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A Futuristic Least-cost Optimisation Model of CO2 Transportation and Storage in the UK/UK Continental Shelf'

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1. Introduction

After capture, the next stage in the CCS value chain is transporting the CO_2 to sinks for either permanent storage or use in CO_2-EOR flooding with subsequent permanent storage.

Worldwide, several projects involving CO_2 capture, transportation and storage are being undertaken. The well known ones are at Weyburn (onshore, Canada), In Salah (onshore, Algeria), Sleipner Vest (offshore, North Sea, Norwegian sector) and Snohvit (onshore-offshore, Norway).

To date, there is no CCS project in the UK, but the UK Government has initiated a competition for the first demonstration project. Given the scale of CO_2 emissions in the UK, there is scope for many CCS projects. A challenge is to determine the totality of the CCS projects that can be undertaken at the minimum resource cost.

Several studies, including Kemp and Kasim (2008) have investigated the costs of undertaking different elements of the CCS value chain in the UK. The purpose of the present study is to develop a futuristic least-cost optimisation model to minimise the cost of transporting given quantities of CO_2 from 8 major sources to specified sinks in the UKCS over a 20-year time period (2018-2037). It is a contribution to the important question of how to optimally utilize the vast CO_2 storage potential in the UK Continental Shelf (UKCS), given the rather limited onshore CO_2 capture potential which preliminary studies have identified.

In the study, CO_2 transportation cost optimisation is carried out with due cognisance taken of the constraints on (a) the annual supply quantities from the sources, (b) the timing of the availability of fields as sinks, (c) the storage capacities of the sinks, as well as (d) the rational utilisation of the pipeline infrastructure over the time period.

2. Methodology

The central issues of concern in the economics of CO_2 transportation – namely, the when, where, and how much of CO_2 delivery - is a constrained optimisation problem that can be formulated and solved as a transportation problem using any of a number of linear programming (LP) software. The present study used the LP package in GAMS to determine the least-cost of shipping CO_2 from i (i = 1, 2, ……m) capture sources to j, CO_2-EOR- (j = 1,2, ……w) and k Permanent storage- sinks (k = 1,2, ……z) or destinations[1]. The approach of the model is useful for matching sources to sinks and determining CO_2 flow rates and pipeline routes. More engineering data would be required for more detailed pipeline routes, diameters and mass flow rates.

The model approach is of direct source-to-sink pipeline connections, similar to that used in ISGS (2005), and, the model solutions are tailor-made inputs into the MIT CO_2 Pipeline Transport and Cost Model (2007)

[1] $w + z = n$ destinations

and Middleton and Bielicki (2009) *SimCCS* models, both of which are designed for detailed pipeline routing solutions.

The model structure in GAMS consists of 3 parts namely, the data inputs, the parameters, and the model equations. The full model consists of an objective function and a series of constraints as follows:

(i) The objective function

Equation 1 expresses the goal of determining the volumes of CO_2 to be shipped from the *i* capture sources to the two storage sink types *j* and *k* at time *t* at an overall minimum cost. That is,

Minimise:

$$\cos t = \sum_{i=1}^{m}\sum_{j=1}^{w} coer_{i,j} xeor_{i,j}^{t} + \sum_{i=1}^{m}\sum_{j=1}^{(n-w)} cperm_{i,k} xperm_{i,k}^{t} \tag{1}$$

where:

$coer_{i,j}$ = *the unit cost of transporting CO_2 from source i to EOR sink j*

$xeor_{i,j}^{t}$ = *the quantity of CO_2 transported from source i to EOR sink j at time t*

$cperm_{i,k}$ = *the unit cost of transporting CO_2 from source i to Permanent Storage sink k*

$xperm_{i,k}^{t}$ = *the quantity of CO_2 transported from source i to Permanent storage sink k at time t*

The objective function is minimised subject to the constraints expressed in equations 2 to 9 as follows:

(ii) CO_2 supply-side constraints

$$\sum_{j=1}^{w} xeor_{i,j}^{t} + \sum_{k=1}^{z} xperm_{i,k}^{t} = \sup_{i}^{t} \tag{2}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{w} xeor_{i,j}^{t} + \sum_{i=1}^{m}\sum_{k=1}^{z} xperm_{i,k}^{t} + \sum_{i=1}^{m} surp_{i}^{t} = \sum_{i=1}^{m} \sup_{i}^{t} \quad (3)$$

where:

$\sup_i^t$ = *the CO_2 supply capacity limit of source plant i at time t*

$surp_i^t$ = *excess supply of CO_2 of the i^{th} plant at time t*

Equation 2 states that at the individual plant level, the sum of the volumes of CO_2 shipped to the *j* EOR- and *k* Permanent Storage- sinks from the i^{th} capture source must equal the gross supply of CO_2 available at the source. Equation 3 is an accounting identity requiring that, across the industry, the total volumes of CO_2 captured at the sources must equal the sum of the delivered and undelivered CO_2 to the sinks.

(iii) CO_2 demand-side constraints

$$\sum_{j=1}^{w} xeor_{i,j}^{t} + shoteor_{j}^{t} = demeor_{j}^{t} \quad (4)$$

$$\sum_{k=1}^{z} xperm_{i,k}^{t} + shotperm_{k}^{t} = demperm_{k}^{t} \quad (5)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{w} xeor_{i,j}^{t} + \sum_{j=1}^{w} shoteor_{j}^{t} = \sum_{j=1}^{w} demeor_{j}^{t} \quad (6)$$

$$\sum_{i=1}^{m}\sum_{k=1}^{z} xperm_{i,k}^{t} + \sum_{k=1}^{z} shotperm_{k}^{t} = \sum_{k=1}^{z} demperm_{k}^{t+1} \quad (7)$$

where:

$demeor_j^t$ = *the annual volume of CO_2 required for injection at EOR sink j at time t*

$demperm_k^t$ = *the annual volume of CO_2 required for injection at Permanent storage sink k at time t*

Given the possibility that system's CO_2 storage capacity may exceed its supply capacity, then according to equations 4 and 5, at the plant level, the respective volumes of CO_2 required for injection into EOR and Permanent Storage sinks must be equal to the sum of the CO_2 volumes actually shipped-in and any shortfall in the required quantity. Equations 6 and 7 state that the same conditions must hold at the aggregate or industry level.

(iv) rational pipeline utilisation constraints

$$xeor_{i,j}^{t+1} \geq xeor_{i,j}^{t} \quad (8)$$

$$xperm_{i,k}^{t+1} \geq xperm_{i,k}^{t} \quad (9)$$

The constraints in expressions (8) and (9) respectively require that the volumes of CO_2 transported to the EOR- and Permanent Storage-sinks, along a particular route in succeeding periods are equal, at least, to those in the immediate preceding period.

(v) Non-negativity constraint

$xeor_{i,j}$, $xperm_{i,k}$, $demeor_j$, $demperm_k$, $shoteor_j$, $shotperm_k$, $surp_i$, ≥ 0

3. The Data

(a) Time horizon for Study

Even though 2014 has been mentioned as the likely take-off date of the Government-sponsored CCS demonstration project, there are no firm dates for the widespread commencement of CCS in the UK. In the present study, investment decisions and actions were modelled over 20 years divided into four 5-year investment cycles with the associated median years shown below.

Time period	Median year	Investment cycle
2018 – 2022	2020	1

2023 – 2027	2025	2
2028 - 2032	2030	3
2033 - 2037	2035	4

The time periods, median years and investment cycles are used interchangeably in the study.

(b) Sources of Captured CO_2

In the study CO_2 is captured and shipped from 8 out of the top 100 large stationary point sources in the UK identified in Map 1[2]. The stationary point sources are the 8 power plants where CO_2 capture investment schemes have already been discussed in public. They are at Peterhead, Killingholme, Teesside, Tilbury, Ferrybridge, Kingsnorth, Longannet and Drax.

The locational co-ordinates as well as the assumptions on the build-up of the CO_2 supply capacity of the i^{th} captured-CO_2 source at time *t, sup (i, t),* are presented in Table 1.

Table 1: CO_2 supply capacities ($MtCO_2$/year)

	Latitude	Longitude	2020	2025	2030	2035
(a) Peterhead	57.50	-1.78	1.42	1.99	2.56	3.53
(b) Killingholme	53.65	-0.28	1.53	2.15	2.76	3.80
(c) Teesside	51.92	-2.60	3.14	4.39	5.65	7.78
(d) Tilbury	52.03	0.57	1.46	2.05	2.63	3.63
(e) Ferrybridge	53.70	-1.23	2.41	3.38	4.34	5.98
(f) Kingsnorth	51.38	0.52	3.02	4.23	5.44	7.49
(g) Longannet	56.07	-3.73	3.70	5.18	6.66	9.18
(h) Drax	53.78	-1.07	8.33	10.66	15.00	20.66
TOTAL			**25.01**	**34.03**	**45.04**	**62.05**

Sources of the planned initial CO_2 capture capacities:

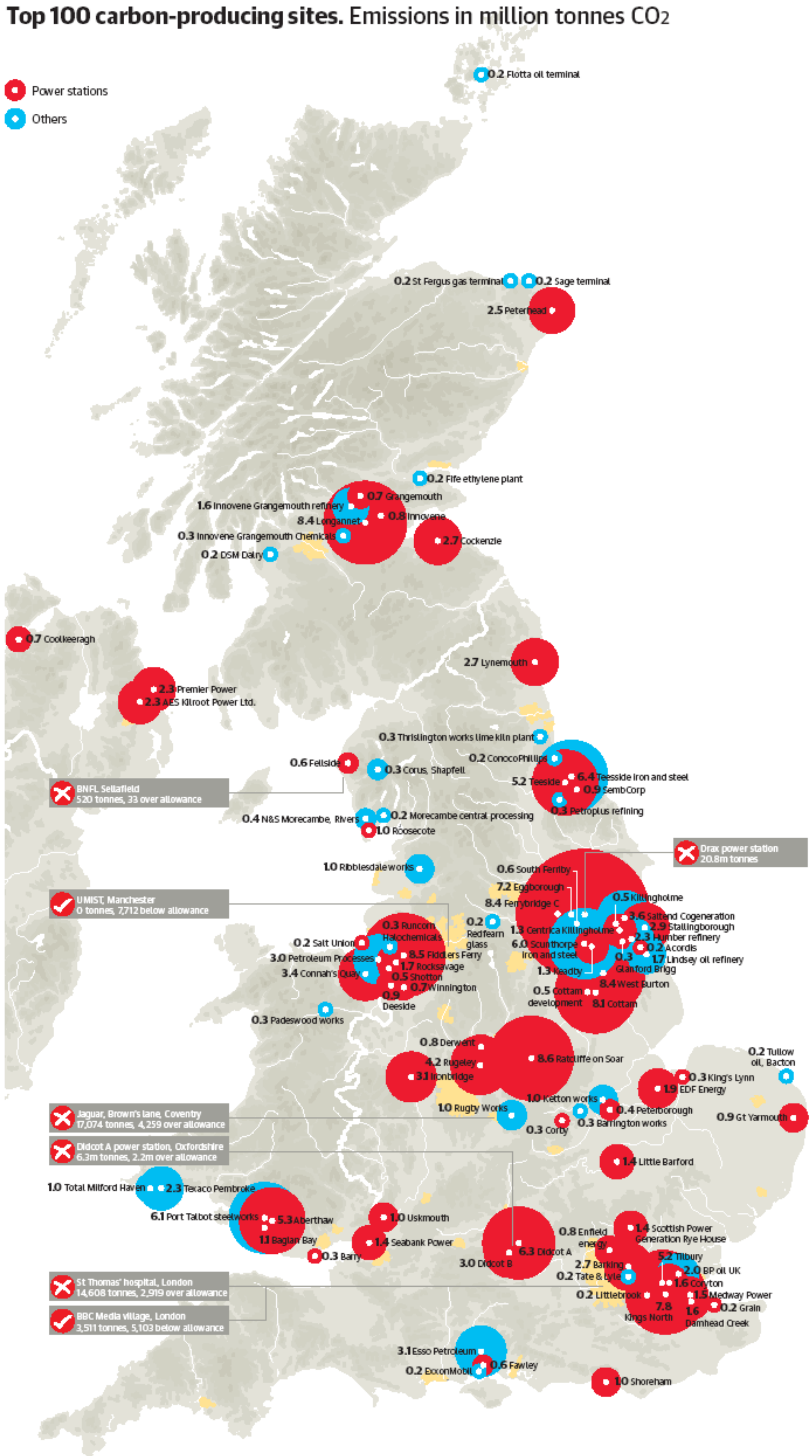
(a) Peterhead: Scottish and Southern Energy PLC, The Peterhead De-Carbonised Fuel (DF) Concept, 2005
(b) Killingholme: Press Release May 24 2006 and Annual Report 2006

[2] See Guardian (16th May 2006).

(c) Teesside: Guardian Unlimited Wednesday November 8, 2006
(d) Tilbury: RWE npower, Press Release April 2006
(e) Ferrybridge: Scottish and Southern Energy PLC, 2006, Powerful Opportunities, Annual Report 2006 p. 16
(f) Kingsnorth: Press Releases: 11 October 2005; 11 December 2006.
(g) Longannet: Scottish Power, Longannet, 2005
(h) Drax: Drax Group PLC, Coal – Fuelling Our Future Generation, April 2006

Considering the uncertainties surrounding the deployment of CCS technology in the UK/UKCS, it is unlikely that the proposed CO_2 capture plants will attain their full supply capacities right from the onset. Rather, consistent with the general view in the literature of a learning-by-doing phase, it is plausible to expect a gradual supply capacity build-up. Hence, the study assumed that the CO_2 supply capacity from the 8 power stations is built up as follows: about 40% during first investment cycle (2018-2022), followed by about 53-56% during the second investment cycle (2023-2027), 70-73% during the third investment cycle, and, full capacity in the fourth investment cycle. The details are shown in Table 1.

Map 1: Top 100 CO_2 Emission Sites in the UK



Source: The Guardian Unlimited, 16th May 2006

(c) CO_2 sinks

CO_2 capture investments serve the end of removing anthropogenic CO_2 from the atmosphere. To accomplish this, the captured CO_2 has to be stored in either one of 2 storage type sinks– namely those that allow CO_2 to be deployed in intermediate applications such as CO_2-flood EOR (enhanced oil recovery), and EGR (enhanced gas recovery) followed by permanent storage, and those which simply permanently store the gas.

BGS (2006) screened UKCS oil and gas fields for their CO_2-EOR and permanent storage potentials, arriving at an estimated total "realistic" storage capacity of 7529 $MtCO_2$[3]. Assuming that the initial CO_2 storage investments are directed at the reservoirs with the largest storage capacities, the present study selected for further scrutiny the sinks with a minimum storage capacity of 50 $MtCO_2$. Next, Bachu's screening criteria (Bachu, 2004)[4], including minimum reservoir capacity and reserves, reservoir temperature, and the specific gravity of oil (light-medium oil) were applied to the shortlist, leaving the study with 20[5] potential sinks[6] in the UKCS, broken down into 7 oilfields and 14 gas and gas/condensate fields. The 6 oilfields selected as being potentially suitable for CO_2-EOR flooding are: Beryl, Brae, Claymore, Forties, Miller, Nelson, and Ninian. The 14 gas and gas/condensate fields found to be potentially suitable for permanent CO_2 storage are Alba, Brae, Britannia, Bruce, Franklin, Fulmar, Galleon, Hewett, Indefatigable, Leman, Morecambe North, Morecambe South, Ravenspurn, and West Sole. The eventual chosen capacities are shown in column 6 of Table 2.

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[3] Broken down into 1175 $MtCO_2$ in oilfields, 5138 $MtCO_2$ in gas fields and 1216 $MtCO_2$ in gas/condensate fields.
[4] See Appendix 1 for more details on the screening criteria.
[5] Counting the Brae and Brae East fields as one Brae complex.
[6] The present study excluded saline aquifers as potential sinks.

Table 2 presents some data on the selected sinks.

Table 2: CO_2 Storage Capacity of Selected Sinks

Sinks	Latitude	Longitude	Storage Capacity ($MtCO_2$)	Possible COP dates	Eventual CO_2 storage capacity ($MtCO_2$)
(1)	(2)	(3)	(4)	(5)	(6)
1. CO_2-EOR					
Beryl	59.60	1.51	279*	2018	126
Brae	58.75	1.29	122	2018	20
Claymore	58.45	-0.25	77*	2024	59
Forties	57.71	1.02	332*	2025	282
Miller	58.76	1.42	141*	2007[7]	53
Nelson	57.40	1.10	66*	2028	64
Ninian	60.75	1.46	213*	2024	185
		Sub-total	**1108**		789
2. Permanent storage					
Alba	58.13	1.10	125*	2028	60
Brae East	58.85	1.42	111	2018	97
Britannia	58.03	1.11	181	2030	71
Bruce	59.67	1.56	197	2021	104
Franklin	57.01	1.84	126	2030	57
Fulmar	56.49	2.15	116*	2018	86
Galleon	53.52	1.80	137	2027	46
Hewett	53.10	1.57	383	2018	381
Indefatigable	53.33	2.63	357	2013	347
Leman	53.08	2.18	1203	2026	1020
Morecambe North	53.58	3.41	144	2018	119
Morecambe South	53.86	-3.63	736	2021	529
Ravenspurn	54.08	1.01	145	2018	138
West Sole	53.70	1.15	143	2019	125
		Sub-total	**4104**		**3180**

Sources:
(a) Column 4: BGS (2006)
(b) * Authors' own calculations[8]
(c) Column 5: Authors' own calculations derived from A.G. Kemp and L. Stephen (2007)
(d) Column 6: Authors' own calculations

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[7] The field has been decommissioned but can be re-entered to exploit the transport cost advantage that the Peterhead-Miller pipeline can be re-used.

[8] Using the data, assumptions and the following formula in BGS (2006):

$$MCO_2 = (URR_{oil} \times B_0)\rho CO_2$$

where:

MCO_2 = CO_2 storage capacity
URR_{oil} = volume of ultimately recoverable oil at standard temperature and pressure ($10^9 m^3$)
B_o = oil formation volume factor
ρCO_2 = density of CO2 at reservoir conditions (kgm^{-3})

In addition to the BGS and Bachu's selection criteria, a third criterion used in the selection of the fields in Table 2 is the non-closure of a field's window of opportunity[9].

There are two dimensions – time and the size of remaining reserves - to the notion of a field's window of opportunity which come into consideration, depending on whether the captured CO_2 is destined for injection for EOR or permanent storage. In order to avoid incurring the extra cost of re-opening closed or decommissioned fields, the injection of CO_2 into permanent storage should start immediately after COP and to continue until the (new) reservoir pressure exceeds the original. For EOR, injection must start before the cessation of production, while a critical mass of remaining oil still remains in the reservoir[10].

Entries in column 4 of Table 2 show the reservoir storage capacities as estimated by or derived from BGS (2006). Column 5 shows the central years of the fields' COP dates, calculated from the authors' economic modelling[11]. Based on the knowledge that not all the storage capacity in column 4 would be available for CO_2 storage, especially the reservoirs that have experienced substantial water invasion and/or flooding, the storage capacity data are refined in column 6 showing the calculated total amount of CO_2 that can eventually be stored at the start of CO_2 injection, given the proportion of the storage capacity already depleted, using data on cumulative hydrocarbon production from the selected reservoirs. How quickly the eventual storage capacity is filled up depends on the assumed project life or lifetime cycle.

[9] It is understood that fields in the UKCS can be reopened for CO_2 storage or EOR purposes, but this adds to costs.
[10] The data on the estimated COP dates are presented in Appendix 2.
[11] See A. G. Kemp and L. Stephen (2007).

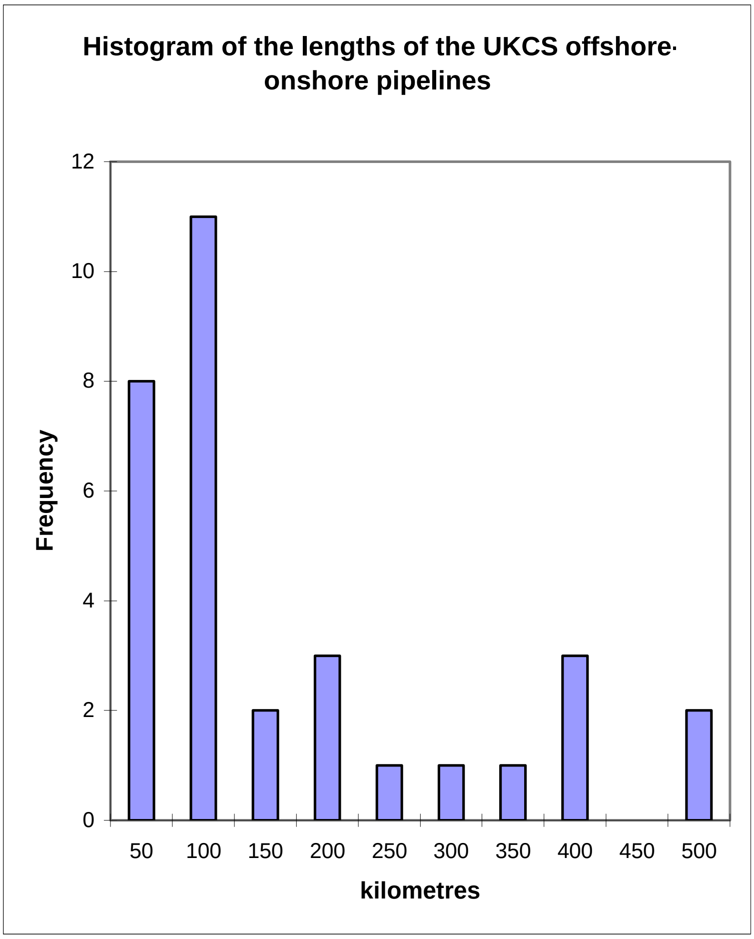
(d) Characterisation of pipelines in the UKCS and elsewhere

Oil and gas in the UKCS are transported in an extensive pipeline network and tankers. The total length of UK's offshore oil and gas pipelines is about 11,500 kilometres (BERR) of which roughly 5000 kilometres are in the offshore-to-onshore direction. The offshore-onshore pipelines are of direct interest to the present study because even though the CO_2 would be transported in the opposite direction, some of the pipelines and their terminals could be re-used in CO_2 transportation. In any case, they would still be required to convey onshore any CO_2-EOR oil that may be produced in CCS projects.

To provide the context for a possible CO_2 transportation network it is useful to give a brief description of the length and diameters of the offshore-onshore pipelines as presented in Tables 3 and 4. Table 3 presents descriptive statistics of the pipeline lengths.

Table 3: Descriptive data on the lengths of the offshore-onshore pipelines in the UKCS

	Length (km)
Mean	140.57
Standard Error	24.38
Median	68.80
Mode	354
Standard Deviation	137.91
Sample Variance	19018.27
Kurtosis	0.11
Skewness	1.17
Range	467.50
Minimum	5.60
Maximum	473.10
Sum	4498.10
Count	32
Largest(5)	354
Smallest(5)	29.60
Confidence Level (95.0%)	49.72



The descriptive statistics on the left panel in Table 3 show that there are 32 offshore-onshore pipelines ranging in length from a mere 6 kilometres to about 480 kilometres, with the modal length being 354 kilometres and the mean and median lengths being about 141 and 69 kilometres respectively. The histogram in the right panel show that about 75 percent of the pipelines are of lengths not exceeding 200 kilometres.

Table 4 shows the descriptive statistics on the diameters of the pipelines.

Table 4: Descriptive data on the diameters of the offshore-onshore pipelines in the UKCS

Diameter (mm)	
Mean	683.81
Standard Error	30.27
Median	762.00
Mode	762.00
Standard Deviation	171.23
Sample Variance	29319.26
Kurtosis	-0.04
Skewness	-0.80
Range	641.30
Minimum	273.10
Maximum	914.40
Sum	21882.00
Count	32
Largest(5)	863.60
Smallest(5)	508.00
Confidence Level (95.0%)	61.73

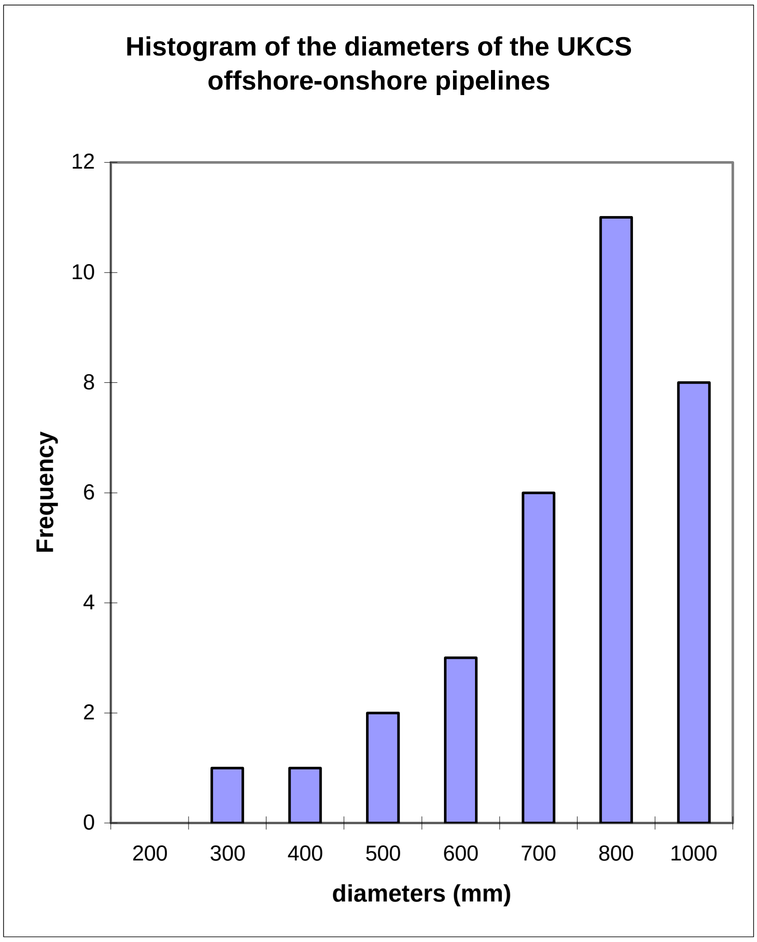


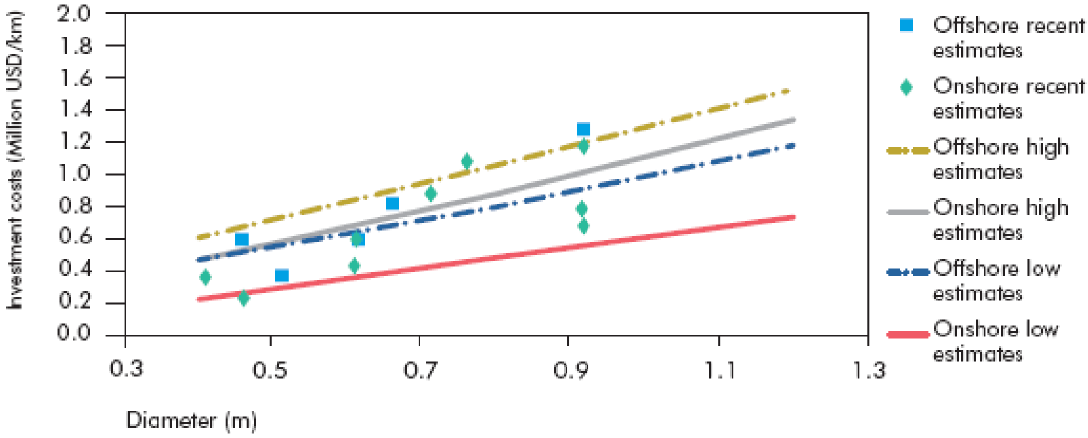
Table 4 shows that the pipeline diameters range from 273 to 914 mm. The modal diameter is 762mm while the mean and median diameters are 684 and 762 mm respectively. The histogram reveals that about 88 percent of the pipelines have diameters in excess of 600 mm.

In the United Kingdom, the CO_2 transportation pipelines can consist of both new build and re-used ones. Expected pipeline transportation costs depend on a number of factors (see IPCC, 2005) including construction costs, the age structure of the pipelines, the source-to-sink distance, geography (onshore/offshore lengths), pipeline diameters, and the material conveyed (dry or wet CO_2).

Given the relatively distant COP dates of many of the producing fields in the CNS and NNS, most of the pipelines conveying CO_2 to these sectors will have to be new-build since most of the existing offshore-to-onshore pipelines will still be transporting oil and gas and will not be available in the medium term. The only pipeline in the CNS that is virtually ready for re-use is the one linking the power plant at Peterhead to the Miller field which is being decommissioned. However, greater pipeline re-use opportunities exist in the SNS because of the imminence of the COP dates of some of the gas fields.

Graph 1 gives an idea of how pipeline diameter and geography affect the capital cost of pipeline networks according to the IEA.

Graph 1: Pipeline Diameters and Investment Costs (USA)

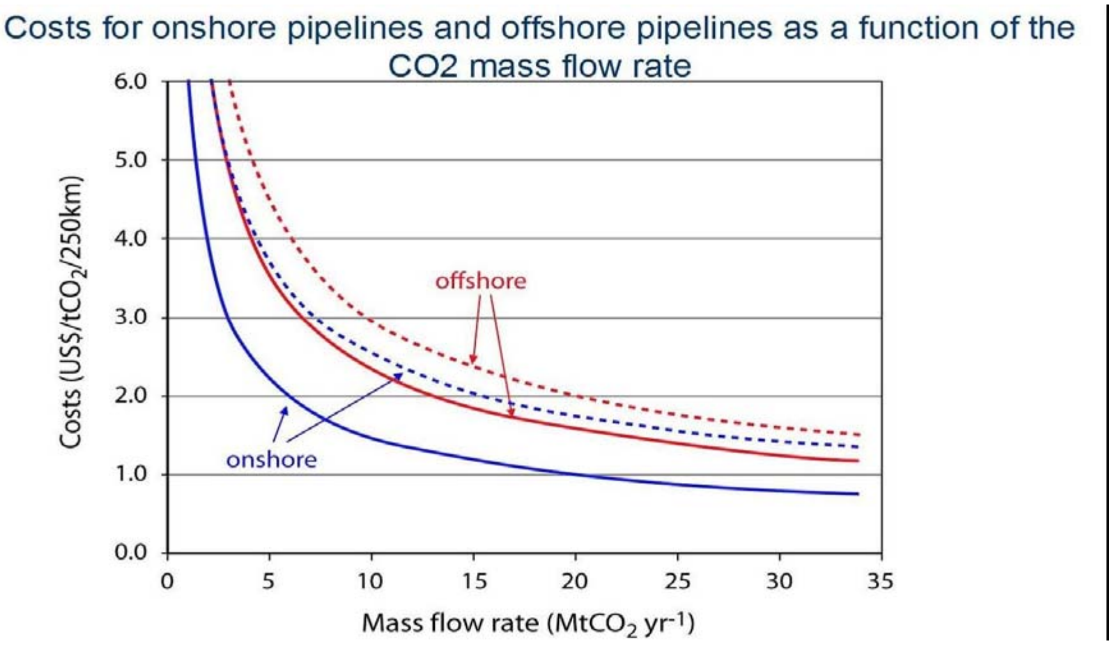


Note: Graph shows recent project costs vs. IPCC (2005) estimates.
Source: IEA, 2008c.

Detailed construction costs of CO_2 pipelines in the UK/UKCS are not available because none has been constructed to date. The present study assumed that a new-build CO_2 pipeline transportation (of an average 0.762m or about 28-inch[12] diameter) network in the UKCS would incur a CAPEX of between £1 and £3 million per kilometre, with £2million/km as the central value. This is higher than the IEA's most recent estimate for a pipeline of the same diameter at offshore USA presented in Graph 1, and reflects the increased costs in recent years. The CAPEX of re-used facilities is assumed to be lower than the stated amount. Specifically, it was assumed that the existing pipelines in the SNS as well as the Peterhead-Miller pipeline are modified and re-used at 50% of new-build costs.

Graph 2 shows that economies of scale exist in CO_2 transportation.

Graph 2:



Source: IPCC (2005)

[12] That is, the median and modal diameter of the UKCS offshore-onshore pipelines (see Table 4 above).

(e) Source-to-sink distances:

The distances between the *i* sources of CO_2 and *j* EOR- and *k* Permanent Storage- sinks are respectively denoted by *diseor (i, j)* and *disperm (i, k)* in the model.

Using data on the locational co-ordinates (longitudes and latitudes) of each sink and source, the shortest source-to-sink distances were calculated using the Haversine formula[13]. The data on the source-to-sink distances are in Table 5.

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[13] Haversine formula: d = R.c
where:
R = earth's radius (mean radius = 6,371 km)
c = 2.atan2(√a,√(1-a))
a = $\sin^2$ (Δlatitude/2) + cos (latitude1).cos (latitude2).$\sin^2$ (Δlongitude/2)
Δlatitude = latitude2 – latitude1
Δlongitude = longitude2 – longitude1

Table 5: Sources-to-sinks distances (km)

(i) Source-to-EOR sinks (CNS and NNS)

	Claymore	Beryl	Forties	Heron	Miller	Ninian	Gryphon	Alwyn North	Nelson	Brae	Dunbar	Magnus
Peterhead	139	302	168	201	234	406	263	418	173	228	403	486
Killingholme	534	672	459	399	579	798	627	807	426	576	792	890
Teesside	435	582	373	324	491	705	537	715	344	488	700	794
Tilbury	717	846	633	566	752	975	802	983	599	750	968	1069
Ferrybridge	532	678	468	414	587	802	633	812	437	583	797	892
Kingsnorth	790	919	706	639	825	1048	875	1056	672	823	1041	1142
Longannet	337	500	341	339	430	602	461	615	330	423	600	678
Drax	522	667	456	402	575	792	622	801	425	572	786	882

(ii) Source-to-Permanent storage sinks (SNS)

	Fulmar	Alba	Brae East	Franklin	Bruce	Shear water	Armada group	Britannia	Hewett	Indefatigable	Raven spurn	West Sole	Leman	Morecambe North	Morecambe South	Galleon	Sean
Peterhead	263	184	240	224	309	230	195	181	534	541	419	461	552	545	358	497	562
Killingholme	352	506	588	397	680	402	451	495	137	196	97	94	175	244	221	138	214
Teesside	297	419	501	328	590	334	372	409	241	282	149	178	274	316	181	224	304
Tilbury	507	680	762	560	854	564	621	669	137	200	230	190	160	257	347	185	201
Ferrybridge	378	514	596	416	687	422	464	504	197	259	153	157	236	306	159	201	277
Kingsnorth	579	753	835	633	927	636	694	742	204	260	302	262	220	313	393	253	257
Longannet	366	371	436	357	508	364	359	365	475	510	374	409	506	535	246	454	532
Drax	364	503	585	404	675	409	452	492	191	250	140	146	229	296	168	191	268

4. Scenario Analysis

The model was applied to investigate two important issues in CO_2 transportation pertaining to (a) investment timing and (b) assumptions on the minimum annual CO_2 injectivity levels. CO_2 can be transported into permanent storage only when the gas and gas/condensate fields have been depleted and made ready to receive it. By contrast, there is relative flexibility in the CO_2-EOR flooding start date, since the technology can be deployed at anytime during secondary and/or tertiary oil production (Bachu, 2004). This flexibility affects the availability of the fields to receive CO_2 and the consequent pipeline network configuration and costs. A scenario analysis was conducted to investigate the most economical way to distribute the captured CO_2 under four scenarios, assuming two alternative CO_2-EOR injection commencement dates and two minimum annual injectivity levels.

(i) Scenario 1: Higher injectivity, with accelerated EOR start date

Scenario 1 is described as a higher injectivity and accelerated EOR start date scenario. In the scenario the minimum CO_2-EOR injectivity level of 5 $MtCO_2$/year injectivity level is assumed. Furthermore, it is assumed that CO_2-EOR injection start dates for all the candidate fields is accelerated to start uniformly during the 2018-2022 investment period. Therefore, to qualify for inclusion in this scenario, a CO_2-EOR sink must have a minimum annual injectivity capacity of 5 $MtCO_2$/year, if primary CO_2-EOR injection is carried out over a 15-year period. CO_2 transportation and injection into permanent storage, however, would be

COP-led, with injection commencing immediately after a gas field is depleted, and continuing throughout the study period.

(ii) Scenario 2: Lower injectivity with accelerated EOR start dates

The assumptions of this scenario are the same as those in Scenario 1 except that the minimum annual injectivity is reduced to 3 $MtCO_2$/year.

(iii) Scenario 3: Higher injectivity with COP-determined EOR start dates

Scenario 3 uses the assumption that the CO_2-EOR flooding starts 2 years before the COP date of each selected field with the higher minimum annual injectivity of 5 $MtCO_2$/year. CO_2 injection into permanent storage starts immediately when a chosen gas field is depleted.

(iv) Scenario 4: Lower injectivity with COP date-determined EOR start dates

Scenario 4 uses the same assumptions as Scenario 3 except for the minimum injectivity which is reduced to 3 $MtCO_2$/year.

5. Results:

Given the model, data parameters, and scenario assumptions, the model solutions determined the quantities of CO_2 transported into E0R and permanent storage, indicating alternative pipeline network configurations. The results are presented below.

Scenario 1:

Scenario 1's model solutions are presented below.

Table 6: <u>**Origination, destinations and volumes of CO_2 transported and injected in Scenario 1**</u>

Sources	**Pipelines only @ Vt+1=Vt**	**Distance (km)**	**type**	**Terminal**	**2020**	**2025**	**2030**	**2035**
Drax	Forties	456	perm		8.33	10.66	14.81	20.47
			Sub-total		**8.33**	**10.66**	**14.81**	**20.47**
Ferrybridge	Ravenspurn	153	perm	Easington	2.41	3.38	4.34	5.98
			Sub-total		**2.41**	**3.38**	**4.34**	**5.98**
Killingholme	West Sole	94	perm	Easington	1.53	2.15	2.76	3.80
			Sub-total		**1.53**	**2.15**	**2.76**	**3.80**
Kingsnorth	Hewett	204	perm	Bacton	3.02	4.23	5.44	7.49
			Sub-total		**3.02**	**4.23**	**5.44**	**7.49**
Longannet	Brae	436			3.70	5.18	6.47	8.99
			Sub-total		**3.70**	**5.18**	**6.47**	**8.99**
Peterhead	**Claymore**	139	**EOR**	Peterhead	1.42	1.99	2.56	3.53
			Sub-total		**1.42**	**1.99**	**2.56**	**3.53**
Teesside	Morecambe South	227	perm	Barrow-in-Furness	3.14	4.39	5.65	7.78
			Sub-total		**3.14**	**4.39**	**5.65**	**7.78**
Tilbury	Hewett	137	perm	Bacton	1.46	2.05	2.63	3.63
			Sub-total		**1.46**	**2.05**	**2.63**	**3.63**
			Grand Total		**25.01**	**34.03**	**44.66**	**61.67**

The results of the ***system-wide*** optimisation of CO_2 transportation costs for Scenario 1 are shown in Table 6. They shed light on some of the issues concerned with CO_2 transportation and sequestration in the UK/UKCS.

CO_2 shipments over relatively long distances such as those from Drax to Forties (conveying between 8 and 20 $MtCO_2$/year) are possible because several studies (see ISGS (2005), IPCC (2005) and Middleton and Bielicki (2009), for examples) have emphasised the economies of scale present in CO_2 transportation. With the possibility of reaping the fruits of scale economies nearness to a source can be less important than the mass flow rate or the volume of CO_2 transported to a sink. Of course, economies of scale do exist over short distances as well, which is why it seems paradoxical that the model solution allocates Drax's output to Forties instead of to Morecambe South, a large permanent storage sink only about 168 kilometres away from Drax. However, an inspection of the detailed results revealed that, while Drax can ship CO_2 to Morecambe South for most of the study period without increasing the optimised system transportation cost, doing so in 2030 violates this condition. Specifically, Drax-Morecambe South shipments in 2030 are sub-optimal and inadmissible because they increase overall network system costs by about £9.8 million. In a setting or model that permits it, the Drax-Morecambe South deliveries would have been temporary. However, the constraints (equations 8 and 9) of the present model prohibit temporary CO_2 deliveries.

In order to test the extent of the scale economies in the model solution both the optimised total and average capital costs functions were specified and estimated. The implied economies of scale were estimated using a double-log regression equation of the total capital cost on the total CO_2 shipments and yielded the following result:

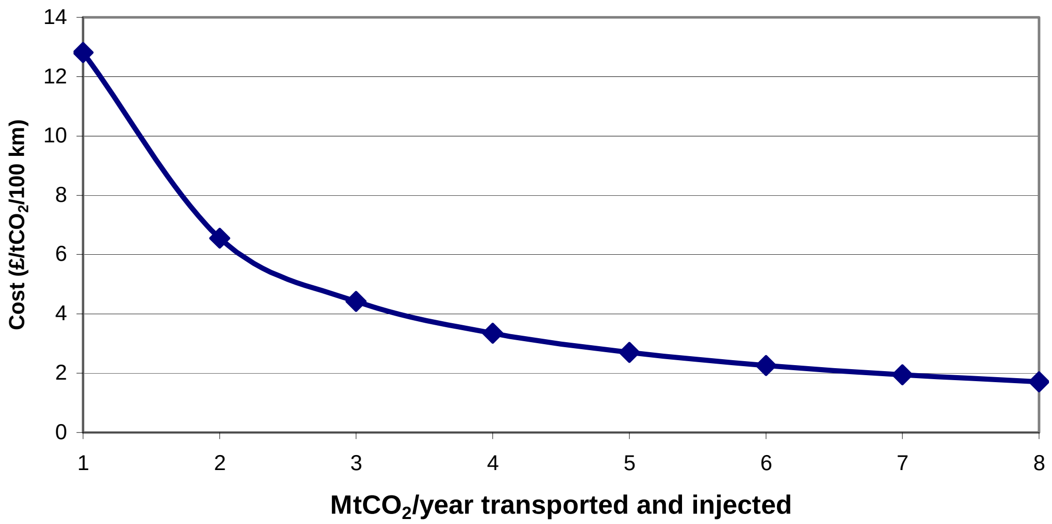
$$ln(total\ CAPEX) = 2.273 + 0.886 ln(cumulative\ CO_2\ shipment\ volumes)$$
$$(3.036) \quad (5.005) \qquad adjusted R^2 = 0.77$$

where:

ln = natural logarithm
t-statistics are in brackets

Using the slope of the regression, the estimated economies of scale factor is 1.129, indicating the presence of substantial scale economies implicit in the optimised pipeline capital costs. A graphical illustration of the average capital cost function is presented in Graph 3.

Graph 3: UKCS: CO_2 pipeline transportation average capital cost curve: Scenario 1



The concavity of the average capital cost curve indicates the presence of both the economies of scale and full pipeline utilisation. Exploiting the benefits of scale economies, close matching of source-sink capacities[14], and minimisation of system-wide costs throughout the study period, are the reasons why Drax can ship CO_2 to Forties instead of to nearer sinks,

[14] For example, wwithout CO_2 deliveries from the largest CO_2 capture plant (Drax), Forties' injectable maximum 20 $MtCO_2$/year would have been met from smaller capture plants at higher costs to the overall system.

such as Morecambe South. CO_2 deliveries are made to Morecambe South from Teesside (181 km) in this scenario.

One effect of promoting only the large CO_2-EOR projects capable of handling a minimum annual injectivity of 5 $MtCO_2$/year over 15 years in this scenario, is to exclude sinks with smaller injectivity. Notably, Miller was dropped from the analysis in this scenario, leaving Beryl, Brae, Claymore, Forties, Nelson and Ninian in contention for CO_2 allocations from the sources. In the event, the model solution allocated the captured CO_2 among (a) three oilfields – Forties, Brae and Claymore – from the three power stations at Drax, Longannet and Peterhead, and (b) four permanent storage sinks – Ravenspurn, West Sole, Morecambe South and Hewett – from the remaining five power plants in the study.

It is noteworthy, however, that in a few cases the optimised CO_2 deliveries and injection levels diverge from the minimum injectivity level. The divergence is inevitable given that the CO_2 supply capacities are built-up over time (for example, Ferrybridge and its shipments to Ravenspurn) and the maximum capture capacities of some plants are less than 5 $MtCO_2$/year in any case.

Also, it is noteworthy that cumulative shipments of CO_2 in excess of 100 $MtCO_2$ would be delivered to two sinks –one CO_2-EOR (Forties) and the other permanent storage (Hewett) over the time period to 2037. Specifically, the Forties field would receive very close to 200 $MtCO_2$ while Hewett would receive roughly 115 $MtCO_2$ from the power plants at Kingsnorth and Tilbury. Brae is the third largest repository of CO_2 in this scenario.

The annual CO_2 mass flow rate rates range between 3 $MtCO_2$/year to about 14 $MtCO_2$/year. In all, the total length of the pipelines to be constructed in this scenario is about 1850 kilometres. Based on the Kinder Morgan (2009) experience, a crude approximation of the implied pipeline diameters is set out in Table 7

Table 7: Scenario 1: Conceptual pipeline routes and pipeline diameters

Source	Sink	estimated diameters (mm)	estimated diameters (inches)
Drax	Forties	914.84	36.02
Ferrybridge	Ravenspurn	451.84	17.79
Killingholme	West Sole	384.09	15.12
Kingsnorth	Hewett	497.31	19.58
Longannet	Brae	516.58	20.34
Peterhead	Claymore	368.23	14.50
Teesside	Morecambe South	504.16	19.85
Tilbury	Hewett	372.01	14.65

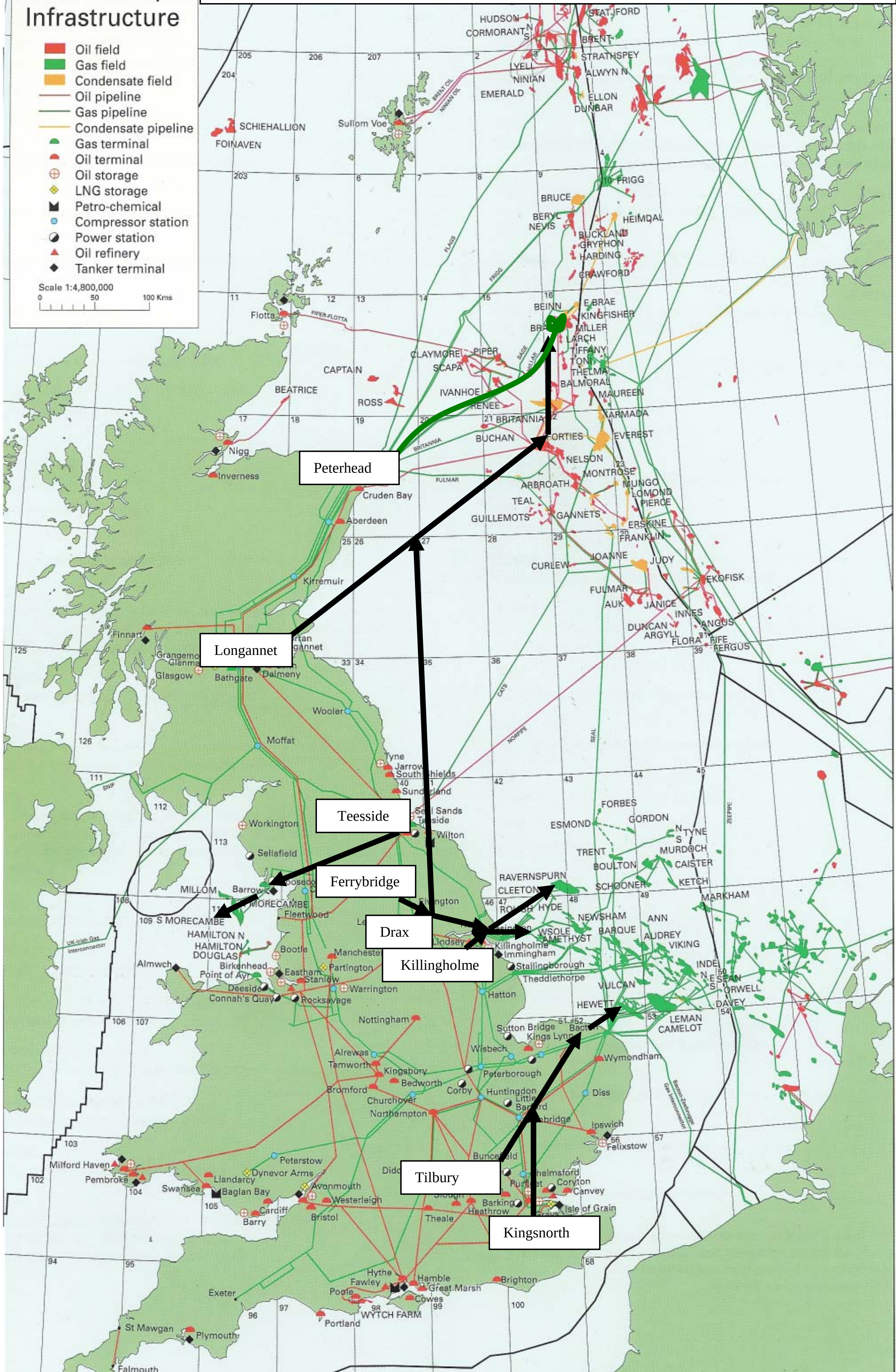
Table 7 indicates that the pipeline diameters range from roughly 368 (or 15”) to 915 mm (or 36”). These are well within the range of pipelines currently in use in the UKCS.

The total CAPEX required in this scenario is about £4bn for pipeline lengths varying from 94 km to 456 km, and diameters varying from 368 to 915 mm. The average capital cost varies from £1 to about £5/tonne/100 km.

Having identified the pipeline routes in this scenario a conceptual pipeline network configuration based on the model solutions is presented in Map 2[15].

[15] The authors' conceptual pipeline routes (in arrows) in Maps 2 to 5 are superimposed on an original map compiled by BERR.

Map 2: Conceptual CO_2 Pipeline routes in Scenario 1



Scenario 2: Accelerated CO_2-EOR start date (3 $MtCO_2$/year minimum injectivity)

Table 8: <u>**Origination, destinations and volumes of CO_2 transported and injected in Scenario 2**</u>

Sources	Pipelines only @ Vt+1=Vt	Distance (km)	type	Terminal	2020	2025	2030	2035
Drax	Forties	456	perm		8.33	10.66	15.00	16.09
Drax	Ravenspurn	140	perm	Easington				3.22
Drax	West Sole	146	perm	Easington				1.35
			Sub-total		**8.33**	**10.66**	**15.00**	**20.66**
Ferrybridge	Ravenspurn	153	perm	Easington	2.41	3.38	4.34	5.98
			Sub-total		**2.41**	**3.38**	**4.34**	**5.98**
Killingholme	West Sole	94	perm	Easington	1.53	2.15	2.76	3.80
			Sub-total		**1.53**	**2.15**	**2.76**	**3.80**
Kingsnorth	Hewett	204	perm	Bacton	3.02	4.23	5.44	7.49
			Sub-total		**3.02**	**4.23**	**5.44**	**7.49**
Longannet	Brae (East)	436			3.70	3.70	3.95	6.47
Longannet	Forties	341	perm			1.48	2.71	2.71
			Sub-total		**3.70**	**5.18**	**6.66**	**9.18**
Peterhead	**Miller**	234	**eor**	Peterhead	1.42	1.99	2.56	3.53
			Sub-total		**1.42**	**1.99**	**2.56**	**3.53**
Teesside	Morecambe South	227	perm	Barrow-in-Furness	3.14	4.39	5.65	7.78
			Sub-total		**3.14**	**4.39**	**5.65**	**7.78**
Tilbury	Hewett	137	perm	Bacton	1.46	2.05	2.63	3.63
			Sub-total		**1.46**	**2.05**	**2.63**	**3.63**
			Grand Total		**25.01**	**34.03**	**45.04**	**62.05**

The results for Scenario 2 are shown in Table 8. There are a few instances of one source shipping CO_2 to more than one sink in this scenario. Source-to-multiple sinks deliveries occur in the model because once the annual CO_2 deliveries to and injection into a sink equal the sink's injectivity level for that year, any excess CO_2 available at the supplying source is shipped to another sink. Thus, for example, while the injectivity levels at Brae are 3.70 $MtCO_2$/year (2018-2022), 3.70 (2023-2027), 3.95 (2028-2032) and 6.47 $MtCO_2$/year (2033-2037) the CO_2 supply capacities at Longannet during the corresponding period are 3.70, 5.18 , 6.66 and 9.18 $MtCO_2$/year. Clearly, apart from the initial period, Longannet has an excess capacity to satisfy the injectivity levels at Brae, which it disposes of by finding another outlet.

The cumulative total volume of CO_2 shipped from the sources to the various sinks in this scenario is about 831 $MtCO_2$ over the period to 2037, yielding an annual average shipment of about 42 $MtCO_2$/year. Unsurprisingly, this is about the same as in Scenario 1 (41 $MtCO_2$/yr). Interestingly, the same number of CO_2-EOR- and permanent storage sinks are determined to be optimally reachable in this scenario as in Scenario 1. Moreover, the same four permanent storage sinks – Ravenspurn, West Sole, Hewett and Morecambe South – were found to be accessible in this scenario as well. Regarding the CO_2-EOR sinks, however, the Miller field replaced Claymore as the third CO_2-EOR sink. Having qualified for inclusion in this scenario because it met the 3 $MtCO_2$/year injectivity level criterion, Miller displaced Claymore as the destination of the CO_2 captured at Peterhead. CO_2 is shipped from Peterhead to Miller in spite of the longer distance (234 versus 139 kilometres) because it is cheaper to re-use the existing Peterhead-Miller pipeline than build a new Peterhead-Claymore pipeline.

Forties remains the largest destination of CO_2, receiving a cumulative total of almost 300 $MtCO_2$ from two sources – Drax and Longannet – instead of the one source (Drax) in Scenario 1. The difference in the CO_2 transportation patterns is caused by the difference in the phasing of the injection through time. In Scenario 1 the CO_2-EOR injection period was reduced to 15 years, raising the minimum injectivity level, (hence pipe sizes) while the primary CO_2-EOR injection period in Scenario 2 is increased to 20 years thereby lowering the minimum injectivity level (and pipe sizes)   Thus, for example the maximum injectivity level at Brae in Scenario 1 is about 8-9 $MtCO_2$/year, virtually matching Longannet's supply capacity which, having no excess supply has no need for another sink. However, by elongating the injection period in Scenario 2 to 20 years, the maximum injectivity is reduced to about 5-6 $MtCO_2$/year, leaving Longannet with a potential ultimate excess supply capacity of about 3 $MtCO_2$/year, hence the recourse to a second sink.

Ravenspurn and West Sole also receive CO_2 from two sources each instead of the single sources in Scenario 1. Both sinks receive the supply "overflows" from Drax in addition to their respective supplies from Ferrybridge and Killingholme. Hewett remains the second largest destination, but Brae is relegated to the fifth position, having been overtaken by Morecambe South and Ravenspurn. Less CO_2 was shipped to Brae from Longannet in this scenario because the injectivity level was lowered.

In general, the annual mass flow rate in this scenario is lower than in Scenario 1, implying smaller pipeline diameters. However, the total volume of CO_2 transported and injected is about 34 percent higher than in Scenario 1. Two closely-related factors account for this. The first is the investment timing advantage of Scenario 2. Spreading the CO_2 (especially CO_2-EOR) and transportation and injection investment over a longer time period, especially the last five years of the study period when full supply capacity is attained, implies that Scenario 2 better synchronises the required CO_2 injectivity levels with the pace of the supply capacity expansion. By contrast, Scenario 1 suffers a relative investment timing disadvantage because the accelerated CO_2-EOR projects are "front-loaded", requiring higher CO_2 injectivity levels (5 $MtCO_2$/year) to be met in the first 15 years from 2018, when the system's CO_2 supply capacity has been developed. Thus, there is a greater mismatch of the respective storage and production capacities of the sinks and sources, or between injectivity and injection levels in this scenario. How well the two scenarios are able to meet the injectivity requirements are shown in columns 6 and 7 of Table 9 below.

Table 9: A comparison of injectivity-injection ratios in Scenarios 1 and 2

Sinks	Sources	Eventual storage capacity ($MtCO_2$)	Cumulative CO_2 shipment ($MtCO_2$)		injection as % of injectivity	
			Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
1	2	3	4	5	6	7
Brae	Longannet	117	**93.66**	**89.1**	80.05	76.15
Claymore	Peterhead	60	**36.58**		60.97	0.00
Forties	Drax	282	193.94	247.5		
	Longannet			34.5		
	sub-total (Forties)	**282**	**193.94**	**282**	68.77	100.00
Hewett	Kingsnorth	381	77.7	100.9		
Hewett	Tilbury		37.62	48.85		
	sub-total (Hewett)	**381**	**115.32**	**149.75**	30.27	39.30
Miller	Peterhead	53		**47.5**	0.00	89.62
Morecambe South	Teesside	529	**80.7**	**104.8**	15.26	19.81
Ravenspurn	Ferrybridge	138	62.03	80.55		
	Drax			16.1		
	sub-total (Ravenspurn)	**138**	**62.03**	**96.65**	44.95	70.04
West Sole	Killingholme	125	39.43	51.2		
	Drax			6.75		
	sub-total	**125**	**39.43**	**57.95**	31.54	46.36
	Grand total	**1685**	**621.66**	**827.75**	**36.89**	**49.12**

Clearly, the lower annual injectivity requirement of Scenario 2 is better matched with the build-up of the supply capacities, especially taking full advantage of the build-up to 100 percent capacity in the last investment cycle to increase CO_2 shipments .along the same routes identified in Scenario 1. Such increases account for two-thirds of the overall increase.

The evolution of additional pipeline routes in Scenario 2 accounted for the remaining one-third difference. The additional pipeline routes are the Longannet-Forties, Peterhead-Miller, Drax-Ravenspurn, and Drax-West Sole. The higher level of CO_2 shipments in Scenario 2 necessitated more pipeline resources, hence the overall length of pipelines in this scenario exceeds that in Scenario 1 by about 40 percent.

Table 10: Scenario 2: Conceptual pipeline routes and pipeline diameters

Source	Sink	estimated diameters (mm)	estimated diameters (inches)
Drax	Forties	761.80	29.99
Drax	Ravenspurn	357.26	14.07
Drax	West Sole	291.06	11.46
Ferrybridge	Ravenspurn	451.84	17.79
Killingholme	West Sole	384.09	15.12
Kingsnorth	Hewett	497.31	19.58
Longannet	Brae	428.53	16.87
Longannet	Forties	310.72	12.23
Peterhead	Miller	354.66	13.96
Teesside	Morecambe South	504.16	19.85
Tilbury	Hewett	372.01	14.65

The total pipeline CAPEX is about £5 bn for pipeline lengths varying from 94 km to 456 km. This is about £1 bn costlier than Scenario 1, but more CO_2 is transported and injected in Scenario 2. The average capital cost varies from £0.8/tonne/100 km to about £6/tonne/100 kilometres in 9 out of the 11 pipeline routes. The average costs of the two remaining pipeline routes from Drax to Ravenspurn and West Sole are outliers at £12 and £28/tonne/100 km respectively, raising the question of why the shipments have been selected by the model. From the results it is seen that the deliveries to Ravenspurn and West Sole are overflows or the excess of supply capacity (at Drax) over the CO_2 injection requirements at Forties (18.80 $MtCO_2$/year) which Drax was supplying up to the last investment period (2033 -2037). The excess supply has to be disposed off in other sinks, at minimum increase in the overall transport cost[16]. Specifically, since one of the model assumptions is the re-use of the SNS pipelines (Ravenspurn-Easington and West Sole-Easington), it is plausible that the two deliveries would be combined and delivered into one Drax-Easington pipeline. At Easington, the CO_2 would be routed appropriately.

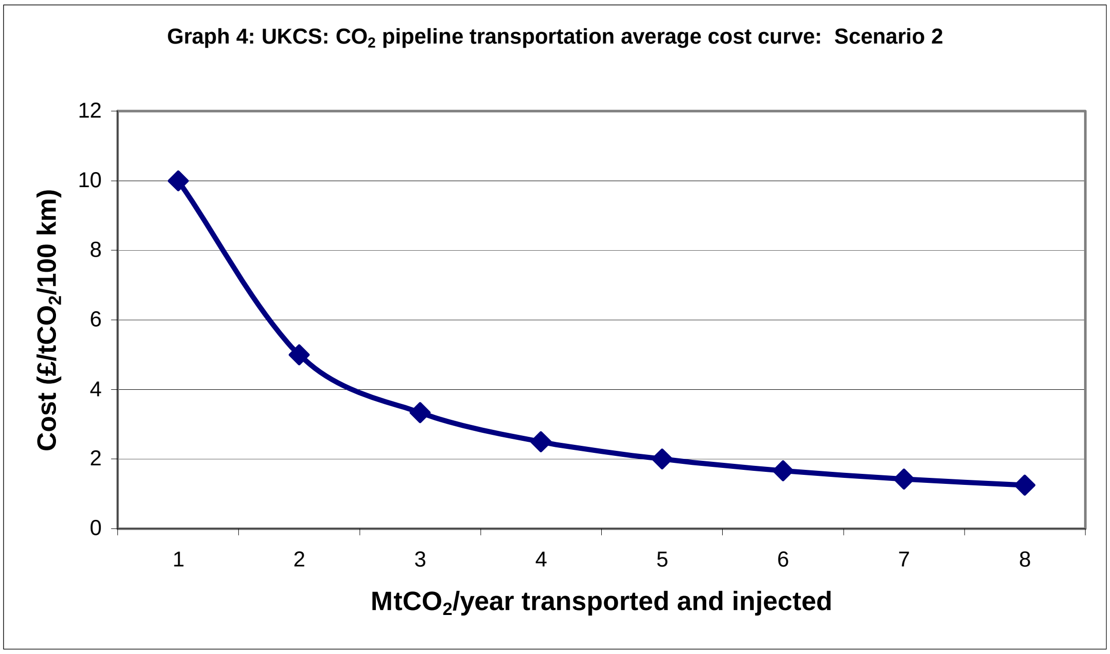
In estimating the total capital transport cost function, it was found that a linear cost function fitted the data better than the double-log function. The estimated linear total cost function is[17]:

$$\textit{(total CAPEX)} = \underset{(3.036)}{284.8488} + \underset{(2.535)}{2.411}\textit{(cumulative } CO_2 \textit{ shipment volumes)} \qquad \textit{adjusted } R^2 = 0.35$$

Thus, in spite of the apparent anomalies, the estimated scale economies at about 1.565 are more substantial in this scenario than in Scenario 1. The optimised average CO_2 transportation capital cost curve of this scenario is presented in Graph 4.

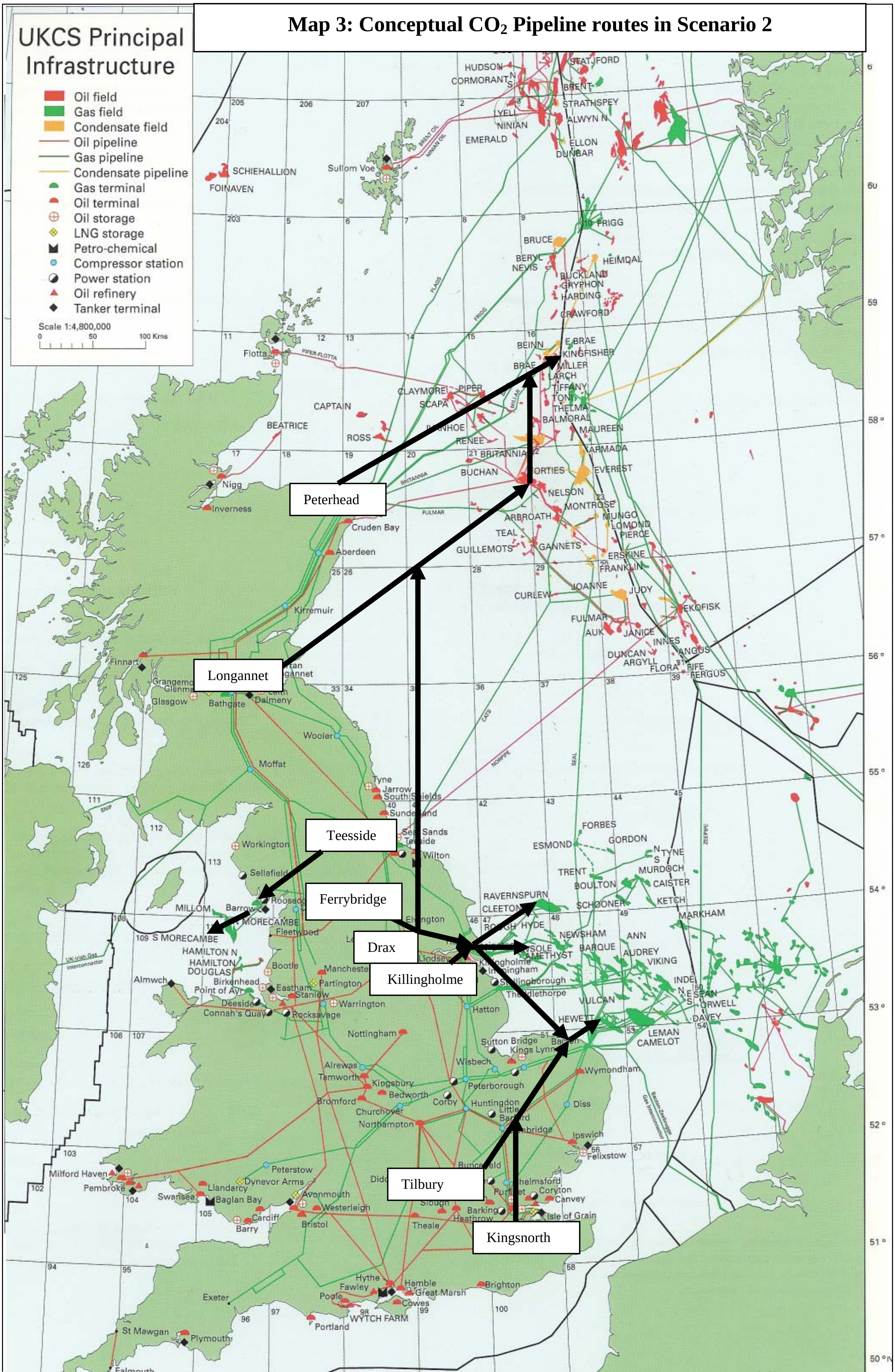
[16] The other ways and manners of disposal of the excess CO_2 are beyond the scope of the present study.
[17] For the interested reader, the estimated log-linear total cost function is:

$$\ln \textit{(total CAPEX)} = \underset{(8.171)}{4.969} + \underset{(1.783)}{0.266}\ln \textit{(cumulative } CO_2 \textit{ shipment volumes)} \qquad \textit{adjusted } R^2 = 0.19$$



A conceptual CO_2 pipeline transportation network based on Scenario 2's model solutions is presented below in Map 3.

Map 3: Conceptual CO_2 Pipeline routes in Scenario 2



*Scenario 3: **COP-driven EOR start date with offset (i.e. EOR-oil revenue credits)***

Table 11: Origination, destinations and volumes of CO_2 transported and injected in Scenario 3

Sources	Pipelines only @ Vt+1=Vt	Distance (km)	type	Terminal	2020	2025	2030	2035
Drax	Forties	456	eor			2.33	6.67	12.33
	Ravenspurn	140	perm		3.80	3.80	3.80	3.80
	West Sole	146	perm		4.53	4.53	4.53	4.53
			Sub-total		**8.33**	**10.66**	**15.00**	**20.66**
Ferrybridge	Ravenspurn	153	perm	Easington	2.41	3.38	4.34	5.98
			Sub-total		**2.41**	**3.38**	**4.34**	**5.98**
Killingholme	West Sole	94	perm	Easington	1.53	2.15	2.76	3.80
			Sub-total		**1.53**	**2.15**	**2.76**	**3.80**
Kingsnorth	Hewett	204	perm	Bacton	3.02	4.23	5.44	7.49
			Sub-total		**3.02**	**4.23**	**5.44**	**7.49**
Longannet	Brae	436	eor/perm		3.70	3.70	5.05	7.57
	Forties	341	eor			1.48	1.61	1.61
			Sub-total		**3.70**	**5.18**	**6.66**	**9.18**
Peterhead	Brae	228	eor/perm		1.42	1.42	1.42	1.42
	Claymore	139	**eor**	Peterhead		0.57	1.14	2.10
			Sub-total		**1.42**	**1.99**	**2.56**	**3.52**
Teesside	Morecambe South	227	perm	Barrow-in-Furness	3.14	4.39	5.65	7.78
			Sub-total		**3.14**	**4.39**	**5.65**	**7.78**
Tilbury	Hewett	137	perm	Bacton	1.46	2.05	2.63	3.63
			Sub-total		**1.46**	**2.05**	**2.63**	**3.63**
			Grand Total		**25.01**	**34.03**	**45.04**	**62.04**

The results for Scenario 3 are shown in Table 11. Scenario 3 is different because unlike the earlier scenarios, the transportation and injection of CO_2-EOR are driven by the COP dates of the fields, rather than via any deliberate effort to accelerate CO_2-EOR start dates. Scenario 3 shares some of the assumptions of Scenario I, particularly the assumption of a 5 $MtCO_2$/year reservoir minimum injectivity.

The model solutions of this scenario are a hybrid of the earlier scenarios. Thus the three favoured CO_2-EOR sinks are the Forties, Brae and Claymore fields while the permanent storage sinks and the respective CO_2 sources remain the same as well. Furthermore, the cumulative total volumes of CO_2 transported and injected at approximately 612 $MtCO_2$ are about the same as in Scenario 1.

In common with Scenario 2, the model solutions of Scenario 3 yielded a relatively lengthy pipeline infrastructure of about 2701 km. Lengthier pipelines are the direct consequence of introducing timelines into the scenario. In matching sources and sinks, timeline considerations force the least-cost transportation model to recognise that some sinks, even though nearer (that is, located at least-cost distances to some sources), may not be ready to receive CO_2 as and when it is available at the sources. Thus, a distant but available sink would be served at first, but, when all the sinks become available and they compete for CO_2 allocation on an equal footing, the least cost algorithm would allocate deliveries to the nearby cheaper sinks as well.

Table 12: Scenario 3: Conceptual pipeline routes and pipeline diameters

Source	Sink	estimated diameters (mm)	estimated diameters (inches)
Drax	Forties	630.42	24.82
Drax	Ravenspurn	377.52	14.86
Drax	West Sole	402.17	15.83
Ferrybridge	Ravenspurn	451.84	17.79
Killingholme	West Sole	384.09	15.12
Kingsnorth	Hewett	497.31	19.58
Longannet	Brae	466.96	18.38
Longannet	Forties	272.29	10.72
Peterhead	Brae	281.79	11.09
Peterhead	Claymore	318.27	12.53
Teesside	Morecambe South	504.16	19.85
Tilbury	Hewett	372.01	14.65

Scenario 3's total CAPEX is roughly £5.4 billion, being larger than in the earlier scenarios. The estimated cost function was:

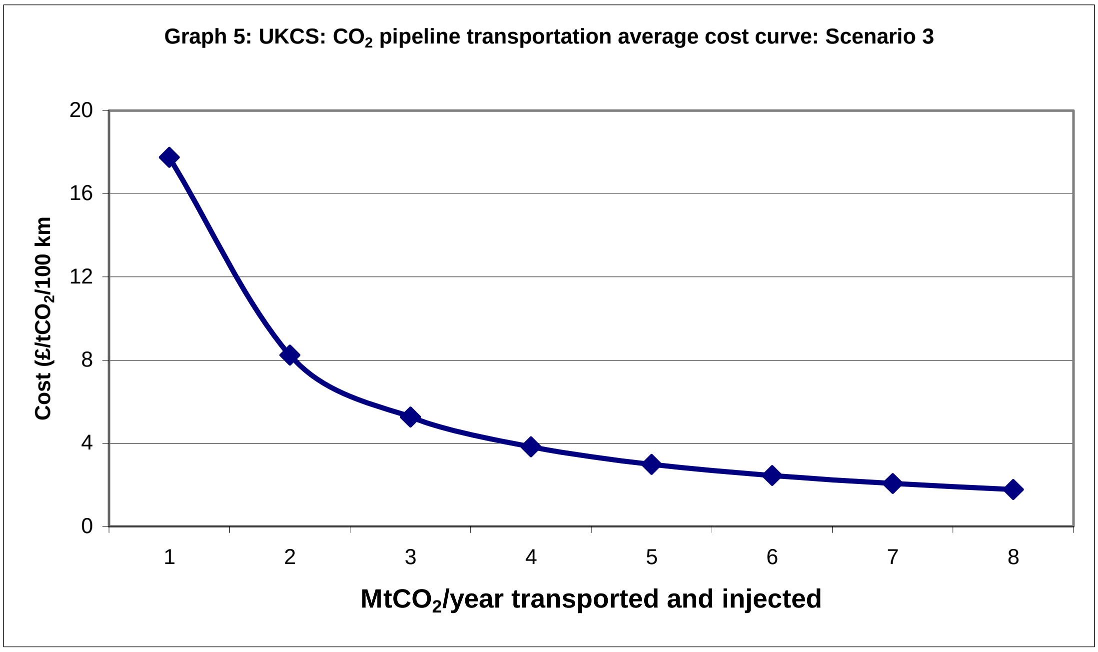
$$\ln(\text{total CAPEX}) = \underset{(2.733)}{13.765} - \underset{(-1.592)}{4.827}\ln(\text{cum } CO_2 \text{ shipment}) + \underset{(1.62)}{0.711}\ln(\text{cum } CO_2 \text{ shipment})^2 \quad \text{adjusted } R^2 = 0.06$$

The economies of scale were found to be variable[18], requiring a higher threshold of CO_2 shipments before scale economies kick-in. The estimated economies of scale on the quadratic term in log cumulative shipments is 1.40. The annual mass flow rate ranges between 1.42 and 8.42 $MtCO_2$/year while average capital cost varies between £2.48 and £9.39/tonne/100 km in ten out of the twelve pipeline routes. The outliers with £15.85 and £16.92/tonne/100 km respectively are the Longannet-Forties and Peterhead-Claymore pipeline routes. The outlier costs are generated by the timeline effects described above. Both Peterhead and Longannet had to ship CO_2 to the relatively distant sink (Brae) initially

[18] That is, the estimated regression model with variable scale economies was better behaved than the fixed scale model.

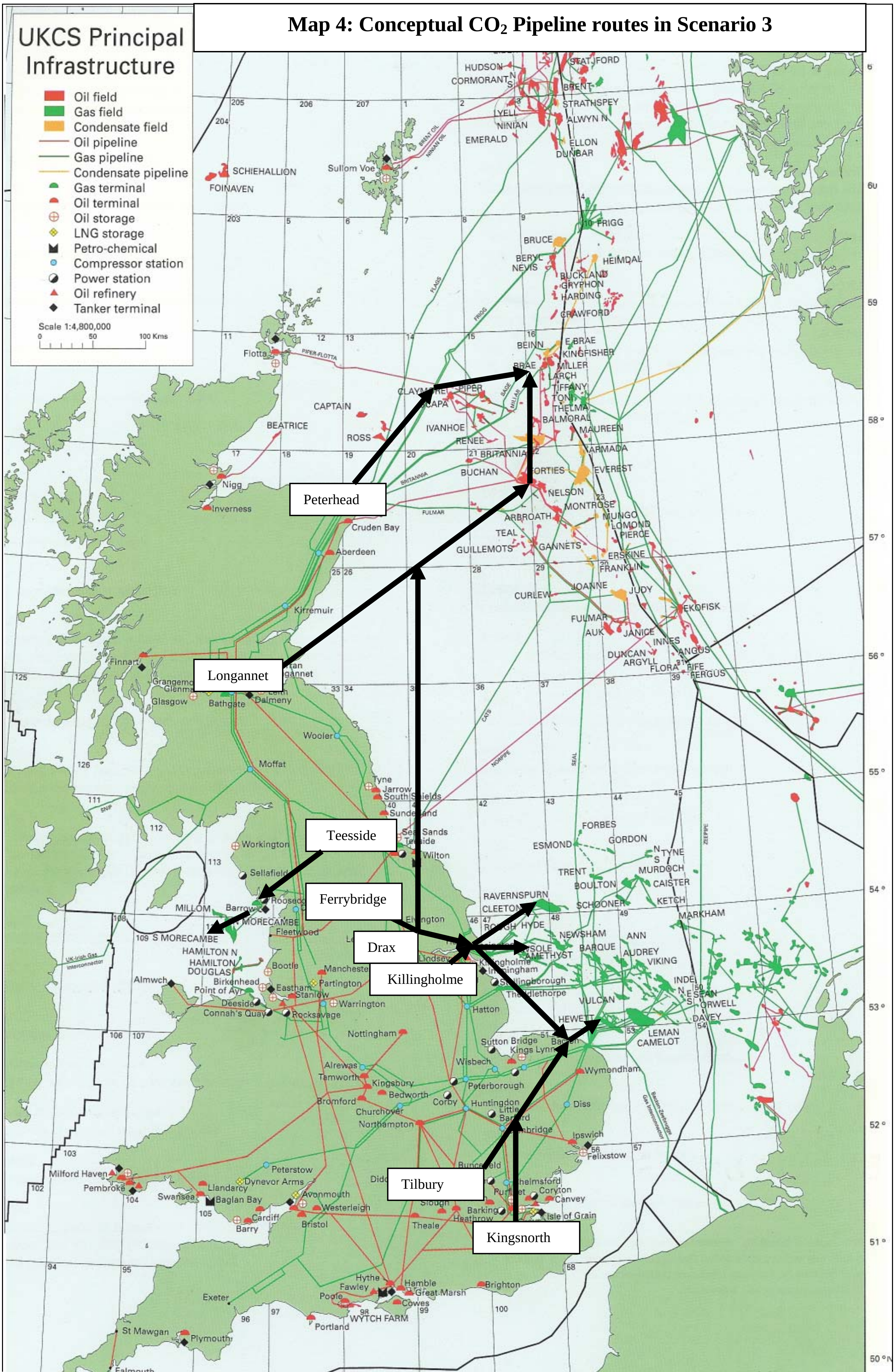
because the nearer sinks (Forties, in the case of Longannet and Claymore, in the case of Peterhead) were not available.

The average capital cost function is presented graphically below in Graph 5.



A conceptual CO_2 pipeline transportation network based on Scenario 3's model solutions is presented below in Map 4.

Map 4: Conceptual CO_2 Pipeline routes in Scenario 3



Scenario 4: ***COP-driven EOR start date with no offset (i.e. EOR-oil revenue credits excluded)***

Table 13: Origination, destinations and volumes of CO_2 transported and injected in Scenario 4

Sources	Pipelines only @ Vt+1=Vt	Distance (km)	type	Terminal	2020	2025	2030	2035
Drax	Morecambe South	168	perm	Barrow-in-Furness	6.93	6.93	6.93	6.93
Drax	Ravenspurn	140	perm	Easington	1.40	3.73	8.07	9.20
Drax	West Sole	146	perm	Easington				4.53
			Sub-total		**8.33**	**10.66**	**15.00**	**20.66**
Ferrybridge	Morecambe South	159	perm	Barrow-in-Furness	2.41	3.38	4.34	5.98
			Sub-total		**2.41**	**3.38**	**4.34**	**5.98**
Killingholme	West Sole	94	perm	Easington	1.53	2.15	2.76	3.80
			Sub-total		**1.53**	**2.15**	**2.76**	**3.80**
Kingsnorth	Hewett	204	perm	Bacton	3.02	4.23	5.44	7.49
			Sub-total		**3.02**	**4.23**	**5.44**	**7.49**
Longannet	Morecambe South	246	perm	Barrow-in-Furness	3.70	5.18	6.66	9.18
			Sub-total		**3.70**	**5.18**	**6.66**	**9.18**
Peterhead	**Miller**	234	**eor**	Peterhead	1.42	1.99	2.56	3.53
			Sub-total		**1.42**	**1.99**	**2.56**	**3.53**
Teesside	Morecambe South	227	perm	Barrow-in-Furness	3.14	4.39	5.65	7.78
			Sub-total		**3.14**	**4.39**	**5.65**	**7.78**
Tilbury	Hewett	137	perm	Bacton	1.46	2.05	2.63	3.63
			Sub-total		**1.46**	**2.05**	**2.63**	**3.63**
			Grand Total		**25.01**	**34.03**	**45.04**	**62.05**

The results of Scenario 4 are shown in Table 13. A feature of the model solution in Scenario 4 is that only the Peterhead-Miller route emerged as a viable candidate for CO_2-EOR shipments. Clearly, re-using the existing Peterhead-Miller pipeline boosted the chances of this particular route.

Having to build new pipelines without the cushion effects of the CO_2-EOR oil revenues on CO_2 transport costs, but with relative delays in the injection start-up dates, the remaining CO_2-EOR sinks were at a relative transport cost disadvantage vis-à-vis the permanent storage fields in the SNS to which the model solution routed the bulk of the CO_2.

The cumulative total volume of CO_2 transported and injected in this scenario is 831 $MtCO_2$ in the period to 2037, the same as in Scenario 2. Of this, the bulk – about 448 $MtCO_2$ (or 54 percent) – is transported from four sources – Drax, Ferrybridge, Longannet and Teesside – and injected into permanent storage in Morecambe South. In this scenario CO_2 could be transported from Ferrybridge and Drax to Morecambe South in a communal pipeline.

In general, the variability in the annual average mass flow rates in this scenario is relatively lower, ranging between 2.27 and 6.93 $MtCO_2$/year, requiring pipe sizes in the range of 14 to 22 inches.

Table 14: Scenario 4: Conceptual pipeline routes and pipeline diameters

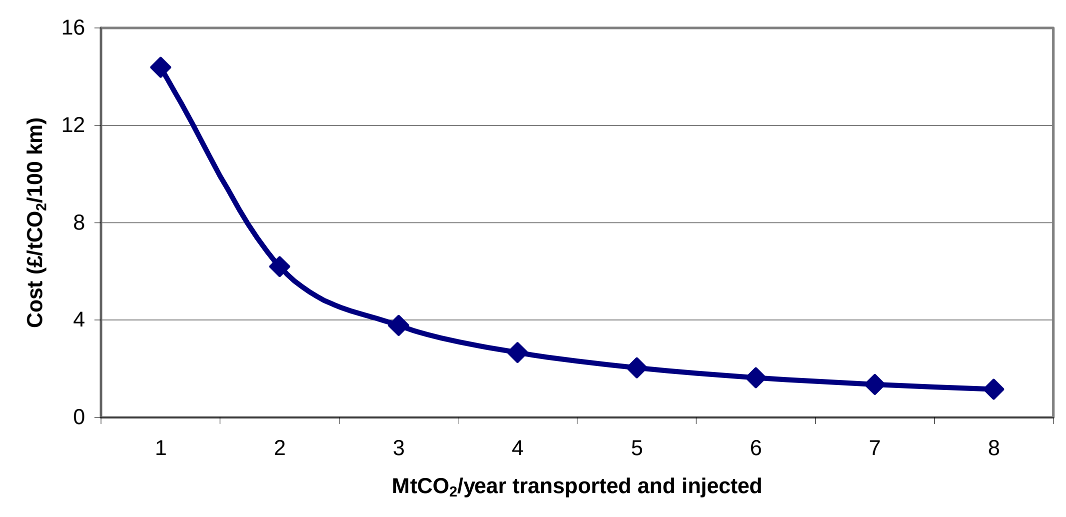
Source	Sink	estimated diameters (mm)	estimated diameters (inches)
Drax	Morecambe South	482.89	19.01
Drax	Ravenspurn	566.20	22.29
Drax	West Sole	402.17	15.83
Ferrybridge	Morecambe South	450.98	17.76
Killingholme	West Sole	384.09	15.12
Kingsnorth	Hewett	497.31	19.58
Longannet	Morecambe South	550.36	21.67
Peterhead	Miller	354.66	13.96
Teesside	Morecambe South	504.16	19.85
Tilbury	Hewett	372.01	14.65

At 1755 kilometres, Scenario 4 has the least pipeline length, being less than the 1846, 2568 and 2701 kilometres of Scenarios 1, 2, and 3 respectively. The total pipeline CAPEX is about £3.5 bn, for pipeline lengths varying from 94 to 246 km. Thus, Scenario 4 is the least costly of the four scenarios. The estimated cost function is:

$$\ln\text{ (total CAPEX)} = \underset{(6.670)}{4.953} + \underset{(1.179)}{0.202}\ln\text{ (cumulative } CO_2 \text{ shipment volumes)} \qquad \text{adjusted } R^2 = 0.042$$

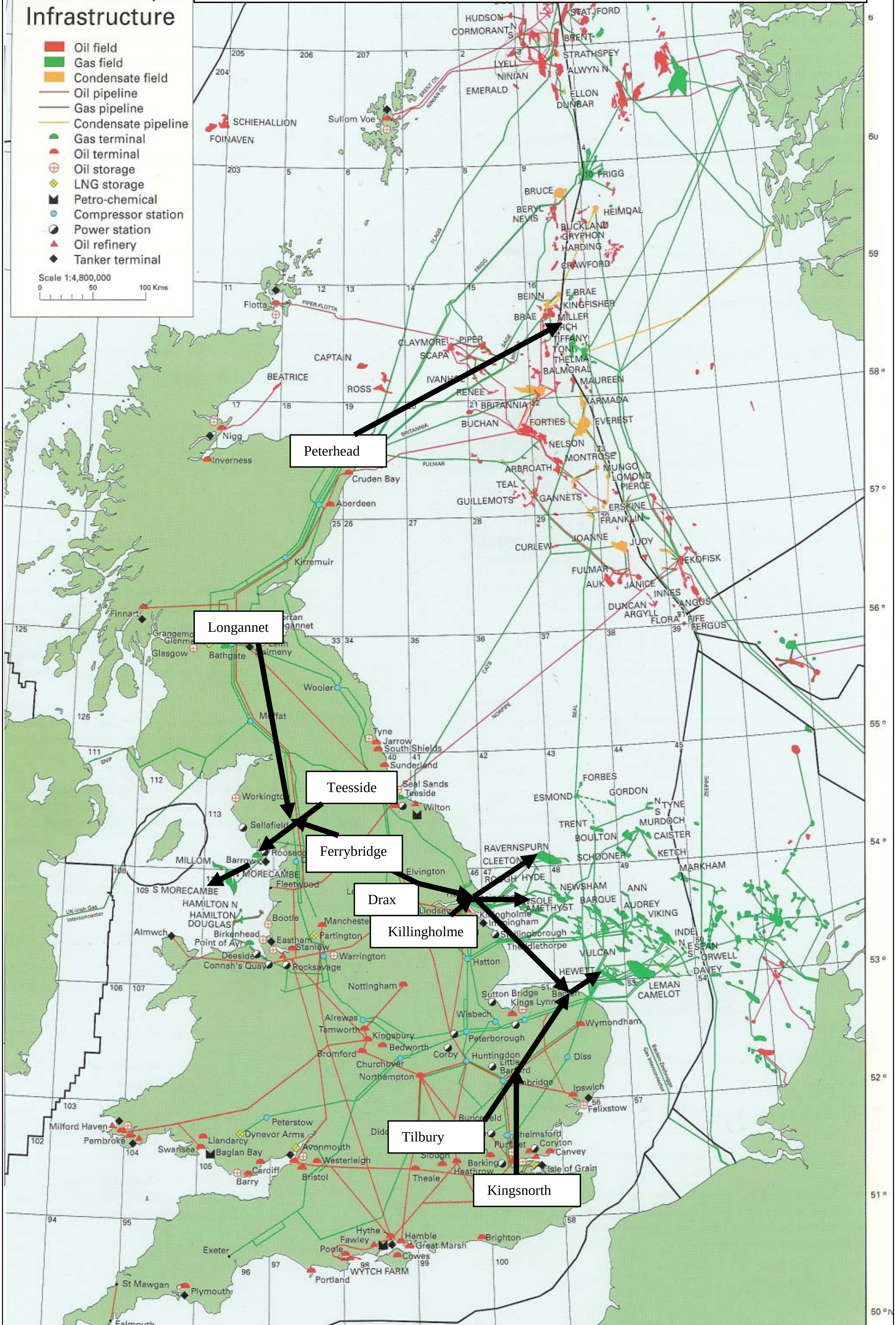
The average capital cost in the entire ten pipeline routes of this scenario ranges between £1.44 to about £8.83/tonne/100 km. The average capital cost function is presented graphically in Graph 6.

Graph 6: UKCS: CO_2 pipeline transportation average cost curve: Scenario 4



A conceptual CO_2 pipeline transportation network based on Scenario 4's model solutions is presented below in Map 5.

Map 5: Conceptual CO_2 Pipeline routes in Scenario 4



6. A brief comparative analysis

A brief comparative analysis of the four scenarios is undertaken below at the two levels of implementation cost implications and contribution to climate change mitigation efforts. The comparisons are summarised in Tables 15 and Graph 7.

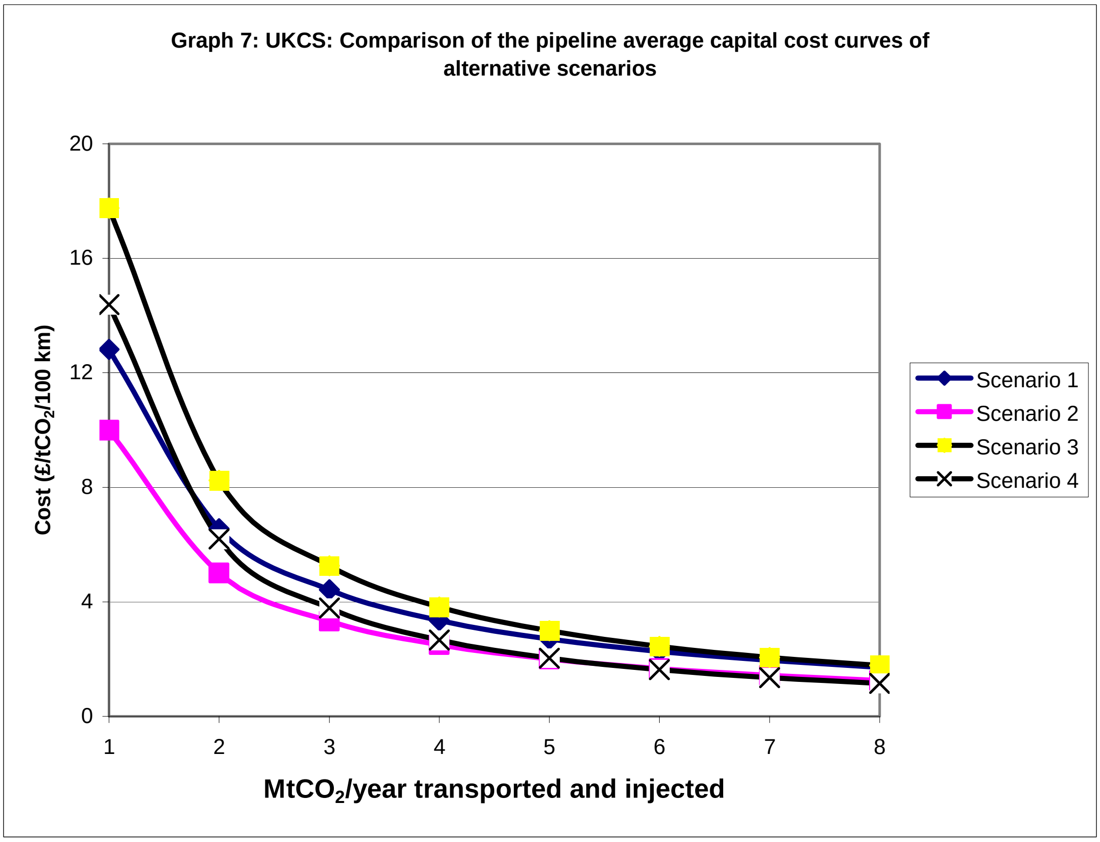
(a) Volumes of CO_2 shipped and pipeline lengths

Table 15: Comparative pipe diameters (in mm) by pipeline lengths (in km) and total CO_2 shipments ($MtCO_2$) under alternative scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
diameter (mm)				
272			341	
282			228	
291		146		
311		341		
318			139	
355		234		234
357		140		
368	139			
372	137	137	137	137
378			140	
384	94	94	94	94
402			146	146
429		436		
451				159
452	153	153	153	
467			436	
483				168
497	204	204	204	204
504	227	227	227	227
517	436			
550				246
566				140
630			456	
762		456		
915	456			
Total length (km)	**1846**	**2568**	**2701**	**1755**
Total CO_2 conveyed ($MtCO_2$)	**622**	**831**	**612**	**831**
CAPEX (£ billion)	**4.0**	**5.0**	**5.4**	**3.5**
Average cost range (£/tCO_2/100 km)	**1.00 - 5.00**	**0.80 - 6.00**	**2.48 - 9.39**	**1.44 - 8.83**

It is clear from Table 15 that, in addition to the cost comparisons already discussed, the cumulative total volume of CO_2 transported and injected in Scenarios 2 and 4 is about 831 $MtCO_2$ in each case. Thus, more CO_2 is removed from the atmosphere in these two scenarios than in Scenarios 1 and 3. Accordingly, from the perspective of their contribution to the goals of climate change mitigation, Scenarios 2 and 4 are preferable.

(b) Transport costs



Graph 7 puts together the average capital cost functions of the pipelines under the four scenarios. It shows that distinct capital cost characteristics are discernible. The curves show that substantial economies of scale are present in the model solutions of the four scenarios. However, Scenario 2 is the least costly while Scenario 3 is the most expensive.

7. Conclusions

Using the standard linear programming technique to solve the CO_2 transportation problem, this study has attempted to make a contribution to the understanding of a rational transport network to support major long term development of CCS in the United Kingdom. The existence of a CO_2 transport infrastructure was identified in IEA (2008) as an important stimulus for "an order of magnitude increase" in the take off of CO_2-EOR.

The scenario analysis conducted in the study to investigate the sensitivities of investments in CO_2 transportation and injection to their timing and scale, concluded that Scenario 2 would generate the least average capital transport cost. The main assumptions of Scenario 2 are a uniformly accelerated CO_2-EOR start date, and the development of CO_2-EOR projects that can accommodate a modestly ambitious minimum annual injectivity of 3 $MtCO_2$/year. The superiority of Scenario 2 supports the proposition that (a) CO_2-EOR oil revenues can be used to accelerate CCS deployment[19] in the UK/UKCS, provided that deliberate and conscious efforts are made to start CO_2-EOR early; and, (b) project size or annual CO_2 injectivity levels matter. While it makes economic sense to focus on the large CCS projects at first, care ought to be taken not to "oversize" or seriously mismatch the capacities of CO_2 sources and sinks.

[19] This result is similar to the finding in Leach, Mason and Veld (2008) for a hydrocarbon province in USA.

The present study focused on issues relating only to the least-cost determination of CO_2 transportation pipeline network configuration, assuming that the eight power plants whose CCS investment plans are in the public domain are the sources of captured CO_2.

However, it is possible that other large stationary point sources of CO_2 may embrace CCS investments during the period. Because most of the large sinks (for examples, Forties, Hewett, Morecambe South and Brae) and sources (for examples, Drax, Longannet, Teesside, Kingsnorth, and Ferrybridge) are already optimally matched in the present model solutions, it is expected that the effects of adding new CO_2 sources on the implied pipeline configuration would be complementary. That is, provided the eight power plants have the assumed head start, additional sources would build on the main features of the optimised pipeline network configuration of the present study.

The viability of CCS projects depends not only on transport costs, but also on the favourable comparison of the overall costs of CO_2 capture, transport, and injection against the revenues derivable from the CO_2-EOR-induced incremental oil and/or commercialised permanent storage activities.

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Appendix 1: Selection[20] criteria for application of CO2-miscible flood EOR

Reservoir Parameter	Geffen (1973)	Lewin et al. (1976)	NPC (1976)	McRee (1977)	Iyoho (1978)	OTA (1978)	Carcoana (1982)	Taber & Martin (1983)	Taber et al. (1997a)
Depth (ft)		>3000	>2300	>2000	>2500	i) >7200 ii) >5500 iii) >2500	<9800	>2000	i) >4000 ii) >3300 iii) >2800 iv) >2500
Temperature (°F)		NC	<250				<195	NC	
Initial Pressure (psia)	>1100	>1500					>1200		
Oil Gravity (°API)	>30	>30	>27	>35	30-45	i) <27 ii) 27-30 iii) >30	>40	>26	i) 22-27.9 ii) 28-31.9 iii) 32-39.9 iv) >40
Fraction of Remaining Oil	0.25	0.25		0.25	0.25		>30	0.30	0.20
Viscosity (cP)	<3	<12	<10	<5	<10	<12	<2	<15	<10
Permeability (mD)		NC		>5	>10		>1	NC	

[20] The values presented in this table are in imperial units, as reported in the original papers by the respective authors. NC stands for "Not a Criterion".

APPENDIX 2: ESTIMATING THE WINDOW OF OPPORTUNITY FOR CO_2 EOR and CO_2 PERMANENT STORAGE IN SELECTED FIELDS IN THE UKCS

Assumptions: $40/bbl; 36ppth; 10% hurdle rate

		2005 Production		Forecast COP dates		Forecast COP Production	
Field Name	**Location**	**oil (tbd)**	**gas (mmcfd)**	**oil (year)**	**gas (year)**	**oil (tbd)**	**gas (mmcfd)**
1Hewett	SNS	0.10	34.70	2007	2008	0.10	23.80
2Morecambe South	IS	1.00	550.00	2008	2021	1.00	25.20
3Arthur	SNS	0.56	85.52	2009	2010	0.03	3.76
4Baird	SNS	0.00	81.21		2010	0.00	29.00
5Nuggets	NNS	0.01	173.56	2010	2011	0.01	15.04
6Galleon	SNS	0.13	109.68	2011	2027	0.00	6.87
7Brae East	NNS	3.85	257.07	2012	2012	1.16	44.72
8Liverpool Bay	IS	36.34	237.60	2012	2012	4.57	62.78
9Morecambe North	IS	0.29	156.00	2012	2012	0.07	19.00
10Indefatigable	SNS	0.02	77.68		2013	0.00	7.00
11Lomond	CNS	2.70	142.19	2013	2013	0.89	29.70
12Minerva	SNS	0.28	74.98	2013	2013	0.06	13.72
13Neptune	SNS	0.37	86.18	2013	2015	0.03	5.17
14Scoter	CNS	5.48	123.32	2013	2013	0.26	13.79
15MacCulloch	MF	22.95	7.17	2014	2013	1.92	0.01
16Skene	NNS	3.30	81.32	2014	2014	0.09	1.96
17Armada group	CNS	8.11	169.60	2015	2015	0.21	3.62
18Brae	NNS	13.32	140.74	2015	2014	2.66	2.05
19Brent	NNS	40.94	279.07	2015	2011	0.01	3.10
20Broom	NNS	27.25	0.00	2015		1.65	0.00
21Fulmar	CNS	4.67	0.00	2015	2015	0.02	0.00
22Goldeneye	CNS	37.24	280.83	2015	2015	1.94	19.28
23Harding	NNS	21.22	0.00	2015	2015	0.62	82.78
24Beryl	NNS	27.24	71.87	2016	2016	8.34	47.30
25Blake	NNS	24.09	4.91	2016	2016	1.68	0.92
26Braemar	NNS	5.24	54.45	2017	2017	0.60	2.03
27Erskine	CNS	12.91	65.64	2017	2017	1.15	6.65
28Everest	CNS	3.78	115.37	2017	2017	0.00	0.25
29Jade	CNS	15.94	177.52	2018	2018	1.17	15.29
30Judy	CNS	17.82	158.60	2018	2018	0.05	1.51
31Carrack	SNS	1.36	92.30	2019	2020	0.13	5.66
32Magnus North West	NNS	35.16	21.10	2019	2019	12.48	38.88
33Marnock	CNS	3.27	78.53	2019	2019	0.39	5.03
34Shearwater	CNS	28.91	143.00	2019	2019	0.08	0.07
35West Sole	SNS	0.00	50.39		2019	0.00	17.44

36Bittern	CNS	44.54	32.98	2020	2020	1.97	1.97
37Gryphon	NNS	22.45	0.00	2020	2020	1.00	55.00
38Heron	CNS	8.77	52.40	2020	2020	2.53	1.26
39Bruce	NNS	28.84	414.55	2021	2021	0.08	2.90
40Grant	NNS	2.78	54.33	2021	2021	0.26	8.38
41Captain	MF	53.26	8.13	2022	2022	7.18	1.41
42Mungo	CNS	32.98	15.46	2022	2022	1.55	6.03
43Alwyn North	NNS	12.20	147.91	2023	2023	1.72	24.07
44Dunbar	NNS	29.44	68.40	2023	2023	3.17	24.31
45Skiff	SNS	0.04	65.46	2025	2025	0.01	12.90
46Claymore	MF	23.69	0.00	2026		6.79	0.00
47Leman	SNS	0.17	232.71	2026	2026	0.01	39.93
48Ninian	NNS	35.39	0.00	2026	2026	7.89	0.00
49Forties	CNS	68.20	2.00	2027	2025	3.36	0.21
50Sean	SNS	0.10	100.06	2027	2028	0.02	8.48
51Alba	MF	59.85	7.58	2028	2010	3.65	0.34
52Millom	IS	0.00	67.90		2028	0.00	2.81
53Britannia	MF	22.20	530.40	2034	2034	0.20	5.00
54 Franklin	CNS	114.47	484.77	2034	2034	2.64	22.24
55Nelson	CNS	49.41	12.01	2034	2034	0.33	0.95
56Pierce	CNS	24.41	0.00	2035	2035	2.44	47.79