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Characterisation of UK Industrial Clusters and Techno-Economic Cost Assessment for Carbon Dioxide Transport and Storage Implementation

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ABSTRACT

The UK Government and British industries are making important efforts for the development and implementation of carbon capture, transport and storage (CCTS). Critical to this will be an understanding of the composition and characteristics of the industrial clusters and 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 of the carbon transport and storage elements together. Moreover, there are a very limited number of UK specific analyses and in some cases the studies are considered to be too historical.

In this paper, we present a review and characterisation of the main UK industrial clusters, in terms of geographical limits, available infrastructure, industries present and level of emissions. We then provide a brief review of carbon transport and storage (T&S) cost models and costing information before conducting a techno-economic assessment of the potential T&S system costs for the UK industrial clusters. To the best of our knowledge, this integrated analysis has not been conducted for the UK context, and this is key for policy development and to assess the wider economic impacts of CCTS.

From our cluster characterisation and techno-economic analysis, we found that there is important potential for CCTS for industrial decarbonisation in the UK. Also, the creation of a CO_2 shipping industry will allow for industrial clusters that do not have an adequate storage sites nearby to use the CCTS infrastructure in other sites. The development of a CO_2 shipping infrastructure also enables carbon management and storage services to be exported to polluters overseas, potentially creating and maintaining jobs and economic growth.

We believe that the cluster characterisation and cost estimates produced here provide valuable insight to inform policy and can be used as a first step for to develop further analysis in policy relevant areas such as an analysis of the wider economic impacts of these investments, the effect on jobs and competitiveness and the impact on the wider society.

1. Introduction

Following the recommendations of the UK Climate Change Committee (CCC) for the 6th Carbon Budget, the UK Government has set a new target to cut greenhouse gases emissions by 78% from 1990 levels by 2035 (UK Government, 2021b). In countries like the UK, industrial emissions make a significant contribution to the total emissions. Also, unlike the power sector, industrial clusters are well placed for decarbonisation as point-sources are located close together, which enables sharing of CO_2 transport and storage infrastructure. In addition to this, industrial decarbonisation could have positive economic impacts by creating new supply chains and avoiding the offshoring of production and jobs (Turner et al., 2021). For these reasons, other industrialised countries are also exploring ways to decarbonise their industries (Friedmann et al., 2021; Schneider et al., 2020; Sun et al., 2021)

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 the investment in carbon capture, usage and storage (CCUS), including the £1 billion CCUS Infrastructure Fund and revenue support mechanisms (UK Government, 2021c).

The UK is currently exploring the development CCUS as a solution to

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help transition to a decarbonised industry, in particular for emissions intensive industries. In addition, the UK has the potential to repurpose existing skills and infrastructure from the oil and gas industries to develop CO_2 transport systems to offshore geological storage sites.

All of these recent policy developments suggest that there is ambition in the UK to develop and implement carbon capture, transport and storage (CCTS) at scale. To realise this ambition, the UK Government has launched the Industrial Decarbonisation Challenge (UKRI, 2021), for the development of decarbonisation technologies, such as CCUS and hydrogen fuel switching, to be deployed at scale within the six largest industrial clusters in the UK, located across England, Scotland and Wales.

The delivery of at least four low carbon clusters by 2030 and one net zero cluster by 2040 is considered necessary to be consistent with the UK's 'net zero' emissions commitments (UK Government, 2021a). CCTS will play a key role in this and it is envisaged that the initial implemented capacity and activity will set the foundations for future expansion to the UK carbon sector. This will enable for example: capture at industry clusters not involved in the initial sequencing; the production and transportation of green and blue hydrogen; and the utilisation of storage capacity in different ways, including exporting carbon management skills and services to other nations.

The UK Government is currently consulting on the role of a CO_2 transport and storage company, defining responsibilities, business models and ownership of assets (UK Government, 2020c). With the development of a new CO_2 transport and storage sector, a number of key research questions emerge concerning the economic and social trade-offs involved and the role of new industrial players. In addition to how different investments and changes in industrial activity will translate on regional and national impacts in terms of economic and well-being indicators such as employment, competitiveness and economic growth. To address these questions detailed economy wide analysis would be required (Turner et al., 2021), and critical to this will be an understanding of the costs for the carbon transport and storage (T&S) systems (Oxburgh et al., 2016).

To be able to estimate the investment and operational costs of the T&S systems for industrial decarbonisation in the UK requires adequate costs models and detailed information on the level of emissions and geographical characteristics of the clusters and storage sites. The latter is necessary to adequately design the pipeline networks (routing and sizing) for CO_2 transport and storage sites. With this information, it is then possible to use cost models to estimate the capital and operation and maintenance (O&M) costs.

The UK has a number of medium to large size industrial clusters across its regions. However, the exact definition of each cluster, in terms of geographical limits, available infrastructure, industries and companies involved, is constantly evolving. On the other hand, the available literature on cost models for carbon management technologies tends to focus more on capture systems, and thus, the number of studies focusing T&S is more limited. Moreover, the T&S 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 CCTS to be characterised. Note that, even though the focus of the paper falls within the UK industrial clusters, we believe that the approach presented here could be of interest and effectively used in other international contexts by adjusting the input parameters to the cost models, namely the transportation options and distances, and emissions levels, also by converting our monetary units into the relevant currency for those potential studies.

2. Literature Review

2.1. Brief description of the CCTS process

As the name suggests, the carbon capture, transport and storage (CCTS) process is composed of three main parts: 1. capture of CO_2 at the emitter site, 2. transport of CO_2 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 transport the CO_2 to a suitable port and shipping can be used to transport CO_2 either to a different port, where the offshore pipeline infrastructure is available, or directly to the storage site.

2.2. UK industrial cluster classifications

There are a number of industrial clusters that have been identified 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.

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 the emitters that are 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 carbon capture, usage, and storage (CCUS). The report analysed seven UK industrial clusters to understand their potential and challenges to the deployment of industrial CCUS. The analysed clusters were 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 is currently funding six projects to develop individual industrial decarbonisation roadmaps for each cluster under the Industrial Decarbonisation Challenge (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

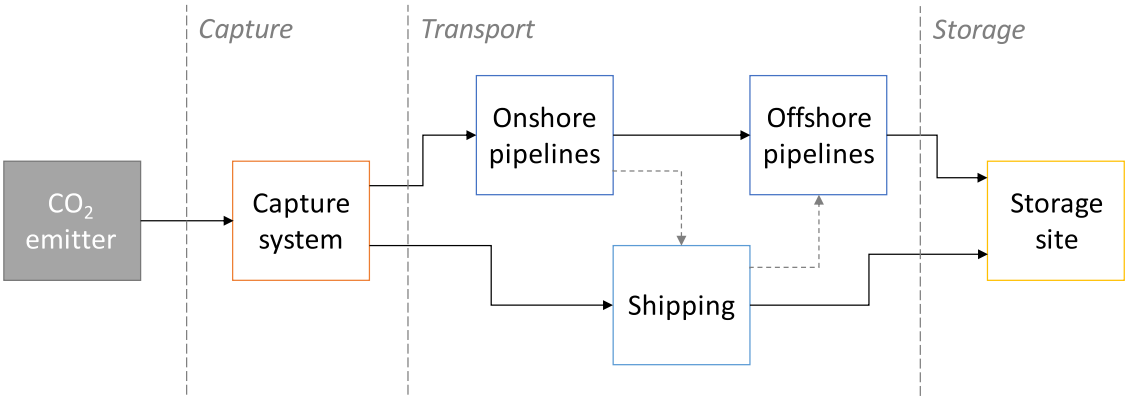

Fig. 1. Carbon capture, transport, and storage (CCTS) process diagram.

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 and 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 to the analysis, but very detailed information may not be openly available.

Taking this information into consideration, in this paper 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 into the four components of the T&S process: onshore pipeline transport, offshore pipeline transport, shipping and storage. Please note that this section is intended to provide a general overview of the main types of techno-economic cost models for T&S technologies, and the reader is directed to the original papers for more detailed explanations of the background theory.

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 by empirical analysis. The direct cost analysis approach involves cost determination for specific characteristics of a project, involving current prices and detailed cost estimation for each part of the process, e.g. materials, labour, construction, equipment, etc. This requires access to key information and specifics about the project, and the latest prices and cost estimates from different contractors. Empirical analysis, on the other hand, involves the use of cost estimation models. It is 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 for the onshore transport of CO_2 within an industrial cluster to a landfall into offshore storage. The key parameters for determining the costs of the pipeline network are either the CO_2 mass flow rate or the 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 factors and 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 the fraction of the 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% for the USA, and 50% for China.

Ghazi & Race (2013), IEA GHG, (2002), Parker (2004) and Mechleri et al. (2017) 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).

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

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).

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

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

Where:

- C_{cap} 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%, 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%.

$$OPEX_{onshore} = CAPEX_{onshore} * O\&Mfactor \quad (5)$$

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 to the storage site offshore. There are many factors that affect the cost of offshore pipelines including the distance to the storage site and the water depth. Overall, the CAPEX of offshore pipelines is larger than the equivalent onshore CAPEX 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), Mechleri et al. (2017), 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.

$$CAPEX_{offshore} = FL * 10^6 * \left[\left(0.4048L_{offshore} + 4.6946\right) - \left(0.00153L_{offshore} + 0.0113\right) * D_o + \left(0.000511L_{offshore} + 0.00024\right) * D_o^2\right] \quad (6)$$

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, the number of wells, the depth and the type of storage site (depleted gas and oil field or saline aquifer) can all significantly affect project costs.

The available literature on 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 details of 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).

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

Where:

- W is the number of wells per sink;
- C_d are the drilling costs (€ per meter); if old wells can be re-used, Cd = 0;
- H is 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 are the fixed costs per well (in €).
- Csf are the 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 is 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 an O&M factor of 5%.

2.3.4. CO2 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, the crew required to operate and thus the capital and operational cost. It is important to note that 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 from an offshore platform with CO_2 conditioning on both the ship and the 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).

2.3.5. Summary of T&S cost models

Table 3 shows a summary of the reviewed costs models, organised by the type of 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.

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 3.3 for further detail on this.

Table 1
Example CO2 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

*ixed OPEX is assumed to be 3% 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% of CAPEX.

3. Methodology

3.1. 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 of providing two cost options for the different parts of the process (see Fig. 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 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 conducting 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, 2020a) to find the exact location (via the postcode) and mass of CO_2 per industrial emitter. We calculated the CO_2 emissions produced on each cluster as the average of the last two recorded years (2017 and 2018) in the UK Government (2020a) database.

In addition, we use the tool UK Grid Reference Finder (2014) to 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 nearest pipeline 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 pipeline landfall point and the location of identified storage sites. Figure 2 shows a schematic diagram summarising the techno-economic assessment methodology.

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 approximate 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).

Shipping costs are calculated, for the clusters for which this could be a CO_2 transportation option (Grangemouth, South Wales, Southampton and Thames), by using the cost data reported in Zero Emissions Platform (ZEP) (2011) and implementing linear interpolation. Figure 3 shows 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. Note that the

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
(Mechleri et al., 2017)	X	X			2015 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)

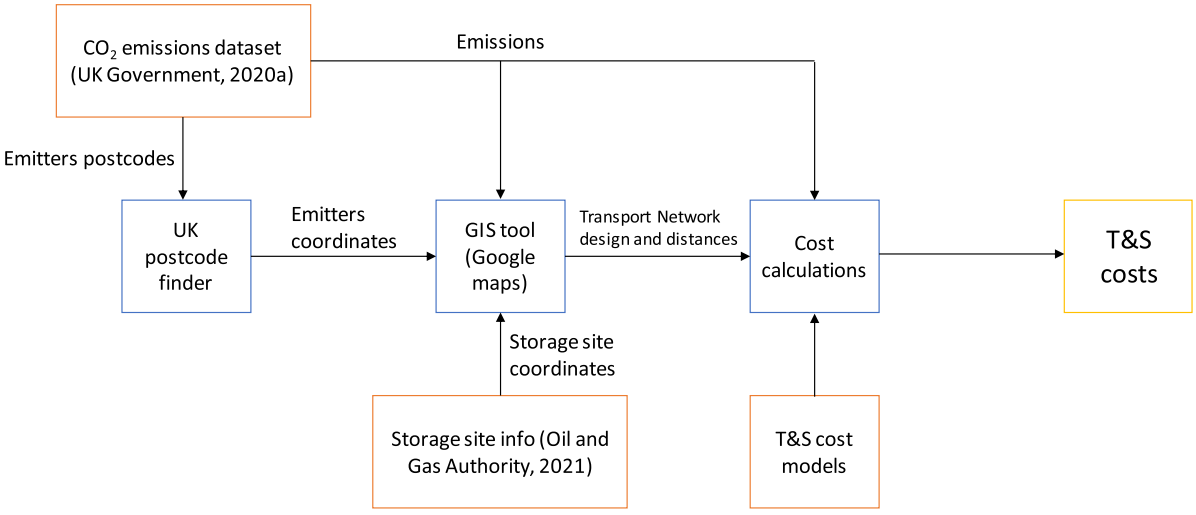

Fig. 2. techno-economic assessment methodology diagram.

CAPEX of this shipping transport includes the cost of the ships, loading buffer storage, port and offshore terminals and gas conditioning. The OPEX includes costs of crew, ship maintenance, fuel, port and offshore terminal maintenance, floating buffer storage and subsea installations maintenance.

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. Therefore, 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. The motivation behind the cost models selected was to use a different range and types of models, using mass flow based models, diameter based models and linear costing models, and different sources to provide a potential range of costs for each cluster and T&S component. Also, when there was more than one cost model available per type, the rationale for selecting a particular cost model was based on a number of elements, including: i) the models used UK specific assumptions or a similar geographical context around the North Sea (e.g. van den Broek, Ramírez, et al. (2010)), ii) the models provided enough detail and/or data that it was possible to replicate their approach to our

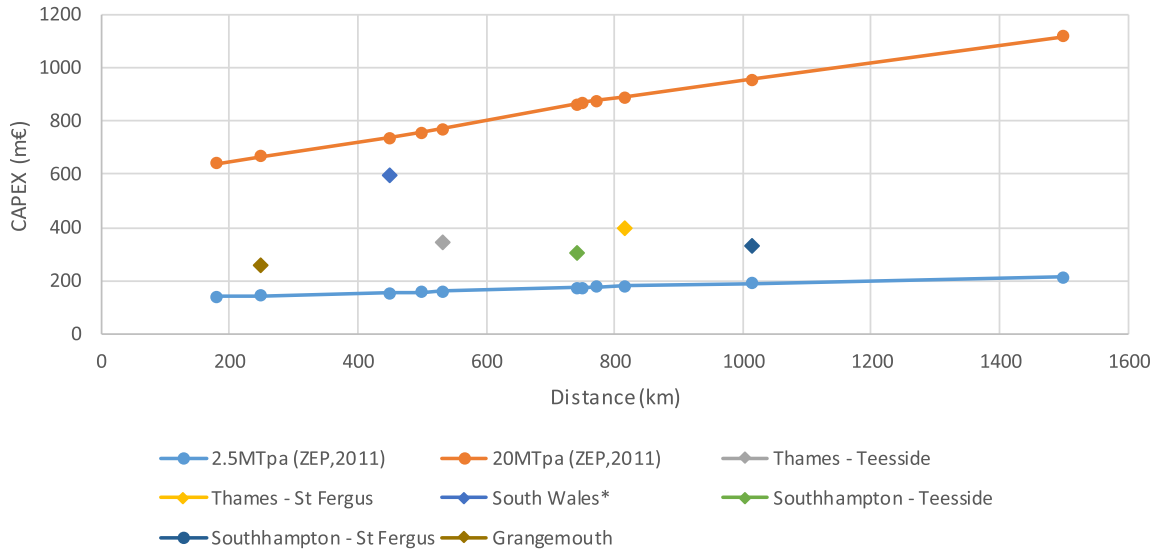

Fig. 3. Shipping cost calculations for the analysed UK clusters, using linear interpolation from ZEP (2011) data.

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%*

* the selected O&M factor is based on the cost model reference, and it varies depending on the cluster emissions and distances.

own context (e.g. Zero Emissions Platform (2011)), iii) they are widely cited in the literature (e.g. McCollum & Ogden (2006)).

3.2. Compression modelling

In the case of reusing existing infrastructure instead of using shipping, as is the case for the Grangemouth cluster reusing Feeder 10, the cost for replacing the compression stations to be able to adequately transport CO_2 has to be considered. For this we use 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% (McCollum & Ogden, 2006).

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

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

Where:

- m is the annual CO_2 mass flow (in kt)
- m_{train} is the CO_2 mass flow rate per compressor train (in kg/s)
- N_{train} is the number of compressor train. According to (McCollum & Ogden, 2006) two compressor trains are required for this mass flow.
- $P_{initial}$ is the initial pressure of the CO_2 gas.
- $P_{cut-off}$ 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.

3.3. Characterization 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 on their CO_2 emissions, their identification in recent literature and potential for T&S technologies. The clusters are: Grangemouth, Teesside, The Humber, Merseyside, South Wales, Southampton and Thames. These clusters use four different offshore storage sites: Goldeneye, Endurance, Hamilton and Hewett. Note that some clusters share storage sites, and these sites are just examples of potential CO_2 storage sites and other similar sites are located near these. Figure 4 shows the approximate location of these clusters and storage sites[1].

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

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

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
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).

Fig. 4. Selected UK industrial clusters.

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). Note that all distances have been calculated using the distance measuring tools available in Google maps. See section 3.1, for further detail on the methodology.

3.4. Description of the Clusters

3.4.1. 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.

Figure 4 shows the approximate location of 'Goldeneye', the CO_2 storage site for Grangemouth (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 (Northeast of Scotland). 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 onshore natural gas pipeline 'Feeder 10' (NECCUS, 2020). The second option is to use shipping. Both options are costed in this study.

The calculated CO_2 emissions produced in this cluster is 6,293.93 (CO_2kt per annum), which is the average of the last two recorded years (2017 and 2018) in the UK Government (2020a) data base. Note that 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. 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 should be considered.

3.4.2. 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 4 show the approximate location of the cluster and 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. The CO_2 emissions produced in this cluster and pipeline network distances are shown in Table 6 and Table 7, respectively.

Table 7
Summary of clusters' CO2 transport distances (in km) and storage sites.

Cluster	Onshore pipeline network	Offshore pipeline network	Shipping	Storage site	Offshore transport option
Grangemouth	163.8	129	249	Goldeneye	Pipeline/ shipping
The Humber	364.5	85	-	Endurance	Pipeline
Teesside	72.9	145	-	Endurance	Pipeline
Merseyside	182.5	26.5	-	Hamilton	Pipeline
South Wales	157.9	-	450	Hamilton	Shipping
Southampton	69.3	-	740/ 1014	Endurance/ Goldeneye	Shipping
Thames	148.8	262	531	Hewett/ Endurance	Pipeline/ Shipping
Teesside + North Humber	203.7	230	-	Endurance	Pipeline
South Humber	260.7	109	-	Hewett	Pipeline

3.4.3. 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 4 show the approximate location of the cluster and storage site. 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. The CO_2 emissions produced in the Teesside cluster and pipeline network distances are shown in Table 6 and Table 7, respectively.

3.4.4. 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,

Table 6
Summary of clusters' CO2 emissions.

Cluster	Emissions (in CO_2kt per annum)			Number of emitters			Emissions considered in this study	Emissions reported in lit.
	80%	90%	100%	80%	90%	100%		
Grangemouth	5173.1	5695.3	6305.9	7	9	21	6293.9	4300[a]
The Humber	33152.3	36036.7	39997.6	7	10	65	39997.6	44000[b]
Teesside	4016.6	4375.9	4804.7	8	11	27	4804.7	3100[a]
Merseyside	7848.4	8584.3	9489.5	8	14	54	9489.5	2600[a]
South Wales	13540.1	14416.4	15783.9	5	7	44	15783.9	8200[a]
Southampton	5034.8	5219.1	5779.8	2	3	19	5636.5	2600[a]
Thames	6544.4	7066.3	7847.2	6	9	37	7847.2	N/A
Teesside + North Humber	21311.3	24445.9	26610.4	9	12	85	26610.4	N/A
South Humber	12888.9	14735.6	16448.7	5	7	35	16448.7	N/A

[a] reported by the UK Government (2017)
[b] reported by Zero Carbon Humber (2021), as the CO_2 capture potential for the wider Humber area

Liverpool, Sefton, St. Helens, Warrington, and Wirral. 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). Figure 4 show the cluster location 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. The CO_2 emissions produced in this cluster and pipeline network distances are shown in Table 6 and Table 7, respectively.

3.4.5. 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. Unlike other clusters, South Wales emitters are located in two main areas: the first around the cities of Cardiff and Swansea, and the second in the Pembroke area. 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 Fig. 4). 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). The CO_2 emissions produced in this cluster and onshore pipeline network distances are shown in Table 6 and Table 7, respectively.

3.4.6. 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 4 show the cluster location. 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 Southampton) which has not been connected to the network due to the large distance and the low level of emissions involved.

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). The CO_2 emissions produced in this cluster, onshore pipeline network and shipping distances are shown in Table 6 and Table 7, respectively.

3.4.7. 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.

This cluster has an available storage site 'Hewett' by the east coast of England (marked in Figure 4), 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, we consider a potential shipping route from the Thames cluster to Redcar (Teesside). The CO_2 emissions produced in this cluster are shown in Table 6, and the distances of onshore pipeline network and to the offshore storage sites are shown in Table 7.

3.4.8. 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. In this assumed case, the North Humber cluster will continue to be part of the North Endurance Partnership (see section 3.3.2), whereas the South Humber cluster will stay independent and will use the Hewett storage site, via the use of an offshore pipeline (see Fig. 4). 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. For this alternative cluster arrangement, 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.

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 the offshore pipeline to Endurance is the same as described in sections 3.3.2 and 3.3.3. 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 (see Table 6 and Table 7).

3.4.9. Summary of clusters characteristics

Table 6 and Table 7 present a summary of emissions and other cluster characteristics. Note that we have organised the emitters by amount of produced CO_2 and classified them in three groups: the largest emitters, representing 80% of the total annual CO_2 emissions. The second group (90%) adds industries with the next 10% of emissions and the third groups adds all the smaller emitters, representing the last 10% to make the 100% emissions total. This tiered approach allows us to design the CO2 transport network focusing on the largest emitters first and adding smaller emitters whenever possible.

Table 6 also shows examples of the cluster emissions reported in the literature. This allows for a comparison of the level of emissions calculated per cluster in this study. From the table it can be seen that there are differences between reported emissions in the literature and the calculated emissions here. However, the emission levels are in the same order of magnitude and the difference can be attributed to the 'build it and they will come approach' we have followed in this study, considering most emitters within the cluster for the emissions calculation, whereas in the literature number of emitters could have been limited.

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

Table 8 and Table 9 show the CAPEX and OPEX, respectively, of the T&S technologies for the analysed industrial clusters. For each cluster, we use the two sets of cost models (set ***a*** and set ***b***) as described in section 3.1 and in Table 1. Note that, even though a direct cost comparison with other pipeline costs considering the transport of CO_2 and other gases/fluids may not be accurate due to differences in context and design parameters, the costs presented here are of the same order of magnitude as other studies (e.g. hydrogen pipelines in Miao et al (2021)).

For the Grangemouth cluster, two transportation options are costed. Option 1 consists of using existing infrastructure (Feeder 10) considering the new compression costs for repurposing the pipeline for CO_2

Table 8
Capital costs (CAPEX) for the UK industrial clusters (in 2020 M£).

Cluster	Transport option and costing set	Onshore pipeline	Offshore pipeline	Storage	Shipping	Total
Grangemouth	Option 1.a	115.61	314.12		64.70	494.43
	Option 1.b	84.29	112.05	83.39	64.70	344.43
	Option 2.a	115.61	314.12		313.36	743.09
	Option 2.b	84.29	112.05	83.39	313.36	593.09
The Humber	Option 1.a	437.22	881.12		-	1318.34
	Option 1.b	783.19	200.15	76.11	-	1059.45
Teesside[a]	Option 1.a	42.11	111.33	-	-	153.44
	Option 1.b	30.61	111.33	-	-	141.94
Merseyside	Option 1.a	150.78	291.44		-	442.22
	Option 1.b	109.01	29.48	74.20	-	212.69
South Wales[b]	Option 1.a	152.93	-		729.57	882.50
	Option 1.b	120.62	-	-	729.57	850.19
Southampton[c]	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
Thames[d]	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
North Humber + Teesside[e]	Option 1.a	180.53	992.45		-	1172.98
	Option 1.b	170.05	227.66	76.11	-	473.82
South Humber[f]	Option 1.a	273.43	706.48		-	979.91
	Option 1.b	272.90	146.63	77.14	-	496.67

[a] The storage cost for Teesside are considered in the Humber cluster. Also, 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 option 1.b.
[b] Offshore pipeline and storage cost considered in the Merseyside cluster.
[c] Offshore pipeline and storage cost considered in the Teesside (opt. 1) and Grangemouth (opt. 2) clusters.
[d] In opt. 2, offshore pipeline and storage cost is considered in the Teesside cluster.
[e] offshore and storage costs calculated as the Humber offshore and storage costs + Teesside offshore pipeline costs.
[f] 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. 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

Table 9
O&M cost (OPEX) for the UK industrial clusters (in 2020 M£/annum).

Cluster	Transport option and costing set	Onshore pipeline	Offshore pipeline	Storage	Shipping	Total
Grangemouth	Option 1.a	2.89	12.47		2.59	17.95
	Option 1.b	2.53	3.36	4.17	2.59	12.65
	Option 2.a	2.89	12.47		53.55	68.91
	Option 2.b	2.53	3.36	4.17	53.55	63.61
The Humber	Option 1.a	13.63	30.76		-	44.39
	Option 1.b	23.49	6.01	3.81	-	33.31
Teesside	Option 1.a	1.05	3.34	-	-	4.39
	Option 1.b	0.92	3.34	-	-	4.26
Merseyside[2]	Option 1.a	3.77	22.53		-	26.30
	Option 1.b	3.27	0.88	3.71	-	7.32
South Wales[3]	Option 1.a	3.82	-		142.72	146.54
	Option 1.b	3.62	-	-	142.72	146.34
Southampton[4]	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
Thames[5]	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
North Humber + Teesside[6]	Option 1.a	4.51	34.10		-	38.61
	Option 1.b	5.10	6.83	3.81	-	15.74
South Humber[7]	Option 1.a	6.84	28.01		-	34.85
	Option 1.b	8.19	4.40	3.86	-	16.45

(the costs of repurposing infrastructure in option 1 are set in the 'shipping column' in Table 8), 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. 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.

The Humber and Teesside clusters both use the Endurance storage site, each with a dedicated offshore pipeline, and they do not have a shipping option. Note that the costs related to the Humber cluster are considerably larger than those for Teesside. This difference is partly due

to the larger onshore transport network distance for the Humber cluster, but more importantly due to the larger CO_2 mass flow for the network.

The Merseyside cluster uses the Hamilton storage site via an offshore pipeline and due to the proximity from the landfall point to storage site, no shipping option is considered. 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 to use the Hamilton storage site), 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. Note that the offshore pipeline costs from Merseyside to the Hamilton storage sites are not considered in the South Wales costing. This is to avoid double counting as they are already considered in the Merseyside cluster costs.

The Southampton cluster also lacks a storage site nearby. Therefore, two shipping transportation options 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). The large shipping distances in this cluster make shipping costs the main component of the total CAPEX, about 10 times the cost of the onshore transportation costs. Note that the offshore pipeline costs from Redcar and St. Fergus to the respective storage sites are not considered in the Southampton costing, as they are already considered in the Teesside and Grangemouth cluster costs.

The Thames cluster considers both an offshore pipeline and a shipping option. Option 1 consist in using an offshore pipeline to the Hewett storage site. However, the distance to the storage site is greater than in other clusters, so a shipping option to use other storage sites could be a cost effective alternative. In this case, we consider a shipping option to the Teesside cluster (option 2) and we can see in Table 8 that this option represents lower costs than the offshore pipeline cost. For option 2, the offshore pipeline costs from the Teesside port to the Endurance storage site are already considered in the Teesside cluster and therefore, not considered in this option.

In the alternative cluster arrangement considering the separation of the south and north Humber, the south Humber cluster now uses the Hewett storage site, whereas the North Humber + Teesside clusters still use Endurance. In both cases, only offshore pipeline transportation is considered. It is interesting to note that the T&S costs of this new cluster arrangement is different than the sum of the separate Humber and Teesside costs, which shows the nonlinearity of the costs models.

From these results, it is clear that these models produce a relatively large range of costs for similar inputs. The transport cost models are set in function of distance (pipeline or shipping) and CO_2 mass flows. However, looking at the composition of these functions (see section 2.3), the biggest contributor to the cost output is the annual flow of CO_2, as in models like Ghazi & Race, 2013) the quadratic component directly relates to CO_2 mass flow (see equations (1) and ((6)). This means that, for example, a 10% increase in CO_2 mass flow would translate into a larger cost increase than a similar 10% in pipeline length. For the shipping costs model used, a similar phenomenon occurs as the cost curve in Fig. 3 for the larger mass flow (20MTpa) is steeper than the curve for the smaller CO_2 mass flow (2.5MTpa).

Looking at OPEX costs in Table 9, these roughly align to the CAPEX cost differences between clusters. This is due to the fact that OPEX is calculated as a proportion of the CAPEX (see Table 1). However, it is interesting to note that shipping operation and maintenance costs are considerably larger than alternative offshore pipelines. See for instance the cost difference in the Thames cluster. The CAPEX of option 1 (offshore pipelines), depending on the cost model uses, it is around +-30% of option 2 costs (shipping), whereas the OPEX of option 2 is 3 to 5 times the cost of option 1.

5. Conclusions

The current UK policy landscape shows important efforts on carbon capture and storage implementation and on industrial decarbonisation more widely. In particular, the UK Government has cited CCTS as an integral part of its 'green growth' and 'levelling up' agendas, arguing that CCTS can help maintain international industrial 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 an international competitive advantage. An example of this will be the creation of a CO_2 and hydrogen shipping industries allowing the import and export of blue and green hydrogen to and from other countries, and to import CO_2 from overseas for safe storage at the UK sites in the North Sea.

The opportunities brought by these new industries, the capacity to decarbonise existing industrial activity, and to do so in ways that help transition Oil and Gas industry capacity and jobs, are the main drivers behind CCTS implementation. However, to make sure that all these goals are achieved, it is necessary to first understand the composition and characteristics of the industrial clusters, including emitters' location, level of emissions and geographical constraints. This will then allow us to analyse the implication on costs to deploy these technologies, where and when do these investments take place and how these investments are paid for.

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. Analysing the UK industrial cluster definitions, we found that certain clusters, in particular those considered to be the largest CO_2 emitters, are continuously mentioned in the literature. However, some discrepancies exist between sources, and some clusters with CCTS potential are not always considered. Moreover, detailed characteristics of the cluster composition including information on the clusters' geographical limits, industries and companies involved, available infrastructure, etc. is rarely available, and thus, complicates the development of an accurate cost estimation analysis and the potential impact of new CCTS related sectors. The UK cluster characterisation developed here, aims provide relevant insight in this area which can be used to understand the potential for industrial decarbonisation and CCTS deployment opportunities.

Analysing carbon transport and storage cost models, it was evident that there can be great variability between different cost models reported in the literature. Also, most studies focus on a particular part of the T&S process, and the regional scope and monetary units used can vary widely, which complicates a direct comparison between analyses. Therefore, in this paper we used different cost models for every T&S element: CO_2 pipeline transport, storage and shipping, with the objective of providing an approximate cost range that could be used as a first step before more specific and detailed direct cost analysis for the clusters.

We found that the T&S costs of the characterised clusters are mainly driven by the size in CO_2 transportation capacity, and the length of the transport networks. The design philosophy we followed is 'build it and they will come' assuming that most emitters will join in a CO_2 transport network. However, this may not be the most cost effective approach. It is therefore, important to optimise the design of the onshore and offshore pipeline networks, to avoid oversizing the pipelines and reduce costs. Also, the creation of a CO_2 shipping industry will allow for industrial clusters that do not have an adequate storage site nearby, such as the Southampton or South Wales clusters, to decarbonise its industrial activity and use the CCTS infrastructure in other sites. This also allows offering carbon management and storage services to polluters overseas.

We believe that the insight and the cost estimates produced in this paper 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. As part of our future work, we intend to expand this characterisation and techno-economic analysis to include optimal pipeline network design,

by developing mixed integer linear optimisation models. Also, we plan to continue to use our outputs to inform wider economy analysis, producing relevant and timely policy insight.

CRediT authorship contribution statement

Christian Calvillo: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Julia Race:** Conceptualization, Methodology, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Enrong Chang:** Conceptualization, Methodology, Investigation, Data curation. **Karen Turner:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Antonios Katris:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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