon intensity is lowest for pipeline.

Comparison against alternative options

A comparison between different transport options is relevant in the context of CCS; however, alternative options to CCS exist, namely hydrogen fuel switching and CCUS. We compared these two alternatives to the CO2 transport options over the same metrics (principal risks, costs and carbon abatement potential).

Considering risks first, we found that technical risks for both H2 fuel switching and CCU were key. For H2 fuel switching, there are product quality concerns and equipment compliancy concerns whilst for CCU, we found a general lack of technology readiness and a small market. In addition, one of the main technical considerations of CCS is the availability and cost of transport infrastructure for CO2. Hydrogen fuel switching would also encounter many of these challenges, as would CCU unless emitters and users are collocated, which for dispersed sites is more unlikely than for clusters.

Considering abatement potential next, we find that for sectors with a large portion of process emissions (cement, glass, lime), CCS achieves a significantly higher level of abatement than H2 fuel switching, as shown in the table below. Note, however, that the abatement potential of CCS is reduced between 0.5% and 1.5% when considering the additional emissions from the fuels utilised in the capture process (i.e. on top of the abatement potential of CCS quoted in the table). Carbon capture fuels are assumed to be grid electricity for the electrical demand and hydrogen for the thermal demand.

Table 19: Carbon abatement potential (%) of CCS and H2 fuel switching

Sector	CCS*	H2 fuel switching
Cement	89%	55%
Chemical industry	89%	94%
Glass	89%	56%
Lime	89%	34%
Other mineral industries	89%	94%
Refining	81%	95%
Iron & steel	54%	51%

* Best available technology between amine capture and calcium looping, see assumptions on capture and treatment rates in the appendix.

Finally, regarding costs, the cost of CCS and H2 fuel switching in each sector is variable, but both technologies offer comparable costs. Note, however, that our cost comparison does not capture the cost associated with the conversion of the gas grid to hydrogen, i.e. the costs assume a fully available H2 grid.

Table 20[12]: Comparison of costs and abatement potentials between CCS and H2 fuel switching in the year 2050

Sector	Levelised cost of abatement in £/tCO2** for CCS	Levelised cost of abatement in £/tCO2** for H2 fuel switching	CO2 transport cost in £/tCO2
Cement	84 – 130	18 - 147	28 - 58
Chemical industry	-	85 - 195	33 - 54
Glass	-	146 - 172	18 - 65
Lime	-	18 - 147	15 - 26
Other mineral industries	-	132 - 200	18 - 65
Refining	116 - 162	71 – 174	18 - 28
Iron & steel	79 – 115	72 - 181	18 - 36

** At 0% discount rate; *** Includes injection.

[12] For hydrogen fuel switching, the range of abatement cost in £/tCO2 depends largely on the initial fuel type. In most cases, the minimum abatement cost corresponds to switching from e.g. fuel oil, gas oil or burning oil, whilst the maximum abatement costs usually corresponds to switching from natural gas, with switching from coal or LPG usually lying in the upper quartile of the range.

The values in this slide are based on the year 2050 because it is assumed that the H2 grid and fuel switching technologies would be fully available.

Appendix

Appendix A: Assumptions

Appendix A1: Assumptions on CO2 emissions threshold

Only sites with yearly CO2 emissions above the minimum threshold of **50ktCO2/yr** were considered sufficiently cost-effective and were therefore included in this study.

To estimate the minimum size of a CO2stream for which carbon capture is economically advisable, the capex of carbon capture plants of various sizes was compared with the cost of carbon emitted over the lifetime of the capture plant. It was chosen to consider as potential candidates for CCS only those sources where the capture **plant capex** would be no larger than **twice the cost of carbon** emitted by the source, in order to ensure that the initial investment in the infrastructure would also be met by a reasonable economic return.

Assumptions: Carbon capture plant

- Technology: amine scrubber
- Lifetime: 20 yr
- Capture plant CAPEX (capacity 100ktCO2/yr): ~£59m
    - Capture plant £55m
    - Compressors £3.75m
- Smaller capture plants have proportional capex
    - 1/2 capacity -> 2/3 CAPEX
    - 1/10 capacity -> 1/5 CAPEX

Assumptions: Cost of carbon

- Cost of carbon equivalent to the Carbon Floor Price (CFP)
- CFP: £18/tCO2

Table 21: Comparison of capture plant capex and cost of carbon

Capture plant size	100 ktCO2/yr	50 ktCO2/yr	10 ktCO2/yr
Capture plant capex	£59m	**£39m**	£12m
Cost of carbon over capture plant lifetime	£36m	**£18m**	£4m

Appendix A2: Assumptions on industries suitable for CCS

Table 22: List of industries suitable for CCS

Sector	Priority	Rationale / comments	Reference
Cement, Ironmaking, Refining, Ethylene, Ammonia	High	Sectors assumed to apply CCS in recent CCC net-zero report.	CCC, Net Zero – Technical report (May 2019)
Ceramics / other mineral industries	Medium	CCS considered necessary to achieve the deepest decarbonisation. Rollout of carbon capture is assumed only to be suitable at the largest sites, and even then, there are challenges of low CO2 concentration and the presence of aggressive acid gases in the exhaust stream. Individual ceramic sites are not considered to be of a sufficient scale to justify their own CO2 pipeline and storage infrastructure.	WSP Parsons Brinckerhoff & DNV.GL for DECC, Industrial Decarbonisation & Energy Efficiency roadmaps to 2050 - Ceramics (2015). Ceramics Appendices
Glassmaking	Medium	Glass companies expressed a preference to avoid carbon capture in favour of other decarbonisation technologies (high perceived cost and disruption of carbon capture equipment, mutual exclusivity with electric furnaces). However, if other options cannot be implemented, then it may be necessary for the glass sector to implement carbon capture. Scale of CO2 emissions in glass sector is such that the implementation of CC at a single glass manufacturing site would be insufficient to justify the implementation of full CCS chain. If not located in an industrial cluster, Glassmaking more compatible with	WSP Parsons Brinckerhoff & DNV.GL for DECC, Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Glass (2015). Glass Appendices

Sector	Priority	Rationale / comments	Reference
		CCU than CCS due to smaller volumes of CO_2 captured. Cost (capex) of carbon capture at Glass making sites is estimated at £40m/site	
Processing & distribution of natural gas	Medium	Natural gas typically undergoes processing before export to markets. Depending on the field conditions, raw natural gas may contain 2% to 70% CO_2 by volume. This needs to be reduced to market or process specifications. Natural gas processing includes production of LNG, where removal of CO_2 is a pre-requisite to the natural gas liquefaction process. This can be a high-purity CO_2 source. CO_2 content in UKCS gas is low, typically only 1% by mass (for references see here and here)	IEA and UNIDO, Technology Roadmap, CCS in industrial applications (2011)
Other chemicals	Medium /low	There is a poor understanding of carbon capture potential for other chemicals. The potential for carbon capture will depend greatly on the site specifics (e.g. the size of the CO_2 streams, concentration of the CO_2, purity etc.). Many of the 'other chemicals' likely to be located in chemical industry clusters. This is a lower priority sector but still included for subsequent case-by-case analysis of larger site not located in industrial clusters.	Element Energy for DECC, BIS, Demonstrating CO2 capture in UK cement, chemicals, iron and steel & oil refining sectors by 2025: Techno-economic Study 2014

Appendix A3: Assumptions on industrial cluster size

Only sites located at a distance higher than **30 km** from the centre of all UK major clusters were considered dispersed and were therefore included in this study.

To estimate the size of a typical area enclosed in an industrial cluster, the capex of the smallest carbon capture plant considered was compared with the capex of a pipeline of various lengths. A location was considered as not included in an industrial cluster (dispersed) if the **capex for a CO2 pipeline** connection with the centre of the nearest cluster is prohibitive. It was therefore chosen to define the area outside of a cluster as any location where the capex of a connecting pipeline would be larger than **1/3 of the capex of a small carbon capture plant**.

This estimate of the size of an industrial cluster is conservative and corroborated by measures of UK industrial clusters:

- Humber cluster: the distance between the eastern tip (Easington compressor station) and the western outskirts of Leeds is about 120km.
- South Wales cluster: the distance connecting the furthers sites is 140km.

Generally, the geographical definition of a cluster depends on the density distribution of the industrial sites. In this study, for simplicity, cluster areas were all assumed to be circular and with the same fixed radius. Only exception was the Humber cluster, assumed to span over the area of 2 such circles.

Assumptions: Carbon capture plant

- Technology: amine scrubber
- Lifetime: 20 yr
- Size of CO2 source: 50ktCO2/yr
- Capture plant CAPEX: ~£39m

Assumptions: Pipeline

- Pipeline CAPEX: ~£0.43m/km

Table 23: Proportion of pipeline capex and capture plant capex

Pipeline length	Pipeline capex / Plant capex
10 km	11%
20 km	22%
30 km	**33%**
40 km	44%

Increasing the radius only captures two more sites, whilst reducing the radius omits sites known to be considered in existing industrial clusters

If the definition of the industrial cluster size is reduced to 15km, more sites are included in the scope of the analysis, especially in the more dispersed industrial clusters of Merseyside and the Humber. However, the results of the analysis remain largely unchanged for the more nucleated industrial cluster at Teesside.

Conversely, if the radius of the industrial cluster is increased to 45km, only 2 fewer sites remain included for this analysis.

These results, coupled with our wider stakeholder engagement and the results of the justification of assumptions, suggest that 30km zone for the cluster definition is appropriate: increasing the size significantly only captures two more sites, whilst reducing the size to 15km omits many of the sites that are known to be considered in existing industrial clusters, with a notable example being the British Steel site in Scunthorpe (annual emissions of 5.2MtCO2)

Table 24: Number of dispersed sites if clusters are defined by a 15km radial zone

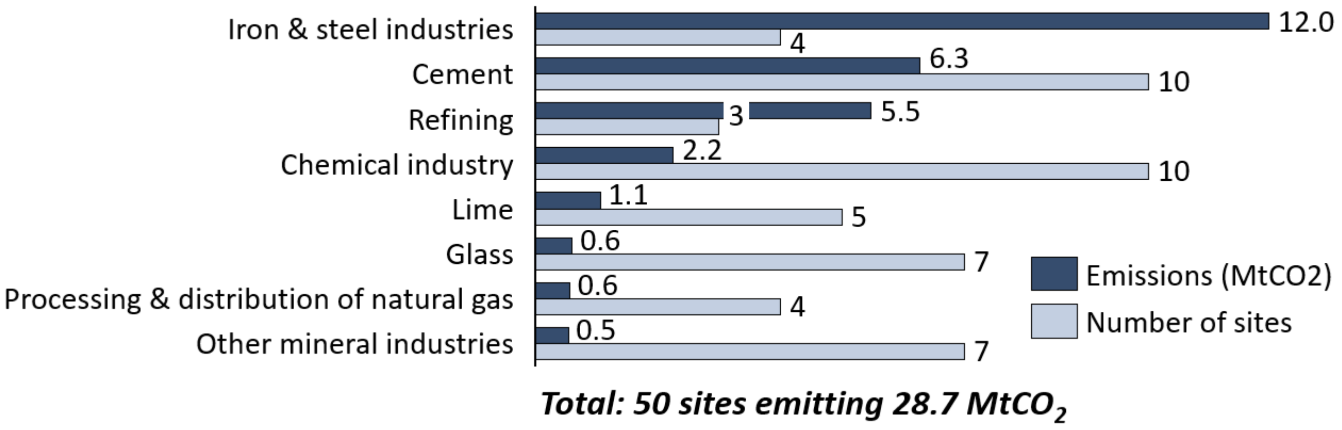
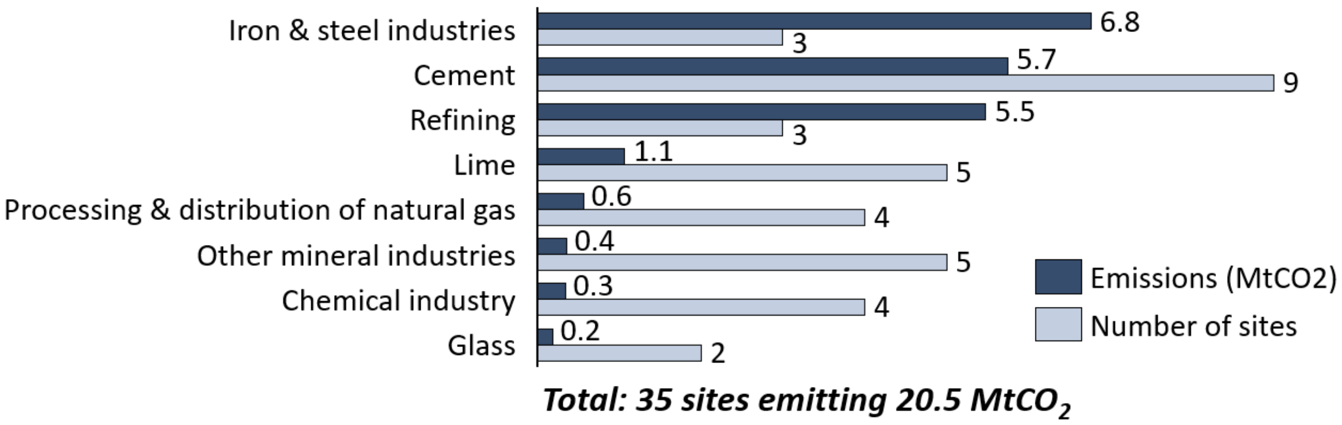


Table 25: Number of dispersed sites if clusters are defined by a 45km radial zone



Appendix A4: Assumptions and cost estimates for transport

Table 26: Onshore pipeline capex

Length (km)	Capex (£/inch/km)	Length (km)	Capex (£/inch/km)
1	£68,509.62	150	£47,646.23
25	£63,241.19	200	£45,072.12
30	£62,349.76	250	£44,170.67
40	£60,546.88	300	£43,860.18
50	£58,804.09	400	£43,652.34
60	£57,024.57	500	£43,550.72
80	£54,537.26	1000	£42,935.36
100	£51,762.82	2000	£42,998.80

- Discount rate: 0%
- Project lifetime: 20 yr
- OPEX = 1.0% CAPEX

Table 27: Considered terminals and ports

Type	Location	Lat	Lon
Terminal	Peterhead	57.502552	-1.77568
Terminal	Humberside	53.633604	-0.197353
Terminal	Teesside	54.614331	-1.162062
Terminal	Liverpool	53.381332	-3.007708
Port	Aberdeen	57.142604	-2.070651

Port	Belfast	54.611017	-5.911617
Port	Bristol	51.510452	-2.70092
Port	Cardiff	51.455852	-3.158999
Port	Clydeport	55.893788	-4.397821
Port	Dundee	56.466647	-2.932577
Port	Falmouth	50.152862	-5.055785
Port	Grangemouth	56.028576	-3.69092
Port	Great Yarmouth	52.580157	1.733809
Port	Harwich	51.947827	1.251855
Port	Londonderry	55.040975	-7.263029
Port	Medway	51.441731	0.744324
Port	Milford Haven	51.712635	-5.0429
Port	Port Talbot	51.584634	-3.788195
Port	Southampton	50.904756	-1.427035

Table 28: Proportion between travelled length and geographical distance

Item	Travelled length / distance
Pipeline	2.0
Road	1.5
Rail	1.5

Table 29: Fuel characteristics

Fuel	Cost	Carbon intensity 2020	Carbon intensity 2050
Electricity	£80.00/MWh	138 kgCO2/MWh	10 kgCO2/MWh
LNG	£19.53/MWh	181 kgCO2/MWh	-
Diesel	-	0.00242 tCO2/l	-
Hydrogen	-	-	11.5 kgCO2/MWh

Table 30: Vehicles

	Truck	Train
Gross weight (tonne)	44	1,000
Load weight (tonne)	25	600
Consumption (l/km)	0.358	2.4
Consumption (l/t-km)	0.014	0.004
Road/railway fees (£/train-km)	-	£2.87
Shunting cost (£/tCO2)	-	£2.61
Total transport cost (£/tCO2)	£13.04 (100 km x2)	£35.22 (500 km x2)

Table 31: Carbon treatment and capture rates

	Treatment	Capture	Net capture
Cement, Chemical industry, Glass, Lime, Other mineral industries, Processing & distribution of natural gas	99%	90%	89%
Refining	90%	90%	81%
Iron & steel industries	60%**	90%	54%

Treatment rate refers to the portion of CO2-emitting sources onsite to which CCS is applied. Capture rate refers to the amount of CO2 that the carbon capture technology is able to capture from a given CO2 stream. The net capture rate is obtained by multiplying both factors and refers to the share of CO2 captured at one site.

The 90% capture rate common to all sectors can be increased to up to 99% at a higher cost.

Appendix A5: Offshore storage availability

While CO2 storage potential in the Northern, Central and Southern North Sea is plentiful, this is more limited in the east Irish Sea.

Table 32: Storage location for each terminal and associated capacity

Terminal	Storage location	Capacity - Oil and gas (GtCO2)	Capacity - Saline aquifer (GtCO2)	Capacity - Total (min) (GtCO2)	Max average injection rate over 40 yr (MtCO2/yr)
St. Fergus	Northern and Central North Sea	2.5 - 5.0	4.6 - 46.0	7.1	**178**
Teesside, Humber	Southern North Sea	3.9	1.7 - 16.7	5.6	**140**
Liverpool	East Irish Sea	1.0	0 - 0.7	1.0	**25**

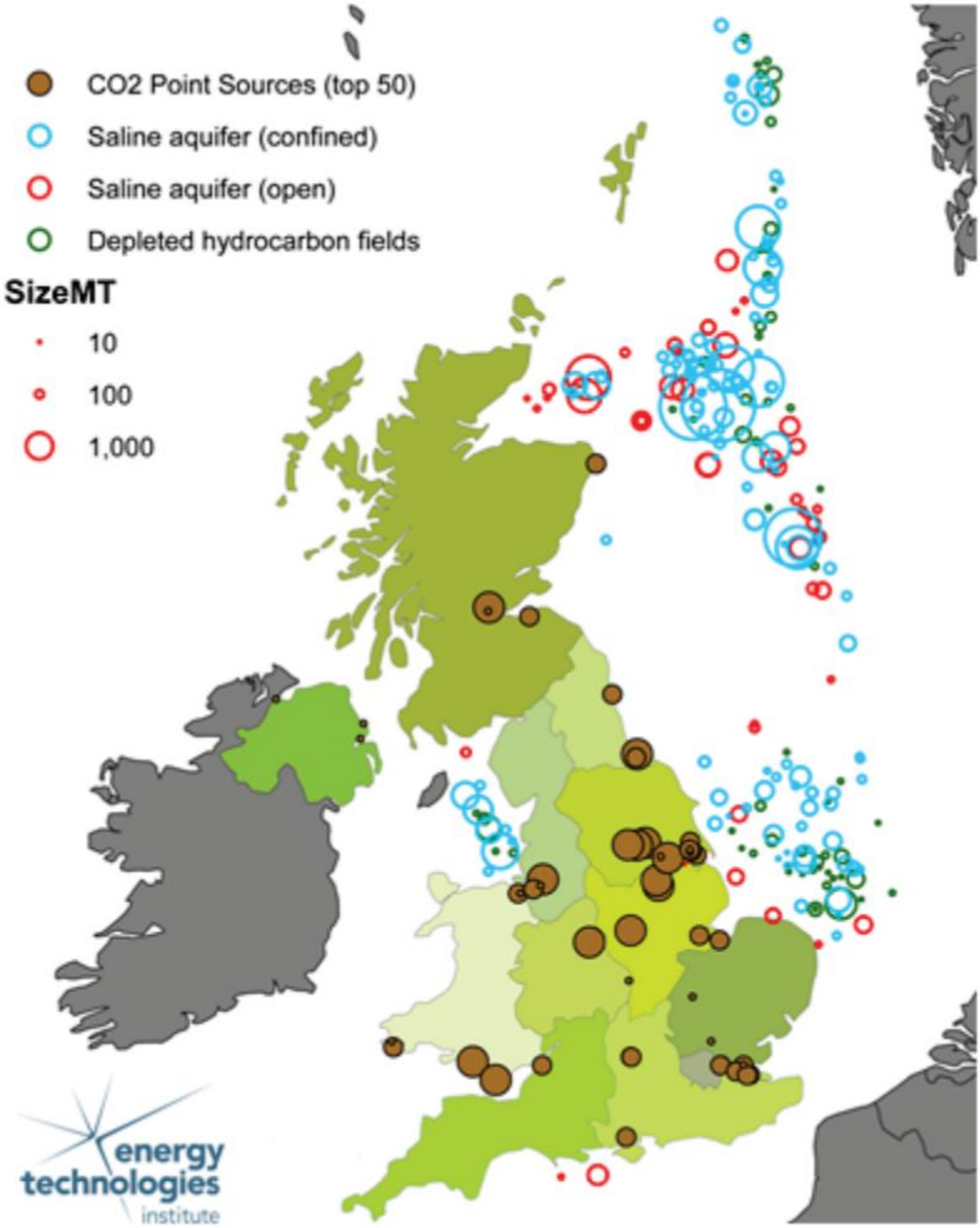
The storage capacity in the East Irish Sea is sufficient to store the projected CO2 stream from the Liverpool port terminal for at least 90 years. This is composed of CO2 from the Merseyside cluster, the South Wales cluster, the Peak district cluster, and some additional dispersed sites transporting CO2 to Liverpool and would amount to **11 MtCO2/yr** maximum.

Table 33: CO2 stream from Liverpool terminal

Source	2016 emissions (MtCO2/yr)	Max CO2 stream flow (MtCO2/yr)
Merseyside cluster	3.2	2.9
South Wales cluster	9.9	6.2
Peak district cluster	2.2	2.0

Additional dispersed sites transporting CO2 to Liverpool	3.2	2.8
Total	**15.3**	**11.0**

Figure 23: Proximity of the UK's largest industrial emitters to CO2 storage sites in the North and Irish Seas (source: DECC 2012 CCS Roadmap, map by Energy Technologies Institute)



Appendix B: Options for CCS deployment at dispersed sites

Appendix B1: Onshore pipeline

Key challenges of onshore pipelines[13]

Safety: there is currently no dedicated legislation and hydrogen is considered a ‘dangerous substance’. In the UK, there is at present no legislation that expressly regulates CO2 transport by pipeline. Until such regulation is introduced, “project developers should consider CO2 as though it were classified as a 'dangerous substance' or a 'dangerous fluid'”. Descriptions of how to handle dangerous fluids/substances are covered in:

- The 1996 Pipeline Safety Regulations (PSR), and
- The 1999 Control of Major Accident Hazards (COMAH).

Permitting: several regulatory requirements for the construction of onshore pipelines that vary by pipeline length. In the UK unless an onshore pipeline is owned/operated by a public gas transporter, water company or the government, legislation is covered by the Pipe-Lines Act 1962:

- Requirements for pipelines <16km in length:
    - Local authority planning permission;
    - Authorisation from landowners OR a Compulsory Purchase Order (subject to a Parliamentary process).
- Requirements for pipelines 16km < length < 40km AND <800mm diameter:
    - Pipeline Construction Authorisation (PCA) - awarded by the Secretary of State for BEIS;
    - Authorisation from landowners OR a Compulsory Purchase Order (subject to a Parliamentary process);
    - An Environmental Impact Assessment statement unless BIS is satisfied that the carrying out of the relevant pipeline works 'is not likely to have a significant effect on the environment’, in which case EIA not necessary.
- Requirements for pipelines >40km in length OR >800mm in diameter OR if another EEA state has requested to participate in the EIA procedure in (2):
    - Pipeline Construction Authorisation (PCA) - awarded by the Secretary of State for BEIS;
    - Authorisation from landowners OR a Compulsory Purchase Order (subject to a Parliamentary process);
    - An Environmental Impact Assessment statement.

[13] https://www.globalccsinstitute.com/; http://www.hse.gov.uk/pipelines/resources/designcodes.htm

Case study 1: CO2 transport pipeline network design for Humber region in the UK (2013)[14]

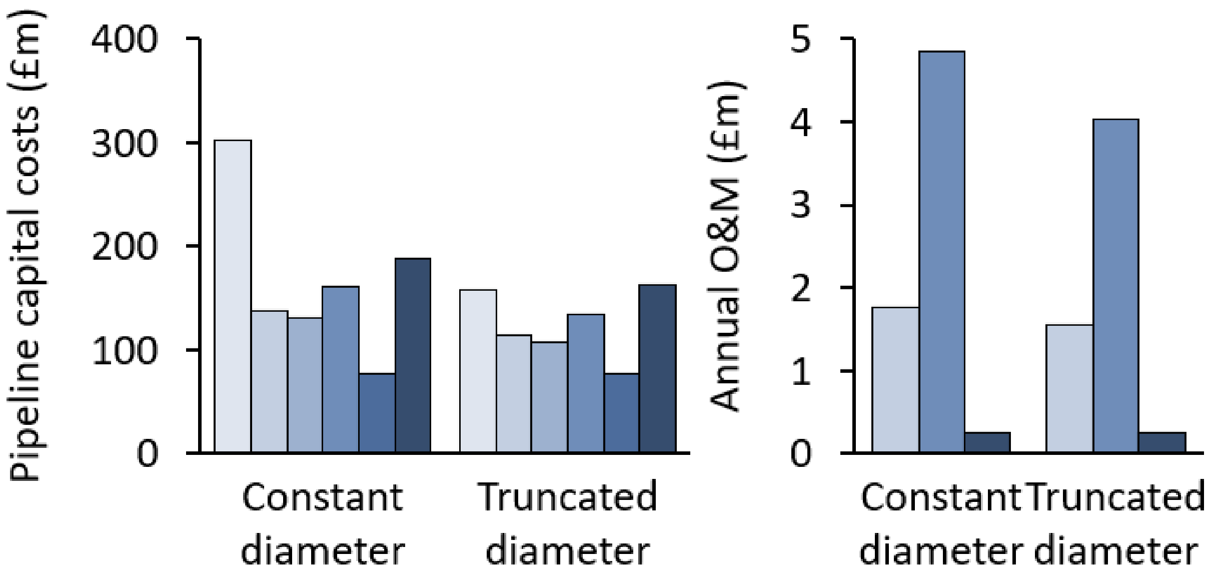
Objective: Evaluate methods for techno-economic assessment of newly proposed onshore CO2 pipelines on a real-life case study in the Humber region.

Key findings: Impurity content (which varies based on the CO2 source and capture method) and phase behaviour of the transported CO2 are major considerations for developing a CO2 pipeline network. Impurity content affects pipeline design, compressor power, recompression distance, and pipeline capacity.

Estimations of pipeline capital cost for a pipeline located in the Humber region was estimated at £78m to £303m. Design considerations:

- Route: from Ferrybridge to Mablethorpe, connecting Drax and sites at Grimsby port
- Length: 91.7km; Lifetime: 35yr; Pressure: 130bar; Depth: 1m; Diameter: 1m to 1.3m
- Assessments based on constant and truncated diameters-
    - Constant diameter: designed to take emissions from all sources at maximum capacity regardless of the point at which they are attached to the pipeline
    - Truncated diameter: increasing diameter in steps as additional sources are added along the pipeline route to accommodate the additional capacity

Figure 24: Humber onshore pipeline capex and opex



14 https://pdfs.semanticscholar.org/969e/4d496907fe38e40ac9e30bda5f9bab1b03f0.pdf

Figure 25: Humber onshore pipeline levelized cost

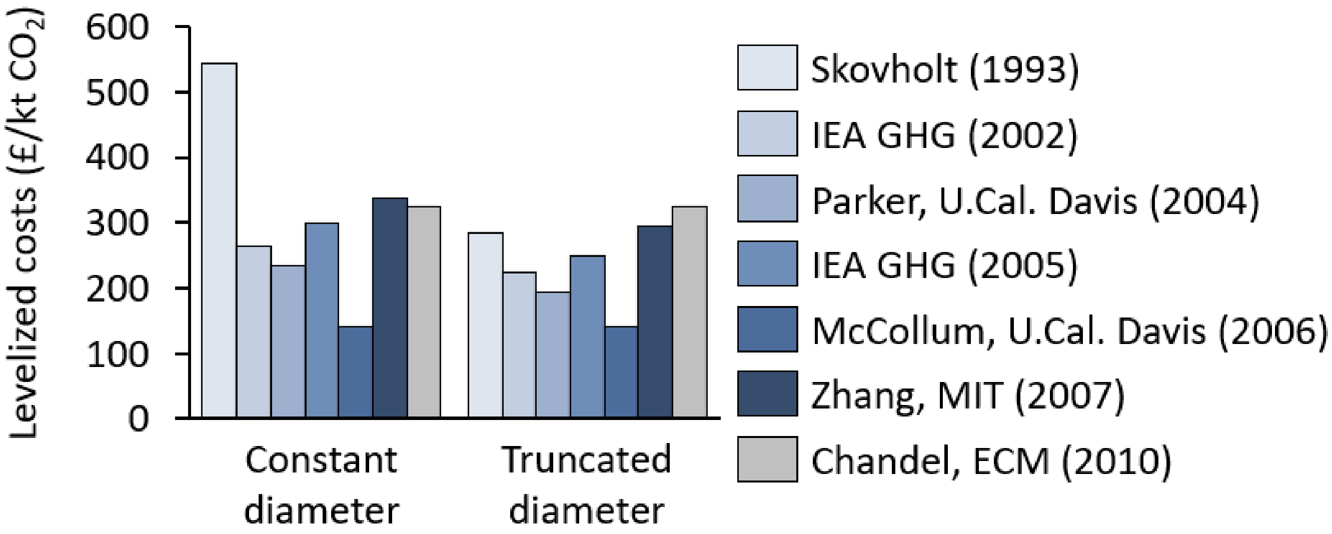
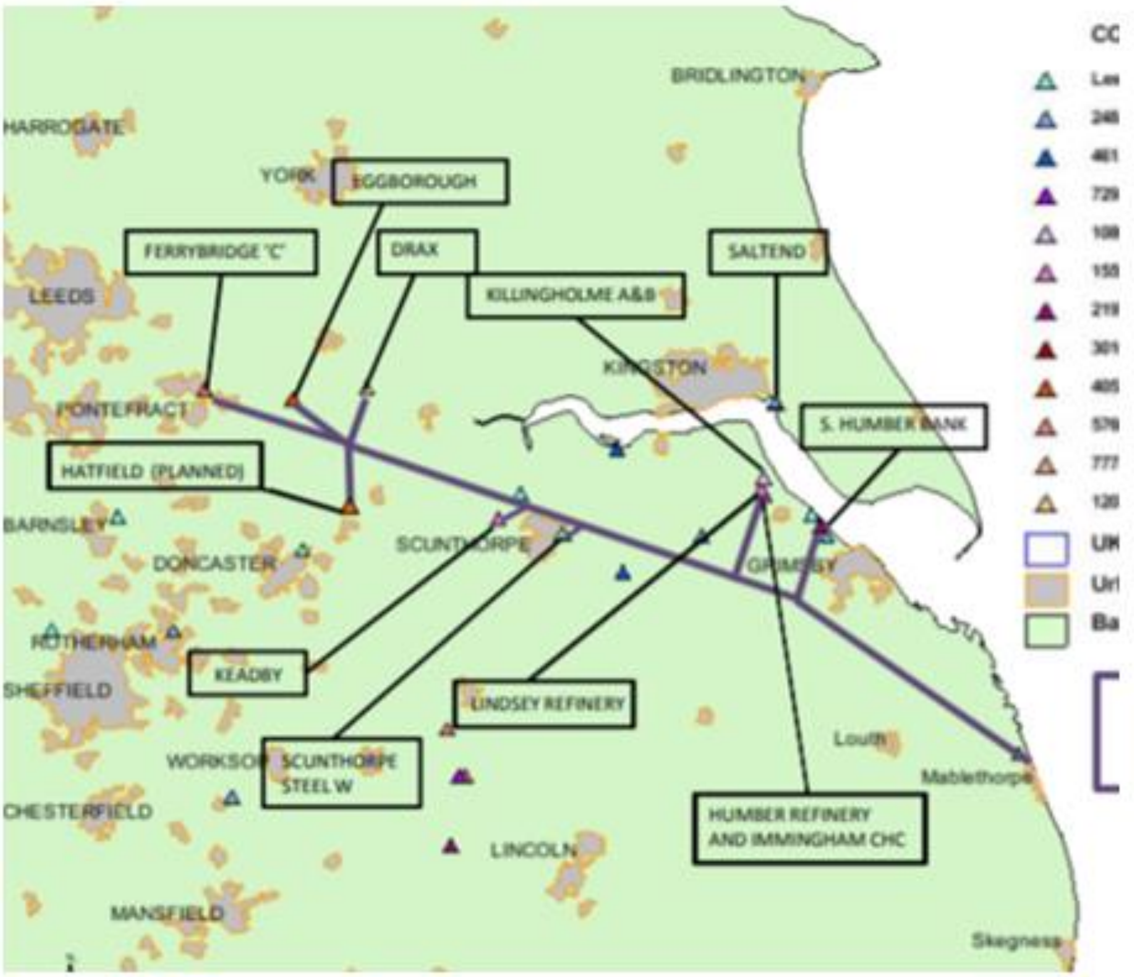


Figure 26: Humber onshore pipeline route



Case study 2: Onshore pipeline permitting in the White Rose project

In the White Rose project, National Grid adopted a precautionary approach which was to consider CO2 as if it were a dangerous fluid. This meant that additional duties were required, including:

- notification to the HSE,
- preparation of a Major Accident Prevention Document (MAPD),
- emergency procedures and arrangements,
- and provision of information to Local Authorities for inclusion in the Emergency Response Plan.

In addition, NG were required to obtain the compulsory purchase order for the land through which the pipeline would be built and the Pipeline Construction Authorisation.

National Grid applied the appropriate regulatory procedure to obtain permission to construct the pipeline, however, planning application was never granted for the construction of the pipeline. The planning application failed because there was not sufficient ‘need for the development’, i.e. the construction of the pipeline was not justified (principally because CCS cluster would never be formed without the Government funding).

Figure 27: Location of the Don Valley project (and the White Rose project) in the Yorkshire and Humber region of the UK, with the planned transportations system[15]

Although there are learnings from the White Rose project which a new CCS project could draw on, the regulatory challenges around CO2 pipeline construction still stand:

- The planning application process is non-trivial and requires a strong evidence base

[15] http://www.ccsassociation.org/index.php/download_file/view/820/469

- Still no specific legislation for CO2 transport (i.e. for a new project today, CO2 would still need to be considered as though it were a dangerous substance)
- The NG CO2 pipeline was never constructed, so there is still no precedent for a major CO2 pipeline in the UK

Onshore pipeline - Technology readiness[16]

Transportation of CO2 by onshore pipeline is already done, mostly in the USA and Canada where some 6,500 km of pipelines actively transport CO2 today in the context of EOR. However, these are located in areas of low population density. There is still a poor understanding of the safety concerns regarding pipeline transmission of CO2 in densely populated areas.

There are significant technical safety hurdles that have been identified, including:

- knowledge gaps exist with regard to failure frequency and dispersion modelling and simulation of consequences
- Release of CO2 can form a spray release with a production of a mixing of solid-liquid-gas phase. The solid phase can be considerable and can produce formation of dry ice (could cause cracks on the surface of the pipeline & toxic cloud).

As a result of these safety considerations, pipelines may be required to avoid densely populated areas, thereby increasing the length of the required pipeline and increasing its cost.

Onshore pipeline - Costs

Cost components: construction (material, equipment and installation), O&M and miscellaneous (design, project management, regulatory, insurance etc.)

Usually broken down into capital costs (pipe, compressor) and operating (compressor)

Pipeline (/unit length) capital costs generally increase linearly with diameter. They vary strongly with geography (population density, rivers, crossings, mountains etc.) and design factors (# and size of compressor stations)

[16] https://www.semanticscholar.org/paper/Risk-Assessment-of-CO-2-Pipeline-Network-for-CCS-%E2%80%93-Vianellob-Macchiettoa/c1a0f0170e1bc8c24151c473d08a56e664d50c70?p2df; http://publications.europa.eu/resource/cellar/4ab1c4e2-398e-426c-b06f-1175d3c5a403.0001.02/DOC_1

Appendix B2: Shipping[17]

Key challenges of CO2 shipping

Key barriers to CO2 shipping include regulations, port constraints and the lack of business models.

- Regulatory – Relevant regulations include the EU-Emissions Trading System Directive, the EU CCS Directive, the United Nations Convention on the Law of the Seas (UNCLOS), the International Convention for the Safety of Life at Sea (SOLAS) and the IMO International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).
- Port constraints - Early projects may be required to meet the specific constraints of existing ports (including maximum ship length, maximum ship draft, berth availability, and storage space) but dedicated infrastructure can be installed in longer-term.
- Limited experience - Currently limited experience in CO2 shipping at the scale needed, demonstration projects may be needed.
- Limited business models - Additionally, business models and incentives for CO2 shipping will be required, as existing LPG/LNG business models and contracts are not expected to be replicable for CO2 shipping.

Key challenges most relevant to dispersed industrial sites: port constraints

Port constraints is the challenge most likely to change if shipping is done from dispersed sites, compared to an existing cluster. Port parameters including ship length, ship draft, berth availability, and storage space requirements, may be too small to accommodate certain CO2 ships. This may change the business case for CO2 shipping.

Risk identified: Port of Aberdeen and Londonderry /Foyle port unable to accommodate the largest (30 kt) ships due to length and draft constraints, however, these ports would still be able to accept medium and small ships.

In addition, local electricity grid capacity may be a factor for the demands of liquefaction plants.

---

17 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

Figure 28: List of ports included from previous grouping exercise

Port	Max length	Max draft	No. of berths	Approx. tonnage (Mt/yr)	Storage open (m2)	Storage covered (m2)
Port of Southampton	Unrestricted	15m	46	34.4	630,000	66,500
Aberdeen	165m	9m	28	5	Ample	1,300
Port of Clyde / Clydeport	-	12.6m		8.9	-	-
Londonderry / Foyle port	193m	9.3m	3	-	-	-
Port of Bristol	210-300m	11-14.5m	28	10	Available	Available
Port Medway / Thamesport	350m	13m	2	4	320,000	17,500
Port Talbot	305m	16.5m	2	6.6	-	-

Technology readiness

Limited experience in large-scale CO2 shipping. Large scale CO2 shipping is considered technically feasible, but a demonstration project of substantial size may be needed to create confidence in the investment environment. Demonstration projects needed to create momentum and confidence.

Lack of viable business models. Existing LNG/LPG model may not be replicable for CO2: LNG/LPG offers value, CO2 is a waste product therefore incentive / government backing required.

Cost components

Liquefaction and ship costs including Capex, Opex and fuel, are the biggest cost components of CO2 shipping. Shipping costs are dominated by operational and fuel costs, unlike pipelines which are dominated by capex.

Port-to-port shipping is likely to be significantly cheaper than utilising a CO2 pipeline for an equivalent CO2 transport requirement – however, this is not always the case. Shipping seen as more favourable in the following circumstances: lower flow rates (<5MPtpa), shorter project durations (<20yrs), longer transport distances (>500km).

Figure 29: Cost components of CO2 shipping

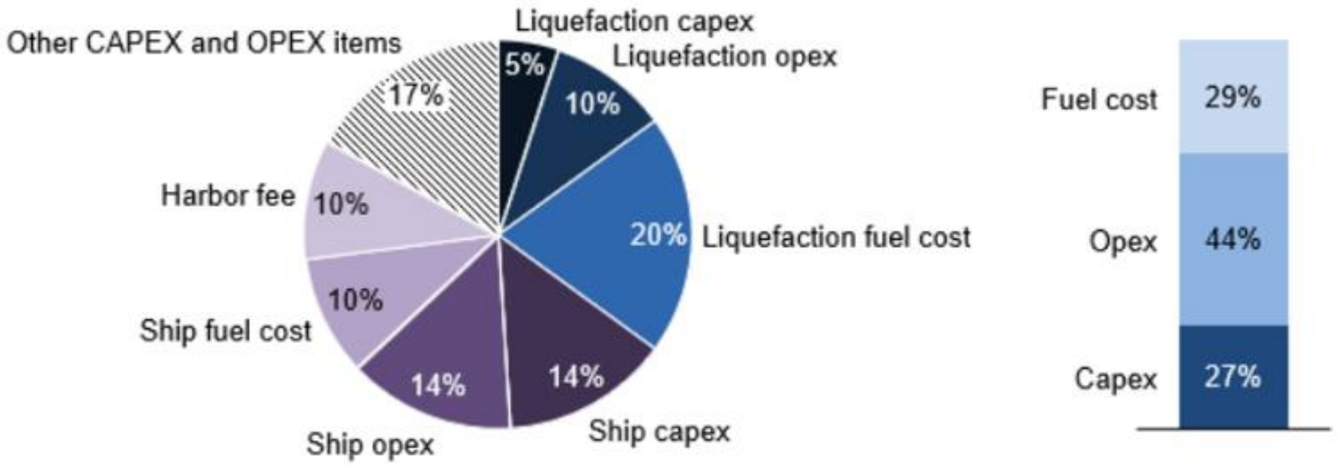
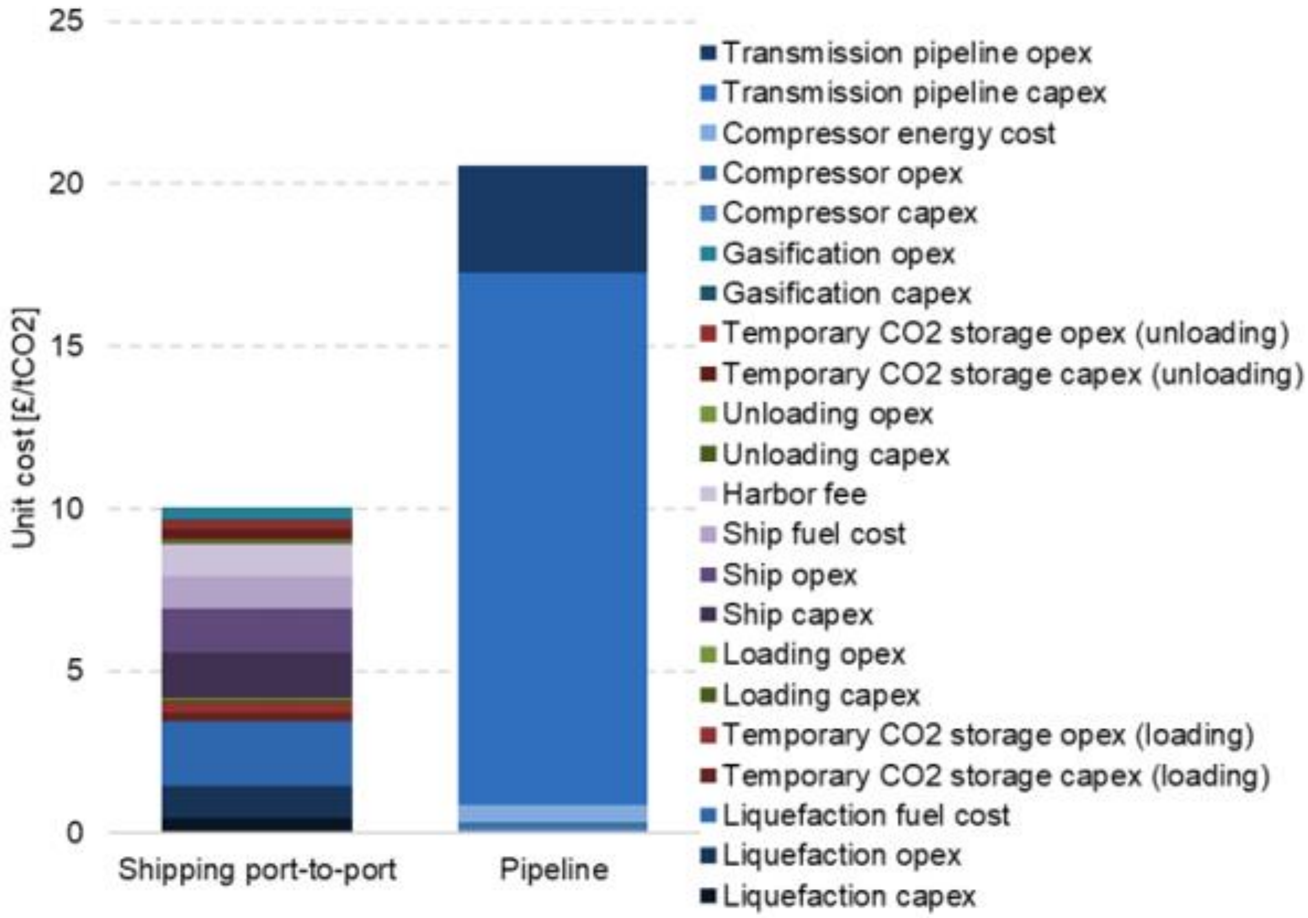


Figure 30: Unit cost of CO2 transport for transporting 1 MtCO2/year over a distance of 600 km and timeframe of 20 yr



Case study: Enabling the deployment of the South Wales CCS cluster via shipping

In 2017 the CCC identified that the CCC identified that "the lack of potential CO2 storage sites close to South Wales presents a greater challenge in deploying CCS".

Three illustrative options for South Wales including Merseyside (450km away), Humber (1,150 km away) and St Fergus (1,300 km away). The shipping costs for these three options are estimated to be between £9.5/tCO2 and £12.4/tCO2 (undiscounted unit costs). Study suggests a single ship would be sufficient to transport 1MtCO2 / annum. Required ship capacity:

- Humber and St Fergus: 20kt
- Merseyside: 8kt

Temporary storage capacity requirement increases to accommodate longer transportation duration for each trip.

Key finding: it would be feasible for South Wales to transport its CO2 to other potential CCS hubs for permanent storage

Figure 31: Options for South Wales to ship CO2 to other ports[18]

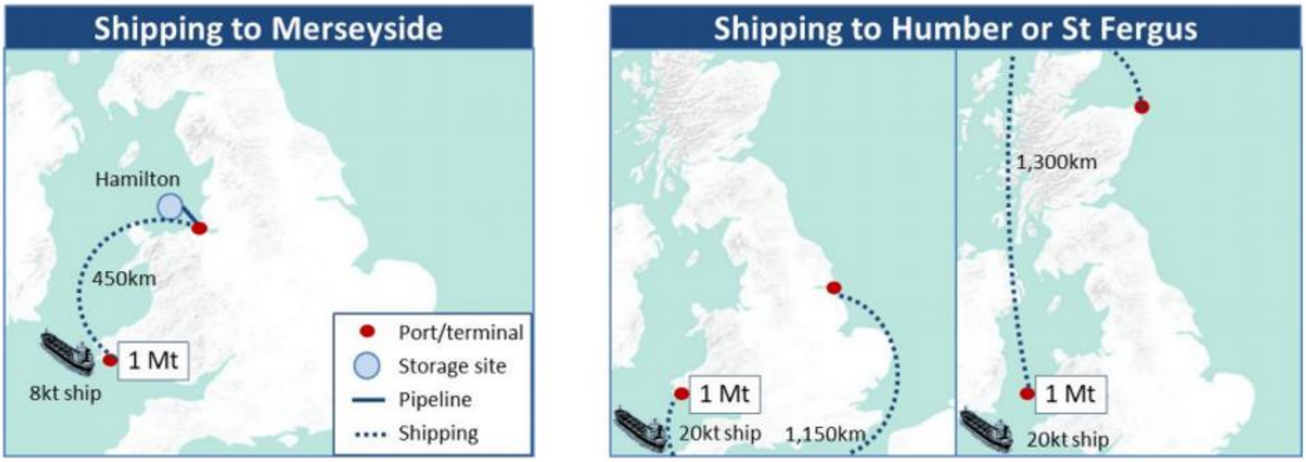


Figure 32: Unit costs of shipping CO2 from South Wales (undiscounted)

18 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf

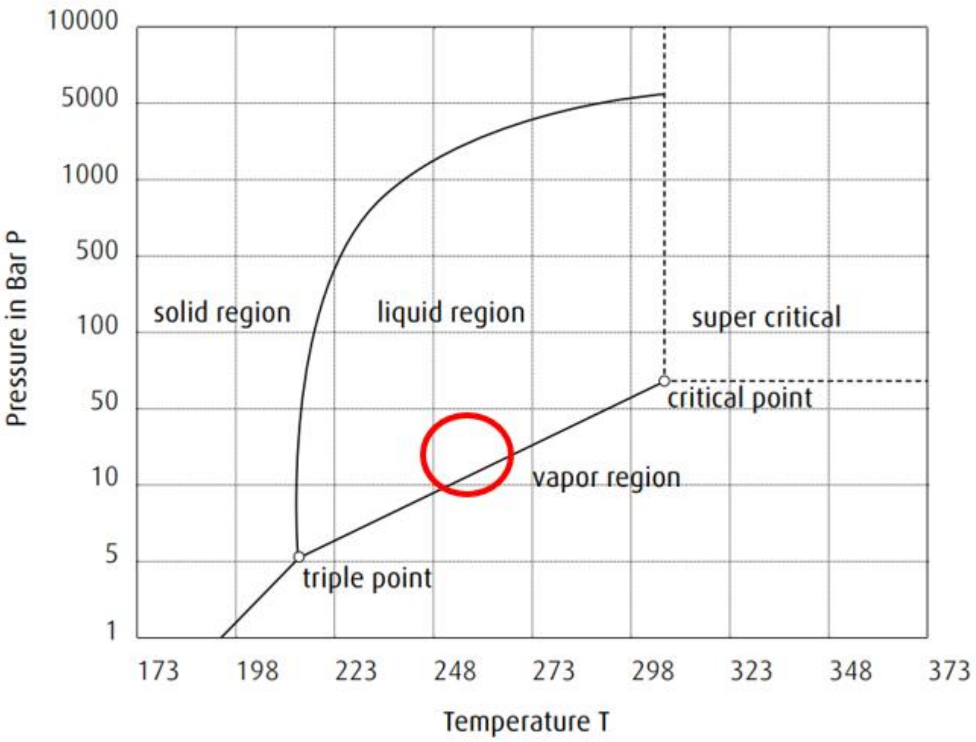
Appendix B3: Road and rail transport

Key challenges and technology readiness[19]

CO_2 land transport is mainly carried out refrigerated and in liquid form. This is done in an insulated steel tank (similarly to LNG). CO_2 trucks have a typical capacity of: 20-26 tCO_2.

	Temperature	Pressure
Insulated CO2 tanker	-35°C to -15°C	12 to 25 bar
Insulated LNG tanker	−163 °C	1-18 bar
Non-insulated CO2 tanker	ambient (up to 31 °C)	45-65 bar

Figure 33: Typical temperatures and pressures of transported CO2



The optimal land transportation method depends on the location and on the volume of CO_2 to be transported.

- **Truck**: Flexible and adaptable, but costly. Ideal for the transport of small volumes from remote locations.
- **Rail**: Requires infrastructure. Ideal for the transport of larger volumes on predetermined routes over long distances.

[19] Linde – Carbon dioxide, IEAGHG – CO2 transport, Coleman 2009 - Transport Infrastructure Rationale, Norisor 2012 - Economical and technical analysis of CO2 transport ways

The key challenges of road/rail transport include:

- Larger costs than for pipeline transport for large volumes and long-term operation.
- CO2 emissions due to boil-off
- Explosion hazard

CO2 is not considered dangerous according to the Dangerous Substances Directive (67/548/EEC), however:

- Suffocation hazard by sudden release of CO2
- Liquid CO2 can cause frostbite burns
- Container explosion may occur when heated

Case study: Transportation of CO2 from (A) the GreenGen IGCC Project in Tianjin to (B) Shengli Oilfield[20]

EU China Cooperation project (COACH): Cost comparison of CO2 transportation via pipeline, ship and railway. Levelised costs for the railway option include:

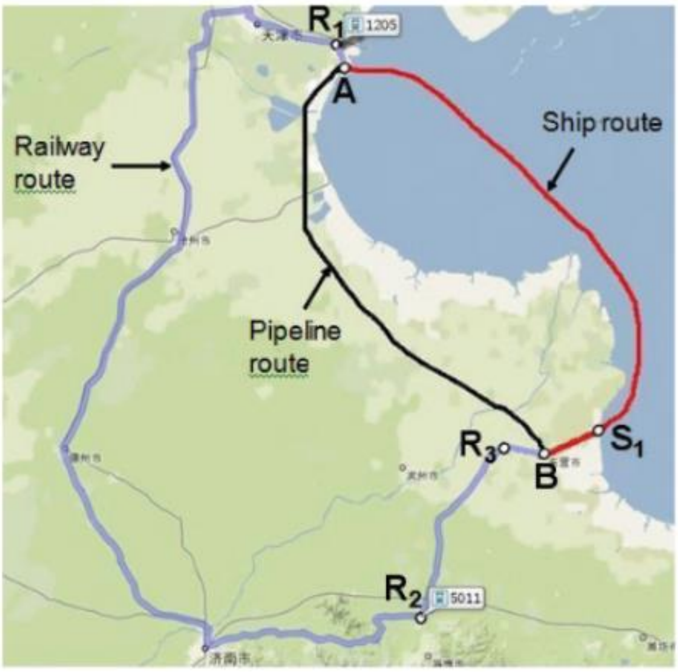
- short pipeline (~30 km)
- intermediate storage
- railway transportation (~600 km)

Table 34: Overview of costs for the three transport options

	Cost (RMB/t)	Cost (£/t)
Pipeline	**43.13**	**5.0**
Ship	**45.79**	**5.3**
Railway	**77.35**	**8.9**
• Pipeline	4.32	0.5
• Storage	5.36	0.6
• Rail	67.7	7.8

[20] Gao 2011 - Cost Analysis of CO2 Transportation: Case Study in China

Figure 34: Overview of the journey of the three transport options[21]



Transport method	Symbol	Module	Distance (km)
Pipeline	AB	Pipeline	300
Ship	A	Intermediate storage	
	AS_1	Ship	300
	S_1B	Short pipeline	25
Railway tank wagon	AR_1	Short pipeline	10
	R_1	Intermediate storage	
	R_1R_2	Railway NO.1205	598
	R_2R_3	Railway NO.5011	
	R_3B	Short pipeline	20

[21] Gao 2011 - Cost Analysis of CO2 Transportation: Case Study in China

Appendix B4: Hydrogen fuel switching

Table 35: Key challenges[22]

Sector	Processes and appliances	Key challenges
Cement	Appliances: Cement kilns High process emissions (~65%)	• Abatement potential restricted by process emissions • High flame temperature (NOx emissions) • Long lifetime of kilns (40 - 80 yr) makes for diverse technologies, making retrofit more difficult • Isolated location renders hydrogen delivery costly
Iron & steel – Blast Furnace (BF) and Basic Oxygen Furnace (BOF)	Smelting and primary steelmaking to be replaced by Hydrogen Direct Reduction of Iron (H-DR) and Electric Arc Furnace (EAF)	• Low TRL • Higher fuel costs (+50% electricity demand) • Higher price of steel (+20-30%) • Declining industry: uncertainty about the return on investment (SEI 2018 - Hydrogen Steelmaking)
Iron & steel – Secondary steelmaking and forming	Integrated steelworks: no fuel switching of MEG Secondary steelworks: natural gas, used in furnaces (metal rolling, forming, melting)	• Steel quality concerns due to hydrogen embrittlement. Additional thermal treatment to solve the issue • Different heat transfer and flue gas composition: additional costs associated to redesigning furnaces • Current equipment unlikely to be ATEX compliant (extra conversions CAPEX) • Declining industry: uncertainty about the return on investment
Refining	Appliances: steam boilers, direct fired furnaces, CHP Fuels: RFG, fuels generated onsite, natural gas	• Small amount of natural gas that can be substituted. Other fuels are produced onsite • Need for bespoke appliances.

[22] Element Energy Hy4Heat, IES 2018 – Breaking through, ETC 2018 – Mission possible

Gas terminals and compressor stations	Appliances: large compressors and boilers Fuels: natural gas	• Technical challenges in upscaling of small 100% H2 gas turbines (Fusina CHP 12 MW, Centrica Storage 26 MW) • Difficulties in use of hydrogen in gas engines • Competition with CCS, as these sites are located close to both natural gas pipelines and CO2 storage
Lime	Appliances: Lime kilns High process emissions (~65%)	• Abatement potential restricted by process emissions • Increased flue gas moisture problematic for product quality and explosion hazard • Isolated location of typical sites makes hydrogen delivery costly • Long lifetime of kilns (40 - 80 yr) makes for diverse technologies, making retrofit more difficult • Few sites connected to the >7 bar gas network • Added cost for refractory materials needed due to higher flame temperature.
Glass	Appliances: glass melting furnace Fuels: mainly natural gas, some electricity	• Competing with electricity in decarbonisation • Low flame luminosity significant barrier for heat transfer mechanism (reliant on irradiation) • Added cost for refractory materials needed due to higher flame temperature • Very infrequent shutdowns (for conversion).
Other mineral industries	Appliances: Mainly ceramic kilns and dryers (direct heat) Fuels: natural gas Dominated by natural gas in kilns	• Legacy equipment • Concerns around product quality due to different flue gas and heat transfer • Long lifetime of kilns (~40 yr) makes for diverse technologies, making retrofit more difficult • Current equipment unlikely to be ATEX compliant (extra conversion CAPEX).

Chemicals	Appliances: mainly boilers (indirect heat) and CHP gas engines or CHP gas turbines	• Small concerns around hydrogen getting trapped in the top of large boilers – smaller boilers needed • Large amount of gas engines instead of turbines in use: conversion to hydrogen problematic

Table 36: Technology readiness and costs[23]

Sector	TRL	Cost
Cement	Cement Kilns: TRL 3	-
Iron & steel – Blast Furnace (BF) and Basic Oxygen Furnace (BOF)	HYBRIT: TRL 2-4	Final cost of steel product expected to be 20-30% higher with HYBRIT
Iron & steel – Secondary steelmaking and forming	SUSTEEL: TRL 1-3	20MW furnace conversion CAPEX: £1.1M
Refining	SALCOS: TRL 1-3	Phillips 66 refinery conversion CAPEX: £10-50M
Gas terminals and compressor stations	Conventional furnace: TRL 5	25MW turbine compressor conversion CAPEX: £2M
Lime	Direct dryer: TRL 4	10 MW kiln conversion CAPEX: £0.5M
Glass	H2 boiler/indirect dryer: TRL 7	20MW furnace conversion CAPEX: £1.2M
Other mineral industries	Conventional furnace: TRL 5	5 MW kiln conversion CAPEX: £0.4M
Chemicals	Gas turbine: TRL 8	10MW boiler conversion CAPEX: £0.5M

[23] IES 2018 – Breaking through, ETC 2018 – Mission possible, Climate Exchange 2017, TKI NIEUW GAS 2018 - Hydrogen Roadmap

Table 37: Case studies[24]

Sector	Case study
Cement	Not yet implemented
Iron & steel – Blast Furnace (BF) and Basic Oxygen Furnace (BOF)	• Project: Investigation of hydrogen-based DRI • Company: ArcelorMittal • Location: Hamburg, DE • Year: announced 2019, pilot plant to be built in the coming years First industrial-scale plant implementing hydrogen based Direct Reduction of Iron. Production of 100 kt/yr steel using grey hydrogen in demonstration scale. CAPEX: ~€65 million.
Iron & steel – Secondary steelmaking and forming	Not yet implemented
Refining	• Project: Fusina 16 MW CCGT • Company: Enel • Location: Venice, IT • Year: 2009 World first 100% hydrogen-fuelled CCGT plant of industrial scale. H2 is provided from the adjacent refinery of Porto Marghera. CAPEX: ~€50 million
Gas terminals and compressor stations	Not yet implemented
Lime	Not yet implemented
Glass	• Project: Hydrogen blend in glass manufacturing • Company: Steklarna Hrastnik, Gen-I and RCeNEM • Location: Hrastnik, SL • Year: 2019

[24] ArcelorMittal 2019 - World first for steel, ENEL 2009 - First hydrogen-fuelled power now on line in Venice, Reuters 2010 – Enel to start major plant conversion to coal, FuelCellWorks 2019 - Slovenian Glass Manufacturer to Use Solar Power Plant to Create Green Hydrogen, The Sovenia Times 2019 - Steklarna Hrastnik turning greener

	Co-use of hydrogen for the smelting of glass. Hydrogen produced thorough electrolysis with electricity from onsite solar PV system (177MWh/yr). Hydrogen use in 10-15% vol blend with natural gas. CAPEX: €172,000.
Other mineral industries	Not yet implemented
Chemicals	Inovyn: H2 boiler at Runcorn site. Modified natural gas burner for up to 100% hydrogen, saturated with water.

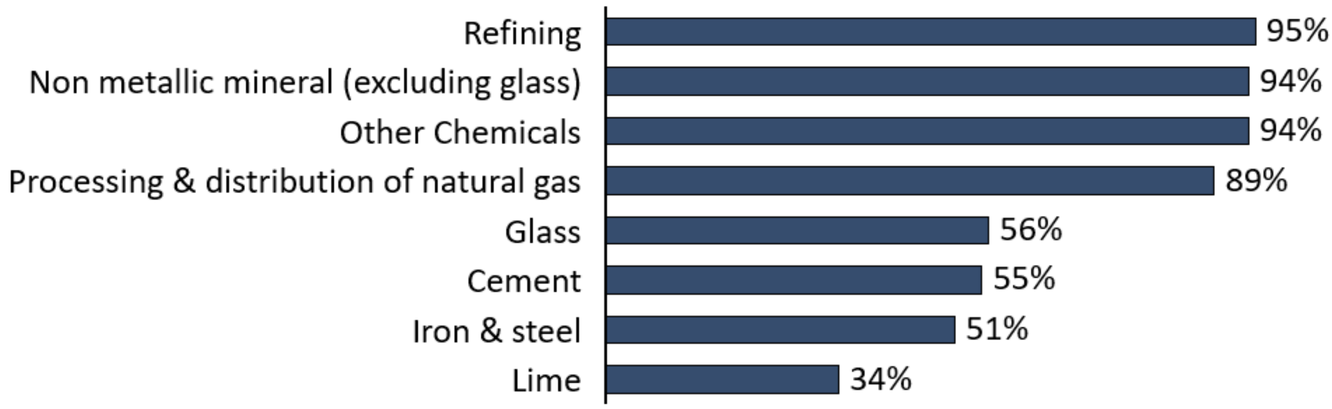
Decarbonisation potential

The abatement potential achievable through H2 fuel switching at dispersed sites is **28.9 MtCO2**. These savings are composed by 97% of **combustion** related emissions and 3% of **process** emissions from ironmaking (H2 to be utilised in direct reduction).

The range of abatement cost in £/tCO2 depends largely on the initial **fuel type**. In most cases, the minimum abatement cost corresponds to switching from e.g. fuel oil, gas oil or burning oil, whilst the maximum abatement costs usually corresponds to switching from natural gas, with switching from coal or LPG usually lying in the upper quartile of the range.

The values in this slide are based on the year 2050 because it is assumed that the H2 grid and fuel switching technologies would be fully available.

Figure 35: Decarbonisation potential from hydrogen fuel switching[25]



The technical decarbonisation potential of H2 fuel switching in the sectors considered in this analysis is a 72% reduction in emissions.

[25] Includes direct emissions abatement and indirect emissions from production of new fuel. Values in this section are based on the year 2050, assumed to be the year in which H2 grid and fuel switching technologies would be fully available.

Table 38: Hydrogen fuel switching abatement costs

Sector	Abatement cost range in 2050 (£/tCO2)[26]
Cement	£18 - £147
Lime	£18 - £147
Iron & steel	£72 - £181
Refining	£71 - £174
Non-metallic mineral (excluding glass)	£132 - £200
Glass	£146 - £172
Other Chemicals	£85 - £195

[26] All values are undiscounted. Results are based on Element Energy's Fuel Switching Options model for the CCC

Appendix B5: Carbon Capture and Utilisation (CCU)

Table 39: CCU technologies – Utilisation destination and CO2 storage potential

Technology	Utilisation	Capture and storage
Direct use in industry	• EOR • Inert atmosphere • Food and drinks	• No storage
Chemical conversion of fuels and chemical feedstocks	• Fuels • Fertilisers (urea) • Pesticides • Solvents • Polymers • Pharmaceuticals • Inorganic complexes	• Temporary / permanent storage
Carbonisation of rocks (calcium and magnesium silicates) through accelerated mineralisation	• Construction materials • Storage	• Permanent storage • Capture of CO2 possible
Biofuels and materials from **algae** in open ponds or photobioreactors	• Biooils • Chemicals • Fertilizers • Fuels	• Temporary / permanent storage • Capture of CO2

Table 40: CCU technologies – Key challenges and advantages[27]

Technology	Key challenges	Advantages
Direct use in industry	No technical challenges Short term release CO2 of into the atmosphere	Replacement of CO2 otherwise sourced from fossil fuels
Chemical conversion of fuels and chemical feedstocks	Pilot scale technologies. Further development required for commercialisation. Limited number of chemical reactions to give a limited number of products. R&D to expand potential market Urea market at saturation point Return on investment of capture technology highly variable and dependent on product demand	Added value for post-combustion CCS Increase in supply chain security and price stability, replacing imported petrochemicals → Refineries
Carbonisation of rocks (calcium and magnesium silicates) through accelerated mineralisation	Large volumes of minerals required: 1.6-3.7 tonnes rock per tonne of CO2 Typically, long distance between mine and capture/carbonation plant Technically exothermic reactions, but very low reaction rate. High amount of energy is required for mining, transport, pre-processing, grinding, heat and pressure. Overall storage efficiency <70%, current costs: €60-100/tCO2 Environmental impact of extensive mining	Permanent, leak-free storage with no need for long term monitoring Sufficient capacity to store all CO2 from fossil fuel reserves Potential for the process to also capture CO2 → Cement and lime
Biofuels and materials from **algae** in open ponds or photobioreactors	High energy requirement for continuous mixing and biomass drying Large land requirement, often unavailable near the capture/carbonation plant Not commercial yet and high costs Fuel price potential: $2.76–8.96 per GGE (1-3 times US petrol price)	High growth rate High carbon concentration: 1.8 tCO2 = 1 tonne algae Use of non-arable land

[27] Centre for Low Carbon Futures – CCU in the green economy, Universal Industrial Gases – CO2, U.S. Department of Energy – National Algal Biofuels Technology Review

Case study 1: Tata Chemicals Europe, sodium carbonate production[28]

Tata Chemicals Northwich site (Cheshire) is Britain's only manufacturer of sodium carbonate (soda ash) and sodium bicarbonate (baking soda). It is also currently the largest single-site user of liquid CO2 in Britain and is implementing **UK's first industrial-scale CCU plant**.

BEIS Carbon Capture and Utilisation Demonstration (CCUD) programme:

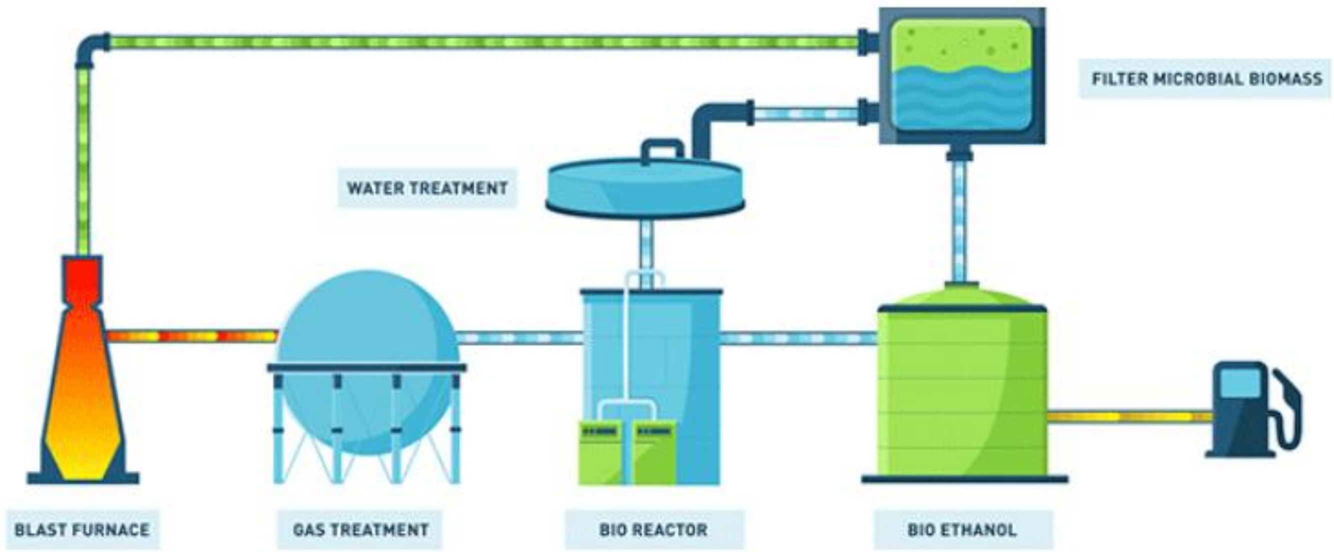
- 40 ktCO2/yr captured from its 96MW natural gas CHP plant
- CO2 purified and liquefied
- CO2 utilised in the manufacturing process of sodium carbonate
- Carbon emissions of CHP plant: -11%
- CAPEX: £16.7m (£4.2m grant)
- Operations start in 2021

Case study 2: ArcelorMittal, ethanol production from CO[29]

The ArcelorMittal Steelworks in Ghent (Belgium) are implementing a CCU solution demonstration in partnership with LanzaTech:

- Carbon monoxide (CO) from exhaust of the blast furnace used as feedstock
- High-grade ethanol produced using microbe digestion of H2 and CO mix
- Production: 63 kt/year ethanol
- Operation start in 2019

Figure 36: Ethanol production with LanzaTech technology



[28] Tata Chemicals Europe – News release, Reuters – Tata chemicals, Essential Chemical Industry – Sodium carbonate
[29] ArcelorMittal - Capturing and utilising waste carbon from steelmaking

This publication is available from: https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-deployment-at-dispersed-sites

If you need a version of this document in a more accessible format, please email enquiries@beis.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.