



ANALYSIS OF CARBON CAPTURE
AND STORAGE COST-SUPPLY
CURVES FOR THE UK

DTI

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ECONOMIC ANALYSIS OF CARBON CAPTURE AND STORAGE IN THE UK



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1. INTRODUCTION

1.1 Aims of the Study

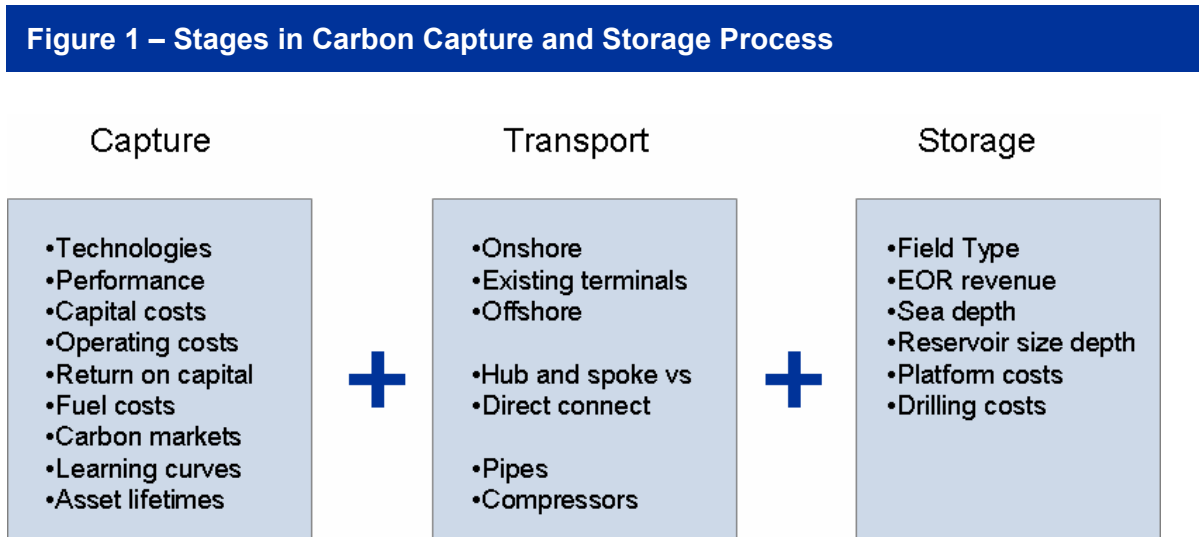
Carbon Capture and Storage (CCS) has the potential to make a significant contribution to the UK's longer term climate change goals. However the precise timing, cost and volume of potential deployment depends on a wide variety of factors, including the policy framework, the evolution of costs and carbon markets, the availability of other abatement options and future fuel prices. This study was commissioned by DTI to develop a detailed understanding of the potential costs of CCS in the UK, and to construct supply curves of CCS for the future, taking account of the most up to date information. This report describes the modelling framework and presents key results.

1.2 Overview

Pöyry Energy Consulting has developed a model for the DTI to examine how the economics of the entire process of carbon capture and storage (CCS) in the UK will change as the volume of deployment increases – ie develops a cost supply curve. The model is designed to:

- be relatively comprehensive, in that it includes:
 - major sources of CO₂ emissions from all industrial sectors;
 - pipelines to transport the CO₂ ; and
 - major potential offshore storage sites.
- allow investigation of sensitivities, so that the many parameters and assumptions involved could be varied to consider a range of cost scenarios.

The elements modelled within each stage of the process are summarised in Figure 1 below.



Source: Pöyry Energy Consulting

Our analysis includes and considers:

- taking the lowest cost technologies from an array of technical alternatives;
- calculating the cost of abatement against alternative counterfactuals;
- the impact of various underlying economic factors, such as fuel prices;
- optimising the transport networks and storage sinks; and
- considering how the situation changes into the future as, for example new power stations are needed, and oil- and gasfields cease production.

The information underlying the model was drawn from the following sources:

- capture facilities came from the IPPC Report *Carbon Dioxide Capture and Storage*;
- transport infrastructure costs came from the International Energy Agency;
- data for offshore sinks were supplied by the British Geological Survey;
- DTI Energy Review Team provided some capture cost assessments; and
- Pöyry estimates were used in absence of other reliable information.

This short report is structured into the following sections:

- An overview of the model (Section 2);
- Results from the model showing the economics of CCS in the UK (Section 3); and
- A fully worked example of the complex calculations involved (Section 4).

1.3 About Pöyry Energy Consulting

Pöyry Energy Consulting is Europe's leading energy consultancy, formed from the merger of ILEX Energy Consulting with the management consulting arms of Electrowatt-Ekono, Verbundplan and Convergence Utility Consulting. Pöyry Energy Consulting provides strategic, commercial, regulatory and policy advice to Europe's energy markets. Our team of over 170 energy specialists, located across eleven European offices in ten countries, offers unparalleled expertise in the rapidly changing energy sector.

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2. CCS MODEL OVERVIEW AND CONCEPTS

2.1 Introduction

The CCS Model examines the costs of each of three separate stages in the CCS process:

- **capturing CO₂** at the source of emissions, that is the major electricity generating units and industrial sites in the UK;
- **optimising the transportation** network to move the CO₂ from the sources to the sinks; and
- **storing the CO₂** in oilfields, gasfields and aquifers.

The study looks at all major sources of CO₂ in the UK and estimates presented here take account of learning curve effects as well as economies of scale.

2.2 Key concepts – CO₂ captured and abated

The cost of abatement is the additional cost of reducing emissions divided by the reduction in volume of emissions, and is expressed in pounds (£) per tonne (t) of reduced emissions (expressed here in £t/CO₂). There is an efficiency penalty in capturing the CO₂, as some of the electricity generated is used to operate the capture plant. This means that the unit with capture plant will use the same amount of fuel and produce the same volume of CO₂ as it did before, but now captures most of the CO₂, so in practice while far less CO₂ is emitted to the atmosphere, somewhat less electricity is sent out to the grid.

Our analysis defines CO₂ abatement and associated costs, as the difference in CO₂ emissions between a unit with capture and one without where they both send out the *same amount of electricity*. We do this by estimating the costs and volumes of emissions from a hypothetical unit, whose capacity has been scaled down so it generates the same amount of electricity that the unit with capture sends out when operating at the same load factor. This unit will use less fuel, and hence produce a lower volume of CO₂, than the existing unit. This hypothetical unit is referred to as the **counterfactual**.

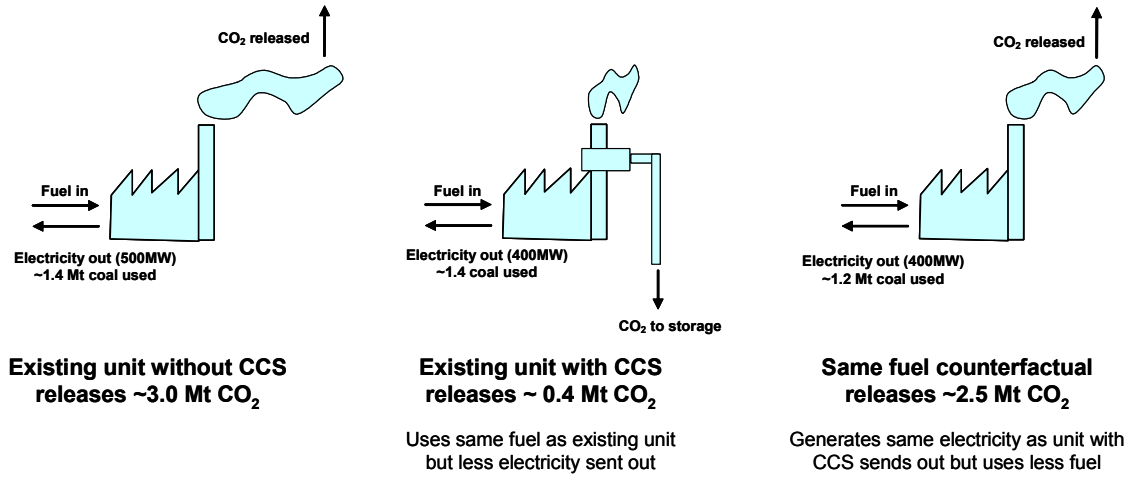
The transport network and sinks need to be sized to carry the volume of CO₂ captured, ie all the volume that the capture plant collects (in practice this is less than 100% of the combustion products).

This is different, and greater than, the volume abated. The volume abated is the amount the *counterfactual* would produce less the amount the unit with capture plant emits. This means that it is necessary to estimate the volumes of CO₂ emissions:

- actually produced; based on the capacity and efficiency of the existing unit, fuel type and load factor;
- emitted from the existing unit with CCS facilities; and
- a hypothetical unit without CCS facilities would produce when generating the same amount of electricity that a unit with CCS sends out.

These different volumes are illustrated using a 500 MW coal fired unit in Figure 2 below.

Figure 2 – Illustrative example of different volumes of CO₂ emissions

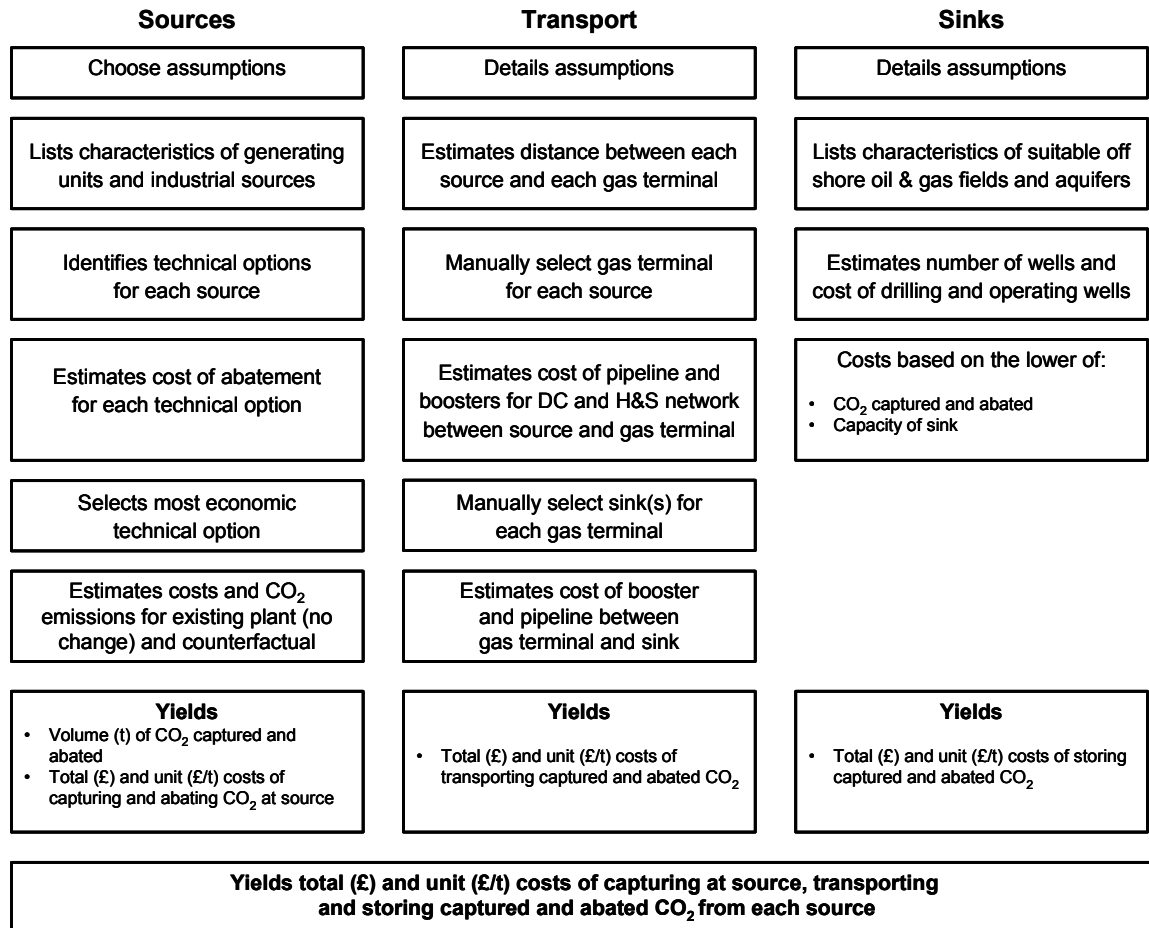


Source: Pöyry Energy Consulting

2.3 Model process

Figure 3 below summarises the steps the model takes to estimate the total cost (£) and unit cost (£/t) of captured and abated CO₂ for each stage in the CCS process.

Figure 3 – Model Structure



Source: Pöyry Energy Consulting

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3. MODEL RESULTS

3.1 Introduction

The model is designed to produce economic cost – supply curves for the application of CCS to emissions from all the major sources of CO₂ in the UK by adding the components for each source – in effect producing abatement curves.

The following section presents a series of abatement curves for our basecase scenario, and then shows how the picture changes with key inputs.

Our basecase scenario is based on the following assumptions:

- the year is 2015;
- the coal gas price relativity favours coal (DTI Central Case favouring coal¹);
- the price of carbon is zero; and
- the counterfactual is the existing source.

3.2 Capture costs

The model selects the optimal type of capture technology for each individual source from an array of different technologies and their associated costs. The capture technologies considered include:

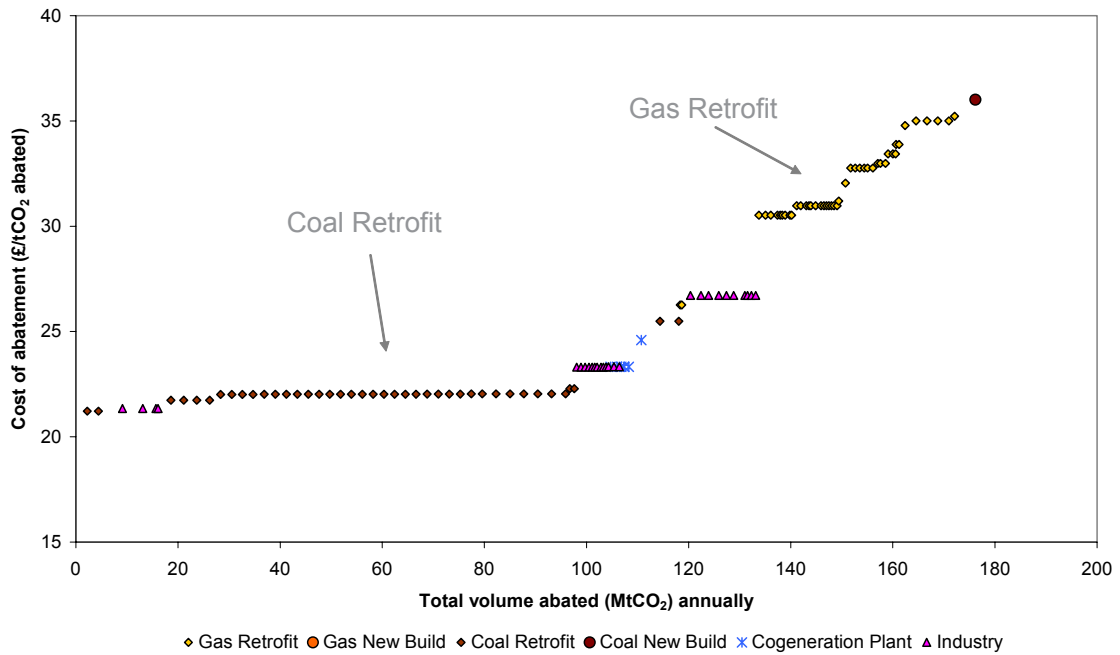
- retrofitting existing CCGT with MEA² technology;
- retrofitting existing sub critical coal fired units with either MEA or oxyfuel technology;
- upgrading existing sub critical coal fired units to super critical units and fitting with MEA technology;
- building new CCGT units with either MEA or oxyfuel technology; and
- building new coal fire units, being either sub critical, super critical or UGCC units with either MEA or oxyfuel technology.

The model selects the most economic technical solution before constructing an abatement curve. Figure 4 below shows such an abatement curve. In this case we see that the cost of retrofitting coal fired plant is just above £20/tonne CO₂, while for gas fired plant, it is above £30/tonne CO₂. A key reason for this difference is that the volume of CO₂ emitted from a coal fired plant is far greater than that from a gas fired plant, so the volume abated will also be far higher – reducing the unit cost of abatement.

¹ see <http://www.dti.gov.uk/files/file31861.pdf>

² MEA is an abbreviation for monoethanolamine, the chemical used to extract CO₂ from flue gases

Figure 4 – Capture economics – cost of abatement in 2015 from carbon capture.



Source: Pöyry Energy Consulting

Note: Estimates expressed in 2006 prices

3.3 Transport

We assume that the CO₂ transport system will not use any existing pipes.

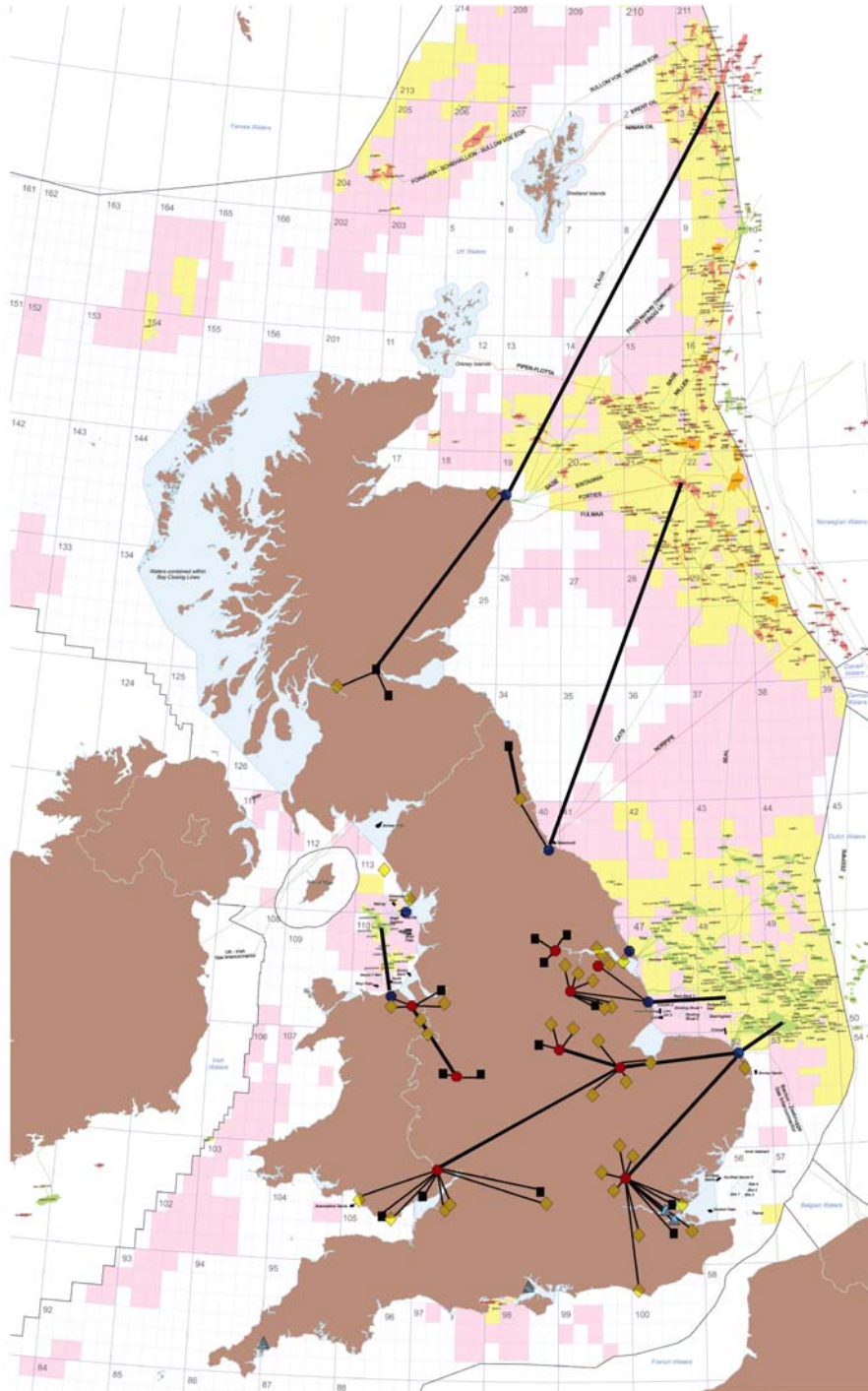
In general transport costs of CO₂ depend on both the cost of the pipe and how many boosters are needed. Both of these depend on the diameter and length of the pipe.

We have investigated the economics of two possible developments for the pipe network:

- **Direct Connect** network, where dedicated pipes transport the CO₂ to terminal sites from where it is transported to a sink; and
- **Hub & Spoke** network, where CO₂ is transported to dedicated hubs, where it is aggregated and transported to terminal sites in larger pipes.

An illustration of our basecase transport network is shown in Figure 5 below.

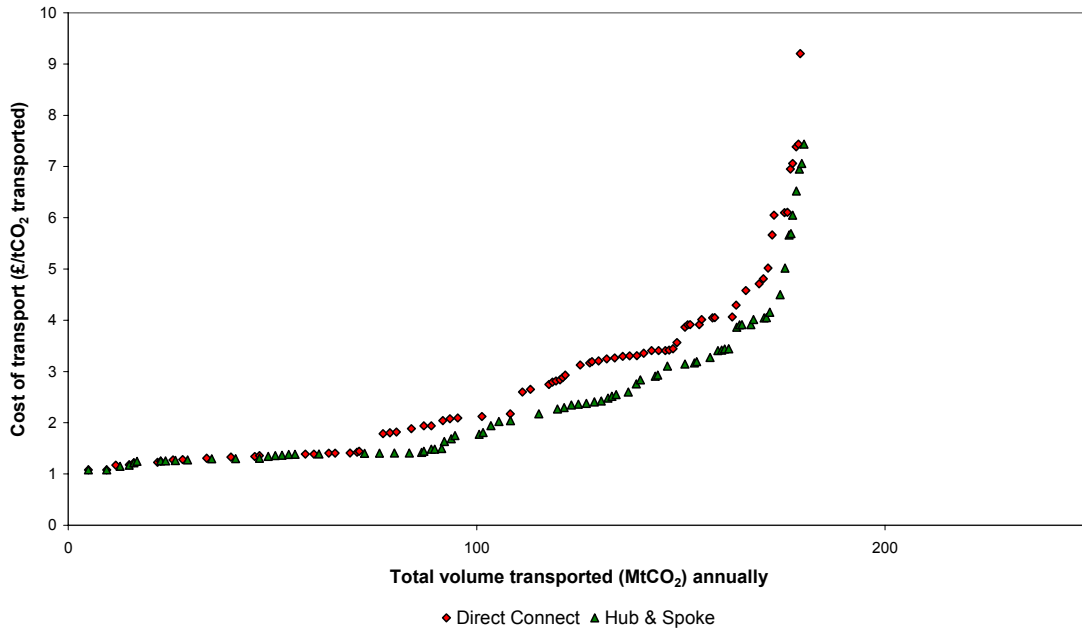
Figure 5 – Basecase transport network



Source: Pöyry Energy Consulting

Figure 6 below compares the transport cost of abatement using both Direct Connect and Hub & Spoke networks. It indicates that while the cost of using a Hub & Spoke network is slightly less than those for a Direct Connect network, the difference is marginal.

Figure 6 – Cost of abatement from transport, 2015



Source: Pöyry Energy Consulting

In practical terms, the main economic impact of the transportation network is to enable the connection of the sources with the lowest cost sinks. For example it may be better to transport CO₂ from sources in the south west of the UK to the cheaper sinks in the North Sea even though the transport costs are higher and effectively the model works by choosing the transport route and sinks that minimise transport & storage costs together.

Transport costs are relatively low to the significant economies of scale realised by the volumes of carbon being transported in the model.

3.4 Storage

The storage sinks are located in the yellow areas in the map in Figure 5 above. The gas and oil fields are in the north off the coast of Scotland and northern England, and the aquifers are in the south off the coast of eastern England.

Figure 7 below shows the storage cost of abatement for the various classes of offshore sinks in the UKCS. It indicates that:

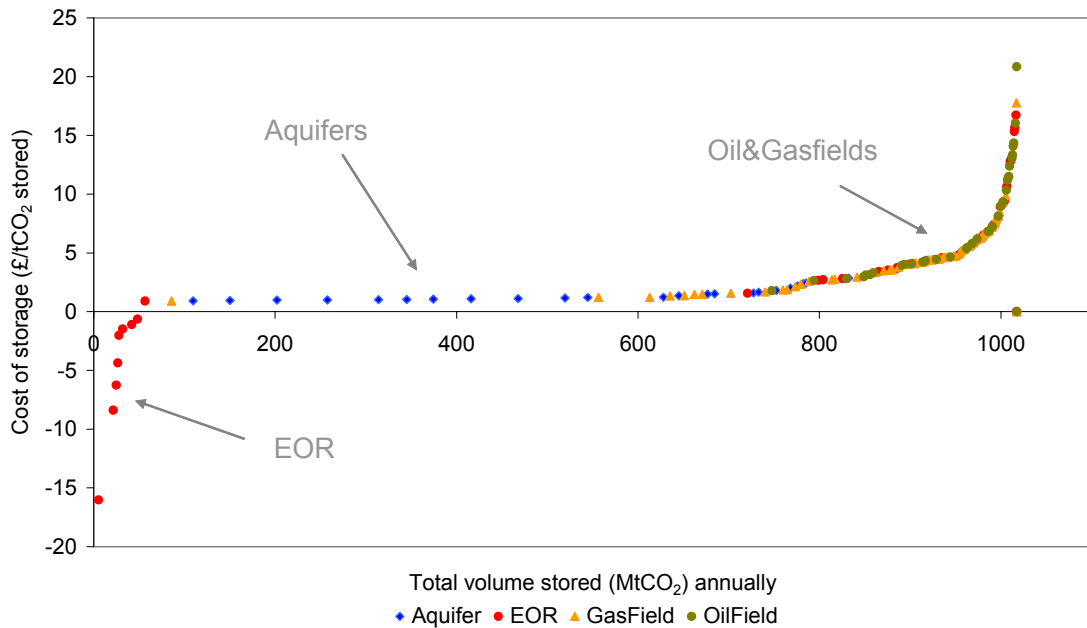
- using CO₂ for Enhanced Oil Recovery (EOR) can generate revenue which offsets the other costs of CCS (before any taxation issues are considered);
- the cost of storing CO₂ in aquifers is close to £1/tonne; and
- the cost of storing CO₂ in oil and gas fields plant ranges from £1/tonne to £20/tonne.

The annual opex costs are assumed to be 10% of the total capex costs, which mainly comprise drilling up the field and installing suitable offshore facilities.

The low unit cost of the aquifers is due to them being:

- in shallow water, minimising the platform costs;
- reservoirs with very high capacities, reducing the unit cost of storage; and
- in shallow rock formations, minimising drilling costs.

Figure 7 – Cost of abatement from storing CO₂, 2015



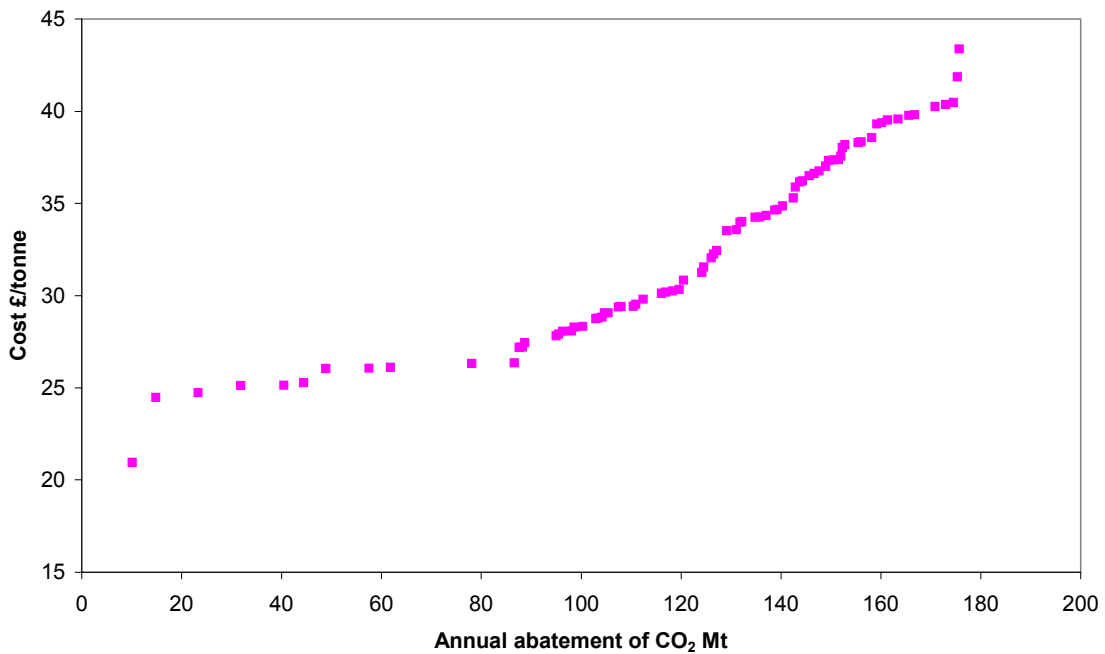
Source: Pöyry Energy Consulting

3.5 Total costs

Figure 8 shows the composite Basecase carbon abatement curve for the UK. This is not simply the addition of the separate elements of CCS described above because there is considerable scope for optimising the connections between sources and sinks.

Although the curve steepens, it does indicate the potential for abatement of around 100mtpa CO₂ at prices below £30/tonne.

Figure 8 – Basecase total abatement costs, 2015



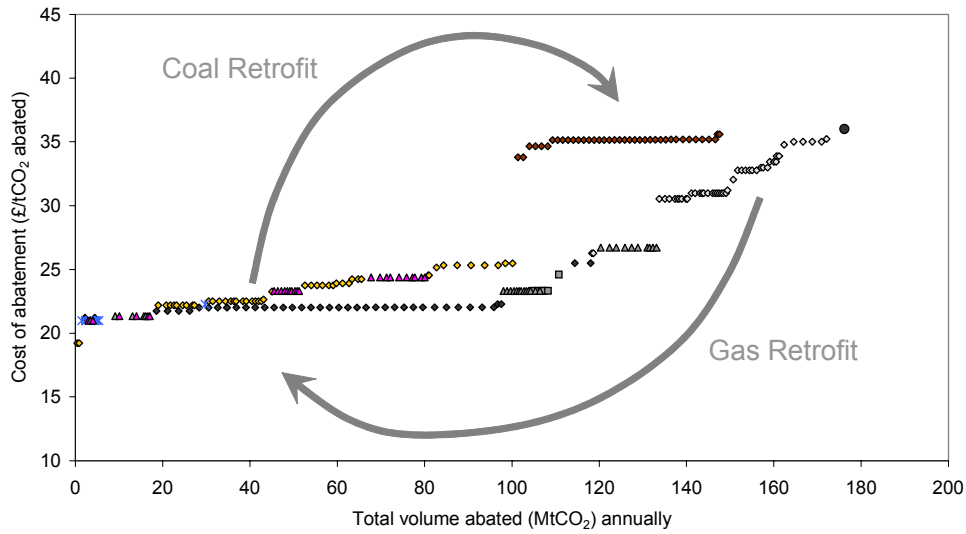
Source: Pöyry Energy Consulting

However, this curve is highly sensitive to the underlying assumptions and the following examples aim to illustrate this by way of selected examples.

3.6 Impact of fuel prices

Figure 9 below shows how in a fuel price scenario in which the price of gas declines from £11.95/MWh to £9.32/MWh while the price of coal remains constant at £3.78/MWh where the counterfactual is the existing unit fitted with CCS facilities. In this case the relative positions of coal and gas fired power stations reverses, although in absolute terms the curve does not move significantly.

Figure 9 – Sensitivity to fuel prices



Source: Pöyry Energy Consulting

3.7 Inclusion of carbon allowances

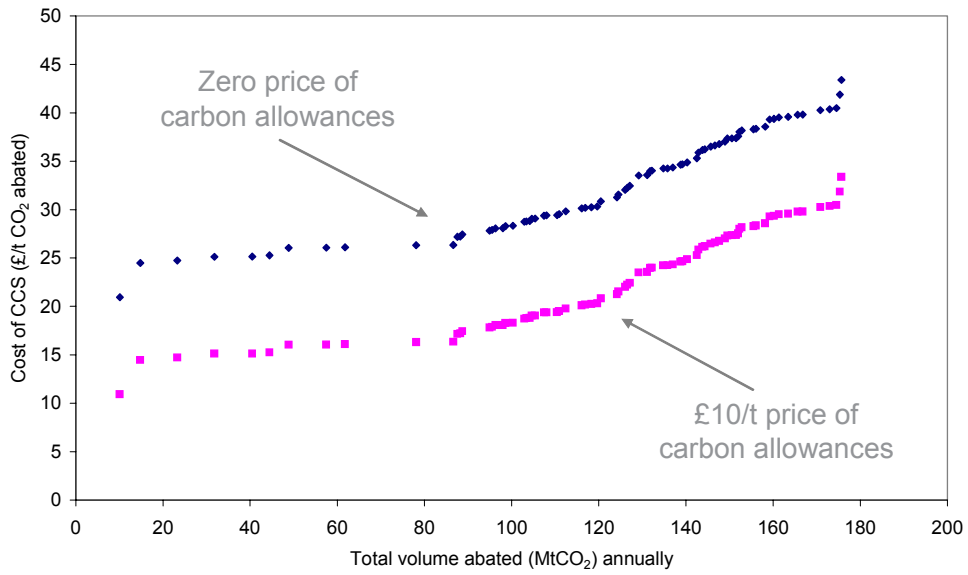
The following analysis assumes that the carbon trading arrangements that apply in 2015 will:

- require all electricity generating operators to purchase all of the allowances that need to be submitted; and
- make provision for installations that install CCS facilities, such that carbon allowances will only need to be submitted for emissions to the atmosphere.

Under these assumptions, the increase in the costs the counterfactual incurs is far greater than the increase in costs the CCS case incurs. This reduction in the difference between the costs for each case results in a fall in the per tonne cost of abatement.

Figure 10 shows that inclusion of carbon allowances leads to a parallel downward shift in the abatement curve. The reason the shift is parallel is because the change in costs is the difference in emissions multiplied by the average price of carbon allowances. As the cost of abatement is defined as the differences in costs divided by the differences in emissions, the impact on the abatement curve is to reduce it by the average price of carbon at all points along the curve.

Figure 10 – Sensitivity to carbon prices



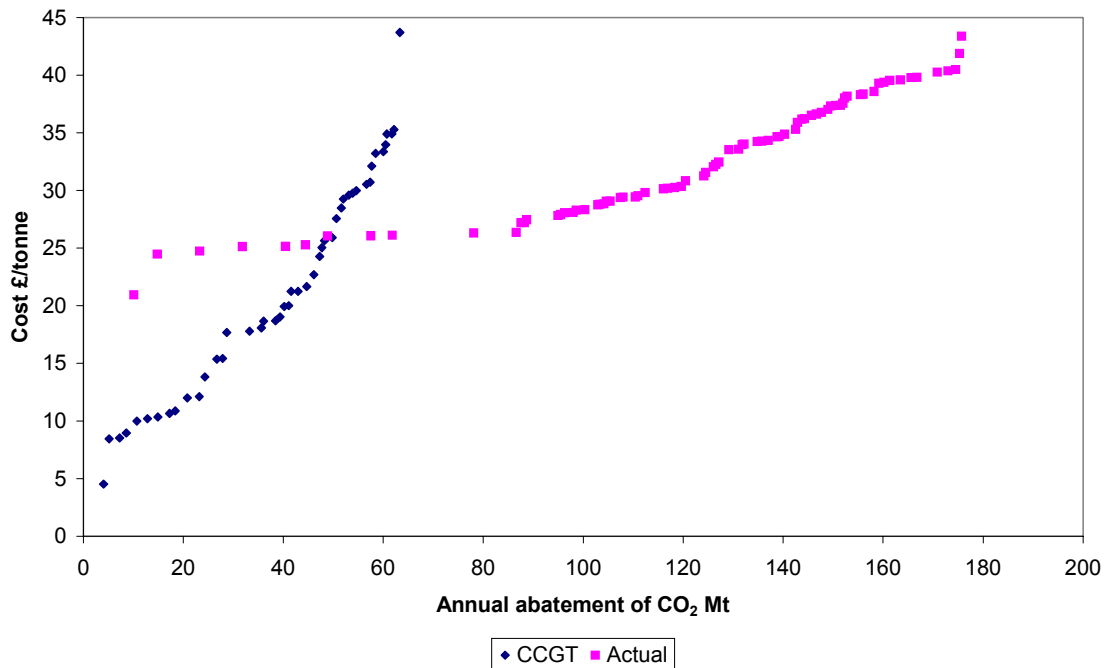
Source: Pöyry Energy Consulting

3.8 Counterfactual

Many commentators consider the costs of abatement in comparison to those of a new CCGT (for the power sector), rather than in comparison to the existing fleet of power stations. In practice this may result in some confusion, because the headline figures for especially coal plant are very sensitive to choice of counterfactual. Given the fundamentally different underlying calculations it is perhaps not surprising that very different curves result, and that they are sensitive to very different input assumptions.

Figure 11 shows the two different counterfactuals for the basecase – and how the CCGT counterfactual is far shorter, because of the lower emissions of CCGT in general. Its steepness is driven by the underlying fuel assumptions.

Figure 11 – Total abatement costs with alternative counterfactuals, 2015



Source: Pöyry Energy Consulting

3.9 Conclusions

Our evaluation of the economics of the entire process of carbon capture, transportation and storage has shown that there is:

- significant potential for CCS at prices below £25/tonne CO₂, but
- this is very sensitive to input assumptions especially fuel and choice of counterfactual; and
- that while costs of capture are the dominant component the transport network can make a considerable contribution to accessing the very cheap sinks the UK has.

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4. WORKED EXAMPLE TO SHOW DETAILED COST CALCULATIONS FROM SOURCE TO SINK

4.1 Introduction

This section illustrates our modelling of a 485MW coal-fired unit at Aberthaw B in 2015. Costs are shown for three different technical approaches for the capture process, and comparison is made against two counterfactuals:

- a hypothetical unit which has the same technical characteristics as the initial unit except that its capacity is scaled down so it generates and send out the same electricity as the unit with CCS facilities when operating at the same load factor, and
- a new CCGT with the capacity to send out the same electricity as the unit with CCS facilities when operating at the same load factor.

In this example, the CO₂ is transported by pipe to the Bacton gas terminal and then offshore to storage in the aquifer known as 48/3.

Table 1 below summarises all three capture options and their impact on the generation capacity and output. This Annex considers in more detail the costs and abatement potential of a boiler upgrade to supercritical and MEA post combustion capture (CCS Option 2).

Table 1 – Characteristics of plant and CCS options

	Existing plant	CCS Option 1	CCS Option 2	CCS Option 3
Technology	Sub critical coal	Retrofit MEA to existing unit	Upgrade to super critical and retrofit MEA	Upgrade to oxy fuel and retrofit MEA
Gross gen' capacity (MW)	485	485	485	485
Efficiency adjustment	-	63%	83%	73%
Net sent out capacity (MW)	485	306	402	355
Carbon capture efficiency	-	96%	87.5%	85%
Load factor	87%	87%	87%	87%
Sent out output (TWh)	3.7	2.3	3.1	2.7

Source: Pöyry Energy Consulting

Fitting capture plant reduces the sent out capacity of the unit because of the works power it needs. Each technical option has different costs and technical characteristics. In order to properly compare both the cost and abatement potential of the different options, it is necessary to compare them to a plant of the same output, rather than the capacity of the unabated plant.

The comparison needs to consider the costs and emissions of:

- the existing 485 MW unit scaled to the same output as CCS Option 2, effectively a 402 MW coal fired unit;
- CCS Option 2, a coal fired sub critical unit upgraded with a super critical boiler and fitted with MEA capture plant with an effective capacity of 402 MW; and
- a new equivalent CCGT unit with capacity of 402 MW.

One difference between the counterfactuals is that industrial sites are excluded from the analysis when the counterfactual is the new CCGT unit, as a CCGT unit is not suitable for such sites. The impact is that the total volume of CO₂ transported and stored in a sink is reduced, meaning that the transport and storage (T&S) costs differ slightly. This is explained in more detail in Table 16 below.

Table 2 summarises the annual costs of each option and the effective level of CO₂ emissions; detail behind these is considered later. For the purposes of this example the:

- fuel prices used are the DTI *central favouring coal* assumptions have been used, as set out in supporting documentation for the DTI Energy Review³, and
- non fuel O&M costs are the low case assumptions used in the financial modelling for the DTI Energy Review.

Table 2 – Comparison of annual costs and emissions

Technology	Existing unit	Hypothetical scaled existing unit	CCS	Equivalent CCGT
	Subcritical coal	Subcritical coal	Upgrade to super critical and retrofit MEA	CCGT
Net sent out capacity MW	485	402	402	402
Sent out output (TWh)	3.7	3.1	3.1	3.1
Capital costs (£M)	-	-	28.6	18.1
Fuel costs (£M)	37.5	31.1	37.5	60.1
Non fuel O&M costs (£M)	12.3	10.2	21.3	8.9
Transport and storage (£M) including industrial sites	-	-	12.1	-
Transport and storage (£M) excluding industrial sites	-	-	12.3	-
Total costs (£M) incl industrial sites	49.8	41.3	99.5	87.1
Total costs (£M) excl industrial sites	49.8	41.3	99.7	87.1
Volume CO ₂ emitted (Mt)	3.0	2.5	0.4	1.0

Source: Pöyry Energy Consulting

Table 2 shows that the T&S costs are slightly higher when the industrial sites are excluded. As will be shown below, this is due to a loss of scale from transporting and storing lower volume of CO₂.

³ The UK Energy and CO₂ Emissions Projections (July 2006), see <http://www.dti.gov.uk/files/file31861.pdf>

The analysis does not consider the costs of replacing the lost capacity, assuming that there is sufficient spare system capacity.

Table 3 shows the differences in annualised costs and emissions between the CCS option and the two counterfactuals. All costs are in 2006 prices.

Table 3 – Abatement costs

Case	Difference in cost (£M pa)	Difference in emission (MtCO ₂ pa)	Cost of abatement (£/tCO ₂ pa)
Scaled existing unit v CCS			
Capital	29		13.7
Fuel	6	2.1	3.1
Non fuel O&M	11		5.3
T&S	12		5.8
TOTAL	58		27.8
Equivalent CCGT v CCS			
Capital	11		18.0
Fuel	-23	0.6	-38.8
Non fuel O&M	12		21.2
T&S	12		21.2
TOTAL	13		21.6

Source: Pöyry Energy Consulting

The following sections show the detail behind the emissions and costs calculations.

4.2 Detail of volume of CO₂ abated

The volume of CO₂ abated is determined by subtracting the volume of CO₂ emitted from the scenarios against which it is being compared. The volume of CO₂ emitted is calculated using the following formula:

$$\frac{\text{Net Sent Out Output}}{\text{Efficiency}} * \text{Emission Factor} * (1 - \text{Capture efficiency})$$

The values for these parameters are detailed in Table 4.

Table 4 – Comparison of annual CO₂ emissions

	Existing unit	Hypothetical scaled existing unit	CCS	Equivalent CCGT
Net sent out Output (TWh)	3.7	3.1	3.1	3.1
Fuel efficiency	37%	37%	31%	61%
Emission Factor (t/MWh)	0.3	0.3	0.3	0.19
Capture efficiency	0	0	87.5%	0
Volume CO ₂ emitted (Mt)	3.0	2.5	0.4	1.0

Source: Pöyry Energy Consulting

4.3 Detail of capital costs

The calculation of the amortised capital costs of the CCS facilities is

$$\frac{CCF * Technical Learning * Cap Cost * Capacity * ACCF}{Plant Life}$$

CCF is the Capital Cost Factor which adjusts the capital costs to account for project finance. The CCF represents the mark up needed for a certain Internal Rate of Return (IRR) over a particular period. Table 5 below shows how for an IRR of 10%, the CCF increases as the number of years increases. We have assumed an IRR of 10% over 15 years and have rounded the CCF up to two (2). We assume the CCF includes Interest During Construction (IDC).

Table 5 – Capital Cost Factors for 10% IRR over various periods

	15	30	35	50
Period of return	15	30	35	50
Capital Cost Factor	1.97	3.18	3.63	5.05

Source: Pöyry Energy Consulting

Technical Learning is the extent to which capital costs are assumed to decline with learning; and ACCF is the Additional Capital Cost Factor, which is used to scale up the cost of complex plant such as refineries. Both are set to one (1) in this example.

The key input assumptions and results are show in Table 6 below. The capacity used in the equation is the gross generating capacity. In this example we use estimates from industry on the CCS facilities and a study for the DTI on the costs of a new CCGT.

Table 6 – Comparison of annualised capital costs

	Existing unit	Hypothetical scaled existing unit	CCS	Equivalent CCGT
Technology	Subcritical coal	Subcritical coal	Upgrade to supercrit and retrofit MEA	CCGT
Gross generating capacity (MW)	485	402	485	402
Net sent out capacity (MW)	485	402	402	402
Capital Cost Factor	2	2	2	2
Technical Learning	1	1	1	1
Cap Cost £/kW	-	-	590	450
ACCF	1	1	1	1
Plant Life	20	20	20	20
Amortised capital cost (£M)	-	-	28.6	18.1

Source: Pöyry Energy Consulting

4.4 Detail of fuel cost

The equation used to determine the fuel cost of the each option is

$$\frac{\text{Net Sent Out Output}}{\text{Efficiency}} * \text{Fuel Price}$$

The elements of the fuel costs used in the above example are detailed in Table 7 below. The capacity used is the Gross Generating Capacity, with the exception of the Scaled Existing Unit, where the Net Sent Out Capacity is used. The fuel used in the Existing Unit with and without capture plant is the same, as both generate the same amount of electricity but the capture plant requires considerable works power to drive it. As mentioned above, the fuel prices are from the DTI's *central favouring coal* scenario.

Table 7 – Comparison of annual fuel costs

	Existing unit	Hypothetical scaled existing unit	CCS	Equivalent CCGT
Net sent out Output (TWh)	3.7	3.1	3.1	3.1
Efficiency (LHV)	37%	37%	31%	61%
Fuel price	£1.05/GJ	£1.05/GJ	£1.05/GJ	35.03 p/therm
Fuel price (£/MWh)	3.78	3.78	3.78	11.95
Total fuel (£M)	37.5	31.1	37.5	60.1

Source: Pöyry Energy Consulting

We have assumed that the thermal efficiency of a new CCGT unit will increase over time, the details of which are shown in Table 8 below. This example analyses the costs for 2015, at which time a new CCGT is assumed to have an efficiency of 61%.

Table 8 – Assumed CCGT efficiency over time

	2005	2010	2015	2020
Efficiency (LHV)	58.0%	59.5%	61.0%	63.0%

Source: Pöyry Energy Consulting

4.5 Detail of non fuel O&M cost

The DTI provided estimates of high and low scenarios of non fuel O&M costs for the following technical options:

- PF ASC with FGD no CCS;
- New PF ASC with FGD and CCS;
- Retrofit PF with FGD and CCS;
- New IGCC no CCS;
- New IGCC with CCS;
- New CCGT with CCS; and
- New CCGT no CCS.

As these did not correspond exactly to the options considered within the CCS model, some interpretation has been used to fit data into the model.

Table 9 below illustrates how the non fuel O&M costs were estimated for each option. The row headed “Unit type costs used” indicates which non fuel O&M costs are used for the options considered in this example.

The non fuel O&M cost were provided as both fixed and variable costs. Fixed costs are applied to the Gross Generating Capacity while the variable costs are applied to the Generated Output. In the case of the CCS option, the Generated Output, 3.7 TWh is greater than the Sent Out Output, 3.1 TWh, the difference being due to the capture plant works power. As the O&M cost will apply to the actual generation, this value is used for the variable cost calculations.

The DTI provided high and low non fuel O&M costs for each technical option except for New CCGT no CCS. The following example is based on the low cost scenario.

Table 9 – Comparison of annual non fuel O&M costs

	Existing unit	Hypothetical scaled existing unit	CCS	Equivalent CCGT
Gross gen' capacity (MW)	485	402	485	402
Net sent out capacity (MW)	485	402	402	402
Unit type costs used	PF ASC with FGD no CCS	PF ASC with FGD no CCS	Retrofit PF with FGD and CCS	New CCGT no CCS
Generated output (TWh)	3.7	3.1	3.7	3.1
O&M fixed (£/kW)	17	17	24.9	7
O&M variable (£/kWh)	0.11	0.11	0.25	0.2
O&M fixed (£M)	8.2	6.8	12.1	2.8
O&M variable (£M)	4.1	3.4	9.2	6.1
Total non fuel O&M (£M)	12.3	10.2	21.3	8.9

Source: Pöyry Energy Consulting

4.6 Detail transport and storage cost

Our model shows insufficient capacity in the Irish Sea, so despite Aberthaw being located in Wales, this example shows costs of transporting the captured CO₂ to Bacton, on the east coast, and storing the CO₂ in the aquifer 48/3.

Aberthaw B has three 485 MW units and Table 10 below shows the costs of transporting the captured CO₂ from the whole station. This means that the volumes and costs will be three times those of the unit considered above, although they still give the same average cost of abatement.

There is a large difference between captured and abated CO₂, with the former far greater than the latter. With capture equipment fitted, the CO₂ emissions are still those of a 485MW operating at 87% load factor, emitting 3.0 MtCO₂ pa. As the carbon capture efficiency is 87.5%, 2.6 MtCO₂ pa is actually captured.

The volume of CO₂ abated is the difference between the actual emissions from the unit with capture and those from the counterfactual. The counterfactual generates the same volume of electricity that the unit with capture plant sends out, and hence produces less CO₂, particularly when the counterfactual is the equivalent CCGT unit.

Transport and storage infrastructure must be dimensioned to treat all of the CO₂ captured. Regarding the estimation of the cost of the transport infrastructure:

- the cost of the pipe depends on its length and diameter;
- the number of boosters depends on the rate pressure within the pipe declines, which depend on its length and diameter; and
- the costs of the boosters includes the actual booster and its operating expenditure.

Table 10 below shows how the cost of building and operating a directly connected pipe between Aberthaw and Bacton gas terminal, and includes the Capital Cost Factor uplift. These costs cover the transport of CO₂ from all three (3) units at Aberthaw to Bacton, where as the costs in the tables above just consider those for one (1) of the units.

Table 10 – Transport costs from Aberthaw B to Bacton

Straight line distance (km)	370
Distance adjusted for terrain (km)	444
Diameter of pipe (m)	0.51
Number of boosters	3 operating and 3 on standby
Cost of pipe (£M)	224
Cost of pipe boosters (£M)	149
Cost of terminal booster (£M)	160
Total cost (£M)	533
Annual cost (£M)	27

Source: Pöyry Energy Consulting

Table 11 shows the calculation of the contribution to the total cost of abatement of the transport of CO₂ from Aberthaw to Bacton against the two counterfactuals. When the counterfactual is:

- the Scaled Existing Unit, the volume of CO₂ abated is 6.3 Mt, and the contribution to the cost of abatement is £4.24 per tCO₂; and
- the Equivalent CCGT, the volume of CO₂ abated is 1.8 Mt, and the contribution to the cost of abatement is £15.24 per tCO₂.

Table 11 – Unit costs for transport from Aberthaw to Bacton

Estimates relate to three units at Aberthaw	Hypothetical scaled existing unit	Equivalent CCGT
CO ₂ Captured (Mt)	7.8	7.8
CO ₂ Abated (Mt)	6.3	1.8
Annual cost (£M)	27	27
Cost of CO ₂ Captured (£/t)	3.41	3.41
Cost of CO ₂ Abated (£/t)	4.24	15.24

Source: Pöyry Energy Consulting

Bacton receives CO₂ from a large number of sources throughout the UK, from where they are transported for storage at aquifer 48/3. Table 12 below shows the costs of transporting the volume of CO₂ that transits Bacton and is transported to Aquifer 48/3 for each counterfactual. The exclusion of industrial sites when the counterfactual is the CCGT unit means that a lower volume of CO₂ is transported, which is reflected in the smaller diameter of the transport pipe and the lower cost.

Table 12 –Transport costs from Bacton to Aquifer 48/3

	Hypothetical scaled existing unit	Equivalent CCGT
Straight line distance (km)	85	85
Distance adjusted for terrain (km)	102	102
Diameter of pipe (m)	0.664	0.601
Number of pipes/platforms	2	2
Total cost (£M)	273	252
Total annual cost (£M/y)	13.7	12.6

Source: Pöyry Energy Consulting

In this case, it is necessary to construct two platforms in both counterfactual, as more than 30 wells are required to store all the CO₂. In such case, it is assumed that there will be distinct pipes from the gas terminal to the platforms, and that each pipe carries an equal volume of CO₂.

Table 13 shows the calculation of the contribution to the total cost of abatement of the transport of CO₂ from Bacton gas terminal to Aquifer 48/3 for the two counterfactuals. When the counterfactual is

- the Scaled Existing Unit, the volume of CO₂ abated is 46.9 Mt, and the contribution to the cost of abatement is £0.29 per tCO₂; and
- the Equivalent CCGT, the volume of CO₂ abated is 18.3 Mt, and the contribution to the cost of abatement is £0.69 per tCO₂.

Table 13 – Comparison of transport costs from Bacton to Aquifer 483

	Hypothetical scaled existing unit	Equivalent CCGT
CO ₂ Captured per year (Mt)	56.4	43.3
CO ₂ Abated per year (Mt)	46.9	18.3
Total annual cost (£M/y)	13.7	12.6
Cost of CO ₂ Captured (£/t)	0.24	0.29
Cost of CO ₂ Abated (£/t)	0.29	0.69

Source: Pöyry Energy Consulting

The cost of establishing and operating a sink suitable for storing CO₂ depends on:

- the depth of the water in which the platform is located, where the costs increase significantly once the depth is beyond 100m;
- the depth of drilling, where the costs increase significantly once the depth is beyond 3,000m;

- the number of wells that a platform can support, as the greater the number of wells, the more the cost of the platform is spread over the wells and we assume that a platform can support a maximum number of 30 wells; and
- OPEX, which is assumed to be 10% of total CAPEX each year.

Aquifer 48/3 is an ideal reservoir for storing CO₂, as it is in shallow water, of a shallow depth and has a substantial capacity, meaning it can support a large number of wells. Table 14 details the cost of establishing and operating a series of wells at aquifer 48/3.

Table 14 – Comparison of storage costs at aquifer 48/3

	Hypothetical scaled existing unit	Equivalent CCGT
Water depth (m)	50	50
Depth of drilling, including reservoir cap (m)	1,500	1,500
Number of wells	46	35
Drilling costs (£M)	249	189
Survey costs (£M)	1	1
Number of platforms	2	2
Platform costs (£M)	34	34
Total CAPEX excluding CCF (£M)	285	225
Total CAPEX including CCF (£M)	569	450
Total OPEX (£M)	569	450
Total cost (£M)	1,137	899
Total annual cost (£M/y)	56.9	45.0

Source: Pöyry Energy Consulting

Table 15 shows the calculation of the contribution to the total cost of abatement of storing CO₂ in Aquifer 48/3 for the two counterfactuals. When the counterfactual is

- the Scaled Existing Unit, the volume of CO₂ abated is 46.9 Mt, and the contribution to the cost of abatement is £1.21 per tCO₂; and
- the Equivalent CCGT, the volume of CO₂ abated is 18.3 Mt, and the contribution to the cost of abatement is £2.45 per tCO₂.

Table 15 – Comparison of storage costs at aquifer 48/3

	Hypothetical scaled existing unit	Equivalent CCGT
CO ₂ Captured per year (Mt)	56.4	43.3
CO ₂ Abated per year (Mt)	46.9	18.3
Total annual cost (£M/y)	56.9	45.0
Cost of CO ₂ Captured (£/t)	1.01	1.04
Cost of CO ₂ Abated (£/t)	1.21	2.45

Source: Pöyry Energy Consulting

The total T&S cost for the transport and storage of CO₂ from a single unit at Aberthaw B to Aquifer 48/3 shown in Table 2 is calculated through summing the separate unit cost of capture and multiplying them by the volume of CO₂ captured at this unit. This is illustrated in Table 16 below. The difference between the cases is due to the inclusion of all the industrial sites when the counterfactual is the existing unit. The exclusion of the industrial sites when the counterfactual is the CCGT, leads to a loss of scale and higher unit costs.

Table 16 – Estimation of T&S costs from single unit at Aberthaw B

	Hypothetical scaled existing unit	Equivalent CCGT
Transport from Aberthaw B to Bacton (£/CO ₂)	3.41	3.41
Transport from Bacton to Aquifer 48/3 (£/CO ₂)	0.24	0.29
Aquifer 48/3 (£/CO ₂)	1.01	1.04
Total T&S costs (£/CO ₂)	4.66	4.74
CO ₂ Captured (t)	2.6	2.6
Total T&S costs (£M)	12.1	12.3

Source: Pöyry Energy Consulting

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