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**A Futuristic Least-cost Optimisation Model of CO<sub>2</sub>  
Transportation and Storage in the UK/UK  
Continental Shelf (UKCS)**

Professor Alexander G. Kemp and  
Dr Sola Kasim

March, 2009

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**DEPARTMENT OF ECONOMICS**

## **NORTH SEA ECONOMICS**

Research in North Sea Economics has been conducted in the Economics Department since 1973. The present and likely future effects of oil and gas developments on the Scottish economy formed the subject of a long term study undertaken for the Scottish Office. The final report of this study, The Economic Impact of North Sea Oil on Scotland, was published by HMSO in 1978. In more recent years further work has been done on the impact of oil on local economies and on the barriers to entry and characteristics of the supply companies in the offshore oil industry.

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A Futuristic Least-cost Optimisation Model of CO<sub>2</sub> Transportation and Storage  
in the UK/UK Continental Shelf (UKCS)

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And  
Dr Sola Kasim

| <u>Contents</u>  | <u>Page</u> |
|--|-------------|
| 1. Introduction .....  | 1           |
| 2. Methodology .....   | 2           |
| (i) The objective function.....  | 3           |
| (ii) CO <sub>2</sub> supply-side constraints .....                             | 3           |
| (iii) CO <sub>2</sub> demand-side constraints .....                            | 4           |
| (iv) rational pipeline utilisation constraints .....                           | 5           |
| (v) Non-negativity constraint.....   | 5           |
| 3. The Data .....  | 5           |
| (a) Time horizon for Study.....  | 5           |
| (b) Sources of Captured CO <sub>2</sub> .....                                  | 6           |
| (c) CO <sub>2</sub> sinks .....  | 9           |
| (d) Characterisation of pipelines in the UKCS and elsewhere .....              | 12          |
| (e) Source-to-sink distances: .....  | 17          |
| 4. Scenario Analysis .....   | 19          |
| (i) Scenario 1: Higher injectivity, with accelerated EOR start date .....      | 19          |
| (ii) Scenario 2: Lower injectivity with accelerated EOR start dates.....       | 20          |
| (iii) Scenario 3: Higher injectivity with COP-determined EOR start dates ..... | 20          |
| (iv) Scenario 4: Lower injectivity with COP date-determined EOR start dates..  | 20          |
| 5. Results: .....  | 20          |
| 6. A brief comparative analysis.....   | 45          |
| (a) Volumes of CO <sub>2</sub> shipped and pipeline lengths .....              | 45          |
| (b) Transport costs .....  | 46          |
| 7. Conclusions .....   | 47          |

# **A Futuristic Least-cost Optimisation Model of CO<sub>2</sub> Transportation and Storage in the UK/UK Continental Shelf (UKCS)**

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## **1. Introduction**

After capture, the next stage in the CCS value chain is transporting the CO<sub>2</sub> to sinks for either permanent storage or use in CO<sub>2</sub>-EOR flooding with subsequent permanent storage.

Worldwide, several projects involving CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> storage potential in the UK Continental Shelf (UKCS), given the rather limited onshore CO<sub>2</sub> capture potential which preliminary studies have identified.

In the study, CO<sub>2</sub> 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<sub>2</sub> transportation – namely, the when, where, and how much of CO<sub>2</sub> 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<sub>2</sub> from  $i$  ( $i = 1, 2, \dots, m$ ) capture sources to  $j$ , CO<sub>2</sub>-EOR- ( $j = 1, 2, \dots, w$ ) and  $k$  Permanent storage- sinks ( $k = 1, 2, \dots, z$ ) or destinations<sup>1</sup>. The approach of the model is useful for matching sources to sinks and determining CO<sub>2</sub> 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<sub>2</sub> Pipeline Transport and Cost Model (2007)

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<sup>1</sup>  $w + z = n$  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<sub>2</sub> 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:**

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

where:

$coer_{i,j}$  = the unit cost of transporting CO<sub>2</sub> from source *i* to EOR sink *j*

$xeor_{i,j}^t$  = the quantity of CO<sub>2</sub> transported from source *i* to EOR sink *j* at time *t*

$cperm_{i,k}$  = the unit cost of transporting CO<sub>2</sub> from source *i* to Permanent Storage sink *k*

$xperm_{i,k}^t$  = the quantity of CO<sub>2</sub> 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<sub>2</sub> supply-side constraints**

$$\sum_{j=1}^w xeor_{i,j}^t + \sum_{k=1}^z xperm_{i,k}^t = sup_i^t \quad (2)$$



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

where:

$sup_i^t$  = the CO<sub>2</sub> supply capacity limit of source plant  $i$  at time  $t$

$surp_i^t$  = excess supply of CO<sub>2</sub> of the  $i^{th}$  plant at time  $t$

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

### (iii) CO<sub>2</sub> 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<sub>2</sub> required for injection at EOR sink  $j$  at time  $t$

$demperm_k^t$  = the annual volume of CO<sub>2</sub> required for injection at Permanent storage sink  $k$  at time  $t$

Given the possibility that system's CO<sub>2</sub> storage capacity may exceed its supply capacity, then according to equations 4 and 5, at the plant level, the respective volumes of CO<sub>2</sub> required for injection into EOR

and Permanent Storage sinks must be equal to the sum of the CO<sub>2</sub> 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<sub>2</sub> 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**

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

### 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.

| <u>Time period</u> | <u>Median year</u> | <u>Investment cycle</u> |
|--------------------|--------------------|-------------------------|
| 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<sub>2</sub>

In the study CO<sub>2</sub> is captured and shipped from 8 out of the top 100 large stationary point sources in the UK identified in Map 1<sup>2</sup>. The stationary point sources are the 8 power plants where CO<sub>2</sub> 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<sub>2</sub> supply capacity of the  $i^{th}$  captured-CO<sub>2</sub> source at time  $t$ ,  $sup(i, t)$ , are presented in Table 1.

**Table 1: CO<sub>2</sub> supply capacities (MtCO<sub>2</sub>/year)**

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

*Sources of the planned initial CO<sub>2</sub> 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

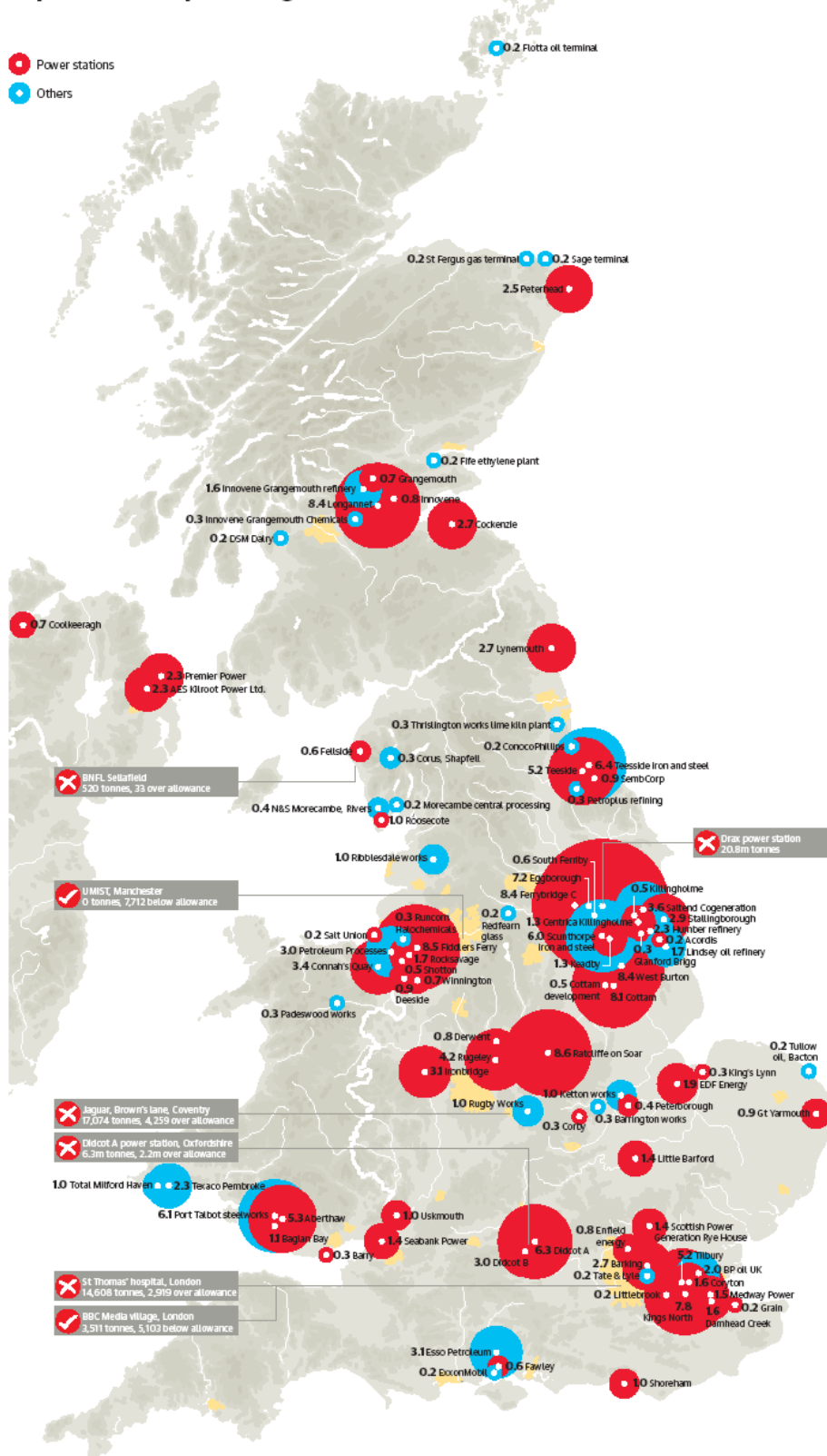
<sup>2</sup> See Guardian (16<sup>th</sup> May 2006).

- (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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> Emission Sites in the UK

Top 100 carbon-producing sites. Emissions in million tonnes CO<sub>2</sub>



Source: The Guardian Unlimited, 16<sup>th</sup> May 2006

### (c) CO<sub>2</sub> sinks

CO<sub>2</sub> capture investments serve the end of removing anthropogenic CO<sub>2</sub> from the atmosphere. To accomplish this, the captured CO<sub>2</sub> has to be stored in either one of 2 storage type sinks– namely those that allow CO<sub>2</sub> to be deployed in intermediate applications such as CO<sub>2</sub>-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<sub>2</sub>-EOR and permanent storage potentials, arriving at an estimated total “realistic” storage capacity of 7529 MtCO<sub>2</sub><sup>3</sup>. Assuming that the initial CO<sub>2</sub> 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<sub>2</sub>. Next, Bachu’s screening criteria (Bachu, 2004)<sup>4</sup>, 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<sup>5</sup> potential sinks<sup>6</sup> 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<sub>2</sub>-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<sub>2</sub> 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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<sup>3</sup> Broken down into 1175 MtCO<sub>2</sub> in oilfields, 5138 MtCO<sub>2</sub> in gas fields and 1216 MtCO<sub>2</sub> in gas/condensate fields.

<sup>4</sup> See Appendix 1 for more details on the screening criteria.

<sup>5</sup> Counting the Brae and Brae East fields as one Brae complex.

<sup>6</sup> The present study excluded saline aquifers as potential sinks.

Table 2 presents some data on the selected sinks.

**Table 2: CO<sub>2</sub> Storage Capacity of Selected Sinks**

| Sinks                        | Latitude | Longitude        | Storage Capacity (MtCO <sub>2</sub> ) | Possible COP dates | Eventual CO <sub>2</sub> storage capacity (MtCO <sub>2</sub> ) |
|------------------------------|----------|------------------|---------------------------------------|--------------------|--|
| (1)                          | (2)      | (3)              | (4)                                   | (5)                | (6)  |
| <b>1. CO<sub>2</sub>-EOR</b> |          |                  |                                       |                    |  |
| 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 <sup>7</sup>  | 53   |
| Nelson                       | 57.40    | 1.10             | 66*                                   | 2028               | 64   |
| Ninian                       | 60.75    | 1.46             | 213*                                  | 2024               | 185  |
|                              |          | <b>Sub-total</b> | <b>1108</b>                           |                    | <b>789</b>   |
| <b>2. Permanent storage</b>  |          |                  |                                       |                    |  |
| 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  |
|                              |          | <b>Sub-total</b> | <b>4104</b>                           |                    | <b>3180</b>  |

**Sources:**

- (a) Column 4: BGS (2006)
- (b) \* Authors' own calculations<sup>8</sup>
- (c) Column 5: Authors' own calculations derived from A.G. Kemp and L. Stephen (2007)
- (d) Column 6: Authors' own calculations

<sup>7</sup> 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.

<sup>8</sup> Using the data, assumptions and the following formula in BGS (2006):

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

where:

MCO<sub>2</sub> = CO<sub>2</sub> storage capacity

URR<sub>oil</sub> = volume of ultimately recoverable oil at standard temperature and pressure (10<sup>9</sup>m<sup>3</sup>)

B<sub>0</sub> = oil formation volume factor

ρCO<sub>2</sub> = density of CO<sub>2</sub> at reservoir conditions (kgm<sup>-3</sup>)

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<sup>9</sup>.

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<sub>2</sub> 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<sub>2</sub> 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<sup>10</sup>.

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<sup>11</sup>. Based on the knowledge that not all the storage capacity in column 4 would be available for CO<sub>2</sub> 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<sub>2</sub> that can eventually be stored at the start of CO<sub>2</sub> 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.

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<sup>9</sup> It is understood that fields in the UKCS can be reopened for CO<sub>2</sub> storage or EOR purposes, but this adds to costs.

<sup>10</sup> The data on the estimated COP dates are presented in Appendix 2.

<sup>11</sup> 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<sub>2</sub> would be transported in the opposite direction, some of the pipelines and their terminals could be re-used in CO<sub>2</sub> transportation. In any case, they would still be required to convey onshore any CO<sub>2</sub>-EOR oil that may be produced in CCS projects.

To provide the context for a possible CO<sub>2</sub> 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**

| <i>Length (km)</i>          |          |
|-----------------------------|----------|
| 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<br>(95.0%) | 49.72    |

**Histogram of the lengths of the UKCS offshore-onshore pipelines**

| Bin Range (km) | Frequency |
|----------------|-----------|
| 50-100         | 8         |
| 100-150        | 11        |
| 150-200        | 2         |
| 200-250        | 3         |
| 250-300        | 1         |
| 300-350        | 1         |
| 350-400        | 1         |
| 400-450        | 3         |
| 450-500        | 2         |

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**

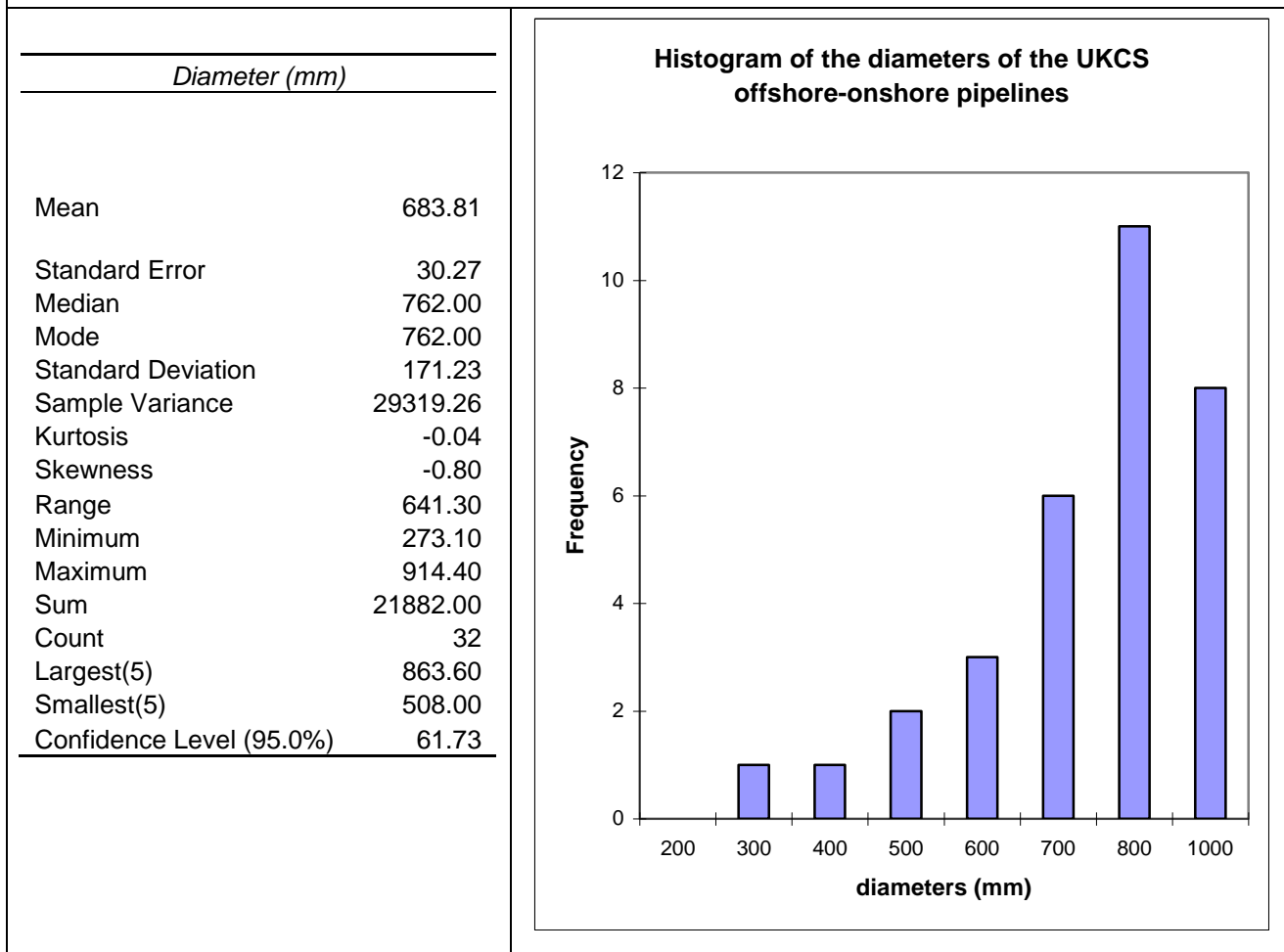


Table 4 shows that the pipeline diameters range from 273 to 914 mm. The modal diameter is 762mm while the mean and median diameters are 684 and 762 mm respectively. The histogram reveals that about 88 percent of the pipelines have diameters in excess of 600 mm.

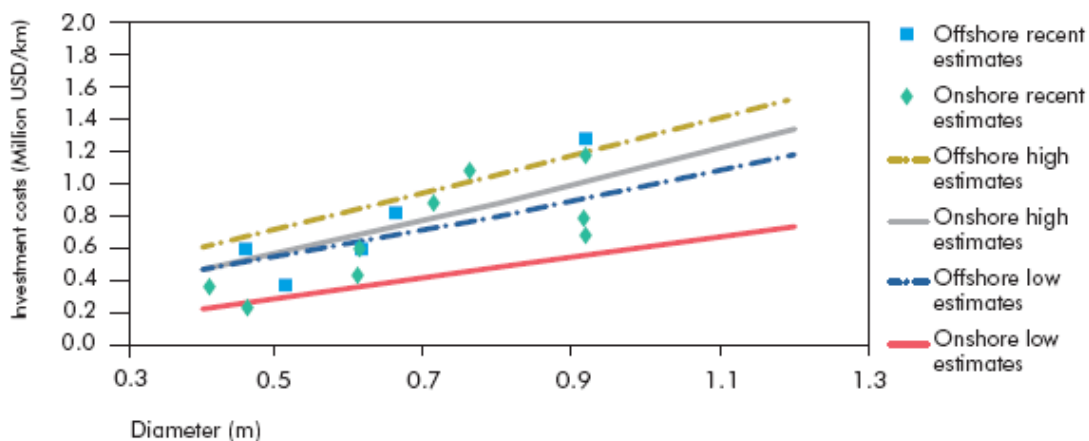
In the United Kingdom, the CO<sub>2</sub> transportation pipelines can consist of both new build and re-used ones. Expected pipeline transportation costs depend on a number of factors (see IPCC, 2005) including construction costs, the age structure of the pipelines, the source-to-sink distance,

geography (onshore/offshore lengths), pipeline diameters, and the material conveyed (dry or wet CO<sub>2</sub>).

Given the relatively distant COP dates of many of the producing fields in the CNS and NNS, most of the pipelines conveying CO<sub>2</sub> 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.

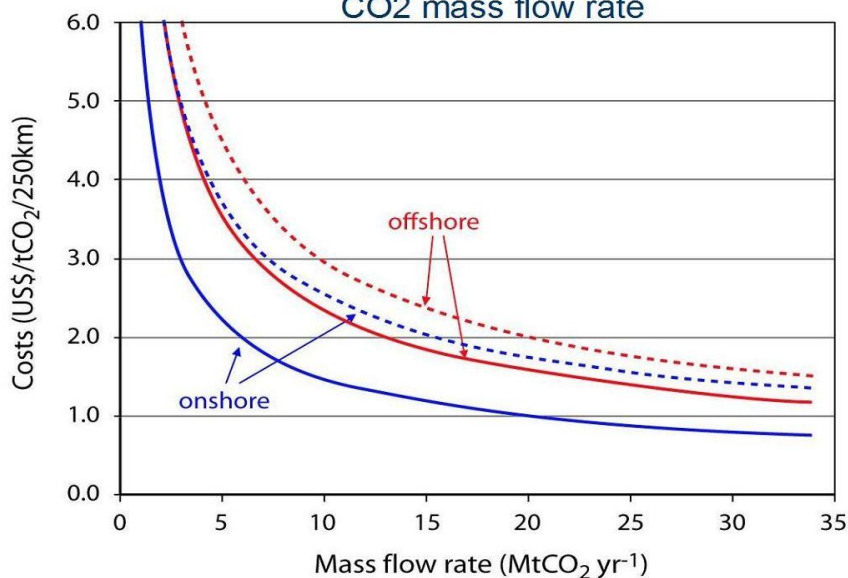
Source: IEA, 2008c.

Detailed construction costs of CO<sub>2</sub> pipelines in the UK/UKCS are not available because none has been constructed to date. The present study assumed that a new-build CO<sub>2</sub> pipeline transportation (of an average 0.762m or about 28-inch<sup>12</sup> 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<sub>2</sub> transportation.

Graph 2:

Costs for onshore pipelines and offshore pipelines as a function of the CO<sub>2</sub> mass flow rate



Source: IPCC (2005)

<sup>12</sup> 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<sub>2</sub> 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<sup>13</sup>. The data on the source-to-sink distances are in Table 5.

---

<sup>13</sup> Haversine formula:  $d = R.c$

where:

$R$  = earth's radius (mean radius = 6,371 km)

$c = 2 \cdot \text{atan2}(\sqrt{a}, \sqrt{1-a})$

$a = \sin^2(\Delta\text{latitude}/2) + \cos(\text{latitude1}) \cdot \cos(\text{latitude2}) \cdot \sin^2(\Delta\text{longitude}/2)$

$\Delta\text{latitude} = \text{latitude2} - \text{latitude1}$

$\Delta\text{longitude} = \text{longitude2} - \text{longitude1}$

**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 | Hewlett | Indefatigable | Raven spum | 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<sub>2</sub> transportation pertaining to (a) investment timing and (b) assumptions on the minimum annual CO<sub>2</sub> injectivity levels. CO<sub>2</sub> 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<sub>2</sub>-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<sub>2</sub> and the consequent pipeline network configuration and costs. A scenario analysis was conducted to investigate the most economical way to distribute the captured CO<sub>2</sub> under four scenarios, assuming two alternative CO<sub>2</sub>-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<sub>2</sub>-EOR injectivity level of 5 MtCO<sub>2</sub>/year injectivity level is assumed. Furthermore, it is assumed that CO<sub>2</sub>-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<sub>2</sub>-EOR sink must have a minimum annual injectivity capacity of 5 MtCO<sub>2</sub>/year, if primary CO<sub>2</sub>-EOR injection is carried out over a 15-year period. CO<sub>2</sub> 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<sub>2</sub>/year.

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

Scenario 3 uses the assumption that the CO<sub>2</sub>-EOR flooding starts 2 years before the COP date of each selected field with the higher minimum annual injectivity of 5 MtCO<sub>2</sub>/year. CO<sub>2</sub> 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<sub>2</sub>/year.

## **5. Results:**

Given the model, data parameters, and scenario assumptions, the model solutions determined the quantities of CO<sub>2</sub> transported into EOR 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: Origination, destinations and volumes of CO<sub>2</sub> transported and injected in Scenario 1**

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

The results of the *system-wide* optimisation of CO<sub>2</sub> transportation costs for Scenario 1 are shown in Table 6. They shed light on some of the

issues concerned with CO<sub>2</sub> transportation and sequestration in the UK/UKCS.

CO<sub>2</sub> shipments over relatively long distances such as those from Drax to Forties (conveying between 8 and 20 MtCO<sub>2</sub>/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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> shipments and yielded the following result:

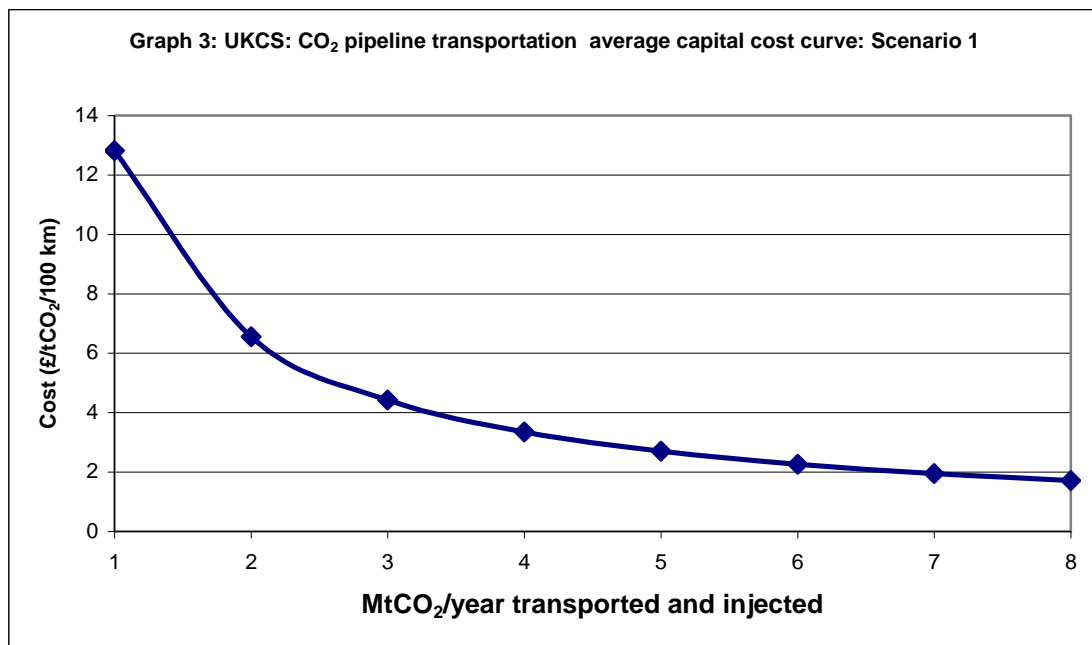
$$\ln(\text{total CAPEX}) = 2.273 + 0.886\ln(\text{cumulative CO}_2 \text{ shipment volumes})$$

(3.036)    (5.005)                    adjustedR<sup>2</sup> = 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.



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<sup>14</sup>, and minimisation of system-wide costs throughout the study period, are the reasons why Drax can ship CO<sub>2</sub> to Forties instead of to nearer sinks,

<sup>14</sup> For example, without CO<sub>2</sub> deliveries from the largest CO<sub>2</sub> capture plant (Drax), Forties' injectable maximum 20 MtCO<sub>2</sub>/year would have been met from smaller capture plants at higher costs to the overall system.

such as Morecambe South. CO<sub>2</sub> deliveries are made to Morecambe South from Teesside (181 km) in this scenario.

One effect of promoting only the large CO<sub>2</sub>-EOR projects capable of handling a minimum annual injectivity of 5 MtCO<sub>2</sub>/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<sub>2</sub> allocations from the sources. In the event, the model solution allocated the captured CO<sub>2</sub> 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<sub>2</sub> deliveries and injection levels diverge from the minimum injectivity level. The divergence is inevitable given that the CO<sub>2</sub> 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<sub>2</sub>/year in any case.

Also, it is noteworthy that cumulative shipments of CO<sub>2</sub> in excess of 100 MtCO<sub>2</sub> would be delivered to two sinks –one CO<sub>2</sub>-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<sub>2</sub> while Hewett would receive roughly 115 MtCO<sub>2</sub> from the power plants at Kingsnorth and Tilbury. Brae is the third largest repository of CO<sub>2</sub> in this scenario.

The annual CO<sub>2</sub> mass flow rate rates range between 3 MtCO<sub>2</sub>/year to about 14 MtCO<sub>2</sub>/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**

| <b>Source</b> | <b>Sink</b>     | <b>estimated diameters (mm)</b> | <b>estimated diameters (inches)</b> |
|---------------|-----------------|---------------------------------|-------------------------------------|
| 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.

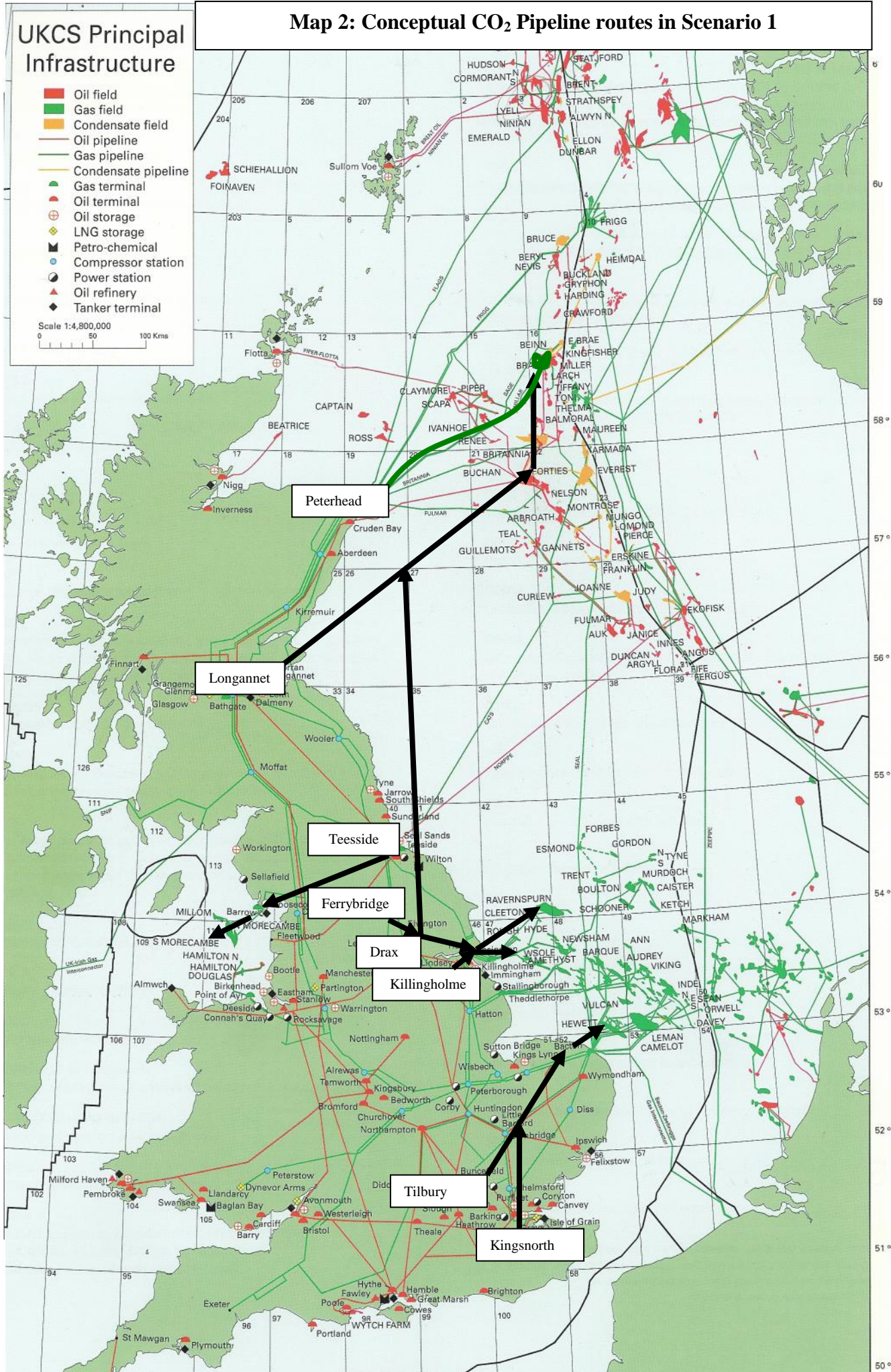
The total CAPEX required in this scenario is about £4bn for pipeline lengths varying from 94 km to 456 km, and diameters varying from 368 to 915 mm. The average capital cost varies from £1 to about £5/tonne/100 km.

Having identified the pipeline routes in this scenario a conceptual pipeline network configuration based on the model solutions is presented in Map 2<sup>15</sup>.

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<sup>15</sup> 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<sub>2</sub> Pipeline routes in Scenario 1





*Scenario 2: Accelerated CO<sub>2</sub>-EOR start date (3 MtCO<sub>2</sub>/year minimum injectivity)*

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

| 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         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>8.33</b>  | <b>10.66</b> | <b>15.00</b> | <b>20.66</b> |
| Ferrybridge        | Ravenspurn               | 153           | perm             | Easington         | 2.41         | 3.38         | 4.34         | 5.98         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>2.41</b>  | <b>3.38</b>  | <b>4.34</b>  | <b>5.98</b>  |
| Killingholme       | West Sole                | 94            | perm             | Easington         | 1.53         | 2.15         | 2.76         | 3.80         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.53</b>  | <b>2.15</b>  | <b>2.76</b>  | <b>3.80</b>  |
| Kingsnorth         | Hewett                   | 204           | perm             | Bacton            | 3.02         | 4.23         | 5.44         | 7.49         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.02</b>  | <b>4.23</b>  | <b>5.44</b>  | <b>7.49</b>  |
| Longannet          | Brae (East)              | 436           |                  |                   | 3.70         | 3.70         | 3.95         | 6.47         |
| Longannet          | Forties                  | 341           | perm             |                   |              | 1.48         | 2.71         | 2.71         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.70</b>  | <b>5.18</b>  | <b>6.66</b>  | <b>9.18</b>  |
| Peterhead          | <b>Miller</b>            | 234           | <b>eor</b>       | Peterhead         | 1.42         | 1.99         | 2.56         | 3.53         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.42</b>  | <b>1.99</b>  | <b>2.56</b>  | <b>3.53</b>  |
| Teesside           | Morecambe South          | 227           | perm             | Barrow-in-Furness | 3.14         | 4.39         | 5.65         | 7.78         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.14</b>  | <b>4.39</b>  | <b>5.65</b>  | <b>7.78</b>  |
| Tilbury            | Hewett                   | 137           | perm             | Bacton            | 1.46         | 2.05         | 2.63         | 3.63         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.46</b>  | <b>2.05</b>  | <b>2.63</b>  | <b>3.63</b>  |
| <b>Grand Total</b> |                          |               |                  |                   | <b>25.01</b> | <b>34.03</b> | <b>45.04</b> | <b>62.05</b> |

The results for Scenario 2 are shown in Table 8. There are a few instances of one source shipping CO<sub>2</sub> to more than one sink in this scenario. Source-to-multiple sinks deliveries occur in the model because once the annual CO<sub>2</sub> deliveries to and injection into a sink equal the sink's injectivity level for that year, any excess CO<sub>2</sub> available at the

supplying source is shipped to another sink. Thus, for example, while the injectivity levels at Brae are 3.70 MtCO<sub>2</sub>/year (2018-2022), 3.70 (2023-2027), 3.95 (2028-2032) and 6.47 MtCO<sub>2</sub>/year (2033-2037) the CO<sub>2</sub> supply capacities at Longannet during the corresponding period are 3.70, 5.18, 6.66 and 9.18 MtCO<sub>2</sub>/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<sub>2</sub> shipped from the sources to the various sinks in this scenario is about 831 MtCO<sub>2</sub> over the period to 2037, yielding an annual average shipment of about 42 MtCO<sub>2</sub>/year. Unsurprisingly, this is about the same as in Scenario 1 (41 MtCO<sub>2</sub>/yr). Interestingly, the same number of CO<sub>2</sub>-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<sub>2</sub>-EOR sinks, however, the Miller field replaced Claymore as the third CO<sub>2</sub>-EOR sink. Having qualified for inclusion in this scenario because it met the 3 MtCO<sub>2</sub>/year injectivity level criterion, Miller displaced Claymore as the destination of the CO<sub>2</sub> captured at Peterhead. CO<sub>2</sub> 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<sub>2</sub>, receiving a cumulative total of almost 300 MtCO<sub>2</sub> from two sources – Drax and Longannet – instead of the one source (Drax) in Scenario 1. The difference in the CO<sub>2</sub> transportation patterns is caused by the difference in the phasing of the

injection through time. In Scenario 1 the CO<sub>2</sub>-EOR injection period was reduced to 15 years, raising the minimum injectivity level, (hence pipe sizes) while the primary CO<sub>2</sub>-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<sub>2</sub>/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<sub>2</sub>/year, leaving Longannet with a potential ultimate excess supply capacity of about 3 MtCO<sub>2</sub>/year, hence the recourse to a second sink.

Ravenspurn and West Sole also receive CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> (especially CO<sub>2</sub>-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<sub>2</sub> injectivity levels with the pace of the supply capacity expansion. By contrast, Scenario 1 suffers a relative investment timing disadvantage because the accelerated CO<sub>2</sub>-EOR projects are “front-loaded”, requiring higher CO<sub>2</sub> injectivity levels (5 MtCO<sub>2</sub>/year) to be met in the first 15 years from 2018, when the system’s CO<sub>2</sub> 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 <sub>2</sub> ) | Cumulative CO <sub>2</sub> shipment (MtCO <sub>2</sub> ) |               | injection as % of injectivity |              |
|-----------|-------------------------------|--|--|---------------|-------------------------------|--------------|
|           |                               |  | Scenario 1   | Scenario 2    | Scenario 1                    | Scenario 2   |
| 1         | 2                             | 3  | 4  | 5             | 6                             | 7            |
| Brae      | Longannet                     | 117  | <b>93.66</b>   | <b>89.1</b>   | 80.05                         | 76.15        |
| Claymore  | Peterhead                     | 60   | <b>36.58</b>   |               | 60.97                         | 0.00         |
| Forties   | Drax                          | 282  | 193.94   | 247.5         |                               |              |
|           | Longannet                     |  |  | 34.5          |                               |              |
|           | <b>sub-total (Forties)</b>    | <b>282</b>                                     | <b>193.94</b>  | <b>282</b>    | 68.77                         | 100.00       |
| Hewett    | Kingsnorth                    | 381  | 77.7   | 100.9         |                               |              |
| Hewett    | Tilbury                       |  | 37.62  | 48.85         |                               |              |
|           | <b>sub-total (Hewett)</b>     | <b>381</b>                                     | <b>115.32</b>  | <b>149.75</b> | 30.27                         | 39.30        |
| Miller    | Peterhead                     | 53   |  | <b>47.5</b>   | 0.00                          | 89.62        |
| Morecambe | Teesside                      | 529  | <b>80.7</b>  | <b>104.8</b>  | 15.26                         | 19.81        |
| South     | Ferrybridge                   | 138  | 62.03  | 80.55         |                               |              |
|           | Drax                          |  |  | 16.1          |                               |              |
|           | <b>sub-total (Ravenspurn)</b> | <b>138</b>                                     | <b>62.03</b>   | <b>96.65</b>  | 44.95                         | 70.04        |
| West Sole | Killingholme                  | 125  | 39.43  | 51.2          |                               |              |
|           | Drax                          |  |  | 6.75          |                               |              |
|           | <b>sub-total</b>              | <b>125</b>                                     | <b>39.43</b>   | <b>57.95</b>  | 31.54                         | 46.36        |
|           | <b>Grand total</b>            | <b>1685</b>                                    | <b>621.66</b>  | <b>827.75</b> | <b>36.89</b>                  | <b>49.12</b> |

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<sub>2</sub> 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<sub>2</sub> 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**

| <b>Source</b> | <b>Sink</b>     | <b>estimated diameters (mm)</b> | <b>estimated diameters (inches)</b> |
|---------------|-----------------|---------------------------------|-------------------------------------|
| 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<sub>2</sub> 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<sub>2</sub> injection requirements at Forties (18.80 MtCO<sub>2</sub>/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<sup>16</sup>. 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<sub>2</sub> 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<sup>17</sup>:

$$(total\ CAPEX) = 284.8488 + 2.411(cumulative\ CO_2\ shipment\ volumes)$$

$$(3.036) \quad (2.535) \quad adjusted\ R^2 = 0.35$$

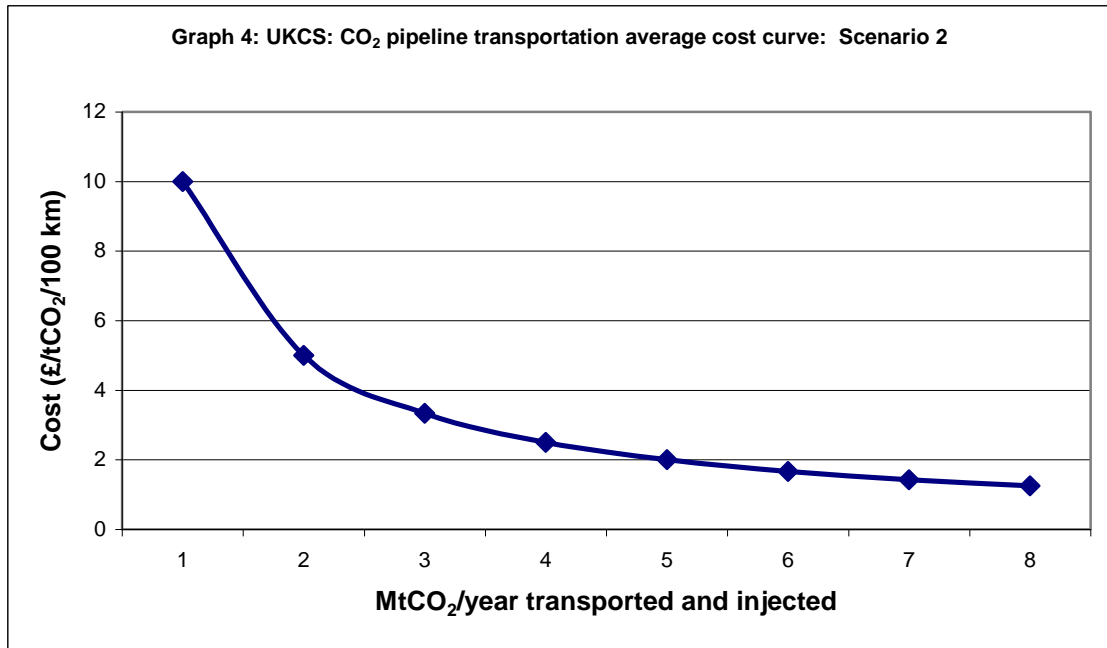
Thus, in spite of the apparent anomalies, the estimated scale economies at about 1.565 are more substantial in this scenario than in Scenario 1. The optimised average CO<sub>2</sub> transportation capital cost curve of this scenario is presented in Graph 4.

<sup>16</sup> The other ways and manners of disposal of the excess CO<sub>2</sub> are beyond the scope of the present study.

<sup>17</sup> For the interested reader, the estimated log-linear total cost function is:

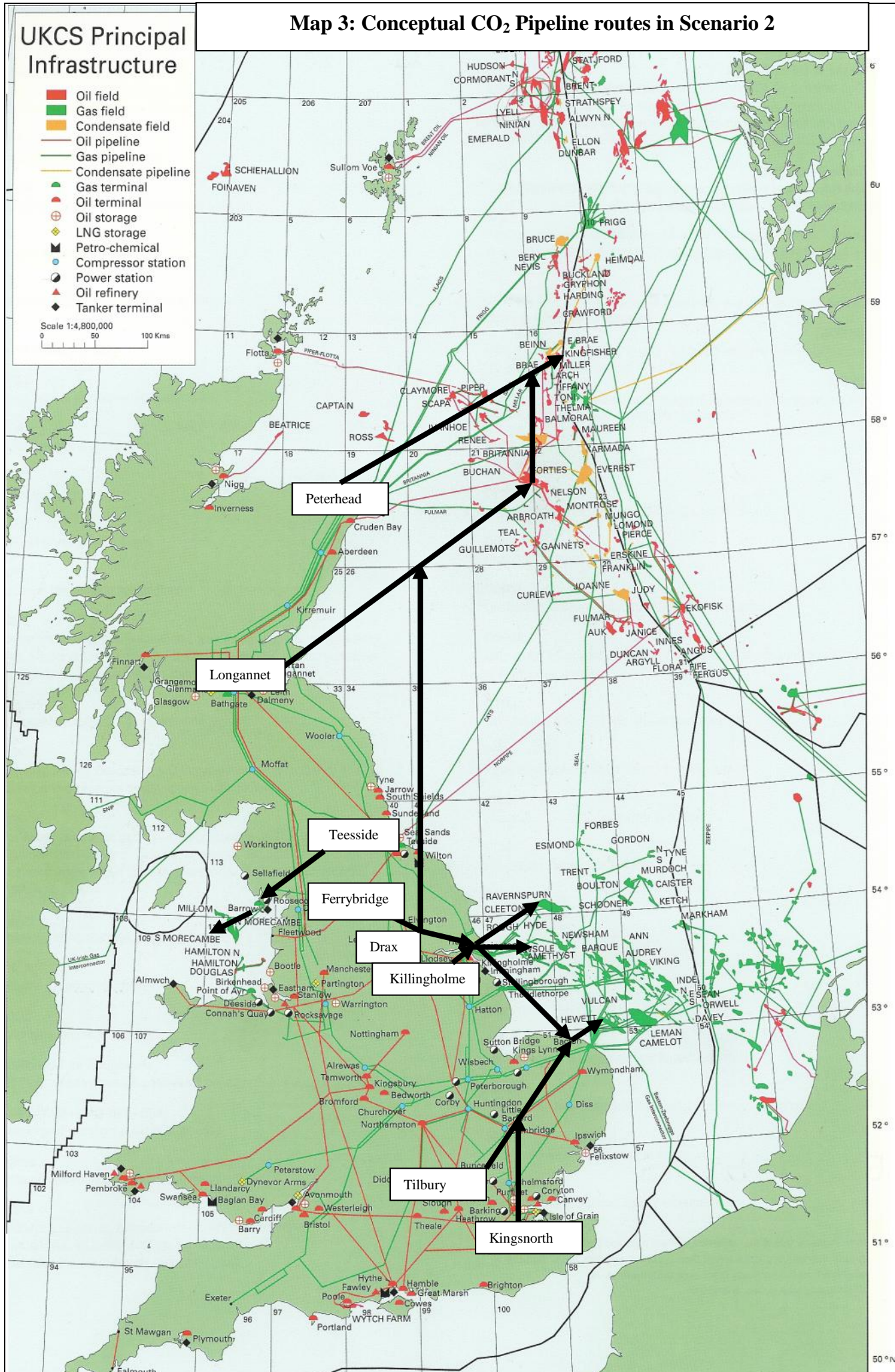
$$\ln(total\ CAPEX) = 4.969 + 0.266\ln(cumulative\ CO_2\ shipment\ volumes)$$

$$(8.171) \quad (1.783) \quad adjusted\ R^2 = 0.19$$



A conceptual CO<sub>2</sub> pipeline transportation network based on Scenario 2's model solutions is presented below in Map 3.

Map 3: Conceptual CO<sub>2</sub> 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<sub>2</sub> transported and injected in Scenario 3**

| Sources            | Pipelines only @<br>V <sub>t+1</sub> =V <sub>t</sub> | Distance<br>(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         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>8.33</b>  | <b>10.66</b> | <b>15.00</b> | <b>20.66</b> |
| Ferrybridge        | Ravenspurn   | 153              | perm             | Easington         | 2.41         | 3.38         | 4.34         | 5.98         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>2.41</b>  | <b>3.38</b>  | <b>4.34</b>  | <b>5.98</b>  |
| Killingholme       | West Sole  | 94               | perm             | Easington         | 1.53         | 2.15         | 2.76         | 3.80         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>1.53</b>  | <b>2.15</b>  | <b>2.76</b>  | <b>3.80</b>  |
| Kingsnorth         | Hewett   | 204              | perm             | Bacton            | 3.02         | 4.23         | 5.44         | 7.49         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>3.02</b>  | <b>4.23</b>  | <b>5.44</b>  | <b>7.49</b>  |
| Longannet          | Brae   | 436              | eor/perm         |                   | 3.70         | 3.70         | 5.05         | 7.57         |
|                    | Forties  | 341              | eor              |                   |              | 1.48         | 1.61         | 1.61         |
|                    | <b>Sub-total</b>                                     |                  |                  |                   | <b>3.70</b>  | <b>5.18</b>  | <b>6.66</b>  | <b>9.18</b>  |
| Peterhead          | Brae   | 228              | eor/perm         |                   | 1.42         | 1.42         | 1.42         | 1.42         |
|                    | <b>Claymore</b>                                      | 139              | <b>eor</b>       | Peterhead         |              | 0.57         | 1.14         | 2.10         |
|                    | <b>Sub-total</b>                                     |                  |                  |                   | <b>1.42</b>  | <b>1.99</b>  | <b>2.56</b>  | <b>3.52</b>  |
| Teesside           | Morecambe South                                      | 227              | perm             | Barrow-in-Furness | 3.14         | 4.39         | 5.65         | 7.78         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>3.14</b>  | <b>4.39</b>  | <b>5.65</b>  | <b>7.78</b>  |
| Tilbury            | Hewett   | 137              | perm             | Bacton            | 1.46         | 2.05         | 2.63         | 3.63         |
|                    |  |                  | <b>Sub-total</b> |                   | <b>1.46</b>  | <b>2.05</b>  | <b>2.63</b>  | <b>3.63</b>  |
| <b>Grand Total</b> |  |                  |                  |                   | <b>25.01</b> | <b>34.03</b> | <b>45.04</b> | <b>62.04</b> |

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<sub>2</sub>-EOR are driven by the COP dates of the fields, rather than via any deliberate effort to accelerate CO<sub>2</sub>-EOR start dates. Scenario 3 shares

some of the assumptions of Scenario I, particularly the assumption of a 5 MtCO<sub>2</sub>/year reservoir minimum injectivity.

The model solutions of this scenario are a hybrid of the earlier scenarios. Thus the three favoured CO<sub>2</sub>-EOR sinks are the Forties, Brae and Claymore fields while the permanent storage sinks and the respective CO<sub>2</sub> sources remain the same as well. Furthermore, the cumulative total volumes of CO<sub>2</sub> transported and injected at approximately 612 MtCO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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:

$$\ln(\text{total CAPEX}) = 13.765 - 4.827 \ln(\text{cum CO}_2 \text{ shipment}) + 0.711 \ln(\text{cum CO}_2 \text{ shipment})^2$$

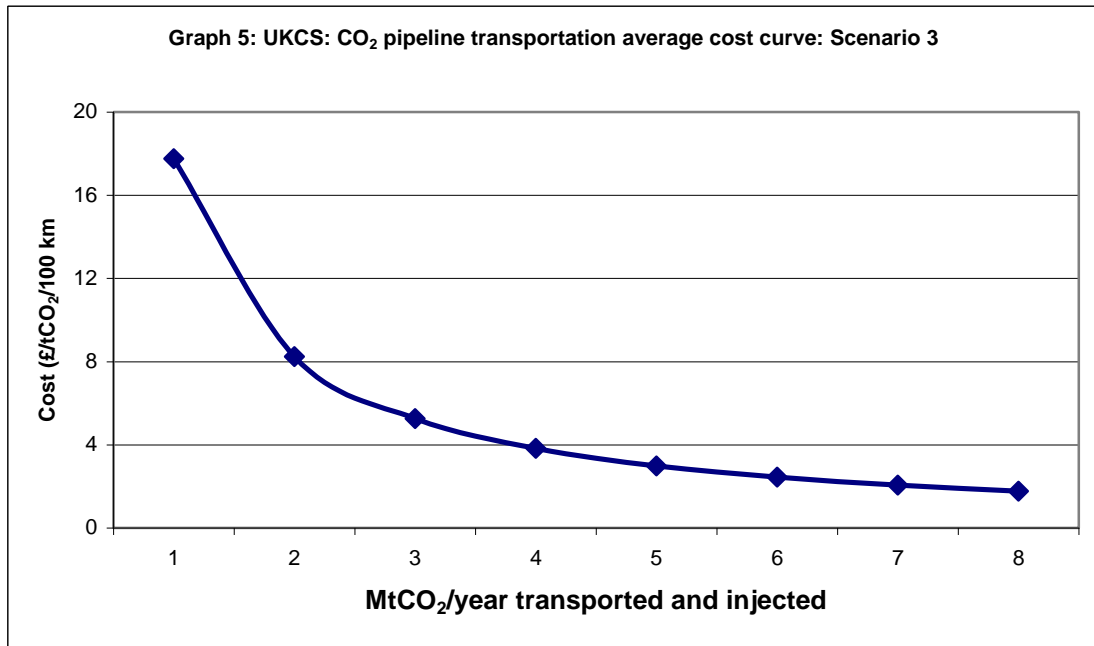
(2.733) (-1.592) (1.62) adjusted R<sup>2</sup> = 0.06

The economies of scale were found to be variable<sup>18</sup>, requiring a higher threshold of CO<sub>2</sub> 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<sub>2</sub>/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<sub>2</sub> to the relatively distant sink (Brae) initially

<sup>18</sup> That is, the estimated regression model with variable scale economies was better behaved than the fixed scale model.

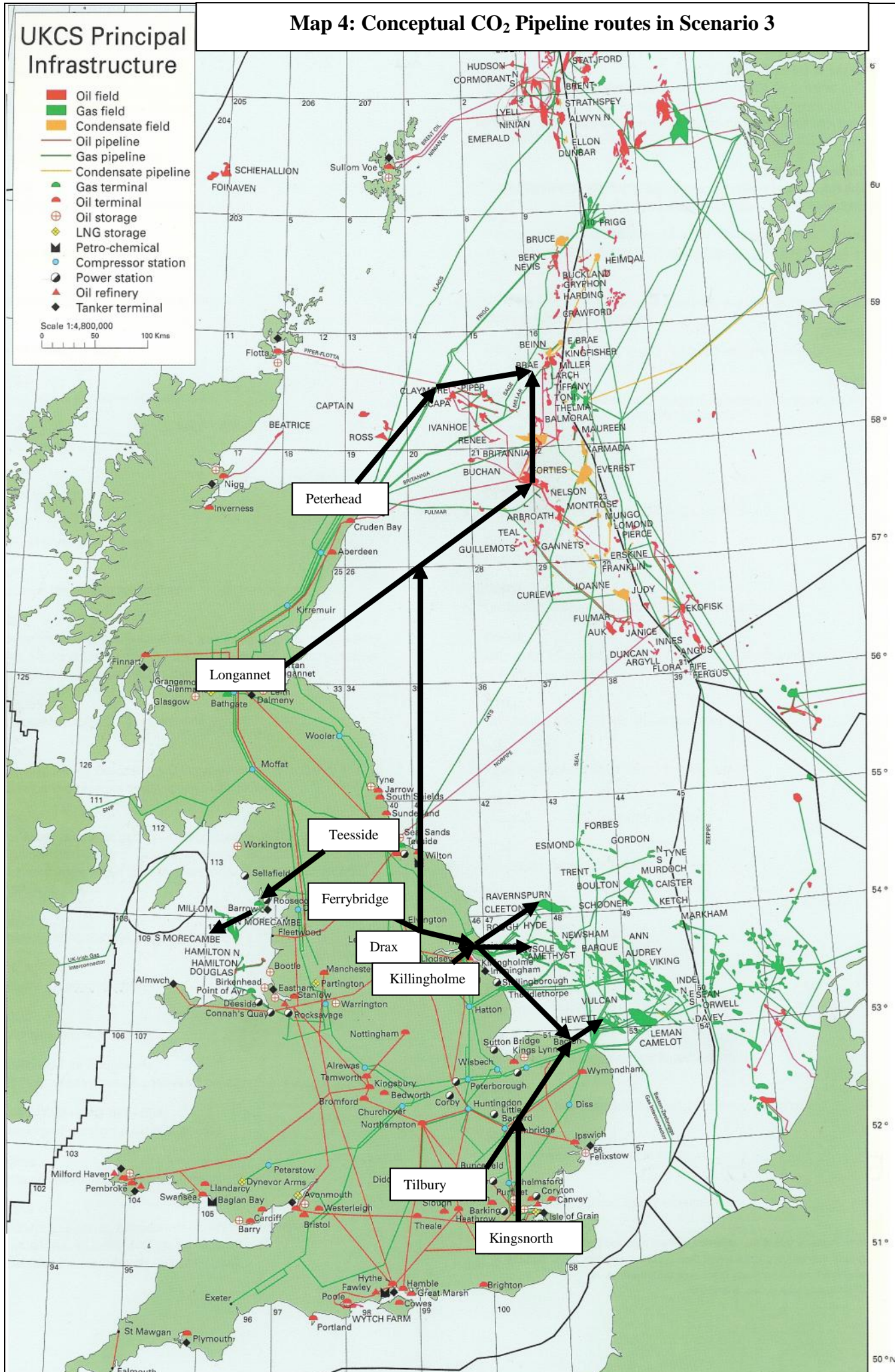
because the nearer sinks (Forties, in the case of Longannet and Claymore, in the case of Peterhead) were not available.

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



A conceptual CO<sub>2</sub> pipeline transportation network based on Scenario 3's model solutions is presented below in Map 4.

Map 4: Conceptual CO<sub>2</sub> 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<sub>2</sub> 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         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>8.33</b>  | <b>10.66</b> | <b>15.00</b> | <b>20.66</b> |
| Ferrybridge        | Morecambe South          | 159           | perm             | Barrow-in-Furness | 2.41         | 3.38         | 4.34         | 5.98         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>2.41</b>  | <b>3.38</b>  | <b>4.34</b>  | <b>5.98</b>  |
| Killingholme       | West Sole                | 94            | perm             | Easington         | 1.53         | 2.15         | 2.76         | 3.80         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.53</b>  | <b>2.15</b>  | <b>2.76</b>  | <b>3.80</b>  |
| Kingsnorth         | Hewett                   | 204           | perm             | Bacton            | 3.02         | 4.23         | 5.44         | 7.49         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.02</b>  | <b>4.23</b>  | <b>5.44</b>  | <b>7.49</b>  |
| Longannet          | Morecambe South          | 246           | perm             | Barrow-in-Furness | 3.70         | 5.18         | 6.66         | 9.18         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.70</b>  | <b>5.18</b>  | <b>6.66</b>  | <b>9.18</b>  |
| Peterhead          | <b>Miller</b>            | 234           | <b>eor</b>       | Peterhead         | 1.42         | 1.99         | 2.56         | 3.53         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.42</b>  | <b>1.99</b>  | <b>2.56</b>  | <b>3.53</b>  |
| Teesside           | Morecambe South          | 227           | perm             | Barrow-in-Furness | 3.14         | 4.39         | 5.65         | 7.78         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>3.14</b>  | <b>4.39</b>  | <b>5.65</b>  | <b>7.78</b>  |
| Tilbury            | Hewett                   | 137           | perm             | Bacton            | 1.46         | 2.05         | 2.63         | 3.63         |
|                    |                          |               | <b>Sub-total</b> |                   | <b>1.46</b>  | <b>2.05</b>  | <b>2.63</b>  | <b>3.63</b>  |
| <b>Grand Total</b> |                          |               |                  |                   | <b>25.01</b> | <b>34.03</b> | <b>45.04</b> | <b>62.05</b> |

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<sub>2</sub>-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<sub>2</sub>-EOR oil revenues on CO<sub>2</sub> transport costs, but with relative delays in the injection start-up dates, the remaining CO<sub>2</sub>-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<sub>2</sub>.

The cumulative total volume of CO<sub>2</sub> transported and injected in this scenario is 831 MtCO<sub>2</sub> in the period to 2037, the same as in Scenario 2. Of this, the bulk – about 448 MtCO<sub>2</sub> (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<sub>2</sub> 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<sub>2</sub>/year, requiring pipe sizes in the range of 14 to 22 inches.

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

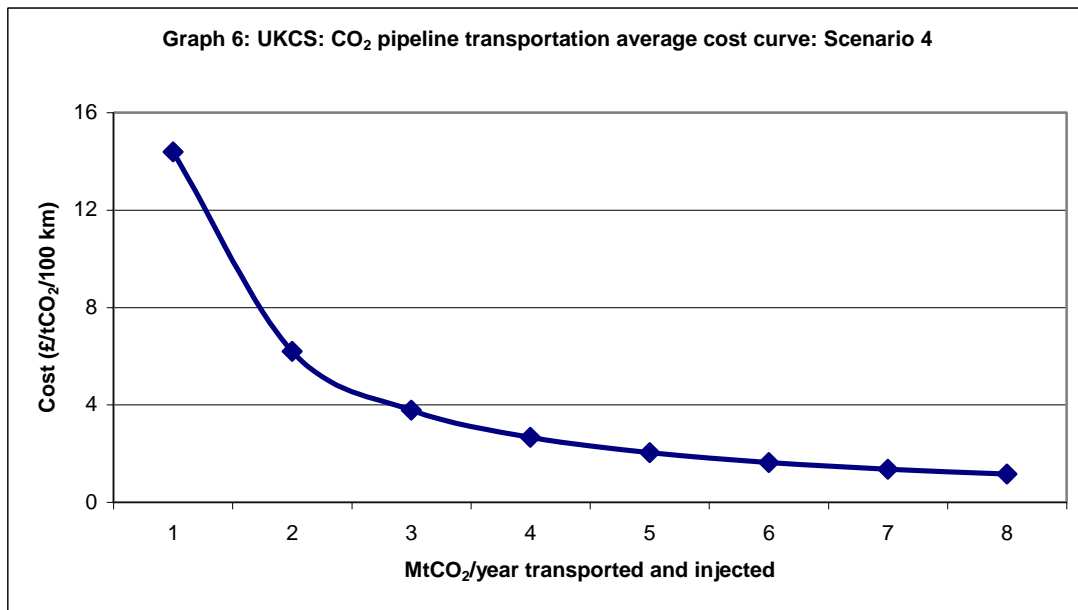
| <b>Source</b> | <b>Sink</b>     | <b>estimated diameters (mm)</b> | <b>estimated diameters (inches)</b> |
|---------------|-----------------|---------------------------------|-------------------------------------|
| Drax          | Morecambe South | 482.89                          | 19.01                               |
| 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:

$$\ln(\text{total CAPEX}) = 4.953 + 0.202 \ln(\text{cumulative CO}_2 \text{ shipment volumes})$$

(6.670) (1.179)      adjusted  $R^2 = 0.042$

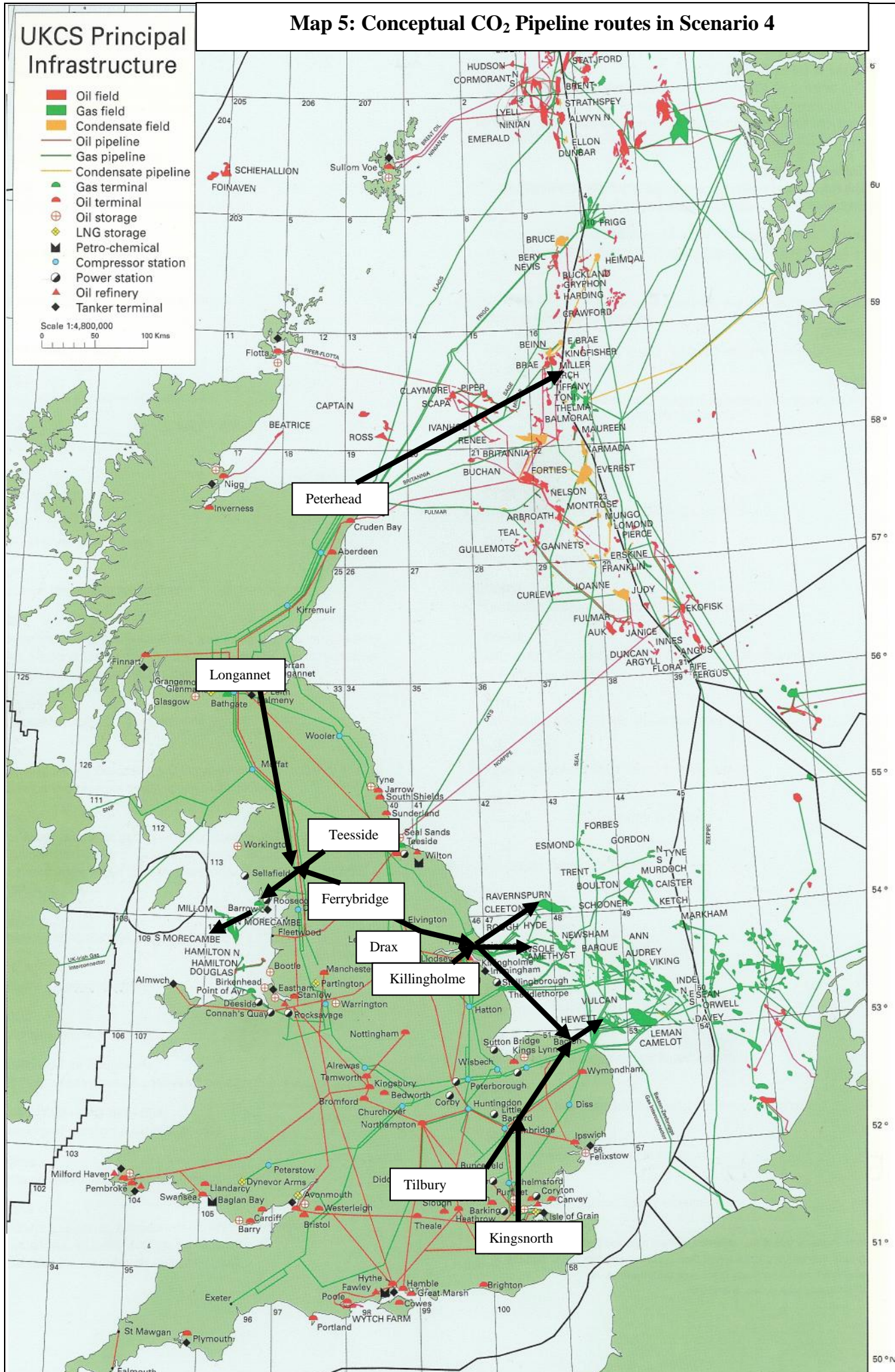
The average capital cost in the entire ten pipeline routes of this scenario ranges between £1.44 to about £8.83/tonne/100 km. The average capital cost function is presented graphically in Graph 6.



A conceptual CO<sub>2</sub> pipeline transportation network based on Scenario 4's model solutions is presented below in Map 5.



Map 5: Conceptual CO<sub>2</sub> 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.

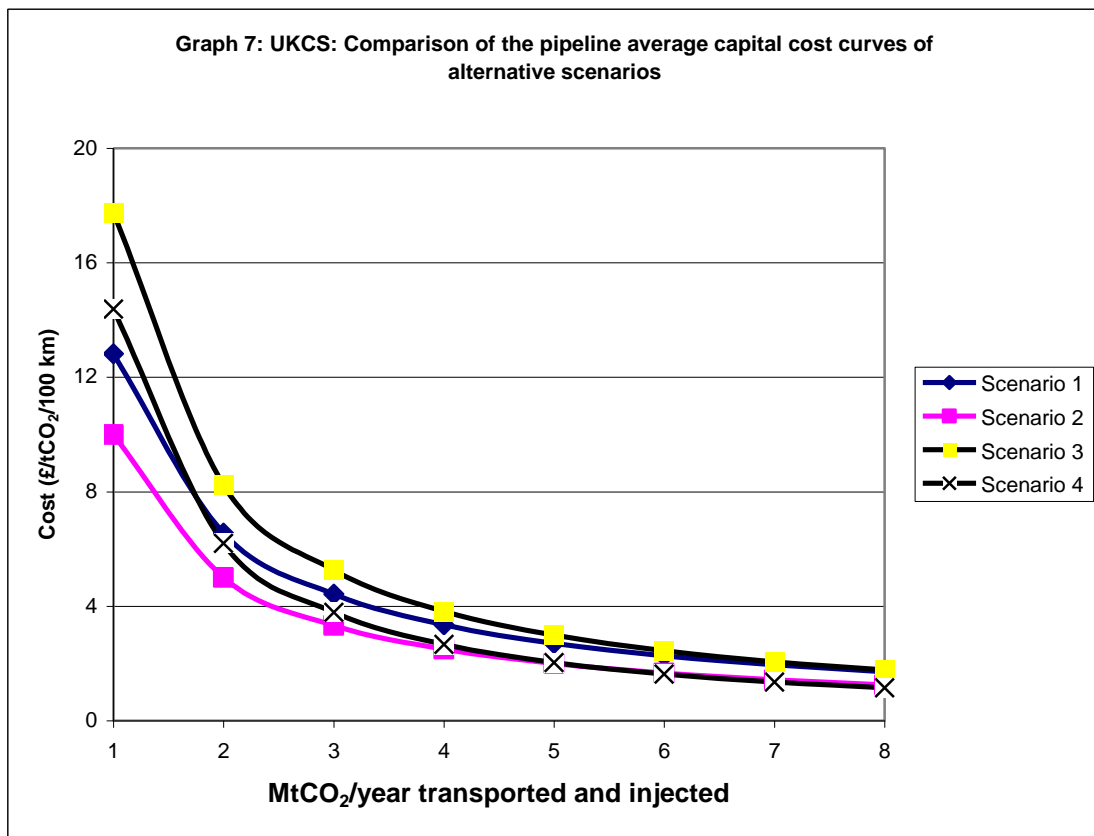
### (a) Volumes of CO<sub>2</sub> shipped and pipeline lengths

**Table 15: Comparative pipe diameters (in mm) by pipeline lengths (in km) and total CO<sub>2</sub> shipments (MtCO<sub>2</sub>) 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                |                    |                    |                    |
| <b>Total length (km)</b>                                | <b>1846</b>        | <b>2568</b>        | <b>2701</b>        | <b>1755</b>        |
| <b>Total CO<sub>2</sub> conveyed (MtCO<sub>2</sub>)</b> | <b>622</b>         | <b>831</b>         | <b>612</b>         | <b>831</b>         |
| <b>CAPEX (£ billion)</b>                                | <b>4.0</b>         | <b>5.0</b>         | <b>5.4</b>         | <b>3.5</b>         |
| <b>Average cost range (£/tCO<sub>2</sub>/100 km)</b>    | <b>1.00 - 5.00</b> | <b>0.80 - 6.00</b> | <b>2.48 - 9.39</b> | <b>1.44 - 8.83</b> |

It is clear from Table 15 that, in addition to the cost comparisons already discussed, the cumulative total volume of CO<sub>2</sub> transported and injected in Scenarios 2 and 4 is about 831 MtCO<sub>2</sub> in each case. Thus, more CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> transport infrastructure was identified in IEA (2008) as an important stimulus for “an order of magnitude increase” in the take off of CO<sub>2</sub>-EOR.

The scenario analysis conducted in the study to investigate the sensitivities of investments in CO<sub>2</sub> 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<sub>2</sub>-EOR start date, and the development of CO<sub>2</sub>-EOR projects that can accommodate a modestly ambitious minimum annual injectivity of 3 MtCO<sub>2</sub>/year. The superiority of Scenario 2 supports the proposition that (a) CO<sub>2</sub>-EOR oil revenues can be used to accelerate CCS deployment<sup>19</sup> in the UK/UKCS, provided that deliberate and conscious efforts are made to start CO<sub>2</sub>-EOR early; and, (b) project size or annual CO<sub>2</sub> 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<sub>2</sub> sources and sinks.

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<sup>19</sup> 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<sub>2</sub> 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<sub>2</sub>.

However, it is possible that other large stationary point sources of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> capture, transport, and injection against the revenues derivable from the CO<sub>2</sub>-EOR-induced incremental oil and/or commercialised permanent storage activities.

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**Appendix 1: Selection<sup>20</sup> criteria for application of CO<sub>2</sub>-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<br>ii) >5500<br>iii) >2500 | <9800           | >2000                 | i) >4000<br>ii) >3300<br>iii) >2800<br>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<br>ii) 27-30<br>iii) >30     | >40             | >26                   | i) 22-27.9<br>ii) 28-31.9<br>iii) 32-39.9<br>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                    |  |

<sup>20</sup> 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<sub>2</sub> EOR and CO<sub>2</sub> PERMANENT STORAGE IN SELECTED FIELDS IN THE UKCS**

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

| Field Name          | Location | 2005 Production |            | Forecast COP dates |            | Forecast COP Production |            |
|---------------------|----------|-----------------|------------|--------------------|------------|-------------------------|------------|
|                     |          | oil (tbd)       | gas (mmcf) | oil (year)         | gas (year) | oil (tbd)               | gas (mmcf) |
| 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      |

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