Programme Area: Carbon Capture and Storage

Project: DECC Storage Appraisal

Title: WP6 – CO2 Storage Development Build-out

Abstract:

A Build-out Portfolio has been fitted to the ETI 2015 CO2 Emissions Scenarios work in terms of timing, geography and quantity. The Build-out Portfolio comprises eight storage sites with a diverse range of geographic and geological characteristics. The Build-out Portfolio can meet the CO2 supply scenario of 50Mt/y and by 2070, could have stored approximately 1645Mt of CO2. Levelised cost of offshore transportation and storage ranges between £9 - £32/t. Transportation and storage costs for the whole Build-out Portfolio contribute £6.9/MWh to the levelised cost of gas fuelled electricity generation. There are many options to expand the storage capacity in each region of the UKCS.

Context:

This project, funded with up to £2.5m from the UK Department of Energy and Climate Change (DECC - now the Department of Business, Energy and Industrial Strategy), was led by Aberdeen-based consultancy Pale Blue Dot Energy supported by Axis Well Technology and Costain. The project appraised five selected CO2 storage sites towards readiness for Final Investment Decisions. The sites were selected from a short-list of 20 (drawn from a long-list of 579 potential sites), representing the tip of a very large strategic national CO2 storage resource potential (estimated as 78,000 million tonnes). The sites were selected based on their potential to mobilise commercial-scale carbon, capture and storage projects for the UK. Outline development plans and budgets were prepared, confirming no major technical hurdles to storing industrial scale CO2 offshore in the UK with sites able to service both mainland Europe and the UK. The project built on data from CO2 Stored - the UK's CO2 storage atlas - a database which was created from the ETI's UK Storage Appraisal Project. This is now publically available and being further developed by The Crown Estate and the British Geological Survey. Information on CO2Stored is available at www.co2stored.com.

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D15: WP6 – CO2 Storage Development Build-out

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1.0 Executive Summary

A Build-out Portfolio has been fitted to the ETI 2015 CO_2 Emissions Scenarios work in terms of timing, geography and quantity.

The Build-out Portfolio comprises eight storage sites with a diverse range of geographic and geological characteristics.

The Build-out Portfolio can meet the CO_2 supply scenario of 50Mt/y and by 2070, could have stored approximately 1645Mt of CO_2.

Levelised cost of offshore transportation and storage ranges between £9 - £32/t.

Transportation and storage costs for the whole Build-out Portfolio contribute £6.9/MWh to the levelised cost of gas fuelled electricity generation.

There are many options to expand the storage capacity in each region of the UKCS.

The Energy Technologies Institute (ETI) Strategic UK CCS Storage Appraisal project, funded by the Department of Energy and Climate Change, brings together existing storage appraisal initiatives, accelerates the development of strategically important storage capacity and leverages further investment in building this capacity to meet UK needs.

The primary objective of the overall project is to down-select and materially progress the appraisal of five potential CO_2 storage sites on their path towards final investment decision (FID) readiness from an initial site inventory of over 500. The desired outcome is the delivery of a mature set of high quality CO_2 storage options for the developers of major power and industrial CCS project developers to access in the future. The work will add significantly to the de-risking of these stores and be transferable to storage developers to complete the more capital intensive parts of storage development.

The five storage sites in the selected portfolio and the three stores evaluated during earlier FEED studies make up the Build-out Portfolio. These are identified on the location map in Figure 1-1, together with the other high potential sites identified earlier in this project (Pale Blue Dot Energy & Axis Well Technology, 2015). This Build-out Portfolio can receive CO_2 from all of the beachheads that are anticipated to be staging points for onshore CO_2 emissions being supplied offshore.

The objective of this part of the project, set in May 2015, was to illustrate how the selected stores might contribute to providing storage for the potential CCS roll out scenarios identified in the ETI's 2015 work, all of which resulted in around 50Mt/year being stored by 2030. All of these scenarios assumed a starting point of injecting CO_2 from the two DECC Commercialisation projects by 2020. Clearly this level of ambition has been affected by the funding decision taken by UK government in November 2015, but for consistency the scenarios adopted in this report illustrate how the portfolio could service the ETI 'Balanced Scenario'. Clearly, in practice, storage needs to be developed according to expected future needs.

The storage growth scenario is assumed to begin in the early 2020s with the Captain aquifer in the Central North Sea (CNS), accessed either via injection at Site X or the Goldeneye area. This aligns with current full chain CCS project development activity and assumes that the earliest CO_2 emissions that would require storage might come from the Grangemouth area. This would be supplemented in 2026/7 with stores at Hamilton in the East Irish Sea (EIS) and Endurance and Bunter Closure 36 in the Southern North Sea (SNS) to store CO_2 from emitter sites supplying the beachheads at Connah's Quay and Barmston respectively. In general, as discussed in Section 4.0, the Build-out portfolio matches very well to the CO_2 emissions scenario outlined in Section 3.0 which is based on the CO_2 Emissions Scenarios work (Energy Technologies Institute, 2015).

In the late 2020s - early 2030s further growth of CO_2 storage resource will come from development of the store at Forties 5 Site 1 in the CNS and the Hewett and Viking A stores in the SNS. Many other stores are available when additional storage capacity is required.

The schedule of developments within the Build-out Portfolio would require an investment over their lifetimes of £2.1 billion (in Real, 2015 PV_{10} terms), during which time approximately 1.6 billion tonnes of CO_2 would have been stored. This equates to £14.4/t when expressed as a levelised cost.

In aggregate for the portfolio, the transportation and storage contributes £6.9/MWh to the levelised cost of gas fuelled electricity generation.

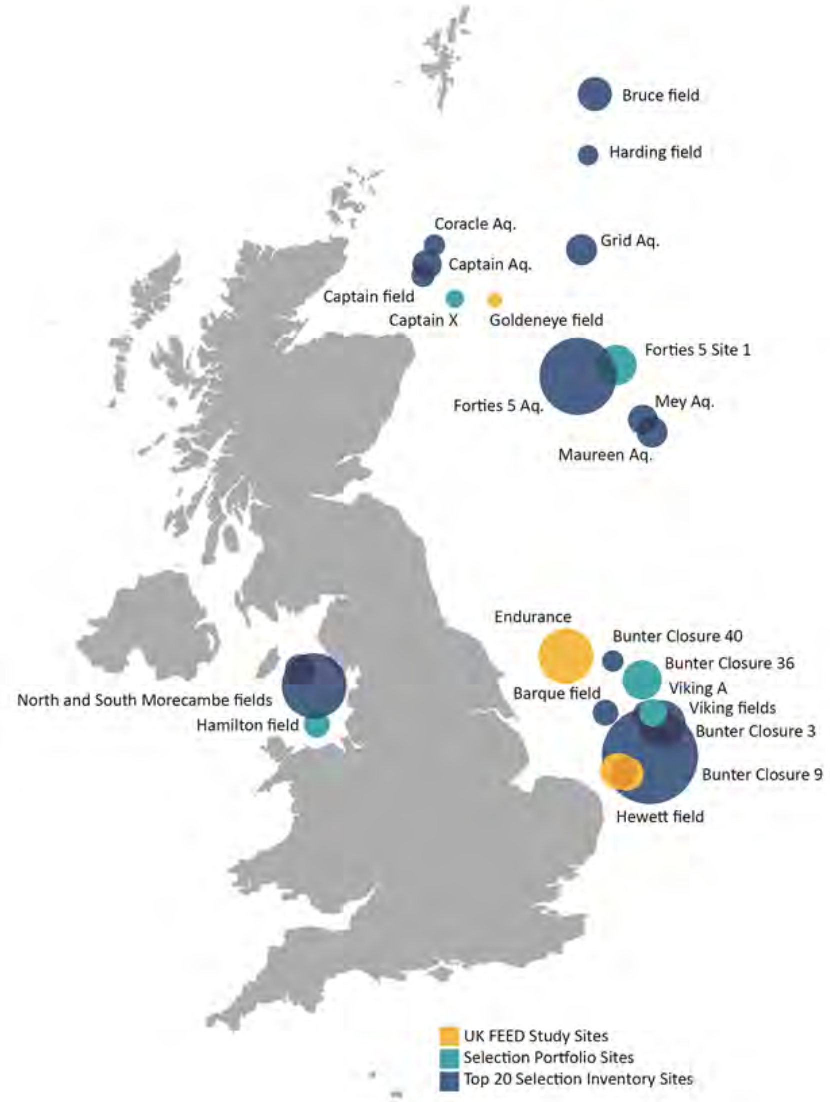

Figure 1-1 Map of Build-out Portfolio and Expansion Options

2.0 Introduction

The Strategic UK CCS Storage Appraisal Project has five objectives, as illustrated in Figure 2-1.

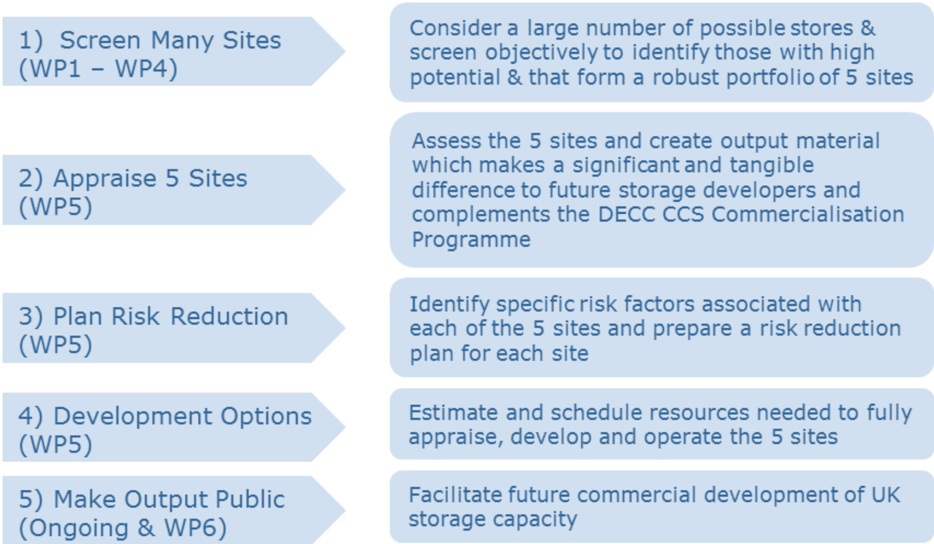

Figure 2-1 Project Objectives

The objective of this stage of the project fits within the broader purpose of the project to "facilitate the future commercial development of UK CO_2 storage capacity".

Specifically, this phase of work aims to:

- Increase confidence of prospective onshore capture projects that sufficient storage would be available in the future.
- Quantify the likely cost of transportation and storage and show how this contributes towards having decarbonised power at less than £100/MWh.
- Describe and assess a CO_2 storage build-out scenario that could accommodate emissions from 10GW of power from thermal plant by 2030 (50Mt/year of CO_2 injection).

Previous stages of this project reviewed over 580 potential CO_2 storage sites in the UKCS and distilled a list of 20 sites for more detailed due diligence work. This inventory of twenty sites had the following attributes.

- A significant overall estimated capacity of 6.8GT.
- A strong balance between saline formations and depleted hydrocarbon fields.
- Strong compliance with IEAGHG screening guidelines for CO_2 storage.
- A strong portfolio with a broad geographic spread across the Southern North Sea (SNS), Central North Sea (CNS) and East Irish Sea (EIS).
- Strong technical diversity of sites.

Following the due diligence process a portfolio of five storage sites with different development timescales, geographical and geological diversity was selected to serve the primary purpose of accommodating 50Mt/y by 2030. The selection includes:

1. The depleted Hamilton gas field in the East Irish Sea;
2. Site X in the saline Captain aquifer in the Central North Sea;

3. Site 1 in the saline Forties 5 aquifer in the Central North Sea;
4. Closure 36 in the saline Bunter aquifer in the Southern North Sea; and
5. The depleted Viking "A" gas field in the Southern North Sea.

Outline storage development plans and budgets were prepared for each of these sites to synthesise outputs from the seismic interpretation, geological characterisation, well design, injection performance modelling, containment assessment, facilities design, development planning and cost estimation work streams.

This project alongside the detailed knowledge transfer products from the Hewett, Goldeneye and Endurance FEED studies represents one of the most comprehensive and mature CO_2 storage potential propositions available within the public domain and will support ongoing public and private debate and also fuel early carbon capture and storage development projects.

The primary purpose of this report is to provide insights into an illustrative scenario for the build-out of CO_2 storage developments across the UKCS. The work upon which this report is based includes:

- Projections of future supplies of CO_2,
- Development plans and cost estimates from this project, and
- Development plans and cost estimates for the three projects from the UK Governments CCS competitions.

Key to the build-out scenario is the geographic distribution, quantity and timing of future CO_2 emissions. This project took as its starting point the CO_2 Scenarios Report (Energy Technologies Institute, 2015), the key conclusions on which are listed below.

1. Developing a 10 GW scale CCS sector by 2030 is feasible and affordable through a number of different pathways, based on co-ordinated cluster/hub development.
2. Early projects can make use of shared infrastructure delivering strike prices at or below £100 per MWh by 2025, with potential further cost reductions by 2030.
3. A 10 GW scale CCS sector would be affordable in terms of the demand on levy control framework funds (an annual support cost of around £1.1 to £1.3 billion by 2025) and efficient in terms of cost per tonne of CO_2 reduction.
4. This scale of CCS deployment could capture and store around 50 million tonnes of CO_2 emissions per annum from power and industry by 2030, enabling CCS to develop in the 2030s to the optimal scale suggested by longer term analysis of the UK energy system.
5. This outcome can be delivered by creating a supportive policy environment with early action on critical issues to bring forward timely investment.

3.0 CO_2 Supply Profile

This study takes as its basis the ETI commissioned report on CO_2 Emissions Scenarios (Energy Technologies Institute, 2015). This provides the quantities of CO_2 potentially available and requiring storage over the period to 2030. These were designed to capture a wide range of possible outcomes resulting from key drivers and policy. The three scenarios are illustrated in Figure 3-1 and described below.

Concentrated. Growth concentrated close to the White Rose and Peterhead CCS demonstration projects.

CO_2 EOR. Clustering of stores in the Central North Sea (CNS) in proximity to the oil fields most likely to benefit from CO_2 enhanced oil recovery.

Balanced. Diverse, regional CO_2 sources using a number of different fuel sources and capture technologies.

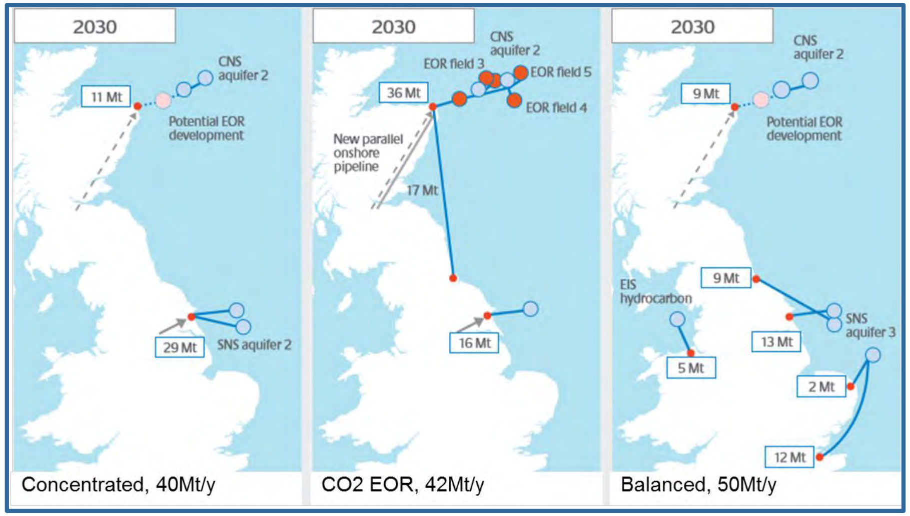

Figure 3-1 Three CO_2 Supply Scenarios (Courtesy ETI)

The geographic diversity of emission sources inherent in the Balanced Scenario mean that it is most relevant to this study and the development of a plausible build-out scenario of CO_2 stores. The Scenarios work only included CO_2 profiles to the year 2030. The infrastructure required for the development of CO_2 storage sites will typically have a useful asset life of approximately 40 years (Pale Blue Dot Energy, 2015) and consequently to examine the development of a series of sites these profiles were extended to 2070. The resulting CO_2 profiles are shown in Figure 3-2 (limited to 2050 to maintain readability).

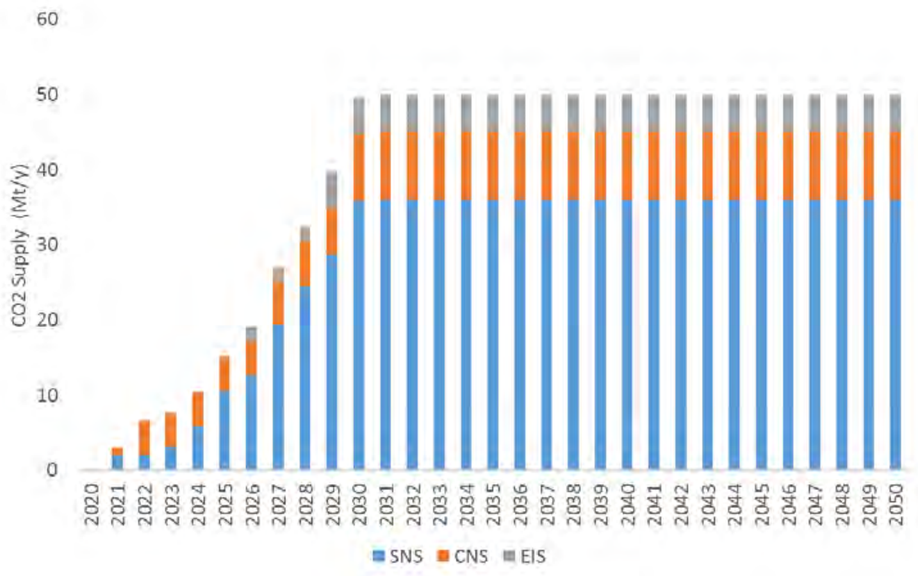

Figure 3-2 Regional CO_2 Supply Scenario

In the Balanced Scenario, CO_2 supplies for offshore storage are anticipated to commence in the early 2020s in the Yorkshire and Aberdeenshire areas, represented respectively by the SNS and CNS offshore sectors. Growth was anticipated to be more rapid in northeast England area because of the greater demands for power and industry in that area, driven in turn by a larger population and higher industrial intensity. Growth of CO_2 supply in northwest England is expected to be less rapid and commence a little later because of assumptions about the amount and timing of new thermal plant in that region.

For the purposes of this study the supply profile is constrained to plateau at approximately 50Mt/y of CO_2 but it is recognised that most 2050 energy system modelling work suggests that the supply rate would continue to rise beyond 2030.

This scenario was based on build out from the Peterhead and White Rose CCS projects. Clearly the cancellation of these projects in late 2015 will cause delays to the roll out of CCS in practice, but for the purpose of this project (i.e. illustrating how the portfolio of stores might support CCS roll out), the Balanced Scenario is used as a base.

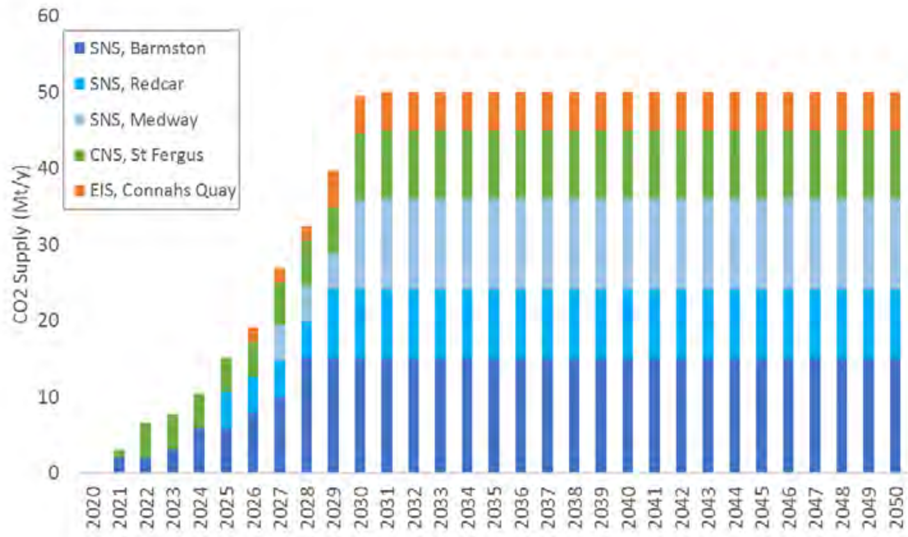

Figure 3-3 CO_2 Supply from Each Beachhead

4.0 CO_2 Storage Growth Scenario

4.1 Storage Sites

Two groups of potential CO_2 stores were used to develop the CO_2 storage growth scenario described in this section of the report:

- The *Project* portfolio of 5 storage sites assessed during the current project (Bunter Closure 36, Forties 5 Site 1, Hamilton, Captain Site X and Viking A; and
- The *Knowledge Transfer* portfolio of 3 storage sites evaluated during the UK CCS Commercialisation programme but not assessed during this current project.

There were differing types and amounts of information available to the Project for these two groups of sites and this fact may influence comparisons between sites in the two groups. Consequently, the issue is highlighted at key points throughout the following text.

4.2 Scenario Definition

The first storage sites to be developed would be those with good access to regions most likely to be capturing CO_2 and requiring storage services. Based on project activity at the time of writing, the central belt of Scotland is a good candidate to be considered most likely to be the first region to require CO_2 storage services. The key attributes of the scenario are highlighted in Table 4-1 and Figure 4-1. This illustration has selected a store portfolio and timing which is based on the Storage Development Plans developed for the portfolio of 5 stores and assumed (but realistic) plans for the three other stores (Hewett, Goldeneye and Endurance). The selected timing of the developments has been chosen to broadly match the Balanced Scenario, although some start delays have been built in.

From St Fergus, the Captain aquifer is likely to be the first target for development. There are two primary access points to the Captain aquifer; the Goldeneye depleted gas field and Site X, both of which have an existing pipeline suitable for re-use to transport CO_2. Evaluation of the Goldeneye store is more mature than for Site X, but only within the Goldeneye structure and for up to 30Mt (Scottish Power CCS Consortium, 2011) i.e. no expansion into the Captain aquifer was considered. Consequently, it is reasonable to assume that Goldeneye might be injecting first. However, it is unlikely to be big enough for a commercial development. Progression of Site X can be expected to occur at a similar time to, if not before, any re-development of Goldeneye as a CO_2 store. Initial development planning for Site X includes reusing an existing pipeline and if were to be developed first it could potentially be extended with an injection centre towards the Goldeneye area. As CO_2 supply from St. Fergus builds, it is anticipated that an additional site at the Forties 5, Site 1 location would be needed by around 2030.

Sites in the SNS will be used to store CO_2 supplied from the three beachheads on the east coast of England. Endurance is probably the most mature site close to Barmston and is likely to be the coastal location for emissions despatch from Yorkshire. As such it is likely to be one of the first sites to be exploited in the SNS. Other sites are required to manage both the CO_2 supply rate, other sources of supply and to build out a robust storage system.

The CO_2 storage sites closest to the Medway area and therefore with the lowest transportation costs are in the southern part of the SNS. The most mature of these is the depleted Hewett gas field which is assumed to be developed first, followed in due course by Viking A. The stores closest to Redcar are in the northern SNS and for the purposes of this illustration Bunter Closure 36 is assumed to service Redcar.

Hamilton is the primary store for CO_2 emissions from north west England via Connah's Quay or the Point of Ayr gas terminal further along the Dee estuary.

	Beachhead	1st Injection	Life (Years)	Inventory (Mt)
Goldeneye*	St. Fergus	2021	15	30
Captain, Site X	St. Fergus	2022	20	60
Hamilton	Connahs Quay	2026	24	125
Endurance#	Barmston	2026	40	520
Bunter Closure 36	Redcar	2027	40	280
Hewett**	Medway	2029	40	200
Forties 5, Site 1	St Fergus	2030	40	300
Viking	Medway	2031	26	130

Table 4-1 Outline Development Schedules

* 30Mt approximation to the 29Mt upside capacity estimate taken from the knowledge transfer deliverables published following the CCS Demonstration Competition (ScottishPower CCS Consortium, 2011). Not assessed during the current project.

** 200Mt approximation to the 206Mt capacity estimate for the Lower Bunter reservoir taken from the knowledge transfer deliverables published following the CCS Demonstration Competition (E.on UK, 2011). Not assessed during the current project.

Capacity estimate taken from CO_2Stored database. Not assessed during the current project.

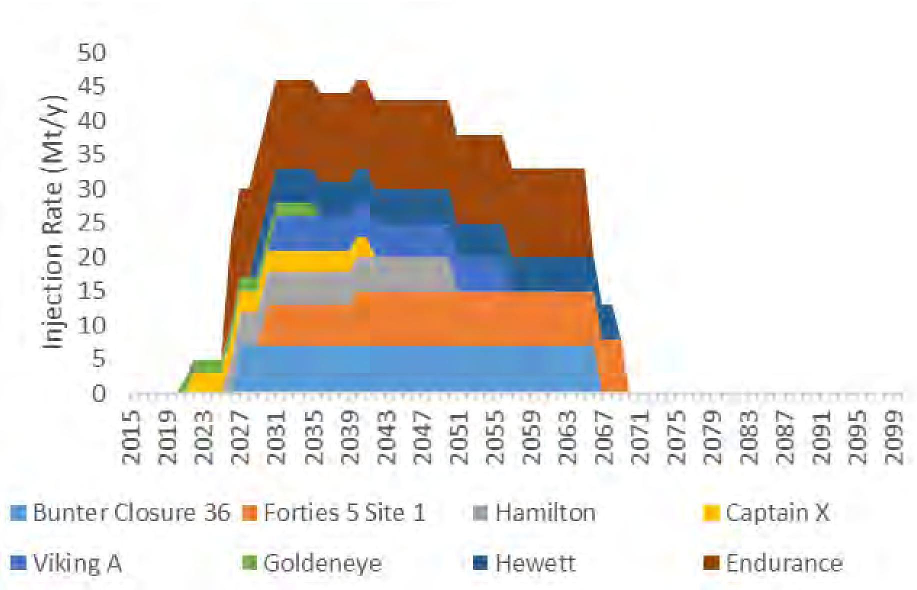

Figure 4-1 Build-out Profile of CO_2 Injection and Storage

Figure 4-2 Location Map

4.3 Matching Supply and Storage of CO_2

Figure 4-2 illustrates the location of these eight stores and the five beachheads (CO_2 supply terminals). Collectively they are referred to here as the "Build Out Portfolio". Other such portfolios could be developed with an alternative mix of stores and beachheads.

The timing of the development of the "Build Out Portfolio" is outlined in Table 4-1 and illustrated in Figure 4-3. The commencement, phasing and duration of these storage developments were developed during this project or adapted from plans published as part of the CCS Commercialisation Programme. The duration of the design phase, construction phase and the post closure monitoring period are the same for all stores and are assumed to be 2 years, 4 years and 20 years respectively.

Project operational life was limited to a maximum of 40 years, because this is typically the maximum useful life of high pressure offshore pipeline infrastructure. The duration of injection operations is dependent upon a wide range of factors, including reservoir quality, store type and dynamic behaviour of the store. Consequently, duration is specific for each store and these range from 15 years at Goldeneye to 40 years for Bunter Closure 36, Forties 5, Site 1, Hewett and Endurance. (Pale Blue Dot Energy & Axis Well Technology, 2016).

Figure 4-4 illustrates that the CO_2 storage growth scenario fits very well with the assumed CO_2 emissions supply profile. The fit is best in the CNS and EIS regions where the available injectivity in the base case development plans exceeds the anticipated supply. For the SNS, the base case storage development plans accommodate approximately 92% of the CO_2 supply. The CO_2 emissions scenario work envisaged CO_2 supplies from Barmston and

Medway in 2020 and 2026 respectively, although such an early start for Barmston is not credible in current circumstances.

In light of current uncertainty in the timing and details of initial CCS roll out, no attempts have been made to accurately match the initial shape of supply growth, although broadly the storage growth is behind the Balanced Scenario supply growth, reflecting delays caused by the 2015 project cancellations.

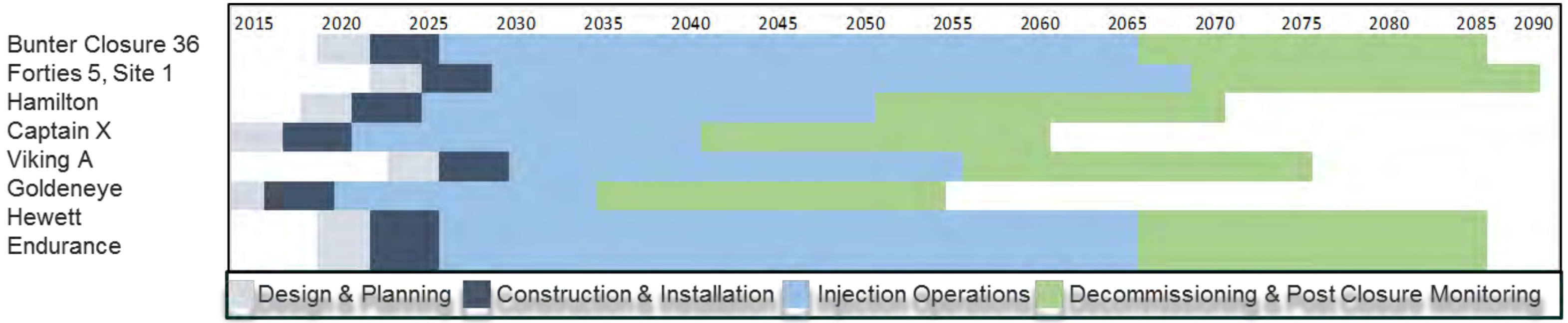

Figure 4-3 Portfolio Development Schedules

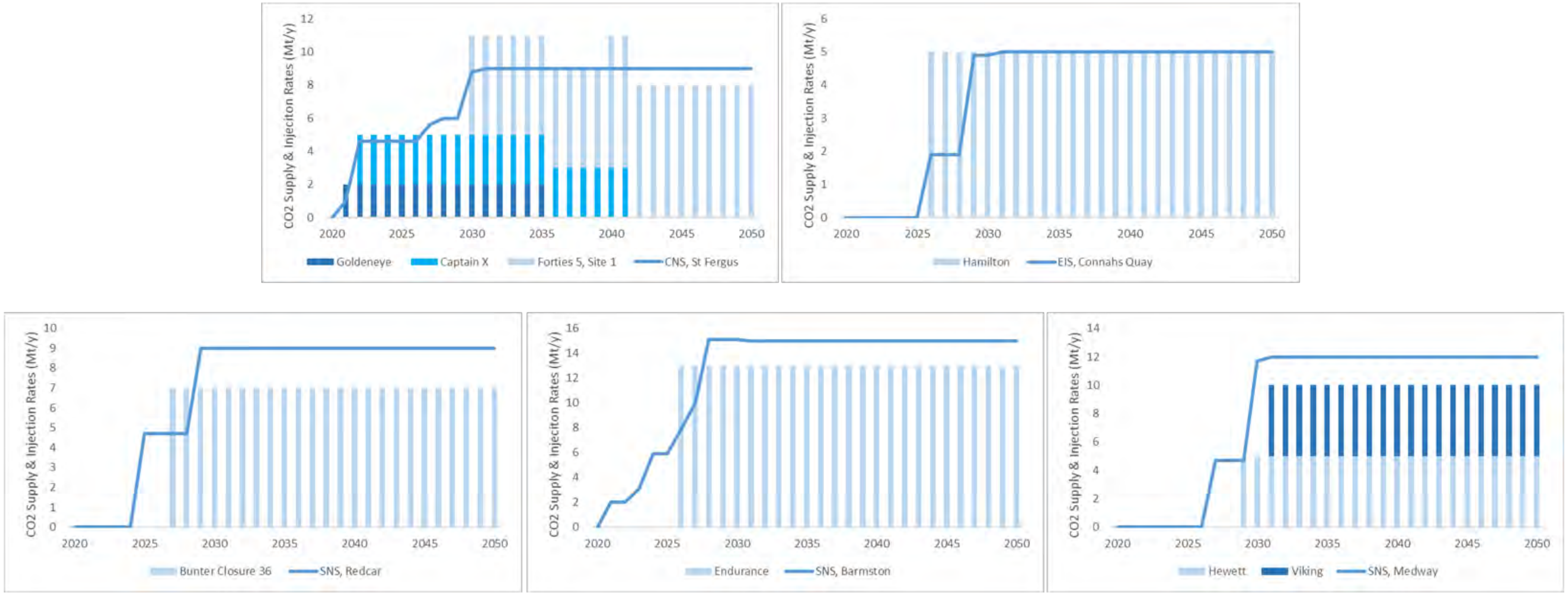

Figure 4-4 Matching Selected CO_2 Supply Scenarios with Storage Development Scenario

Overall the portfolio provides for approximately 46Mt/y (92%) of CO_2 injection capability, compared to a target demand of 50Mt/y.

This "Build-out Portfolio" of storage sites and the assumed development plans provide for a CO_2 storage capacity of approximately 1645Mt out to the year 2070. Figure 4-5 illustrates the contribution of each of the storage developments to this total. Demand for CO_2 storage beyond 2070 in excess of the amounts considered here can be accommodated by a multitude of other stores and is discussed in the following section.

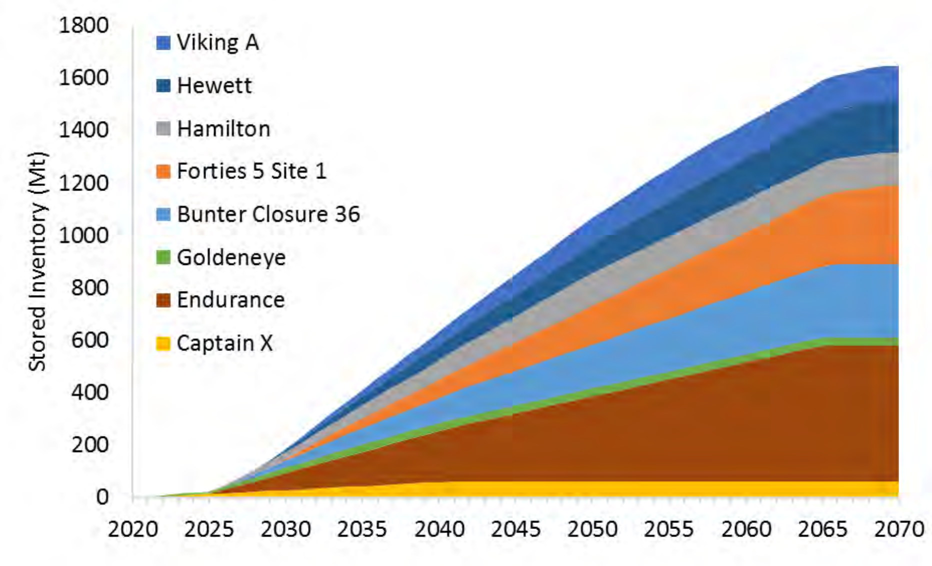

Figure 4-5 Cumulative Inventory of CO_2 Injected, to 2070

4.4 Opportunities for Expansion

This project has distilled a portfolio of five storage sites from an initial inventory of 580. An important criterion for their selection was the ability to materially progress the understanding of these sites on their pathway towards being capable of supporting a final investment business case. It is important to understand that there are many other high quality storage sites that have not been considered in the Build-out Portfolio for a wide range of reasons. Of the Select Inventory of 20 sites, many already have been the subject of either proprietary or academic research and CO_2 storage concept development studies and represent clear additional opportunities for storage. In particular, the following sites are worthy of particular note because of the step out potential to the Build-out Portfolio that they offer;

- **South Morecambe**. A very large depleted gas field in the EIS likely to be available to CO_2 storage operations in the early 2030s. Preliminary estimates are that the site has a capacity of around 850Mt.
- **North Morecambe**. A large depleted gas field in the EIS likely to be available to CO_2 storage operations in the early 2030s. Preliminary estimates are that the site has a capacity of around 180Mt.
- **Bunter Closure 9**. A very large saline aquifer site with a potential capacity of nearly 2000Mt above the giant Leman gas field which itself has a capacity estimated to be around 1300Mt (Energy Technologies Institue, 2011).
- **Bunter Closure 3**. A large saline aquifer site very close to the Viking A store. Potential capacity is estimated to be 230Mt.
- **Forties 5, Site 3**. Similar size and characteristics to the Forties 5, Site 1 store.

- **Forties 5, Site 4**. Similar size and characteristics to the Forties 5, Site 1 store.
- **Forties 5, Site 5**. Similar size and characteristics to the Forties 5, Site 1 store.

4.5 Infrastructure

The primary opportunity for significant cost saving in the development of multiple CO_2 stores is in the sharing of key offshore infrastructure, primarily pipelines. However, given the wide geographic spread of stores and CO_2 beachheads the opportunity to share pipelines might be limited.

In some instances, pipelines that have been used for oil and gas production operations may be suitable for re-use for CO_2, provided that they still have an adequate pressure rating for transporting CO_2 and sufficient remaining life for the CO_2 project. These pipelines are likely to be limited to oil and gas developments that had short lifetimes (5-7 years), such as those to the Goldeneye and Site X (Atlantic and Cromarty) areas of the Captain aquifer.

Typically, the useful life of offshore infrastructure assets is designed to be approximately 40 years. The longevity of a storage development is likely to be designed to be similar to the useful life of its infrastructure. Consequently, conventionally designed pipelines etc. will have no residual value and not be suitable for reuse by a later project. To maximise the opportunity for several storage sites to use common infrastructure either sequentially or concurrently it may be desirable to invest in infrastructure that has a design life sufficient for two or more storage projects and enough capacity for both projects. However, it should be noted that this could introduce commercial complexity due to potential timing and ownership differences.

4.6 Key messages emerging

A build-up of CO_2 supply around the country and the 50Mt/y plateau would require multiple sites across the offshore regions. In this illustration the assumed UK CCS build out can be achieved by using eight initial sites: the five sites evaluated as part of this study and the three sites that were evaluated during the UK CCS Commercialisation Programme.

There is significant storage potential at each of the beachheads with further potential build out to supplement to the Build-out Scenario.

5.0 Development Cost Estimates

5.1 Storage Site Developments

Details of the outline development plans and budgets for the five study sites are provided in Deliverables D10, D11, D12, D13 and D14 (Pale Blue Dot Energy & Axis Well Technology, 2016). These documents contain detailed estimates of the appraisal cost, capital investment, operating expense, decommissioning cost and post-closure monitoring cost for each of the sites.

Where possible, publically available information on the three Commercialisation Programme sites was used to develop cost estimates for those sites (Department of Energy and Climate Change, 2013). In some instances, this included FEED-quality cost estimates.

The location of the stores, the beachheads and connecting pipelines are illustrated in Figure 5-1. The development plans used to develop the cost estimates are summarised in Table 5-1.

Figure 5-1 Storage Site Locations

	Beachhead	Appraisal	Facility	Pipelines & Cables	Active Wells	Injection Rate (Mt/y)	Comments
Bunter Closure 36	Barmston	1 well Seismic	12 slot NUI 75m of water	20", 160 km	8 in 2 phases	7	3D seismic survey required prior to FID.
Forties 5, Site 1	St Fergus	1 well Seismic	6 slot NUI 4 slot subsea 85m of water	24", 217km 12", 24km	12 in 2 phases	6 then 8	3D seismic survey required prior to FID. Subsea template follows 10 years after platform development
Hamilton	Connah's Quay	No drilling	6 slot NUI 25m of water	16", 26km 33kV cable	4 in 2 phases	5	Continuous wellhead heating required for first 17 years for CO_2 phase management, power from Point of Ayr gas terminal.
Captain, Site X	St Fergus	No drilling	4 slot NUI 115m of water	16", 78km 16", 8km	2 in 1 phase	3	Reuse of the Atlantic and Cromarty pipeline
Viking	Barmston or Medway	No drilling	4 slot NUI 28m of water	20", 185km 33kV cable	2 in 1 phase	5	Continuous wellhead heating required for first 20 years for CO_2 phase management. Power from Bacton
Goldeneye	St Fergus	No drilling	6 slot NUI 120m of water	20", 100km	5 in 1 phase	3	Re-use of the Goldeneye platform, pipeline & wells as outlined in DECC CCS competition outputs
Endurance	Barmston or Redcar	No drilling	2 * 4 slot NUI 60m of water	24", 90km 16", 20km	16 in 2 phases	13	Based on information in the public domain
Hewett	Barmston or Medway	No drilling	4 slot NUI 37m of water	20", 250km 12" 30km 33kV cable	4 in 2 phases	5	Based on information outlined in DECC CCS competition outputs. Wellhead heating required for CO_2 phase management, power from Bacton

Notes: Each development is assumed to have a baseline seismic survey and 1 backup injection well but these are excluded from the numbers present in this table.

Table 5-1 Development Plan Summaries

5.2 Cost Estimates

Cost estimates for each of the major components of each of the developments are provided in the following table. The estimates provided here are in Real, 2015 terms. See Section 6.0 for an explanation of economic terms.

Real, 2015. *These values represent current-day cost estimates and exclude the effects of cost escalation, inflation and discounting.*

	CO_2	Cost Components (£, millions)					
	Mt	Pre-FID#	Capex	Opex	Abex	PC MMV*	Total
Goldeneye	30	38	277	170	110	33	629
Captain, Site X	60	31	201	385	96	92	804
Hamilton	125	24	257	497	77	19	874
Viking A	130	28	429	639	94	14	1,204
Bunter Closure 36	280	52	617	751	148	40	1,609
Hewett	200	24	623	988	130	81	1,846
Endurance	520	30	777	1,085	313	81	2,285
Forties 5, Site 1	300	103	922	1,446	205	293	2,968
Total	1,640	330	4,103	5,961	1,173	651	12,218

Table 5-2 Store Development Costs (Real, 2015)

* PC MMV includes monitoring activity during the 20-year post closure and the handover payment (equivalent to the cost of 10 years of post closure monitoring. Monitoring activity during the operational period is included within the opex figure.

For the three stores that have already completed FEED, the Pre-FID costs include estimates for any ongoing operating cost of the facilities prior to conversion to CO_2 duty and the effort a new project developer would need to expend in order to adapt the knowledge transfer items into a decision support package that meets their own corporate governance requirements.

Figure 5-2 Relative Magnitude of Life-cycle Cost Components (Real, 2015)

Figure 5-2 shows that, when the Build-out Portfolio is considered in aggregate, Facilities Opex accounts for the bulk (43%) of the costs. Capex for wells and transportation account for 13-14% each, Abex represents 10% and the other categories between 2-6%. These figures ignore the impact of timing and development schedule which is considerable and is discussed in Section 6.0.

The Facilities Opex comprises four main items as shown in Table 5-3.

Component	Comment
Platform	Annual costs calculated as 5.5% of capital outlay, based on estimating Norms Wellhead heating costs (where appropriate) calculated based on estimated power requirements and cost of electricity supplied to the installation.
Wells	Based on an assessment on likely well intervention requirements, frequency and cost.
Operations MMV	Primarily related to area and frequency of seismic surveys required during the operating period.
Financial Securities	Predominantly linked to the life-time operating cost of the offshore facility and penalties for an assumed minor migration of CO_2 outside the defined storage complex. Security provided by a financial instrument renewed annually.

Table 5-3 Four Components within Facilities Opex

Figure 5-3 illustrates the relative ranking of the stores according to the development cost.

In absolute terms, Forties 5, Site 1 is the costliest site to develop. This is because it covers the largest area, has a low storage efficiency and consequently requires the most wells and has the longest pipeline.

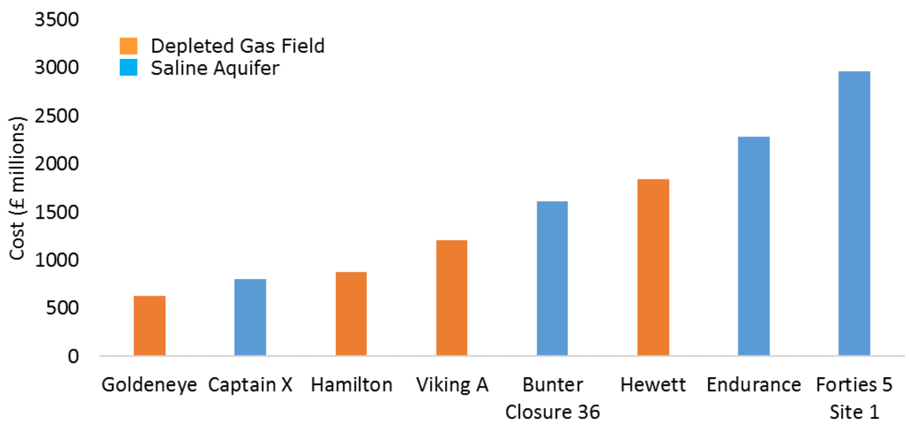

Figure 5-3 Store Development Costs (Real, 2015)

Development costs depend on a variety of factors including size, location, store depth, storage efficiency and the development plan itself (i.e. the number of wells and facilities required to meet the desired injection rate). Figure 5-4 illustrates the relationship between the amount of CO_2 stored and the development cost.

Goldeneye is the least costly to develop for three primary reasons: it has the smallest CO_2 inventory, existing infrastructure suitable for re-use and the shortest field life. However, as illustrated in Figure 5-5, it seems that the ability to reuse some existing infrastructure presents little direct cost benefit if the quantity that can be stored is modest.

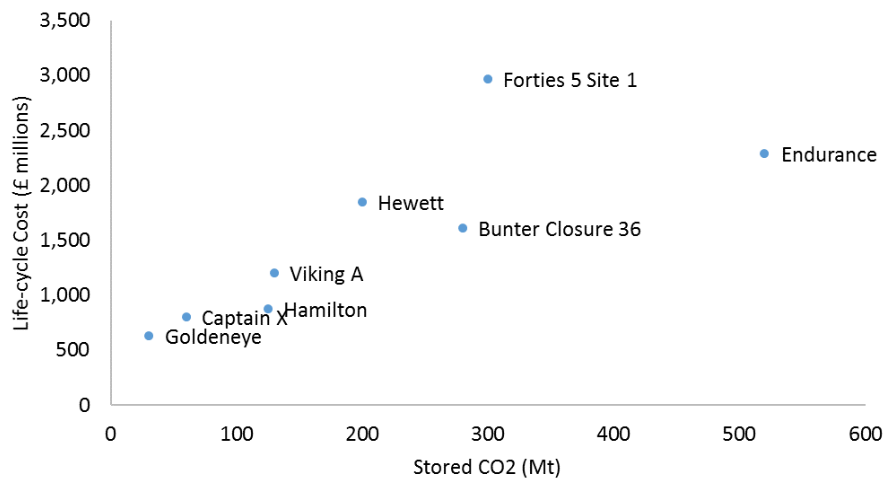

Figure 5-4 Development Costs (Real, 2015) vs Storage Capacity

The development costs are presented on a unit basis in Figure 5-5.

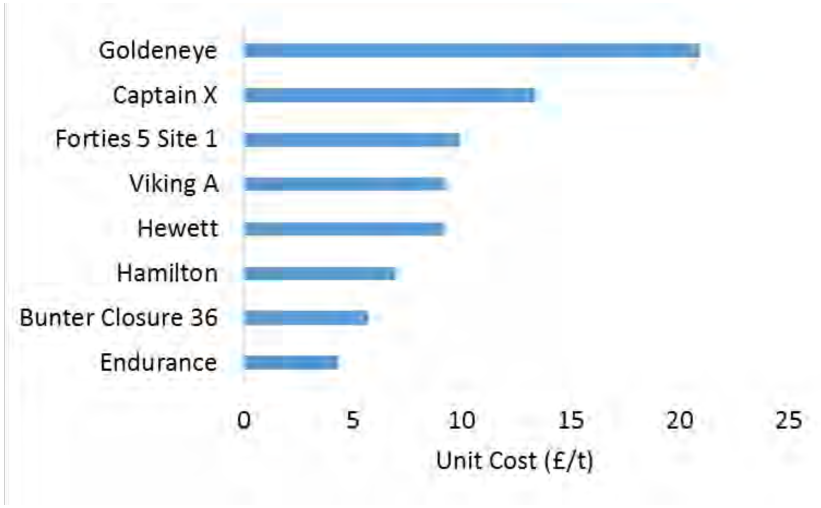

Figure 5-5 Development Costs on a Unit Basis (Real, 2015)

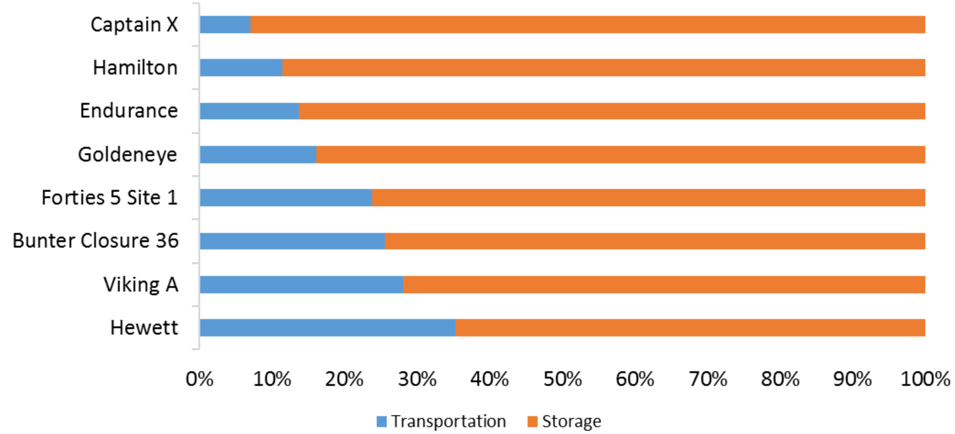

Figure 5-6 Ratio of Transportation and Storage Costs (Real, 2015)

Storage costs are typically 77% of the life-cycle costs for a storage development and range between 61 - 93% for individual stores. The transportation costs account for the balance, as illustrated in Figure 5-6. The lower transport costs arise either from short distances between beachhead and store (e.g. Hamilton, Endurance) or where existing pipelines can be used (e.g. Captain X and Goldeneye).

5.3 Regional Comparison

The five storage sites evaluated during this project are in one of three regions on the UK Continental Shelf: the East Irish Sea, the Southern North Sea and the Central North sea. These areas differ in many ways: water depth, depth of stores, number of stores, type of stores and distance from the assumed CO_2 supply terminal, or beachhead.

5.4 Cost Estimating Basis

The cost estimates were prepared so that they could be readily translated into a levelised cost metric. The estimates include the appraisal, capital investment, operating, decommissioning, post closure monitoring and handover costs for the offshore transportation and storage plant but exclude the cost of capital and any profit for the store developer. This is sometimes called a life-cycle cost, which emphasises the "cradle to grave" aspect of the definition. The levelised cost estimates do not consider revenue streams available to store owners (e.g. from sale of storage capacity or revenues from other sources) so that the estimates reflect the cost of CO_2 transportation and storage only.

The levelised cost of transportation and storage is the discounted lifetime cost of ownership and use of the offshore transportation and storage assets, converted into an equivalent unit of cost of transportation and storage in £/tonne.

The levelised cost is the ratio of the total costs of a CO_2 storage development to the total amount of CO_2 expected to be stored over the store's lifetime. Both are expressed in net present value terms. This means that future costs and outputs are discounted, when compared to costs and outputs today. The calculation is illustrated in Figure 6-3.

The cost estimates for the five storage sites evaluated during this project were prepared on a consistent basis and derived from a bespoke development plan as detailed in the Storage Development Plans (Pale Blue Dot Energy & Axis Well Technology, 2016). The Goldeneye, Endurance and Hewett stores were not evaluated during this study primarily because the evaluations were already mature and this project would be unlikely to add any significant new understanding (Pale Blue Dot Energy & Axis Well Technology, 2015). The basis for estimating the cost of the storage developments are shown in Table 5-4.

Stores	Approach
Bunter Closure 36, Captain X, Forties 5 Site 1, Hamilton and Viking A	Project derived storage development plan based on an assessment of the subsurface, wells and facilities requirements
Endurance	Used Bunter Closure 36 development plan as an analogue, distances taken from material published by National Grid Carbon
Hewett	Used Hamilton & development plan as an analogue due to similarities in development requirements, depths and distances from DECC Knowledge Transfer documents
Goldeneye	DECC Knowledge Transfer documents escalated from 2011 to 2015 and adjusted to take account of most recent development for Goldeneye

Table 5-4 Basis of Cost Estimates for the Build-out Portfolio

The different bases described in Table 5-4 coupled with the restricted information available for the Endurance, Hewett and Goldeneye stores mean that there is less confidence in the cost estimates for those stores than for the five storage sites evaluated during this project. It is understood that the current owners of those projects have studied the development options and cost in detail but that these were not available to this project.

The development at the Goldeneye storage site was planned as a brownfield modification project to the existing Goldeneye gas production platform and pipeline. The modification project activities described in the 2011 Knowledge Transfer documents remain relevant to changing the use of the Goldeneye infrastructure for CO_2 storage operations. Namely: local strengthening of the platform jacket; modification to the platform topsides (piping, pig-launcher, injection manifold etc.); replacement of the subsea isolation valve and recompletion of 4 of the existing 5 wells to CO_2 injectors. The capex estimate for this modification was reported as £252 million in 2011, excluding abandonment costs.

Details of the more recent development planning work for Goldeneye have yet to be published. However, the offshore transportation infrastructure is known to be different (Shell, 2015) from the 2011 plan – a new section of offshore pipeline is planned to run directly from the Peterhead power station to intersect with the existing Goldeneye pipeline approximately 20km offshore. The cost estimate used in this project for the Goldeneye development is shown in Table 5-5.

Item	£m	Comment
Base Estimate	252	Per 2011 Knowledge Transfer documents
Less **2011 St Fergus transport cost**	(18)	Per 2011 Knowledge Transfer documents
Escalate to 2015 basis	23	Compound inflation of 9.9% between 2011 and 2015
Add **New beach crossing at Peterhead** **New Pipeline section**	32 26	Estimated using same Norms as for the other development plans in this project
Estimate used in this project	315	

Table 5-5 Basis of Goldeneye Storage Development Cost Estaimte (Real, 2015)

Hewett and Endurance are both greenfield developments and cost estimating approach used on the five project sites was also used to generate the estimates for Hewett and Endurance shown in Table 5-2. The bases for these estimates are the outline storage development plans described in Table 5-1.

Development of the pressure depleted Hewett gas field is assumed to be analogous to those for Hamilton and Viking A. The reservoir is assumed to have high storage efficiency, in common with the other depleted gas fields evaluated, and therefore a single well centre would be required with only a few wells. Heating is required to manage the CO_2 phase issues and therefore a minimum facilities platform has been assumed.

Development of the structurally closed saline aquifer at the Endurance location is assumed to be analogous to that for Bunter Closure 36. Namely that the reservoir will have a moderate storage efficiency, requiring several drill centres each with 4 wells (replaced after 20 years). The assumed development includes two minimum facilities platforms linked by a 20km infield pipeline and a 24” diameter main trunkline to Barmston.

Estimates of the capital cost components for Hewett and Endurance have been calculated in the same way as for the five project sites and depend primarily on water depth, well depth, number of wells, pipeline diameter and pipeline length.

6.0 Economic Modelling

Discounted cash flow modelling was used to incorporate the impact of the portfolio build-out schedule as well as the development schedule for the specific stores. Cost estimates for each of the major components of each of the developments are provided in Table 6-1. The estimates provided in this section are Real, 2015 PV_{10}.

Real, 2015 PV_{10}. *These values incorporate the time value of money into the estimates. They exclude the effects of cost escalation and inflation. Values are discounted back to a common base year of 2015 using an annual discount rate of 10%.*

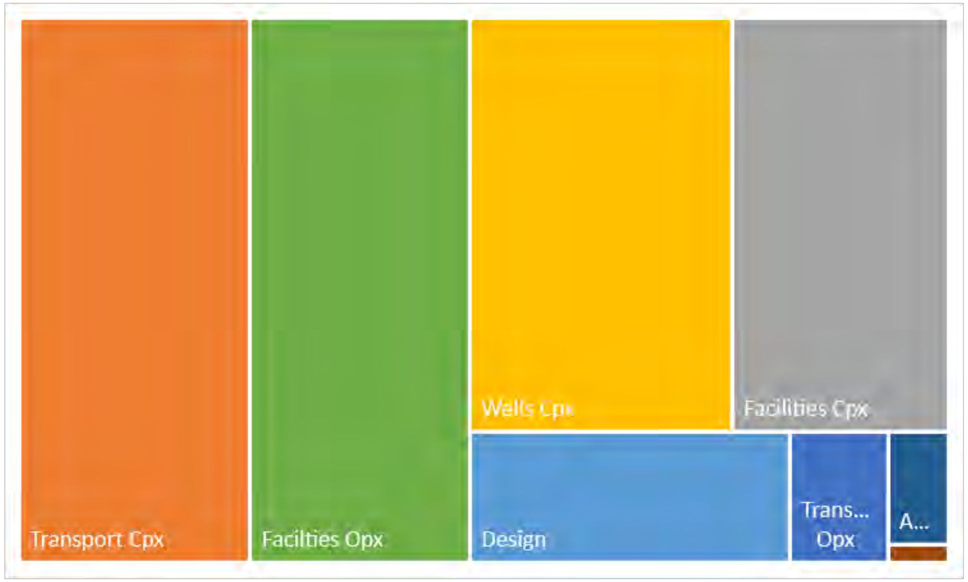

Figure 6-1 Relative Magnitude of Life-cycle Cost Components (Real, 2015 PV_{10})

The total life-cycle cost of the Build-out Portfolio scenario is £2061 million (Real, 2015 PV_{10}), as summarised in Table 6-1 and Figure 6-2.

	Cost Components (£, millions)					
	Pre-FID	Capex	Opex	Abex	MMV	Total
Viking A	9	106	49	1	0.1	166
Hamilton	13	89	69	2	0.2	174
Captain X	24	116	84	6	2.1	233
Hewett	11	173	64	1	0.2	248
Bunter Closure 36	28	182	59	1	0.1	269
Goldeneye	33	181	49	13	1.2	278
Forties 5 Site 1	34	181	72	1	0.5	288
Endurance	18	292	93	2	0.2	405
Total	170	1320	538	27	5	2061

Table 6-1 Store Development Costs (Real, 2015 PV_{10}) – Portfolio Schedule

Figure 6-1 shows that, when the Build-out Portfolio is considered in aggregate and including the time and schedule influences facilities opex (this includes well remediation costs) is still the largest component but now only represents 26% of the costs. Capex for wells and transportation account for 21-25% each, facilities capex represents 18% and the other categories are 0.5-7%. These figures include the impact of timing and development schedule; they are presented on an undiscounted basis in Section 5.0.

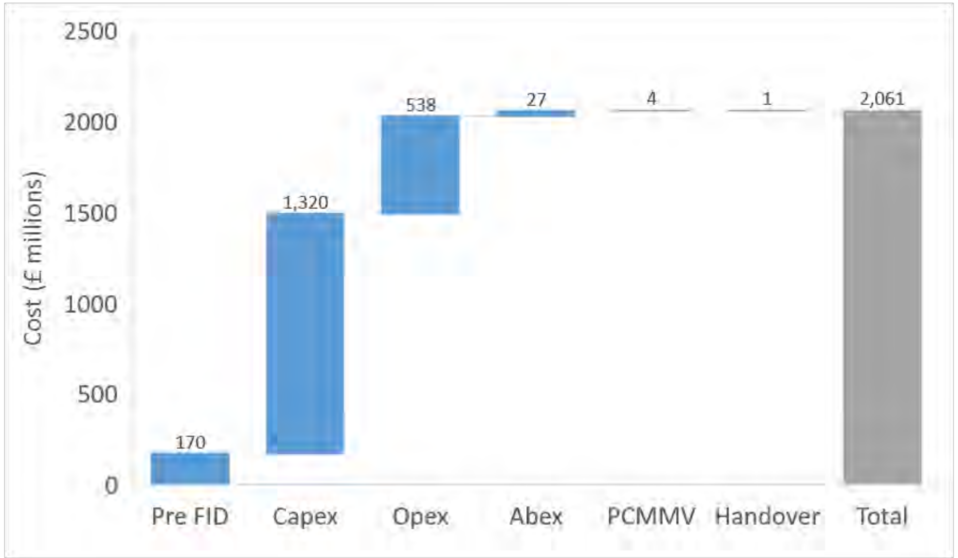

Figure 6-2 Waterfall Chart of Cost Components for the Build Out Portfolio (Real, 2015 PV_{10})

Table 6-1 is provided to enable comparison with the values generated during the study and reported in the Store Development Plans for Bunter Closure 36, Forties 5 Site 1, Hamilton, Captain Site X and Viking (Pale Blue Dot Energy & Axis Well Technology, 2016). Implicit in these discounted values is the impact of the injection start date and other schedule assumptions derived during the planning work.

The levelised cost of the offshore transportation and storage assets was calculated in the standard manner for calculating the levelised cost of electricity generation (DECC, 2013) as illustrated in Figure 6-3. The results are shown in Table 6-2 and Figure 6-4.

Step 1: Gather Data

Capital Costs	Operating Costs	Operating Data
Pre-development	Fixed Opex	CO_2 injection rate
Design	Variable Opex	Injection quantity
Construction	Planned maintenance	Timing
Installation	Unplanned Maintenance	
	Decomissioning	

Step 2: Sum the net present value of total expected costs for each year

NPV of Total Costs = $\Sigma n \dfrac{Annual\ total\ capex\ and\ opex\ costs}{(1+discount\ rate)^n}$

n = time period

Step 3: Sum the net present value of expected CO_2 injection for each year

NPV of CO_2 Injection = $\Sigma n \dfrac{Annual\ CO2\ injection}{(1+discount\ rate)^n}$

n = time period

Step 4: Divide 2 by 3

Levelised Unit Cost of CO_2 Injection = $\dfrac{NPV\ of\ Total\ Costs}{NPV\ of\ CO2\ Injection}$

Figure 6-3 Calculation of Levelised Cost

	Contribution to Levelised Costs				
	Transportation (£/t)	Storage (£/t)	Total (£/t)	Gas Power (£/MWh)	Coal Power (£/MWh)
Endurance	1.9	7.2	9.1	4.3	8.7
Hamilton	2.0	8.9	10.9	5.2	10.4
Bunter Closure 36	4.8	7.5	12.3	5.9	11.7
Viking A	6.7	10.0	16.7	7.9	15.9
Captain X	1.9	15.8	17.7	8.4	16.9
Forties 5 Site 1	7.9	10.4	18.3	8.7	17.4
Hewett	10.3	9.0	19.2	9.2	18.3
Goldeneye	6.3	26.1	32.3	15.4	30.7
Aggregate	4.4	10.0	14.4	6.9	13.7

Table 6-2 Levelised Costs of Offshore Tranpsport and Storage and contribution to cost of electricty (Real, 2015 PV_{10})

Endurance appears to offer the lowest levelised cost of offshore transportation and storage (i.e. the cost of ownership). This is due to the large storage capacity attributed to the site (Energy Technologies Institute, 2010) and has not been verified in the current study.

For the five sites evaluated during the current work the levelised costs range between £11 - £28 per tonne of CO_2 and the whole portfolio has a volume-weighted mean value of £14/t. Levelised costs for all storage sites are shown in Figure 6-4.

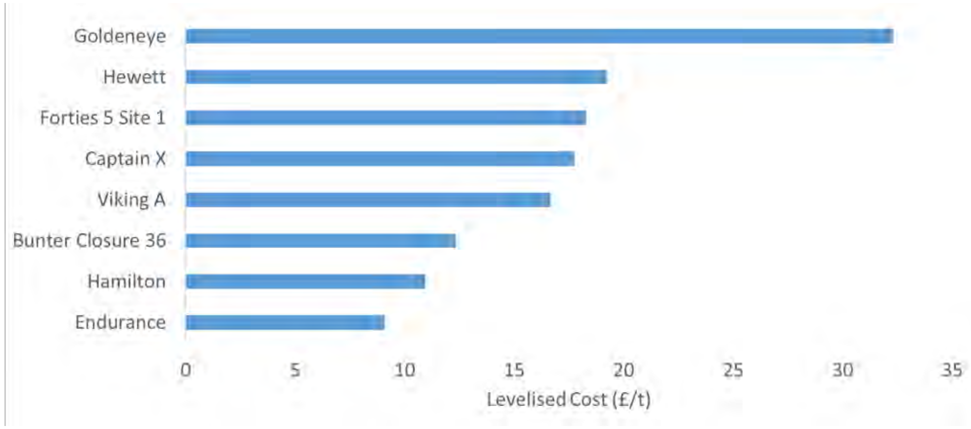

Figure 6-4 Levelised Costs (Real, 2015 PV_{10})

Storage at Goldeneye is expensive due to the relatively small quantity of CO_2 planned to be stored and the 15-year project life required for the UK Commercialisation programme.

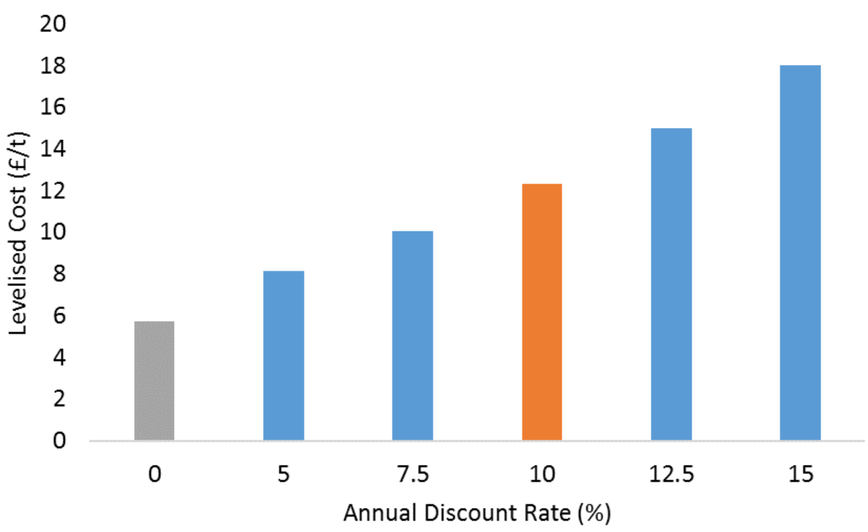

Figure 6-5 Influence of Discount Rate on Levelised Costs – Bunter Closure 36 Example

The discount rate has a significant impact on the levelised cost; as the discount rate increases so does the levelised cost, as illustrated in Figure 6-5 which uses Bunter Closure 36 as an example. The column shown in grey, at a zero discount rate, is the £5.9/t Real 2015 figure illustrated in Figure 5-5. The orange column represents the 10% discount rate used during this project and corresponds to the £12.3/t shown in Table 6-2.

6.1 Storage Efficiency

The lifecycle unit cost of CO_2 transport and storage developments is complex and dependent upon many factors. The influence of some factors such as the length of the pipeline or the number and depth of wells required are both obvious and clear. Factors such as the volume of CO_2 stored in any project are equally important but often less obvious.

Storage efficiency is another factor that has a very strong influence on the lifecycle unit cost. Whilst it is far less well understood than other factors, it is a fundamental influence on overall life-cycle costs.

Storage Efficiency. This is a key parameter which describes the volume proportion of pore space within the target storage complex reservoir volume that can be filled with CO_2 given the development options considered. This ranges from 2 to 5% in some open aquifers without structures, through to 70-80% in highly depleted gas fields. It is broadly the equivalent of recovery factor in the oil and gas industry.

Storage efficiency is high in pressure depleted gas fields which means that a large mass of CO_2 can be stored safely in a relatively small area. This means fewer platforms and wells and lower monitoring costs. Pressure depleted gas fields may however require heating of the CO_2 early in their injection periods which can increase the operating costs. Aquifers within structures have lower storage efficiencies, meaning developments require more space and more wells. Open aquifer systems have very low storage efficiencies and require large development areas with multiple drill centres, many more wells and more expensive monitoring.

The storage efficiency was calculated for each of the five storage sites in the Select Portfolio (Pale Blue Dot Energy & Axis Well Technology, 2016) and these are summarised in Table 6-3.

Storage Site	Storage Efficiency (%)
Captain Site X, open aquifer	3
Forties 5, Site 1, open aquifer	6
Bunter Closure 36, dome aquifer	19
Viking A, depleted gas field	70
Hamilton, depleted gas field	78

Table 6-3 Storage Efficiencies

Storage efficiency is a complex attribute of a CO_2 store, incorporating reservoir quality, development plan activities, fluid flow, sweep etc. and clearly varies quite significantly with store type.

Early indications are that the correlation between storage efficiency and the levelised cost of storage is quite strong, with costs generally decreasing with increasing storage efficiency. Further research is required to establish the statistical robustness of the apparent trend which has clear implications for focusing cost reduction efforts.

Finally, whilst all the sites presented here have been significantly matured as potential CO_2 storage sites and have comparable cost estimates, each site has its own specific risk profile. In detail, the cost of mitigating these site specific risks will depend upon the experience, cost of capital and risk appetite of the developer and its financiers together with the approach of the regulator. Due to the evolving nature of the sector, it is likely that these risk elements have not yet been fully embedded within the cost estimates.

7.0 Conclusions

1. The Build-out Portfolio of eight stores can accommodate a CO_2 supply profile of up to 50Mt/y out to 2070.
2. A total of 1645Mt is stored in the Build-out scenario by 2070.
3. The cost estimates for the project portfolio of five stores and the three additional stores were prepared on different bases and this introduces uncertainty when the two groups are compared.
4. The unit cost of offshore transportation and storage ranges between £8 – 16/t in Real, 2015 terms.
5. The location and character of the stores impacts the cost of transportation and storage more than any specific regional issues.
6. The operating cost for the injection facility and the wells represents the largest component of cost.
7. Storage costs account for 65 – 85% of the total cost of offshore CO_2 transportation and storage.
8. The Build-out Portfolio would require an investment of approximately £2.1 billion (Real, 2015 PV_{10}) over the lifetime of the portfolio.
9. The aggregate levelised cost of transportation and storage of the eight stores is £14.4/t.
10. Offshore transportation and storage contributes £6.9/MWh to the levelised cost of gas fuelled electricity.
11. There appears to be a relationship between the levelised cost of storage and the storage efficiency factor. As the storage efficiency increases so the cost of storage decreases. Understanding this relationship more thoroughly would contribute significantly to the knowledge of developing CO_2 stores.

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