DELIVERABLE D2.1 REPORT

Methodologies for cluster development and best practices for data collection in the promising regions

Part 2 - Bridging the Gap

Storage Resource Assessment Methodologies

Release Status: FINAL

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Date: 17 January 2020

Filename and version: STRATEGY-CCUS-WP21-SRAM-v1.docx

Project ID NUMBER 837754

STRATEGY CCUS (H2020-LC-SC3-2018-2019-2020/H2020-LC-SC3-2018-NZE-CC)

This project has received funding from the European Union’s Horizon 2020
research and innovation programme under grant agreement No. 837754

Document History

Location

This document is stored in the following location:

Filename	STRATEGY-CCUS-WP21-SRAM-v1.docx
Location	Google Drive, short link: www.bit.ly/WP21-SRAM-Report

Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename/Location stored:	Brief Summary of Changes
Version 0.1 to 0.8	02/08/19 – 01/12/19	WP21-SRAM-0.2,0.4,0.8	Drafting
Version 1.1 to 1.3	01/12/19 – 15/01/20	WP21-SRAM-v1.1, v1.3	Reviewing and editing
Version 1	17/01/20	WP21-SRAM-v1	Final version

Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
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For Deliverables, the Project Leader should receive the final version at least one week prior to the due date.

Distribution

This document has been distributed to:

Name	Title	Version Issued	Date of Issue
Júlio Carneiro	WP Leader	WP21-SRAM-v1	20/01/2020

Please reference this report as:

Cavanagh, AJ, Wilkinson, M and Haszeldine, RS. 2020. Bridging the Gap, Storage Resource Assessment Methodologies, EU H2020 STRATEGY CCUS Project 837754, Report, pp 67.

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Table of Contents

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Storage Resource Assessment Methodologies

Executive Summary

This report for the EU project, STRATEGY CCUS, reviews and describes resource assessment methodologies, providing a best practise approach to the regional appraisal of geological CO_2 utilisation and storage. The report complements the accompanying STRATEGY CCUS report on methodologies for characterising industrial clusters and CO_2 transport systems.

The best practise approach identifies and lists data requirements necessary for the rapid maturation of European storage. The report also considers the assessment of CO_2 utilisation and storage, i.e. low-carbon technologies and industries that store captured CO_2 during production. The report is intended to support the regional teams in STRATEGY CCUS establish the suitability and capacity of their storage resources. The outcomes are intended to be comparable across regions. The resources are primarily deep saline aquifers, depleted hydrocarbon fields, and unmineable coal beds.

The work is introduced by a consideration of the European requirement for mature storage resources within the context of Net Zero ambitions and agreed EU targets and goals. This highlights the huge discrepancy between expected storage supply and embedded demand in the coming decades. The European resource has not matured adequately beyond a theoretical estimate, and the required maturation rate is steep: a gigatonne of storage by the mid-2030s and several gigatonnes by 2050. The EU storage rate increases from one hundred million tonnes a year in 2030 to more than half a gigatonne a year in 2050.

The report draws on experience from existing regional storage resource assessment projects in Northern Europe and North America, including the CO_2 Storage Atlas of the Norwegian North Sea, the UK's CO_2 Storage Evaluation Database, the North American Carbon Storage Atlas, Fifth Edition, and the Society of Petroleum Engineers' Storage Resource Management System (SPE-SRMS). A review of these projects informs the proposed methodology which includes the data requirements for each resource option. These form the basis of the data lists provided to the regions.

The North American approach is notable for pioneering the basic concepts and equations that underpin regional CO_2 storage resource assessments. The Norwegian approach is notable for its methodical approach to the qualitative assessment of essential storage attributes beyond capacity. The UK assessment is notable for going beyond a theoretical evaluation to mature a shortlist portfolio of offshore candidate sites for rapid investment. Both Norway and the EU would do well to emulate this. The SPE tool, SRMS, is notable for indicating a large capacity shortfall both globally and regionally. SRMS applies two bars to maturation; the low bar, a targeted data well, consigns most UK, Norwegian, and EU prospects to its lowest 'undiscovered' classification; an undrilled prospect is not contingent. The higher bar, a 'firm intention to proceed' within five years, further culls all European projects.

SRMS identifies less than 200 million tonnes of commercial capacity globally. The SRMS contingent resource exceeds 300 gigatonnes, but this is largely located in North America, and is almost entirely represented by enhanced oil recovery prospects with no clear path or timeline to development within a decade.

The challenge for Europe is to move beyond a storage portfolio that is largely theoretical by rapidly maturing the resource to a bankable reserve sufficient to meet expectations implicit in EU mitigation targets and goals. The proposed methodology allows for the rapid screening and ranking of available regional storage resources and supports gap analysis to accelerate the maturation of that strategic resource to a level commensurate with the ambition to decarbonise over the coming decades. Given the lead time between resource banking and operational storage, time is short.

Storage Resource Assessment Methodologies

1 Introduction

Storage resource assessment is an essential element of strategic CO_2 Capture, Utilisation and Storage (CCUS) planning. Geological storage removes carbon dioxide from the atmosphere for the thousands of years required to mitigate climate change, while utilisation offsets storage costs in a product chain that results in mitigation.

Globally, mitigation is expected to transition from reduction to recapture in the 2030s with the introduction of negative emission technologies (Figure 1-1). This requires an unprecedented acceleration of CCUS, which necessitates the rapid identification and maturation of the global storage resource to enable capture and utilisation technologies, that in the wording of the European Union's sustainable finance taxonomy have a "clear mitigation impact" (TEG, 2019).

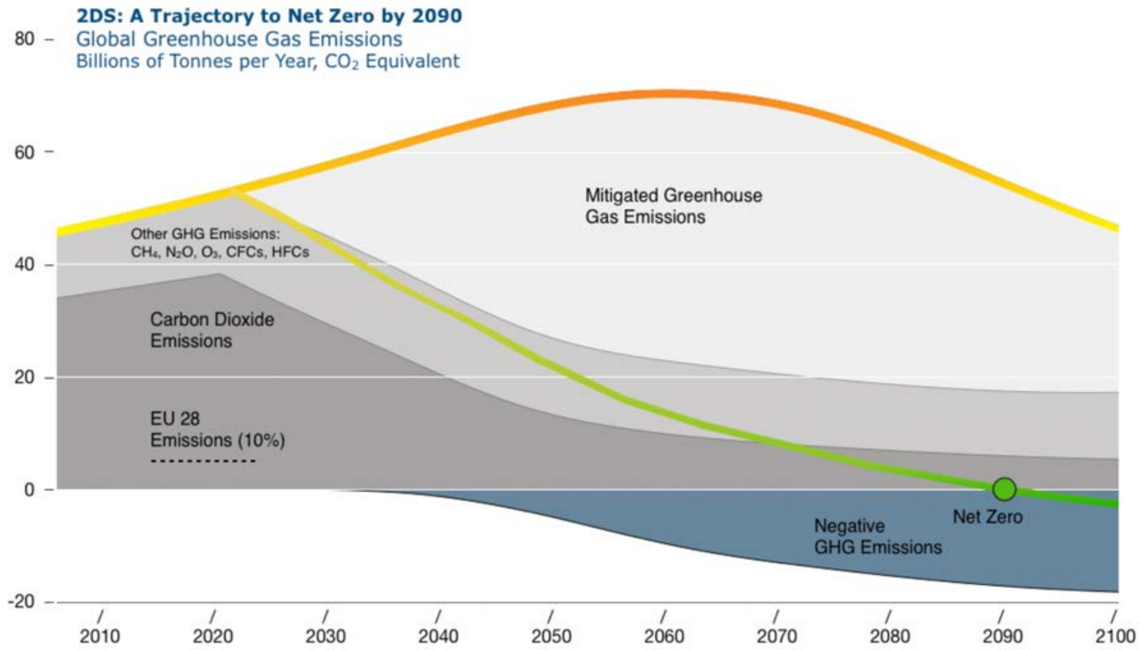

Figure 1-1 2DS, the two-degree scenario greenhouse gas pathway to Net Zero by 2090 (UNEP, 2017). This anticipates the introduction of negative emissions technologies to recapture CO_2 from 2030.

In 2017, the EU was ranked as the world's third largest emitter of greenhouse gases at 10% by contribution of a global 45 gigatonnes per annum - China was the largest at 30%, followed by the USA at 15%; the UK ranked 16th at 1%, whereas Norway was 80th at 0.1% (WRI, 2014). It follows that the EU has a pressing need to strategically identify and develop CCUS in the coming decades.

Regional assessments for the EU typically indicate many gigatonnes of theoretical storage which appear to match the gigatonne-scale requirement embedded in emission reduction targets. The theoretical qualification is significant, referring to the lowest level of a resource assessment or first approximation. The available resource is a fraction of this first approximation when assessed for practical and commercial viability. An effective assessment methodology matures the resource estimate towards a bankable reserve of regional candidate sites while identifying gaps in knowledge and data that delay the maturation from theoretical to discovered and contingent prospects.

1.1 Storage supply and demand in the European Union

Europe, at 10% of global emissions, has committed to reduction targets and goals that follow a two-degree scenario (2DS) path to 2030 and go beyond (B2DS) for 2050 (IEA, 2017; EEA, 2018). Analysis suggests that decarbonisation is likely impossible and much more expensive without CCS (IEA, 2019).

Assuming that (a) the IEA is correct in forecasting a 14 per cent CCS contribution to 2DS, and 32 per cent to B2DS, and (b) the EU total emission reduction targets of -40 per cent for 2030 and -95 per cent for 2050 are achieved, this requires a reduction of 81 Mt CO_2e per year from 2020, doubling to 157 Mt per year CO_2e from 2030 (Figure 1-2). It follows that the European resource must be sufficient to provide one hundred million tonnes of geological storage per year by 2030 and exceed half a gigatonne every year before 2050 (Figure 1-2). This sums to 580 million tonnes of storage by 2030, 3 Gt by 2040, and 8 Gt by 2050. Net Zero in 2050 means 30 Gt of storage by 2090.

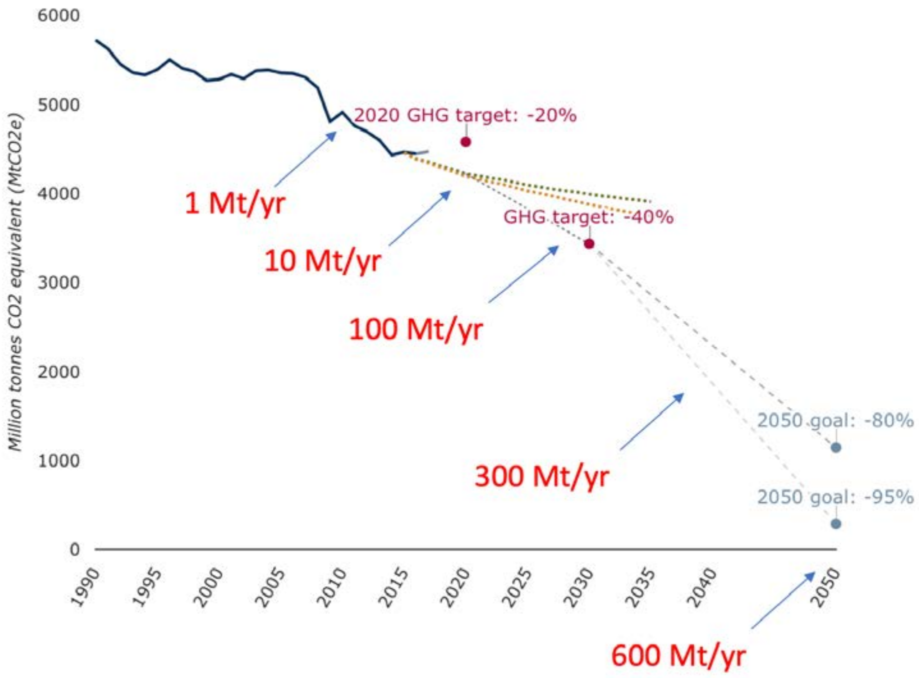

Figure 1-2 EU targets and goals (EEA, 2018), and forecasted CCS contributions requiring gigatonnes of storage by 2050 and order-of-magnitude increases in storage rates by 2050.

While theoretical estimates imply that there is enough geological storage, the EU pathway suggest that storage demand will exceed supply, and indications are that much of the early provision will be offshore (IOGP, 2019). Both Norway and the UK are working in partnership to develop domestic CCS in the North Sea region, while jockeying for position to provide storage to the EU which has been slow to mature the onshore resource. The main financial support mechanism in Europe is the EU ETS, a carbon price market which has traded a ton of CO_2 at less than €10 for much of the last decade, currently trades at about €25, and so has struggled to reach the value required to make CCS happen. There are no full-scale CCS projects in the EU despite their expected role in meeting targets.

Norway has positioned itself primarily as a storage provider to the EU. It has an abundance of offshore storage in the North Sea and very few options for domestic onshore capture of a widely dispersed 0.1% of global emissions. Norway and Statoil/Equinor have pioneered the demonstration of storage with the Sleipner, Snøhvit, and Northern Lights projects since the 1990s (Furre et al., 2019). The local tax regime has supported this with a CO_2 price of around \$50-\$70/tonne. These large Norwegian CCS projects are also underwritten by producing oil and gas at Snøhvit and Sleipner. The hydrocarbons are CO_2 rich and require cleaning up before going to market. While the fossil fuels more than pay for the CCS component, these projects are net emitters, not greenhouse gas mitigators, despite their apparent CCS credentials and effective demonstration of storage.

The UK at 1% of global emissions has a much more pressing domestic need than Norway to store CO_2, and yet has so far failed to build large CCS demonstration projects with two cancelled government-led competitions, 2008-2015. The goal remains CO_2 capture on gas power, industrial clusters, and hydrogen. The UK also has an abundance of offshore storage, primarily in the North Sea, which it also expects to market to the EU (BEIS, 2018). The UK portfolio has matured despite failed capture projects (CCSA, 2016) and is in a stronger position than the largely theoretical Norway provision which is overly reliant on the Sleipner project and Utsira formation for contingent capacity.

The EU, Norway, and the UK need to rapidly accelerate action if CCS is going to make a significant contribution to Net Zero by 2050. The EU requirement for gigatonne-scale storage within two decades will need to be stress tested by storing around 100 million tonnes per year within 10 years.

Where is this storage and when will it be ready? Norway has stored almost 20 Mt of CO_2 beneath the North Sea since 1996. The 2DS target requires a ten-fold increase by 2025, and a forty-fold increase in activity by 2030. This seems highly unlikely given the lead-time for storage appraisal and high cost of projects, with the IEA expected to revise CCUS scenarios in the next Energy Technology Perspectives forecast, circa June 2020. By comparison, solar PV has grown twenty-fold over a decade, from a global capacity of 35 gigawatts in 2010 to a forecasted 700 gigawatts in 2020 (Bloomberg, 2019); an exponential growth attributed to tumbling costs and soaring demand.

And yet regional resources appear adequately large ((Figure 1-3) with an estimated 116 Gt of European onshore storage (GeoCapacity, 2009), and offshore estimates for the Norwegian North Sea of 72 Gt (Halland et al., 2014), and the United Kingdom of 78 Gt (Bentham et al., 2014). How reliable are these large theoretical estimates and how do they convert to available matched storage?

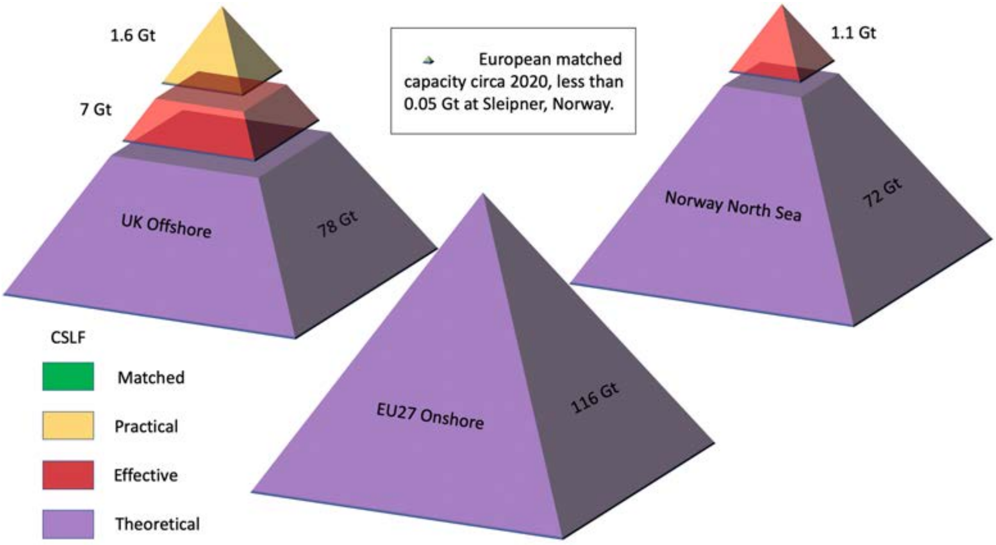

Figure 1-3 European storage resource: theoretical (266 Gt), effective (8.1 Gt), and practical (1.6 Gt). Tiers are based on Carbon Sequestration Leadership Forum nomenclature: Theoretical, a regional first approximation; Effective, sum of identified prospects and exploration targets; Practical, matured prospects and candidate sites; Matched, storage sites with bankable capacity available for injection.

Closer scrutiny reveals that only 1.6 Gt of UK storage has matured to investable developments. Norway's assessment of a matured 1.1 Gt seems to be unproven given the lack of identified prospects or drilling (OGCI, 2017). The onshore European resource remains entirely theoretical, having not matured to the same degree. A global appraisal using the SPE's Storage Resource Management System classification is more sceptical. The appraisal is based on decades of experience from oil and gas evaluation, and downgrades all of the Norwegian and much of the UK storage to contingent, i.e. dependent on further characterisation, and undiscovered, i.e. undrilled. Globally, the SRMS study indicated just 160 Mt of available storage, and 600 Mt of economically viable storage that is on hold, requiring further development.

1.1.1 Strategic need to minimise delay and de-risk portfolio

It is reasonable to conclude that the European 2030 target and Net Zero ambitions rest on an immature CO_2 storage reserve which is currently highly dependent on the UK North Sea sector to deliver 580 Mt by 2030 and 3 Gt by 2040. A rapid acceleration of European storage and targeted appraisals of Norwegian locations are required to de-risk the portfolio over the coming decade.

These are immense gaps in storage capacity that indicate the discrepancy between top-down and bottom-up resource appraisals. Spanning these gaps by 2030 seems improbable. Realistically, the conversion from theoretical to practical storage requires a science, technology, and engineering effort over decades, likely reducing the forecasted contribution of CCS to Net Zero by 2050. And yet, this level of activity has happened before in the North Sea race to develop oil (Figure 1-4). Assuming an injection rate of one million tonnes of CO_2 per well, drilling rates of twenty-to-thirty wells a year in the 2030s and 2040s would approach the storage rates required by 2050. Failing that, the EU will almost certainly move to long-term strategic scenarios that limit CCUS.

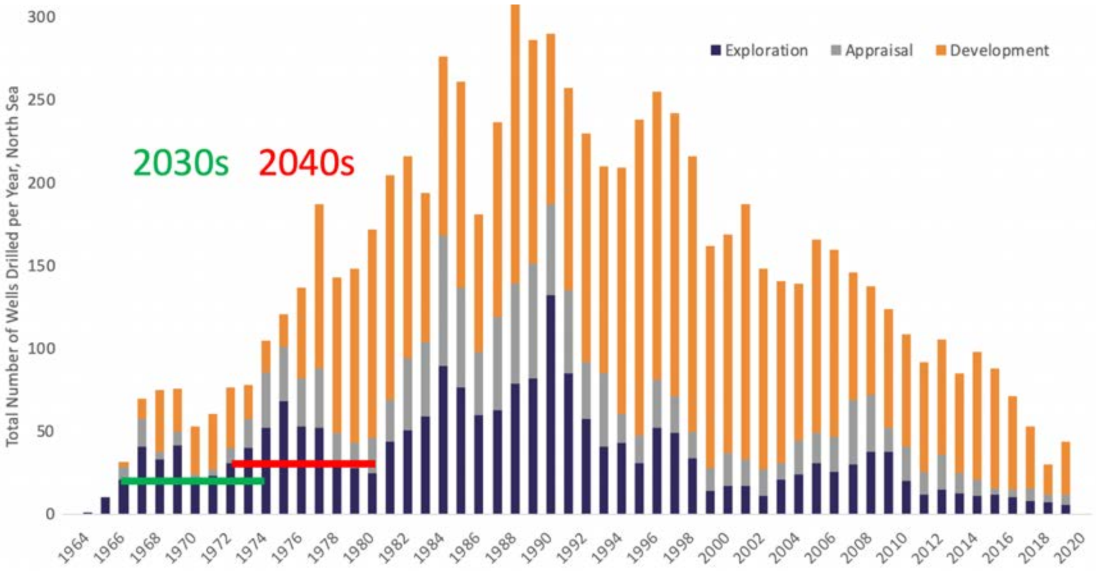

Figure 1-4 Historic UK North Sea well completions (Source: OGA, 2019) and EU storage development. Green and red bars estimate drilling activity levels commensurate with required CO_2 injection rates.

The strategic nature of rapid CCUS development in Europe is apparent. A storage capacity shortfall and divestment may reframe this technology's contribution to mitigation actions over the coming decade, delaying the contribution of negative emission technologies such as BECCS and DACCS (Bioenergy and Direct Air CCS) to Net Zero. This potentially displaces captured CO_2 into even more challenging carbon sinks such as mineral weathering, shale adsorption, and deep ocean storage.

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1.2 Approach to storage resource assessment methodology

The following sections cover relevant regional studies and the SRMS review that inform the resource assessment (2 - Reviews); propose a common storage methodology for use across the promising regions (3 - Best Practise), including the governing analytical equations for storage capacity and utilisation appraisal; and list parameters needed to furnish those equations (5 - Data Requirements).

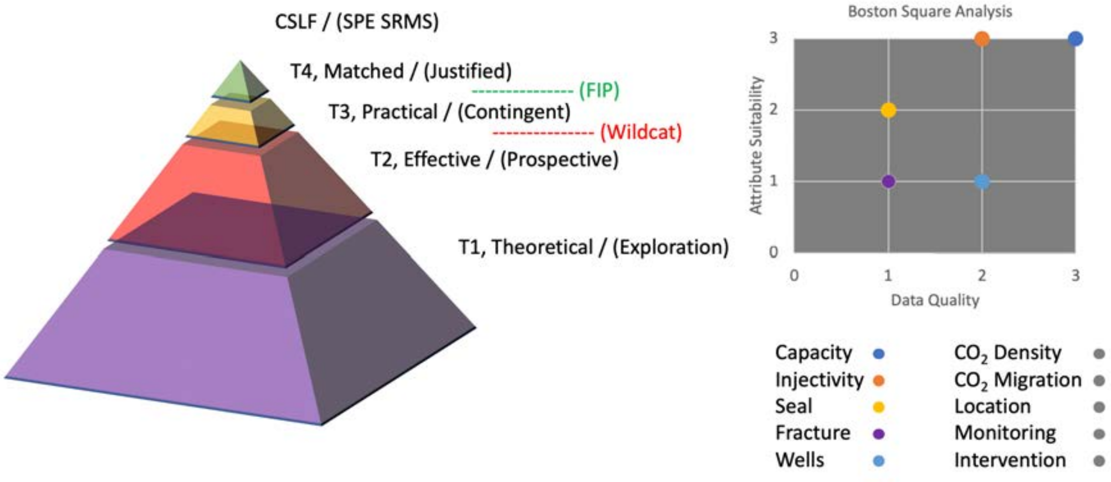


Figure 1-5 Four-tier capacity pyramid with CSLF and SRMS terminology, Boston square analysis

In general, we recommend a tiered approach to quantitative capacity estimation based on the CSLF pyramid, and a Boston square analysis to represent the broader assessment for data quality and suitability of attributes (Figure 1-5). These aspects are addressed in detail below (4 – Summary). We also recommend that storage efficiency factors (SEFs) are included at the lowest tier (theoretical) as generic values for regional formations and their storage units. This will bring the theoretical capacity outcomes into alignment with the second (effective) and third tiers (practical) of tailored SEFs for discovered prospects, that may be considered contingent if drilled and suitable. We anticipate that the top tier (matched) requires reservoir simulation, well planning, and project integration to justify a firm intention to proceed. Our recommendations for tier four are general but essentially test the validity of SEFs and the analytical equations applied in lower tiers.

We do not recommend that the promising EU regions apply SRMS as the principal method, as the bars to maturation are high. For example, the bar to a prospect being ranked as discovered is a wildcat, a targeted and drilled data well to test the prospect; the bar to commercial rankings is a firm intention to proceed within five years (Figure 1-5). In the recent Pale Blue Dot study of global storage (OGCI, 2017), 97 percent of the resources tested by SRMS failed the discovery bar, and 99.99 percent failed the commercial bar. If a promising region has a prospect that is sufficiently mature to be rated as a potential storage site candidate in the shortlisted STRATEGY CCUS selection, it may merit being screened with SRMS to establish a technical and economic evaluation using SPE criteria.

The vast majority of prospects and entire regions will fall in the 97 percent of undiscovered resources. The SRMS outcomes are very much a commercial perspective and do little to identify the potential for increasing the available resource over the coming decades. However, they clearly identify the discrepancy between bottom-up resource estimates and top-down need for deployable storage. This may aid in focusing gap analysis when attempting to mature contingent prospects.

1.2.1 Summary of recommendations

- Norwegian approach and Boston square analysis for qualitative assessment of attributes.
- Sensible to proceed with CSLF resource pyramid maturation for capacity estimate.
- P90-P50-P10 outcomes for capacity estimates at every level of the pyramid.
- Storage efficiency factors at every level of the pyramid. Upper tier based on simulation.
- Generic, specific, and matured SEFs for first three tiers, reflecting data and maturity.
- Detailed reservoir simulation at top tier; model verification of prior SEF outcomes.
- Lower tier analytical equations based on the North American Atlas, Fifth Edition.
- Maturation framed by CSLF nomenclature and equivalent SRMS classification.

2 Reviews

The following reviews cover the Norwegian and UK approaches to regional resource assessments, and the SPE SRMS approach to categorisation and classification of resource outcomes. North American analytical equations for capacity are reviewed in the best practise section.

2.1 Norwegian Storage Atlas

First published in 2011 and revised in 2014, the Norwegian CO_2 Storage Atlas takes a qualitative approach to storage resource assessment based on two decades of CO_2 storage experience (Halland and Riis, 2014). Given the extraordinary data resources in the Norwegian North Sea (seismic coverage, data wells, published research), the qualitative approach is an interesting choice that reflects the emerging nature of resource assessment and challenges of regional coverage.

The Norwegian atlas is data-led but flexible in its indicative outcomes. The outcomes are accurate for prospecting but remain largely theoretical and descriptive, deliberately avoiding the precision of a quantitative and probabilistic approach. The resulting capacity estimates are equivalent to P50 but without a P90-P10 spread. Estimates are informed by models and simulations in some cases, though details and access to the models are limited to brief descriptions showcased in the atlas.

The regional Norwegian North Sea resource as a whole is considered, with promising aquifers and hydrocarbon fields identified on the basis of essential attributes including supercritical reservoir conditions, good capacity, good injectivity, and good sealing potential.

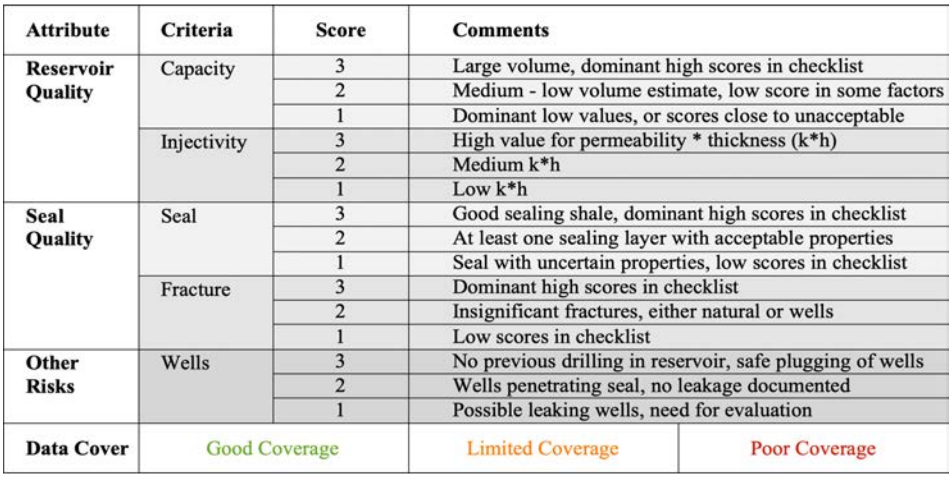
2.1.1 Site screening and characterisation

The regionally identified formations, structures, and hydrocarbon fields are screened for suitability using a 3-2-1 score reflecting good-moderate-poor outcomes on similar criteria to the initial identifying exercise, namely: reservoir capacity, reservoir injectivity; seal quality; presence of fractures; and wells. All criteria are further flagged on data quality using a green-amber-red traffic light indication for good-limited-poor coverage (Table 2-1).

The data is primarily seismic, supported by well data and reports. Other factors considered are monitoring and intervention, potential need for pressure relief in deep saline aquifers (DSA), EOR support for depleted hydrocarbon fields (DHF), and spatial conflicts with future petroleum activity.

The Norwegian atlas identifies DSA and DHF resources, then evaluates and ranks formations, structures and fields. Capacity is evaluated separately for DSA and DHF prospects. DHF estimates are based on reservoir simulations that consider the pressure and production history and development plan for a CO_2 flood. DSA prospects use a capacity formula similar to the North American atlas. Namely a volumetric estimate, converted to mass based on the storage density and efficiency.

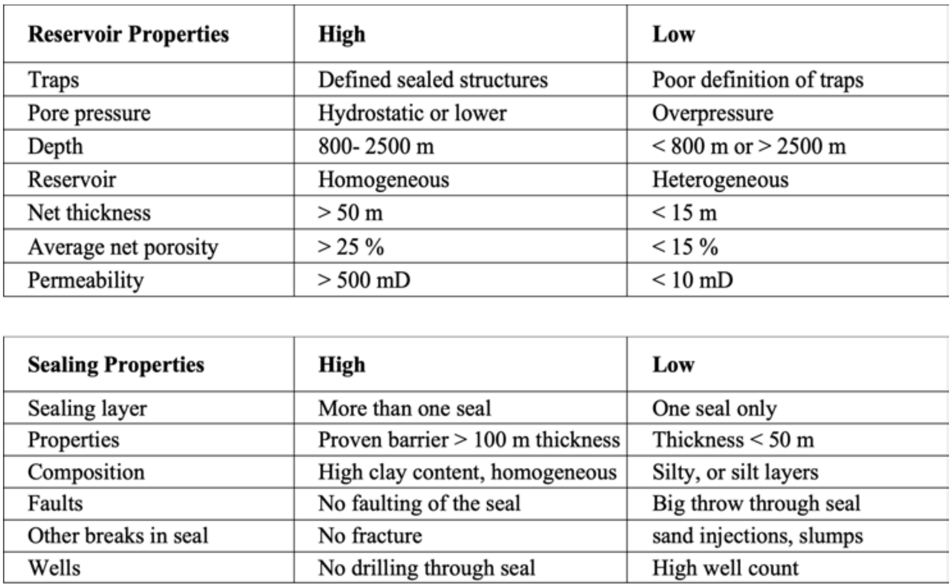
Table 2-1 Storage criteria and data quality attribution in the Norwegian atlas



Attribute	Criteria	Score	Comments
Reservoir Quality	Capacity	3	Large volume, dominant high scores in checklist
		2	Medium - low volume estimate, low score in some factors
		1	Dominant low values, or scores close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Seal Quality	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Seal with uncertain properties, low scores in checklist
	Fracture	3	Dominant high scores in checklist
		2	Insignificant fractures, either natural or wells
		1	Low scores in checklist
Other Risks	Wells	3	No previous drilling in reservoir, safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells, need for evaluation
Data Cover	Good Coverage	Limited Coverage	Poor Coverage

Attributes leading to high and low scores in reservoir quality and seal quality are described below (Table 2-2). Unacceptable attributes, scoring zero, include no seal over parts of the reservoir, active faults, active gas chimneys. A zero score excludes the aquifer or field from the resource assessment.

Table 2-2 Reservoir and seal property characterization in the Norwegian atlas



Reservoir Properties	High	Low
Traps	Defined sealed structures	Poor definition of traps
Pore pressure	Hydrostatic or lower	Overpressure
Depth	800- 2500 m	< 800 m or > 2500 m
Reservoir	Homogeneous	Heterogeneous
Net thickness	> 50 m	< 15 m
Average net porosity	> 25 %	< 15 %
Permeability	> 500 mD	< 10 mD

Sealing Properties	High	Low
Sealing layer	More than one seal	One seal only
Properties	Proven barrier > 100 m thickness	Thickness < 50 m
Composition	High clay content, homogeneous	Silty, or silt layers
Faults	No faulting of the seal	Big throw through seal
Other breaks in seal	No fracture	sand injections, slumps
Wells	No drilling through seal	High well count

2.1.2 Geological storage capacity estimation

The capacity estimate is dependent on standard parameters (bulk volume, porosity, net-to-gross, CO_2 density) and a modifying term, the storage efficiency factor. This value represents the fraction of pore volume occupied by CO_2, and typically ranges from less than one per cent to a few per cent. Generic SEFs for common storage settings are described in Section 3.2 on DSA characterisation.

The Norwegian atlas SEF values are based on their own reservoir simulations. For example, a closed system prospect with 200 mD permeability and 100 m reservoir thickness, and a pressure increase of

5 to 10 MPa, has a storage efficiency of 0.4 to 0.8 per cent. A similar reservoir in an open system with no pressure change has an efficiency factor of around 5 per cent, increasing to as much as 12 per cent as the vertical to horizontal permeability ratio (kv/kh) decreases from 0.1 to 0.001.

DHF capacities are also first approximations based on the available volume after depletion and natural porewater re-flooding prior to CO_2 injection. Injection can be at constant pressure or increasing reservoir pressure. The Norwegian atlas uses a SEF of 5 to 10 per cent for the former, dependent on kv/kh, and a lower value of 1 per cent for the latter. The Norwegian values are based on open aquifers that include a large buffering pore volume, or semi-closed systems that have been hydrodynamically recharged, and as such are much lower than estimates for pressure-depleted gas fields in the UK.

It should be noted that the assumptions behind SEF values in general have been much debated, reflecting differing expectations about open, closed and semi-closed systems, dynamic and static formulations, analytical and simulated outcomes. No approach will satisfy all positions, but SEFs need to be either based on published reservoir simulations or to clearly state the assumptions and analytical derivation so as to provide a pragmatic and defensible method for capacity estimates.

The simple equation used in the Norwegian atlas for DSA capacity estimates is as follows:

$$M_{CO2} = Vb \times Ø \times n/g \times \rho_{CO2} \times SEF \qquad \textbf{[Equation 2.1-1]}$$

Dimensions: Mass as a function of $L^3 \times L^3 / L^3 \times (\%) \times M/L^3 \times (\%)$

M_{CO2}	Mass of CO_2 stored
Vb	Bulk volume of prospect
$Ø$	Reservoir rock porosity
n/g	Net-to-gross ratio of reservoir
ρ_{CO2}	CO_2 density at reservoir conditions
SEF	Storage efficiency factor

Outcomes presented in the atlas are a dashboard of prospect information typically including a map, stratigraphic column, well log and porosity data; a capacity estimate; qualitative scores for the five main attributes; data quality; and maturity evaluation. No economic assessment is undertaken.

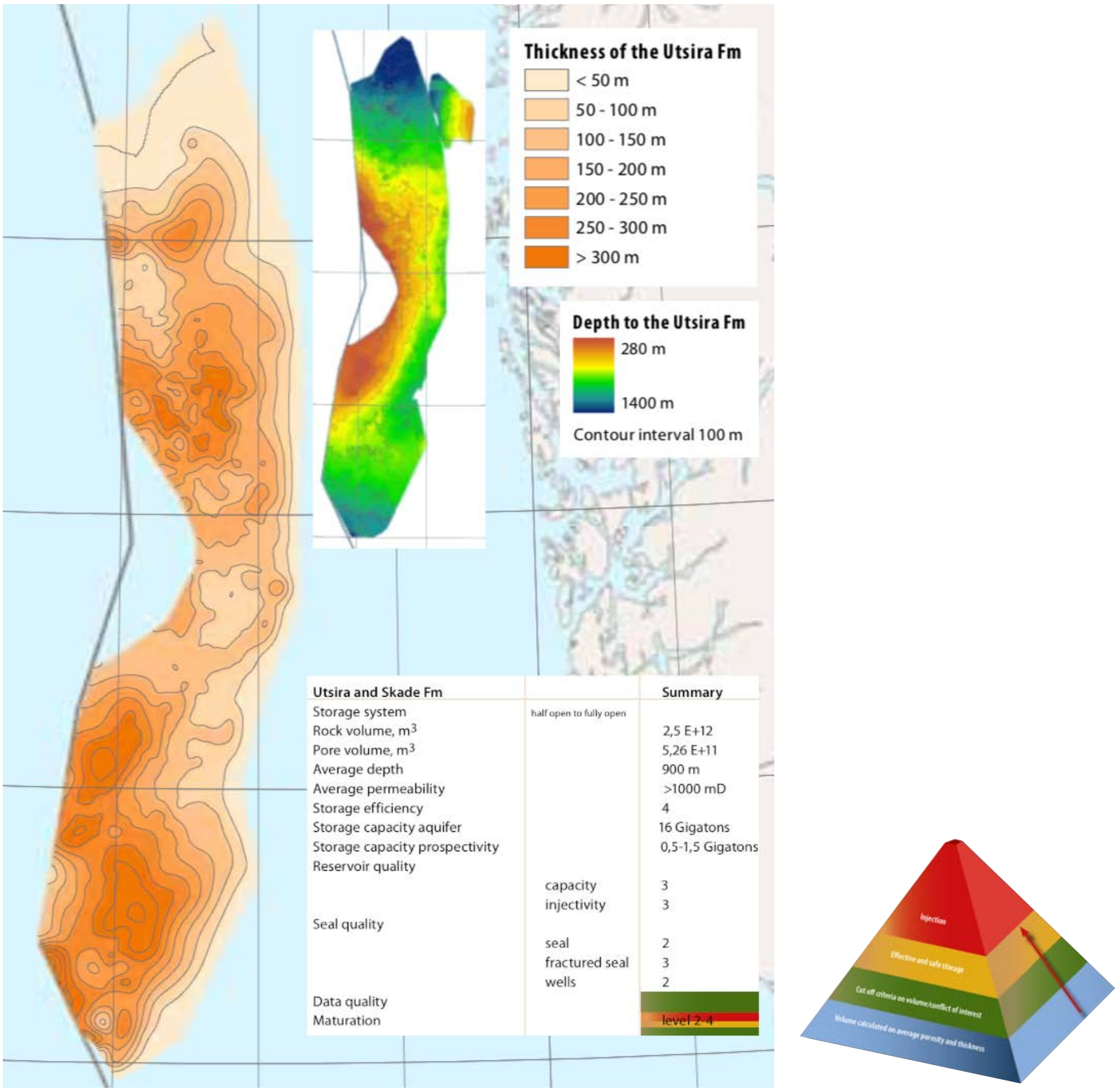
Norwegian maturation is a four-step pyramid (Figure 2-1) from theoretical volume, to exploration, to suitable site selection, and operational injection. The theoretical tier is blue. The upper tiers follow a traffic light scheme: green (exploration) through amber (suitable) to red (in development). The Norwegian atlas steps of maturation from theoretical to development tiers are as follows:

Table 2-3 Steps in the maturation of Norwegian regional storage assessments and CSLF equivalent

Step 4	Development phase	Injection commenced and ongoing evaluation	Tier 4 - Matched
Step 3	Suitability phase	Safe, effective long-term storage potential	Tier 3 – Practical
Step 2	Exploration phase	Cut-off criteria and conflicts of interest	Tier 2 – Effective
Step 1	Theoretical phase	First approximation volume calculation	Tier 1 – Theoretical

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

In summary, the Norwegian atlas is constrained by two important criteria: “no interference with the petroleum activity” and “volumes verifiable”. The atlas identifies a theoretical storage potential of 48 gigatonnes in DSA and 24 gigatonnes in DHF. Most of this qualifies as second tier “exploration” in the technical maturity pyramid, with only 4 gigatonnes of DSA being left at level one. Only 1.1 gigatonnes of storage matures to amber level three, i.e. safe and effective storage “suitability”. This is almost entirely in the Utsira formation and none of the matured storage is considered to be DHF. Only the Sleipner storage site registers as “in development” at 0.02 gigatonnes.



Utsira and Skade Fm		Summary
Storage system	half open to fully open	
Rock volume, m^3		2,5 E+12
Pore volume, m^3		5,26 E+11
Average depth		900 m
Average permeability		>1000 mD
Storage efficiency		4
Storage capacity aquifer		16 Gigatons
Storage capacity prospectivity		0,5-1,5 Gigatons
Reservoir quality		
	capacity	3
	injectivity	3
Seal quality		
	seal	2
	fractured seal	3
	wells	2
Data quality		
Maturation		level 2-4

Figure 2-1 Utsira formation thickness and depth maps, dashboard, and Norwegian atlas pyramid.

The one gigatonne of level three DSA storage does not qualify as discovered or contingent when screened by SRMS, as prospects have not been targeted with exploration and appraisal wells. From an SRMS perspective, a level three outcome would make sense if the prospects had been drilled. DSA storage may be contingent in the Norwegian North Sea, if discovered, given the high carbon price, an offshore carbon tax at around $60 per tonne. DHFs do not feature as matured prospects; CO_2 EOR is economically unviable as it is in competition with methane, an established and cheaper alternative displacement fluid for enhanced oil recovery (Cavanagh & Ringrose, 2014).

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2.2 UK CO_2Stored

The CO_2 Storage Evaluation Database (CO_2Stored) launched as an online resource in 2014, building upon the preceding UKSAP project (ETI, 2011), the first audit of UK offshore storage capacity. CO_2Stored provides information on nearly 600 offshore storage units (Bentham et al., 2014), with a mixed portfolio of 361 DSA and 218 DHF prospects (Figure 2-2). CO_2Stored is intended to provide a comprehensive, auditable and defensible estimate of the offshore resource (Gammer et al., 2011).

The UK atlas provides a capacity estimate across the 80-per centile range (P10-P50-P90) and expected cost estimates for development. The follow-on Strategic Appraisal Project (ETI, 2016) further matured the portfolio, identifying twenty prospects as a selection pool to promote five storage site candidates.

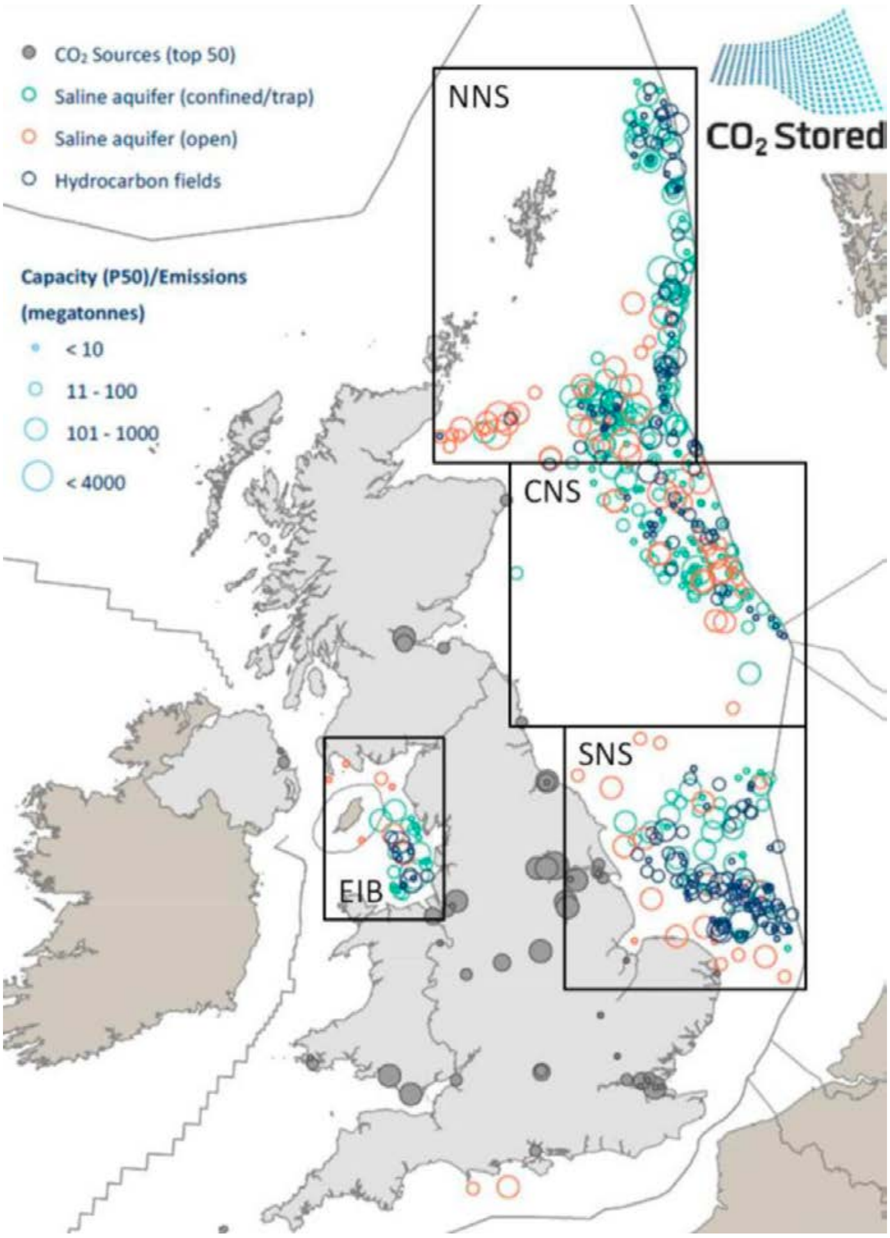

Figure 2-2 The CO_2Stored atlas for the UK offshore portfolio of DSA and DHF prospects SNS, CNS, NNS: Southern, Central and Northern North Sea, EIB, East Irish Basin.

Bentham et al. (2014) and Gammer et al. (2011) describe the methodology of regional offshore formation screening for potential “storage units”. DHF and DSA prospects within the storage units are classified as “daughter units”. DSA units are subdivided as “closed” or “open” based on geological understanding, and pressure data where available. Each unit was assessed for capacity, the primary selection criterion. Capacities of less than 50 million tonnes were excluded.

The data sources for CO_2Stored are predominantly public seismic surveys, well logs, and published geological reports. Identified prospects with sufficient data were further modelled to simulate the likely impact of fluid dynamics on static capacity estimates. For DHF prospects, production and injection data were used to estimate capacity by fluid replacement. All sites were qualitatively assessed for containment with respect to seals, faults, fractures, and legacy well issues. It was noted in 2011 that data gaps prevented the maturation of many sites from a theoretical resource to effective and practical reserves. A concerted effort by UK parties over the period 2011 to 2016 led to a significant maturation of resources to reserves, as published in the ETI strategic appraisal (2016).

2.2.1 Site screening and identification

Initial screening conditions were applied: sufficient porosity, permeability and seal integrity. Identified storage units within suitable regional formations were screened for supercritical storage; units shallower than 800 meters were excluded. Units were also screened for conflicts of interest such as other commercial activities and boundaries that extended beyond the UK border. Physical boundaries such as low permeability barriers and fault compartments were also considered. Isolated pressure cells were recognised as individual storage units. The low cut of 50 million tonnes minimum capacity excluded small prospects. Where large formations lacked data for regional subdivision, such as large faults, dykes, and salt walls, an arbitrary division was based on UK licence block gridding. Extensive formations with known overpressure regimes were subdivided into units of similar overpressure. All storage units were classified as either open or closed with respect to pressure boundary conditions. Structural and stratigraphic closures within DSA storage units and all DHFs are subclassified as daughter units (Table 2-1). All daughter units are prospective targets.

Table 2-1 Hierarchy of classification for identified UK storage potential

3	Daughter units	Structural and stratigraphic traps and depleted hydrocarbon fields
2	Storage units	Reservoirs within formations; supercritical storage; sealing potential
1	Reservoir formations	Regionally extensive formations with suitable reservoir properties

The CO_2Stored database identifies 579 units consisting of 361 DSA prospects and 218 DHF prospects (Bentham et al. 2014). The theoretical resource was estimated at 78 gigatonnes. An initial shortlist of 37 prospects ranked higher than theoretical with a net effective capacity of 8 gigatonnes. Twenty prospects were selected for the follow-on strategic appraisal (Figure 2-3).

2.2.2 Maturation through strategic appraisal

The strategic appraisal (ETI, 2016) applied a “twenty to five” selection to identify the most promising prospects for maturation from the resource pool. The five candidate sites (Viking, Captain X, Forties, Bunter, Hamilton) were selected as representative of storage geologies around the UK, and prepared for rapid maturation from practical to matched capacity by providing much of the essential data required to support a ‘firm intention to proceed’ (Figure 2-4).

Figure 2-3 The UK inventory of 20 prospects and 8 matured sites: three early CCS competition FEED sites, and five later ETI strategic appraisal sites from 2016. Note the Mey prospect, Central North Sea, promoted as the ninth site in 2018.

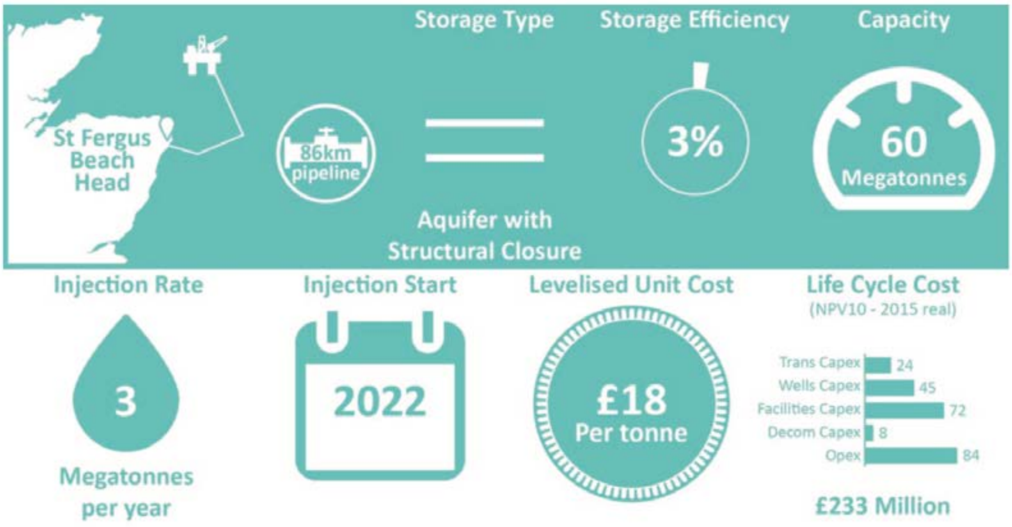

Figure 2-4 The 2016 strategic appraisal summary for Captain X, including TEA analysis.

These sites contributed 895 million tonnes of practical capacity in addition to three existing sites (Goldeneye, Hewett, Endurance) that had matured to a practical/matched capacity of 750 million tonnes during the earlier UK competitions. As of 2016, the portfolio had matured a reserve of eight sites and 1.6 gigatonnes of storage, consisting of 1.1 gigatonnes in four DSA sites and 0.5 gigatonnes in four DHF sites (Figure 2-3). Notably, the four DHF prospects are all abandoned gas fields. The sites are associated with seven follow-on prospects shortlisted for future maturation.

The efficacy of the UK approach was demonstrated by the recent ACT Acorn project (Alcalde et al., 2018). This added a ninth site, East Mey, and 152 Mt of storage to the UK's practical reserve. The site selection focused on 113 CO_2Stored prospects within 50 km of a CO_2 transport network with access to the North Sea from North East Scotland. Six screening criteria (50 million tonne cut-off, reservoir porosity >10 per cent, permeability >100 millidarcy, good seismic coverage, well data availability, development by 2022) shortlisted 16 prospects. These were then prioritised by six ranking criteria (capacity, injectivity, development cost, containment risk, storage efficiency, and upside potential).

The best Acorn candidates underwent more detailed due diligence (3D seismic quality and access, detailed reservoir properties, well log interpretation, engineering and geological containment risks, and indicative costs). The top ranked site, East Mey, has a P50 practical capacity of 152 million tonnes and is close to Captain X, one of five sites identified in 2016. Both are ready for reservoir simulation to support a matched capacity estimate and final investment decision (PBD, 2019).

2.3 SPE Storage Resource Management System

In 2017, the SPE responded to market and regulatory needs for rigorous CO_2 storage reporting by releasing the Storage Resource Management System. An early progenitor was published in Australia (Kaldi and Gibson-Poole, 2008), based on the Petroleum Resource Management System approach to oil and gas reporting. Released in 2000, PRMS has been widely adopted by oil companies and financial markets. PRMS unifies reporting for a mature global hydrocarbon industry. SRMS (SPE, 2017) is intended to place nascent storage resource assessment on a similar footing.

The SRMS is both a classification (economic viability) and categorisation (technical uncertainty) scheme that ranks storage by maturation towards commerciality. In this respect, it is not a resource assessment methodology, but aligns existing assessments by categorising their outcomes and classifying them in a rigorously comparable fashion primarily for economic and investment analysis.

Elements of SRMS are roughly equivalent to the Techno-Economic Resource-Reserve (TERR) pyramid proposed by CSLF in 2007. However, the SRMS approach explicitly filters by commercial maturity, with nine classes covering commercial and sub-commercial discoveries. A brief description follows.

2.3.1 SRMS classification and evaluation

There are four commercial classes in the SRMS ranking of discoveries. At the top level, with a firm intention to proceed established, storage sites are ranked in increasing commerciality as either "justified", "approved" or "on injection"; these three classes are considered to be available capacity. The top-tier class "stored" is for injected CO_2 that has been accounted for and credited (Figure 2-5).

There are five classes in the sub-commercial ranking, the upper four of which are considered to be contingent, i.e. dependent on a change in conditions. Economically viable prospects that do not meet the high commercial bar for "justified capacity", which is a firm intention to proceed but awaiting all necessary approvals, are classed as either "pending" if likely to proceed within 5 years,

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or “on hold” if longer. Discovered prospects that have significant delays or no current plans to proceed are classed as “not viable” and “unclarified” respectively. Those hampered by regulatory or physical constraints are classed as “inaccessible”, the fifth and lowest class of sub-commercial ranking. The lower three sub-commercial classes are considered to be economically not viable.

A further three classes cover undiscovered resources and their maturation from “play” to “lead” to “prospect”. The low sub-commercial bar for a “prospect” to be considered a discovery is a drilled target with positive data indications from the well. A “prospect” requires a target, otherwise it is classed as a “lead”. An exploration interest but insufficient data or evaluation to propose a drilling target is classed as a “play”. The SRMS twelve classes are clearly designed to clarify the status of both individual prospects and regional maturity in a robust fashion. How does this work in practise?

2.3.2 OGCI assessment, an SRMS road test

SRMS was tested by the OGCI who tasked Pale Blue Dot, a management consultancy specialising in CCS, to apply the system to existing storage assessments (OGCI, 2017). Pale Blue Dot (PBD) has experience in several regional resource assessments including CO_2Stored. The PBD study combined outcomes from seven regions: China, North America, India, Brazil, Australia, United Kingdom and Norway. These represent more than fifty six percent of world emissions and are considered to be relatively advanced with respect to resource assessment. The assessment identified a huge total resource in these advanced regions: 12 000 gigatonnes, i.e. sufficient global storage for centuries to come. However, through the lens of SRMS, only 360 gigatonnes or 3 percent of that resource is considered discovered, i.e. meeting the low sub-commercial bar of a drilled prospect; and a tiny fraction, 230 million tonnes, 1/500th of that 3 percent, met the higher commercial bar of a “firm intention to proceed” within five years, of which 60 million tonnes is already stored. A further 580 million tonnes ranked as sub-commercial, either “on hold” or “pending”. The discovered resource, at 360 gigatonnes, dwarfs the commercial and economically viable reserve, 750 million tonnes.

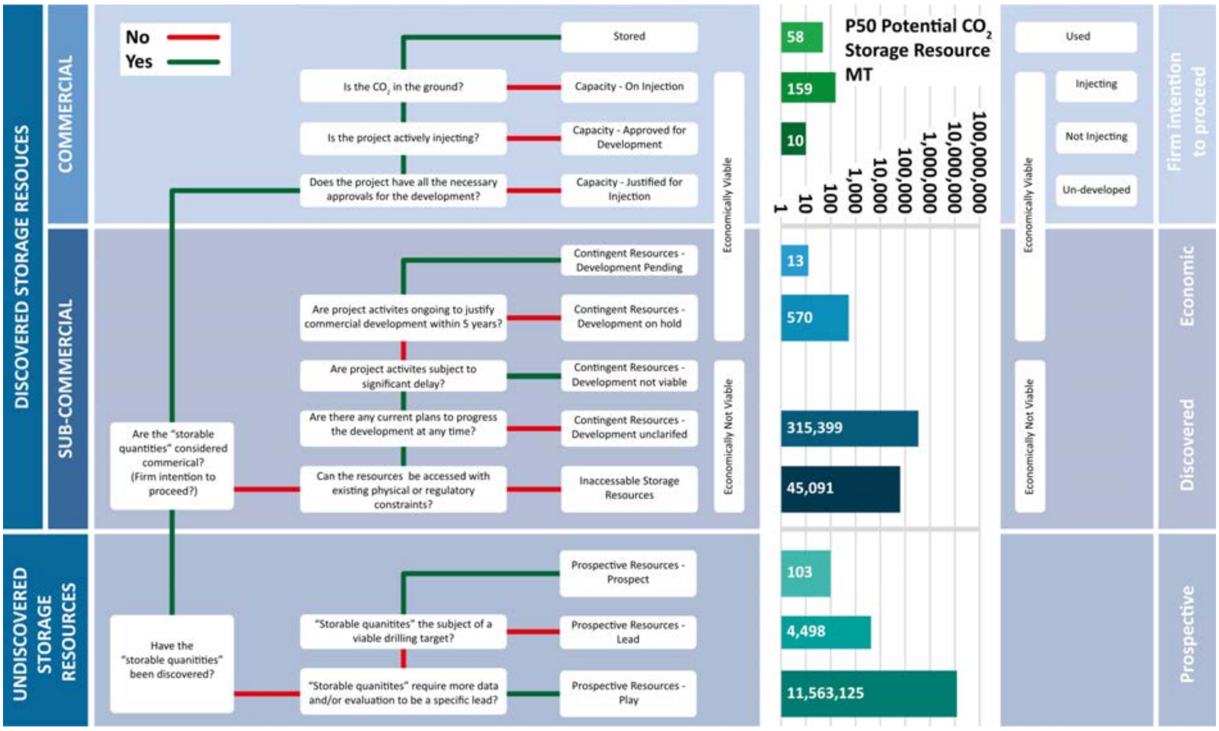

Figure 2-5 SPE-SRMS classification workflow for the OGCI/PBD regional resource assessment (OGCI, 2017)

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From an SRMS perspective, it is clear that globally there is very little commercial storage available. The 3 percent that is the discovered 361 gigatonnes needs to be rapidly matured to achieve the gigatonnes of storage needed in years to come and hundreds of gigatonnes required globally in the decades to come. Notably, the SRMS discovered resource inventory of 3 percent is almost entirely represented by existing DHFs with an expectation of EOR and abandoned gas field storage.

This outcome reflects (a) the low bar drilling requirement for contingent classification, a given for DHF prospects which are always drilled, and (b) the heavily subsidised nature of deep saline aquifer storage to date, which on current carbon price support mechanisms such as EU ETS makes DSA storage a non-commercial proposition in most regions.

The SRMS outcome contrasts with the mixed portfolios of the North American, Norwegian and UK atlases. These present a more balanced portfolio of deep saline aquifer and depleted hydrocarbon field options. For example, the Norwegian atlas identified just over 1 gigatonne of deep saline aquifer storage as suitable, i.e. mapped and evaluated as ready by their technical criteria. None of the Norwegian depleted hydrocarbon field storage potential reached this level. Likewise, the UK strategic appraisal follow-on to CO_2Stored estimated around 1.6 gigatonnes of ready storage in eight mature prospects, half DHF and half DSA, and a further 7 gigatonnes in twenty identified and maturing prospects. The UK balance between saline aquifers, 1 gigatonne, and depleted hydrocarbon fields, 0.6 gigatonnes, reflects the broader resource expectation for deep saline aquifers, with 361 DSA prospects identified relative to 213 depleted hydrocarbon fields (ETI, 2016).

The Norwegian and UK assessment criteria differ from SRMS which requires a more exacting low bar to a sub-commercial contingent classification, the targeted and drilled prospect well. This relegates most saline aquifers to the SRMS suite of undiscovered categories, namely “prospect”, “lead” and “play”. SRMS downgrades saline aquifers by requiring expensive appraisal drilling, while upgrading hydrocarbon fields based on a legacy of field appraisal necessary to oil and gas exploration and production (Seldon et al., 2018).

It is noticeable then that the SPE SRMS tool appears to foreground the known estate of oil and gas field management, rather than the potential of deep saline aquifers, despite the demonstrated readiness of aquifers in the UK, Norway, and North America, and the necessary role of DSA storage in the decades to come. While this DHF bias may be unintended, it raises questions about the fair representation of saline aquifer potential in SRMS. Is the fastest route to sufficient storage on the European continent likely to be met by focusing on depleted hydrocarbon fields?

The commerciality of deep saline aquifers will presumably change as carbon pricing mechanisms respond to increasing regional ambitions such as Net Zero, and as DHF and DSA technical constraints such as well remediation and pressure management are better understood. However, the SRMS tendency to highlight DHF and lowlight DSA may not be strategic for Europe on a decadal timescale.

3 Best Practise

Our best-practise recommendation for resource assessment is two-fold: a qualitative suitability appraisal that supports the capacity estimate. Suitability covers all technical aspects of storage from reservoir capacity and quality to seals, faults and wells. The appraisal consists of a Boston square score for both attribute suitability (y-axis) and data quality (x-axis). Each attribute is plotted to provide an overview of the site and data gaps that may need addressing (Figure 1-5, p.12).

The capacity estimate is a quantitative resource pyramid approach consisting of four tiers that reflect the increasing maturity of data and understanding about potential storage capacity from regional first approximations to targeted storage site candidates. The requirements for each tier reflect this maturation. The described tiers are compatible with existing schemes (CSLF TERR, SPE SRMS), allowing outcomes to be transferred to equivalent classifications if required (Figure 1-5).

3.1.1 Capacity tiers and suitability criteria

- Tier 1 - Regional assessment; the lowest tier, equivalent to Exploration (Theoretical), with generic global or regional SEFs. Formation and storage unit estimates. First approximation. Low data burden and global SEF values if data is poor and boundary conditions poorly constrained.

- Tier 2 - Discovery assessment; equivalent to Prospective (Effective), with tailored SEFs. Daughter unit estimates, second approximation. Moderate data burden and lithology-specific storage efficiency. Distinction between DSA, DHF, and UCB. Boundary conditions established.

- Tier 3 - Prospect assessment; equivalent to Contingent and pending/on hold (Practical), detailed data, prospective candidates. Third approximation with a more taxing data burden, including sub-attributes of the main factors used to estimate capacity and lithology-specific local storage efficiency factors. Each candidate prospect requires either existing or targeted data acquisition sufficient to build a simple geomodel for simulation and proposed injection well location.

- Tier 4 - Site assessment; equivalent to Justified/Approved/On Injection (Matched), site project. The final approximation prior to operation. This has the highest data burden and requires a detailed geomodel for reservoir simulation. Simulations test the accuracy of storage efficiency factors and provide well placement/scheduling scenarios to maximise capacity.

Suitability is scored by expert judgement. High values indicate good attributes such as high capacity, high reservoir porosity and permeability, an effective seal, an absence of problematic faulting, fracturing or well issues; low scores flag a prospect for review. Data quality indicates strengths and gaps in the evidence base (Table 3-1).

3.1.2 General recommendations

The following recommendations are suggested for the resource assessment output. To set the context, a regional context map with identified formations and exploration areas, highlighted discoveries, prospects and candidate sites, and the overall maturity distribution of the region displayed using a Boston square summary. A regional stratigraphic column highlighting suitable formations and storage units, significant seals, barriers and relevant features of the overburden.

For identified discoveries and prospects, each named prospect should be supported by a data sheet including a local map and stratigraphic column, with key parameter values and outcomes from Tier 2, (and Tier 3 where matured), supported by a prospect-specific Boston square analysis, and brief comments on the nature of data gaps and recommendations.

Matured prospects and candidate storage site data sheets at Tier 3 and 4 would also be supported by key parameter values and capacity outcomes, as well as reference models, simulation summary, well planning summary, and brief comments on required technical work to complete the maturation to bookable storage. A matured resource assessment might include referral links to project resources, data owners, and current status of a site including brief outlining of the expected capture partnership and transport provision. Capacity outcomes would mature through the following stages:

- Regional overview, theoretical capacity: P90-P50-P10 (All)
- Discovery overview, effective capacity: P90-P50-P10 (Many)
- Prospect overview, practical capacity: P90-P50-P10 (Few)
- Site overview, matched capacity: P90-P50-P10 (One)

Table 3-1 Suitability of attribute criteria and associated data quality for storage prospects

Definitions Table

Attribute	Criteria	Score	Comments
Storage Suitability	Capacity	3	Large volume, dominant high scores in checklist
		2	Medium - low volume, low score in some factors
		1	Dominant low values, or scores close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Seal Suitability	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Seal with uncertain properties, low scores in checklist
	Fracture	3	Dominant high scores in checklist
		2	Insignificant fractures, either natural or wells
		1	Low scores in checklist
	Wells	3	No previous drilling in reservoir, safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells, need for evaluation
Other Suitability Attributes	CO_2 Density	3 / 2 / 1	Supercrtical, high density gas, or low density gas
	CO_2 Migration	3 / 2 / 1	Low migration risk, moderate risk
	Location	3 / 2 / 1	Location suitability relative to other sinks and sources
	Monitoring	3 / 2 / 1	Suitability of site for performance monitoring
	Intervention	3 / 2 / 1	Suitability of site for remedial interventions
	Upside	3 / 2 / 1	Sutiability of site for growth as a storage hub
Data Quality	All Criteria	3	High quality data with good coverage and density
		2	Adequate data with some gaps in coverage
		1	Low quality and/or sparse data with known gaps

3.2 Deep Saline Aquifers

Deep saline aquifers represent the largest and most widely distributed resource for CCUS. For example, the North American atlas indicates that the DSA resource is somewhere between two thousand and twenty thousand gigatonnes across twenty-six basins, with about half that located in the gulf coast region, south-eastern USA. This is about 10x to 100x the estimated North American DHF resource at approximately two hundred gigatonnes, which is primarily EOR and clustered onshore in the Permian Basin, West Texas and New Mexico. (USDOE, 2014).

By comparison, the theoretical UK resource balance is much closer at approximately fifty gigatonnes DSA to thirty gigatonnes DHF (PBD, 2016). Norway is similar to the UK at approximately forty gigatonnes DSA to twenty gigatonnes DHF (Halland and Riis, 2014). This reflects conditions in the

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North Sea. The larger North American DSA theoretical estimate reflects a continental setting with many regional sedimentary basins and formations that have no DHF potential.

The Carbon Storage Atlas, Fifth Edition (USDOE, 2014) estimates the onshore and offshore DSA storage resource for North America using a simple analytical formula (Equation 3.2-1). The same approach is used by both the UK and Norwegian atlases to establish their theoretical resource:

$$G_{CO2} = A \times h_g \times f_{tot} \times \rho_{res} \times E_{saline} \qquad \textbf{[Equation 3.2-1]}$$

Dimensions: Mass, function of $L^2 \times L \times L^3/L^3 \times M/L^3 \times [\%]$

G_{CO2}	CO_2 storage potential of a prospect field as a mass (Mt, 1E+9 kg: M)
A	Total area of prospect reservoir (km^2, 1E+6 m^2: L^2)
h_n	Gross reservoir thickness (m: L)
f_{tot}	Average total porosity (%: L^3/L^3)
ρ_{res}	CO_2 density at reservoir storage conditions (kg/m3: M/L^3)
E_{saline}	Storage efficiency factor, fraction of volume occupied (% - dimensionless)

The first three factors of the equation ($A \times h_n \times f_{tot}$) provide an estimate of the potential pore volume available for storage. The *in-situ* CO_2 density converts this to a mass, and the storage efficiency downgrades this to reflect a partial compression or partial displacement of porewater from the pore space at a regional scale.

3.2.1 Prospect maturation and storage efficiency

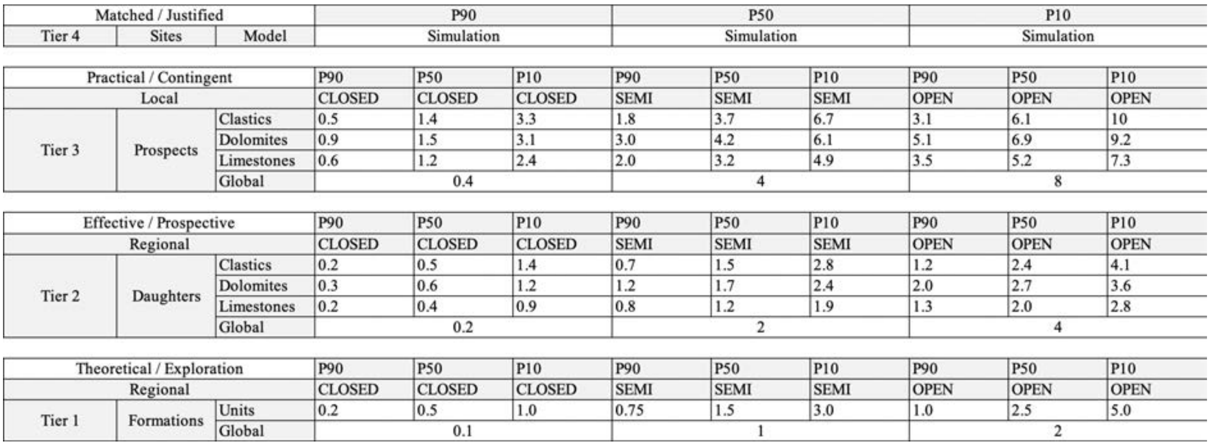
Beyond bottom-tier regional estimates, local studies that exclude the surrounding unaccessed formation tend to have higher efficiency factors. More detail and rigour at the prospect scale further refine this value to a typically higher fraction (Bachu, 2010). Storage efficiency values also reflect general geologic characteristics and boundary conditions. For example, carbonates and open systems have a higher efficiency than clastic reservoirs and closed systems.

The lowest storage efficiency values, applied globally as a conservative first approximation, reflect a lack of data and characterisation (Table 3-2). At the higher tiers of assessment, detailed reservoir characterisation and reservoir simulation ultimately supersede analytical approximations of efficiency. Both simulations and analytical models are then challenged and refined by observations from operational sites.

Gigatonne storage potentials are theoretically easy to establish in large regional basins with suitable properties. However, the maturation path to practical and banked storage capacity requires a detailed gap analysis of available data, and targeted exploration campaigns to firm up contingent prospects and justify investment.

In North America, site identification from a regional assessment is expected to take a year, selection and detailed characterisation at least three years, and permitting of selected candidates at least two more years (USDOE, 2014). It is reasonable to infer that the maturation from theoretical pool to justified reserve takes approximately a decade.

Table 3-2 Storage efficiency factors as percentages for deep saline aquifers at different levels of maturity



Matched / Justified			P90			P50			P10		
Tier 4	Sites	Model	Simulation			Simulation			Simulation		

Practical / Contingent			P90	P50	P10	P90	P50	P10	P90	P50	P10
Local			CLOSED	CLOSED	CLOSED	SEMI	SEMI	SEMI	OPEN	OPEN	OPEN
Tier 3	Prospects	Clastics	0.5	1.4	3.3	1.8	3.7	6.7	3.1	6.1	10
		Dolomites	0.9	1.5	3.1	3.0	4.2	6.1	5.1	6.9	9.2
		Limestones	0.6	1.2	2.4	2.0	3.2	4.9	3.5	5.2	7.3
		Global	0.4			4			8		

Effective / Prospective			P90	P50	P10	P90	P50	P10	P90	P50	P10
Regional			CLOSED	CLOSED	CLOSED	SEMI	SEMI	SEMI	OPEN	OPEN	OPEN
Tier 2	Daughters	Clastics	0.2	0.5	1.4	0.7	1.5	2.8	1.2	2.4	4.1
		Dolomites	0.3	0.6	1.2	1.2	1.7	2.4	2.0	2.7	3.6
		Limestones	0.2	0.4	0.9	0.8	1.2	1.9	1.3	2.0	2.8
		Global	0.2			2			4		

Theoretical / Exploration			P90	P50	P10	P90	P50	P10	P90	P50	P10
Regional			CLOSED	CLOSED	CLOSED	SEMI	SEMI	SEMI	OPEN	OPEN	OPEN
Tier 1	Formations	Units	0.2	0.5	1.0	0.75	1.5	3.0	1.0	2.5	5.0
		Global	0.1			1			2		

- Open system values, 1-10 percent, are from Goodman et al. (2011), a detailed analysis of the USDOE approach. These are the values in the North American atlas (USDOE, 2015).

- Closed system values, 0.1-3.3 percent, are derived as a fraction of the open system values (1/6th for P90, 2/9th for P50 and 1/3rd for P10), summarised in the review by Bachu (2015).

- Semi-closed system values, 0.75-6.7 percent, are mid-point approximations based on open and closed values. Semi-closed systems have non-trivial boundary conditions and, with maturation, require detailed numerical simulation on a case-by-case basis (Zhou et al., 2008).

- Global values represent conservative estimates for formations, storage and daughter units. This applies to lower tiers where a unit is mapped but where the boundary conditions are poorly understood either through a lack of data or conflicting conceptual models. More data and understanding will allow for the assignation of sediment type and open, closed or semi-closed boundary conditions at higher tiers in the resource assessment pyramid.

Selection, characterisation and permitting of sites typically runs in parallel. Recent UK experience documents a maturation of nine sites and 1.6 gigatonnes, two per cent of the theoretical resource, to a pre-permitting practical stage over a decade, with around thirty to forty associated prospects, approximately 7 gigatonnes, having reached selection during the process (PBD, 2016, Alcalde et al., 2018). It seems reasonable to conclude that the first wave of maturation from theoretical resource to a small number of operational sites takes around a decade. The second wave matures tens of sites within another decade. The European storage requirement for 2030 needs to double this rate.

While a small number of full-scale projects globally have established the efficacy of individual storage site operations from injection to trapping, monitoring and verification, the need for regional gigatonne storage in Europe within two decades has raised questions about basin-scale pressure changes related to brine displacement and the physical boundary conditions of storage sites.

These boundary conditions are reflected in the broad range of storage efficiency factors from open to closed systems (Table 3-2). Both end-member positions of (a) bountiful storage, and (b) pressure-limited shortfalls requiring brine extraction, reflect hypothetical arguments that are reliant on modelling assumptions. A pragmatic test of storage realities lies in the hundred million tonne per year storage rates required by 2030, and their performance to 2040, as the third wave of hundreds of storage sites follows on.

3.2.2 Notes on deep saline aquifer assessment and storage efficiency

Bachu (2010) described the essential elements of regional DSA resource assessment and went on to review storage efficiency in detail (Bachu, 2015). The following notes summarise his findings:

- Maturing site suitability and capacity estimates are essential to provide assurance that storage is capable of the injection rates and total capacity required over the lifetime of a CCS chain.

- The regulatory requirement and expectations are that a site will not leak, or that leakage will not exceed an acceptable level with respect to emissions and health and safety.

- The aim of a regional DSA assessment is to identify high quality prospects and rank potential sites for progression to further investment and eventually a successful operational status.

- Regional opportunities vary in quality with respect to data and prospect characteristics. Ranking poorer quality sites in emerging regions is essential to focus gap analysis and maturation.

- Experience has established that screening is a two-stage process, consisting of an early regional assessment within sedimentary basins, followed by local and site-specific assessments. This can be further described by four tiers: a regional theoretical approximation; data gathering and prospect identification for an effective estimate; gap analysis and detailed prospect characterisation for a practical estimate; site-specific simulation for a matched estimate.

- Capacity estimates change with increasing maturity, initially depending on the fluid and rock attributes described by both aquifer and aquitard characteristics, then operational design including well plan and injection strategy, and ultimately regulatory constraints such as maximum injection pressure, storage boundary limits, and assessment timing of plume mobility.

- As a consequence, DSA storage efficiencies range from 0.1 to 10 per cent with no universal value applicable. The chosen value for a given prospect is dependent on both spatial and temporal constraints, as well as rock attributes, and the maturing understanding of conditions.

- Beyond the spatial shift from global, to regional, to local approximations, and the attribution of rock type, storage efficiencies reflect the boundary pressure conditions of the system. These can be open, closed, or in between, primarily reflecting the permeability of vertical and lateral seals.

- For truly closed systems, storage efficiency is dependent on the compressibility of the system. As the pressure limit is reached, a spatial limit is imposed by an inability to inject more fluid.

- Semi-closed systems allow for brine displacement into the surrounding aquitards, dissipating pressure and effectively increasing the storage capacity of the system. The modelled limit for pressure dissipation through low permeability rocks appears to be of the order of a microdarcy (Zhou et al., 2008; Cavanagh and Wildgust, 2011).

- For a large open system, capacity is a function of the maximum injection rate and duration of injection, dependent on the number of wells and limited by imposed or natural boundary limits.

- Regional theoretical estimates need to apply conservatively low efficiency values that reflect the low maturation and data uncertainties inherent in first approximations.

- Beyond theoretical and effective estimates, well counts and modelled injection periods need to reflect real project limitations to ascertain practical storage capacities.

- Data maturity and detailed prospect characterisation lead to numerical simulations and dynamic capacity estimates at the local reservoir scale. These models challenge and test the assumptions that inform storage efficiencies for the preceding static analytical approximations.

- Where simulations and operational outcomes indicate low storage efficiencies, secondary active management techniques such as brine production may increase the capacity of a site.

3.3 Depleted Hydrocarbon Fields

Depleted hydrocarbon fields potentially represent a major resource for CCUS. Regionally significant storage potential, abundant legacy data, and a relatively low cost of entry usually result in high ranking positions for DHF prospects. Oil fields also provide a utilisation opportunity prior to abandonment by injecting CO_2 to enhance oil recovery (EOR).

Early estimates of the expected storage ratio for North American EOR indicated approximately one million tonnes of CO_2 utilised for every three million barrels of oil recovered (NETL, 2011). The 1:3 tonne per barrel ratio reflects historical EOR data which maximised oil extraction for purchased CO_2. Utilisation that maximises storage may be closer to 1:1 (Bachu, 2010).

Gas fields differ as they are typically post-production storage-only prospects and may be notable for high storage efficiencies due to pressure depletion during production. Expected storage efficiencies of around seventy per cent are not uncommon in closed systems, as evident in values for UK gas fields matured as site candidates (PBD, 2016).

High gas field storage efficiencies are supported by recent research on depleted gas fields which estimated a high-low storage efficiency range of 56 to 84 per cent (Hannis et al., 2017). Depleted gas fields with open boundary conditions and aquifer support behave more like DSA prospects with much lower efficiency factors of around 5 to 10 per cent (Halland et al., 2014).

The Carbon Storage Atlas, Fifth Edition (USDOE, 2014) maps potential DHF storage areas and provides a simple analytical formula for estimating the EOR resource. While individual EOR operations are typically associated with site-specific models and reservoir simulations, the need for regional appraisals across many varied sites, and potential restrictions on data access, require an analytical approach.

The following equation has been the North American storage formula for DHF since the first Atlas in 2007 and is analysed in some detail by Peck et al. (2017). The fifth edition of the Atlas (USDOE, 2014) also provides a brief comment on utilisation, i.e. injection into oil fields under production, summarised and expanded on below. The Atlas equation for DHF storage in oil fields, as interpreted by Peck et al. (2017) is as follows:

Depleted oil fields

$\boldsymbol{G_{CO2} = A \times h_n \times f_e \times (1\text{-}S_{wi}) \times B_o \times \rho_{sta} \times E_{oil}}$ **[Equation 3.3-1]**

Dimensions: Mass, function of $L^2 \times L \times L^3/L^3 \times (1\text{- } L^3/L^3) \times L^3/L^3 \times M/L^3 \times L^3/L^3$

G_{CO2}	CO_2 storage potential of the field as a mass (Mt, 1E+9 kg: M)
A	Total area of reservoir within the oil or gas field (km^2, 1E+6 m^2: L^2)
h_n	Net reservoir thickness for the hydrocarbon field (m: L)
f_e	Average effective porosity of the field (%: L^3/L^3)
$1\text{-}S_{wi}$	Oil fraction at discovery, the pore volume not initially saturated by water (%: L^3/L^3)

The first four factors ($A \times h_n \times f_e \times 1\text{-}S_{wi}$) are an estimate of the discovered hydrocarbon volume i.e. OOIP, original oil in place at in-situ conditions, expressed as millions of barrels (1 bbl: 0.158987 m^3). The remaining terms ($E_{oil} \times B_o \times \rho_{sta}$) can be handled separately.

$\boldsymbol{E_{oil} = RF \times UF}$

E_{oil}	Storage efficiency factor (%OOIP x MScf/stb: $L^3/L^3 \times L^3/L^3$),
RF	Recovery factor, oil from CO_2 flood as a percentage of OOIP (%OOIP: L^3/L^3)
UF	Utilisation factor, amount of CO_2 used to recover a unit of oil (Mscf/stb: L^3/L^3)

Note that RF, the recoverable volume from CO_2 flooding is a percentage of OOIP. Recovered oil is measured in stock tank barrels (stb) and needs to be converted to barrels at reservoir conditions (bbl) which is typically larger by up to a factor of one-to-three. $OOIP \times RF \times B_o$. Note that the total volume of used CO_2 is at standard conditions: $(OOIP \times RF \times B_o) \times UF$ Multiply by standard CO_2 density to calculate the mass: $(OOIP \times RF \times B_o) \times UF \times \rho_{sta}$

B_o	Oil formation volume factor, formation volume relative to stock tank (bbl/stb: L^3/L^3)
ρ_{sta}	CO_2 density, 1.842 kg/m^3 at standard conditions of 70°F and 101 kPa (kg/m^3: M/L^3)

For mass balance, the history of produced and injected water also needs to be considered. An EOR field's decline curve provides an alternative estimate of a field's remaining oil recovery volume. This replaces the first five terms of equation 3-1:

$\boldsymbol{G_{CO2} = STB \times B_o \times \rho_{sta} \times E_{oil}}$ **[Equation 3.3-2]**

Dimensions: Mass as a function of $L^3 \times L^3/L^3 \times M/L^3 \times (\%)$

STB	Volume of recoverable oil at standard conditions (barrels, 1/6.29 m^3: L^3)
B_o	Reservoir volume factor (%: L^3/L^3)
ρ_{sta}	CO_2 density at standard conditions, 1.842 kg/m^3 (kg/m3: M/L^3)
E_{oil}	Storage efficiency factor ($L^3/L^3 \times L^3/L^3$)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

Depleted and abandoned gas fields

$$G_{CO2} = OGIP \times DF \times Bg \times \rho_{res} \times E_{gas} \qquad \textbf{[Equation 3.3-3]}$$

Dimensions: Mass as a function of L^3 x (%) x$L^{3/}L^3$ x M/L^3 x (%)

G_{CO2}	CO_2 storage potential of a prospect gas field as a mass (Mt, 1E+9 kg: M)
$OGIP$	Volume of recoverable gas at standard conditions (Scf, 0.0283 m^3: L^3)
DF	Depletion factor at abandonment (% - dimensionless)
Bg	Reservoir volume factor for gas, Res.ft^3/Scf (%: $L^{3/}L^3$)
ρ_{res}	CO_2 storage density at reservoir conditions (kg/m^3: M/L^3)
E_{gas}	Storage efficiency factor (% - dimensionless)

Note for depleted gas fields, the storage efficiency, E_{gas}, is simply a percentage of the available volume. The storage volume is the original gas in place, OGIP, adjusted for reservoir conditions, Bg, and gas depletion at abandonment, DF, then multiplied by the efficiency factor and CO_2 density at storage conditions, i.e. the end of CO_2 injection.

Note that pressure-depleted gas fields have a large pressure transience from the onset of storage operations to the end of injection. Initial injection pressures may be well below the critical point. The final density and storage mass for a field will depend on pressure.

Typically, oil and gas field operations have access to simulations using detailed reservoir models which are data-intensive and provide a more accurate estimate of volumes and the expected storage efficiency. These can replace analytical approaches where available and may be used to test the accuracy of analytical approximations. For example, Peck et al. (2017) considered thirty-one sites for incremental oil recovery from CO_2 flooding and 16 sites for CO_2 utilisation using a combination of reservoir simulations and analytical approximations.

The Peck study indicated E_{oil} values ranging from 0.007 to 0.089 with a P50 variance of 0.019 to 0.057 (absolute values not percentages). Larger CO_2 injection volumes increased efficiency. The authors caution against applying these values arbitrarily to unrelated EOR prospects. However, the Peck study demonstrated that for an assumed 50 mmbbl OOIP, an E_{oil} value of 0.055 would return a storage estimate of 2.75 million tonnes for between 5.5 and 6 million standard barrels of oil recovered; a ratio of 1:2 tonnes/stb. This detailed work supports the earlier general approximations of storage efficiency by Bachu (2010) and NETL (2011), and also indicates that a 1:1 ratio is atypical of normal EOR operations, requiring a maximised storage strategy.

The analytical approach is likely to be a reasonable and necessary first approximation if access to simulations is limited or time-consuming. In general, it is difficult to screen regions for suitable fields by comparing reservoir simulations (Bachu, 2016). Hence, their restriction to the upper tier of resource assessments. Lower tier screening requires comparative information typically available in reserves databases and public records. Bachu (2010) and Núñez-López and Moskal (2019) provide more detail on these entry-level, lower-tier screening criteria.

3.3.1 Bachu CO_2 EOR screening and selection review

Bachu (2010) distinguishes between injection after field abandonment (storage) and during production (utilisation and storage). The latter offsets the cost of CCS with enhanced oil recovery (EOR). Utilisation and storage require consideration of the following criteria specific to CO_2 EOR:

- Utilisation typically refers to oil fields, where low primary recovery factors, often less than 30 per cent, and a much higher value of oil relative to gas, justify the cost of CO_2 injection. Enhanced gas recovery with CO_2 is uncommon. Gas has a recovery factor that typically exceeds 80 per cent. Pressure depletion is reflected in high storage efficiencies of around 70 per cent.

- At the low reservoir pressures associated with depleted gas fields, CO_2 rapidly expands and comingles with produced gas resulting in inefficient separation and recycling processes. Gas fields are typically post-production storage prospects only.

- North American experience has identified guideline criteria for screening oil fields as potential CO_2 EOR prospects. The primary criterion is sufficient size, a proxy for economics. The threshold is estimated to be around one million barrels of recoverable oil in place, equivalent to approximately 0.3-1 Mt of CO_2 utilised. Candidate prospects are typically much larger than this.

- Typical EOR operations have a 1:3 tonnes of CO_2 per barrel utilisation ratio, estimated by NETL (2011). Typically, fields have at least one third of recoverable oil remaining prior to injection.

- A field depth of greater than 800 meters is a proxy for pressure and temperature relating to supercritical storage. A reservoir temperature of 30°C to 120°C and a reservoir pressure greater than the minimum miscibility pressure and less than the original formation pressure is recommended. The fracture pressure of the reservoir must not be exceeded.

- CO_2 EOR may be miscible or immiscible, depending on reservoir pressure conditions. Miscible floods are far more common and require pressure maintenance. Gravity drainage (top-down non-miscible displacement) has the highest recovery and storage efficiency.

- Oil gravities of 27 to 45 API and a viscosity of less than 6 cP/mPas are suitable for miscible floods. A porosity and permeability minimum of 3% and 5 mD is suggested for screening.

- Strong aquifer support may be a factor. Where a field is in communication with a flowing aquifer, water will invade the field during and after production, raising the in-situ pressure and refilling drained pore space. Local field hydrodynamics and overpressure need to be considered.

- This also applies to fields artificially flooded during secondary and tertiary production. A water flood and/or strong aquifer support will decrease the available storage volume.

- The time of availability is important. This relates to the timing of depletion and abandonment. EOR is typically a secondary or tertiary phase of production, and as such has a specific time window for application which must coincide with CO_2 availability. Storage-only preparations ideally need to combine with abandonment and decommissioning to significantly reduce costs.

3.3.2 Núñez-López and Moskal review of CO_2 EOR potential

Núñez-López and Moskal (2019) have recently reviewed the status of EOR as a CCUS technology, concluding that it remains a low-cost option for supporting the global transition to decarbonisation. The paper covers a wide range of factors including the technical aspects summarised below:

- Approximately 85 billion barrels, 1/5th of the USA's remaining oil resource base, is technically recoverable using CO_2 EOR. The Permian Basin, Texas and New Mexico, accounts for three quarters of global CO_2 EOR production (77 percent of 450,000 BOPD). The CO_2 is almost entirely sourced from natural reservoirs on the Colorado Plateau, and as such is not CCUS.

- Enhanced oil recovery with captured CO_2 may be defined as utilisation and storage, i.e. commercial activity leading to the geological storage of a greenhouse gas. Weyburn, West Hastings, and West Ranch EOR are cited as North American examples of CCUS.

- CO_2 EOR is historically by far the largest CCUS technology by volume. Captured CO_2 is injected, circulated, separated and recycled back into an EOR field. Life cycle analysis by the authors suggest that 90-95% of the injected CO_2 is eventually trapped. The product and associated emissions make for a wide divergence in life cycle analyses and outcomes of CCUS and EOR.

- Captured CO_2 is a commodity. EOR production is optimised to reduce CO_2 use. Incentives may maximise storage, shifting the utilisation ratio from 3:1 towards 1:1 tonnes per barrel. The IEA (2015) has identified three CCUS models for EOR: (1) Conventional EOR+, requiring monitoring and verification of storage; (2) Advanced EOR+, as for (1) but with increased CO_2 use; (3) Maximum Storage EOR+, as for (2) but maximising the long term storage of CO_2.

- Storage integrity is supported by the geological history of oil trapping. Storage mechanisms include structural trapping beneath a seal, residual trapping as an immobile phase, and dissolution trapping. The industrial history of oil fields suggest that legacy well issues need to be assessed. Water wells may be prone to corrosion. High well densities may impact trap integrity.

- CO_2 as a separate phase has a strong viscosity contrast with oil, resulting in high CO_2 mobility and fingering towards production wells. This adversely impacts oil recovery. Injection is frequently alternated between water and CO_2 (WAG) to reduce fingering and stabilise the displacement front. Over 90% of CO_2 EOR operations use WAG.

- Miscibility of CO_2 in the oil phase causes the mixture to expand and lowers viscosity, promoting oil mobility and enhancing recovery. This favours injection above the minimum miscibility pressure (MMP). MMP is a common screening criterion for CO_2 EOR. This may also be screened for by using related criteria: lighter hydrocarbons, higher pressures, and lower temperatures.

In summary, the storage capacity resource for an abandoned hydrocarbon field is a relatively simple matter of establishing the available volume, expected reservoir conditions and storage efficiency. Utilisation is more complicated, as the setting is dynamic and integrated with the economics of field production. Practical and matched resource estimates typically require simulation. Analytical equations are useful for regional screening and effective capacity estimation.

CCUS life cycle analyses of CO_2 EOR vary widely on approach and outcomes. For example, Stewart and Haszeldine (2015) estimate that North Sea CO_2 EOR would be slightly more carbon intensive than conventional Saudi oil, whereas Núñez-López and Moskal (2019) estimate that more than 90% of utilised CO_2 is eventually stored. These very different metrics suggest the contradictory possibility of high storage volumes that contribute to poor mitigation outcomes.

The framing of utilisation in STRATEGY CCUS is technology "to support the development of low-carbon energy and industry." This excludes uses "with no clear mitigation impact" (TEG, 2018). Utilisation needs to have a negative greenhouse gas contribution or clearly enable other low-carbon actions. Questions that may help to screen for and rank utilisation options are listed in Table 3-1:

Table 3-1 CCUS mitigation framing and storage assessment for utilisation technologies

1	Quantity in	How much captured CO_2 is used per unit of production?
2	Quantity out	How much CO_2 is emitted per unit of production?
3	Scale	How many units will be produced per year?
4	Storage rate	How much of the used CO_2 will be stored per year?
5	Impact	Does the storage rate exceed the emission rate?
6	Permanence	How long will the CO_2 be stored for?
7	Accounting	How will storage be monitored and verified?
8	Other	How else does the technology mitigate emissions?

With respect to database inputs, essential utilisation criteria including the size, location and availability of prospects are also required for abandoned DHF storage screening. Additional utilisation criteria are listed below (Table 3-2) and included in the data list for EOR assessment:

Table 3-2 EOR utilisation criteria and storage framing for utilisation prospect

1	Recoverable Oil Volume (stb)	5	Miscible Flood and WAG Suitability
2	Reservoir Volume Factor (bbl/stb)	6	Alternative Injection Strategy (Gravity?)
3	Water Injection-Production Balance (m^3)	7	IEA Model Class for CCUS (1,2,3)
4	CO_2 Required to Produce Oil Volume (Mt)	8	Strength of Aquifer Support (High/Low)

Both Bachu (2010) and Núñez-López and Moskal (2019) concur that on a technical level utilisation screening can be limited to EOR and shortlisted by two principle criteria: the size of the field and the suitability for a miscible flood. (Gravity drainage is a notable exception).

Size is a proxy for the economics. Bachu (2010) suggests a minimum of one million barrels of recoverable oil. This requires less than 1 million tonnes of CO_2; high ranking candidates will have much larger recoverable reserves. Miscibility is a proxy for effective recovery relating to physical parameters including reservoir temperature and pressure, oil viscosity and gravity.

These two criteria can rapidly screen a region for prospective oil field utilisation. Another essential criterion is availability timing. Is the field plan for enhanced oil recovery compatible with CO_2 supply? If the field is abandoned prior to CO_2 availability, it becomes a storage-only prospect.

The shortlist of suitable EOR fields are then screened for porosity and permeability, storage volume depletion either by natural aquifer support or water flooding, and suitability for monitoring and verification. These prospects can be matured further with detailed data analysis, reservoir simulation, and well planning. In many cases, fields will have legacy data and models that may help.

A notable absence from the criteria above is location. Depleted hydrocarbon fields, whether storage prospects or EOR candidates, require a significant upstream investment in capture and transport infrastructure. Strategically locating DHF prospects potentially opens up storage areas and access to other fields and deep saline aquifers.

Associated storage may provide a buffer to manage CO_2 oversupply during EOR operations and a destination for CO_2 beyond the expected lifetime of DHF storage. As such, screening should be mindful of the role early CCUS projects play in establishing transport networks beyond the lifetime of low-cost quick-entry DHF opportunities.

3.4 Unmineable Coal Beds

Unmineable coal beds are coal resources that that are either too shallow to be mined, too deep to be stripped, or too low value to be extracted, but are accessible for CO_2 injection by depth, geology, and geographic location. This includes stranded assets devalued in the shifting global energy market.

UCB assets can be dewatered and depressurised for methane extraction. This can be enhanced by injecting CO_2 to displace the large amount of natural gas trapped within the coal beds. CO_2 adsorbs to free sites on coal surfaces and displace weakly bonded molecules, typically methane and water.

Enhanced coal bed methane (ECBM) can potentially be optimised for storage to provide a net greenhouse gas reduction. The mitigation impact of utilisation needs to account for thief methane emissions (34x CO_2e over 100 years) and the product's post-extraction emissions life cycle.

The Carbon Storage Atlas, Fifth Edition (USDOE, 2014) highlights potential areas in North America where UCB resources exist, providing a preliminary theoretical resource estimate of eighty gigatonnes (P50).

Globally, pilot studies have highlighted technical challenges in realising this potential (Li and Fang, 2014), with early pilots indicating cleat swelling, permeability reduction, and injectivity being potential issues for large-scale storage.

The Carbon Storage Atlas (USDOE, 2014) equation is as follows:

$$\boldsymbol{G_{CO2} = A \times h_g \times C_s \times \rho_s \times E_{coal}} \qquad \textbf{[Equation 3.4-1]}$$

Dimensions: Mass as a function of $L^2 \times L \times ML^3/ML^3 \times M/L^3 \times \%$

G_{CO2}	CO_2 storage potential of prospect as a mass (Mt, 1E+9 kg: M)
A	Total area of prospect (km^2, 1E+6 m^2: L^2)
h_g	Gross seam thickness (m: L)
C_s	adsorbed CO_2 as a function of coal density, adsorption, moisture and ash content (kg/m^3 x [0.0283 x scf/tonne] x (1-(%+%)), 1 scf = 2.83E-5 m^3: ML^3/ML^3)
ρ_s	CO_2 density at standard conditions (kg/m^3: M/L^3)
E_{coal}	Storage efficiency, fraction of the pore volume occupied (%: L^3/L^3)

This has essentially been the same equation since the first Atlas in 2007. However, the North American Atlases are short on detail with respect to C_s. Bachu (2010) unpacks the equation in a review of CO_2 storage screening and selection criteria. The reviewed equation is coloured below to highlight operations within the formulation:

$$\boldsymbol{M_{CO2} = (V_L P/(P+P_L)) \times (1 - (f_a + f_m)) \times [A \times h \times \rho_{coal}] \times [E \times \rho_{CO2S}]} \qquad \textbf{[Equation 3.4-2]}$$

Dimensions: Mass, a function of $L^3/M \times (1- (L^3/L^3 + L^3/L^3)) \times [L^2 \times L \times M/L^3] \times [\% \times M/L^3]$

The volume of CO_2 adsorbed per unit mass of coal is termed the 'gas saturation' or 'gas content' and is calculated in scf/tonne using a Langmuir isotherm ($V_L P/(P+P_L)$). See appendix.

This assumes a dry and ash-free coal, and so is modified by the ash and moisture content ($1 - (f_a + f_m)$), i.e. the fraction of coal not available for adsorption.

The gas saturation value (scf/tonne) is multiplied by the mass of coal in the prospect to give the potential volume of CO_2 adsorbed at 100% saturation. The mass is a product of the area, effective thickness, and coal density ($A \times h \times \rho_{coal}$). See notes on thickness and density below.

The CO_2 volume is converted to mass at standard conditions for density (ρ_{CO2S}) and modified by the expected storage efficiency factor (E), correcting for partial exposure and saturation. This is the estimated storage resource, M_{CO2}. The standard density for CO_2 is 1.873 kg/m^3.

Note that the effective coal thickness is the sum of all suitable seams. Frailey et al. (2006) assume a suitable seam thickness for UCB in the Illinois Basin to be 0.5-1.1 m. The coal density is the "bank" density for *in situ* coal, not the more typical bulk density of mined and broken coal. The bank density for bituminous coal is around 1400 kg/m^3, whereas the bulk density is much lower at around 800 kg/m^3. See appendix on typical coal attributes.

The storage efficiency range was initially estimated for the North American atlas as 28 to 40 per cent (15%-85% confidence) with a P50 value of 33 per cent by the USDOE (2007). This is equivalent to a 27-33-41 per cent range (P90-P50-P10) assuming a straight line fit. These values are revised in the Fifth Edition (USDOE, 2014) to 21-37-48 per cent (P90-P50-P10).

3.4.1 Review comments on storage potential

American coal basins are widely considered to be potential early movers, with large pilots (10-100 kilotonnes) in New Mexico, West Virginia, and Alberta. Elsewhere, UCB has seen a number of small pilot demonstrations (0.1-1 kilotonnes) in Poland, China and Japan (Li and Fang, 2014). The EU RECOPOL pilot in the Upper Silesian Basin, Poland (760 tonnes circa 2005) is highly relevant to STRATEGY CCUS, providing basic analogue information on a number of variables. Bachu (2010) makes a number of review comments on UCB in general, summarised below.

- Uneconomic coal beds (UCB) and enhanced coal bed methane (ECBM) are closely related. The terms are almost synonymous. ECBM dates back to the 1980s and refers to the secondary recovery of methane from coal beds that were considered uneconomic for stripping or mining. Nitrogen and CO_2 were considered to be useful displacement gases. Whichever was cheapest.

- Since the 1990s greenhouse gas mitigation has raised the possibility of methane production from coal as a by-product of CO_2 storage. As methane is a potent greenhouse gas, the product needs to be accounted for if the mitigation impact of injected CO_2 is to be quantified.

- Unmineable coal is loosely defined as a thin-seamed bituminous coal bed at moderate depths. Global changes in market conditions may greatly increase this reserve with stranded assets.

- UCB is considered to be a relatively immature technology with respect to CO_2 storage. Regional gigatonne theoretical capacities are typically lower than a region's DSA and DHF estimates.

- UCB is highly relevant in regions with vast unmineable coal bed assets close to the large point source emissions of coal-fired power stations in southern Poland, North America, and China.

- Kaldi & Gibson-Poole (2008) suggest that UCB prospects need to be assessed by coal type and quality, as this effects adsorption efficiency, impacting on storage potential. A correction for ash, moisture, and coal density covers this consideration.

- Generally desirable criteria for UCB CCUS are a moderate depth profile at around 400 to 800 m, a sub-bituminous-bituminous rank, and an uneconomic setting for extraction.

- The nominal ceiling of 400 m is based on protected groundwater as a limiting factor in North America. Regional limitations will vary by jurisdiction and land usage.

- Carbon dioxide is typically injected as a gas phase at a depth range of 400 to 800 m. This lowers compression costs at the wellhead. The supercritical point is 31 °C and 7.4 MPa, equivalent to approximately 800 m assuming normal geothermal and hydrostatic gradients.

- Prospective coal beds may require draining by water production to free up the cleat porosity for gas injection. This reduces the subsurface pressure to a value that lies on a Langmuir isotherm. This pressure determines the expected gas content in scf/tonne for the operation.

- The injectivity limit is estimated to be a permeability of 1 millidarcy. Coal swelling is expected to reduce permeability by one order of magnitude; this may be an issue for liminal assets.

- Typically cleat permeability declines with depth, setting a floor of around 1 km for injectivity.

- UCB requires a dense infrastructure of injection wells and distribution pipelines, as well as methane harvesting wells. Monitoring and verification need to quantify thief emissions.

3.4.2 A heuristic-based approach for utilisation

An alternative approach for assessing CO_2 utilisation is based on local heuristics for produced methane in Poland. In this scenario the recoverable methane content of a prospect is calculated as:

$$\boldsymbol{V = A \mathrm{\ x\ } h_g \mathrm{\ x\ } r \mathrm{\ x\ } (1-(f_a + f_m)) \mathrm{\ x\ M}} \qquad \textbf{[Equation 3.4-3]}$$

Dimensions: Volume as a function of L^2 x L x M/L^3 x (%) x L^3/M

V	*Extractable methane volume* (m^3: L^3)
A	*Total area of prospective coal seam* (km^2, $1E+6\ m^2$: L^2)
h_g	*Gross seam thickness* (m: L)
r	*Coal density* (kg/m^3: M/L^3)
$f_a + f_m$	*Ash and moisture content of coal (%)*
M	*Extractable methane content as a volume per unit mass of coal* (m^3/kg: L^3/M)

This formulation calculates the recoverable methane volume, V, from the mass of coal for the prospect (A x h x r), adjusted for coal moisture and ash content ($1-(f_a + f_m)$). This is multiplied by the methane recovery volume per unit mass of coal, M. The volume is sensitive to temperature and pressure: adsorption decreases with temperature and increases with pressure (Bachu, 2007). The tendency is decreasing adsorption with depth, i.e. temperature dominates. Seams may be undersaturated, in which case the volume extracted will be less than V. The methane volume is the primary consideration in utilisation. The volume of CO_2 used to displace the methane is secondary and calculated as follows:

$$\boldsymbol{Q = V \mathrm{\ x\ } r \mathrm{\ x\ B\ x\ RF\ x\ CF}} \qquad \textbf{[Equation 3-6]}$$

Dimensions: Mass as a function of L^3 x M/L^3 x (N) x (%) x (%)

Q	*Mass of utilised* CO_2 (kg: M)
V	*Extractable methane volume* (m^3: L^3)

r Density of CO_2 at standard conditions (kg/m^3: M/L^3)

B CH_4: CO_2 replacement volume factor, typically 2 (N, dimensionless: L^3/L^3)

RF Recovery factor (%)

CF Completion factor (%)

The CO_2 mass, Q, is estimated as a product of heuristics: firstly, CO_2 adsorption is assumed to be double the recovered methane volume, (V x B), based on experience (Tomasz Urych, pers.comm. 2019). While the displacement is not fully understood, wettability, permeability reduction due to cleat swelling, and PVT conditions are all expected to play a role. Secondly, the mass of CO_2 adsorped (V x r x B) is adjusted for recovery and completion efficiency (RF x CF). The recovery factor adjusts from the ideal to expected efficiency of methane recovery based on experience. The completion factor adjusts from gross to net coal thickness for seams accessed for gas exchange by the well.

Note that Langmuir isotherms are not required in this formulation for methane recovery and CO_2 utilisation. The approach relies on knowledge of local coal characteristics, with recent ECBM trials in the Pawlowice-Mizerow area of the Upper Silesian Coal Basin indicating values of 50 percent and 40 percent for recovery and completion factors, and a ratio of 2:1 for the CO_2-methane exchange (Jureczka et al., 2012). Typical completion factors range from 0.4 to 0.9 (van Bergen and Pagnier, 2001). Recovery factors range from 0.2 to 0.8 depending on the technology (Stevens and Pekot, 1999).

CO_2 injection may be further enhanced by fracking techniques. This may be required in low permeability coal seams that respond to CO_2 injection with cleat swelling (van Bergen, 2009). Preliminary frack tests have recently been undertaken in the Gilowice area as part of the “Geo-Metan” project. A six-month test period in 2017 recovered approximately 800 thousand cubic meters of methane (Tomasz Urych, pers.comm. 2019). The surface disposal of produced brine for both fracked and unfracked ECBM is also expected to be an economic and environmental factor.

4 Summary and Conclusions

European Union goals and targets and Net Zero ambitions imply a matched and deployable gigatonne storage resource in Europe by 2030 and annual injection rates that increase from one hundred million tonnes in 2030 to over half a gigatonne by 2050. At present, European storage is largely theoretical. Portfolios of assessed storage in Europe including offshore UK and Norway have not matured sufficiently to meet this demand and need to be rapidly appraised to deliver sufficient storage in the coming decades. Less than 4 percent, or 10 gigatonnes, of the total theoretical European resource of 266 gigatonnes has matured beyond an initial exploration indication. SRMS criteria downgrade this to less than 0.5 percent.

Based on the IEA Energy Technology Perspectives forecast (IEA, 2017) for 2DS and B2DS CCUS contributions to mitigation, Europe requires injection rates of 52 million tonnes per year from 2025 to 96 million tonnes by 2030 to meet established targets. Injection rates and storage requirements increase steeply beyond 2030 to 2050, requiring several gigatonnes of capacity to be rapidly matured from theoretical to matched in the 2030s. If the EU decarbonisation path is successful and the IEA forecast holds, Europe will have stored approximately 8 gigatonnes of CO_2 by 2050 and reach a sustained injection rate of 0.57 gigatonnes per year in 2050. Beyond 2050, Europe will need to book tens of gigatonnes of storage before the end of the century (Figure 4-1). If the EU long-term strategy for Net Zero aligns on scenarios with a limited CCUS contribution, Europe will still require a matured storage reserve measured in hundreds of millions of tonnes, deployable prior to 2050.

To rapidly increase the reserve, we recommend a combined approach based on the reviews, that follows the Norwegian atlas method of qualitative expert judgement for essential elements beyond capacity (Halland et al., 2014). This lends itself to a Boston square analysis (Figure 1-5, p 12) for data suitability and data quality across a range of aspects from seal quality and reservoir injectivity to fault and well considerations.

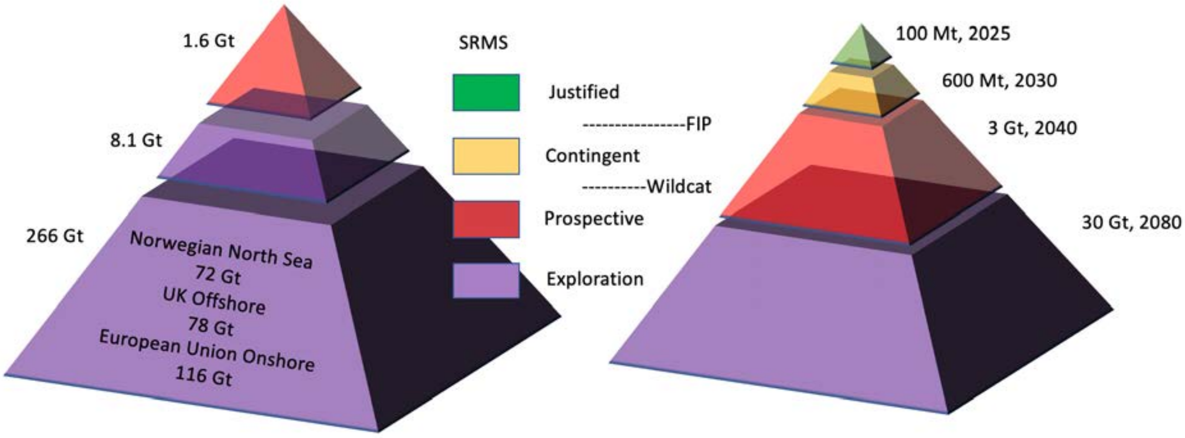


Figure 4-1: European storage inventory (left) and forecasted requirements (right). Only 0.5% of the estimated resource has matured beyond the SRMS exploration level. Europe needs 600 Mt of justified capacity by 2025 to meet deployed demand by 2030. Gigatonnes must be rapidly matured in the 2030s.

We propose a four-tiered pyramid based on the pioneering North American CSLF approach (Bachu et al., 2007) for the capacity estimate with levels mapped to CSLF and SRMS terminology (SPE, 2017). The capacity quantification is based on the common P90-P50-P10 estimation (CO_2Stored) which matures from generic formation level estimates to more detailed daughter prospects and candidate site estimates. The recommendations allow for outcomes to be transferred to an SRMS analysis.

These recommendations are in keeping with contemporary regional assessments and allow for the outcomes to be incorporated into an SRMS analysis. We recommend that storage efficiency factors (SEFs) are included at the lowest theoretical/exploration tier as generic values for formations and related storage units. This will bring the theoretical capacity outcomes into alignment with the second tier of discoveries or daughter units (effective/prospective) and third tier (practical/ contingent) of tailored SEFs for prospects and candidate sites. We anticipate that the top tier (matched/justified) requires detailed reservoir simulation, well planning, and project integration, so our recommendations for tier four are general, but essentially test the validity of the SEFs and analytical equations applied in the tiers below.

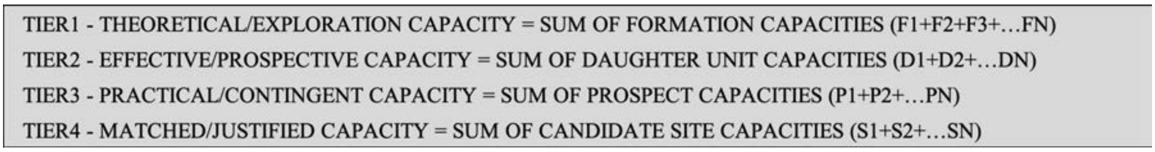
We do not recommend that regions apply SRMS as the principal method, as the bars to maturation are high. If a region has a prospect that is sufficiently mature to be rated as a potential shortlist candidate in the STRATEGY CCUS selection, it may merit being screened with SRMS. Our expectation is that the vast majority of regional prospects will not have matured to this level.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

5 Formulae and Data Requirements

This section documents the formula and data required to furnish assessments at each tier of the resource pyramid and related attribute assessments. Data necessary to frame the storage potential of utilisation technologies are also listed. The lists are archived as Excel spreadsheets – see appendix.

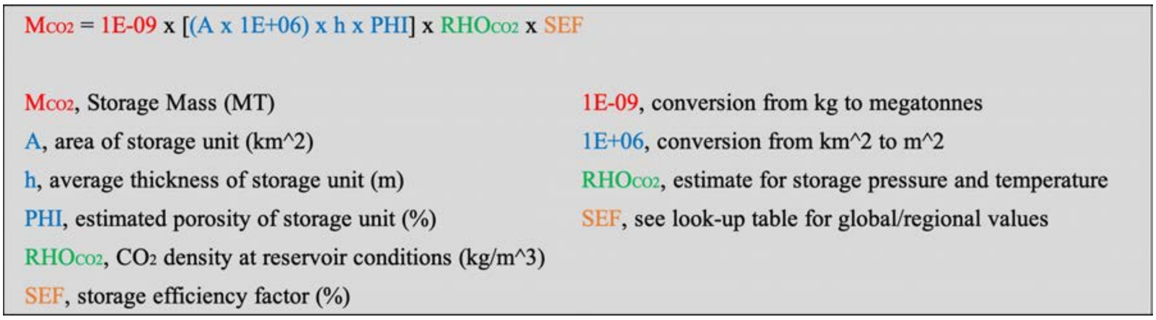
Tier Hierarchy for Capacity Assessment



TIER1 - THEORETICAL/EXPLORATION CAPACITY = SUM OF FORMATION CAPACITIES (F1+F2+F3+…FN)
TIER2 - EFFECTIVE/PROSPECTIVE CAPACITY = SUM OF DAUGHTER UNIT CAPACITIES (D1+D2+…DN)
TIER3 - PRACTICAL/CONTINGENT CAPACITY = SUM OF PROSPECT CAPACITIES (P1+P2+…PN)
TIER4 - MATCHED/JUSTIFIED CAPACITY = SUM OF CANDIDATE SITE CAPACITIES (S1+S2+…SN)

TIER1 - FORMATION CAPACITY = SUM OF STORAGE UNIT CAPACITIES (U1+U2+…UN)

Tier 1 Storage Unit Capacity Assessment* (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



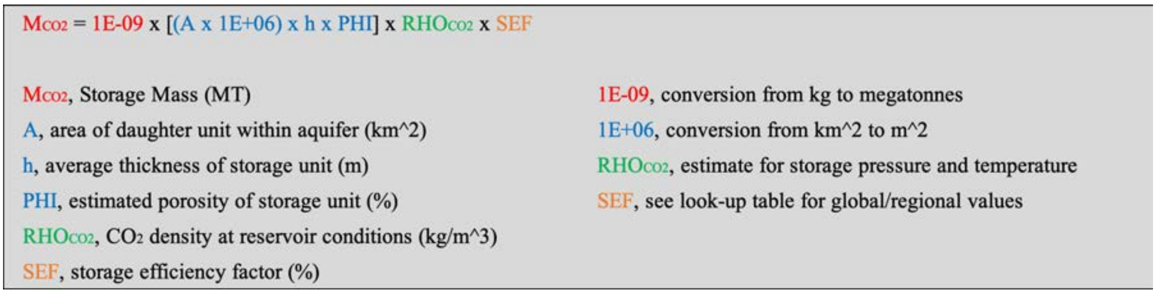
$M_{CO_2} = 1E\text{-}09 \times [(A \times 1E{+}06) \times h \times PHI] \times RHO_{CO_2} \times SEF$

M_{CO_2}, Storage Mass (MT)
A, area of storage unit (km^2)
h, average thickness of storage unit (m)
PHI, estimated porosity of storage unit (%)
RHO_{CO_2}, CO_2 density at reservoir conditions (kg/m^3)
SEF, storage efficiency factor (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
RHO_{CO_2}, estimate for storage pressure and temperature
SEF, see look-up table for global/regional values

* Note: if storage unit contains UCB or DHF, unit estimate is for Tier 2 (UCB + DHF) + Tier 1 DSA

Tier 2 Daughter Unit Capacity Assessment, DSA (Carbon Storage Atlas, 5th Edition - USDOE, 2014)

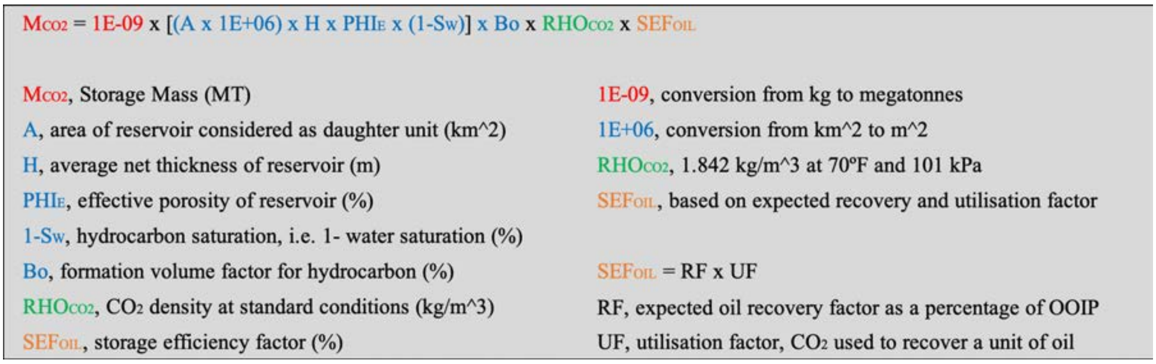


$M_{CO_2} = 1E\text{-}09 \times [(A \times 1E{+}06) \times h \times PHI] \times RHO_{CO_2} \times SEF$

M_{CO_2}, Storage Mass (MT)
A, area of daughter unit within aquifer (km^2)
h, average thickness of storage unit (m)
PHI, estimated porosity of storage unit (%)
RHO_{CO_2}, CO_2 density at reservoir conditions (kg/m^3)
SEF, storage efficiency factor (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
RHO_{CO_2}, estimate for storage pressure and temperature
SEF, see look-up table for global/regional values

Tier 2 Daughter Unit Capacity Assessment, DHF EOR (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



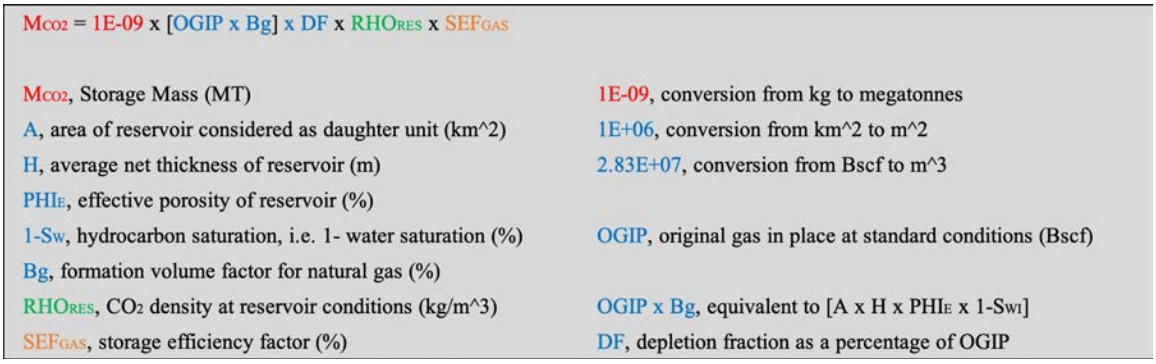
$M_{CO_2} = 1E\text{-}09 \times [(A \times 1E{+}06) \times H \times PHI_E \times (1\text{-}S_w)] \times B_o \times RHO_{CO_2} \times SEF_{OIL}$

M_{CO_2}, Storage Mass (MT)
A, area of reservoir considered as daughter unit (km^2)
H, average net thickness of reservoir (m)
PHI_E, effective porosity of reservoir (%)
$1\text{-}S_w$, hydrocarbon saturation, i.e. 1- water saturation (%)
B_o, formation volume factor for hydrocarbon (%)
RHO_{CO_2}, CO_2 density at standard conditions (kg/m^3)
SEF_{OIL}, storage efficiency factor (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
RHO_{CO_2}, 1.842 kg/m^3 at 70ºF and 101 kPa
SEF_{OIL}, based on expected recovery and utilisation factor

$SEF_{OIL} = RF \times UF$
RF, expected oil recovery factor as a percentage of OOIP
UF, utilisation factor, CO_2 used to recover a unit of oil

Tier 2 Daughter Unit Capacity Assessment, DHF Gas (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



$M_{CO_2} = 1E\text{-}09 \times [OGIP \times Bg] \times DF \times RHO_{RES} \times SEF_{GAS}$

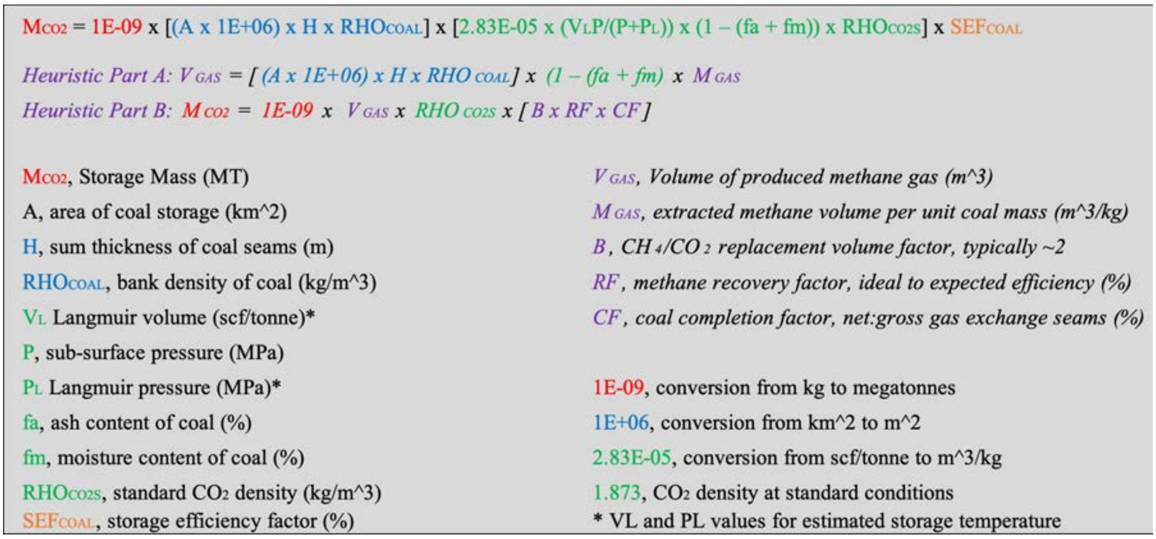
M_{CO_2}, Storage Mass (MT)
A, area of reservoir considered as daughter unit (km^2)
H, average net thickness of reservoir (m)
PHI_E, effective porosity of reservoir (%)
1-Sw, hydrocarbon saturation, i.e. 1- water saturation (%)
Bg, formation volume factor for natural gas (%)
RHO_{RES}, CO_2 density at reservoir conditions (kg/m^3)
SEF_{GAS}, storage efficiency factor (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
2.83E+07, conversion from Bscf to m^3

OGIP, original gas in place at standard conditions (Bscf)

OGIP x Bg, equivalent to [A x H x PHI_E x $1\text{-}S_{WI}$]
DF, depletion fraction as a percentage of OGIP

Tier 2 Daughter Unit Capacity Assessment, UCB (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



$M_{CO_2} = 1E\text{-}09 \times [(A \times 1E{+}06) \times H \times RHO_{COAL}] \times [2.83E\text{-}05 \times (V_L P/(P+P_L)) \times (1 - (fa + fm)) \times RHO_{CO_2S}] \times SEF_{COAL}$

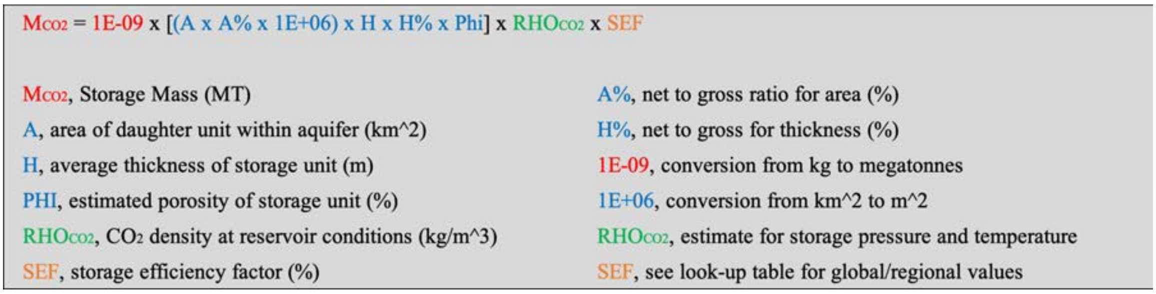
Heuristic Part A: $V_{GAS} = [(A \times 1E{+}06) \times H \times RHO_{COAL}] \times (1 - (fa + fm)) \times M_{GAS}$
Heuristic Part B: $M_{CO_2} = 1E\text{-}09 \times V_{GAS} \times RHO_{CO_2S} \times [B \times RF \times CF]$

M_{CO_2}, Storage Mass (MT)
A, area of coal storage (km^2)
H, sum thickness of coal seams (m)
RHO_{COAL}, bank density of coal (kg/m^3)
V_L Langmuir volume (scf/tonne)*
P, sub-surface pressure (MPa)
P_L Langmuir pressure (MPa)*
fa, ash content of coal (%)
fm, moisture content of coal (%)
RHO_{CO_2S}, standard CO_2 density (kg/m^3)
SEF_{COAL}, storage efficiency factor (%)

V_{GAS}, *Volume of produced methane gas (m^3)*
M_{GAS}, *extracted methane volume per unit coal mass (m^3/kg)*
B, *CH_4/CO_2 replacement volume factor, typically ~2*
RF, *methane recovery factor, ideal to expected efficiency (%)*
CF, *coal completion factor, net:gross gas exchange seams (%)*

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
2.83E-05, conversion from scf/tonne to m^3/kg
1.873, CO_2 density at standard conditions
* VL and PL values for estimated storage temperature

Tier 3 Prospect Capacity Assessment, DSA (Carbon Storage Atlas, 5th Edition - USDOE, 2014)

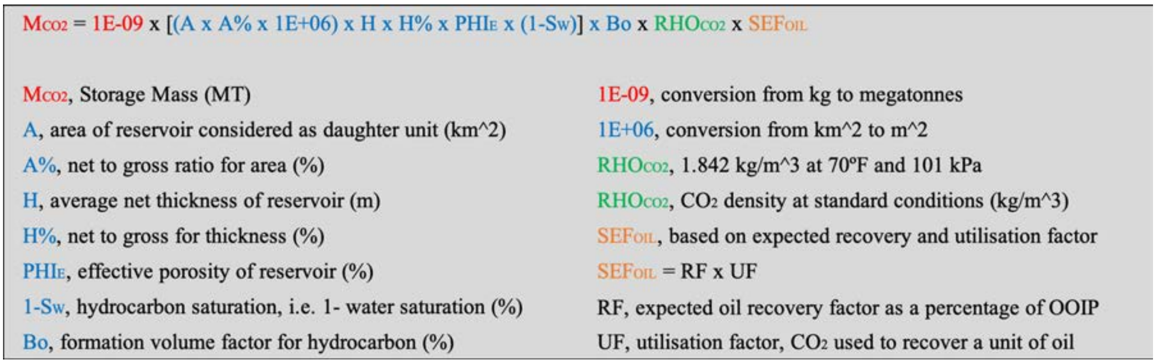


$M_{CO_2} = 1E\text{-}09 \times [(A \times A\% \times 1E{+}06) \times H \times H\% \times Phi] \times RHO_{CO_2} \times SEF$

M_{CO_2}, Storage Mass (MT)
A, area of daughter unit within aquifer (km^2)
H, average thickness of storage unit (m)
PHI, estimated porosity of storage unit (%)
RHO_{CO_2}, CO_2 density at reservoir conditions (kg/m^3)
SEF, storage efficiency factor (%)

A%, net to gross ratio for area (%)
H%, net to gross for thickness (%)
1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
RHO_{CO_2}, estimate for storage pressure and temperature
SEF, see look-up table for global/regional values

Tier 3 Prospect Capacity Assessment, DHF EOR (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



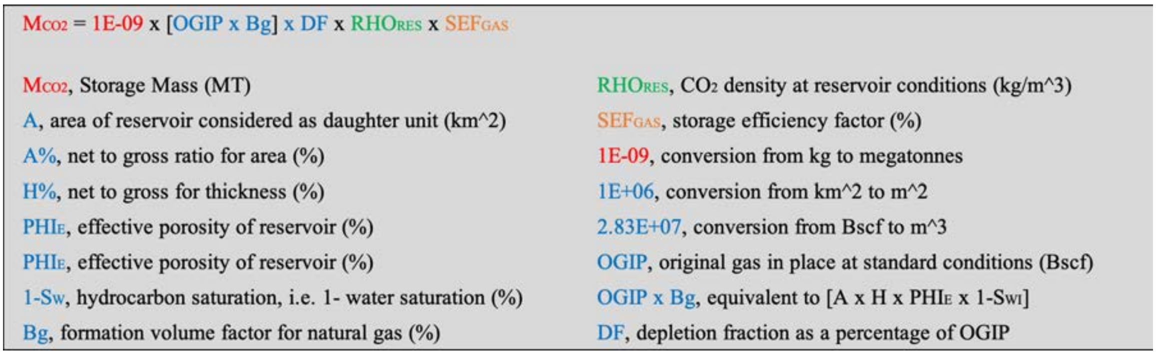
$M_{CO_2} = 1E\text{-}09 \times [(A \times A\% \times 1E{+}06) \times H \times H\% \times PHI_E \times (1\text{-}Sw)] \times Bo \times RHO_{CO_2} \times SEF_{OIL}$

M_{CO_2}, Storage Mass (MT)
A, area of reservoir considered as daughter unit (km^2)
A%, net to gross ratio for area (%)
H, average net thickness of reservoir (m)
H%, net to gross for thickness (%)
PHI_E, effective porosity of reservoir (%)
1-Sw, hydrocarbon saturation, i.e. 1- water saturation (%)
Bo, formation volume factor for hydrocarbon (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
RHO_{CO_2}, 1.842 kg/m^3 at 70°F and 101 kPa
RHO_{CO_2}, CO_2 density at standard conditions (kg/m^3)
SEF_{OIL}, based on expected recovery and utilisation factor
SEF_{OIL} = RF x UF
RF, expected oil recovery factor as a percentage of OOIP
UF, utilisation factor, CO_2 used to recover a unit of oil

Tier 3 Prospect Capacity Assessment, DHF GAS (Carbon Storage Atlas, 5th Edition - USDOE, 2014)

This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No. 837754

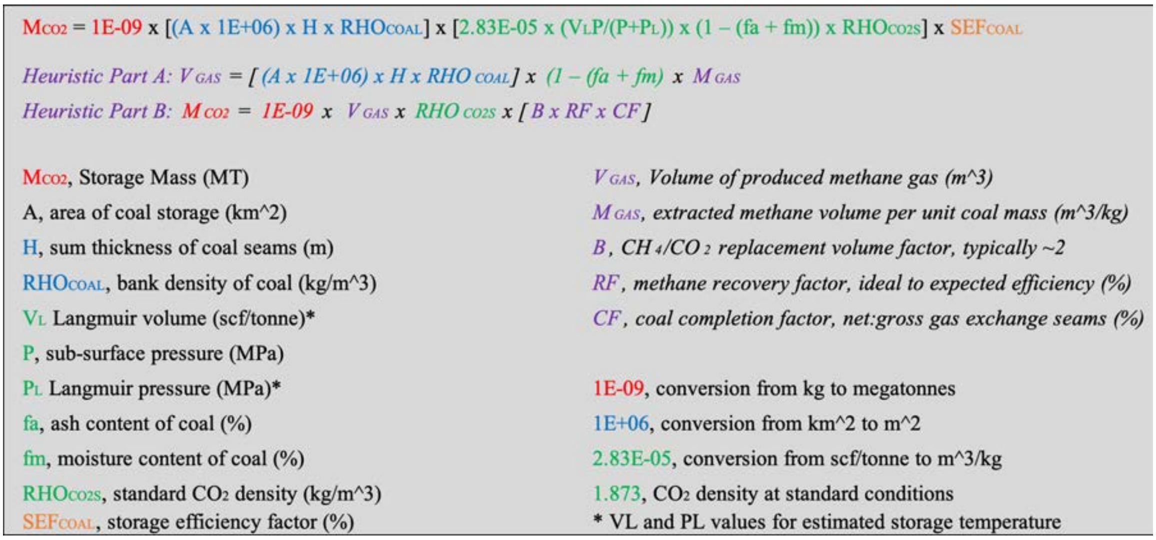


M_{CO_2} = 1E-09 x [OGIP x Bg] x DF x RHO_{RES} x SEF_{GAS}

M_{CO_2}, Storage Mass (MT)
A, area of reservoir considered as daughter unit (km^2)
A%, net to gross ratio for area (%)
H%, net to gross for thickness (%)
PHI_E, effective porosity of reservoir (%)
PHI_E, effective porosity of reservoir (%)
1-Sw, hydrocarbon saturation, i.e. 1- water saturation (%)
Bg, formation volume factor for natural gas (%)

RHO_{RES}, CO_2 density at reservoir conditions (kg/m^3)
SEF_{GAS}, storage efficiency factor (%)
1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
2.83E+07, conversion from Bscf to m^3
OGIP, original gas in place at standard conditions (Bscf)
OGIP x Bg, equivalent to [A x H x PHI_E x 1-S_{WI}]
DF, depletion fraction as a percentage of OGIP

Tier 3 Daughter Unit Capacity Assessment, UCB (Carbon Storage Atlas, 5th Edition - USDOE, 2014)



M_{CO_2} = 1E-09 x [(A x 1E+06) x H x RHO_{COAL}] x [2.83E-05 x (V_LP/(P+P_L)) x (1 – (fa + fm)) x RHO_{CO_2S}] x SEF_{COAL}

Heuristic Part A: V_{GAS} = *[(A x 1E+06) x H x* RHO_{COAL}*] x (1 – (fa + fm) x* M_{GAS}
Heuristic Part B: M_{CO_2} = *1E-09 x* V_{GAS} *x* RHO_{CO_2S} *x [B x RF x CF]*

M_{CO_2}, Storage Mass (MT)
A, area of coal storage (km^2)
H, sum thickness of coal seams (m)
RHO_{COAL}, bank density of coal (kg/m^3)
V_L Langmuir volume (scf/tonne)*
P, sub-surface pressure (MPa)
P_L Langmuir pressure (MPa)*
fa, ash content of coal (%)
fm, moisture content of coal (%)
RHO_{CO_2S}, standard CO_2 density (kg/m^3)
SEF_{COAL}, storage efficiency factor (%)

V_{GAS}, Volume of produced methane gas (m^3)
M_{GAS}, extracted methane volume per unit coal mass (m^3/kg)
B, CH_4/CO_2 replacement volume factor, typically ~2
RF, methane recovery factor, ideal to expected efficiency (%)
CF, coal completion factor, net:gross gas exchange seams (%)

1E-09, conversion from kg to megatonnes
1E+06, conversion from km^2 to m^2
2.83E-05, conversion from scf/tonne to m^3/kg
1.873, CO_2 density at standard conditions
* VL and PL values for estimated storage temperature

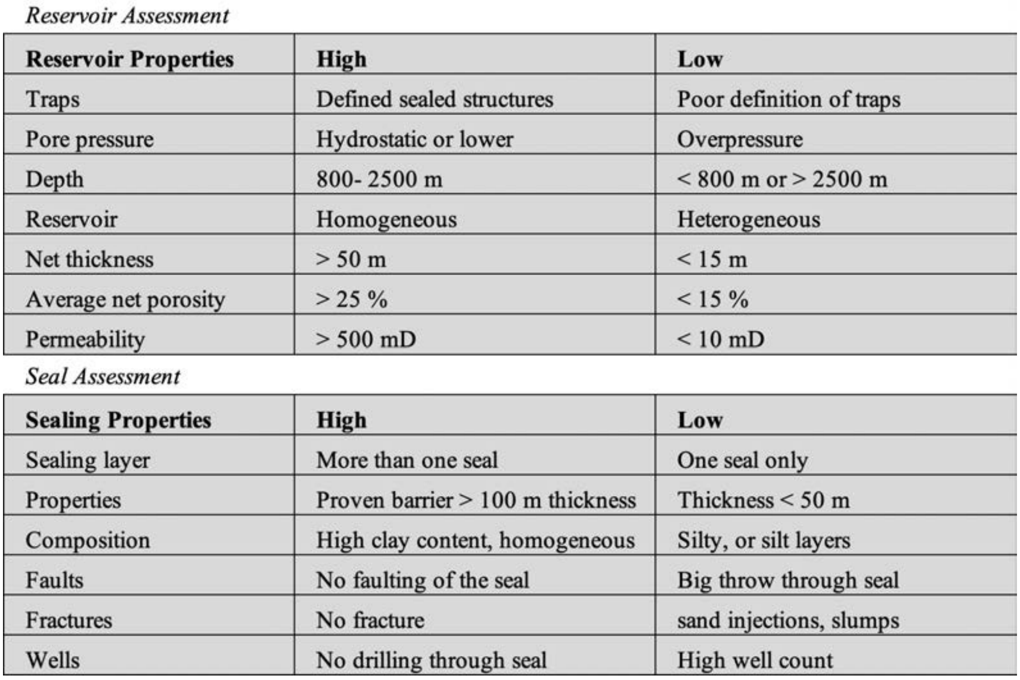
Boston square scoring for attributes (adapted from Norwegian atlas, Halland et al., 2014)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

Definitions Table

Attribute	Criteria	Score	Comments
Storage Suitability	Capacity	3	Large volume, dominant high scores in checklist
		2	Medium - low volume, low score in some factors
		1	Dominant low values, or scores close to unacceptable
	Injectivity	3	High value for permeability * thickness (k*h)
		2	Medium k*h
		1	Low k*h
Seal Suitability	Seal	3	Good sealing shale, dominant high scores in checklist
		2	At least one sealing layer with acceptable properties
		1	Seal with uncertain properties, low scores in checklist
	Fracture	3	Dominant high scores in checklist
		2	Insignificant fractures, either natural or wells
		1	Low scores in checklist
	Wells	3	No previous drilling in reservoir, safe plugging of wells
		2	Wells penetrating seal, no leakage documented
		1	Possible leaking wells, need for evaluation
Other Suitability Attributes	CO_2 Density	3 / 2 / 1	Supercrtical, high density gas, or low density gas
	CO_2 Migration	3 / 2 / 1	Low migration risk, moderate risk
	Location	3 / 2 / 1	Location suitability relative to other sinks and sources
	Monitoring	3 / 2 / 1	Suitability of site for performance monitoring
	Intervention	3 / 2 / 1	Suitability of site for remedial interventions
	Upside	3 / 2 / 1	Sutiability of site for growth as a storage hub
Data Quality	All Criteria	3	High quality data with good coverage and density
		2	Adequate data with some gaps in coverage
		1	Low quality and/or sparse data with known gaps

Guide ranges for principle attribute quality (after Norwegian Atlas, Halland et al., 2014)



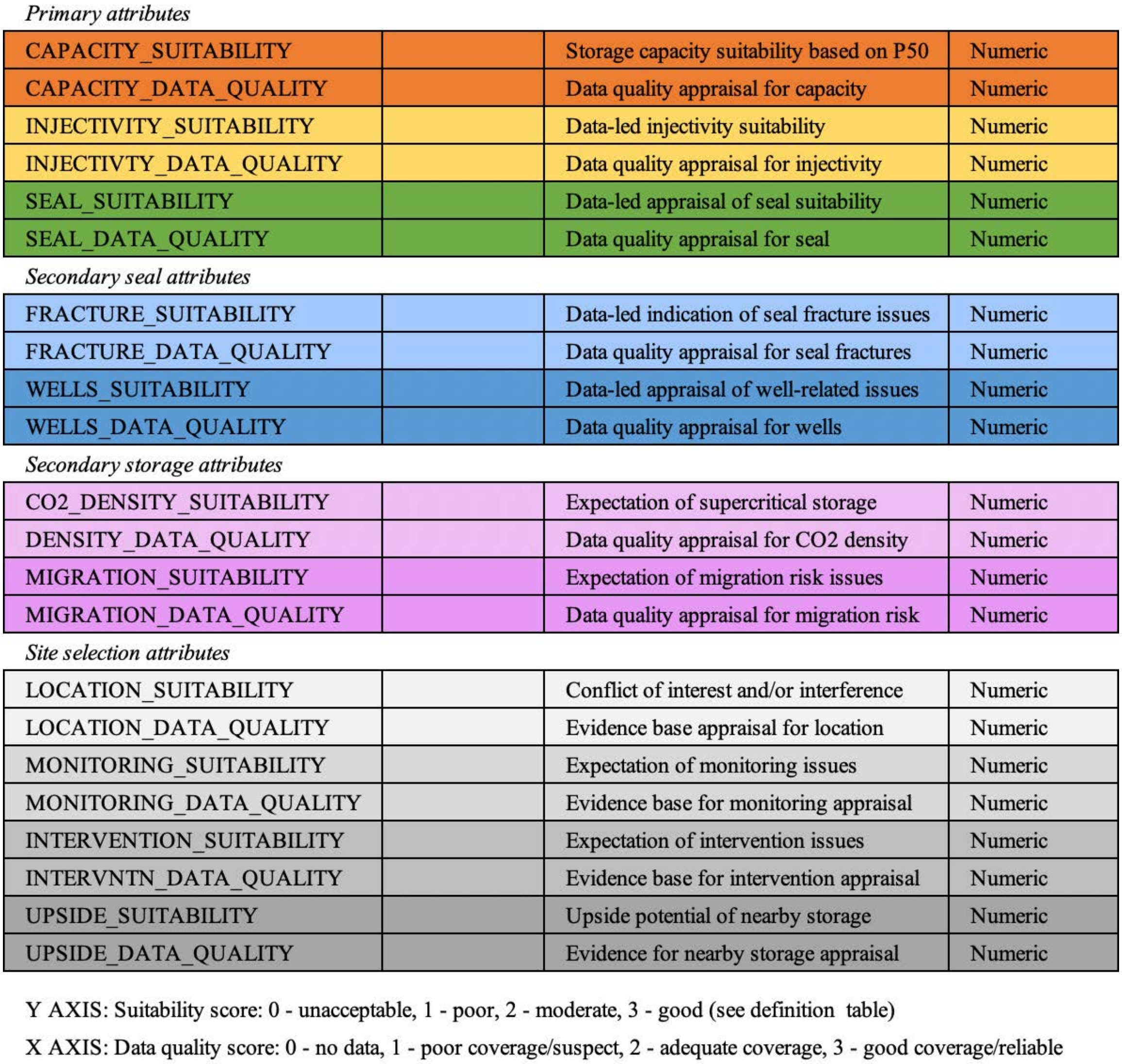
Reservoir Assessment

Reservoir Properties	High	Low
Traps	Defined sealed structures	Poor definition of traps
Pore pressure	Hydrostatic or lower	Overpressure
Depth	800- 2500 m	< 800 m or > 2500 m
Reservoir	Homogeneous	Heterogeneous
Net thickness	> 50 m	< 15 m
Average net porosity	> 25 %	< 15 %
Permeability	> 500 mD	< 10 mD

Seal Assessment

Sealing Properties	High	Low
Sealing layer	More than one seal	One seal only
Properties	Proven barrier > 100 m thickness	Thickness < 50 m
Composition	High clay content, homogeneous	Silty, or silt layers
Faults	No faulting of the seal	Big throw through seal
Fractures	No fracture	sand injections, slumps
Wells	No drilling through seal	High well count

Attribute list for Boston square analysis (adapted from Norwegian atlas, Halland et al., 2014)



Primary attributes

CAPACITY_SUITABILITY		Storage capacity suitability based on P50	Numeric
CAPACITY_DATA_QUALITY		Data quality appraisal for capacity	Numeric
INJECTIVITY_SUITABILITY		Data-led injectivity suitability	Numeric
INJECTIVTY_DATA_QUALITY		Data quality appraisal for injectivity	Numeric
SEAL_SUITABILITY		Data-led appraisal of seal suitability	Numeric
SEAL_DATA_QUALITY		Data quality appraisal for seal	Numeric

Secondary seal attributes

FRACTURE_SUITABILITY		Data-led indication of seal fracture issues	Numeric
FRACTURE_DATA_QUALITY		Data quality appraisal for seal fractures	Numeric
WELLS_SUITABILITY		Data-led appraisal of well-related issues	Numeric
WELLS_DATA_QUALITY		Data quality appraisal for wells	Numeric

Secondary storage attributes

CO2_DENSITY_SUITABILITY		Expectation of supercritical storage	Numeric
DENSITY_DATA_QUALITY		Data quality appraisal for CO2 density	Numeric
MIGRATION_SUITABILITY		Expectation of migration risk issues	Numeric
MIGRATION_DATA_QUALITY		Data quality appraisal for migration risk	Numeric

Site selection attributes

LOCATION_SUITABILITY		Conflict of interest and/or interference	Numeric
LOCATION_DATA_QUALITY		Evidence base appraisal for location	Numeric
MONITORING_SUITABILITY		Expectation of monitoring issues	Numeric
MONITORING_DATA_QUALITY		Evidence base for monitoring appraisal	Numeric
INTERVENTION_SUITABILITY		Expectation of intervention issues	Numeric
INTERVNTN_DATA_QUALITY		Evidence base for intervention appraisal	Numeric
UPSIDE_SUITABILITY		Upside potential of nearby storage	Numeric
UPSIDE_DATA_QUALITY		Evidence for nearby storage appraisal	Numeric

Y AXIS: Suitability score: 0 - unacceptable, 1 - poor, 2 - moderate, 3 - good (see definition table)

X AXIS: Data quality score: 0 - no data, 1 - poor coverage/suspect, 2 - adequate coverage, 3 - good coverage/reliable

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7 Appendix

7.1 Coal: general attributes for UCB coal prospects

Typical Bank Density of Coal

Anthracite	1800 kg/m^3
Bituminous	1400 kg/m^3
Lignite	1100 kg/m^3

Typical Bulk Density of Coal

Anthracite Coal	800 - 929 kg/m^3
Bituminous Coal	673 - 913 kg/m^3
Lignite Coal	641 – 865 kg/m^3

Typical Fixed Carbon Content in Coal

Anthracite	80.5 - 85.7 weight %
Bituminous	44.9 - 78.2 weight %
Lignite Coal	31.4 weight %

Typical Moisture Content in Coal

Anthracite	2.8 - 16.3 weight %
Bituminous	2.2 - 15.9 weight %
Lignite	39 weight %

Typical Ash Content in Coal

Anthracite	*9.7 - 20.2 weight %*
Bituminous	*3.3-11.7 weight %*
Lignite Coal	*4.2 weight %*

Typical Sulphur Content in Coal

Anthracite	*0.6 - 0.77 weight %*
Bituminous	*0.7 - 4.0 weight %*
Lignite Coal	*0.4 weight %*

7.2 Coal: a comparison of the USDOE (2014) Atlas equation and Bachu (2010) review formulation

Atlas: $\mathbf{G_{CO2} = A \times h_g \times C_s \times r_{s,max} \times E_{coal}}$

Review: $\mathbf{M_{CO2} = E \times \rho_{CO2S} \times A \times h \times \rho_{COAL} \times (V_L P/(P+P_L)) \times (1 - (f_a + f_m))}$

G_{CO2}, equivalent to M_{CO2}, CO_2 storage potential

A, equivalent to A, total area of prospect

h_g, equivalent to h, gross seam thickness

C_s, equivalent to $\rho_{COAL} \times (V_L P/(P+P_L)) \times (1 - (f_a + f_m))$

$r_{s,max}$, equivalent to ρ_{CO2S}, CO_2 density at standard conditions

E_{coal}, equivalent to E, storage efficiency, fraction of pore volume occupied by CO_2

Review: ρ_{COAL}, bank coal density
Review: $(V_L P/(P+P_L))$, CO_2 adsorption capacity
Review: $(1 - (f_a + f_m))$, coal moisture, and ash content

7.3 Coal, a description of Langmuir isotherms

Methane and CO_2 commonly adsorb onto free surfaces in coals. The adsorption is described by a semi-empirical pressure relationship called the Langmuir isotherm (Langmuir, 1916; Masel, 1996). Langmuir isotherms assume that the gas attaches to the surface of the coal and covers the surface as a single layer of molecules. At low pressures, this dense state allows significantly larger volumes to be stored by sorption than by compression of free gas into the pore space of the coal, typically cleats. The common formulation of the Langmuir isotherm is:

$$C_g = V_L P / (P_L + P) \qquad \textbf{[Equation 3-7]}$$

C_g *Gas content in scf/ton*

V_L *Langmuir volume*

P_L *Langmuir pressure*

P *Pressure at storage conditions*

The Langmuir volume is the maximum amount of gas adsorbed at infinite pressure. The Langmuir pressure, or critical desorption pressure, is the pressure at which half the Langmuir volume is adsorbed. Langmuir isotherms are temperature-specific as implicit in their name. The correct isotherm for a given prospect will be that associated with the sub-surface temperature for the prospect and the type of coal. This typically requires laboratory assays of the prospective coal to determine the Langmuir volume, Langmuir pressure, and ash and moisture content.

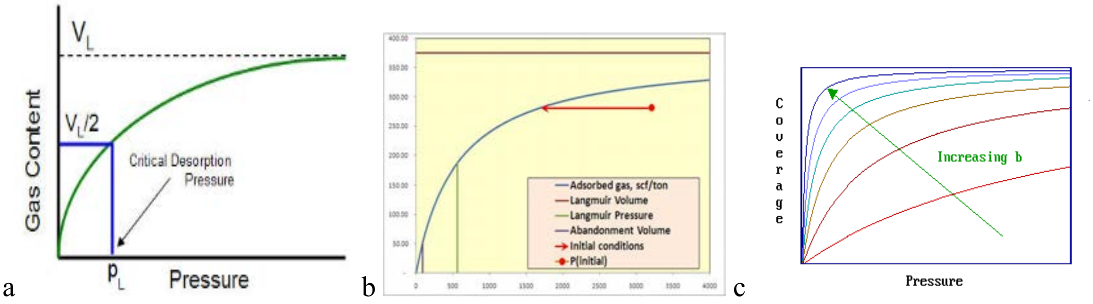

Figure 3-3(a) Langmuir isotherm components; (b) water production; (c) decreasing temperature

It follows that the exponential estimate assumes that the temperature of the system is constant. At infinite pressure, the gas content reaches maximum saturation, VL. The adsorption capacity decreases as temperature increases. When estimating the gas content, it is important to use the representative Langmuir isotherm for the average sub-surface temperature and coal type.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

Cg, the gas content, assumes 100% saturation of a dry, ash-free coal. Moisture competes with methane and CO_2 for adsorption sites on the surface of coal. There is also a possibility that moisture blocks gas access to micropores. Gas adsorption measurements for dry coal usually give higher values for gas content than for wet coal. Ash is the non-combustible part of coal that does not adsorb gas. The Langmuir isotherm formulation is modified for the coal fraction unavailable for adsorption:

$$\mathbf{Cg = V_L P/(P_L + P) \times (1 - (f_a + f_m))} \qquad \textbf{[Equation 3-8]}$$

f_a	Ash fraction by weight
f_m	Moisture fraction by weight

The modified Langmuir isotherm formulation describes the maximum amount of gas that a given coal can hold at a specified pressure and temperature. Several factors may result in a coal holding less than the maximum amount of gas. Such coals are termed undersaturated. The storage efficiency factor, E_{COAL}, addresses the correction between the ideal saturation and expected exposure efficiency.

7.4 Data Lists, archived as STRATCCUSWP21-SRAM-DATALISTS-v1.xlsx

Regional Overview Header

Attribute	Description	Unit
REGION	Name of promising region	Text
REGION_ID	Unique identifier for this formation	Alpha-Numeric
COUNTRY	Name of country	Text
COUNTRY_CODE	ISO country code	Numeric
DATE_ENTERED	Date of data entry	Alpha-Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation or water depth (+/-)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
STRAT_FILE	Name of file for strat column	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
FORMATIONS	Number of storage formations	Numeric
UNITS	Number of storage units	Numeric
DAUGHTERS	Number of identified daughter units	Numeric

Assessment

THEORETICAL_CAPACITY	Tier 1 theoretical capacity, P50	Mt
THEORETICAL_CAP_RANGE	Tier 1 theoretical capacity, P90-P10	Mt
EFFECTIVE_CAPACITY	Tier 2 effective capacity, P50	Mt
EFFECTIVE_CAP_RANGE	Tier 2 effective capacity, P90-P10	Mt
PRACTICAL_CAPACITY	Tier 3 practical capacity, P50	Mt
PRACTICAL_CAP_RANGE	Tier 3 practical capacity, P90-P10	Mt
MATCHED_CAPACITY	Tier 4 matched capacity, P50	Mt
MATCHED_CAP_RANGE	Tier 4 matched capacity, P90-P10	Mt
REMARKS	Any other relevant information	Text

Tier 1 - Formation Header

Attribute	Description	Unit
FORMATION	Name of storage formation	Text
FORMATION_ID	Unique identifier for this formation	Alpha-Numeric
REGION	Name of promising region	Text
COUNTRY	Name of country	Text
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees

LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text
STORAGE_UNITS	Number of storage units	Numeric

Output

FORMATION_CAPACITY	Regional capacity, P50	Mt
FORMATION_CAP_RANGE	Regional capacity, P90-P10	Mt
REMARKS	Any other relevant information	Text

Tier 1 - Storage Unit

Attribute	Description	Unit
STORAGE _UNIT	Name of storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
FORMATION	Parent storage formation	Text
FORMATION_ID	Formation unique identifier	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters

LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Elevation water depth (+/-)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text
DAUGHTERS	Number of daughter units	Numeric

Seal

SEAL	Primary seal name	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area	km
UNIT_THICKNESS	Representative thickness	meters
UNIT_POROSITY	Representative porosity	%
UNIT_PERMEABILITY	Representative permeability	mD

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Representative temperature	°C
UNIT_PRESSURE	Representative pressure	MPa
CO2_DENSITY	Representative CO_2 density	kg/m3

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Estimated upper storage efficiency	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Estimated lower storage efficiency	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Storage capacity of unit, P50	Mt
CAPACITY_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
STORAGE_DHF	Depleted hydrocarbon field capacity	Mt
STORAGE_DSA	Deep saline aquifer capacity	Mt
STORAGE_UCB	Unmineable coal bed capacity	Mt
INJECTIVITY	Function of permeability x thickness	mDm
REMARKS	Any other relevant information	Text

Header Daughter Unit - Tier 2, DSA

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text
STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this parent unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text

ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area	km^2
UNIT_THICKNESS	Representative thickness	meters
UNIT_POROSITY	Representative porosity	%
UNIT_PERMEABILITY	Representative permeability	mD

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Representative temperature	°C
UNIT_PRESSURE	Representative pressure	MPa
CO2_DENSITY	Representative CO2 density	kg/m^3

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Upper storage efficiency factor	%
SEF_P50	Storage efficiency factor	%
SEF_P10	Lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Storage capacity of unit, P50	Mt
STOR_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY	Function of permeability x thickness	mDm
REMARKS	Any other relevant information	Text

Header Daughter Unit - Tier 2, DHF

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit, field name	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text
FIELD_HC_CONTENT	Hydrocarbon type: oil, gas, condensate	Text
FIELD_STATUS	Producing, Suspended, Abandoned	Text
FIELD_AVAILABILITY	Year when CO_2 injection can commence	Numeric
STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text

AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area	km^2
UNIT_THICKNESS	Representative thickness	meters
UNIT_POROSITY_EFFECTIVE	Effective reservoir porosity	%
UNIT_PERMEABILITY	Representative permeability	mD

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Representative temperature	°C
UNIT_PRESSURE	Representative pressure	MPa
CO2_DENSITY	Representative CO2 density	kg/m^3
WATER_SATURATION	Expected water fraction in field	%
RECOVERY_FACTOR	Fraction of hydrocarbon recovered	%

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Estimated upper storage efficiency factor	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Estimated lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Expected storage capacity of unit, P50	Mt
STOR_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY	Function of permeability x thickness	mDm
REMARKS	Any other relevant information	Text

Header Daughter Unit - Tier 2, UCB

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text
STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area, A	km^2
UNIT_THICKNESS	Sum thickness of coal seams, h	meters
UNIT_DENSITY	Bank density of coal, RHOCOAL	kg/m^3
ASH_CONTENT	Fraction of coal that is ash, fa	%
MOISTURE_CONTENT	Fraction of coal that is moisture, fm	%
UNIT_PERMEABILITY	Representative permeability	mD

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Isotherm temperature	°C
UNIT_PRESSURE	Representative pressure, P	MPa
LANGMUIR_PRESSURE	Critical desoprtion pressure, PL	MPa
LANGMUIR_VOLUME	Maximum adsorbed gas content , VL	scf/tonne
CO2_DENSITY	Representative CO2 density	kg/m^3

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Estimated upper storage efficiency factor	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Estimated lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Expected storage capacity of unit, P50	Mt
STORAGE_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY	Function of permeability x thickness	mDm
REMARKS	Any other relevant information	Text

Header Prospect - Tier 3, DSA

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text

STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this parent unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA_EXPECTED	Representative area, expected	km^2
UNIT_AREA_MAXIMUM	Representative area, maximum	km^2
UNIT_AREA_MINIMUM	Representative area, minimum	km^2
UNIT_AREA_NET_TO_GROSS	Expected net to gross for storage area	%

UNIT_THICKNESS	Representative thickness, expected	meters
UNIT_THICKNESS_MAXIMUM	Representative thickness, maximum	meters
UNIT_THICKNESS_MINIMUM	Representative thickness, minimum	meters
UNIT_THICK_NET_TO_GROSS	Expected net to gross for thickness	%
PERFORATION_FRACTION	Well perf' as a fraction of thickness	%
UNIT_POROSITY_EXPECTED	Representative porosity, expected	%
UNIT_POROSITY_MAXIMUM	Representative porosity, maximum	%
UNIT_POROSITY_MINIMUM	Representative porosity, minimum	%
UNIT_PERMEABILITY	Representative permeability, expected	mD
UNIT_PERM_MAXIMUM	Representative permeability, maximum	mD
UNIT_PERM_MINIMUM	Representative permeability, minimum	mD
UNIT_COMPRESSIBILITY	Representative bulk compressibility	1/MPa

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Representative temperature	°C
UNIT_PRESSURE	Representative pressure	MPa
CO2_DENSITY	Representative CO2 density, expected	kg/m^3
CO2_DENSITY_MAXIMUM	CO2 density, maximum	kg/m^3
CO2_DENSITY_MINIMUM	CO2 density, minimum	kg/m^3
PORE_WATER_SALINITY	Pore water salinity	ppm

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Upper storage efficiency factor	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Expected storage capacity of unit, P50	Mt
STOR_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY_EXPECTED	Permeability x thickness x well perf %	mDm

INJECTIVITY_RANGE	Max-Min range for k*h*%	MDm
REMARKS	Any other relevant information	Text

Injectivity

UNIT_PERMEABILITY	Representative permeability, expected	mD
UNIT_THICKNESS	Representative thickness, expected	meters
PERFORATION_FRACTION	Well perf' as a fraction of thickness	%
HYDROSTATIC_PRESSURE	Hydrostatic pressure at injection depth	MPa
AMBIENT_PRESSURE	Reservoir pressure at injection start	MPa
LITHOSTATIC_PRESSURE	Lithostatic pressure at seal/reservoir	MPa
FRACTURE_PRESSURE	Fracture pressure of seal	MPa
PRESSURE_HEADSPACE	Fracture pressure - Ambient pressure	MPa
INJECTION_RATE	Expected injection rate for a vertical well	MT/Yr/Well
INJECTION_DURATION	Expected duration of injection for a well	Years/Well

Header Prospect - Tier 3, DHF

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit, field name	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text
FIELD_HC_CONTENT	Hydrocarbon type: oil, gas, condensate	Text
FIELD_STATUS	Producing, Suspended, Abandoned	Text
FIELD_AVAILABILITY	Year when CO2 injection can commence	Numeric
STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text

GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma
STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area	km^2
UNIT_AREA_MAXIMUM	Representative area, maximum	km^2
UNIT_AREA_MINIMUM	Representative area, minimum	km^2
UNIT_AREA_NET_TO_GROSS	Expected net to gross for storage area	%
UNIT_THICKNESS	Representative thickness	meters
UNIT_THICKNESS_MAXIMUM	Representative thickness, maximum	meters
UNIT_THICKNESS_MINIMUM	Representative thickness, minimum	meters
UNIT_THICK_NET_TO_GROSS	Expected net to gross for thickness	%
UNIT_POROSITY_EFFECTIVE	Effective reservoir porosity	%
UNIT_POROSITY_EFF_MAX	Effective porosity, maximum	%
UNIT_POROSITY_EFF_MIN	Effective porosity, minimum	%
UNIT_PERMEABILITY	Representative permeability	mD
UNIT_PERM_MAXIMUM	Representative permeability, maximum	mD
UNIT_PERM_MINIMUM	Representative permeability, minimum	mD

UNIT_COMPRESSIBILITY	Representative bulk compressibility	1/MPa

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Representative temperature	°C
UNIT_PRESSURE	Representative pressure	MPa
CO2_DENSITY	Representative CO2 density	kg/m^3
CO2_DENSITY_MAXIMUM	CO2 density, maximum	kg/m^3
CO2_DENSITY_MINIMUM	CO2 density, minimum	kg/m^3
WATER_SATURATION	Expected water fraction in field	%
WATER_SAT_MAX	Maximum water fraction in field	%
WATER_SAT_MIN	Minimum water fraction in field	%
RECOVERY_FACTOR	Fraction of hydrocarbon recovered	%
RECOVERY_FACTOR_MAX	Maximum fraction of recovered HC	%
RECOVERY_FACTOR_MIN	Minimum fraction of recovered HC	%

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Estimated upper storage efficiency factor	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Estimated lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Expected storage capacity of unit, P50	Mt
STOR_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY_EXPECTED	Function of permeability x thickness	mDm
INJECTIVITY_RANGE	Max-Min range for k*h	MDm
REMARKS	Any other relevant information	Text

Injectivity

UNIT_PERMEABILITY	Representative permeability, expected	mD
UNIT_THICKNESS	Representative thickness, expected	meters
PERFORATION_FRACTION	Well perf' as a fraction of thickness	%
HYDROSTATIC_PRESSURE	Hydrostatic pressure at injection depth	MPa

AMBIENT_PRESSURE	Reservoir pressure at injection start	MPa
LITHOSTATIC_PRESSURE	Lithostatic pressure at seal/reservoir	MPa
FRACTURE_PRESSURE	Fracture pressure of seal	MPa
PRESSURE_HEADSPACE	Fracture pressure - Ambient pressure	MPa
INJECTION_RATE	Expected injection rate for a vertical well	MT/Yr/Well
INJECTION_DURATION	Expected duration of injection for a well	Years/Well

Header Prospect - Tier 3, UCB

Attribute	Description	Unit
DAUGHTER _UNIT	Name of daughter unit	Text
DAUGHTER_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
STORAGE_TYPE	DSA, DHF, UCB	Text
STORAGE_UNIT	Name of parent storage unit	Text
STORAGE_UNIT_ID	Unique identifier for this unit	Alpha-Numeric
DATE_ENTERED	Date of data entry	Numeric

Geography

EASTING	X Lambert projection	meters
NORTHING	Y Lambert projection	meters
LATITUDE	X WGS84 decimal degrees	degrees
LONGITUDE	Y WGS84 decimal degrees	degrees
ELEVATION	Mean elevation (-) or water depth (+)	meters
ELEVATION_DATUM	Datum used for elevation	Text
GEOGRAPHIC_AREA	Surface location	Text
ON_OFF_SHORE	Onshore or offshore	Text
REMARKS	Any other relevant information	Text

Geology

GEOLOGIC_BASIN	Sedimentary basin name	Text
MAP_FILE	Name of map file if available	Alpha-Numeric
SHAPE_FILE	Name of volume shape if available	Alpha-Numeric
STORAGE_TYPES	DSA DHF CBM	Text
AGE_MIN	Minimum age of formation	Ma
AGE_MAX	Maximum age of formation	Ma

STRAT_GROUP	Stratigraphic Group	Text
STRAT_FORMATION	Stratigraphic formation	Text
LITHOLOGY	Predominant lithology	Text

Seal

SEAL	Name of predominant primary seal	Text
SEAL_LITHOLOGY	Representative lithology	Text

Storage Unit Parameters

UNIT_AREA	Representative area, A	km^2
UNIT_AREA_MAXIMUM	Representative area, maximum	km^2
UNIT_AREA_MINIMUM	Representative area, minimum	km^2
UNIT_THICKNESS	Sum thickness of coal seams, h	meters
UNIT_THICKNESS_MAXIMUM	Sum thickness, maximum	meters
UNIT_THICKNESS_MINIMUM	Sum thickness, minimum	meters
UNIT_DENSITY	Bank density of coal, RHOCOAL	kg/m^3
UNIT_DENSITY_MAXIMUM	Bank density maximum	kg/m^3
UNIT_DENSITY_MINIMUM	Bank density minimum	kg/m^3
ASH_CONTENT	Fraction of coal that is ash, fa	%
ASH_CONTENT_MAXIMUM	Maximum fraction of coal that is ash	%
ASH_CONTENT_MINIMUM	Minimum fraction of coal that is ash	%
MOISTURE_CONTENT	Fraction of coal that is moisture, fm	%
MOISTURE_CONTENT_MAX	Maximum moisture fraction	%
MOISTURE_CONTENT_MIN	Minimum moisture fraction	%
UNIT_PERMEABILITY	Representative permeability	mD
UNIT_PERM_MAXIMUM	Representative permeability, maximum	mD
UNIT_PERM_MINIMUM	Representative permeability, minimum	mD

Storage Unit Fluid Parameters

UNIT_TEMPERATURE	Isotherm temperature	°C
UNIT_TEMPERATURE_MAX	Isotherm temperature, maximum	°C
UNIT_TEMPERATURE_MIN	Isotherm temperature, minimum	°C
UNIT_PRESSURE	Representative pressure, P	MPa
UNIT_PRESSURE_MAX	Maximum pressure, P	MPa

UNIT_PRESSURE_MIN	Minimum pressure, P	MPa
LANGMUIR_PRESSURE	Critical desoprtion pressure, PL	MPa
LANGMUIR_PRESSURE_MAX	Desoprtion pressure, maximum	MPa
LANGMUIR_PRESSURE_MIN	Desoprtion pressure, minimum	MPa
LANGMUIR_VOLUME	Aadsorbed gas content, VL	scf/tonne
LANGMUIR_VOLUME_MAX	Adsorbed gas content, maximum	scf/tonne
LANGMUIR_VOLUME_MIN	Adsorbed gas content, minimum	scf/tonne

Storage Efficiency

UNIT_BOUNDARY_CONDITION	Open, closed, semi-closed, unknown	Text
SEF_CLASS	Global, Regional	%
SEF_P90	Estimated upper storage efficiency factor	%
SEF_P50	Expected storage efficiency factor	%
SEF_P10	Estimated lower storage efficiency factor	%
REMARKS	Any other relevant information	Text

Output

STORAGE_CAPACITY_P50	Expected storage capacity of unit, P50	Mt
STOR_CAP_RANGE_P90-P10	Storage capacity range, P90-P10	Mt
INJECTIVITY_EXPECTED	Function of permeability x thickness	mDm
INJECTIVITY_RANGE	Max-Min range for k*h	MDm
REMARKS	Any other relevant information	Text

Attributes for screening utilisation and storage, EOR

Parameter	Attribute	Value
U1	Recoverable Oil Volume (stb)	
U2	Reservoir Volume Factor (bbl/stb)	
U3	Water Injection-Production Balance (m3)	
U4	CO2 Required to Produce Oil Volume (Mt)	
U5	Miscible Flood and WAG Suitability	
U6	Alternative Injection Strategy (Gravity?)	
U7	IEA Model Class for CCUS (1,2,3)	
U8	Strength of Aquifer Support (High/Low)	

Framing storage assessment for utilisation technologies

Question	Criteria	Framing Question
1	Quantity in	How much captured CO2 is used per unit of production?
2	Quantity out	How much CO2 is emitted per unit of production?
3	Scale	How many units will be produced per year?
4	Storage rate	How much of the used CO2 will be stored per year?
5	Impact	Does the storage rate exceed the emission rate?
6	Permanence	How long will the CO2 be stored for?
7	Accounting	How will storage be monitored and verified?
8	Other	How else does the technology mitigate emissions?