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Working Paper

Characterisation of Industrial Clusters in the UK and Techno-Economic Cost Assessment for CCTS Implementation.

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1. Introduction

Following the recommendations of the UK Climate Change Committee (CCC) for the 6th Carbon Budget, the UK Government has set up a new target to cut greenhouse gases emissions by 78 per cent by 2035 compared to 1990 levels (UK Government, 2021b). In addition to this, and as a part of its Covid recovery plans, the UK Government has presented a 10-point plan for a green industrial revolution, describing investments and developments across different sectors of the economy (UK Government, 2020b). One key point of this plan is a multi-million investment in carbon capture, usage and storage (CCUS), linked to the industrial decarbonisation challenge launched by the UK Government (UKRI, 2021), for the development of decarbonisation technologies such as carbon capture and storage (CCS) and hydrogen fuel switching. The technologies will be deployed at scale within the six largest industrial clusters in the UK.

All these recent policy developments suggest that there will be important efforts in the UK for the development and implementation of carbon capture, transport and storage (CCTS). Critical to this will be an understanding of the costs for the CCTS systems. However, the available literature presents a wide range of cost values and many of the studies do not tend to consider all transport and storage elements together (onshore and offshore pipeline transport networks, shipping and storage). In addition, in some cases the studies are considered to be too historical, and there are very limited number of UK specific analyses.

In this paper, we present a review and a detailed characterisation of the main UK industrial clusters. We then provide a brief review of carbon transport and storage cost models and costing information before conducting a techno-economic assessment of the potential transport and storage costs for the UK industrial clusters. To the best of our knowledge, this integrated analysis has not been conducted for the UK context, and such analysis is key for policy analysis to enable the wider economic impacts of CCUS to be characterised.

2. Literature Review

2.1 Brief description of the CCTS process

As the name suggest, the CCTS process is composed by three main parts: 1. capture of CO_2 at the emitter site, 2. transport of CO_2 via pipelines and/or shipping and 3. Storage of CO_2, as shown in the simplified diagram in **Figure 1**. The transport of CO_2 can be achieved via a network of onshore and offshore pipelines or via shipping. In the case of the UK industrial clusters, it is likely that an onshore pipeline network will connect the different industrial emitters located at the cluster, directing the CO_2 to a landfall point where an offshore pipeline will transport the CO_2 to the storage site. Alternatively, the onshore pipeline network can direct the CO_2 to a suitable port and shipping can be used to transport CO_2 to a different port where the offshore pipeline infrastructure is available or directly to the storage site.

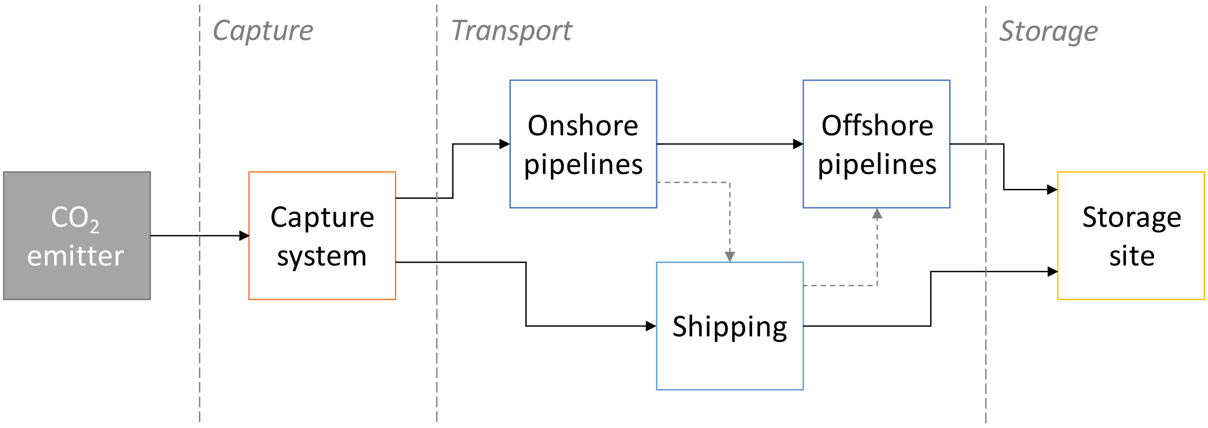

Figure 1. Carbon capture, transport, and storage (CCTS) process diagram.

2.2 UK industrial cluster definitions

There are a number of well-known industrial clusters in the UK. However, the exact definition of each cluster, especially in terms of interest and ability to implement CCS, is not clear. In other words, information on the clusters' geographical limits, industries and companies involved, available infrastructure, etc. is not readily available in the public domain. In addition to this, the list of UK industrial clusters is continuously evolving, which makes it difficult to keep track and develop further analysis.

Griffin et al. (2016, 2018) present an analysis of UK industrial clusters' energy use and carbon emissions reduction potential, also providing a map of the main industrial clusters with CCS potential, identifying five main clusters: Firth of Forth, Teesside, The Humber, Thames Estuary and Merseyside. The authors provide a comprehensive overview of the industrial CO_2 reduction potential in the UK, but they follow a sectoral approach and not a geographical one, so there is less detail on what is actually included in each cluster. Moreover, the authors do not analyse cluster specific CCS technology requirements and implementation costs.

The UK Government's Department for Business, Energy & Industrial Strategy (BEIS) commissioned an independent report (Stork & Schenkel, 2018) to assess the readiness of UK industrial clusters for the deployment of industrial CCUS to understand their potential and challenges to the deployment of industrial CCUS. The analysed clusters are Grangemouth (i.e. the Firth of Forth or Scottish Cluster), Humberside, Merseyside, Port Talbot (South Wales), Scunthorpe (part of the Humber cluster identified by Griffin et al. (2016, 2018) consisting mainly of a large Steel plant), Southampton and Teesside.

The UK Government in its industrial decarbonisation strategy policy paper (UK Government, 2021a) defines the six largest industrial clusters in the UK, based on emissions levels. These clusters are Grangemouth, Teesside, Humberside, Merseyside, South Wales and Southampton. However, the paper does not provide specific detail on the clusters' composition, in terms of the emission sites included, and their individual CCS implementation plans. In addition to this, the UK Government launched the industrial decarbonisation challenge in 2021 and it is currently funding six projects to develop individual industrial decarbonisation roadmaps for each cluster (UKRI, 2021). These projects are: Net Zero Tees Valley, Scotland's Net Zero Roadmap, Humber Industrial

Decarbonisation Roadmap, North West Hydrogen and Energy Cluster: Route to Net Zero, South Wales Industrial Cluster, and Repowering the Black Country.

We can see from these sources that certain clusters, in particular those considered to be the largest CO_2 emitters, are continuously mentioned in the UK clusters lists. However, some clusters are not always mentioned and/or are defined differently, so discrepancies exist between sources. For instance, the Thames Estuary or the Southampton clusters are only mentioned in some references. Also, the Scottish cluster is sometimes defined only as Grangemouth, or as the Firth of Forth, or in some cases the whole eastern coast of Scotland is considered (NECCUS, 2020).

These policy documents and reports focus on general sectoral overviews on potential decarbonisation. They do not necessarily analyse how each cluster is defined and the specific options for CCS implementation. Individual cluster projects (UKRI, 2021) can add detail on this, but very detailed information may not be openly available.

Taking this information into consideration, in this report seven industrial clusters have been characterised and the definitions of these clusters are discussed further in Section 3.1.

2.3 Carbon T&S cost models

In this section we will review the available literature on T&S cost models, organised in the four parts of the T&S process: onshore pipeline transport, onshore pipeline transport, shipping and storage. Please note that this is section does not intend to provide a comprehensive review, but a general overview of the main types of techno-economic cost models for T&S technologies.

The cost assessment of the T&S processes, in terms of CAPEX and OPEX, can be estimated through either a direct cost analysis approach or empirical analysis. The direct cost analysis approach involves cost determination for specific characteristics of a project, involving current prices and detailed cost estimation from each part of the process, including materials, labour, construction, equipment, etc. This is laborious and requires access to the latest prices and cost estimates from different contractors. Empirical analysis, on the other hand, involves the use of cost estimation models. It is less laborious, quicker but less accurate. These rough estimates are nevertheless useful for the feasibility and front-end engineering design (FEED) studies of the projects (Cotton et al., 2017) and can provide reasonable estimates of capital investment and operating cost of the T&S process. Owing to the lack of direct cost data, this review focuses on empirical analysis studies. However, this approach is considered to be reasonable to enable comparison between the different transport options and clusters.

2.3.1 Onshore pipeline CO_2 transport cost models

A network of pipelines is the preferred option to transport CO_2 effectively from emitters within an industrial cluster to a landfall into offshore storage. The key parameters for determining the costs are the CO_2 mass flow or pipeline diameter and the average distance between sources and sinks. There are two main types of capital cost models for pipeline transport: diameter-based models and mass flow based models.

The CO_2 pipeline transport models relating diameter to costs can also differ in type and assumptions behind the model. For instance, Element Energy (2010), Heddle et al. (2003), and van den Broek, Brederode, et al. (2010) propose linear cost models based on length of the pipeline and diameter. These models use a constant cost factor (e.g. in £/m^2) and correction factors for different terrains and/or regions. These are simple, easy to use models. However, their accuracy is highly dependent on the parameters used.

(Gao et al. (2011) and Piessens et al. (2008) use the weight of the pipeline for their cost-estimating models. These models first calculate the weight of the pipeline, based on diameter and length, then use the price of steel pipelines (e.g. in £/kg) and a constant number representing fraction of material costs in the total pipeline costs. For instance, Gao et al., 2011, consider that the fraction of material costs is between 22 and 34 per cent for the USA, and 50 per cent for China.

Ghazi & Race (2013), IEA GHG, (2002) and Parker (2004) propose quadratic equations cost models. These models derive their cost equations by fitting to the available cost data, i.e. they formulate an equation with the highest adjusted-r^2 value. The equation below is an example of one such model, taken from (Ghazi & Race, 2013).

$$CAPEX_{onshore} = FL * FT * 10^6 * [(0.057L_{onshore} + 1.8663) + (0.00129L_{onshore}) * D_o + (0.000486L_{onshore} - 0.000007) * D_o^2] \quad (1)$$

Where:

- $CAPEX_{onshore}$ is the capital expenditure (investment) for the onshore pipeline network.
- FL is the location factor
- FT is the terrain factor
- D_o is pipeline's external diameter
- $L_{onshore}$ refers to the length of the pipeline which is situated onshore

The diameter of the pipeline is calculated using equation (2).

$$D^5 = \frac{8 * f * m^2}{\pi^2 \rho * \frac{\Delta P}{L}} \quad (2)$$

Where:

- f is the Darcy friction factor.
- m is the mass flow rate (in kg/s).
- ρ is the CO_2 density.
- ΔP is the pressure difference between the inlet and outlet pressure to the pipeline (in MPa).
- L is the pipeline length (in m).

The second type of pipeline network cost models are those based on CO_2 mass flow rates. In most cases, these models are derived from diameter-based models, making assumptions on the CO_2 mass flow rate per pipeline diameter. A number of studies include examples of these models, including: Chandel et al. (2010), Dahowski et al. (2005), McCollum & Ogden (2006), Serpa et al. (2011). Equations (3 and 4) show an example of a model relating mass flow to costs, taken from McCollum & Ogden (2006).

$$C_{cap} = 9970 \times (m^{0.35}) * (L^{0.13}) \quad (3)$$

$$CAPEX_{onshore} = FL * FT * L * C_{cap} \quad (4)$$

Where:

- *Ccap* is the pipeline capital cost of unit length in \$/km.
- m is mass flow rate (kg/s).
- FL and FT are the location factor and terrain factor, respectively.
- L is the pipeline length (in km).

The operation and maintenance (O&M) cost for the pipeline transport network is commonly calculated in annual terms. These are generally expressed as a percentage of the capital costs, in the range of 1.5 to 4 per cent, or expressed as a fixed value per unit length ranging from 2.8 to 7.0 $€_{2010}$/m (Knoope et al., 2013).

In the McCollum and Ogden (2006) model, the annual O&M costs are calculated using (5) by applying an O&M factor of 2.5 per cent.

$$OPEX_{onshore} = CAPEX_{onshore} * O\&Mfactor \tag{5}$$

2.3.2 Offshore pipeline CO_2 transport cost models

Offshore pipelines are a potential solution for transportation of CO_2 from the industrial cluster onshore into the storage site offshore. There are many factors that affect the cost of offshore pipelines including the distance to storage site and the water depth. Overall, the CAPEX of offshore pipelines is larger than the equivalent onshore due to the challenges associated with the marine environment.

The offshore cost models available in the literature are similar to the onshore ones, with some difference in parameters. Some of the studies proposing onshore cost models also have offshore versions. For instance, , Element Energy (2010), Ghazi & Race (2013), Heddle et al. (2003), and van den Broek, Brederode, et al. (2010) present onshore and offshore models with different constants and terrain factors. Equation (6) show the offshore version of the cost model proposed by Ghazi & Race (2013). This equation has the same quadratic structure as (1) but with larger constants to reflect the increased cost of offshore operations.

Note that the OPEX calculation cost for the offshore pipelines, as proposed by Ghazi & Race (2013), is similar to that for onshore pipelines (see equation (5)) but with a different O&M factor.

$$\begin{aligned} CAPEX_{offshore} = FL * 10^6 * [&(0.4048L_{offshore} + 4.6946) \\ &- (0.00153L_{offshore} + 0.0113) * D_o + (0.000511L_{offshore} + 0.00024) \\ &* D_o^2] \end{aligned} \tag{6}$$

Where:

- FL is the location factor
- D_o is pipeline's external diameter
- $L_{offshore}$ refers to the length portion of the pipeline that is situated offshore.

2.3.3 CO_2 storage cost models

There are several factors that affect the overall capital cost of offshore CO_2 storage sites. Certainly, the size and length of the pipeline going into the storage site are key in determining cost, but also the presence of existing infrastructure, number of wells, the depth and type of storage site (depleted gas and oil field or saline aquifer) can affect significantly project costs.

The available literature in CO_2 storage cost models is more limited than for pipeline transport systems. Most studies present FEED analyses using linear cost models (IEA GHG, 2002, 2005; van den Broek, Ramírez, et al., 2010). Other studies present cost analyses of specific CO_2 storage projects, combining offshore pipeline transport and storage, such as Pale Blue Dot (2016), which details cost assessments for different offshore pipeline transport and storage sites in the UK. However, this report only provides the calculated CAPEX and OPEX figures for the project but does not provide detail in the cost modelling used for the analysis.

Equation (7) show the CO_2 storage linear cost model proposed by van den Broek, Ramírez, et al. (2010).

$$CAPEX_{storage} = W * (C_d * H + C_w) + C_{sf} + C_{sd} \tag{7}$$

Where:

- W= number of wells per sink;
- Cd = drilling costs (€ per meter); if old wells can be re-used, Cd = 0;
- H = the drilling distance being the depth of the reservoir starting at the bottom of the sea plus the thickness of the reservoir (in meter);
- Cw = fixed costs per well (in €).
- Csf = investment costs for the surface facilities on the injection site and investments for monitoring (e.g. purchase and emplacement of permanent monitoring equipment) (in €).
- Csd = investment costs for the site development costs. E.g. site investigation costs, costs for preparation of the drilling site and costs for environmental impact assessment study (in €).

The authors propose different constant parameter values for this formulation, depending on the location and type of site (hydrocarbon or aquifer site; onshore, near offshore or far offshore). Note that this linear equation does not explicitly consider CO_2 mass flow rate or injection pipeline diameter.

The O&M cost calculation in van den Broek, Ramírez, et al. (2010) follows the same formulation shown in (5), assuming a O&M factor of 5 per cent.

2.3.4 CO_2 shipping cost models

The shipping of CO_2 is a potential alternative to offshore pipeline networks. Shipping can be cost effective when transporting CO_2 from port to port and with larger distances between the landfall and the storage sites (Zero Emissions Platform (ZEP), 2011). Distances and the amount of CO_2 mass that needs to be transported affect the size of the ship and the crew required to operate, and thus the capital and operational cost. Also, shipped CO_2 is normally transported as a cryogenic liquid. However, pipeline transportation and injection is commonly conducted either as a gas or a dense phase liquid depending on the pressure. Therefore, port and/or platform infrastructure to condition the shipped CO_2 is also required, which must be included in the cost estimation.

The literature available on CO_2 shipping costs is limited, and the available studies do not present a detailed cost formulation but a FEED type study with approximate costs for a particular context, such as the studies presented by IEA GHG, (2020), Neele et al. (2017), and Zero Emissions Platform (ZEP) (2011).

Looking at one of these examples, Neele et al. (2017) analyse the shipping costs for a generic European CO_2 transport and storage project, considering different ship sizes, route lengths and three ship offloading options: 1) direct injection from the ship into the injection well; 2) injection takes place from an offshore platform, CO_2 conditioning on both ship and platform; 3) Fast ship offloading into temporary storage near the platform, with injection and conditioning taking place on the platform. Table 1 and Table 2 show the ship and offshore infrastructure cost used by (Neele et al., 2017).

Table 1. Example CO_2 shipping cost table, taken from (Neele et al., 2017)

Capacity	CAPEX (M€)			OPEX (M€/yr)		
	Low	High	Mid-point	Low	High	Mid-point
10 $ktCO_2$	50	60	55	0.9	1.2	1.1
20 $ktCO_2$	63	73	68	1.5	1.8	1.7
30 $ktCO_2$	75	85	80	1.9	2.2	2.0
50 $ktCO_2$	100	110	105	2.3	2.6	2.4

** Fixed OPEX is assumed to be 3 per cent of initial CAPEX. Harbour fee at 1.3 €/tCO2 is not included in fixed OPEX cost.*

Table 2. Example of offshore infrastructure cost table (in M€), taken from (Neele et al., 2017)

Category	Variant	Sub-item	Low	High	Mid-point
Mooring system/offshore connection system	Single anchor leg mooring	Option 1	16	27	20
	Tower Mooring system	Option 2	39	60	45
Offshore platform incl. storage and offshore transport	Floating storage vessel	Option 3	70	150	110

** Fixed OPEX is assumed to be 5 per cent of CAPEX.*

2.3.5 Summary of T&S cost models

For this study, we use different cost models to provide a range of potential costs. For instance, we use the McCollum & Ogden (2006) model for the onshore pipeline costs, the Ghazi & Race (2013) cost models for onshore and offshore pipelines, van den Broek, Ramírez, et al. (2010) for storage costs, offshore pipeline and storage costs are also taken from Pale Blue Dot (2016), and shipping costs are taken from Zero Emissions Platform (2011). We have selected these cost models because they are commonly used in the literature and/or they provide UK specific data. See section 3.2 for further detail on this.

Table 3 shows a summary of the reviewed costs models, organised by type T&S model employed, the monetary unit used and the geographic scope of the study. It can be seen from the table that most references focus on a particular part of the T&S process, and we are not aware of a study that presents a cost model for CO_2 pipeline transport, storage and shipping. Also, the regional scope and monetary units used can vary widely, which complicates a direct comparison between analyses.

Table 3. Summary of T&S cost models.

	T&S techno-economic cost model						
Reference	**Onshore network**	**Offshore network**	**Offshore storage**	**Shipping**	**Monetary unit**	**Notes**	**Geographic scope**
(Gao et al., 2011)	X				2010 RMB (Chinese Yuan)	Weight based model	China
(Piessens et al., 2008)	X				2008 EUR	Weight based model	Belgium
(Parker, 2004)	X				2000 USD	Quadratic equation model	US
(Chandel et al., 2010)	X				2008 USD	CO_2 mass flow rate model	US
(Serpa et al., 2011)	X				2010 EUR	CO_2 mass flow rate model	World
(Dahowski et al., 2005)	X		X		2000 USD	CO_2 mass flow rate model	US and Canada
(McCollum & Ogden, 2006)	X		X		2005 USD	CO_2 mass flow rate model	World
(Ghazi & Race, 2013)	X	X			2012 GBP	Quadratic equation model	UK
(Element Energy, 2010)	X	X			2008 USD	Linear model based on diameter	World
(Heddle et al., 2003)	X	X			2000 USD	Linear model based on diameter	US
(van den Broek, Brederode, et al., 2010)	X	X			2007 EUR	Linear model based on diameter	The Netherlands
(IEA GHG, 2002)	X	X	X		2000 USD	Quadratic equation model	World
(IEA GHG, 2005)	X	X	X		2000 EUR	Linear cost model (Storage)	Europe
(van den Broek, Ramírez, et al., 2010)			X		2007 EUR	Linear cost models	The Netherlands
(Pale Blue Dot, 2016)		X	X		2015 GBP	Cost assessment only (no model)	UK

(IEA GHG, 2020)		X	X	X	2018 EUR	Cost assessment only (no model)	Europe (North Sea)
(ZEP), 2011)		X	X	X	2009 EUR	Cost assessment only (no model)	Europe
(Neele et al., 2017)				X	2009 EUR	Cost assessment only (no model)	Europe (North Sea)

3. Methodology

3.1 Characterisation approach of UK industrial clusters

Based on the available literature on the UK industrial clusters (see section 2.2), seven main industrial clusters have been identified for this study. This selection is based in their CO_2 emissions, their identification in recent literature and potential for T&S technologies. The clusters are: Grangemouth, The Humber, Teesside, Merseyside, Thames, South Wales and Southampton. Figure 2 show the location of these clusters[1].

Figure 2. Selected UK industrial clusters

In the following subsections we provide a detailed characterisation and a cost assessment of T&S technologies for each cluster. We defined the geographical limits of each cluster and we identified the list of emitters considered in each cluster based on the available literature reviewed in section 2.2, using the UK Government's data on CO_2 emissions by local authority and region (UK Government, 2020a), and the CO_2 interactive map (NAEI, 2018). Also, whenever possible, we have consulted the cluster specific webpages to inform our assumptions, including: Teesside (Net Zero Teesside, 2020), The Humber (Zero Carbon Humber, 2021), The Scottish Cluster (NECCUS, 2020), Merseyside (Net Zero North West, 2021), and South Wales (SWIC, 2021).

3.2 Techno-economic assessment methodology of carbon T&S requirements for the UK industrial clusters

For the T&S techno economic analysis for each cluster, a number of cost models have been used with the objective to provide two cost options for the different parts of the process (see Figure 1). As noted by Knoope et al. (2013) and Neele et al. (2017), there can be great variability between different cost models and we believe it is good practice to have a

[1] Note that this and all other maps used in this study have been constructed using Google Maps (Google, 2021).

potential range of cost values. However, the focus of this study is not to provide an extensive cost range analysis, but an approximate cost range that could be used as a first step before more specific and detailed direct cost analysis for the clusters.

With the geographical/council limits of each cluster defined, we used the CO_2 emissions by local authority and region dataset (UK Government, 2020) to find the exact location (via the postcode) and mass of CO_2 per industrial emitter. Using the tool (UK Grid Reference Finder, 2014) we translate the emitters' postcodes into latitude-longitude coordinates and mapped the emitters' locations using Google Maps. This allowed us to create an onshore pipeline network for CO_2 transport from the industrial cluster to the landfall point or port, then from these points to the storage site. We used the oil and gas activity map from the (Oil and Gas Authority, 2021) to locate the landfall point and location of storage sites. Note that we are assuming a simple pipeline network design, where distances between locations have being measured following straight lines whenever possible and using the distance measuring tools available in Google maps. We believe that this is a reasonable design approach to be able to calculate approximated costs. However, a more detailed costing would include a pipeline routeing study to consider population and geographical features such as rivers.

We used the models from Ghazi & Race (2013) (see eqs. (1) and (2)) and McCollum & Ogden (2006) (eq. (3) and (4)) to calculate the onshore pipeline transport network. For the offshore pipeline transport we used the model from Ghazi & Race (2013) (see eq. (6)) and costs provided by the Pale Blue Dot (2016) report. We also used the CO_2 storage cost model from (van den Broek, Ramírez, et al. (2010) and the storage costs from Pale Blue Dot (2016). Lastly, shipping costs are computed, for the clusters for which this could be a CO_2 transportation option, by using the cost data reported in Zero Emissions Platform (ZEP) (2011) and implementing linear interpolation (Elsevier, 2021). Figure 3 show the resulting shipping cost for the analysed UK industrial clusters with shipping requirements, as a function of their CO_2 mass flow and shipping route distance. The data points from the ZEP (2011) study provide the upper and lower cost bounds for the linear interpolation.

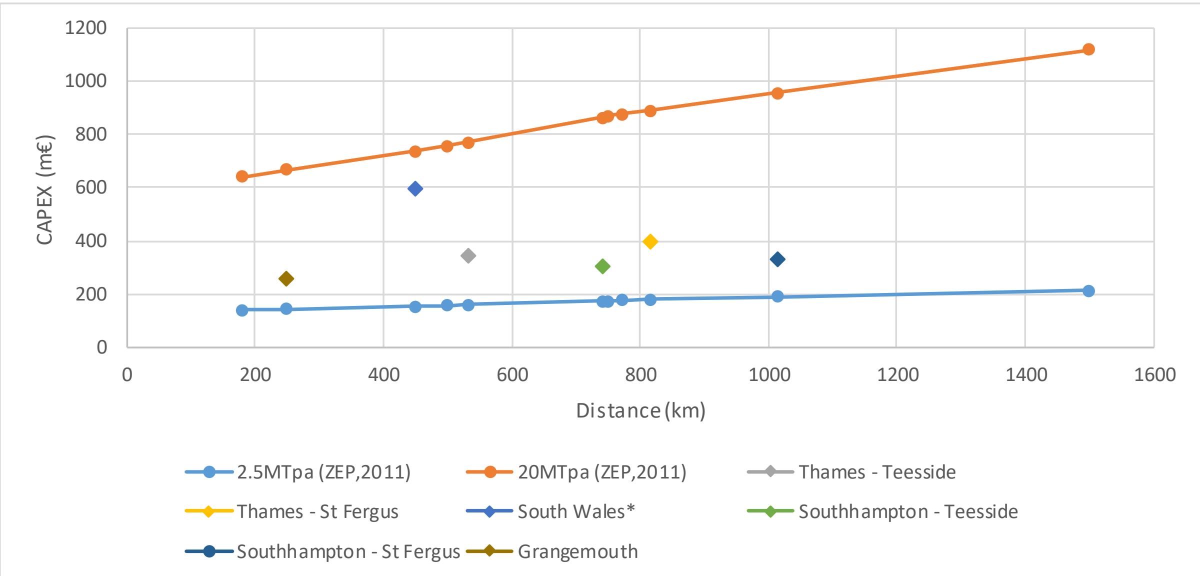

Figure 3. Shipping cost calculations for the analysed UK clusters, using linear interpolation from ZEP (2011) data.

In order to provide a range of T&S costs for each cluster, the cost models we use to assess the CAPEX and OPEX costs for the different steps of the T&S process are organised in two sets: a and b, as described in Table 4. Set ***a*** considers the McCollum & Ogden (2006) model for the onshore pipeline and the offshore pipeline and storage costs are taken from Pale

Blue Dot (2016). Set ***b*** considers the Ghazi & Race (2013) cost models for onshore and offshore pipelines and the storage cost model is taken from van den Broek, Ramírez, et al. (2010). Shipping costs are the same for both sets and are taken from Zero Emissions Platform (2011). Table 5 summarises the different parameters used for the T&S cost models described above.

Table 4.T&S cost models sets and O&M factor for OPEX calculation.

	Onshore pipeline	**Offshore pipeline**	**Storage**	**Shipping**
Cost models set a	(McCollum & Ogden, 2006)	(Pale Blue Dot, 2016)		(ZEP, 2011)
Cost models set b	(Ghazi & Race, 2013)	(Ghazi & Race, 2013)	(van den Broek, Ramírez, et al., 2010)	(ZEP, 2011)
O&M factor set a	2.5%	3 – 8%*		15 – 20%*
O&M factor set b	3%	3%	5%	15 – 20%*

** O&M factor varies depending on the cluster characteristics.*

Table 5. Parameters used for the different cost models used in this study.

Parameter	**Description**	**Value**	**Equation**	**Reference**	**Notes**
FL	location factor	1.2	(1), (4), (6)	(Ghazi & Race, 2013)	Location factor for the UK
FT	terrain factor	1.1	(1), (4)	(Ghazi & Race, 2013)	Terrain factor for the cultivated land
f	Darcy friction factor	0.0107	(2)	(Ghazi & Race, 2013)	Assumed as to match the results from reference
ρ	CO_2 density	800 kg/m3	(2)	(Ghazi & Race, 2013)	Value as of reference. The density can change depending on CO_2 temperature and pressure
Pin	CO_2 pressure entering the pipeline (after compression)	125 bar	(2)	(Ghazi & Race, 2013)	Value as of reference
Pout	CO_2 pressure out of the pipeline	100 bar	(2)	(Ghazi & Race, 2013)	Value as of reference
W	number of wells per sink	1	(7)	(van den Broek, Ramírez, et al., 2010)	Assumed 1 for easier comparison between storage sites
Cd	drilling costs	5314 €/m	(7)	(van den Broek, Ramírez, et al., 2010)	Aquifer or hydrocarbon site, near offshore

Parameter	Description	Value	Equation	Reference	Notes
H	the drilling distance (depth)	2510m (Goldeneye) 1300m (Hewett) 1100m (Endurance) 730m (Hamilton)	(7)	(Pale Blue Dot, 2016)	Values as of reference
Cw	fixed costs per well	M8.2 €	(7)	(van den Broek, Ramírez, et al., 2010)	Aquifer or hydrocarbon site, near offshore
Csf	investment costs for the surface facilities on injection site and monitoring	M61 €	(7)	(van den Broek, Ramírez, et al., 2010)	Aquifer or hydrocarbon site, near offshore
Csd	site development costs	M3.3€	(7)	(van den Broek, Ramírez, et al., 2010)	hydrocarbon site, near offshore
Pinitial	initial pressure of the CO_2 gas (before compression)	0.1MPa	(9)	(McCollum & Ogden, 2006)	Value as of reference
Pcut-off	Critical CO_2 pressure where it transitions from gas to a liquid or dense phase.	7.38 MPa	(9)	(McCollum & Ogden, 2006)	Value as of reference

Note that the cost models use different monetary units from different years. To allow for a consistent cost analysis, all costs are translated to Pounds Sterling (GBP, £) for the year 2020, using historical exchange rates from UKForex Limited (2021) and translating to the year 2020 using the annual inflation rate from the Bank of England (2021).

4. Characterisation and techno-economic assessment of carbon T&S for the UK industrial clusters

4.1 Grangemouth cluster

The core Grangemouth cluster is a highly specialised cluster with a focus on petrochemical industries. However, across the Firth of Forth, other types of industries are also present. This cluster is located in the central belt of Scotland, by the firth of Forth. In our analysis, we include in this cluster the councils of City of Edinburgh, Clackmannanshire, East Lothian, Falkirk, Fife and West Lothian. See Figure 4 for a cluster map with the emitters' locations. We have organised the emitters by amount of produced CO_2 and classified them in three groups: the largest emitters, representing 80 per cent of the total annual CO_2 emissions, are marked with the light blue tag. The next 10 per cent of emissions come from the industries marked with the orange tag and the smaller emitters, representing the last 10 per cent, are marked with a purple tag. Note that the two small emitters located in the city of Edinburgh are assumed not to partake in the CO_2 transport network, due to potential planning constraints within the city of Edinburgh.

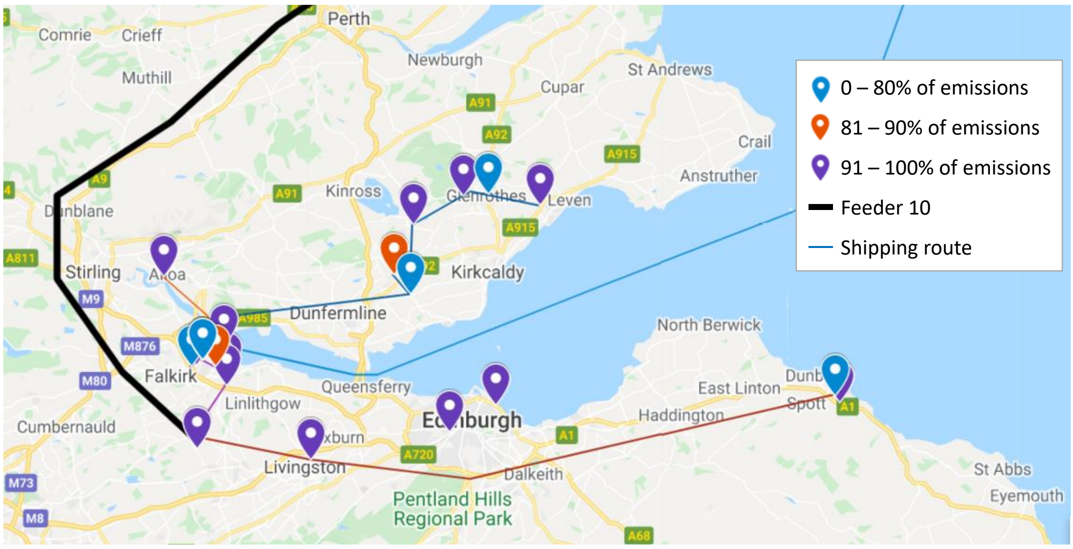

Figure 4. Industrial emitters at the Grangemouth cluster.

Figure 5 shows the approximate location of 'Goldeneye', the CO_2 storage site for Grangemouth, with a yellow flag (NECCUS, 2020; Pale Blue Dot, 2016). In the figure, it can be seen that the storage site is at a considerable distance from the cluster so the CO_2 needs to be transported to the landfall point in St. Fergus. From this point, an offshore pipeline will transport the CO_2 to the storage site. There are two options to reach St. Fergus from the Grangemouth cluster. The first and more commonly discussed option is to reuse the existing infrastructure of the natural gas pipeline 'Feeder 10' (NECCUS, 2020). The second option is to use shipping. Both options are costed in this study.

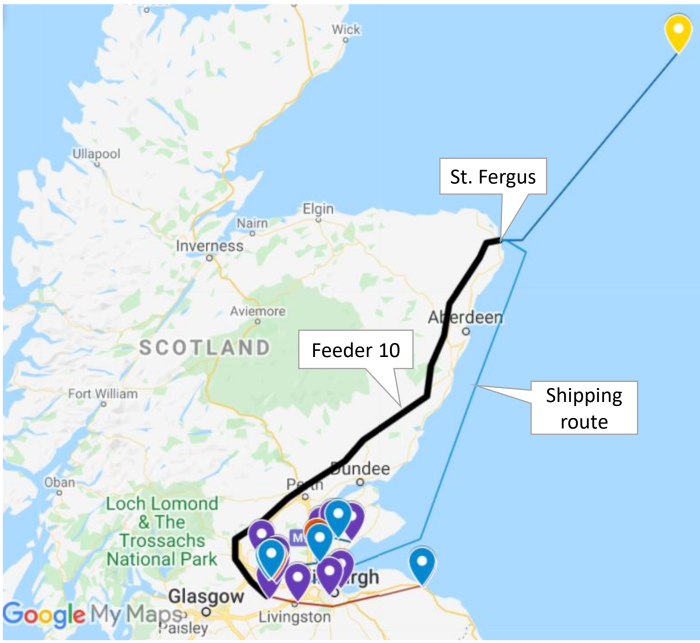

Figure 5. CO_2 transport options and storage site for the Grangemouth cluster.

The calculated CO_2 emissions produced in this cluster is 6,305.88 (CO_2kt per annum), which is the average of the last two recorded years (2017 and 2018) in the UK Government (2020a) data base. The calculated distances for the onshore pipeline network is 163.79 km, and for the offshore pipeline is 129km (from St. Fergus to Goldeneye). The shipping route distance is calculated as 249km. In the case of reusing existing infrastructure instead of using shipping, there is no need to replace the long distance pipeline of Feeder 10, however, a cost for replacing the compression stations to be able to adequately transport CO_2 has been considered, using the cost model proposed by McCollum & Ogden (2006) in equations (8) and (9). Note that the costs from this formulation are in 2005 USD. Moreover, OPEX costs are calculated following the same form as in equation (5) with an O&M factor of 4 per cent (McCollum & Ogden, 2006).

$$m_{train} = (1000 * m)/(24 * 3600 * N_{train}) \tag{8}$$

$$Cost_{compressor} = m_{train} * N_{train} * \left[(0.13 * 10^6) * (m_{train})^{-0.71} + (1.40 * 10^6) * (m_{train})^{-0.60} * \ln\left(\frac{P_{cut-off}}{P_{initial}}\right)\right] \tag{9}$$

Where:

- m is the annual CO_2 mass flow (in kt)
- mtrain is the CO_2 mass flow rate per compressor train (in kg/s)
- Ntrain is the number of compressor train. According to (McCollum & Ogden, 2006) two compressor trains are required for this mass flow.
- Pinitial is the initial pressure of the CO_2 gas.
- Pcut-off is the critical pressure of CO_2 where it transitions from gas to a liquid or dense phase. At which point a pump is required rather than a compressor.

Table 6 and Table 7 show the CAPEX and OPEX, respectively, of the T&S technologies for the Grangemouth cluster. Two transportation options from Grangemouth to St. Fergus (see Figure 5) are costed. Option 1 consists of using existing infrastructure (Feeder 10) considering the new compression costs for repurposing the pipeline for CO_2, whereas option 2 is using shipping from Grangemouth to St. Fergus, instead of feeder 10. Both options consider the offshore pipeline transport to the storage site. Moreover, we use the two sets of cost models (set ***a*** and set ***b***) as described in section 3.2 above and in Table 4.

From the cost tables, we see that the shipping costs are larger than the cost of reusing infrastructure. Also, it is evident that the set of cost models ***a*** is generally larger than the set ***b***, showing once again the potential variability of results from costing methodologies.

Table 6. Capital costs (CAPEX) for the Grangemouth industrial cluster (in 2020 M£).

<table>
<tr><th></th><th>Onshore pipeline</th><th>Offshore pipeline</th><th>Storage</th><th>Shipping/ Feeder 10</th><th>Total</th></tr>
<tr><td>Option 1.a</td><td>115.61</td><td colspan="2">314.12</td><td>64.70</td><td>494.43</td></tr>
<tr><td>Option 1.b</td><td>84.29</td><td>112.05</td><td>83.39</td><td>64.70</td><td>344.43</td></tr>
<tr><td>Option 2.a</td><td>115.61</td><td colspan="2">314.12</td><td>313.36</td><td>743.09</td></tr>
<tr><td>Option 2.b</td><td>84.29</td><td>112.05</td><td>83.39</td><td>313.36</td><td>593.09</td></tr>
</table>

Table 7. O&M cost (OPEX) for the Grangemouth industrial cluster (in 2020 M£/annum).

<table>
<tr><th></th><th>Onshore pipeline</th><th>Offshore pipeline</th><th>Storage</th><th>Shipping/ Feeder 10</th><th>Total</th></tr>
<tr><td>Option 1.a</td><td>2.89</td><td colspan="2">12.47</td><td>2.59</td><td>17.95</td></tr>
<tr><td>Option 1.b</td><td>2.53</td><td>3.36</td><td>4.17</td><td>2.59</td><td>12.65</td></tr>
<tr><td>Option 2.a</td><td>2.89</td><td colspan="2">12.47</td><td>53.55</td><td>68.91</td></tr>
<tr><td>Option 2.b</td><td>2.53</td><td>3.36</td><td>4.17</td><td>53.55</td><td>63.61</td></tr>
</table>

4.2 The Humber cluster

The Humber cluster is the largest UK cluster in terms of CO_2 emissions. The cluster includes a varied set of industries, including power generation, steel and manufacturing, and oil refining, among others. It is located in the northeast of England, to the south of the Teesside cluster, and in our analysis we include in this cluster the industrial emitters from the councils of: Bradford, Doncaster, East Lindsey, East Riding of Yorkshire, City of Kingston upon Hull, Leeds, North East Lincolnshire, North Lincolnshire, Selby, and Wakefield. Figure 6 show the cluster map with the emitters' locations, classified into three groups as in previous clusters. The location of the storage site 'Endurance' is also indicated with a yellow flag.

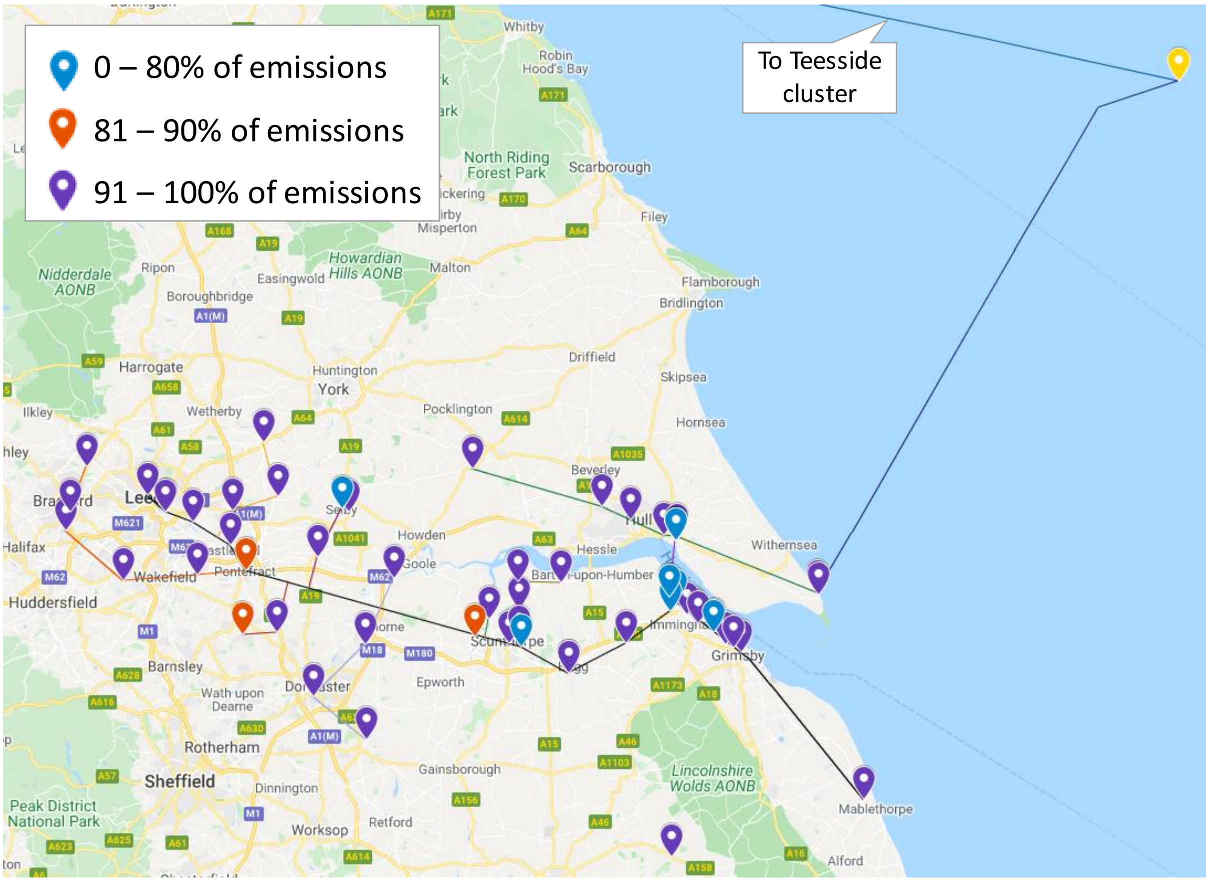

Figure 6. Industrial emitters and storage site for the Humber cluster.

Figure 7 show the approximate location of ‘Endurance’ the CO_2 storage site for Teesside and the Humber clusters (Net Zero Teesside, 2020; Zero Carbon Humber, 2021). These clusters are part of Northern Endurance partnership (Equinor, 2020) with the objective to use the ‘Endurance’ storage site jointly. However, each cluster will have its own offshore pipeline to the storage site (Equinor, 2020). Note that considering the proximity of the storage site, these clusters do not consider a shipping option.

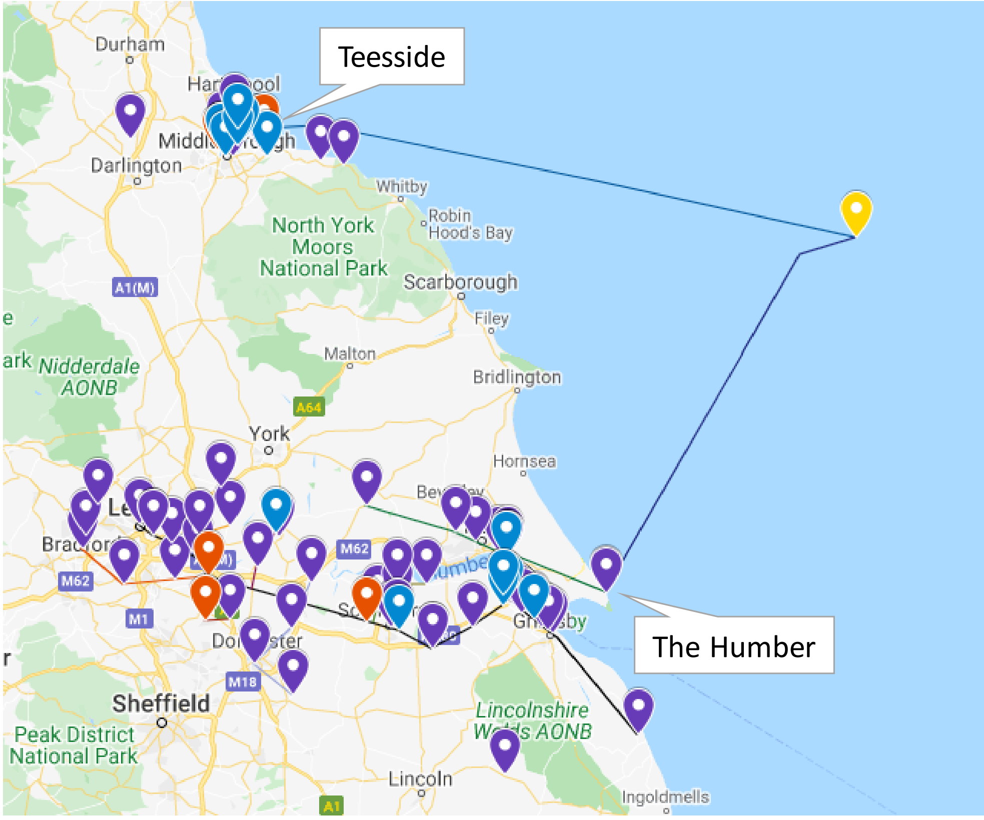

Figure 7. CO_2 offshore transport network and storage site for the Teesside and Humber clusters.

The CO_2 emissions produced at the Humber cluster are 39,997.57 (CO_2kt per annum), which is considerably larger than in any other UK cluster. The calculated distances for the onshore pipeline is 364.5 km, and the network design roughly follows the one proposed by (Zero Carbon Humber, 2021). The distance of the offshore pipeline to Endurance is 85 km.

Table 8 shows the T&S infrastructure CAPEX and OPEX costs for the Humber cluster. This cluster does not have the shipping option, only the offshore pipeline option. However, we use the same two sets of cost models as described in section 3.2 and in Table 4.

Table 8. Capital (CAPEX) and O&M (OPEX) costs for the Humber industrial cluster (in 2020 M£).

	Onshore pipeline	**Offshore pipeline**	**Storage***	**Shipping**	**Total**
CAPEX 1.a	437.22	881.12		-	1318.34
CAPEX 1.b	783.19	200.15	76.11	-	1059.45
OPEX 1.a	13.63	30.76		-	44.39
OPEX 1.b	23.49	6.01	3.81	-	33.31

4.3 Teesside Cluster

The Teesside cluster is a relatively small cluster with a varied set of industries, including chemicals, manufacturing and steel. It is located in the northeast of England and in our analysis we include in this cluster the industrial emitters from the councils of Darlington, Hartlepool, Middlesbrough, Redcar and Cleveland, and Stockton-on-Tees. Figure 8 show the cluster map with the emitters' locations. Similar to previous clusters, we have organised the emitters by the amount of produced CO_2 and classified them in three groups. Note that both the Humber and Teesside cluster are part of the Northern Endurance partnership (Equinor, 2020) and they both use the Endurance storage site (see Figure 7).

Figure 8. Industrial emitters at the Teesside cluster.

The CO_2 emissions produced in the Teesside cluster are 4,804.72 (CO_2kt per annum), calculated as the average of the last two recorded years in the CO_2 data base (UK Government, 2020a). The calculated distance for the onshore pipeline network is 72.9 km, and for offshore pipeline is 145km (from Redcar to Endurance).

Table 9 shows the CAPEX and OPEX costs for the T&S infrastructure in the Teesside cluster. Similar to The Humber cluster, this cluster does not have a shipping option, only the offshore pipeline option. However, we use the same two sets of cost models as described for previous clusters (see Table 4). Note that the storage costs for this cluster are already considered in the Humber cluster (see Table 8).

Table 9. Capital (CAPEX) and O&M (OPEX) costs for the Teesside industrial cluster (in 2020 M£).

	Onshore pipeline	**Offshore pipeline**	**Storage***	**Shipping**	**Total**
CAPEX 1.a	42.11	111.33**	-	-	153.44
CAPEX 1.b	30.61	111.33	-	-	141.94
OPEX 1.a	1.05	3.34**	-	-	4.39
OPEX 1.b	0.92	3.34	-	-	4.26

** Storage cost considered in the Humber cluster (see Table 8).*

*** Offshore pipeline costs (opt. 1.a) for this cluster are not explicitly included in the Pale Blue Dot* (2016) *report. Therefore, we assumed the offshore pipeline cost as calculated for opt. 1.b.*

4.4 Merseyside cluster

Merseyside is a medium sized cluster, in terms of CO_2 emissions, with a varied set of industries including electricity generation, oil refining, cement and manufacturing. The cluster is located in the northwest of England and we include in this cluster the industrial emitters from the councils of Cheshire West and Chester, Flintshire, Halton, Knowsley, Liverpool, Sefton, St. Helens, Warrington, and Wirral. Figure 9 show the cluster map with the emitters' locations and the ‘Hamilton’ storage site. The Hamilton site is considerably closer to the landfall point than other clusters, so an offshore pipeline is the best option to transport CO_2 to storage.

Figure 9. Industrial emitters and storage site for the Merseyside cluster.

The industrial CO_2 emissions in the Merseyside cluster are 9,489.46 (CO_2kt per annum). The calculated distances for the onshore pipeline network is 182.5 km. The design of the onshore network roughly follows the design proposed in (IEA GHG, 2007). The distance measured of the offshore pipeline is 26.5 km (from Talacre to Hamilton).

Table 10 shows the CAPEX and OPEX costs for the Merseyside cluster T&S infrastructure. Similar to Teesside, this cluster does not have a shipping option, only offshore pipeline. However, we use the same two sets of cost models as previously described.

Table 10. Capital (CAPEX) and O&M (OPEX) costs for the Merseyside industrial cluster (in 2020 M£).

	Onshore pipeline	**Offshore pipeline**	**Storage**	**Shipping**	**Total**
CAPEX 1.a	150.78	291.44		-	442.22
CAPEX 1.b	109.01	29.48	74.20	-	212.69
OPEX 1.a	3.77	22.53		-	26.30
OPEX 1.b	3.27	0.88	3.71	-	7.32

4.5 South Wales cluster

As the name suggests, the South Wales cluster is located in the southern part of Wales. It is a relatively large cluster with a varied set of industries, including steel, electricity generation, electronics manufacturing, etc. We include in this cluster the industrial emitters from the councils of Bridgend, Caerphilly, Cardiff, Carmarthenshire, Monmouthshire, Neath Port Talbot, Newport, Pembrokeshire, Rhondda Cynon Taf, Swansea, Torfaen, Vale of Glamorgan. Figure 10 shows the cluster map with the emitters’ locations. Unlike other clusters, South Wales emitters are located in two main areas. Also, since there is no storage site nearby, the cluster relies on shipping to connect between the two areas, using the docks located in Port Talbot and Pembroke Dock. The storage site identified is the Hamilton storage site, located at the Merseyside cluster (see Figure 11).

Figure 10. Industrial emitters and shipping docks at the South Wales cluster.

Figure 11. CO_2 shipping transport options and storage site for the South Wales cluster.

The industrial CO_2 emissions in the South Wales cluster is 15,783.87 (CO_2kt per annum). The calculated distances for the onshore pipeline network is 157.9 km. The distance for the shipping route is 450 km, which includes both sections of the route: from Port Talbot to Pembroke, and from Pembroke to Talacre (Merseyside).

Table 11 shows the T&S technologies CAPEX and OPEX costs for the South Wales cluster. Unlike previous clusters, South Wales does not have a direct offshore pipeline option as it lacks an adequate storage site nearby and it needs to rely on other clusters (in this case Merseyside), so shipping is the best solution to transport CO_2 out of the cluster. Therefore, we calculate the cost of shipping, as option 1, and we use the same two sets of cost models as in previously clusters.

Table 11. Capital (CAPEX) and O&M (OPEX) costs for the South Wales industrial cluster (in 2020 M£).

	Onshore pipeline	Offshore pipeline*	Storage*	Shipping	Total
CAPEX 1.a	152.93	-		729.57	882.50
CAPEX 1.b	120.62	-	-	729.57	850.19
OPEX 1.a	3.82	-		142.72	146.54
OPEX 1.b	3.62	-	-	142.72	146.34

** Offshore pipeline and storage cost considered in the Merseyside cluster (see Table 10).*

4.6 Southampton cluster

The Southampton cluster is a relatively small cluster with a strong focus on petroleum extraction industries. This cluster is located in the south of England, and in our analysis, we consider as part of this cluster the councils of Bournemouth, Christchurch and Poole, Dorset, Eastleigh, Havant, Isle of Wight, New Forest, Portsmouth, Southampton, Test Valley, Wiltshire, and Winchester.

Figure 12 show the cluster map with the emitters' locations. Similar to previous clusters, we have organised the emitters by amount of produced CO_2 and in three groups: the largest emitters with the light blue tag, the medium to small emitters with the orange tag, and the very small emitters marked with a purple tag. Note that a number of very small emitters are not considered for the CO_2 transport network, as connecting those to the west of Southampton would involve routing the pipeline through national parks and or designed areas of outstanding natural beauty (AONB). There is also an emitter near Chippenham (northwest of the map) which has not been connected to the network due to the large distance and the low level of emissions involved.

Figure 13 show the considered shipping options for the Southampton cluster. Similar to the South Wales cluster, Southampton does not have available storage sites nearby so it needs to use the storage capabilities of other clusters. For this cluster, shipping is the most cost effective transport option and in this study, we consider two potential shipping routes: to Redcar (Teesside cluster) or to St. Fergus (Grangemouth cluster).

Figure 12. Industrial emitters and shipping dock (Portsmouth) for the Southampton cluster.

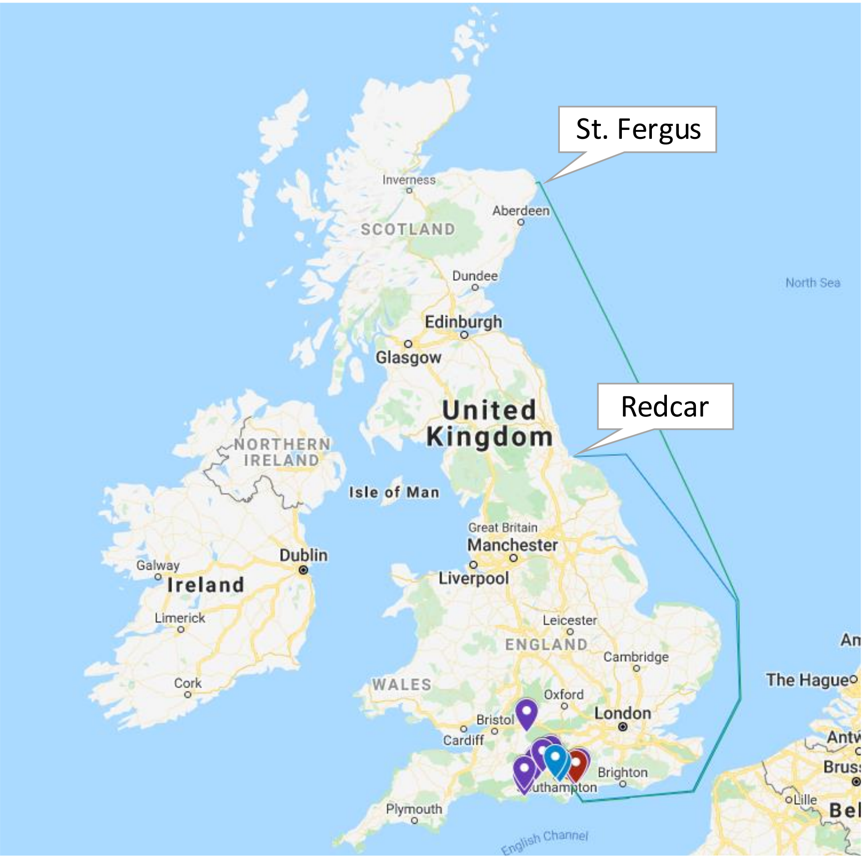

Figure 13. CO_2 shipping transport options for the Southampton cluster.

The CO_2 emissions produced at the Southampton cluster are 5,636.45 (CO_2kt per annum). The calculated distances for the onshore pipeline network is 69.34 km. The shipping distance for the route to Redcar is 740 km and for the route to St. Fergus is 1014 km.

Table 12 and Table 13 show the CAPEX and OPEX, respectively, of the Southampton cluster T&S infrastructure. Two shipping transportation options (see Figure 5) are costed. Option 1 is the shipping route from Southampton to Redcar (Teesside cluster), whereas option 2 is the shipping route to St. Fergus (Grangemouth cluster). We also use the same two sets of cost models (***a*** and ***b***) as in previously clusters.

Table 12. Capital costs (CAPEX) for the Southampton industrial cluster (in 2020 M£).

	Onshore pipeline	Offshore pipeline*	Storage*	Shipping	Total
Option 1.a	42.45	-		370.18	412.63
Option 1.b	23.89	-	-	370.18	394.07
Option 2.a	42.45	-		405.93	448.38
Option 2.b	23.89	-	-	405.93	429.82

** Offshore pipeline and storage cost considered in the Teesside (opt. 1) and Grangemouth (opt. 2) clusters (see Table 6 and Table 9).*

Table 13. O&M cost (OPEX) for the Southampton industrial cluster (in 2020 M£/annum).

	Onshore pipeline	Offshore pipeline*	Storage*	Shipping	Total
Option 1.a	1.06	-		56.59	57.65
Option 1.b	0.72	-	-	56.59	57.31
Option 2.a	1.06	-		62.13	63.19
Option 2.b	0.72	-	-	62.13	62.85

** Offshore pipeline and storage cost considered in the Teesside (opt. 1) and Grangemouth (opt. 2) clusters (see Table 7 and Table 9).*

4.7 Thames Cluster

The Thames cluster is located in the southeast of England. It is a relatively small cluster with a varied set of industries including power generation, waste treatment and disposal, and food and drinks. In this study, we include in this cluster the industrial emitters from the councils of Barking and Dagenham, Basildon, Bexley, Canterbury, Dartford, Gravesham, Greenwich, Havering, Medway, Newham, Swale, Thurrock, and Tonbridge and Malling. Figure 14 show the cluster map with the emitters' locations. Similar to previous clusters, we have organised the emitters by amount of produced CO_2 and classified them in three groups.

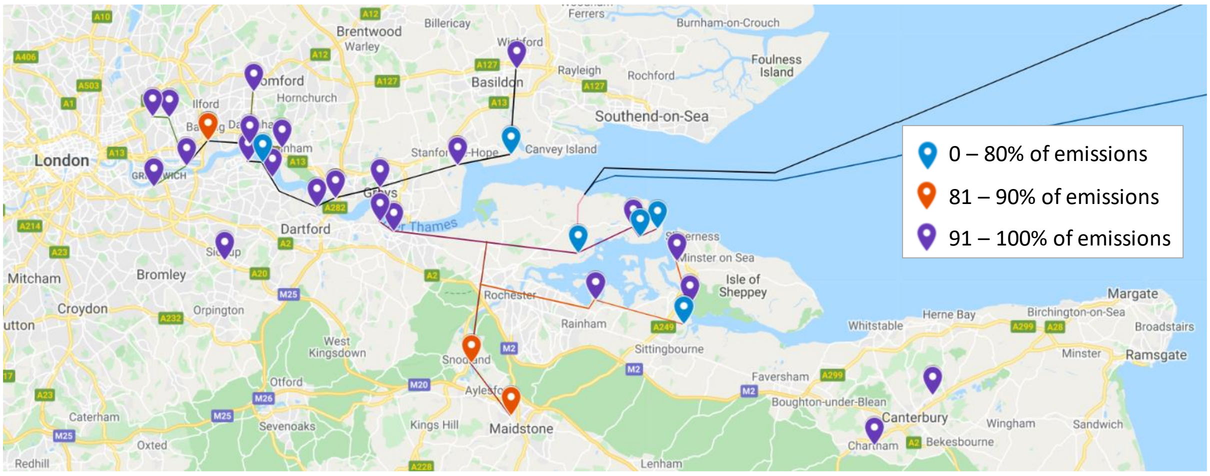

Figure 14. Industrial emitters at the Thames cluster.

Figure 15 show the considered offshore transport options for the Thames cluster. This cluster has an available storage site ‘Hewett’ by the east coast of England (marked with the yellow flag in Figure 15), so an offshore pipeline transport option it’s feasible and it has been explored in the literature (E.ON UK, 2010; Pale Blue Dot, 2016). However, such an offshore pipeline would have a length over 250 km and would involve significant costs, so a shipping option to a different storage site could be a cost effective option. For instance, in the figure we show a potential shipping route from the Thames cluster to Redcar (Teesside).

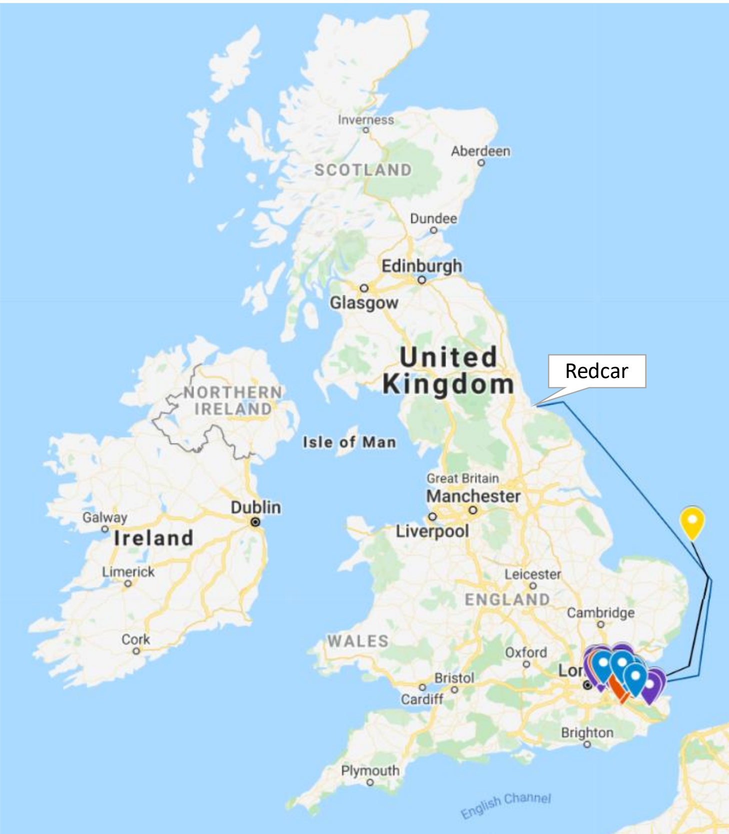

Figure 15. CO_2 transport options and storage site for the Thames cluster.

The CO_2 emissions produced at the Thames cluster are 7,847.22 (CO_2kt per annum). The calculated distances for the onshore pipeline network is 148.81 km. the length of the offshore pipeline to the Hewett storage site (option 1) is 262 km, and the shipping distance for the route to Redcar (option 2) is 531 km.

Table 14 and Table 15 show the CAPEX and OPEX, respectively, of the Thames cluster T&S infrastructure. As described previously, two shipping transportation options are costed (see Figure 15), also using the same two cost modelling sets (***a*** and ***b***) as in previous clusters.

Table 14. Capital costs (CAPEX) for the Thames industrial cluster (in 2020 M£).

	Onshore pipeline	Offshore pipeline*	Storage*	Shipping	Total
Option 1.a	111.99	706.48		-	818.47
Option 1.b	97.38	241.35	77.14	-	415.87
Option 2.a	111.99	-		422.31	534.3
Option 2.b	97.38	-	-	422.31	519.69

** In opt. 2, offshore pipeline and storage cost is considered in the Teesside cluster (see Table 9).*

Table 15. O&M cost (OPEX) for the Thames industrial cluster (in 2020 M£/annum).

	Onshore pipeline	Offshore pipeline*	Storage*	Shipping	Total
Option 1.a	2.80	28.01		-	30.81
Option 1.b	2.92	7.24	3.86	-	14.02
Option 2.a	2.80	-		70.45	73.25
Option 2.b	2.92	-	-	70.45	73.37

** In opt. 2, offshore pipeline and storage cost is considered in the Teesside cluster (see Table 9).*

4.8 Alternative cluster arrangements: Teesside + North Humber, and South Humber

In addition to the clusters presented in this section, there are potential alternative clustering options, that could appear depending on economic and policy drivers. One such option is the division of the Humber cluster into two separate areas: North Humber and South Humber. It is assumed that the North Humber cluster will continue to be part of the North Endurance Partnership (see Figure 16), whereas the South Humber cluster will stay independent and will use the Hewett storage site, via the use of an offshore pipeline (see Figure 17). Note that there is no shipping option for these clusters.

The River Humber provides the notional divide between the North Humber and South Humber areas. The North Humber includes the councils of East Riding of Yorkshire, City of Kingston upon Hull, and Selby; Whereas South Humber comprises Bradford, Doncaster, East Lindsey, Leeds, North East Lincolnshire, North Lincolnshire, and Wakefield.

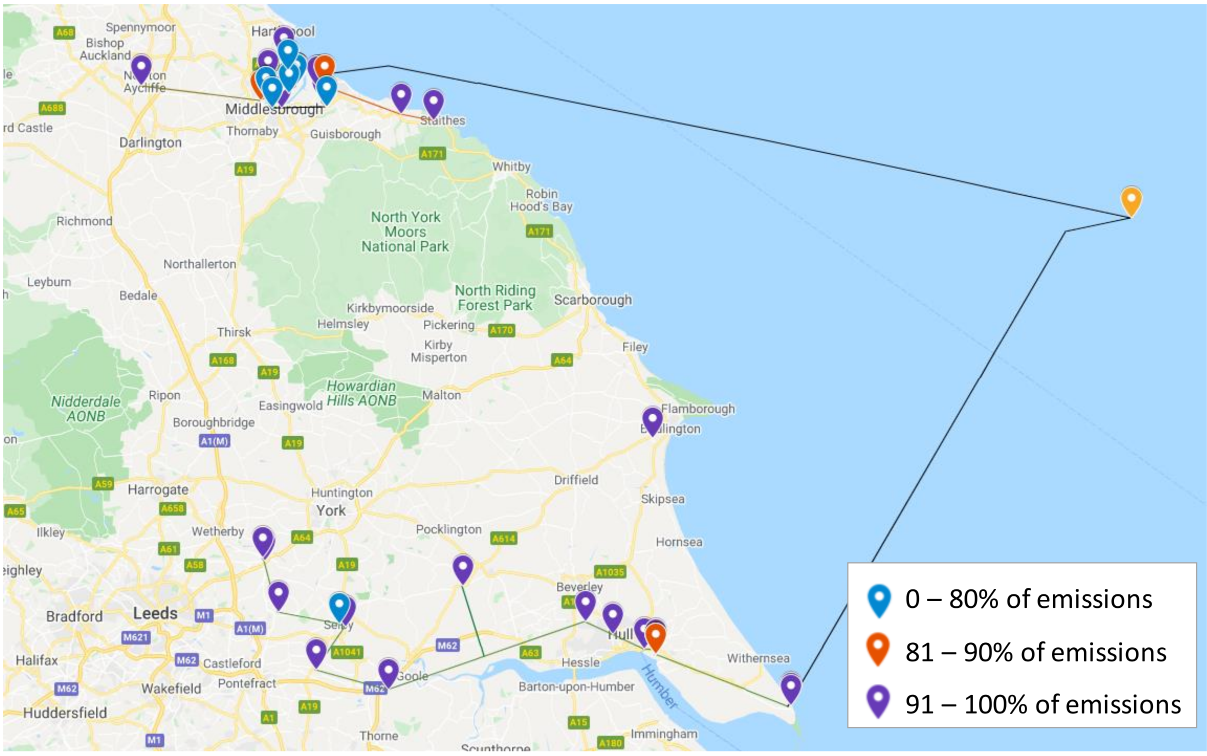

Figure 16. Alternative cluster arrangement: Teesside + North Humber.

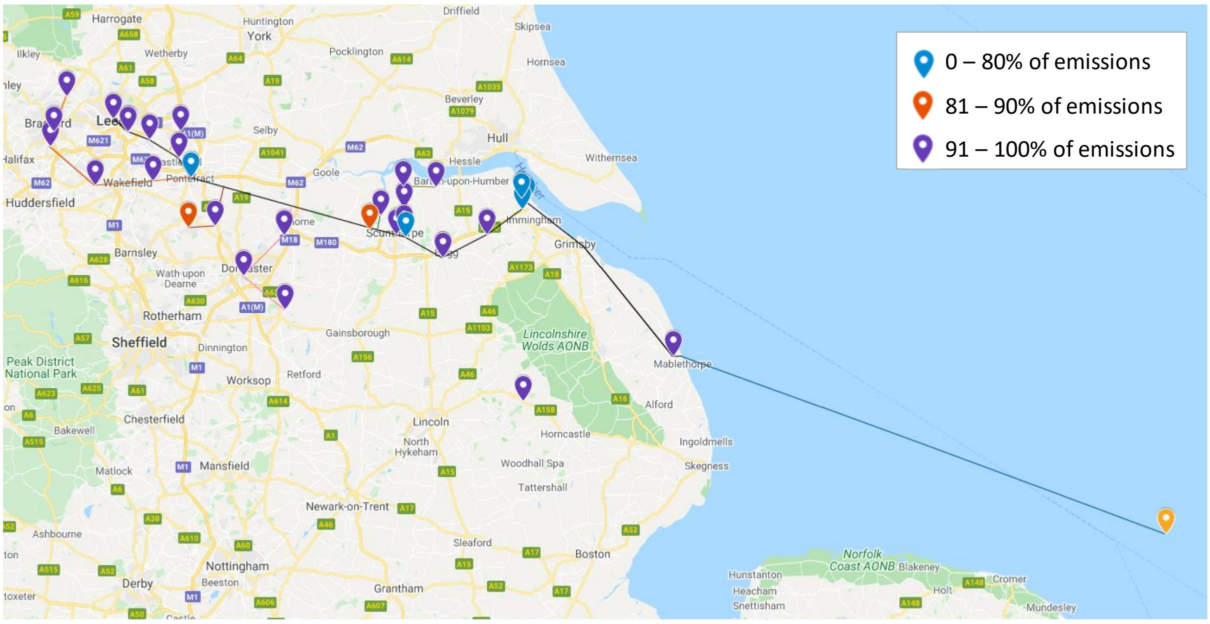

Figure 17. Alternative cluster arrangement: South Humber.

The CO_2 emissions produced in North Humber sub-cluster are 21,805.68 (CO_2kt per annum), and the calculated distance for the onshore pipeline network is 130.8 km. the distance of the Teesside cluster pipeline network and for offshore pipeline to Endurance is the same as described in sections 4.2 and 4.3. For the case of the South Humber sub-cluster, the calculated emissions are 16,448.66 (CO_2kt per annum). The onshore pipeline length is 260.71 km and the offshore pipeline, from Mablethorpe to Hewett, is 109 km.

Table 16 and Table 17 shows the CAPEX and OPEX costs for the T&S infrastructure in the Teesside + North Humber cluster and the South Humber cluster, respectively. Both these clusters do not have shipping options. Also, we use the same two sets of cost models as in previous clusters (see Table 4).

Table 16. Capital (CAPEX) and O&M (OPEX) costs for the Teesside + North Humber industrial cluster (in 2020 M£).

	Onshore pipeline	Offshore pipeline	Storage	Shipping	Total
CAPEX 1.a	180.53	992.45*		-	1172.98
CAPEX 1.b	170.05	227.66	76.11	-	473.82
OPEX 1.a	4.51	34.10*		-	38.61
OPEX 1.b	5.10	6.83	3.81	-	15.74

** calculated as the Humber offshore and storage costs (Table 8) + Teesside offshore pipeline costs (Table 9).*

Table 17. Capital (CAPEX) and O&M (OPEX) costs for the South Humber industrial cluster (in 2020 M£).

	Onshore pipeline	Offshore pipeline	Storage	Shipping	Total
CAPEX 1.a	273.43	706.48**		-	979.91
CAPEX 1.b	272.90	146.63	77.14	-	496.67
OPEX 1.a	6.84	28.01**		-	34.85
OPEX 1.b	8.19	4.40	3.86	-	16.45

*** Offshore pipeline and storage costs for this cluster are not included in the Pale Blue Dot* (2016) *report. However, we assumed the same reported costs as for the Thames cluster which also uses the Hewett storage site (see Table 14 and Table 15, opt. 1.a). Although it is recognised that the offshore distance for the Thames cluster is considerable longer, the mass flow rate in The South Humber cluster is considerably greater than in Thames, so we believe that this is a reasonable cost assumption for this cluster in the absence of other sources of data.*

5. Conclusions

The current UK policy landscape shows important efforts on carbon capture and storage implementation and on industrial decarbonisation more widely. This is to maintain international competitiveness and to keep high quality jobs within the UK, as part of achieving a just transition to net zero. Also, this has been identified as a key area for the UK to lead in the development of skills and expertise of carbon T&S technologies, with the potential of creating new industries and international competitive advantage.

This study presents a review and characterisation of UK industrial clusters and a techno-economic analysis of the potential carbon T&S implementation to decarbonise those industries. These cost are of key importance to develop further analysis in policy relevant areas such as wider economic impacts of these investments, the effect on jobs and competitiveness, and the impact on the wider society, based on the way on how, and in which time frames, those investments are paid for.

As part of our future work, we intend to expand this characterisation and techno-economic analysis to also include the capture element of CCTS. Also, to continue to use our outputs to inform wider economy analysis, producing relevant and timely policy insight.

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