Strategic UK CCS Storage Appraisal Project, funded by DECC - ETI Open Licence for Materials

ETI Open Licence for the Strategic UK CCS Storage Appraisal Project

The Energy Technologies Institute (the "ETI") is making materials from the Strategic UK CCS Storage Appraisal Project available to use under the following conditions. This is intended to make this information available on a similar basis as under the Open Government Licence but it is not Crown Copyright and it is owned and licenced separately by the ETI.

You are encouraged to use and re-use the Information that is available under this licence freely and flexibly, with only a few conditions.

Using Information under this licence

Use of copyright and database right material expressly made available under this licence (the 'Information') indicates your acceptance of the terms and conditions below.

The ETI grants you a worldwide, royalty-free, perpetual, non-exclusive licence to use the Information subject to the conditions below.

This licence does not affect your freedom under fair dealing or fair use or any other copyright or database right exceptions and limitations.

You are free to:

- copy, publish, distribute and transmit the Information;
- adapt the Information;
- exploit the Information commercially and non-commercially for example, by combining it with other Information, or by including it in your own product or application.

You must, where you do any of the above:

- acknowledge the source of the Information by including the following acknowledgement:

  "Information taken from the Strategic UK CCS Storage Appraisal Project, funded by DECC, commissioned by the ETI and delivered by Pale Blue Dot Energy, Axis Well Technology and Costain"

- Provide a copy of or a link to this licence;

- State that the Information contains copyright information licensed under this ETI Open Licence.
- Acquire and maintain all necessary licences for any Third Party needed to use the Information.

These are important conditions of this licence and if you fail to comply with them the rights granted to you under this licence, or any similar licence granted by the ETI, will end automatically.

Exemptions

This licence only covers the Information and does not cover:

- personal data in the Information;
- trade marks of the ETI, DECC, Pale Blue Dot Energy, Axis Well Technology or Costain; and
- any other intellectual property rights, including patents, trade marks, and design rights.

Non-endorsement

This licence does not grant you any right to use the Information in a way that suggests any official status or that the ETI endorses you or your use of the Information.

Non warranty and liability

The Information is made available for use without charge. In downloading the Information, you accept the basis on which the ETI makes it available.

The Information is licensed ‘as is’ and the ETI excludes all representations, warranties, obligations and liabilities in relation to the Information to the maximum extent permitted by law.

The ETI is not liable for any errors or omissions in the Information and shall not be liable for any loss, injury or damage of any kind caused by its use. This exclusion of liability includes, but is not limited to, any direct, indirect, special, incidental, consequential, punitive, or exemplary damages in each case such as loss of revenue, data, anticipated profits, and lost business.

The ETI does not guarantee the continued supply of the Information.

Governing Law

This Agreement and any dispute or claim arising out of or in connection with it (including any non-contractual claims or disputes) shall be governed by and construed in accordance with the laws of England and Wales and the parties irrevocably submit to the non-exclusive jurisdiction of the English courts.

Definitions

In this licence, the terms below have the following meanings:

‘Information’ means information protected by copyright or by database right (for example, literary and artistic works, content, data and source code) offered for use under the terms of this licence.

‘DECC’ means the Department of Energy and Climate Change or any other successor department(s) or agency(ies) from time to time.

'ETI' means the Energy Technologies Institute, a limited liability partnership (OC333553), whose registered office is at Holywell Building, Holywell Park, Loughborough, LE11 3UZ.

"**Third Party Software**" means any third party software identified in or associated with the Information which is required by you to use the Information.

'Use' means doing any act which is restricted by copyright or database right, whether in the original medium or in any other medium, and includes without limitation distributing, copying, adapting, modifying as may be technically necessary to use it in a different mode or format.

'You' means the natural or legal person, or body of persons corporate or incorporate, acquiring rights under this licence.

ETI April 2016 v2.1

2015

D01: UK CO2 Storage Site Screening and Selection Methodology
10113ETIS-Rep-01-03

July 2015

www.pale-blu.com

www.axis-wt.com

Contents

Document Summary			
Client	The Energy Technologies Institute		
Project Title	Strategic UK CCS Storage Appraisal Project		
Title:	UK CO2 Storage Site Screening and Selection Methodology		
Distribution:	A Green, D Gammer	**Classification:**	Client Confidential
Date of Issue:	3rd July 2015		
	Name	**Role**	**Signature**
Prepared by:	A James, S Baines & S McCollough	Chief Technologist, Scientific Advisor & Subsurface Lead	
Approved by:	S J Murphy	Project Manager	

Amendment Record						
Rev	**Date**	**Description**	**Issued By**	**Checked By**	**Approved By**	**Client Approval**
V01	08/06/15	1st Draft	A James	S Gomersall		
V02	10/06/15	Issued for Comment	A James	S Gomersall	S Murphy	
V03	03/07/15	Final	A James	F Harding	S Murphy	

Table of Contents

Figures

Tables

Executive Summary

The lack of appraisal of CO_2 storage sites is considered a key hurdle to progressing CCS in the UK.

This UKStore project will screen, select and progress appraisal of 5 CO_2 stores applying international best practice.

The methodology involves screening over 500 aquifer and depleted hydrocarbon fields to select the most suitable 20 and then assessing the suitability of these to select 5.

The 5 selected sites will be appraised to materially progress understanding and reduce risk.

The UK Government is committed to supporting the commercialisation and cost reduction of Carbon Capture and Storage (CCS) as a key mechanism for delivering a secure, affordable, low carbon energy system. The UK Department of Energy and Climate Change (DECC) have identified that one of the main hurdles to a successful roll-out of CCS technology in the UK is the risk component associated with CO_2 storage and the impact that this risk has upon deterring investment in CCS.

The UK CCS Cost Reduction Task Force has suggested that the cost to appraise a CO_2 storage site can exceed £80M and take 7 years or more to complete. Few commercial organisations have the capacity to carry such pre-FID costs on their balance sheets on a speculative basis. Furthermore, no power station developer or operator of industrial plant will be comfortable taking a final investment decision on capture plant and CO_2 transportation infrastructure without having significantly de-risked the chosen offshore storage site well in advance.

This Energy Technologies Institute (ETI) Strategic UK CCS Storage Appraisal Project, UKStore will bring together existing storage appraisal initiatives, screen the UKCS for the most suitable storage sites, accelerate the appraisal of strategically important storage capacity and leverage further investment in building this capacity to meet UK needs. The project has been funded by DECC and has an 11 month duration. It will progress the appraisal of selected storage sites towards readiness for Final Investment Decisions, de-risking these stores for potential future storage developers and improving confidence for CCS developers.

The project comprises seven work packages which are outlined in Table 1:

Work Package	Title
WP1	Development and Documentation of a Screening, Selection and Appraisal Methodology
WP2	Identification of Information Requirements, Sources and Collation of Data
WP3	Initial Screening and Down-Select
WP4	Final Down-Select
WP5	Maturing of Selected Stores
WP6	Options for UK Strategic Storage Development
WP7	Project Management and Stakeholder Engagement

Table 1: Project Work Breakdown Structure

Wide stakeholder engagement will be sought throughout the project via several events and workshops.

This report details the technical methodology and approach to the Screening (WP3), Down Select (WP4) and Appraisal (WP5) phases of the project and forms the deliverable for Work Package 1 (WP1).

Wherever possible, the methodologies used are compliant with developing international best practice guidelines - notably DNV CO2QUAL guidelines and DNV RP J203 recommended practice.

A **basis of design** has been developed which will form the base assumptions on which the screening and appraisal process will take place. It includes beachheads from which stores will be connected by pipeline, details of required store attributes, CO_2 phase and composition assumptions and details of the offshore facilities.

WP3 will take an initial inventory of over 570 potential storage sites largely based upon the inventory of sites held in CO2Stored and reduce this down to twenty. It will comprise the following steps:

- Development of an “Initial Inventory”.
- A qualification check to ensure that the site meets basic levels of storage qualifications through use of IEAGHG criteria for containment, capacity and injectivity.
- A further qualification check to ensure that the site can make a material contribution towards meeting the objective using the basis of design.
- The “Qualified Inventory” will then be screened to rank the remaining sites according to key criteria including containment, capacity and injectivity together with cost factor and upside potential.
- Sensitivity analysis on ranking criteria.
- Final selection of twenty primary sites for further consideration – the “Select Inventory”.

CO_2 storage site selection is a multi-criteria decision making problem involving a range of data types which have both quantitative and qualitative elements. The primary ranking methodology selected for this analysis is TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). This algorithmic ranking will then be subject to expert judgement checks to verify and sense check the outcomes.

WP4 will then consider the twenty down selected sites further and in more detail. It will start to consider real site data from commercial and third party sources and use a two-step process:

1. Each site will be subject to careful due diligence to make sure that the site really does merit its position in the final twenty. This step will be evidence based and will check the CO2Stored assessments of containment, capacity and injectivity against original subsurface information. This due diligence will be summarised on a site due diligence summary sheet.
2. Portfolio creation and assessment will draw a series of portfolio steps from the down selected inventory and test their strength as a portfolio in meeting the objectives of the study. In particular an assessment will be made of how much progression the site can achieve with the available data and the study time and budget constraints. The portfolios will be ranked and the best portfolio of five sites will be recommended for detailed study in WP5.

WP5 will consider each of the final five sites in turn.

Subsurface seismic and well data will be interpreted and a series of digital earth and dynamic models will be constructed to assess capacity, injectivity and containment in some detail.

An outline storage development plan and cost estimate based on detailed subsurface characterisation and dynamic modelling work from available data will be developed for each site together with a risk assessment.

The WP5 work plan will be further reviewed and refined once the five final sites have been identified to ensure that an optimised bespoke plan is used for each site.

1.0 Introduction

The UK Department of Energy and Climate Change have identified that one of the main hurdles to a successful roll-out of CCS technology in the UK is the risk component associated with CO_2 storage and the impact that this risk has upon deterring investment in CCS.

The UK CCS Cost Reduction Task Force has suggested that the cost to appraise a CO_2 storage site can exceed £80M and take 7 years or more to complete[1]. Few commercial organisations have the capacity to carry such pre-FID costs on their balance sheets on a speculative basis. Furthermore, no power station developer or operator of industrial plant will be comfortable taking a final investment decision on capture plant and CO_2 transportation infrastructure without having significantly de-risked the chosen offshore storage site well in advance.

Development of the two stores identified in the DECC CCS Commercialisation Programme (Goldeneye depleted gas field for Peterhead and 5/42 saline aquifer for White Rose) will initially seek to prove a combined working practical storage capacity of around 140 million tonnes (MT). To reach a target of having 10GWe of power production fitted with CCS by 2030 some 1500MT of capacity will have to be appraised by the late 2020s. This is an order of magnitude more CO_2 storage than is appraised in 2015 and, with potentially long lead times, work on this appraisal needs to be started now.

As set out in its 2014 Policy Scoping Document[2] the UK Government's position is that investment in transport and storage infrastructure should be private-sector led. DECC has secured funding for strategic CCS Storage R&D in FY15/16, and the Energy Technologies Institute (ETI) on behalf of DECC has commissioned this ETI CO_2 Storage Appraisal project which will bring together existing storage appraisal initiatives, accelerate the development of strategically important storage capacity and leverage further investment in building this capacity to meet UK needs.

The project has been funded by DECC and has an 11 month duration. It will progress the appraisal of selected storage sites towards readiness for Final Investment Decisions, de-risking these stores for potential future storage developers. On behalf of DECC, the ETI has selected a consortium led by Aberdeen-based consultancy Pale Blue Dot Energy to deliver the project. The consortium includes:

- Pale Blue Dot Energy - A Management consultancy for the Energy Transition.
- Axis Well Technology - A provider of independent consultancy services in well technology and reservoir development.
- Costain - An engineering solutions provider operating in Energy, Water and Transportation.

The project is also supported by experts from the Scottish Centre of Carbon Capture and Storage, British Geological Survey, Liverpool and Durham universities, and through engagement with a wide range of interest holders in stakeholders across the CCS industry in the UK and around the world.

Objectives

The primary objective of this project is to develop storage options which contribute to an extendable storage scheme for 1500MT of storage, injecting 50Mt/a, by 2030, incorporating storage previously de-risked by other initiatives. This will include expansion from both Phase 1 projects. Appraisal, in this project refers to the process of taking five high potential CO_2 Storage sites and materially progressing their appraisal maturity on their path towards FID readiness (Figure 1). The desired outcome is the delivery of a mature set of high

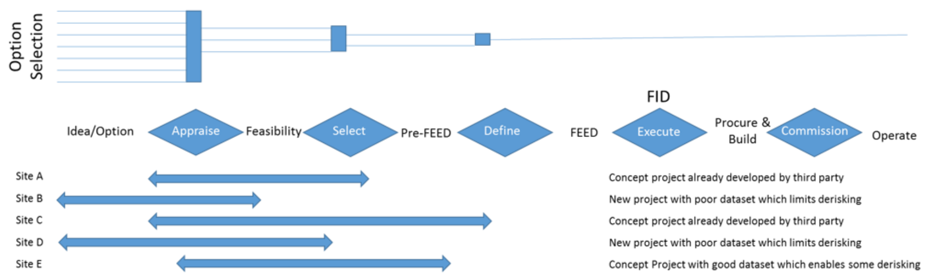


Figure 1 - Progression of Appraisal Maturity towards FID Readiness

quality CO_2 Storage options for the developers of major power and industrial CCS projects to access in the future. The work will add significantly to the de-risking of these five stores and be available to storage developers as a basis for them to commission the more capital intensive parts of storage site appraisal.

Each of the five sites will be selected to be progressed materially from its current state of appraisal maturity as far as time, budget and data permit towards FID readiness.

Specific objectives include:

- Develop and deploy a CO_2 storage screening methodology.
- Down select a portfolio of 5 stores for detailed de-risking, which builds on Phase 1 infrastructure.
- Progress 5 sites through appraisal process as far as possible.
- Develop site specific data packages, models and information which can be widely licensed onward by the ETI to provide a significant platform for further storage development work.
- De-risk 5 specific locations and identify specific risk factors remaining for each selected storage location.

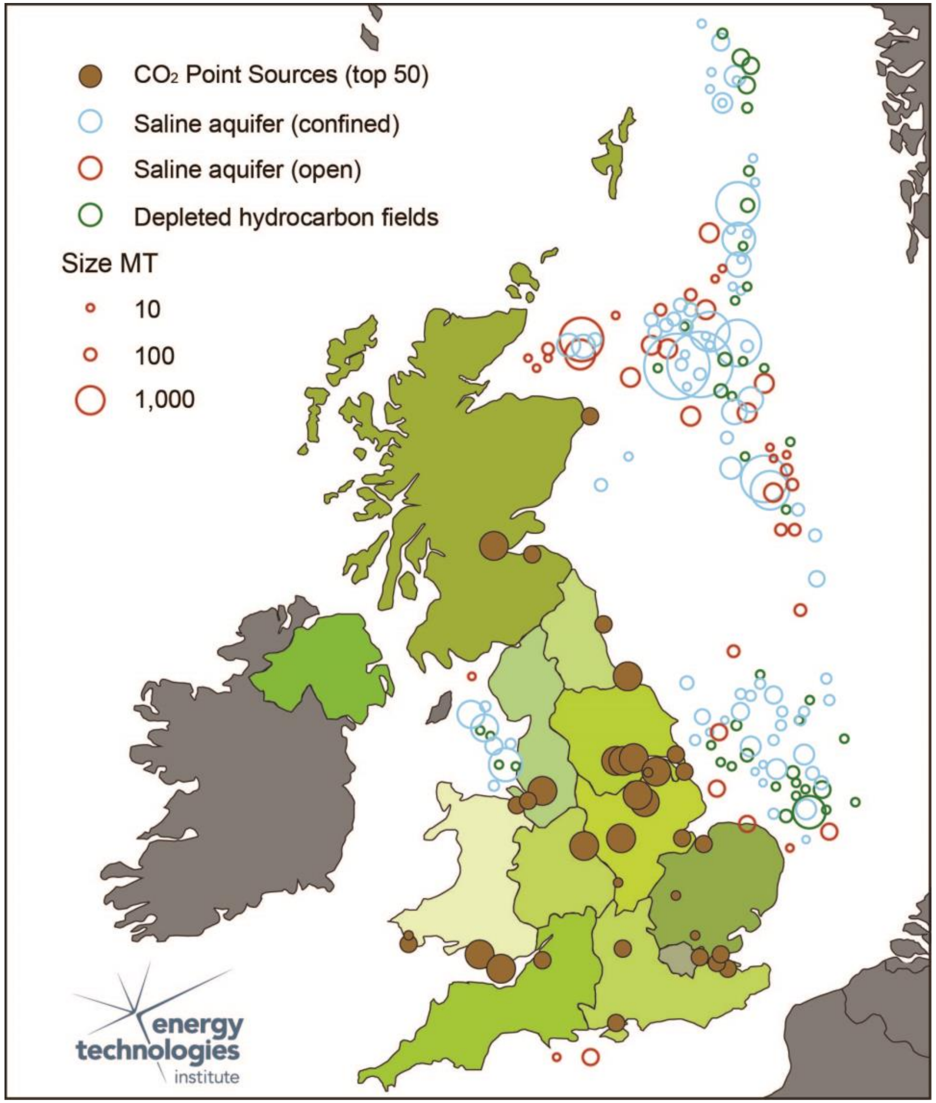


Figure 2: Major offshore areas covered by CO2Stored (© Energy Technologies Institute)

- Provide assurance to CO_2 capture project developers that storage locations exist with capacity and in the correct timeframe.
- Develop storage material of significant national value to complement the DECC CCS Commercialisation programme.
- Develop CO_2 storage cost understanding for specific sites and phases.
- Identify critical further work for subsequent appraisal progression.
- Develop a forward plan for subsequent appraisal.
- Demonstrate how CO_2 storage can evolve over time through a spatial plan and timetable.
- Prepare comprehensive reports on the project activities and findings.
- Prepare a summary report for publication and wider distribution.

Desired outcomes from the project include:

- Accelerating development of strategically important storage capacity.
- Leveraging investment in building storage capacity.
- Bringing together existing storage appraisal initiatives.
- Informing a national strategy for roll-out of storage capacity development.

This project will build upon previous work from a wide range of sources, but importantly the UK CO_2 Storage Evaluation Database, CO2Stored[3]. This is hosted and under development by the British Geological Survey (BGS) and The Crown Estate. The original data in CO2Stored was developed by the UK Storage Appraisal Project[4] (UKSAP), which was commissioned and funded by the ETI during 2011. CO2Stored currently provides an overview of CO_2 storage data for 574 potential CO_2 storage sites on the UK Continental Shelf as illustrated in Figure 2.

During 2015 to 2017, The Crown Estate and The British Geological Survey will continue to develop and update CO2Stored to improve the data and functionality of the original database according to the needs of the sector.

The project will leverage CO2Stored plus other existing third party data and interpretations. The project will provide deliverables (reports, databases and software models) which the ETI will make publically available. Major emitters and developers will be able to access this material under licence from ETI to support and accelerate their own considerations and decision making around specific Phase 2 and build-out CCS projects. The project will also inform the ongoing update of CO2Stored.

2.0 Basis of Design

The overall purpose of the project is to support the rapid build out of CCS in the UK through the material progression of five storage sites towards FID readiness. The purpose of the initial basis of design is to frame the screening and appraisal methodology to ensure that this is well designed and matched to deliver the project objectives. Published ETI scenarios work is used as the basis for the location of CO_2 emission points, commissioning schedules and CO2 supply volumes profile. The initial basis of design is therefore high level. It must be flexible enough to guide the project towards its objectives and also provide a reasonable basis for site eligibility testing

The project builds on many previous studies. Of particular significance is a study completed in 2015 *CCS Sector Development Scenarios in the UK* commissioned by ETI[6]. This identifies many of the steps needed over the period to 2030 to build a UK CCS sector that can:

- Move rapidly towards cost competitive low carbon electricity generation during the 2020s.
- Deliver low cost emissions reductions to efficiently meet the 4th and 5th carbon budgets.
- Put the broader UK energy system on a trajectory towards its long term objectives of affordable and secure low carbon energy.

The analysis uses three development scenarios for the UK CCS sector to 2030 (Table 2).

- **Concentrated** - Geographic concentration around two competition projects to reduce T&S costs and barriers; dominant role for gas CCS with SNS storage.
- **CO2-EOR** - Scenario dominated by EOR in CNS under a Wood report-style push to maximise UKCS oil production. Market pull for CO_2 for EOR supported by policy (e.g. tax incentives).
- **Balanced** - Push "on all fronts" to create a flexible base of deployment and win support from diverse stakeholders. A variety of regional clusters, with multiple fuels and capture technologies.

Figure 3 illustrates the key five elements of the Basis of Design. These are detailed more fully in Table 3 to Table 7. It should be noted that all sites under consideration have already passed the UKSAP key threshold tests of suitability for CO_2 storage.

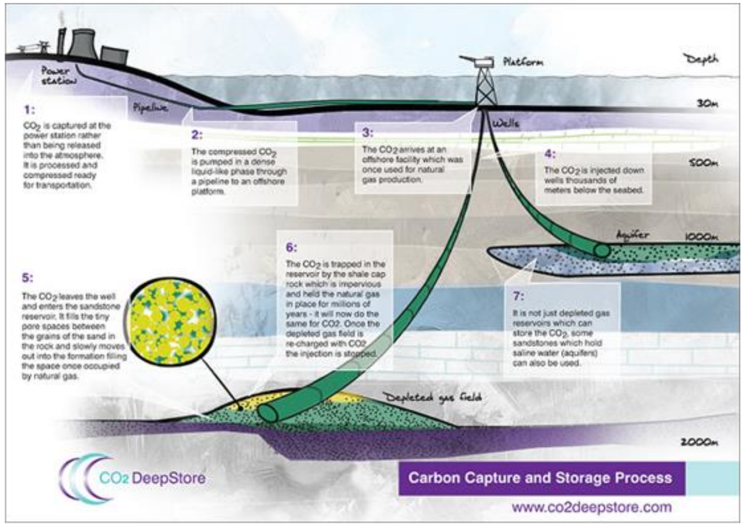
- The reservoir formations mapped must consist dominantly of sandstone or porous and permeable carbonate.
- Mapped storage units have to sit at depths greater than 800m below sea level (exceptions include formation where only a minor part of the formation sits at a shallower level; expert judgement was used to include/exclude these sites).
- All geological formations included are off-shore on the UKCS.
- All reservoir formation are either directly overlain by a sealing unit, or overlain by other sealed reservoir formations.
- Reservoir formation compartments (sub-divisions of a wider reservoir unit) had to have an estimated accessible storage capacity >50MT to qualify for inclusion.

Scenario	Costs	Strike Prices	Benefits / Issues
Concentrated			
Geographic concentration around the two competition projects to reduce T&S costs and barriers; dominant role for gas CCS with SNS storage.	CfD payments total around £14bn to 2030, rising to £2.1bn per annum in 2030. Cumulative capex in 2030 is £21.4bn.	Fall quickly from early Phase 2 projects to < £100/MWh for new gas fired projects in 2030 (close to prevailing wholesale price).	Achieves fastest cost reduction, but geographic concentration limits future optionality & leaves cost of developing further T&S hubs to 2030s.
CO2-EOR			
Scenario dominated by EOR in CNS under a Wood report-style push to maximise UKCS oil production. Market pull for CO_2 for EOR supported by policy (e.g. tax incentives).	CfD payments total around £14bn to 2030. CfD payments rise to £2.2bn per annum in 2030 reflecting the benefits of EOR via lower strike prices. Cumulative capex in 2030 is £27.2bn.	Strike prices for both coal and gas plants fall below £90/MWh by 2030 as EOR benefits feed through. Assumes £20/t CO_2 sale prices at the oil field for flows that go to EOR.	Could help to safeguard jobs and tax revenues from North Sea oil & gas, with costs partly offset by oil and gas revenue. Clearly at risk of oil price volatility affecting viability of EOR.
Balanced			
Push "on all fronts" to create a flexible base of deployment and win support from diverse stakeholders. A variety of regional clusters, with multiple fuels and capture technologies.	CfD payments total around £18bn to 2030, rising to £3.2bn per annum in 2030, reflecting the cost of developing two further hubs. Cumulative capex in 2030 is £31.2bn.	Strike prices remain comparatively high as multiple technologies are deployed and new infrastructure hubs are developed. Strike prices for both coal and gas plants drop below £100/MWh by 2030.	This approach delivers valuable optionality for lower cost CCS roll out in the 2030s, location of low carbon industry and potentially lower risks (through diversity of storage & technology).

Table 2: CCS Sector Development Scenarios, ETI

Beachheads
St Fergus, Aberdeenshire
Redcar, Teesside
Barmston, East Yorkshire
Connah's Quay, Flintshire
Medway, Kent

Site Attributes
>1MT/well
Average capacity of 200MT in Portfolio
Minimum P50 Site capacity of 50MT



©CO2DeepStore Ltd

Facilities
New facilities and wells
Subsea unless more cost effective for a jacket
No Water Production wells in the base development plan
Achieve monitoring without dedicated Monitoring Wells where possible
Use existing pipelines where possible

Composition
Longannet KT Specification
All emitters process to this code

Phase
Dense phase at compressor outlet
25 Deg C compressor outlet
Unless site specific low pressures are needed

Figure 3: Initial Basis of Design

Beachheads	
Location	**Rationale**
St Fergus, Aberdeenshire	CNS hub connected by Feeder 10 to C Scotland, focus for storage and EOR in CNS. Close to Peterhead and Goldeneye project.
Redcar, Teesside	Focus for Teesside Collective, industrial emissions cluster, Storage in SNS or CNS.
Barmston, E Yorkshire	Beachhead for NGC pipeline from Drax to 5/42. Representative export point for all Humberside CO_2.
Connah's Quay, Flintshire	Focus for N W England emissions at Connah's quay, new CCGTs at Carrington, Stanlow refinery and various industrial plants. Link to EIS storage.
Medway, Kent	Nominal focal point at Kingsnorth, representing SE England emissions from Thames area with offshore transport to SNS.

Table 3: BoD - Beachheads

Site Attributes	
Per Site	**Rationale**
Injection >1MT/yr/well	To limit the number and therefore cost of wells. These injection rates have been achieved at Sleipner for over a decade and should be achievable at the best sites. This will be achieved with a k & h threshold in site qualification and an injectivity (kh product) criteria in ranking.
Capability to inject 3 to 15 MT/yr for a minimum of 15 years	Lower capacities may be acceptable for sites available early or with especially low cost, low risk etc.
Minimum practical capacity to be considered 50MT	To screen out stores considered too small.
Distance from beachhead less than 450km	To avoid a primary requirement for offshore pumping using a platform in the stores servicing phase 2 projects. Offshore pumping will only be considered if absolutely essential.
No Miscible Flooding	There will be no injection into oil reservoirs involving miscible flooding (Enhanced Oil Recovery). The rationale for this is that the oil and gas industry will work up these options in detail once CO_2 is "in the locale" and so is not required here. Storage sites proximal to EOR candidates which could support EOR activities will be viewed positively.
IEAGHG Qualification	All sites must exceed the basic cautionary levels of site attributes defined by best practice to ensure containment, injectivity and capacity.

Table 4: BoD - Site Attributes

Facilities	
New facilities & wells	With possible rare exceptions, existing platform facilities and wells are considered to have insufficient remaining life and/or be inappropriately designed and/or too high risk for CO_2 storage.
No water production	Initial assumption is that no water production wells are required for pressure maintenance or capacity management. (These would cause a significant cost escalation potentially doubling the capex for wells).
No monitoring wells	Monitoring will be completed using development wells wherever possible, dedicated new wells for monitoring will not be included unless there is no other solution available.
Use existing pipelines where possible	In order to reduce costs, existing pipelines should be considered first, where evaluated as being suitable and available.
Use network pipelines where possible	In order to reduce costs, storage sites should consider shared pipeline networks, but always considering portfolio aspects and common failure risks.
Offshore facilities/pipelines only	No costs or facilities will be included onshore. Compression is excluded from scope. No offshore boosting/pumping is anticipated for these stores servicing phase 2 projects.
Offshore facilities	Facilities and compressor outlet pressures should address phase management in the pipeline and wells system.
Monitoring of the seabed and subsurface	Required for the duration of the project and for 20 years thereafter.

Table 5: BoD – Facilities

CO_2 Composition and Condition	
CO_2 composition standards and pvt based on Longannet project	Longannet post FEED BOD "UKCS Demonstration Competition, Post FEED End to End Basis of Design", Section 6.2. This has been compared with the proposed Peterhead composition and considered to be a reasonable exemplar.
Dense phase (already compressed)	Beach pressure is determined by pipeline length and wellhead injection pressure/reservoir pressure (note gas phase may be required initially for some depleted gas fields). It is assumed that beachhead compression will normally be to dense phase and high enough to manage direct injection without offshore pumping.
Notionally 25deg C beach pipeline inlet	Longannet post FEED BOD.

Table 6: BoD - CO2

Portfolio	
Match to ETI scenarios	Strong Portfolios should include a component that enables future EOR.
Provide geographical coverage	Strong Portfolios should provide for T&S for all major industrial centres.
Ensure diversity	Portfolio should provide diversity of reservoir types (geology, fluid type etc.) to manage early stage risks.
Build out from Competition	Portfolio should "build out" from 2 Competition projects wherever such build out can reduce the overall unit costs for CCS.

Table 7: BoD - Portfolio Aspects

3.0 Methodology

The overall study workflow has been divided into the following seven work packages (Table 8).

Work Package	Title
WP1	Development and Documentation of a Screening, Selection and Appraisal Methodology
WP2	Identification of Information Requirements, Sources and Collation of Data
WP3	Initial Screening and Down-Select
WP4	Final Down-Select
WP5	Maturing of Selected Stores
WP6	Options for UK Strategic Storage Development
WP7	Project Management and Stakeholder Engagement

Table 8: Project Work Breakdown Structure

There are many industry best practice manuals and guidelines available for various stages of CO_2 storage identification, screening and characterisation. Some key documents are highlighted in Section 4.0. The process outlined here draws significantly from them in many respects and intends to be compliant with the identified best practices wherever possible. It is notable however that there are no guidelines available on portfolio selection - which is a specific and possibly unique aspect of this early stage work.

The screening methodology itself is captured in work packages 3, 4 and 5.

WP3 will take an "Initial Inventory" of over 574 potential storage sites largely based upon the inventory of sites held in CO2Stored and reduce this down to twenty. It will comprise two steps:

1. An eligibility check to ensure that the site can make a material contribution towards meeting the objectives of the study.
2. A screening step to rank the remaining sites according to key criteria and deliver twenty primary sites for further consideration.

WP4 will then consider the twenty down-selected sites in more detail using real site data from commercial and third party sources in a two-step process:

1. Due diligence, using an evidence based logic approach, to ensure that each site merits its position in the final twenty. Each site will be subject to careful due diligence to make sure that the site really does merit its position in the final twenty. This step will be evidence based and will check the CO2Stored assessments of containment, capacity and injectivity against original subsurface information. This due diligence will be summarised on a site due diligence summary sheet.
2. The portfolio assessment step will first create a series of portfolios from the inventory and then test the robustness of each portfolio in meeting the objectives of the study. In particular an assessment will be made of how much progression the site can achieve with the available data, the study time and budget constraints. The portfolios will be ranked and the best portfolio of five sites will be recommended for detailed study in WP5. In particular an assessment will be made of how much progression the site can

achieve with the available data and the study time and budget constraints. The portfolios will be ranked and the best portfolio of five sites will be recommended for detailed study in WP5.

WP5 will consider each of the final five sites in detail. Geological, seismic and well data will be used to construct a series of static earth and dynamic models. A risk assessment of each site will be combined with these models which will be used to assess the capacity, injectivity and containment. An outline storage development plan and cost estimate will be developed for each site. The work plan outlined in Section 3.3 for WP5 will be reviewed and refined once the five final sites have been identified to ensure that an optimised bespoke plan is used for each site.

The three stage screening process that follows an initial eligibility step is illustrated below and described in more detail in Sections 3.1, 3.2 and 3.3 below.

The data available for this study will be a critical factor controlling its ultimate value. The strategy and plan for data access is outlined in more detail in the WP2 report.

"Play Fairway Approach"

The potential CO2 storage sites in CO2Stored database are arranged by geological age. Whilst this is not a strict "Play Fairway Approach" as might be used in the oil and gas industry, it is a potentially useful context within which to consider selection of storage sites. We have considered such an approach to the selection process and have reviewed the reservoir and seal formations within CO2Stored. A summary of these is presented in Table 9. There are clear general trends of capacity and containment factors linked with formation age:

1. The older the formation the more likely it has undergone multiple periods of deformation which can result in deep burial and loss of reservoir quality. It is also more likely to have experienced periods of tectonism and development of fault related georisk.
2. Older formations in pre and syn-rift basins often have more complex reservoir architecture commonly linked with some non marine depositional envrionments. These are described in the oil and gas industry as "jigsaw" or "labyrinth" architectures. This are likely to make plume management more complex and difficult to predict.
3. Older tight sandstone formations and many limestone and chalk intervals can have complex dual porosity systems that depend fundamentally upon natural fractures for essential permeability. This will make plume management more complex and difficult to predict.

Overall we have concluded that, whilst a "play fairway approach" is interesting, the uncertainties associated with risk assessment at this early stage mean that it should not carry undue weight in any selection and screening process. The preference is for each site to work on its own merits backed up by evidence. It is however useful to characterise any screening and downselection outcomes by formation and geological age to ensure that the portfolio carries essential diversity and avoids any potential common critical risk elements.

Geological Age	Reservoir Characteristics	Sealing Formations	Average Georisk Factor (lo=6 high = 18)	Average Fault Georisk Factor (lo=3 high = 9)	Average Seal Georisk Factor (lo=3 high = 9)
Devonian	Often deeply buried low porosity and permeability, braided stream, lacustrine and alluvial fan sandstones often with natural fractures contributing essential permeability.	Often Jurassic or Cretaceous sealing formations above an unconformity.	11.71	6.43	5.29
Carboniferous	Often deeply buried, fluvial channel and fan or braided delta sandstones, often with complex sand body architecture.	Often sealed by evaporitic sections of the Zechstein formation in the southern gas basin, but further north often relies upon Jurassic and Cretaceous shales above an unconformity for containment.	11.20	6.60	4.60
Permian	The formations of the UKs primary gasfields. Aeolian, fluvial and sabkha sandstones of the Leman, Auk, Findhorn and Collyhurst formations form the primary storage reservoirs. Reservoir quality is variable and often impaired by diagenetic change leaving low permeability in some areas. These are accompanied by much more complex carbonate reservoirs of the Zechsteinkalk and Halibut Fm which have complex dual porosity systems which can make their injectivity and storage properties unpredictable.	The primary seals are often the very effectoive evaporitic sections of the overlying Permian including the Silverpit, and Zechstein. These seals have been regionally effective as hydrocarbon caprocks.	9.35	5.45	3.90
Triassic	Fluvial, Aeolian, lacustrine and sheet flood sandstones with reservoir quality often controlled by depositional environment. Some formations can contain complex reservoir architectures which would create complex plume development paths. Storage formations include the Bunter, St Bees, Ormskirk, Cormorant and Skagerrak formations. The sandstones are the results of deposition in arid continental environments. Forms the East Irish Sea oil and gas reservoirs.	The primary sealing formations are often the overlying and associated mudstone and evaporitic intervals of the Triassic which include the Bunter Shale, Mercia mudstones and Rot Halite. Occasionally primary seal and more often secondary seals comes from overlying Jurassic and Cretaceous shales above an unconformity.	10.73	6.22	4.51
Lower Jurassic	These are normally coastal plain, deltaic and shallow water marine shelf sandstones and include the Bridport, Darwin, Cook, Nansen, Statfjord, Orrin and Mains formations. They cover a wide range of reservoir types and carry very varied reservoir quality and sandstone architectures.	Primary seals are often provided by Lower Jurassic marine shales of the Dunlin Group and the Amundsen formation. Upper Jurassic and Cretaceous shales and mudstones also provide primary and secondary seals. These are widespread proven hydrocarbon seals.	12.00	6.40	5.60

Geological Age	Reservoir Characteristics	Sealing Formations	Average Georisk Factor (lo=6 high = 18)	Average Fault Georisk Factor (lo=3 high = 9)	Average Seal Georisk Factor (lo=3 high = 9)
Mid/Upper Jurassic	This is a very diverse range of formations ranging from the fluvial sandstones of the Pentland Formation to the coastal and deltaic sandstones of the Brent Group, the shallow water marine sandstones of the Fulmar formation and the deep water submarine fan sandstones of the Humber Group. These formations collectively for the reservoirs for a large proportion the UK's oilfields.	Effective, thick seal primary seal formations are provided by the Upper Jurassic Heather and Kimmeridge clay formations and the overlying lower Cretaceous mudstones.	10.46	5.49	4.67
Lower Cretaceous	Normally deep water marine mass and submarine flow sands deposited in a post rift subsiding basin. Key formations are the Wick and Britannia Sandstones and the Valhall formations. Primary reservoirs for the Captain, Goldeneye and Britannia fields.	Primary seals provided by overlying calcareous mudstones of the Lower Cretaceous Hidra, Sola, Rodby and Valhall formations. Secondary seals provided by tight calcareous formations of the Chalk Group.	10.11	4.78	5.33
Upper Cretaceous	Deep Marine chalks often deposited from a mass flow event. Characterised by the Tor, and Mackerel formations. Primary reservoir in the Banff and Machar oilfields. Reservoirs can be very complex pore systems sometimes enhanced by natural fractures which provide assisting permeability.	Primary seals provided by overlying calcareous mudstones within the Chalk Group itself. Secondary seals provided by numerous Palaeogene claystones.	12.19	5.08	7.12
Palaeogene	Submarine fan sandstones deposited in a slowly subsiding basin. Often the result of mass flow deposits and remobilised sands dumped into deep water. Sometimes overprinted by sand injection events which can result in complex architectures. These reservoirs hold some of the large oilfields in the UKCS such as Forites, Alba Nelson, Maureen and Montrose. They are often characterised by structural simplicity, but depositional complexity.	Primary seals are provided by the overlying Palaeogene mudstones of the Sele, Baler and Horda formations.	10.47	5.84	4.62
Notes	*Georisk factor is calculated from CO2Stored database risk assessment for Fault Density, Fault Throw and Seal, Fault Vertical Extent, Fracture Pressure Capacity, Seal Chemical Reactivity and Seal Degradation. The Georisk factors are the sum of scores where low risk = 1, medium risk =2 and high risk =3. Note that at this stage confidence factors on these risk assessments are not accounted for. Higher numbers equate to higher risk.*				

Table 9: Overall Reservoir and seal formation characteristics by Geological Age

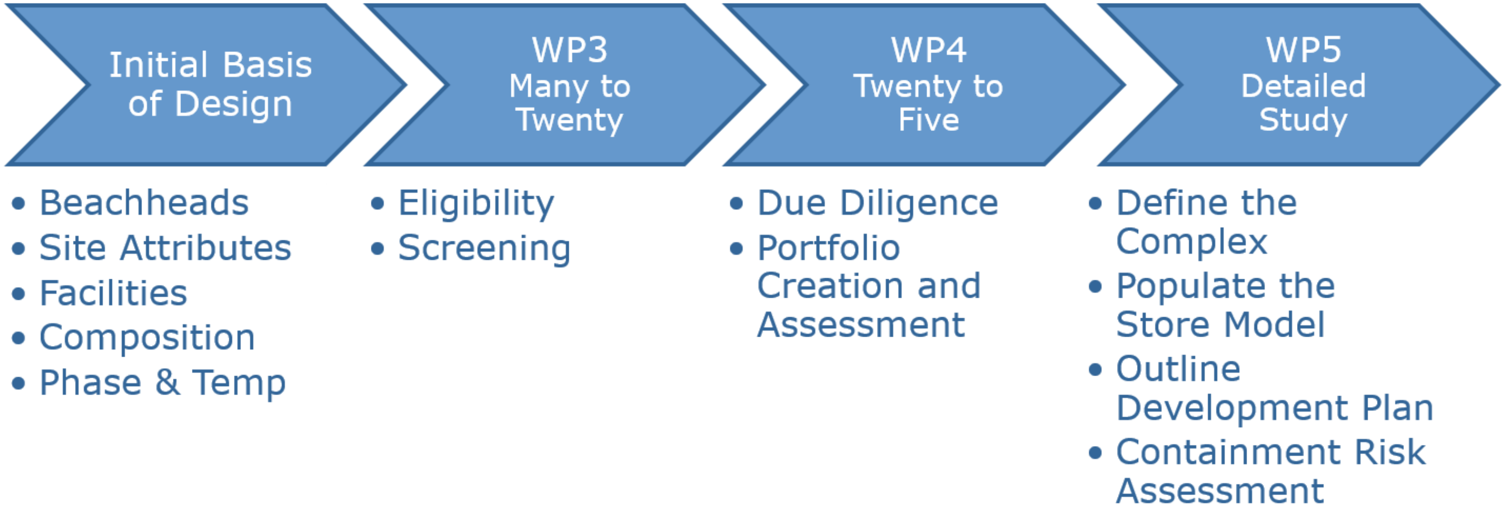


Figure 4: Site Screening and Selection Methodology

3.1 WP3 – Many to Twenty

Approach

The overall aim of this work package is the selection of twenty optimal storage sites on the UKCS which meet the project requirements. This 'Many to Twenty' down-selection follows a screening process, based on both physical character and geographic location, designed to generate a portfolio of sites with the greatest potential for safe, material and long term storage of CO_2. In addition, the work flow complies with the requirements of the EU Directive 2009/31/EC on the Geological Storage of Carbon Dioxide[10] and other recommended practice guidelines[7,8].

Work Package 3 (WP3) has been divided into the following 4 tasks:

1. Procure screening data and build the "Initial Inventory" of potential sites.
2. Deliver a "Select Inventory" of twenty sites with five reserves.
3. Document the screening results and develop presentation.
4. Present to Stakeholders and gain approval of the "Select Inventory".

This chapter presents the work flow and detailed description of the first two steps, WP3.T1 and T2.

Method Statement Specification

The 5 step work flow for the WP3 'Many to Twenty' site selection is shown in Figure 5. The relatively linear selection process is designed to reduce the number of qualifying sites at each step:

1. Development of the "Initial Inventory".
2. Qualification and Compliance with Basis of Design screening process.
3. Site Ranking Process.
4. Sensitivity Analysis.
5. Final "Select Inventory" of Top Twenty.

Handling of Uncertainty

Uncertainty is a part of any work with subsurface assets. CO2Stored is the result of a two year project and has been fully peer reviewed. It represents the best compilation of CO2 storage site data available in the UK. The results and information contained within CO2Stored are however uncertain. Several factors have confidence flags attached, whilst capacity is subject to a monte carlo assessment to try to encapsulate uncertainty in the results.

In WP3 with so many sites, it is important to take a balanced approach to avoid eliminating the more uncertain saline aquifer sites whilst just retaining oil and gas sites. To this end, mid case parameter values were used wherever possible, together with p50 capacity estimates.

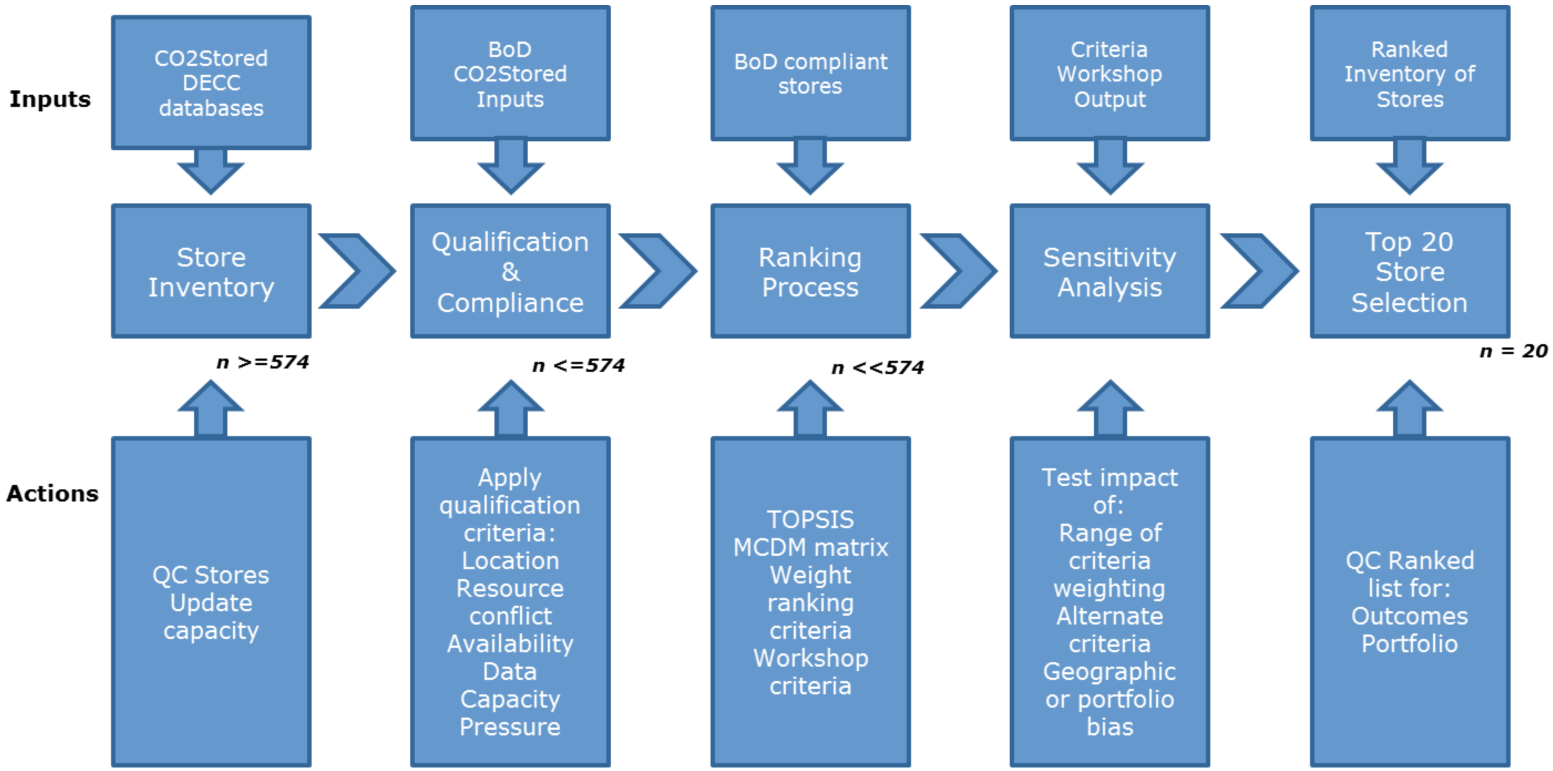


Figure 5: Work Flow for WP3: 'Many to Twenty'

Detailed Workflow & Key Criteria

Development of the "Initial Inventory"

The backbone of the "Initial Inventory will be the CO2Stored database which provides the "first comprehensive, auditable and defensible estimate of CO_2 storage capacity, using a standardised methodology, on the UKCS[4]. As such, it provides a source of relatively recent, internally-consistent data for use in this project. The database contains 574 storage site entries, although only 505 are currently well populated with data. 213 oil and gas fields and 361 saline (brine-filled) aquifers are included in the database and are sub-divided into categories based on physical character:

- Fully Confined: units forming sealed compartments where fluid cannot migrate vertically or laterally, i.e. pressure compartments.

- Open Units: reservoir units overlain by an impermeable seal but where lateral migration of aqueous fluids and CO_2 is not geologically-constrained (sub-divided in CO2Stored into 'Open, no confinement' and 'Open, identified confinement': referring to mapped boundaries which may act as permeability barriers to fluid flow but this cannot be demonstrated).
- Structural/Stratigraphic Traps: units in which injected CO_2 would be physically-confined within a trap (e.g. all oil and gas fields; some saline aquifers).

Table 10 below shows the number of each store type in the current CO2Stored database.

Store Type	Saline Aquifer	Oil & Gas	Gas Cond.	Gas	Total
Fully Confined (closed box)	228	3	1	8	240
Open (with identified structural/stratigraphic confinement)	20	0	0	0	20
Open (no identified structural/stratigraphic confinement)	62	0	0	0	62
Structural/Stratigraphic Trap	50	85	15	101	251
Uncategorised	1	0	0	0	1
Total	361	88	16	109	574

Table 10: Number of 'Store Types' held in CO2Stored Database

Interrogation of CO2Stored Database

The first step in the WP3 work flow is to interrogate and QC the currently-available CO2Stored dataset. The objectives here are to ensure that the input data and calculations used by UKSAP are both understood and can be replicated by this project. Data trends and the confidence (uncertainty) associated with each data type will be reviewed. This is an important step as any uncertainty in any data or calculation input will be carried through the work flow. For example, estimated capacity values will be used to screen and rank the sites, and therefore it is necessary to understand the source and confidence level of the input data used in calculating these values.

Update of "Initial Inventory"

The objectives of this step are two-fold:

- To ensure the Initial Inventory is as complete as possible.
- To ensure that the data contained is up-to-date as appropriate.

The CO2Stored database is based on the mapping and high level appraisal of geological formations carried out during the UKSAP and on hydrocarbon field data available in both the public domain (DECC Production databases) and by license (IHS and DEAL). A quick-look review indicated that not all fields are included in the CO2Stored database. This view was verified by the ETI. The Initial Inventory will be reviewed against the current DECC field database and any additional hydrocarbon fields added as appropriate where such fields may represent significant potential storage sites. The Initial Inventory will also be cross-checked against the sites identified in carbon storage reports available in the public domain e.g. EU GeoCapacity[11], SiteChar[12], CGSEurope[13] etc.

For producing hydrocarbon fields, especially gas fields, the CO_2 capacity is linked to the volumes of hydrocarbons produced. The workflow will consider the most recent estimates of ultimate recovery available to the project to verify the estimates held within the CO2Stored database. Where appropriate, updated capacity values will be calculated. As per the BoD, the Initial Inventory will focus on potential storage sites which do not require miscible injection of CO_2, i.e. CO_2 -EOR will not be considered during the WP3 screening and ranking process. EOR candidates will be considered as “not available” for CO2 Storage. A major assumption for this Work Package is that the data for the saline aquifer stores is both reasonable and unchanged from the UKSAP reporting.

Qualification and Compliance

The Initial Inventory will have around 574 sites with data available (based on pre-project CO2Stored database). The Qualification & Compliance step therefore aims to reduce this number to a more manageable figure through a simple screening process to focus on those sites most likely to comply with project objectives.

The sites in the Initial Inventory all passed the UKSAP key threshold tests of suitability for CO_2 storage.

- The reservoir formations mapped must consist dominantly of sandstone or porous and permeable carbonate.
- Mapped storage units have to sit at depths greater than 800m below sea level (exceptions include formation where only a minor part of the formation sits at a shallower level; expert judgement was used to include/exclude these sites).
- All geological formations included are off-shore on the UKCS.
- All reservoir formation are either directly overlain by a sealing unit, or overlain by other sealed reservoir formations.
- Reservoir formation compartments (sub-divisions of a wider reservoir unit) had to have an estimated accessible storage capacity >50MT to qualify for inclusion.

An additional set of screening criteria is proposed which will ensure all sites included in the Inventory used for the Ranking process comply with both the overall project objectives and best practice guidance.

Qualification Criteria	Qualification Threshold
IEAGHG Cautionary Factors	Sites with subsurface attributes (permeability, thickness, depth, porosity, Salinity) considered by IEAGHG as cautionary will be excluded
Geographic Location	Sites must lie within 450 km of one of the beachheads stated in the BoD.
Resource Conflict	Sites must not be located where direct conflict with existing surface and subsurface use or designation would prevent site permitting for CO_2 Storage or require excessive pipeline detour.
Site Availability	Sites must be available for access by 2030 (+/- 3 years).
Data Availability	Sites must be within a 3D seismic dataset available to this project and must have at least 1 well penetration within its mapped boundaries.
Capacity	Sites must have a theoretical capacity of at least 50MT.
Reservoir Pressure	Sites must not initially require any pressure management (e.g. through water production) in order to comply with capacity threshold or to meet the BoD injectivity requirements (set at 1MT/well).
Store Type	Sites which significant miscible flooding EOR potential will be excluded as unavailable.
Reservoir Type	Sites with complex dual porosity systems such as some carbonate reservoirs and naturally fractured sandstones will be avoided due to the extreme challenges in managing and modelling plume movement in such sites.
Containment Risk	Any saline aquifer site with a containmet factor ranked as high risk with high confidence levels will be excluded.

Table 11: Qualification and Basis of Design Threshold Criteria

Each screening criterion will be reviewed on an individual basis to test its impact and the sensitivity of the Initial Inventory to it. Specifically, the differing outcome of screening using each criterion separately, and then a cumulative impact will be assessed.

The objective of this screening phase is to generate a strong “Qualified Inventory” of sites which has the potential to meet both the technical and portfolio requirements of the project. It is anticipated that several iterations of the screening process may be required to ensure a strong “Qualified Inventory” is retained.

Ranking Process

The aim of the Ranking step of the work flow is to organise the “Qualified Inventory” by preferred characteristics so that the final 'Top Twenty' sites (“The Select Inventory”) can be progressed to WP4. The final selection process will identify the 20 sites from which robust portfolios of 5 sites will later be considered.

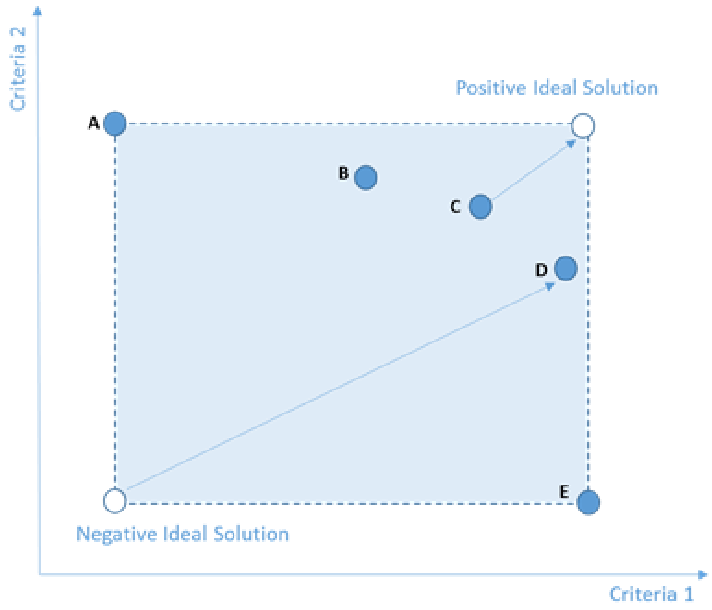


Figure 6: Example of TOPSIS Analysis

CO_2 storage site selection is a multi-criteria decision making problem involving a range of data types which have both quantitative and qualitative elements. The ranking methodology which has been chosen for this analysis is TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)[14]. The principle is illustrated in Figure 6 using five alternatives (A-E). The alternatives have been compared to the positive and negative ideal solutions hypothesised by two criteria (C1 & C2). Alternative C is closest to the positive ideal solution while D is the furthest from the negative ideal solution.

TOPSIS is an ideal point multi-criteria decision analysis method. The principle of TOPSIS is that a pair of positive and negative ideal solutions are hypothesised by the decision maker. These are derived from the ideal solution of a selected set of weighted (or rated) criteria and the worst solution for the same criteria, i.e., the positive ideal solution is the one that maximises the positive criteria and minimises the negative criteria, while the negative ideal solution is the solution which maximises the negative criteria and minimises the positive criteria. The optimal 'alternative' (in this case, a potential store) will have the shortest distance from the positive ideal solution and the furthest distance from the negative ideal solution illustrated in Figure 6.

The benefits of the TOPSIS method are:

- It allows simultaneous evaluation of several alternatives.
- It can handle a large number of both criteria and alternatives.
- It is a compensatory process in which no alternatives are excluded due to a single poor result against one criteria. A good value in one criteria can compensate for a bad value in another.
- It is able to handle both quantitative and more subjective (qualitative) data inputs.
- It is flexible to changes in both alternatives and criteria[15,16] – a characteristic essential for sensitivity analysis.
- It can be set-up to support group decision making.
- The analytical process is rapid, relatively straightforward to set-up and can be run using an Excel worksheet.

The key input requirements of TOPSIS are that the selected criteria are independent of each other and that the value of each criteria should increase and decrease on a linear scale.

Alternative multi-criteria decision analytical methods were considered (AHP: Analytic Hierarchy Process, SMART: Simple Multi-Attribute Rating Technique and PAPRIKA: Potentially All Pairwise Ranking of All Possible Alternatives), however TOPSIS was selected because it is simple, effective and has good applicability to this project.

Selection and Relative Weighting of Criteria

A key, and possibly the most subjective, input to the TOPSIS process is the selection and relative weighting of the criteria. Final selection of the criteria will take place after the Initial Inventory interrogation and QC is complete. It is anticipated that a maximum of 6 criteria, representing the key technical elements of a carbon storage site (two containment factors representing both engineering and geological, capacity and injectivity) plus a derived economic 'proxy' combining cost factors such as pipeline requirements (distance to beachhead) and driling cost. A factor capturing upside build out potential will be also applied in the first instance. With varying data confidence across the inventory, care will be taken in selecting the criteria for use such that the weighting of any highly speculative data will be limited. The results will be subject to final review and edit by expert judgement and stakeholder engagement.

The project team will assign the relative weighting to the criteria, however it is suggested that the project stakeholders contribute their opinions and preferences on both the criteria selected and their relative weighting. This will likely produce a broad range of inputs which will be reviewed and used during the sensitivity analysis step of the work flow. This process could be carried out at the first stakeholder meeting or by a questionnaire sent to each interested party.

Application of the TOPSIS Method

A test dataset using just the saline aquifer 'Bunter Structures' from the Southern North Sea was evaluated using the TOPSIS method. The work flow used here is derived from a University of Leeds publication[16]. Table 12 shows the basic matrix of criteria and alternatives with the relative weighting for each criteria.

Example	Criteria 1	Criteria 2	Criteria 3
	P50 Capacity	Distance to Beach	Water Depth
Weight	0.4	0.3	0.1
Closure 14	107	193	25
Closure 13	100	185	40
Closure 5	158	122	45
Closure 35	554	85	60
Closure 36	232	114	80
Closure 37	224	150	55
Closure 39	205	129	50
Closure 46	108	57	60
Closure 21	892	113	35
Closure 24	63	97	20
Closure 26	140	109	30
Closure 17	103	175	25
Closure 3	600	141	25
Closure 28	409	158	25
Weighted Normalised Matrix	**1366**	**508**	**166**

Table 12: TOPSIS Decision Matrix for Bunter Structure dataset.

For each criterion, an ideal positive and negative solution is hypothesised and the separation between each alternative and the positive and negative ideal solutions determined, below.

Capacity: positive ideal solution = highest value available

Distance: positive ideal solution = lowest value available

Water Depth: positive ideal solution = lowest value available

A final TOPSIS "Score" is calculated as the separation from the negative ideal solution divided by the sum of the ideal positive and negative solutions. From the example shown in Figure 7, it is clear that Bunter Structure 35 one of the highest scores (for this set of criteria); a comforting outcome given this is the White Rose project 5/42 storage site.

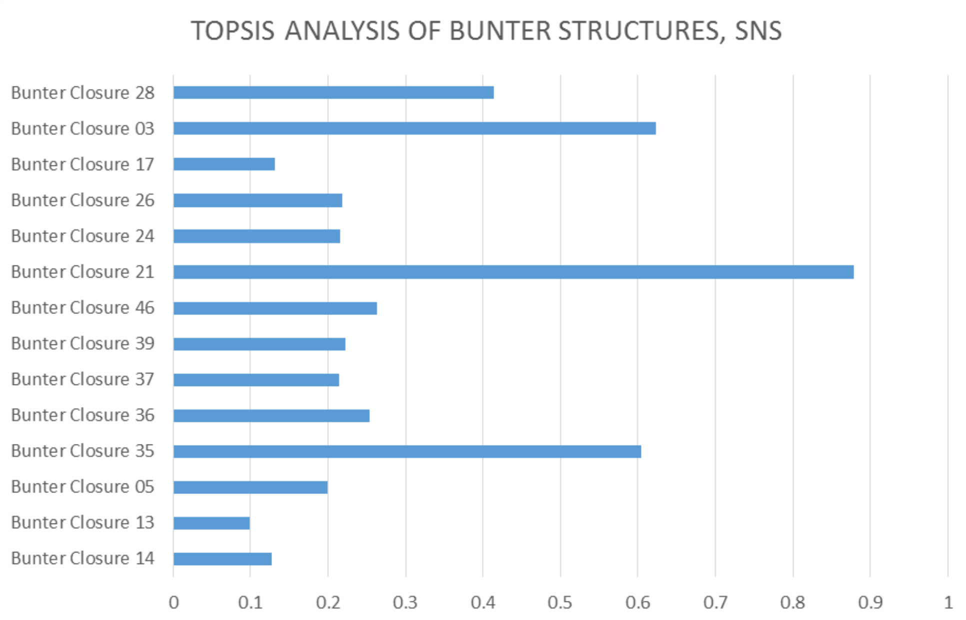


Figure 7: Example TOPSIS Scores for the Bunter Structure dataset.

Sensitivity Analysis

Sensitivity analysis of each criterion, and the relative weighting assigned to it, will be carried out after the stakeholder input has been gathered. The TOPSIS results will also be compared with simple average rankings to sense check the outcome. This process should highlight those sites which consistently rank highly and therefore most likely to meet the overall project objectives from the perspective of each stakeholder.

Ultimately, the success of the ranking process is controlled by the criteria selected and the quality of the values applied to each alternative. For the saline aquifer storage sites in particular, there will be significant uncertainty carried in this process. The aim of the sensitivity analysis is to evaluate the impact of this uncertainty on the overall ranked order of the Store Inventory. To ensure that this uncertainty is sensibly handled, The results will be checked using expert judgement and any anomalies will be corrected manually before a final "Select Inventory" is recommended.

Final Selection: 'Many to Twenty'

The final step in the screening part of WP3 is the down-selection from the Qualified Inventory to a 'Top Twenty' Select Inventory. As previously noted, this will not necessarily involve taking the sites with the top 20 TOPSIS scores. The ranked Inventory will be evaluated with respect to ranking, store type, geographic location and contribution to the overall portfolio. The results will be summarised by nearest beachhead, store type, unit designation and also formation age to ensure that there is strong diversity across the Select Inventory. While the technical storage potential of the sites will be the priority factor in final selection, the project team will use each aspect to generate a 'Top Twenty' which carries the potential to meet a range of portfolio options and ensure that the technical risks of selected sites are as independent of each other as is feasible.

The TOPSIS analysis can be used to visualise the relative position of each site against the ideal positive and negative solutions – this approach can be used to compare groups of sites (coded by storage type etc.) and help selection of the optimal sites for this project.

Data Implications

The successful implementation of this WP3 work flow is dependent on access to the data required for updating the Store Inventory. Access to the CO2Stored database has been secured as has the final report and appendices of the UKSAP to help with the QC and interrogation process. Review of the number of hydrocarbon fields in the database can be done using the current DECC oil and gas production databases, however, generating the most accurate capacity estimates for the hydrocarbon field stores requires access to several data items including:

- Cumulative production of each fluid type.
- Formation volume factors.
- Reservoir temperature and pressure.
- Best estimate of cessation of production date (CoP).
- Estimated Ultimate Recovery.

It is anticipated that some data will be accessed from published sources, however if the calculation process carried out by the UKSAP cannot be replicated, alternative methods to estimate storage capacity may be implemented. There is a strong correlation between cumulative oil production and theoretical capacity in CO2Stored and this may be deployed as an alternative method to estimate storage capacity at this early stage. These will be tested against the current dataset to ensure the methods produce reasonable results.

Identified Issues

One of the recognised limitations of the WP3 workflow is that the process does not inherently allow for recognition of alternative storage options other than the single store concept. For example, by using a capacity cut-off aimed at creating a portfolio with an average of 200MT/store (as per the BoD), a cluster of small sites which collectively comprise a larger total capacity might seem to be overlooked. The project objectives, however require hubs of significant core capacity to be developed. The build out of such a hub to adjacent sites is an entirely reasonable proposition and will be considered in WP4 when the Select Inventory is subjected to a more in-depth evaluation. At this stage, whilst the key aspects of a hub and spoke development are considered fundamentally important the notion a complex cluster of very small sites is not envisaged at this stage due to the anticipated greater cost of such a project.

Anticipated Outcomes

WP3 will deliver a ranked list of potential storage sites which meet both the project objectives and the conditions set-out by the project BoD. The 'Top Twenty' sites will be selected to support the technical, geographic and maturity of appraisal objectives. It is anticipated that the final list will include both saline aquifers and large depleted gas fields as these hold the potential to meet the 200MT average capacity articulated by the BoD. The selected sites will support development of either or both of the 'Concentrated' or 'Balanced' CCS Sector Development Scenarios; the CO_2-EOR scenario will be indirectly progressed through identification of potential supporting storage sites to enable and help de-risk long term CO_2-EOR projects.

3.2 WP4 –Twenty to Five

Approach

The Purpose of Work Package 4 (WP4) is to deliver a final down selected portfolio of five viable CO_2 Storage sites that are capable of being materially progressed within WP5 from the short list of twenty sites delivered by WP3. It is illustrated in Figure 8 and Figure 10.

It is anticipated that at least one of the five down-selected sites will be capable of progressing through towards the end of the Appraisal stage by the end of the project or shortly thereafter. As such, it is expected that one or more of the five sites will be suitable to serve an early Phase 2 CCS project (FID ~ 2020). It is also anticipated that at least one other site will be a substantial new storage play aimed at much later FID in the late 2020s.

At the end of WP3, the project will have a well-qualified portfolio of twenty potential CO_2 storage sites that are aligned with the project objectives. Even with this reduced number of sites, it is impractical to seek significant new insight through original work which will result in a reduction of uncertainty. Instead, an evidenced based approach to site assessment will be applied. This will start to more rigorously qualify each site with respect to the hard evidence available. Such evidence will either support or refute the ability of the site to meet the CO_2 Storage role asked of it.

The WP4 down select process has two key steps.

1. **Due Diligence** - The twenty sites (Select Inventory) are subject to due diligence review and the storage site scorecard updated.
2. **Portfolio Evaluation** - Portfolio selections comprising five sites from the twenty candidates will be considered as a group.

WP4 has been divided into the following 5 tasks culminating in WP4 Report (D05), a key Stakeholder Workshop (R04) and Stage Gate Review 1 (R05). It will deliver the final recommendation on the five sites (plus one reserve) to progress to detailed appraisal in WP5.

- **WP4.T1** - Complete Due Diligence Checks on each of twenty potential storage sites as described below. Due diligence process on the key attributes developed in WP3 will be extended through the access to representative well and seismic data. This step will include a dialogue with the incumbent petroleum operator where possible to seek further specific data input and test collaboration options. This due diligence will be compiled into storage site summary sheets (D06) and will deliver a due diligence score for each site.
- **WP4.**T2 - Execute the portfolio creation and assessment methodology specified below. The selection will be subject to sensitivity testing to ensure that its components are robust and fully qualified members. Near miss sites will be captured and held in reserve. Specifically there will be an initial Stakeholder Workshop (R04) at which the down select process will be presented. Stakeholder comments to the final selection will be sought to ensure that the final portfolio meets general industry expectations.
- **WP4.T3** - Complete a report of the portfolio selection process and the results in WP4 Report (D05).

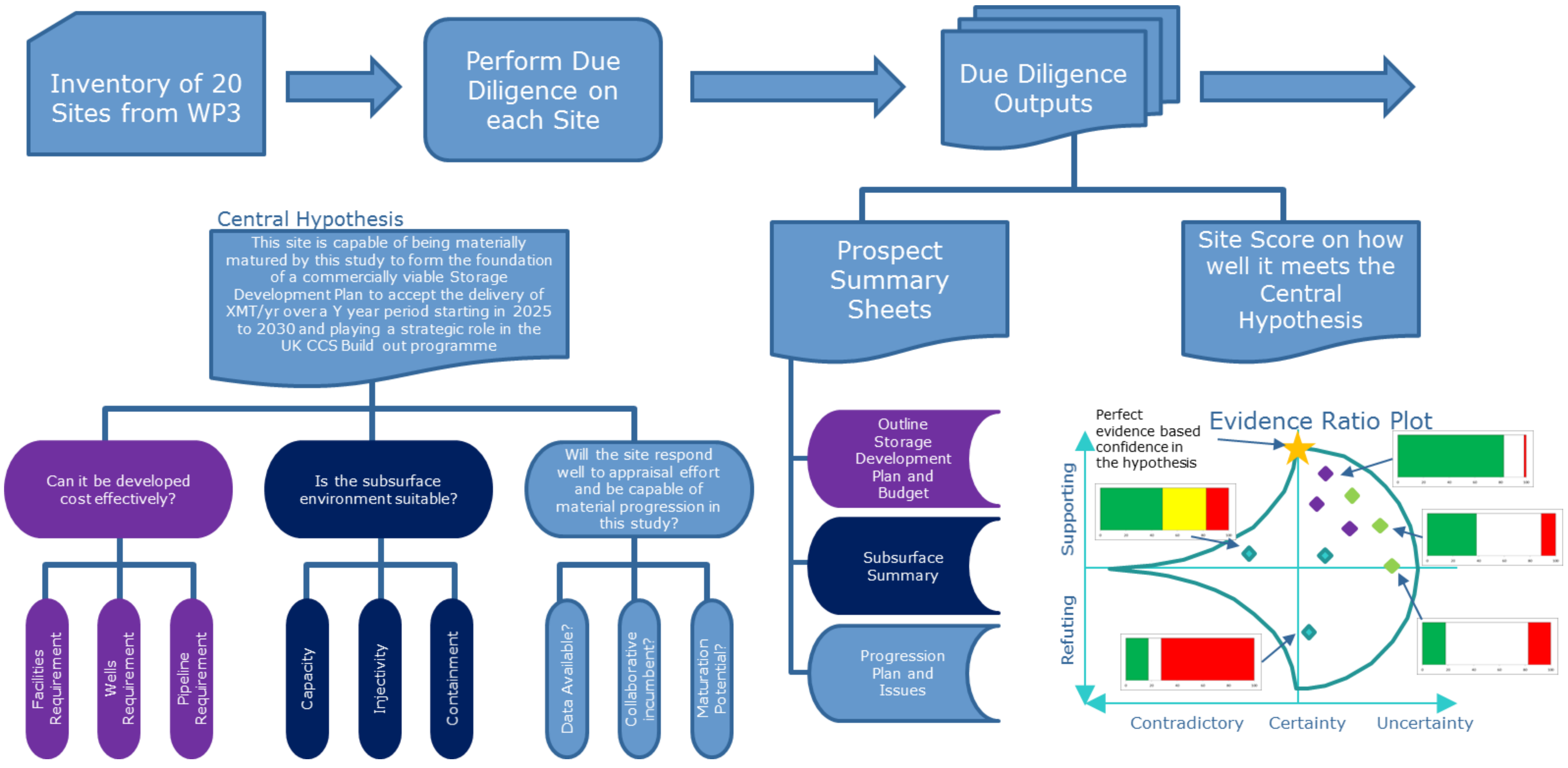


Figure 8: WP4 Site Due Diligence

- **WP4.T4** – Review lessons learned from other projects and highlight those specifically relevant to the five selected storage sites. Identify target work programmes for each selected site together with a stated objective of what uncertainty reduction such work programme will try to achieve. This will refine the WP5 plan and deliver a bespoke work programme for each selected site.
- **WP4.T5** - Present the down-select programme and results to stakeholders and gain approval of the five site portfolio for WP5. Finally the results from WP1 through to WP4 will be presented to the ETI Stage Gate Review (R05) for approval.

WP4.T1 - Due Diligence

The Methodology for WP3 culminated in the delivery of a ranked list of storage sites that have good potential to meet the requirements of the project as articulated in the basis of design. The initial step in WP4 is a Due Diligence check on each of twenty high ranked sites to ensure that they have the full potential to meet the project objectives (Figure 8). As part of the due diligence assessment, the following central hypothesis will be tested:

Primary Hypothesis

This site is capable of being materially matured by this study to form the foundation of a cost effective and viable Storage Development Plan to accept the delivery of between 3 and 10 MT/yr over a minimum 15 year period starting between 2025 and 2030 and thus playing a strategic role in the UK CCS build-out programme.

The hypothesis will be broken down into three key areas of consideration:

1. **Subsurface Environment**

Does the site have appropriate blend of capacity, injectivity and containment properties that give confidence that the site can meet the primary hypothesis?

2. **Development Potential**

Does the site have a potentially important role in the build-out programme of UK CCS infrastructure and can it be developed in a cost effective manner such that the pipeline, facilities, and wells capex requirements together with anticipated opex (collectively rendered to a levelised cost of offshore transport and storage) provide confidence that the site can meet the primary hypothesis?

3. **Appraisal Response**

Does the site have the right combination of data availability (type, quality and quantity), uncertainty reduction potential and Operator collaboration or support (from whichever domain oil & gas, offshore wind, sand & gravel etc.) to materially progress the appraisal status of the site in this project given the time, and budgetary constraints.

An evidence based approach will be used to test each site against each hypothesis. This due diligence step will capture a consistent and clear understanding of the existing key attributes of each store candidate (Figure 9) including:

1. **Subsurface Environment**

An outline subsurface description will be captured from existing sources. Subsurface structural configuration, reservoir quality review and potential injection well performance including risk of geochemical sensitivity will be considered.

Initial dynamic capacity review potentially including a material balance overview of the storage site.

Review of connectivity and medium to long term injection well performance, reservoir pressure, aquifer connectivity and injectivity. Review of caprock resilience and evidence for containment and integrity from both a geological (seal) and engineering (wells) perspective.

- **Capacity**: The site has appropriate capacity to give confidence that it can meet the primary hypothesis and make a material contribution to a portfolio of site capacity towards 1500MT.
- **Injectivity**: The site has appropriate injectivity of >= 1MT/yr per well giving confidence that it can meet the primary hypothesis and be fully capable to injecting CO_2 volumes at a rate of between 3 and 10MT/yr on a long term basis.
- **Containment**: The site has appropriate containment properties to ensure that the inventory of injected CO_2 remains within the storage complex indefinitely giving confidence that the site can meet the primary hypothesis.
- **Monitoring**: It is fully anticipated that the site will respond well to appropriate monitoring programme to meet all the requirements of the EU CCS Directive[10] and enable full operational and post closure monitoring of the injected CO_2 inventory giving confidence that the site can meet the primary hypothesis.

2. **Development Potential** - can it be developed cost effectively?

Commercial review of factors likely to influence time and cost to FID including interaction with competing subsurface users, decommissioning timetables and practicality of transport connections to CO_2 sources.

Estimated levelised cost of storage at the site and consideration of the potential role that each site might play within the ETI CCS Scenarios to ensure it has a strategic fit with the Project Objectives.

- **Scenario**: Does the site have a potentially important role in the build out programme of UK CCS infrastructure providing confidence that the site can meet the primary hypothesis?
- **Pipeline**: The site has a cost effective pipeline option (rendered as a levelised cost of offshore transport) which provides confidence that the site can meet the primary hypothesis.
- **Facilities**: The site has a cost effective option for offshore facilities (rendered as a levelised cost of offshore operations) which provides confidence that the site can meet the primary hypothesis.

3. **Appraisal Response** - will the site respond to appraisal effort and be capable of material progression in this study?

Review of initial state of maturity of the site characterisation. This will include any pre-existing CO_2 storage studies which are available together with a consideration of how the maturity of the site could be developed through WP5, i.e. the maturity improvement potential. Availability of detailed well history and status of well integrity. Willingness of any incumbent petroleum operator to collaborate and share information into the Project.

- **Data**: The site has the right combination of data availability (type, quality and quantity) to materially progress the appraisal status of the site in this project given the time, and budgetary constraints.

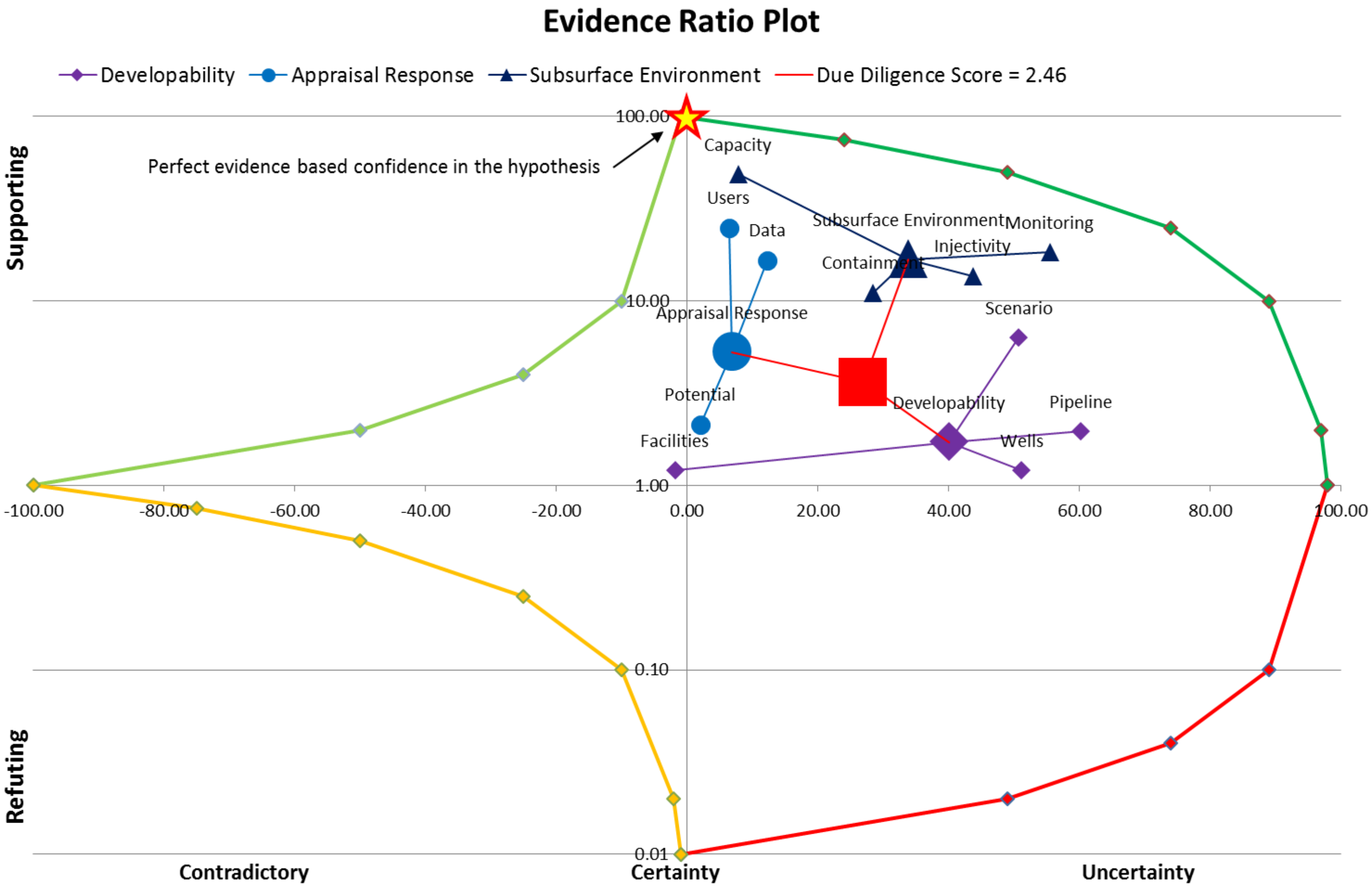


Figure 9: Evidence Ratio plot

- **Users**: This site has sufficient Operator collaboration or support (from whichever domain oil & gas, offshore wind, sand & gravel etc.) to materially progress the appraisal status of the site in this project given the time, and budgetary constraints.
- **Potential**: The site has significant uncertainty reduction potential which if addressed could materially progress the appraisal status of the site in this project given the time, and budgetary constraints available.
- **Wells**: The site has a cost effective option for injection wells (rendered as a levelised cost of offshore injection) which provides confidence that the site can meet the primary hypothesis.

A storage site "prospect summary pack" will be developed for each candidate site. This will document the key aspects of the site and the evidence in a consistent manner. An outline example of such a pack is provided in Appendix A – Example Store Summary Sheets.

The due diligence process will deliver an overall score for each site regarding how well the site meets the primary hypothesis, as illustrated in Figure 9. This is described as the plot distance of the site due diligence findings (Red Square) from the ideal solution where there is perfect evidence based confidence in the central hypothesis. This score will be used in subsequent portfolio selection.

Should due diligence identify any issues that represent significant downgrades for a site then the site may be replaced by the next ranking site in the list delivered by WP3.

WP4.T2 - Portfolio Creation and Assessment

The second step in WP4 involves portfolio creation and assessment (Figure 10). Here, a large set of portfolios of five sites will be drawn from the twenty which passed due diligence. This represents just over 15500 combinations. Each portfolio is then assessed as a unit. The portfolio assessment will include three key elements:

A. Site Combination Score - A summation of key site scores after due diligence including total capacity, levelised cost of storage and due diligence scores.

B. ETI Scenario Score - a measure of how well the portfolio matches the key requirements of the ETI CCS build out scenarios including:

a. Does the portfolio build out from the two competition projects?

b. Does the portfolio facilitate EOR development through its transport and / or storage infrastructure?

c. Does the portfolio service all the key industrial clusters including the Central Belt of Scotland, Teesside, Humber, Thames and Mersey areas?

C. Portfolio Risk Score - a measure to ensure that future project risks are managed by minimising the dependency of the portfolio on single risk factors.

a. Does the portfolio set out to appraise and develop a range of different geological formations as storage sites to minimise the probability of single point of failure risk?

b. Does the portfolio include a range of store types from hydraulically closed stores to open stores with and without structures and saline aquifers as well as depleted hydrocarbon fields?

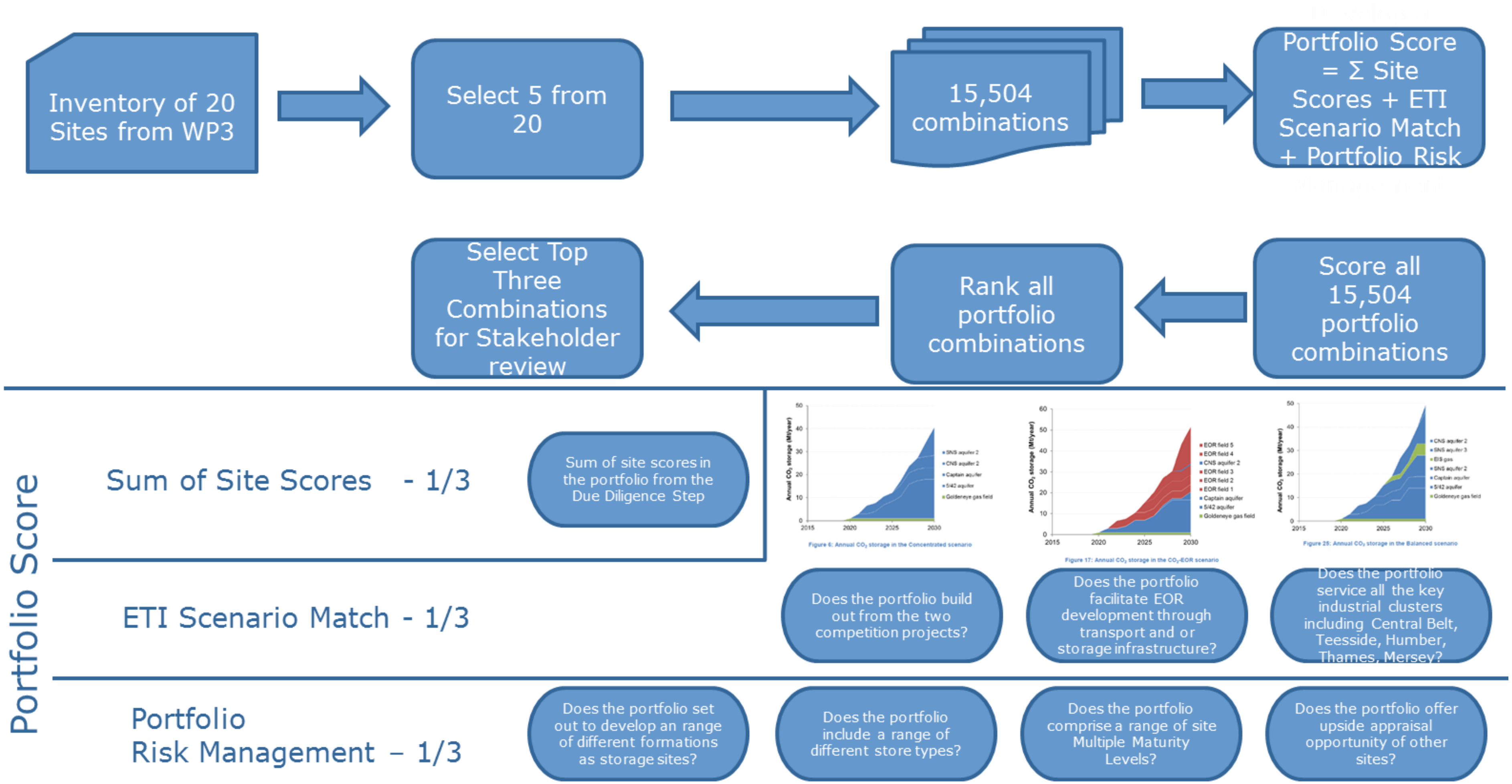


Figure 10: WP4 – Methodology - Portfolio Creation & Assessment

c. Does the portfolio include a range of sites that are data rich and have the potential to reach FID readiness before 2025 as well as stores in which further invasive appraisal is required such that they will not be ready for FID until 2030?

d. Does the portfolio offer upside appraisal opportunities to quickly mature further potential sites perhaps through a low cost slipstream injection programme?

Using this approach each portfolio will be scored and ranked in order of their combined score. The robustness of these rankings and of the top five scoring portfolios in particular will be tested through sensitivity analysis to ensure that the solution is both robust and clear. It will focus upon ensuring that the most appropriate five sites are taken through for consideration in WP5.

A development scenario build out for the top three portfolios will be outlined and a final recommendation made on which five sites to progress to detailed review in WP5.

3.3 WP5 - Appraisal

The Purpose of Work Package 5 (WP5) is to deliver five viable storage sites which could be the basis of further development work by a CO_2 storage developer. Each will have been materially matured at the end of WP5 (Figure 11).

The five down selected sites will enter WP5 at different levels of maturity and risk. Each will be advanced to different levels of maturity depending upon the available data, timeframe and budget. Without detailed knowledge of the CO_2 supply source location and operational patterns, it will not be possible to finalise an offshore storage development concept. Consequently, sites are expected to carry a range of development options for as long as possible until there is enough information to be able to make a quality option select decision. WP5 will be tailored to meet the requirements and database availability for each down selected store as part of WP4 (WP4.T4).

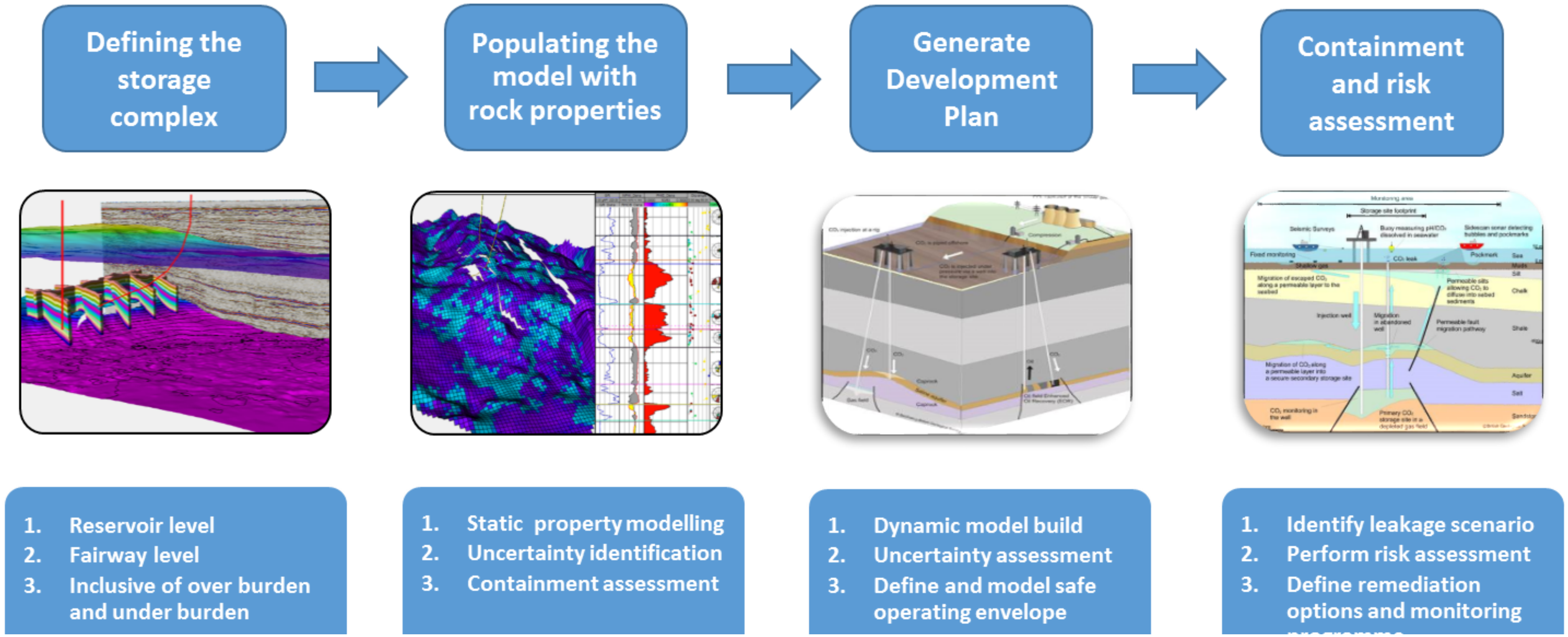


Figure 11: WP5 Evaluation Methodology

The outline work programme presented below is for a Data Rich site. This programme aligns and complies with current UK/EU directives for site licensing and certification. The work programme for Data Poor sites will be drawn from this and contain all the same elements. The key difference will be that the much smaller data volumes will reduce the resource requirements of such stores and also move the balance of effort from data interpretation into data modelling.

Following selection of the five stores and Stage Gate 1, it is expected that bespoke work programmes will be agreed for each selected store. Each storage site is however unique and detailed work programmes will vary.

The evaluation for each store complex comprises four main steps:

1. Defining the Storage Complex.
2. Populating the Storage Model with Rock Properties.
3. Generate Development Plan.
4. Containment and Risk Assessment.

Each step is described in more detail in the following sections.

1. Defining the Storage Complex

Schlumberger's integrated Petrel software platform will be the primary tool used for the seismic interpretation and structural modelling workflows. The required

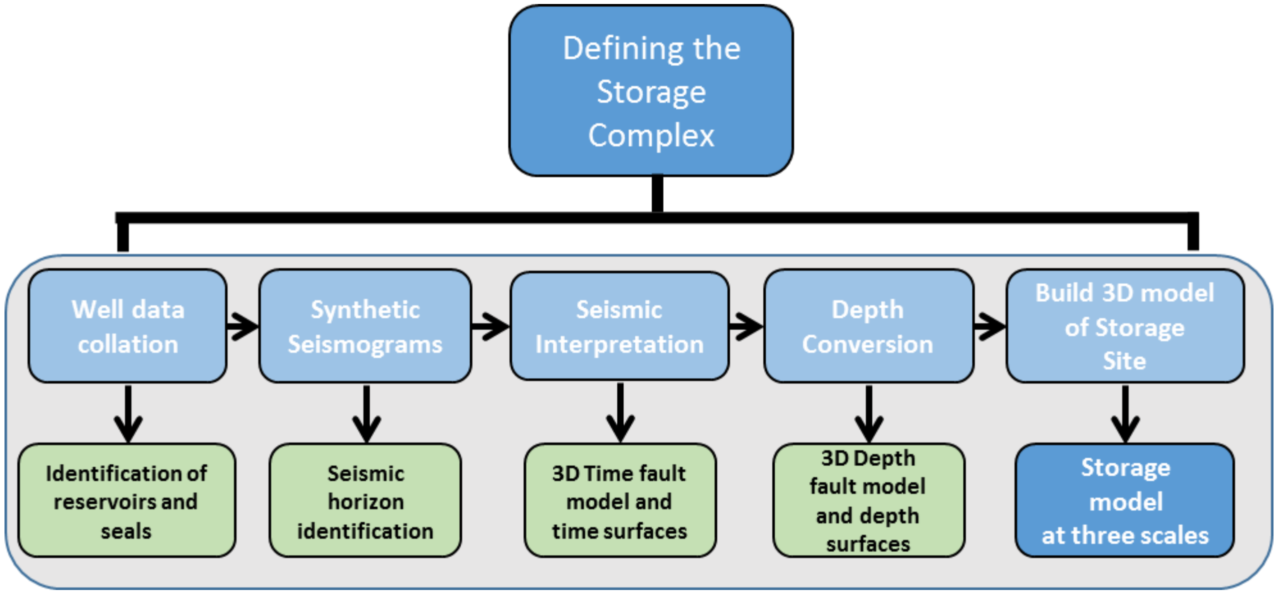


Figure 12: Defining the Storage Complex

wells, well logs and 3D seismic will be imported into a Petrel project and quality checked prior to use for interpretation steps (Figure 12).

Identification of reservoirs and seals (Geological and Sedimentological Review)

A high level sedimentological review will be undertaken to develop an understanding of the controls on reservoir quality and seal distribution. Within the reservoir modelling this will guide the distribution of permeability baffles and impermeable zones, which can strongly influence storage efficiency and plume migration pathways. This will be carried out using regional and field published papers, a rapid review of available core analysis (including core reports and possible core viewing), in addition to available operator reports (e.g. end of well geological reports).

Well log correlations will be undertaken to establish a stratigraphic framework, subdividing the storage reservoir into appropriate intervals for use as input to interpretation and modelling workflows, ensuring permeable and impermeable formations are accurately represented within the reservoir model(s).

Defining the store boundaries (Seismic Interpretation of appropriate 3D seismic volumes)

For robust horizon identification, synthetic seismograms will be generated to tie seismic and well tops.

Once identified, using synthetic seismograms, appropriate horizons and faults will be interpreted for both the store and fairway (including over- and under burden). Additional seismic attribute volumes will be generated to assist with fault and fracture detection (e.g. similarity volumes).

Static structural modelling of the storage site at three different scales (3D structural framework modelling)

The Petrel functionality, to build the fault framework model whilst interpreting the seismic, will be utilised to define the fault framework. The benefits of this are both in quality and efficiency of the reservoir model building. The Time horizon interpretation is then incorporated to create the first-pass 3D Structural Framework. This 3D structural framework is created at a fine scale e.g. X and Y=50x50m.

The next step is to depth convert the Time Structural Framework using an appropriate velocity model. A brief depth conversion evaluation study will be undertaken to select the most appropriate functions and depth residual correction method.

The fine scale Depth Structural Framework model will then be used to create 3D corner point grids for the Storage Site, Fairway and Overburden Models.

The fairway is defined as a trend along which a particular geological feature is likely, in this case a sand reservoir fairway that will be used for geological storage of CO_2. They typically cover an area of 100’s to 1000’s km^2. The storage site is a defined volume area contained within this fairway, immediately surrounding the injection wells and typically covers an area of 10’s to 100’s km^2. Interpretation of the geological units above and below the reservoir (over- and under burden) is required to identify the extent of reservoir seals, potential leak paths and any potential secondary containment reservoir which can an impact on storage integrity and security.

- The fine scale model will be limited to the Storage Site area of interest (and immediate over- and under burden). The model resolution and layering will be at a scale which supports both static and dynamic modelling of the storage site.

- The model is resampled to generate a coarse scale Fairway Model. The model resolution and layering will be at a coarser scale to allow for the dynamic modelling of a large area within a reasonable time frame, in cases where the plume exceeds the boundaries of the Storage Site. The Fairway Model is important for understanding long term CO_2 containment and possible impact on other subsurface users.
- A coarse scale Overburden Model will also be created containing the over- and under burden. This will be used to identify possible secondary containment horizons and used during the subsequent leakage workshops to identify potential migration pathways out of the storage complex.

The resulting 3D grids for the Storage Site and Fairway Models will be used as input to the 3D Property Modelling.

2. Populating the Storage Model with Rock Properties

Petrophysical log interpretation (calculated logs)

The starting point for filling the storage site is the estimation of reservoir properties through the petrophysical analysis of wire line log and core data. Interactive Petrophysics (IP) is the preferred software tool planned for this work, and an IP database of log data will need to be collated prior to the analysis being undertaken (Figure 13).

Petrophysical analysis will be performed on a representative number of pre-selected wells, for each storage site, to derive reservoir and fluid properties. Where available these will be calibrated to core data. Calculated logs will include, but not be limited to: lithology, volume of clay, total and effective porosities, permeability estimates, and water salinity. For depleted hydrocarbon reservoirs the calculation of water saturating from logs, and generation of saturation functions for modelling will also be carried out.

The results of the petrophysical analysis are used as inputs to the 3D property modelling and the distribution of subsurface properties in the 3D reservoir models.

3D Property Modelling (distribution of subsurface properties throughout the 3D Models)

As with step 1, Schlumberger's integrated Petrel software platform will be the primary tool that will be used to build the static models.

The calculated logs (output from petrophysical analysis) and core data are loaded to Petrel. To improve model build efficiency petroleum operator's reports and models will be reviewed (where available and appropriate). The well logs will be upscaled to 3D grid scale, in preparation for modelling. Data analysis of available well log and core data will be carried out and combined with the results of the geological and sedimentological review to understand the trends and controls on facies and rock property distribution.

The modelling of reservoir properties for the Storage Site Model will be at a suitable scale to capture heterogeneity which impacts horizontal and vertical flow (barriers and baffles). The methods (algorithms) used for each stage of the property modelling will vary depending upon the geology of the storage site and the available data.

The following will be modelled:

- Geological facies (where required).
- NTG (where required).
- Porosity.
- Permeability (horizontal and vertical).

Water saturation (in hydrocarbon reservoirs where understanding the initial distribution of hydrocarbons will be important).

The results of the static modelling will be used as input to the dynamic model construction, with the objective of understanding CO_2 flow into and migration within the Storage Site.

Where a Fairway Model is required, reservoir properties will be modelled at a coarser scale and used as input to the dynamic model construction. The objective is to understand the lateral migration of the CO_2 plume and pressure interactions with other subsurface users beyond the Storage Site boundaries. To preserve consistency the properties from the Storage Site Model will be incorporated into the Fairway Model, prior to the full fairway properties being modelled.

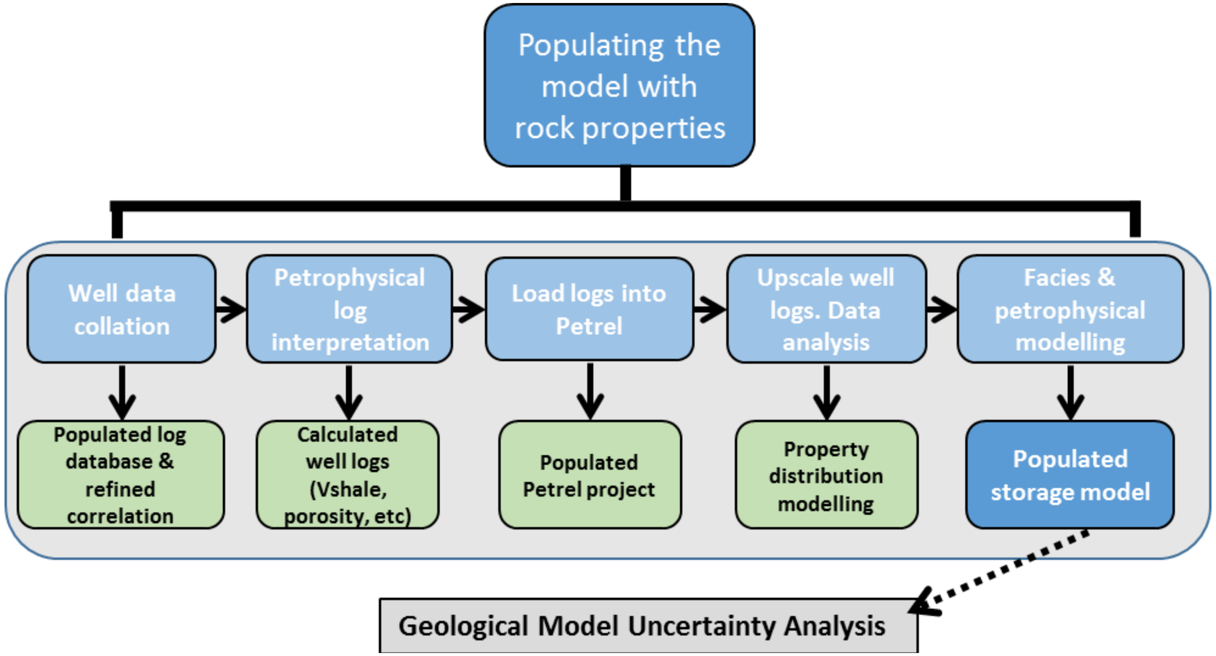


Figure 13: Populating the Storage Model with Rock Properties

Geological Model Uncertainty Analysis

Key reservoir and geological uncertainties impacting store capacity, injectivity and containment will be identified, listed and evaluated.

The uncertainties evaluated will depend on the storage site but could include:

- Top reservoir structure which can impact both storage capacity, and likely migration pathways and rates.
- The presence of faults within the reservoir or caprock may result in possible compartmentalisation and/ or the potential for fault migration pathways.
- Reservoir properties such as porosity and permeability will impact potential storage capacity, likely migration pathways and rates, injectivity and reservoir performance. Understanding controls on these reservoir properties and reservoir heterogeneity (barriers and baffles) is also key. This includes factors such as distribution of depositional facies and controls on diagenesis.

Those identified will be used as input to subsequent reservoir simulation sensitivities, with the objective of understanding their impact.

3. Generating the Development Plan

The objective of this step is to define and evaluate a range of potential development concepts for the five selected stores and to carry out a risk assessment for each development concept. It will not be possible to finalise an offshore development concept at this stage and so a viable range of store development options including their associated risks and costs will be an output from this step. Generating the development plan workflow is shown in Figure 14.

Conceptual Development Plan

A series of development plan options for the site will be devised using the experience of the team. This will comprise an outline plan of the facilities required from the delivery flange of the offshore transport system through to the reservoir and will comprise wells, flowlines, and where appropriate offshore subsea and/or platform / floating structures. All development options will be maintained as possibilities for as long as possible and refined by delivery of outline cost assessments.

Dynamic Modelling

The dynamic modelling section is aimed at studying the injection performance (field and well based) of the site and to assess the performance of the caprock formations using both the static models constructed as well as collected data.

The area extant of the static model is based upon geological and geophysical interpretation work and a developed view of the storage complex. The static model is the base for subsequent dynamic simulations. These will include model input and assumptions as well as appropriate history matching using production and injection data, where this is available, to calibrate the dynamic performance of the models. Storage sites capable of being dynamically history matched in this way can be significantly de-risked in terms of their medium to long term injectivity performance. Data Poor sites are likely to have limited dynamic data to support model calibration.

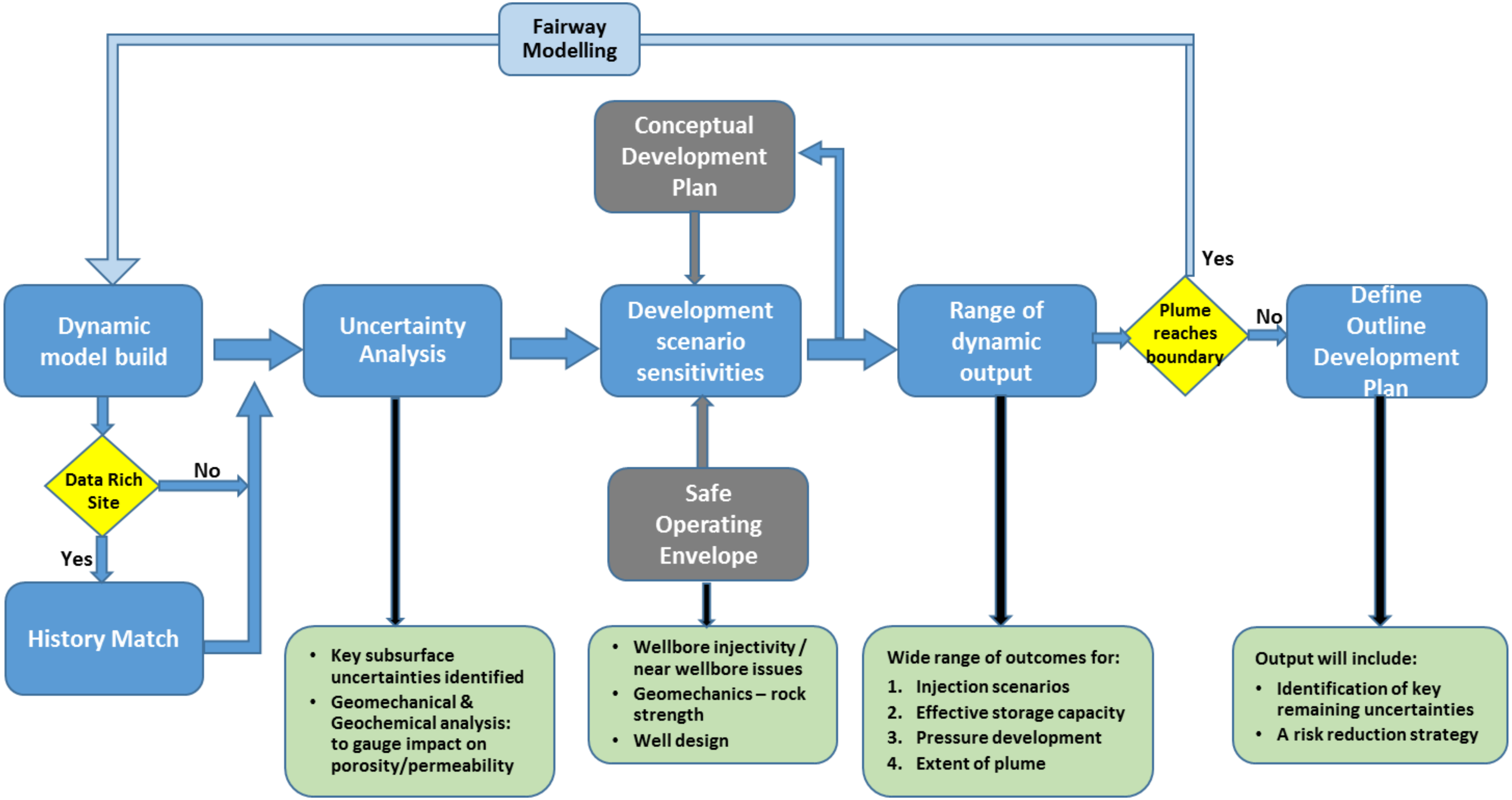


Figure 14: Generating the Development Plan

An uncertainty assessment will be carried out to help define key subsurface uncertainties that will need to be carried forward into the risk assessment stage for the range of development concepts. In addition, results from the geo- be incorporated into the uncertainty analysis and development scenario screening sensitivities.

After an initial concept for development is defined comprising well count, well type and facilities requirements, dynamic reservoir simulations will be performed to study the possible injection scenarios, effective dynamic storage capacity, reservoir pressure development during CO_2 injection and the extent of CO_2 plume migration from the injection points. From a developer perspective, these well placement, and numerous subsurface factors are sensitised so that a development plan can be designed to optimise the store. For this study and the models may be used across many scenarios in which injection rates, well count, timeframe available it is proposed that between 5 and 10 carefully selected scenarios are deployed for each site with the purpose of describing a wide range of potential performance outcomes.

In the event that the pressure distribution during injection exceeds the boundaries of the storage site model and/or the CO_2 plume escapes the modelled area, the "Fairway" static model could then be used to run additional simulations if required. These models will also be important to understand the possible impact on other subsurface users, such as oil and gas fields currently in production or perhaps other CO_2 Storage operations.

Wellbore Injectivity and Near Wellbore Issues

Wellbore injection simulations will give a first look at the technical challenges related to the flow of CO_2 in the wellbore studying the potential impacts of different wellhead temperatures, different CO_2 phase injections, mass rates, different tubing sizes, impurities or possible transient regime studies such as start-up, ramp-up or down operations. The outcome of the simulations would include a CO_2 flow regime along the wellbore, wellhead pressures, flowrates, required number of injector wells and bottomhole temperatures for each of the simulations performed. This is of particular significance for heavily depleted reservoirs such as some gas fields where the reservoir pressure is so low that early injection might have to be in gas phase rather than dense phase.

Geochemical and Geo-mechanical Review

Geochemical and geo-mechanical reviews will be performed to assess their potential impact on injectivity and geological containment. The geo-mechanical review will include consideration of pore pressure and local stress regime which will influence the selection of well types and well geometry. This is essential work and will contribute to the risk assessment and eventually injection operations. It will also assess the risk of fault reactivation during the injection phase. Geochemical review of both the reservoir and the primary caprock will be completed to investigate whether a significant chemical reaction between the injected CO_2 and the formations could occur, which could lead to a change in porosity and permeability or rock strength and hence could have an impact on field injectivity and geological containment. Geo-mechanical modelling will study the geo-mechanical effects associated with CO_2 injection on a site basis.

Safe Operating Envelope

The results of the dynamic modelling, incorporating injection constraints defined by the geochemical, geo-mechanical and wellbore injectivity reviews will inform and provide guidance on the safe operating envelope. This will be guidance only since it is not known at this point what the dispatch pattern of the power or industrial CO_2 sources might be. It will focus upon issues including; maximum injection rates per well at any given point in the operations so that the integrity of the site can be protected at all times; composition of the CO_2 stream requirements of injected CO_2; wellhead temperature operating envelope, this is required to prevent thermal damage to casing or cement which might results from a series of operational well shut ins over a short period of time; maximum reservoir pressure limits - to preserve geo-mechanical integrity.

4. Containment and Risk Assessment

The objective of this step is to evaluate whether the CO_2 can be effectively contained within the storage complex after injection. The evaluation steps are outlined in Figure 15.

Storage complex integrity assessment

The storage complex (as per EU CCS directive 2009/31/EC[10]) will be defined based on the performance modelling and assessments carried out in the generation of the Development Plan. Its suitability as a secure site such that CO_2 is extremely unlike to migrate outwith the storage complex will be assessed. For the purposes of licensing, it is also important that the CO_2 should not migrate out of the license area.

Containment can be divided into two broad categories, Natural and Engineered. Potential breaches of natural containment potentially include faults and fractures in the overburden, or permeable formations through which the CO_2 could move under its natural buoyancy or other pressure differential. Potential breaches of engineered containment include due to loss of well integrity. Aspects that will be considered include cap rock assessment, geomechanics, geochemical integrity, well integrity and full overburden configuration. A well integrity summary will be prepared for a representative number of legacy wells.

Leakage Scenario Definition

Degradation modelling will be undertaken to review the potential for future change in the subsurface and well environment resulting largely from chemical interaction. In wells, the rate at which completions and abandoned well materials will corrode and react in the presence of CO_2 will be considered and an assessment made of the impact of such degradation on well integrity. In the subsurface, a similar assessment on the potential for rock fluid interaction of both the reservoir and the primary caprock will be completed to investigate whether a significant chemical reaction between the injected CO_2 and the formations could occur, which could lead to a change in porosity and permeability or rock strength and hence could have an impact on geological containment.

A Leakage Scenario workshop will be held to brainstorm an inventory of potential leak path. These potential hazard events will form an inventory for subsequent risk assessment using all available evidence.

Subsurface and Wells Containment Risk Assessment

Once the inventory of identified issues for a site containment has been assembled, they will be ranked according to their impact and likelihood of occurrence as:

- ● Critical
- ● Serious
- ● Moderate
- ● Minor

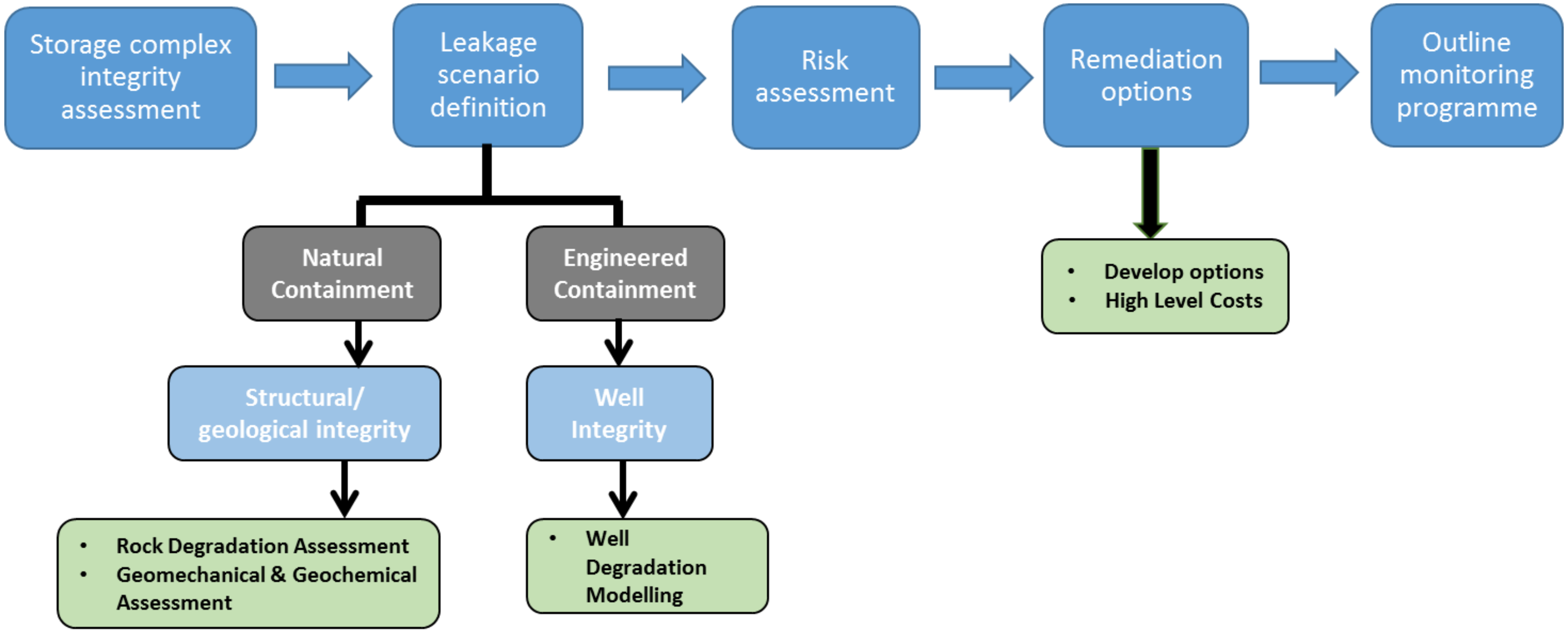


Figure 15: WP5: Containment, Risk-Assessment and Modelling

The containment attributes of the site will then be considered against a hypothesis such as “Site A subsurface environment has the attributes which will enable the containment of 100MT CO_2 on an indefinite basis”.

Remediation Option Development

For each key risk event a remediation option will be established and a high level cost will be developed. This will give a clear view of the storage site integrity across the complex.

A key output will be a containment risk assessment table which will include a clear description of the containment risk, an assessment of the likelihood of loss of containment and its impact, potential options for remediation and high level cost. Options to improve the integrity status will be identified as required.

Monitoring Programme – Feasibility Assessment & Plan

A proposed outline programme of monitoring will be developed to carefully monitor subsurface and well integrity across the storage complex according to the risk assessment and remediation options completed. The objective being early warning of integrity loss so that it can be managed and where appropriate remediated. This will include a range of options from the use of downhole monitoring through to seabed sampling and 4D seismic to monitor the CO_2

plume movement. A range of techniques will be reviewed for their suitability. Monitoring is not generic and must be tailored to the specific nature of each site. Further details of the approach to monitoring design are outlined below.

Considerations for the design of appropriate monitoring programmes:

- Operational Monitoring for operational efficiency.
- Verification Monitoring to confirm that the store is performing within the planned response.
- Assurance monitoring to confirm that the store is not releasing CO_2 from its containment.

4.0 Industry Best Practice Guidelines

In 2013 a technical group from the Carbon Sequestration Leadership Forum produced a report on Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2. This study completed a thorough review of available best practice guidelines building upon work completed by a CO2CRC assessment in 2011. These are listed in Table 13.

The CSLF group went further and progressed and extended the assessment by CO2CRC to build a profile of the relative contribution of each best practice source to each lifecycle stage in a CO_2 Storage project. This provides an exceptionally useful tool to cut through to key areas of reference which are of particular value to this study. This UKStore project is primarily focussed upon pre-operational workflows. Table 13 highlights the particular relevance of the guidelines and recommended practice documents from DNV in this regard. These are particularly relevant since they have been developed with offshore operations in mind. This contrasts with some of the guidance from North America which focus almost exclusively on onshore sites.

Despite this detailed landscape of best practice documents, some components of the methodology used for the UKStore project are not well covered by documented best practice. Specifically, the majority of CO_2 storage projects have been focussed upon finding a single storage site for a specific source of CO_2. The creation and assessment of early stage site portfolios is not well covered although such a process has been completed by several projects around the world. Of specific note is the work completed by the CarbonNet team on CO_2 Storage Site selection in the Gippsland Basin[19].

This 2 year AU$20M project started with an inventory of 14 sites. This was down-selected to 6 through peer review and then to a portfolio of 3, before selecting a single site. The CarbonNet team point out:

"*There are many learnings to be gleaned from the petroleum industry. Oil companies do not, in general, seek a single isolated oilfield. They seek a cluster of fields which can be explored for and developed with economy of number by shared technical analysis and shared infrastructure. This type of approach develops a Portfolio of sites which are selected so as to share some geological characteristics, and be independent in others. This type of approach is generally described as a play fairway, where a suite of prospective targets is evaluated within a single geological system.*

The reason for this approach is exploration risk management. If one of these sites is drilled and some major defect is discovered with the trap concept (such as lack of reservoir, or seal), then all sites that share that attribute are similarly affected. A single well could thus rule-out a whole family of prospective targets. However, a successful well would improve the ranking of that whole family. It is therefore prudent to have several families of prospective targets available within a close enough area that information from one exploration well can inform independently (be it favourably or unfavourably) on the different families."[19]

Shortcode	Best Practice Manual Scope	Planning & pre-feasibility	Site screening, selection & characterisation	Simulation & modelling
CO2STORE	Best practice for the storage of CO2 in saline aquifers	Basic	Technical	Technical
CCP	A technical basis for carbon dioxide storage		Basic	
DNVCO2QUAL	Guideline for selection and qualification of sites and projects for geologic storage of CO2	Detailed	Detailed	Basic
DNV CO2WELLS	CO2WELLSGuideline for the risk management of existing wells at CO2 geological storage site		Technical	
DNV RP-J203	Geological Storage of Carbon Dioxide (DNV-RP-J203)	Basic	Detailed	Basic
DNV CO2RISKMAN	Risk management guidance document for most of the CCS chain in four parts.			
LBNL/GEOSEQ	Geologic carbon dioxide sequestration: Site evaluation to implementation		Basic	Basic
NETL MVA	Best practices for: Monitoring, verification, and accounting of CO2 stored in deep geologic formation			
NETL GS	Best practices for: Geologic storage formation classification: Understanding its importance and impacts on CCS opportunities in the United States	Technical	Technical	
NETL SS	Best practices for: Site screening, site selection, and initial characterization for storage of CO2 in deep geologic formations	Basic	Detailed	Basic
NETL RA	Risk analysis and simulation for geologic storage of CO2			Technical
NETL WM	Best practices for: Carbon Storage Systems and Well Management Activities			
WRI CCS	Guidelines for CCS	Basic	Detailed	Basic
IEA Weyburn	Best Practice Manual developed through learning from Weyburn project		Technical	Technical
CSA	Z741-12 Geological storage of carbon dioxide	Basic	Detailed	Detailed
AU1	Australian Guiding Principles for Carbon Dioxide Capture and Geological Storage(Guiding Principles)			
AU2	Environmental Guidelines for Carbon Dioxide Capture and Geological Storage – 2009			
EC1	Guidance Document 1. CO2 Storage Life Cycle Risk Management Framework			

EC2	Guidance Document 2. Characterization of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures		Detailed	Basic
OSPAR	OSPAR Guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formations	Basic	Basic	
London	London Convention and Protocol: Specific Guidelines to Risk Assessment and Management Framework (RAMF) 2006		Very basic	
EPA	Geologic Sequestration of Carbon Dioxide: Underground Injection Control (UIC) Program Class VI Well Project Plan Development Guidance			

Key to assessment grades	
	Not covered specifically
Basic	Briefly covered in a generic way
Technical	Provides technical details of projects, generally comprehensive
Detailed	Comprehensive discussion, generally generic

Table 13: Industry Best Practice Guidelines. CO2CRC, 2011[20].

5.0 Conclusions

This purpose of this project is to identify and progress five potential storage sites that can materially be appraised and contribute to delivering CO_2 storage solutions for UK Phase 2 CCS projects.

The five sites are anticipated to have an average individual practical capacity to store some 200MT of CO_2 safely and securely for an indefinite period and will support the strategic build of a CCS industry for the UK.

The CO2Stored database and the UK Storage Appraisal programme that developed it has been instrumental in enabling this project to proceed. Without this strong and consistently developed storage site inventory, then it would have not been possible to design this project.

As with any study, the screening and appraisal methodology presented here is necessarily conditioned by the budget, timeframe and data available.

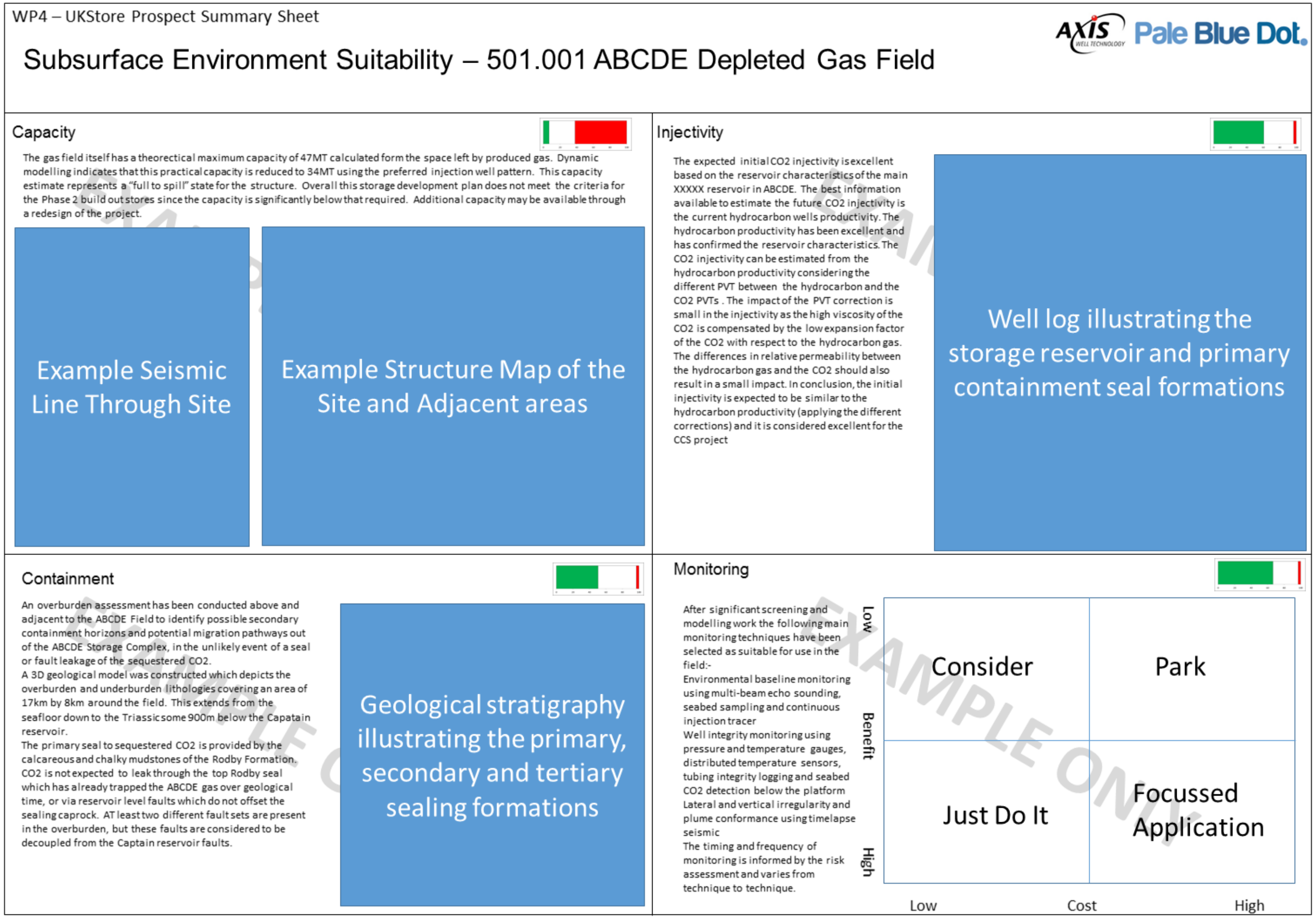
A two stage appraisal process has been adopted to screen an initial inventory of over 500 potential CO_2 storage sites down to 5 sites.

The initial stage (WP3) focusses on reducing the inventory from over 500 sites to 20 sites. This stage relies very significantly upon the contents of the CO2Stored database. It has two steps, the first is a qualification and compliance cut which is anticipated to reduce the number of sites under consideration to around 200. The second is a ranking process using information from the CO2Stored database and using a process called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to deliver a ranking score. The highest ranking 20 sites will be progressed to the next stage.

The second stage (WP4) seeks to interrogate other available data and complete a due diligence on each of the 20 sites. This will deliver an additional score for each site based upon its ability to significantly contribute to the project objectives. All possible combinations of 5 sites from the 20 site down-select list will then be considered on a portfolio basis. A portfolio score will depend upon the quality of each site in the portfolio, the match of the portfolio to the ETI CCS build out scenarios and the ability of the portfolio to manage critical risk exposure into the future.

At the end of WP5, there will be outline storage development plans for five sites incorporating detailed subsurface characterisation and dynamic modelling work from available data. These outputs in report and digital model form will be made available by the ETI for stakeholders to further develop their own CCS considerations.

Appendix A – Example Store Summary Sheets



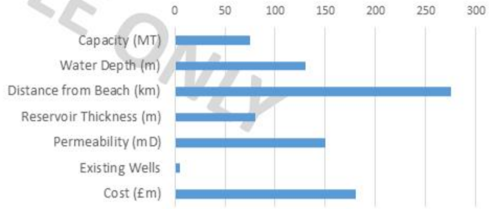
WP4 – UKStore Prospect Summary Sheet

Developability – 501.001 ABCDE Depleted Gas Field

General

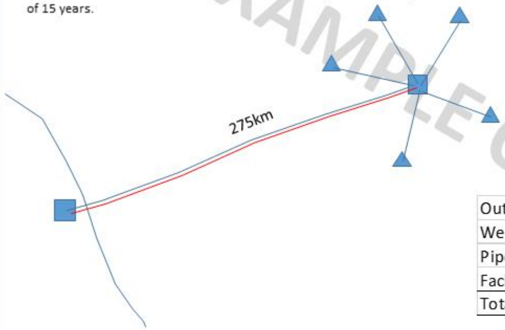
- Description
- Location & Map
- Water depth
- Reservoir depth
- Existing wells – description
- Role in Build Out Programme

Location Map



Outline Development Concept

This development will be a subsea project with a dedicated new 16" pipeline from the St Fergus Beachhead. There will be 5 new subsea wells capable of injecting in excess of 5MT/yr. The well s will be drilled from a central template and will be deviated in trajectory with an anticipated short horizontal section at the base of the reservoir interval.. The wells will be controlled from the beach through hydraulic controls and will also be wired for standard pressure and distributed temperature to enable detailed wellhead monitoring. The site is expected to have a practical capacity of 75MT and a lifetime of 15 years.



Outline Development Cost Summary	
Wells (£M)	100
Pipeline (£M)	275
Facilities (£M)	150
Total (£M)	525

Scenario

Outline how the site fits into the Build out scenarios as specified by ETI
Describe the potential timing for the development including when the site becomes available from previous users if there are any.

Strategic Build Out Map

Wells

Early suggestion of well type and geometry to achieve injection requirements, estimation of well cost & type of drilling rig requirement
Estimation of cost of wells

Pipeline

Early assumptions of Pipeline concept route, diameter and throughput.
Estimate of the cost of the pipeline

Risks / Opportunities

Outline the main risks associated with the site as perceived now together with any opportunities for upside or further cost reduction or cost sharing.

Facilities

Outline of subsea facilities and flow lines together with control systems for the wells
Estimated cost of the facilities

WP4 – UKStore Prospect Summary Sheet

Appraisal Potential – 501.001 ABCDE Depleted Gas Field

Data

Provide an outline description of the data which is available to the project together with its IP classification

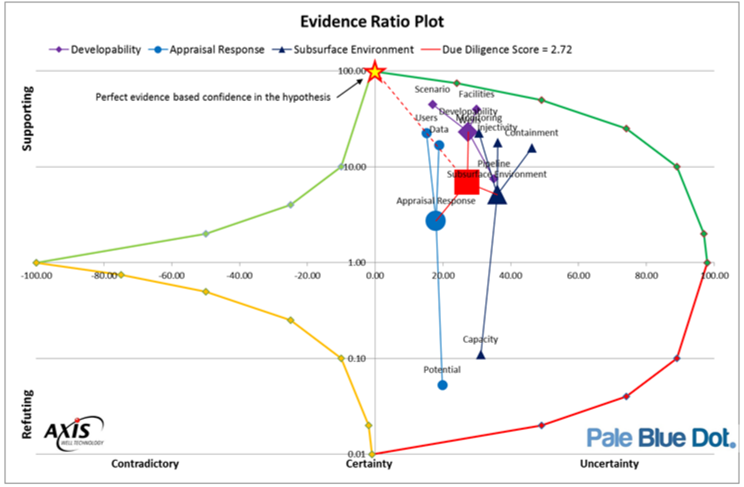
Note here any issues regarding data access or commercial matters that might complicate data access.

Users

There are no other surface site users from the offshore wind or sand and gravel extraction sectors. Fishing has continued around the vicinity of the platform during its oil and gas operations and poses no additional concerns at this time. The Operator of the store is also the operator of the petroleum asset and so is well placed to manage any conflict between the different owners structures there. With regards to subsurface users, there are no other users of the pore space within which CO_2 will be stored, however other petroleum and CO_2 storage operators in the Captain fairway will be impacted hydraulically by the injection at ABCDE due to the strong pressure connectivity. In most situations ABCDE injection is expected to be a neutral of slightly beneficial effect for petroleum extraction along the fairway. Of course injection at ABCDE will also be impacted by the operating pressures at the oil and gas fields along the fairway also.

Potential

With a significant FEED study in place and no new available information there is negligible opportunity for this study to progress the appraisal of the site during this study



The ABCDE site is the root of the Northern CCS build out infrastructure. It has been worked extensively since 2009 and been through two FEED programmes. The store is well characterized and the facilities are in good condition to support a 10 year demonstration programme.

As a result, with the data currently available and the FEED stage maturity of the project there is minimal opportunity to make more progress with this site without further significant data acquisition.

As a Stage 2 build out site, the current development plan configuration would not be sufficient to present a material progression and an alternative storage development scenario would be required. The FEED work completed to date suggests however that the ABCDE area has significant additional CO_2 Storage upside potential

References

1. *Delivering CO_2 storage at the lowest cost in time to support the UK decarbonisation goals. UK Transport and Storage Development Group, 2013.*

   http://www.thecrownestate.co.uk/media/389719/ei-delivering-co2-storage-to-support-decarbonisation-goals-tsdg.pdf

2. *Next Steps in CCS: Policy Scoping Document. DECC, 2014.*

   https://www.gov.uk/government/publications/ccs-policy-scoping-document

3. *UK CO2 Storage Evaluation Database - CO2Stored.* The Crown Estate, 2009.

   http://www.co2stored.co.uk

4. *UK Storage Appraisal Project: Final Report (UKSAP). The Energy Technologies Institute (ETI), 2011.*

   http://www.eti.co.uk/project/uk-storage-appraisal-project/

5. CO2 STORage Evaluation Database (CO2Stored). The UK's online storage atlas*. Bentham, M. et. al., 2014.*

   http://nora.nerc.ac.uk/509387/1/1-s2.0-S1876610214023558-main.pdf

6. *CCS Sector Development Scenarios in the UK. Element Energy & Pöyry, 2015.*

   http://www.eti.co.uk/wp-content/uploads/2015/05/2015-04-30-ETI-CCS-sector-development-scenarios-Final-Report.pdf

7. *DNV-DSS-402 Qualification Management for Geological Storage of CO_2. DNV, 2012*

   http://www2.dnvgl.com/DNV-DSS-402

8. *DNV-RP-J203 Geological Storage of Carbon Dioxide. DNV, 2012.*

   http://www2.dnvgl.com/DNV-RP-J203

9. *UKCS Demonstration Competition, Post FEED End to End Basis of Design, Section 6.2. Shell, 2011*

   http://webarchive.nationalarchives.gov.uk/20111209170139/https://www.decc.gov.uk/en/content/cms/emissions/ccs/demo_prog/feed/scottish_power/scottish_power.aspx

10. *Directive 2009/31/EC on the Geological Storage of Carbon Dioxide. European Parliament, 2009*

    http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

11. *Assessing European Capacity for Geological Storage of Carbon Dioxide. Geological Survey of Denmark and Greenland, 2009.*

    http://www.geology.cz/geocapacity/publications/D42%20GeoCapacity%20Final%20Report-red.pdf

12. *Choosing good sites for storing CO_2 underground. SiteChar, 2014.*

http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=339&IdType=557

13. *EU Geocapacity - Assessment of CO2 Geological Storage Potential of Europe, Vangkilde-Pedersen, Geus et al, 2011*

    http://www.cgseurope.net/UserFiles/file/1st%20Kickoff%20meeting/Presentations/17-Vangklide-Pedersen.pdf

14. *Multiple Attribute Decision Making: Methods and Applications. Hwang and Yoon, 1981.*

15. *A comparison of Fuzzy AHP and Fuzzy TOPSIS methods to supplier selection. Applied Soft Computing 21, 194–209. Lima Junior, F.R., Osiro, L. & Ribiero Carpinetti, L.C., 2014.*

16. *TOPSIS in Excel. Hodgett, R., 2014*

    http://hodgett.co.uk/topsis-in-excel/

17. *Oil and Gas: Licensing for Carbon Storage. Oil & Gas Authority. 2013.*

    https://www.gov.uk/oil-and-gas-licensing-for-carbon-storage--3

18. *Evidence Support Logic: A Guide for TESLA Users. Quintessa Limited, 2008.*

    https://www.quintessa.org/repository/files/Evidence_Support_Logic_Guide_v3.0.pdf

19. *CarbonNet storage site selection & certification: challenges and successes. Carman, G. & Hoffman, N., 2012.*

    www.energyandresources.vic.gov.au/carbonnet

20. *A review of best practice manuals for carbon dioxide storage and regulation. CO2CRC, 2011.*

    http://www.globalccsinstitute.com/publications/review-existing-best-practice-manuals-carbon-dioxide-storage-and-regulation