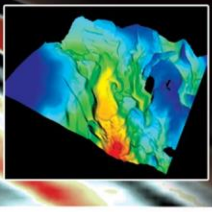
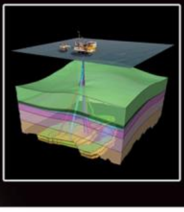




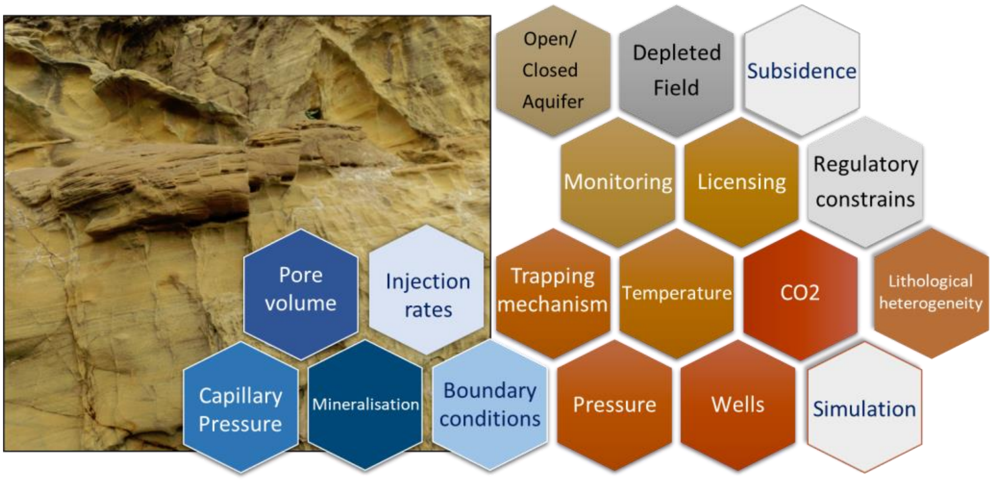
The Geological Society

Call for poster abstracts – deadline 15th July

CO2 Storage Efficiency:

Challenges with standards and consistency in capacity estimations

14-15 September 2023
The Geological Society, Burlington House, Piccadilly London



The amount of CO2 that can be stored in underground reservoirs is often summarised by the Storage Efficiency ‘E’. Storage Efficiency is a key factor - but its calculation is arguably complicated as E is impacted by lithological heterogeneity, trapping structures, injection rates, well spacing, fluid properties etc.

Due to this complexity, there is much controversy on how to estimate E, with some arguing it should not be used at all and that reservoir simulation is a better path. However, estimates for E are used in most regional mapping studies, and applicability of these screening estimates to project specific Storage Efficiency studies is unclear and potentially misleading.

The industry needs a consistent and multidisciplinary approach for using storage efficiency estimates in storage capacity studies, as well as guidelines for when this measure is useful in the process of maturing CO2 storage prospects towards investment decisions.

This convention aims to bring together industry and academic experts to establish a workflow or tables for the calculation of Storage Efficiency. The ultimate objective is to come up with a set of procedures on how to define that crucial E number, and to develop guidelines for when it should be used.

This two-day event will be a mix of keynote talks, poster pitches, and panel discussions. The committee welcomes the submission of poster abstracts!

For further information please contact:
Samira Bashar, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Email: samira.bashar@geolsoc.org.uk

Corporate Supporters:

bp

equinor

Convenors:

Tina Lohr
ERCE

Philip Ringrose
Equinor/ NTNU

Clare Glover
ExxonMobil

Adrian Topham
The Crown Estate

Florian Doster
Heriot Watt

Ellen Mitchel
ERC Evolution

Conference Supporters:

ExxonMobil

ERCE
The expertise tomorrow needs

THE CROWN ESTATE

ENERGY GROUP

At the forefront of energy geoscience

www.geolsoc.org.uk/energygroup

CO_2 Storage Efficiency:
Challenges with standards and consistency in capacity estimations

14 - 15 September 2023

Hybrid Conference – The Geological Society London, and Zoom

Programme

Day One	
08.30	**Registration**
08.50	**Welcome** Tina Lohr, ERCE
08.55	**Introduction** Ellen Mitchell, ERCE
	Morning Session with Keynote talks: **Experience and use of storage efficiency in describing and comparing CCS globally** Session chairs: Tina Lohr, Adrian Topham
09.05	**The journey from CS license award to storage permit** Matteo Tazzi, UK North Sea Transition Authority (NSTA)
09.40	**NETL's Perspective on Storage Efficiency and CO_2-SCREEN** Angela Goodman, US Department of Energy, NETL
10.20	**Communicating readiness for CO_2 operations using Storage Readiness Levels, and its application to the UK national CO_2 storage resource** Maxine Akhurst, British Geological Survey (BGS)
11.00	**BREAK**
11.30 Virtual	**To "E" or not to "E", that is the Question.** Scott M. Frailey, Illinois State Geological Survey, University of Illinois
12.10	**CO_2 storage efficiency: experiences and reflections** Chick Wattenbarger, ExxonMobil
12.50	**LUNCH**
	Afternoon Session with mini-talks & Posters: **Experience and use of storage efficiency in describing and comparing CCS globally** Session chairs: Florian Doster, Clare Glover
13.50	P1 - **Calculating a consistent storage resource across a growing portfolio** Alison Isherwood, Storegga
13.58	P2 - **What industry needs to estimate storage resource and why most published Storage Efficiency Coefficients don't help us** Peter Zweigel, Equinor
14.06 Pre-Recorded	P3 - **E-mission, the quest to forecast E prior to injection of CO_2 for storage** Jon Gluyas, University of Durham, Geospatial Research Ltd, UK

14.14	P4 - **Strengths and weaknesses of the SPE SRMS** Xavier Troussaut, TotalEnergies
14.22	P5 - **The Importance of Storage Efficiency in the Application of SRMS** Gordon Taylor, RPS
14.30	P6 - **Storage efficiency and reduced complexity modelling** Hariharan Ramachandran, Heriot Watt University, UK
14.38	P7 - **CO_2 storage resources in saline aquifers – pressure analytical methods and CO_2 migration challenges** Sylvain Thibeau, TotalEnergies
14.46	P8 - **Pressure-based Storage Capacity Mapping and Implications for Storage Efficiency** Alex Bump, BEG University of Texas, USA
14.54	P9 - **EASiTool 5.0 for CO_2 storage capacity estimation** Seyyed Hosseini, BEG University of Texas, USA
15.00	**BREAK**
15.30	**Panel Session 1:** **Experience and use of storage efficiency in describing and comparing CCS globally** Session chairs: Tina Lohr, Ellen Mitchell Panel session leader: John Underhill, University Director for Energy Transition and Professor of Geoscience at Aberdeen University Panel speakers: Angela Goodman (DoE-NETL), Adrian Topham (The Crown Estate), Peter Zweigel (Equinor), Maxine Akhurst (BGS) 1) Does the concept of total capacity have a place in evaluating and comparing storage potential? 2) How applicable are conventional or unconventional HC projects to CO_2 storage? 3) Is CO_2 storage efficiency calculation more useful as a project-based approach or rather using a generic approach? 4) How useful are comparisons between depleted gas fields and saline aquifers?
17.00 **17.00-18.00**	**End of day one** **Drinks reception**

Day Two

08.30	**Registration**
08.50	**Welcome**
	Morning Session with Keynote talks: **Methodologies and applications of storage efficiency calculations** Session chairs: Philip Ringrose, Ellen Mitchell

09.00	**Storage efficiency at opposite ends of scales of interest** Sam Krevor, Imperial College London
09.40	**Storage capacity assessment techniques for gigatonne-scale CCS** Sarah Gasda, NORCE Research
10.20	**Geomechanical pressurization constraint development – Example from the Northern Lights project, offshore Norway** Nic Thompson, Equinor
11.00	**BREAK**
11.30	**How does the early 0.5 MT performance inform the calculation of an Efficiency Factor at the Aquistore Project, Canada** Rick Chalaturnyk, University of Alberta, Canada
12.10	**Using sand-tank experiments to visualize and quantify flow and saturation for predicting CO_2 storage efficiency in clastic materials** Tip Meckel, BEG University of Texas, USA
12.50	**LUNCH**
	Afternoon Session with mini-talks & Posters: **Methodologies and applications of storage efficiency calculations** Session chairs: Florian Doster, Clare Glover
13.50	P10 - **Screening for Open Saline Aquifers - Estimating Storage Efficiency based on Plume Shape** Martin Neumaier, ArianeLogiX
13.58	P11 - **Materiality of Plume size Calculations and storage efficiency** Prasanna Krishnamurthy, ExxonMobil
14.06	P12 - **Estimating the contacted pore space and CO_2 saturation using seismic data from the Sleipner CO_2 storage project** Philip Ringrose, Equinor & NTNU
14.14	P13 - **A proxy model for CO_2 injection during a typical storage project** Lex Rijkels, ExploCrowd
14.22 **Virtual**	P14 - **A Compositional Numerical Model Study on the Impacts of Aquifer Formation Geological and Geochemical Properties on CO_2 Injectivity and Storativity: A Case Study Cameroon Gulf of Guinea** Gregory T. Mwenketishi, University of Bradford, UK
14.30	P15 - **Utilizing Machine Learning Power to Predict the Performance of Carbon Dioxide Trapping in Saline Aquifers** Mustafa Alkhowaildi, King Abdullah University, Saudi Arabia
14.38 **Virtual**	P16 - **CO_2 Storage Efficiency for Capacity Estimation – Integrating Geological and Engineering Risks in a Clastic Saline Aquifer in Central Alberta, Canada** Vicky Wang, GLJ, Canada
14.46	P17 - Title TBC Jules Reed, Premier Corex
15.55	**BREAK**

15.30	**Panel Session 2:** Methodologies and applications of storage efficiency calculations Session chairs: Tina Lohr, Ellen Mitchell Panel session leader: Chick Wattenbarger, Reservoir Engineer at ExxonMobil Panel speakers: Sylvain Thibeau (TotalEnergies), Alex Bump (BEG Uni Texas), Fiona Sutherland (Storegga), Rick Chalaturnyk (Uni Alberta) 1) How do we ensure consistency of methodology across the evolving stage of site evaluation? 2) Do different project stages require different approaches, and if so which ones? 3) What appraisal processes need to be used to prove the efficiency calculation?
17.00	**Closing Remarks**
17.15	**End of Convention**

The Energy Group of the Geological Society would like to thank the following for their support for this conference:

Conference Sponsors:

Corporate Sponsors:

CONTENTS PAGE

ORAL ABSTRACTS
(In Programme Order)

Session One - Experience and use of storage efficiency in describing and comparing CCS globally

Matteo Tazzi
The journey from CS license award to storage permit

Matteo Tazzi, Senior Development Geologist at NSTA

The CCUS industry can transpose many of the skills learned from decades of North Sea oil and gas production, but Operators must also adapt to new ways of thinking and develop new technical competencies to deliver carbon storage projects. To assist Operators in doing so and as the regulator responsible for granting Storage Permits which gives consent to the injection of CO2 into a suitable underground geological formation in the UKCS, the North Sea Transition Authority (NSTA) has developed two key guidance documents to Steward carbon storage project developers through the NSTA licence and permitting process:

1. Guidance on Applications for a Carbon Storage Permit
2. Guidance on the content of Offshore Carbon Storage Permit Applications

These documents combine to provide the technical, regulatory, process and planning requirements as well as the behaviours and good practices expected to deliver a viable carbon storage development and be granted a storage permit by the NSTA.
Along with planning and delivering a viable carbon storage development, and at the core of the NSTA's role in granting storage permits, an Operator must satisfy the NSTA that under the proposed conditions of use of the storage site, that there is no significant risk of leakage. This is demonstrated over three distinct phases of the Appraisal Term of a Carbon Storage licence, each with different objectives and considerations that are in place for a carbon storage development to evolve effectively while understanding and managing the risks and uncertainties to containment, capacity and injectivity.
This presentation describes the 'road map' of the different phases of the Appraisal Term of a CS licence, from licence award to grant of a storage permit as captured in the guidance documents highlighting the key deliverables and expectations. These include the evolution of the containment risk assessment, characterisation of the storage site and complex, the carbon storage development plan, and the closely integrated monitoring and corrective measures plans among others, while also highlighting the parallel requirements of other regulators.
The documents aim to support the UK's vision of becoming a global technology leader in the offshore geological storage of CO2 and unlocking the large CO2 storage potential of the North Sea.

NETL’s Perspective on Storage Efficiency and CO2-SCREEN

Angela Goodman, US Department of Energy, NETL

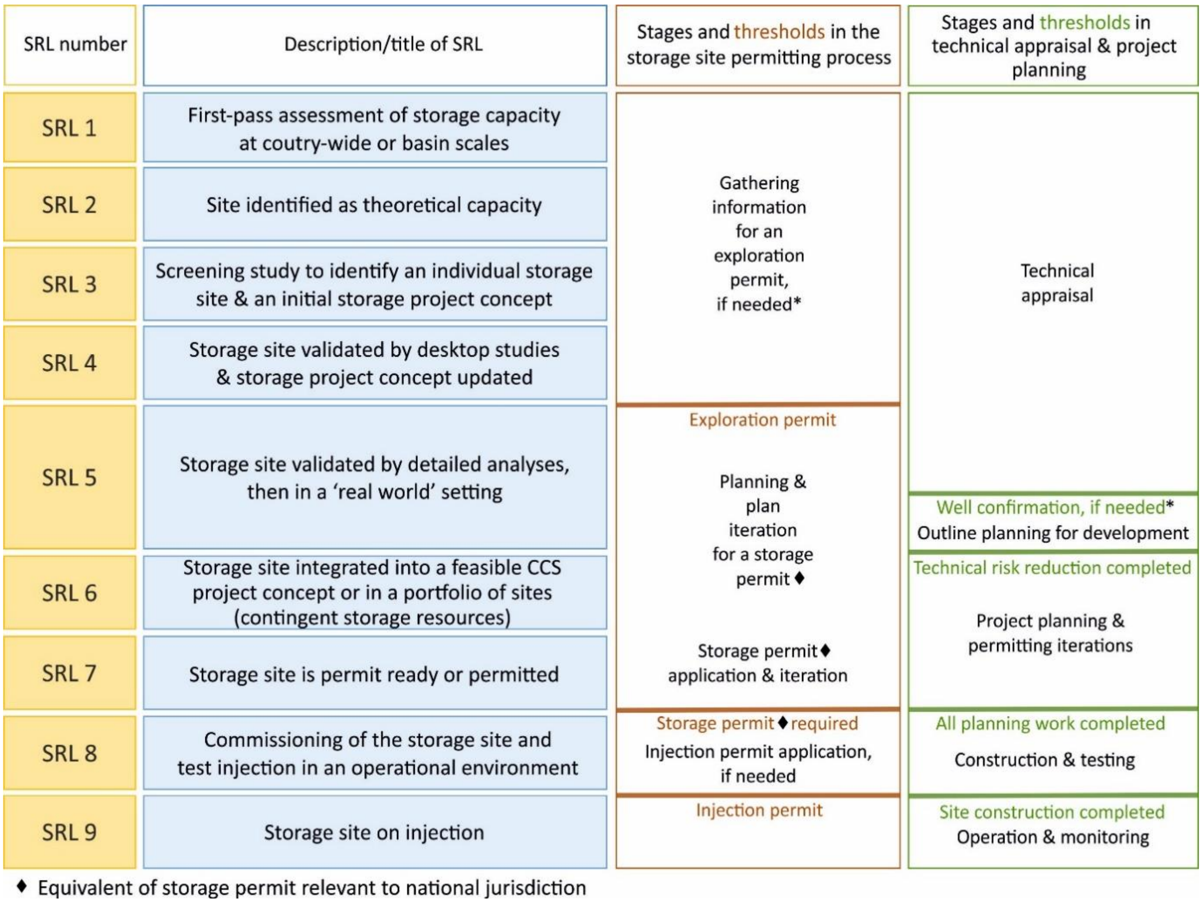
Carbon capture and storage (CCS) is a process that captures carbon dioxide (CO2) by separating it from anthropogenic emissions sources before atmospheric release and storing that CO2 in deep geologic reservoirs. CCS is a powerful method for reducing anthropogenic CO2 which can ultimately diminish the effects of climate change. Prospective CO2 storage resource is the amount of carbon dioxide that can be stored in a given geologic formation typically given as a mass (e.g., metric tons). Obtaining accurate estimates of CO2 storage resources is necessary for governments and industries to make energy-related policy decisions.

Researchers at the National Energy Technology Laboratory (NETL) under the Department of Energy (DOE) developed a methods and a tool [CO2-SCREEN (Storage prospeCtive Resource Estimation Excel aNalysis) https://edx.netl.doe.gov/dataset/co2-screen] to estimate prospective carbon storage resources for saline formations, unconventional shale formations, and residual oil zones. The methods and tool provide CO2 storage and efficiency outputs in the form of probability estimates (i.e. P10 and P90) as well as partitioning storage and efficiency estimates based on storage mechanism (total, free phase, sorbed phase, and dissolution phase). This presentation will focus on how storage efficiency is calculated based on numerical modeling efforts, how it’s applied in the storage methods and tool, and then highlighting needs for future development.

Communicating readiness for CO_2 operations using Storage Readiness Levels, and its application to the UK national CO_2 storage resource

Maxine Akhurst and Karen Kirk
British Geological Survey
mcak@bgs.ac.uk

A framework of CO_2 Storage Readiness Levels (SRLs) is presented to communicate the entirety of technical appraisal, permitting and planning activities achieved at a potential CO_2 storage site and what remains to be completed for CO_2 storage operations (Figure 1). The schema, based on learning gained from the experience of researchers, regulators and industry from the 1990s, is described and assessed by application to 742 saline aquifer formation and hydrocarbon field sites, offshore the UK, Norway and The Netherlands (Akhurst et al., 2021). The framework is flexible to accommodate national differences in procedures and practise and the unique character of each site. It is applicable regardless of the timescale of appraisal or scale of assessment.



SRL number	Description/title of SRL	Stages and thresholds in the storage site permitting process	Stages and thresholds in technical appraisal & project planning
SRL 1	First-pass assessment of storage capacity at coutry-wide or basin scales	Gathering information for an exploration permit, if needed*	Technical appraisal
SRL 2	Site identified as theoretical capacity		
SRL 3	Screening study to identify an individual storage site & an initial storage project concept		
SRL 4	Storage site validated by desktop studies & storage project concept updated		
SRL 5	Storage site validated by detailed analyses, then in a ‘real world’ setting	Exploration permit Planning & plan iteration for a storage permit ♦	Well confirmation, if needed* Outline planning for development
SRL 6	Storage site integrated into a feasible CCS project concept or in a portfolio of sites (contingent storage resources)		Technical risk reduction completed Project planning & permitting iterations
SRL 7	Storage site is permit ready or permitted	Storage permit ♦ application & iteration	
SRL 8	Commissioning of the storage site and test injection in an operational environment	Storage permit ♦ required Injection permit application, if needed	All planning work completed Construction & testing
SRL 9	Storage site on injection	Injection permit	Site construction completed Operation & monitoring

♦ Equivalent of storage permit relevant to national jurisdiction

Figure 1. SRLs framework, stages and thresholds in the storage site permitting process and storage project technical appraisal and planning (green). The thresholds for permitting are illustrated and labelled in brown. The technical appraisal and planning thresholds are illustrated and labelled in green. *An exploration permit or well confirmation may not be needed for re-use of a hydrocarbon field for CO_2 storage.

The framework is consistent with and extends the industry commercial project development classification to include categories for sites with a lesser level of data and evaluation (Figure 2).

<table>
<tr><th>Storage Readiness Level (SRL)</th><th colspan="3">Storage Resources Management System
Storage project maturity classes and subclasses
(SPE-SRMS, 2017)</th></tr>
<tr><td>SRL 9 – Storage site on injection</td><td rowspan="6">Discovered storage resources</td><td rowspan="3">Commercial (capacity)</td><td>On injection</td></tr>
<tr><td>SRL 8 – Commissioning of the storage site and test injection in an operational environment</td><td>Approved for development</td></tr>
<tr><td rowspan="2">SRL 7 – Storage site is permit ready or permitted</td><td>Justified for development</td></tr>
<tr><td rowspan="3">Sub-commercial (contingent storage resources)</td><td>Development pending – Project activities ongoing</td></tr>
<tr><td rowspan="2">SRL 6 – Storage site integrated into a feasible CCS project concept or a portfolio of sites (contingent storage resource)</td><td>Development on hold or unclarified</td></tr>
<tr><td>Development not viable</td></tr>
<tr><td rowspan="2">SRL 5 – Storage site validated by detailed analyses, then a relevant ‘real world’ setting</td><td colspan="2" rowspan="3">Undiscovered storage resources</td><td>Prospect – Project sufficiently well-defined to be viable drilling target</td></tr>
<tr><td>Lead – Project poorly defined and needs data and/or evaluation</td></tr>
<tr><td>SRL 4 – Storage site validated by desktop studies and storage project concept updated</td><td>Play – Requires more data and/or evaluation</td></tr>
<tr><td>SRL 3 – Screening study to identify an individual storage site and an initial project concept</td><td colspan="3"></td></tr>
<tr><td>SRL 2 – Site identified as theoretical capacity</td><td colspan="3"></td></tr>
<tr><td>SRL 1 – First-pass assessment of storage capacity at country-wide or basin scales</td><td colspan="3"></td></tr>
</table>

Figure 2. Equivalence of SRLs framework with Storage Resources Management System (SPE-SRMS, 2017) project maturity classes and subclasses.

Application of the SRLs framework to the UK national storage resource from 2021 to present day illustrates the increasing maturity of UK sites for CO_2 storage and used to inform a strategic approach to site appraisal.

References

Akhurst, M, Kirk, K, Neele, F, Grimstad, A-A, Bentham, M, and Bergmo, P. 2021. Storage Readiness Levels: communicating the maturity of site technical understanding, permitting and planning needed for storage operations using CO_2. International Journal of Greenhouse Gas Control, https://doi.org/10.1016/j.ijggc.2021.103402

SPE-SRMS, 2017. CO2 Storage Resources Management System, sponsored by the Society of Petroleum Engineers (SPE), published October 2017. https://www.spe.org/industry/docs/SRMS.pdf

To “E” or not to “E”, that is the Question

Scott M Frailey, Illinois State Geological Survey, U of Illinois at Urbana-Champaign
SFrailey@Illinois.edu

The ubiquitous yet misunderstood storage efficiency seems to disappoint those who make estimates of storage. But disappointment comes from ill-defined usage and misplaced and unrealistic expectations. Storage efficiency is storage efficiency: the quantity of CO2 stored or projected to be stored in a volume of rock…a numerator and a denominator. To define the numerator and denominator, the purpose of the estimation must be known a priori, and a project must be specified, with adequate specifications to realize the storage efficiency. Estimation purposes may be a regional resource assessment of a basin or sub-basin or a site-specific assessment with defined area or specific quantity of CO2 from a single or multiple sources. Project specifications are needed so the attributes controlling storage efficiency can be represented regardless of the actual method used (e.g. volumetrics or dynamic modeling). Project specifications examples are a single vertical well perforated at the base of a specified geologic formation within an anticline or five vertical wells on regional dip, perforated across the entire geologic formation with a center well extracting brine. To this end, storage efficiency is not a standalone value, storage efficiency must be derived in the context of the estimation purpose and project specifications.

Project specifications

Storage efficiency is applicable to all stages of project development (i.e. maturity): site screening, site selection, site characterization, and active injection. The stage of development often dictates the data available for storage efficiency estimates. For site screening, storage efficiency can be used to estimate the Total Storage Resources of a basin or site. For site selection, storage efficiency can be used to estimate Contingent Storage Resources of a site with detailed project specifications while the project is developed for active injection. For an actively injecting project, storage efficiency can be used to estimate Storage Capacity, the storage that is likely to be realized with the specifications of an active project. Consequently, the data available and method used for storage efficiency will be dependent on the purpose of the estimation and the maturity of project development.

Nevertheless, depending on the purpose, storage efficiency may be a means to an end…the quantity of CO2 storage (i.e. mass or volume). If so, dynamic modeling defined by a project may be most appropriate and can lead to the quantity of CO2 without estimating storage efficiency. However, if variations in the project specifications are warranted (e.g. different well orientation, depth of perforations, brine extraction), storage efficiency is a good metric (among many) to compare a project’s specifications in the effectiveness of the varying projects to store CO2 at the same site.

Storage efficiency works and works well when derived and applied to the problem at hand. Only proper context, purpose and project specifications can yield storage efficiency that are useful and meet expectations.

Methods used to estimate storage efficiency

Concerns regarding the usage of storage efficiency arise mostly from regional assessments that provide very high estimates of CO2 storage in comparison to assessments that are more closely related to a specific project. This is evident from comparisons of dynamic and static storage efficiency. (Dynamic is based on flow modeling, and static is based on volumetric equations.) However, there is no such thing as dynamic and static storage efficiency, per se, except in the literature. There are dynamic (flow modeling) and static (volumetric) methods used to simulate and represent different processes and projects, but dynamic and static are not proper adjectives for the term storage efficiency.

Recognized or not, even the most basic and fundamental usage of a dynamic method has a project specified as soon as a well is placed in the dynamic model; the essence of a specifying a project has been started. The perforated interval of the well and orientation of the well are project specifications. The porosity and permeability model, representative of a specific geologic formation, is a project specification. The simulated rate of injection, maximum pressure injected, and the injection schedule are all project specifications. The number of wells, locations of wells, and use of brine extraction are all project specifications. Because dynamic modeling requires input that are all project specifications, storage efficiency derived from a model has elements of a project explicitly specified, recognized or not.

The inference of a project is not as obvious when using static (volumetric) methods to estimate storage efficiency. Static methods typically involve macroscopic and microscopic displacement terms, which each represent a unique process due to an injection scheme and are dependent on specific geologic features. Injection schemes and the geologic formation are project specifications. Therefore, implicit in the terms of the static methods are project specifications; because, the terms only implicitly specify a project, project specifications are most often not considered or stated when using the static methods.

Comparisons of storage efficiency from static and dynamic methods generally show that static methods yield relatively smaller values because of the varying assumptions made without consideration of similar projects or purpose. However, the storage efficiency from static methods are generally applied to very large areas (e.g. entire basins) and yield very large estimates of storage that dynamic methods do not support. Furthermore, static methods are often related to bulk properties such as total thickness and total porosity instead of effective thickness and effective porosity. In comparison to dynamic methods that most often use effective properties. When storage efficiency is scaled from total to effective properties (for similar projects), storage efficiency values are larger and compare similarly to those estimated from dynamic models.

Applications of storage efficiency

The application of storage efficiency methods (static and dynamic) is the culprit leading to disappointment in the use of storage efficiency to calculate storage. Specifically, the choice of area and net thickness (the denominator) may be the root of the disappointment, not storage efficiency itself. Dynamic modeling provides an area and thickness based on the distribution of the CO2 plume (the numerator). However, for an actual project, the distance to the next well or project area will not be chosen based on plume size but chosen based on pressure front or proximity to an emission site or even real estate ownership and subsurface storage rights; whichever is stated in the project specification should be used in the storage efficiency calculation. The volumetrics-based storage efficiency (static) applied to large areas (e.g. regional assessment), assumes that multiple wells with immediately adjacent plumes would be part of the project specification. In comparison to dynamic modeling, this would not be the case. Therefore, to compare storage estimate using storage efficiency derived from volumetrics and dynamic modeling requires using identical area and thickness (i.e. project specifications) in the calculation.

Depending on the estimation purpose and method, storage efficiency may not be necessary, and a storage estimate can be used directly. For active projects, storage efficiency can be used to monitor performance with time to understand the storage process, for example, in terms of land available for storage and the need for additional perforated intervals. For site screening and selection, storage efficiency is useful when comparing multiple projects for the same site or same project at different sites. Assessment of performance and comparisons are good reasons to use storage efficiency. When the purpose of the assessment does not require performance assessment or comparisons, storage efficiency may not be needed. Also, static methods require use of storage efficiency, but dynamic methods do not. Therefore, when using dynamic methods and purpose is to estimate storage (without comparison or performance assessed), storage efficiency is not necessary to estimate storage.

CO2 Storage Resources Management System

In 2017, the Society of Petroleum Engineers published the CO2 Storage Resources Management System (SRMS) that standardizes classes of storage estimates (called storable quantities) based on project maturity and categories based on geologic uncertainty. In order of higher to lower project maturity, the SRMS Classifications are Storage Capacity, Contingent Storage Resources (CSR), and Prospective Storage Resources. The SRMS Categories are named only for Storage Capacity; from most to least certain, the Categories are Proved Capacity, Probably Capacity, Possible Capacity.

For an actively injecting project, projections of the Storage Capacity and the Storage Resources are useful. Storage Capacity is storage that is assigned to and associated with an active project's specifications. The project's CSR would be the additional storage within the same area through relative major changes to the active project or development of a new project. Depending on the project specifications, the CSR might require developing new technology, improved economics, new investments (e.g. longer pipeline to another source). Volumetric-based storage efficiency may be best for Storage Resource assessment compared to dynamic modeling may be best for Storage Capacity. Moreover, storage efficiency has a role in monitoring storage performance and validation of a project's Storage Capacity and CSR. Storage efficiency comparisons should be made for the same SRMS storage class and category.

Conclusion

To E or not to E, that is the question. No, E for me: I am interested in well-defined, mature or active projects and the CO2 that the project can store. I am uninterested in performance analyses or comparison to other sites or alternative projects to this project. Yes, E for me: I am interested in the Storage Resources and the Storage Capacity. I am interested in the performance of an active site and comparison between sites and projects.

Storage Efficiency: Experiences and Reflections

Robert Wattenbarger, Lisa Lun, and Prasanna Krishnamurthy
ExxonMobil Technology and Engineering Co., Spring, Texas, USA
chick.wattenbarger@exxonmobil.com

Storage efficiency (SE) is increasingly being used as a performance metric for assessment of potential CO2 storage sites. Despite its widespread usage, there is quite a bit of variability in its definition, formulation, and its usage during the different stages of a project. This variability can undermine the usefulness of storage efficiency for geoscience, engineering, and business application and, at times, create more confusion than clarity. Owing to the implications of storage efficiency reporting on business decisions and regulatory applications, it’s become important to further clarify definitions, usage, and re-evaluate the scope of applicability.

This talk will reflect on our experiences and lessons learned from defining and using storage efficiency within ExxonMobil.

Session Two - Methodologies and applications of storage efficiency calculations

Storage efficiency at opposite ends of scales of interest

Sam Krevor, Imperial College London

In this presentation I will address two distinct topics at opposite ends of the spatial scales of relevance for CO_2 storage efficiency.

The first topic is constrained by length scales of observation in the laboratory. The efficiency of the use of pore space and the extent of CO_2 trapping within storage resources depends in part on the flow processes governed by petrophysical properties. These properties are often observed by tests on rock cores with length scales of order centimeters to a meter. The spatial scales of observations resolved in these measurements now begins at the micrometer scale of individual rock pores. I review the state of play in laboratory based reservoir characterization of flow properties. I describe the state of the art and highlight what is novel to CO_2 storage, contributions from advances in digital rock techniques, and those practices which are successfully being carried over from core analysis rooted in the oil and gas industry.

In the second topic I address questions the representation of resource use in techno-economic models used to identify scaleup trajectories and identify climate change mitigation plans. I will review the varied uses and demands for resource assessment in these assessments and place this in the historical context of resource assessment for the oil & gas industry. I argue for both a standardised reporting of storage resource use and an inclusion of growth modelling in the consideration of future resource potential.

Bio

Dr Samuel Krevor is a Reader and Royal Academy of Engineering Senior Research Fellow in the Department of Earth Science & Engineering. His research group investigates the physics of flow in porous rocks, reservoir simulation and engineering, and resource use and scaleup in application to subsurface CO_2 storage. He is an Associate Editor for the International Journal of Greenhouse Gas Control and was a 2022-23 Distinguished Lecturer for the Society of Petroleum Engineers.

Storage capacity assessment techniques for gigatonne-scale CCS

Sarah E. Gasda
NORCE Norwegian Research Centre, Bergen, Norway
University of Bergen, Bergen, Norway

CO2 injection rates for permanent storage will need to increase substantially to reach global climate targets set out by the IPCC. For Europe, this implies scale up of current CO2 storage activity to 100-300 Mtpa by 2050. Continental margins in the North Sea have enormous undiscovered storage potential, but extensive efforts are needed to further mature these regions into commercial assets. To help reduce per unit storage costs, sites will likely be clustered around common surface infrastructure. The resulting impact of multi-site storage development on storage capacity and injectivity is an open area of research.

Gigatonne-scale storage capacity and injectivity assessment requires computational approaches that are suitable for regional-scale, multi-site storage scenarios. Of particular interest is assessment of pressure interaction between sites that share a common hydraulic unit, i.e. saline aquifer. Here, it is important to consider the influence of local heterogeneity, fluid flow and trapping mechanisms of individual sites on regional pressure buildup and vice versa. Despite recent advances in high performance computing (HPC) simulation technology for CO2 storage, it is computationally expensive to resolve all salient processes at the necessary level of detail. There are also practical constraints in merging several individual dynamic models owned and operated by different parties.

We describe a two-stage approach to regional-scale simulation that allows for seamless and non-invasive exchange of pressure-related information between local and regional scales. The novel approach speeds up computational time and preserves the autonomy of individual site simulation with respect to model and simulator choices. In addition, we describe a new upscaling concept that captures CO2 dissolution from centimeter- to field-scale. This method is important for quantifying the contribution of dissolved CO2 to local storage capacity and its subsequent impact on pressure development at the regional scale. Finally, we apply accelerated methods to quantify the impact of regional geologic uncertainty on pressure interaction between multiple sites. The results of this study provide new insight into the risk of overpressure for sustaining gigatonne-scale regional injection rates over time.

Geomechanical pressurization constraint development – Example from the Northern Lights project, offshore Norway

Nicholas Thompson (*nicth@equinor.com*), *Northern Lights Joint Venture DA*/*Equinor ASA*, *Trondheim*, *Norway*

CO_2 injection inherently entails potential pressurization of the host storage reservoir. While storage potential is controlled by many factors, a primary control – particularly in virgin pore pressure saline aquifer conditions in geologic balance – are the pressurization limitations given by geomechanical conditions. These limitations, defined by the margins to tensile (“hydraulic fracturing”) and/or shear (“fault slip/reactivation”) failure, essentially cap the pressurization potential, ultimately defining the system design, committable volume resources and overall project potential/value.

The Northern Lights project is a first-mover establishment of a flexible solution for European industrial decarbonization at scale. Phase 1 (start 2024) includes transport, temporary onshore storage, permanent subsea injection and storage of up to 1.5 Mt/year liquid CO_2 via one to two dedicated injector wells, with Phase 2 (anticipated start 2026) ambitions of scaling up to full pipeline capacity expected to be 5+ Mt/year. As Phase 2 involves significant volume increases, the project has had increased focus on defining the ultimate pressuization capacity of the storage system. This process has included focused data collection to better quantify the in situ stress conditions, development of depth-dependent geomechanical constraints that account for all relevant failure mechanisms and implementation of these constraints in a suite of dynamic reservoir simulations. Each of these steps has been designed to account for uncertainly in and variability of the geologic storage system; the final product resulting in a well-constrained forecast of committable volume storage potential, significantly aiding Phase 2 investment and related business development decisions.

The aim of this presentation is to focus on reviewing the importance of essential early-phase data collection, understanding geomechanical limitations and review the approach the Northern Lights project has taken to account for these factors in realizing ultimate project potential. While Northern Lights is given as an example, most approaches considered are not unique to this project and thus universally applicable to other developling CCS projects.

How does the early 0.5 MT performance inform the calculation of an Efficiency Factor at the Aquistore Project, Canada.

Rick Chalaturnyk, PhD, PEng, FEIC
NSERC/Energi Simulation Industrial Research Chair
Professor of Geotechnical Engineering, University of Alberta
rjchalaturnyk@ualberta.ca

The Aquistore CO2 Storage Project is an integral component of SaskPower's Boundary Dam CO2 Capture Project located in southeastern Saskatchewan, Canada. Operational synergies between the capture facility (supply) and CO2-EOR (demand) also require excess CO2 to be transported via pipeline to the Aquistore injection well. The Aquistore site includes one injection well and one observation well approximately 150m offset from the injection well. Both wells are completed with various measurement and monitoring equipment, including distributed temperature sensing (DTS), distributed acoustic sensing (DAS) and tubing/casing-conveyed pressure gauges at different levels to measure pressure and temperature changes downhole during to CO2 injection.

The storage reservoir is 200m thick at the injection site and extends from 3130m to 3350m depth at the injection well. The reservoir comprises the Deadwood and Winnipeg formations. The Deadwood Formation is sandstone with silty-to-shaley interbeds. It is overlain by the Winnipeg Formation, which includes the Icebox (shale) and Black Island (sandstone). The Icebox constitutes a shale caprock and is the primary seal to the reservoir. A secondary storage seal is provided by the Prairie Evaporite Formation which is a ~150 m thick evaporitic unit that resides ~500m above the reservoir. The Winnipeg/Deadwood formations at the Aquistore site have porosities ranging from 0.04-0.17 and permeabilities of 0.1-20 mD. The reservoir temperature is approximately 115 °C, initial average reservoir pressure is 35 MPa and the pore fluid is a hypersaline brine with a TDS of approximately 330 g/L.

Historical dynamic data has been recorded since the drilling and completion of the CO2 injection and observation well in 2012 and the start of CO2 injection on April 16, 2015. Figure 1 shows the early dynamic responses at these wells during the early startup phases. This dynamic data has provided insight on issues ranging from well integrity to reservoir simulation to seismic monitoring (Figure 2 and 3) based on this valuable historical data as well as salt precipitation within the wellbore (Figure 4). The time-lapse seismic data has provided opportunities to update dynamic reservoir simulation predictions of plume position. In addition, the project has provided a valuable opportunity to collect real-time monitoring data of CO2 phase changes in the injection stream under fully integrated, high dynamic operational conditions and this provides unparalleled information for understanding geological storage under these conditions and optimizing completion systems.

Estimating CO2 storage capacity is complex due to various trapping mechanisms that operate throughout a CO2 geological storage project and involves the injection phase and the post-injection evolution of the injected CO2 plume. Storage capacity evaluations use a storage efficiency coefficient considering factors like aquifer heterogeneity, CO2 buoyancy, sweep efficiency, and relative permeability effects among others. CO2 storage also depends on interplay between capillary forces, viscous forces, gravitational buoyancy forces and on relative permeability saturation relationships in aquifer rocks which poses significant challenges. Several parameters such as in-situ pressure, injectivity etc., also influence this capacity estimation process indirectly affecting each other ultimately influencing overall potential for storing carbon dioxide effectively. Many of the significant contributions to storage capacities have been evaluated previously using both open & closed systems with computational efficiencies mostly based on numerical models (see Bachu (2015), Goodman, et al. (2011), Gorecki et al. (2009), Myshakin et al (2023), Ranjith et al. (2013), USDOE (2012))

While no efforts were made during the initial planning stages of the Aquistore project to compute the storage capacity within the vicinity of the Boundary Dam Project, we have returned to the early 0.5MT performance history of the Aquistore Project to examine whether this history matched data can help inform what an appropriate efficiency factor would be for the Deadwood Formation. While numerical simulations are used from the perspective of a history match analysis, we attempt to utilize four time-lapse seismic surveys along with updated simulations improving model accuracy & petrophysical properties matching interpreted position of plume.

The goal is to utilize known parameters including amount of injected mass & monitored shape/volume occupied by CO2 in reservoir zones for early performance evaluation providing insights about on the effective utilization factor within the Deadwood Formation being targeted for Aquistore project.

Using sand-tank experiments to visualize and quantify flow and saturation for predicting CO2 storage efficiency in clastic materials

Tip Meckel, Hailun Ni
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin
Corresponding author's e-mail address: tip.meckel@beg.utexas.edu

Keywords: storage efficiency, resource optimization, capacity, capillary flow, sand tank experiment

One of the most common uncertainties when developing a CO2 storage project relates to the storage capacity. This has been a topic of great debate in the CCS community for decades due to the complex fluid flow behavior of CO2 in brine-saturated rocks, with multiple methodologies having been developed. Practically, most of these methods rely dominantly on a storage efficiency factor, conceived in a variety of ways for different geologic and fluid settings. However, verifying the low efficiencies expected from theoretical considerations is a difficult task. To attempt to better understand multiphase flow, expected saturations, and storage efficiencies, a novel experimental apparatus and methodology were developed to visualize and quantify saturation during multiphase flow in a two-dimensional sand tank with engineered depositional heterogeneity [1], [2]. After years of development, the facility is now generating exciting results, and a summary of many recent publications will be presented. This presentation will briefly cover the laboratory setup that utilizes a 60 by 60 cm tank (similar to a Hele-Shaw cell) with a programmable depositional apparatus allowing for realistic bedform formation and high repeatability. Results focus on the documentation of fluid flow characteristics at a scale far larger than a rock core (although only in 2D). The ability to history match through numerical simulation the complex fluid flow at these scales will be demonstrated, and the understanding of how that informs storage efficiency will be summarized [3]–[7]. Lastly, the ability to use numerical simulations of 3D numerical models of bedforms allows for a predictive model based on grain size and bedform architecture.

REFERENCES

[1] P. G. Krishnamurthy, T. A. Meckel, and D. DiCarlo, “Mimicking Geologic Depositional Fabrics for Multiphase Flow Experiments,” Water Resour. Res., vol. 55, no. 11, pp. 9623–9638, 2019, doi: 10.1029/2019WR025664.

[2] P. G. Krishnamurthy, “Geologic Heterogeneity Controls On CO2 Migration and Trapping,” The University of Texas at Austin, 2020.

[3] H. Ni and T. A. Meckel, “Characterizing the Effect of Capillary Heterogeneity on Multiphase Flow Pulsation in an Intermediate-Scale Beadpack Experiment Using Time Series Clustering and Frequency Analysis,” Water Resour. Res., vol. 57, no. 11, pp. 1–17, 2021, doi: 10.1029/2021WR030876.

[4] P. G. Krishnamurthy, D. DiCarlo, and T. Meckel, “Geologic Heterogeneity Controls on Trapping and Migration of CO2,” Geophys. Res. Lett., vol. 49, no. 16, 2022, doi: 10.1029/2022GL099104.

[5] H. Ni and T. Meckel, “Effects of Flow Pulsation on CO2 Buoyant Migration and Capillary Trapping,” SSRN Electron. J., no. October, pp. 1–9, 2022, doi: 10.2139/ssrn.4273191.

[6] H. Ni, R. Braganca, N. Tisato, and T. Meckel, “Monitoring CO2 Plume Migration with Lab-Scale Ultrasonic Experimental Setup,” SSRN Electron. J., no. October, pp. 1–9, 2022, doi: 10.2139/ssrn.4273218.

[7] A. Bump et al., “Composite confining systems: Characterizing, de-risking and permitting unconventional seals for CO2 Storage,” SSRN Electron. J., no. October, pp. 1–11, 2022, doi: 10.2139/ssrn.4286411.

POSTER ABSTRACTS

Calculating a consistent storage resource across a growing portfolio

Alison Isherwood, Elaine Campbell, Storegga

Acorn, Storegga’s cornerstone project based in the UK, will sequester CO_2 from a variety of customers into well understood reservoirs, using repurposed infrastructure. Using this experience, Storegga has expanded internationally and now has a portfolio of projects in the US, Europe and is evaluating opportunities elsewhere, including Asia Pacific.

Achieving consistency across our growing portfolio has required consistency in the calculation of storage resource. We have observed that across the industry, storage resource estimations can vary greatly between projects and even between different estimations of the same storage site. One key aspect in these evaluations is storage efficiency, which is often misrepresented or excluded. How storage efficiency is applied needs to be understood and benchmarked during the early screening of potential storage opportunities. Conversely, verification of modelled storage efficiency outputs as storage sites are matured should be consistent to ensure project viability is uniformly assessed.

What industry needs to estimate storage resource and why most published Storage Efficiency Coefficients don't help us

Peter Zweigel1*, Bamshad Nazarian 1, Tarald Svanes 1
1: Equinor ASA, Norway, *pzw@equinor.com

Simple, "static" methods that combine simplified calculations of the available or accessible pore volume with a storage efficiency coefficient (SEC) are in use for estimation of storage resource (1) at regional or basin scale and (2) for early resource assessment of potential storage sites before site characterization has matured sufficiently to allow meaningful site-specific dynamic reservoir simulations. This paper focuses on storage site application (2) and argues that most published studies, and SECs therein, are not applicable for estimation of storage resource at site scale. However, these published SECs are uncritically used in industry, which leads to wrong (typically too low) estimates of storage resource. Whereas industry is interested in optimal utilization of the available pore space at a site (safe, cost-efficient, utilizing the available total "in-place" resource), published studies are typically highly simplified (often only one well) and study which fraction of the pore space in a plume footprint area will be filled by CO2. Depleted petroleum reservoirs have typically sufficient data and subsurface models available and do not need simplified methods for storage resource estimation. Thus, here we focus on saline aquifers.

Aquifer storage sites can be grouped into two classes: (a) sites with structural and/or stratigraphic closures, and (b) open monoclines, where trapping of CO2 relies on residual gas trapping and dissolution in brine. Storage resource in closure sites consists of two components: (i) storage in the closure and (ii) storage below the closure's spill-point depth in the pore space contacted around the injection wells and during migration towards the closure.

How much of the pore space in the closure (i) can be utilized depends on many factors; amongst the typically more important ones are closure size, closure height, reservoir properties and their heterogeneity, volume fraction of permeable facies (which steers 3D connectivity), compart-mentalization, seal capacity, and site design (number, placement and design of injection and brine production wells). While published studies address the influence of important factors such as reservoir properties, heterogeneity, structural dip etc. on CO2 plume footprint area and pore space utilization in the footprint-based reference volume, they do not shed much light on how much of the closure pore volume can be effectively filled by CO2. Controlled fill of the closure can achieve high storage efficiency. Dynamic reservoir simulations by Equinor for a potential real storage site in a 4-way closure yielded SEC of 40% and above, depending on the injection design; these values are approximately one order of magnitude larger than typical published SECs. Recovery factors from analogue hydrocarbon fields may also give an indication of achievable storage efficiency.

Storage resource below spill-point depth (ii) depends on how much pore space is contacted by CO2, which is a function of the number of wells, and on how large fraction of injected CO2 will be trapped deep and thus never reach the closure pore volume. Published studies can provide some guidance on the effect of, e.g., reservoir properties (particularly permeability and residual gas saturation), reservoir geometry (particularly dip of the layers in which CO2 migrates), migration distance to the closure, well design and injection rate on trapping. However, SECs from these cases have little value in practical application because they depend on an arbitrary and study-specific reference quantity (the pore space within an arbitrarily chosen envelope around the plume footprint, which is used as denominator to calculate the SEC). In real cases, large fractions of the aquifer vertically below and down-flank of the closure will not be utilized (not be part of any plume footprint volume) because economic constraints will limit the number of injection wells and thus volumetric reservoir access. The reference pore volume to which SECs could be applied is thus not defined in real cases and would require to be estimated by dynamic simulations – which in turn makes the need for SECs obsolete.

For storage in monoclines (b), much of the argumentation applies that was provided above for the aquifer below spill-point depth. SECs from published studies of monocline settings are in most cases not useful for estimation of storage resource; again, mainly because the reference pore volume is defined by the simulated case and cannot easily be estimated for a real case. However, these studies can inform on, e.g., plume footprint area and maximum migration distance as a function of various reservoir and site design characteristics. Simulated maximum migration distance can help to estimate how much CO2 can be injected before any leakage occurs.

For all cases discussed above, the acceptable pressure increase that does not compromise storage integrity is an additional limiting factor. In fact, storage resource in many saline aquifer storage sites is mainly limited by acceptable pressure increase. SECs have been calculated based on this limit for cases of complete or partial pressure isolation of investigated subsurface units (regional or site scale). Such pressure-limited SECs have some relevance for regional resource estimates. However, site studies can estimate pressure-limited storage resources directly, without resort to SEC, based on a combination of estimates of the pore space of the connected aquifer, the acceptable pressurization limit, and brine and rock compressibility.

Substantial uncertainty for estimation of storage resource, and thus realistic storage efficiency, for geological sites stems from lack of experience data. Observations of plume development (e.g. at the Sleipner site) have been used to calculate “storage efficiency” for the plume footprint volumes. However, no industrial storage site has yet reached final plume stabilization, and thus empirical data on final footprint are lacking. For Sleipner, the estimated final areal footprint is much larger than the present footprint; thus, final storage efficiency for the whole reservoir thickness in the footprint area will likely be substantially lower than published values. Industrial sites in operation with published plume monitoring data are either monoclines (Quest) or very subtle closures (Sleipner) and thus not suitable to derive SECs applicable to the closure part of typical storage sites under evaluation. Further, planned and actual injection into industrial storage sites have in all present cases been limited by access of CO2 rather than by subsurface site limits, thus these sites do not provide information about optimized pore space utilization.

Similar to recovery factors in petroleum industry, SECs may serve for benchmarking of sites and site design. However, while the reference volume for recovery factors is clearly defined (hydrocarbons in place), it is less clear for CO2 storage, where also pore volume below the spill-point depth contributes. A meaningful parameter for benchmarking could be SEC for the closure volume, with the caveat that quantification of CO2 actually present in the closure may be challenging.

In conclusion, the practical value of published storage efficiency coefficients from simplified, often single-well settings, is very limited for estimation of the storage resource in real sites. However, the studies underlying these SECs can provide important information about factors that influence plume development and CO2 migration, which can aid storage resource estimates. Publication of studies that aim for effective resource utilization of storage sites could provide realistic SECs for closures, which would help early estimates of storage resources. Unfortunately, plume footprint-based SECs are often used uncritically in industry and beyond their realm of validity. The intention of this paper is to raise awareness of wrong applications and to stimulate generation of realistic SECs, particularly for closures.

E-mission, the quest to forecast E (Storage Efficiency) prior to injection of CO2 for storage

J.G. Gluyas[1,2], **S.E. Daniels[1,3],** V.M. Hunn[1], R.R. Jones[1,3], and G.F.T. Watts[1,4]
[1]*GeoEnergy Durham Ltd, Durham*
[2]*Durham Energy Institute, Durham University*
[3]*Geospatial Research Ltd, Durham*
[4]*Watts Geoscience Consulting, Dorchester*
s.e.daniels@durham.ac.uk

Storage Efficiency 'E' in the carbon capture and storage industry is used to describe the saturation of CO2 at an injection site at the end of the CO2 injection phase. Calculations of E tend to assume that the CO2 remains as a discrete supercritical fluid. E has been applied to basin-scale and to site specific evaluations of CO2 storage capacity. For the large-scale basin assessments, the net to gross of the reservoir as an unknown is often included in E. This results in the inference that E is very small, typically a percent or less. However, we know from open systems of CO2 enhanced oil recovery that the saturations of CO2 in pore fluids at the end of injection may be many tens of percent. For injection of CO2 into saline aquifers (confined or unconfined) we have too few data and too little history to derive reliable saturation statistics that we can use for pre-injection site development studies. Similarly, we know very little about the impacts of injection rate, fluctuation of rate, or CO2 phase changes on transient or final saturation efficiencies.

Here we examine measured and modelled data for a variety of systems and compare these data with natural CO2, petroleum, and other non-hydrocarbon systems as we attempt to define how to assess E before injection begins.

Strengths and weaknesses of the SPE SRMS

Xavier TROUSSAUT, *TotalEnergies*, xavier.troussaut@totalenergies.com

Sylvain THIBEAU, *TotalEnergies*, sylvain.thibeau@totalenergies.com

Abstract:

SPE SRMS was established to classify and categorize CO2 storage resources as a twin system to well-known SPE PRMS, an international standard for hydrocarbon resources widely adopted by Oil & Gas companies and some financial market regulators.

SRMS is a project-based system, meaning that resources are those accessed by a specified project. Project's resources can be calculated by modeling or estimated by analogy with other projects exposed to similar conditions.

SRMS displays key information via a two-dimensional table (see figure):

1. The horizontal axis displays uncertain resource quantities
2. The vertical axis displays project maturation towards commerciality.

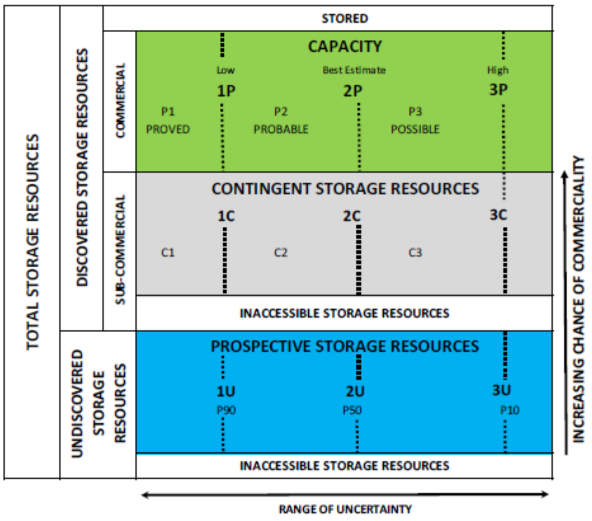


Fig. 1.1 – Resources Classification Framework

Due to its PRMS inception, we believe that the SRMS suffers weaknesses due to dissimilarities between O&G production and CO2 geological storage.

Prospective class

We believe the concept of prospective resources poorly applies to CO2 storage.

PRMS classes mimic Oil & Gas industry processes: Exploration followed by Appraisal and eventually Project execution. Exploration primarily requires proving petroleum presence. Appraisal aims at sizing the development that will optimize the project value.

For CCS in depleted reservoirs, dataset is largely complete, and no Exploration or Appraisal is required.

The large regional saline aquifers targeted are very frequently recognized by legacy drilling and described in geological atlases. As with household waste removal, CO2 storage is a subsidized industry that will strive to minimize expenditure while ensuring safe disposal. Appraisal expenditures will focus on reducing uncertainties, but very rarely will expenditures go to "discovering" undrilled aquifers.

In both cases, CO2 quantities can be injected in any porous media, and ensuring containment will simply depend on the quantity to be injected. This is very different from petroleum production that requires a petroleum accumulation in the first place.

So, we believe term as « Prospectivity » or « Discovery » are not helpful in the context, confuse the public and lead to misunderstanding in the data acquisition process. It is proposed that acreage Permitting underpins a more meaningful threshold.

Commerciality

The SRMS describes with a lot of details commercial criteria of a CO2 storage project, when, in this nascent industry, every project is based on a specific funding scheme. Some are based in Contract For difference of the decarbonized electricity they will produce, some are based on direct State funding of the Transportation and Storage infrastructure, some other are based on tax reduction schemes.

One could argue that a CCS project might not be “economic” in oil and gas industry sense but still be decided and pursued for strategic reasons. In other words, a project final investment decision (FID) should be sufficient for the project to become “commercial” and future injected volumes should be reported, whether “economic” or not, for meaningful accounting of CO2 storage “Capacities”.

Finally, capacity uncontracted of projects that have taken FID should be distinguished from capacity contracted by emitters at date of evaluation.

Categories

Since high confidence of containment is required in waste management, launching a CO2 storage project should be based on the high confidence estimate (P90 or 1P) only. A project cannot afford to have 50% chance of succeeding in storing the CO2 volumes emitters commit to supply. Whereas for oil & gas decisions are mostly based on best estimate (P50 or 2P) and the market will absorb the projects’ volume whatever they are.

During the injection period however, the performance of the store may be better understood through adequate monitoring and so allowing to increase P90, unlocking more capacity for marketing without additional CAPEX.

The Importance of Storage Efficiency in the Application of SRMS

Taylor, G., Kirchin, A., Bradly, J. and Offer, D.
RPS Energy

Increasing the storage of large quantities of carbon dioxide is imperative as the energy transition progresses and the world strives to meet the key targets of the Paris Agreement by 2050. Estimates by the Global CCS institute[1] indicate that large scale gas storage capacity, which requires some form of underground (geological), storage will need to increase, at least 100 fold above current capacity. The necessity to finance various storage schemes requires rigorous estimation of 'bookable' storage capacity using recognised, auditable standards that a financial institution can depend on.

The purpose of this talk is twofold: a) to discuss the application of the existing guidelines (the CO_2 Storage Resources Management System, SRMS)[2] b) to highlight the concept of efficiency within the SRMS system when applied to both depleted fields and saline aquifers.

Similar to hydrocarbon Reserves classification (the Petroleum Resource Management System, PRMS), the SRMS is a project-based system that rigorously defines CO_2 storage in major storage resource classes: Stored, Capacity, Contingent Storage Resources, and Prospective Storage Resources, as well as Inaccessible Storage Resources. The basic classification requires establishment of criteria for the discovery of storable quantities, and thereafter, the distinction between commercial and sub-commercial projects (and hence between Capacity and Contingent Storage Resources). Implicit in the assessment of storable quantities is the assessment of efficiency for the lifetime of the project. Again, as with the PRMS there is a range of uncertainty in volume assigned to each class.

In both depleted fields and saline aquifers, the key attributes of the geological store are the ability to receive the CO_2 efficiently and to trap it effectively. CO_2 in a super critical state would be the most optimal phase for storage, allowing more CO_2 to be stored (depending on pressure and temperature) than gaseous form. However, practical requirements may mean that many projects are initiated in the gaseous phase before moving to a supercritical phase when reservoir conditions allow. In both depleted fields and saline aquifers, understanding the characteristics of the host rock, indigenous fluid and modelling the flow of CO_2 as a gas or super-critical liquid through the porous and permeable host is critical in assessing Storage Efficiency.

This talk will discuss the major hurdles that have to be overcome to move a project from Prospective Storage Resources to Contingent Storage Resources and finally Capacity, given factors that impact the Storage Efficiencies of depleted fields and saline aquifers. Inherent in the process of classifying storable volumes is the determination of commerciality which will be critical when raising project finance.

---

[1] *Ref: https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf*

[2] *CO2 Storage Resources Management System, Approved July 2017, Sponsored by the Society of Petroleum Engineers (SPE)*

Storage efficiency and reduced complexity modelling

Hariharan Ramachandran+, Ian de Jonge-Anderson+, Sebastian Geiger*, Florian Doster+
+: Institute of Geoenergy Engineering, School of Energy, Geoscience, Infrastructure and Society, Heriot Watt University
*: Department of Geoscience and Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology

This conference is about the factor storage efficiency to estimate storage capacity in a target formation. This factor is used to account for lithological heterogeneity, trapping structures, boundary conditions, injection rates, well spacing, fluid properties etc. A robust value for the storage efficiency factor can be obtained by comparing the target formation with previous projects. Unfortunately, CCS is still a young industry with limited experience to draw from for a robust estimate. The established alternative are detailed project specific reservoir simulation studies. These are costly and time consuming and hence inadequate at early project stages. In this contribution we present a portfolio of reduced complexity models that can serve as a middle ground. More specifically we present vertically integrated models, spill point analysis and flow diagnostics inspired approaches to obtain storage efficiency factors with a higher level of confidence than estimates but less effort than full reservoir simulations.

CO_2 storage resources in saline aquifers – pressure analytical methods and CO_2 migration challenges

Sylvain Thibeau, Kevin Hernandez-Perez

TotalEnergies, sylvain.thibeau@totalenergies.com; U.Pau et Pays de l'Adour

We discuss here on CO_2 storage resources in saline aquifer by injection only, not considering brine extraction.

The CO_2 storage resources in a set formation on a given geographical area is limited, amongst others by pressure constraints and CO_2 migration constraints, ensuring CO_2 does not migrate out of the defined geographical area. As such, the CO_2 storage resources will be lower than each of the pressure-derived resources and the CO_2 migration-derived resources.

Pressure analytical methods have been proposed as early-stage methods to estimate the pressure-derived resources of a project. It consists in applying Van Everdingen Hurst 1949 approach, while solving the superposition challenge of the method (later approximated by Carter Tracy) by assuming a pressure ramp-up in the store under evaluation (figure 1).

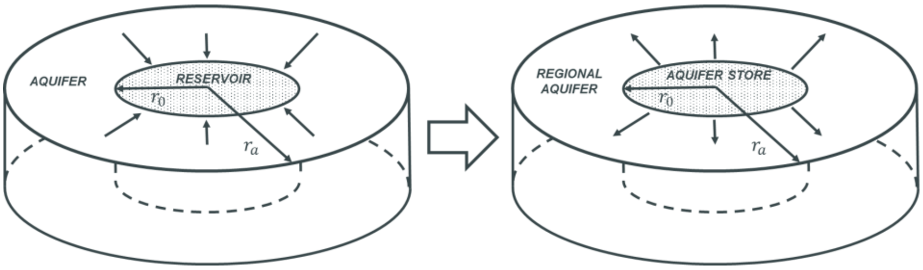


Figure 1: Extension of the analytical aquifer approach as applied to aquifer inflow for oil production evaluation (left) to CO_2 storage in saline aquifer (right)

The benefit of the method is the simplicity (CO_2 storage resources can be estimated with a spreadsheet once the input parameters are evaluated). It enables to perform sensitivity studies and evaluate the main impacting parameters, such as regional aquifer dimensions. The method was validated by comparison to multiphase, 3D flow modelling, and developed to estimate far field pressure and potential impacts on third party activities such as seasonal gas storage or geothermal plants.

Storage efficiency E is directly provided by the pressure analytical method, which simplifies for radial stores (local or regional) into $E = C_t \Delta P (1 + 2\overline{W}_D)$ with $C_t \Delta P$ the closed aquifer storage efficiency obtained from the total compressibility C_t and the applied overpressure ΔP and $\overline{W}_D$ a correction term accounting for pressure dissipation into the larger regional aquifer, whether open or closed.

This formalism has large implications.

For CO_2 stores within a geological structure, pressure derived storage efficiency may be significantly smaller than volumetric storage efficiency, meaning that maximum acceptable overpressure would be reached before a reasonable store fill-up with CO_2.

When assessing storage efficiency in regional aquifers, $\overline{W}_D$ will remain small (significantly below 1), due to scale considerations: injection time may not be sufficient to dissipate significant amount of brine towards open boundaries of the aquifer, such as outcrops, compared to the large water volume of the aquifer. This would result to storage efficiency similar to a closed aquifer, whether the regional aquifer is geologically open or closed. This also has consequences in term of pressure management at basin scale. The pressure constraint could be lifted by brine extraction from the formation, leading however to other infrastructures, costs, environmental and legal issues.

However the pressure analytical method does not address the ultimate CO_2 migration distance when storing CO_2 in monoclines (out of a structural or stratigraphic closure). Indeed, long migration distances may limit storage efficiency in large, tilted aquifers.

High quality literature on this topic explains the issue of plume thinning with distance along centuries with a plume potentially continuing its migration when considering two phase flow models with residual trapping, as illustrated by figure 2.

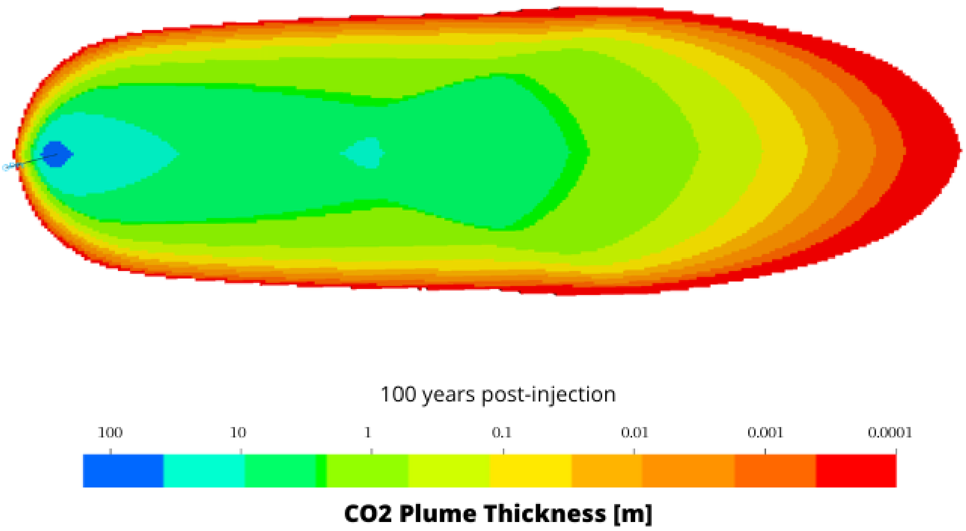


Figure 2: top view of the modelling of CO_2 plume extension with a 2° dip monocline. Plume continues its expansion by further thinning.

Comparing 2D (Vertical Equilibrium approach) and 3D models confirms this finding, leading to the issue on how refined the 3D grid should be below the cap rock or what CO_2 saturation or relative permeability threshold to use on a 2D model to conclude on plume finally stopping within a slope.

Several processes may explain CO_2 plume reaching its ultimate extension in a shorter timeframe, such as CO_2 dissolution through molecular diffusion or convective mixing, capillary transition zone below a cap rock, capillary entry pressure, saturation shocks at the tip of the plume or cap rock-aquifer interface rugosity.

We believe this issue remains open for further research, including analytical developments, modelling and experiments to provide consolidated views on this challenge. This would lead to establishing the conditions under which the plume would stabilize in a timeframe practical for CO_2 operations (significantly below one century) and enable defining resources within a given area.

Pressure-based Storage Capacity Mapping and Implications for Storage Efficiency

Alexander P. Bump
Susan D. Hovorka
Gulf Coast Carbon Center, Bureau of Economic Geology, University of Texas at Austin

Regional storage capacity maps are the basis for key decisions by a variety of stakeholders. For landowners, they quantify the size of the storage resource, providing an important constraint on value. For policymakers, maps showing regional variation in storage capacity are key inputs for planning pipelines and deciding on project spacing. For investors and storage developers, they provide an overview of the resource base, enabling confident investment decisions. Small wonder then, that such maps are a staple of CO2 storage atlases.

In all cases, these maps are produced using a volumetric, or “static” capacity estimation (i.e., pore volume multiplied by a Storage Efficiency factor, SE). That method bears a comforting similarity to oil and gas volumetrics and may be appropriate where storage site boundaries can reasonably be considered open, such that pre-injection pore waters can be efficiently displaced by injected CO2. However, no injection interval extends forever. At the very least, basins have edges and floors and no regulation permits displacement of pore water to surface—at basin-scale, the boundaries are closed. Faults and depositional geometries commonly further subdivide basins, creating smaller closed pressure compartments. In the absence of water production, accurate regional capacity estimation therefore requires a pressure-based calculation. While this is routinely done with dynamic simulations, such models are time-consuming to create and computationally expensive to run, which is perhaps why static approaches persist, even at regional-scale.

This study presents a pressure-based approach to regional capacity mapping. Using gridded maps of injection zone depth, thickness, net:gross and porosity along with calculated pressure and temperature gradients, we apply a pressure-based storage capacity calculation to each grid node to create regional maps showing both the variations in local capacity as well as the total capacity available, assuming that the entire injection zone could be pressured up to some pre-defined value. Application to a published example shows in an order-of-magnitude reduction in storage capacity as compared to the published static capacity. Dissolution and/or pressure dissipation into non-net reservoir (i.e., interbedded low-permeability zones), might increase our calculated capacity but back-of-the envelope calculations show that the effect is modest at best.

Back-calculation of the SE factor implied by the pressure-based calculation shows that it varies with both depth and the final reservoir pressure. At 90% of frac pressure, SE is less than 0.5% at 2000m and 1% at 3200m. Compare that with published SE numbers for the 224 saline aquifers documented in the OGCI Storage Resource Catalog, which range from less than 1% up to 25%. While these numbers might be achievable for specific injection sites, given a narrowly-defined project volume, the work presented here makes it clear that such numbers are only achievable through consumption of pressure space beyond the defined project boundaries. At present, regulations require storage operators to lease only the pore space to be occupied by CO2, which creates a significant advantage for first-movers who may raise pressure well beyond their lease lines, limiting the injection capacity of subsequent storage projects. While that may work to the advantage of early storage operators, landowners, regulators and policymakers would be well advised to base their decisions on a regional average SE of 1% or less, far below the values commonly used in published storage atlases.

EASiTool 5.0 for CO2 storage capacity estimation

*Seyyed A. Hosseini, Zhicheng (William) Wang
The University of Texas At Austin
Bureau of Economic Geology
Austin, TX, USA
Seyyed.Hosseini@beg.utexas.edu ; +1-512-4710-2360
Zhicheng.wang@beg.utexas.edu

Site screening and selection is an important initial step to klick start a CCS project ensuring enough geological storage capacity can be provided to accommodate the targeted emissions. EASiTool incorporates science-based CO2 storage capacity estimation for Geological Carbon Storage (GCS) and offers a range of powerful features to support efficient and science-based CO2 storage estimation.

The new EASiTool V5.0 brings a significant advantage with its modern, updated web-based platform, eliminating the need for software installation. Using advanced analytical models for closed- and open-boundary basins, the tool enables users to obtain reservoir-scale storage capacity estimates, while the running time is typically within seconds. This accelerated science-based CO2 storage capacity estimation process facilitates faster decision-making and enhances project planning efficiency at early stages of site selection.

EASiTool 5.0 comprises four modules tailored to different scenarios and reservoir geometries:

Uniform Injection/Extraction Rate (Symmetric Geometry/Pattern Reservoirs); Fixed Bottomhole Pressure (Symmetric Geometry/Pattern Reservoirs); General Geometry/Pattern (User-Given location for wells) and Sensitivity Analysis (Fixed Bottomhole Pressure). The general geometry module offers features, including pressure contour maps, CO2 plume extension maps; moreover, a Geographic Information System (GIS) map and Area of Review (AOR) evaluation—two new additions to this version. The sensitivity analysis module in EASiTool 5.0 continues to offer the useful tornado chart. An exciting addition is the random sampling sensitivity analysis, allowing users to assess the impact of input parameters on capacity estimation, providing 90% confidence range and median estimations. This enhanced functionality greatly supports risk assessment and decision-making processes, enabling users to make informed choices by understanding the sensitivity of capacity estimation to different input parameters.

EASiTool utilizes a simplified reservoir model to reduce computational complexity, which may omit certain geological complexities. Future versions of EASiTool aim to address some of these limitations and incorporate more comprehensive models.

Screening for Open Saline Aquifers - Estimating Storage Efficiency based on Plume Shape

Martin Neumaier *m.neumaier@ariane-logix.com*
Ben Kurtenbach, Ian Bryant, Eva Gebhardt – ArianeLogiX

Estimating the CO2 storage efficiency during early project screening is elemental for acreage acquisition decisions. The presented geology-based, multivariable and 3-dimensional Monte-Carlo workflow for saline aquifers reduces uncertainties and provides scientific assessment and ranking of potential assets.

Key is a consistent probabilistic prediction of storage efficiency, containment risk and effective storage capacity of plumes in open saline aquifers. The approach is designed for quick, transparent, and robust screening in the early exploration phase and does not require any reservoir simulation.

Plumes and their respective subsurface volumes are calculated, considering uncertainty ranges for pore volume, PVT-derived density, seal integrity and capacity, and geometrical plume shape (Figure 1), with underlying assumption for reservoir thickness, porosity, pore throat radii, reservoir dip, CO2 injection volume, etc.

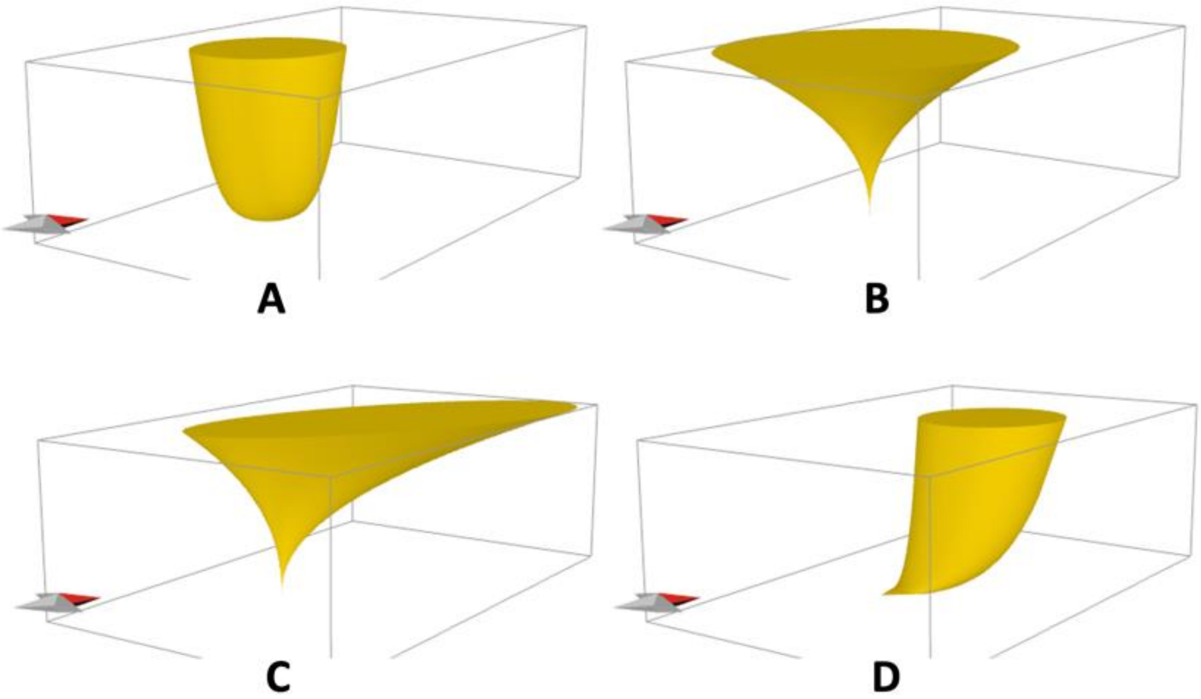
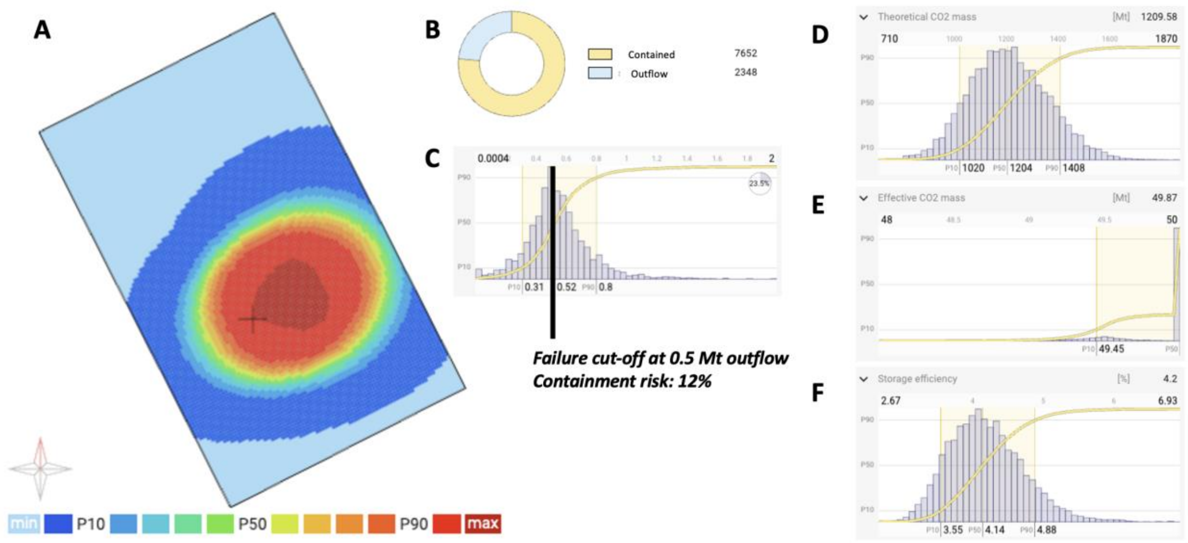


Figure 1: Various shapes for 50 Mt plumes resulting from different geometric assumptions (everything else equal): trough (a), teardrop (b), elongated (c) lateral flow (d).

Since the assumptions taken in our approach are highly uncertain, we propose a probabilistic approach involving input uncertainties and a Monte Carlo simulation with 10,000 iterations. In each iteration, it is checked whether the plume fits into the concession (defining the theoretical storage capacity), and effective storage capacity and lateral outflow volumes and masses are calculated. This allows for the estimation of containment risk based on specified failure cut-offs (e.g., outflow superior to 0.5 Mt). Finally, the storage efficiency is calculated for each individual plume as effective storage capacity divided by theoretical storage capacity.

As a result, probabilistic ranges of theoretical storage capacity, effective storage capacity, storage efficiency and outflow masses as well as a prediction of containment risk are obtained for a given development scenario.



Failure cut-off at 0.5 Mt outflow
Containment risk: 12%

Figure 2: Probabilistic plume map (a), likelihood of containment (b), outflow mass (c), theoretical storage capacity (d), effective storage capacity (e) and storage efficiency (f).

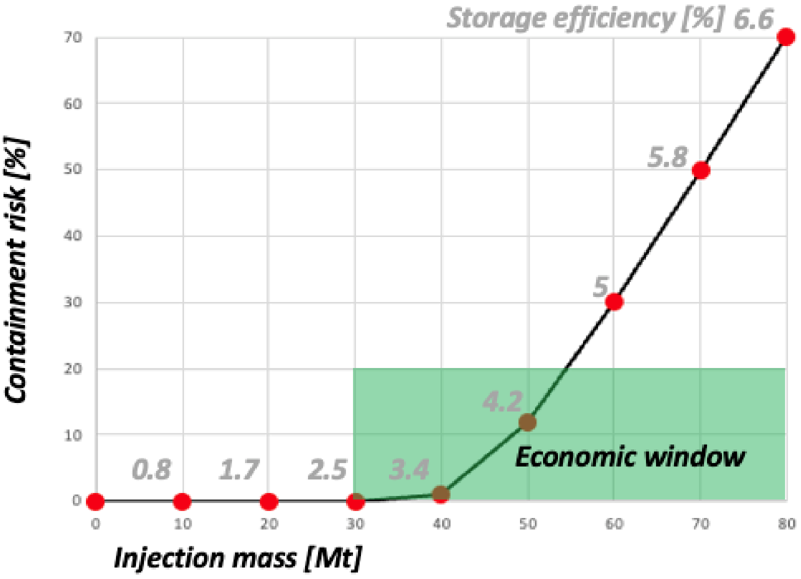


Figure 3: Summary chart with containment risk and economic mass cut-offs.

Running those assessments for different injection masses allows for the construction of a function for various development scenarios (Figure 3). On such a diagram, thresholds for project-specific containment risk tolerance (e.g., 20%) and minimum economic effective storage capacity (e.g., 30 Mt) can be applied for selection purposes.

The diagram highlights the fact that storage efficiency and containment risk are correlated. Importantly, those parameters are not a single number for a specific opportunity but variable, dependent on the injected CO2 mass. Finally, storage efficiency and containment risk are not an geological fact which cannot be changed but rather a development decision.

To conclude, storage efficiency is a parameter which depends on the specific geology (e.g., reservoir architecture) and development case, and constitutes a result of the assessment rather than an uncertain input to the assessment.

Materiality of Plume Size Calculations and Storage Efficiency

Prasanna Krishnamurthy*, Lisa Lun, George Eleftheriou, Pipat Likanapaisal and Robert Wattenbarger
ExxonMobil Technology and Engineering Co., Spring, Texas, USA
**prasanna.g.krish@exxonmobil.com*

As the global CCS industry grows, it’s become increasingly important to identify robust metrics for quantifying CO2 storage performance and risk. Storage efficiency, defined as the total volume injected divided by a semi-arbitrary, subsurface pore volume is widely used. Storage efficiency calculations have relied on obtaining the extent of the CO2 plume based on gas saturations using analytical solutions or numerical simulations. The plume sizes and storage efficiencies thus calculated are highly dependent on the inputs for simulations and the post processing methods. The absence of any standards and protocols defined for such methods results in inconsistencies and low confidence in the numbers reported. These metrics also feed into project risk calculations like the total storage capacity, pore space/ acreage needed, monitoring costs and the contractual injection rates.

In this work we highlight some of the practical challenges of relying on gas saturations to calculating plume sizes and storage efficiencies. We propose a mass-intensity based framework for evaluating storage performance and designing monitoring plans.

Estimating the contacted pore space and CO_2 saturation using seismic data from the Sleipner CO_2 storage project

Philip Ringrose[1,2]**,** Anne-Kari Furre[1], Andrea Santi[2,1] Bamshad Nazarian[1] & Peter Zweigel[1]

[1]*Equinor ASA,* [2]*NTNU*

Abstract

Time-lapse seismic data at Sleipner have given numerous insights into the behaviour of CO_2 within the sandstone saline aquifer storage unit. These insights include the effects of internal shale layers and shale breaks in controlling the actual multi-layer CO_2 distributions (Furre et al. 2023), the likely contribution of different of trapping mechanisms (Ringrose et al. 2021; Nazarian & Furre, 2022) and the effectiveness of the overlying caprock (Furre 2017). Another set of insights gained from these data are estimates of the use of the pore space, e.g. the storage efficiency was estimated to be around 5 % of the pore volume by the 2010 survey, after 14 years of CO_2 injection (Ringrose, 2018). However, it is not clear how useful these general estimates are for future sites, or how relevant they might be to sites with different geological architectures. Furthermore, estimates of the storage efficiency depend very much on how the size of the storage unit is estimated (e.g., using the structural closure volume or an arbitrary volume prescribed by a cylinder around the plume). Figure 1 illustrates this problem using a seismic amplitude map at the Layer 9 anomaly at Sleipner. How should we estimate the contacted pore volume? Using an ellipse around the plume would give a lower estimate than when using the actual polygon around the detected plume.

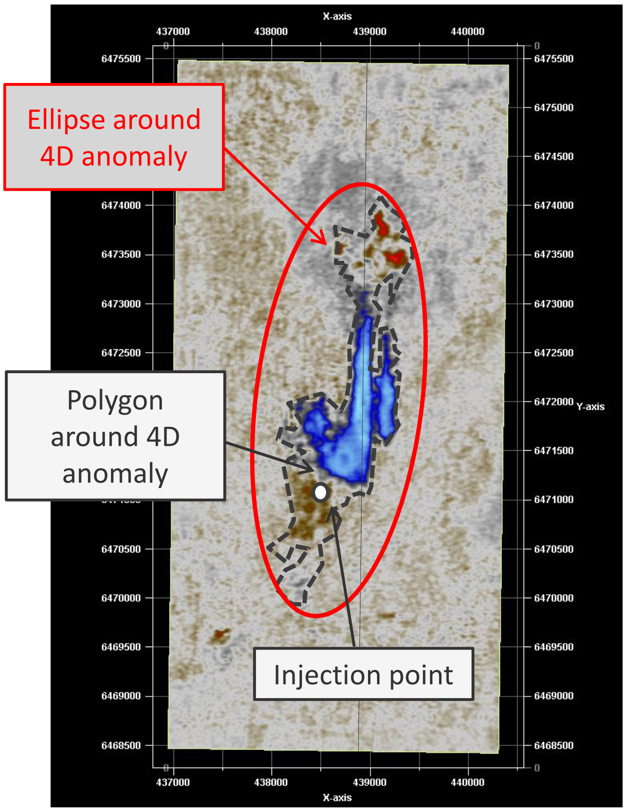


Figure 1. *Seismic reflection amplitude map at Sleipner Layer 9 (2010 survey) showing a polygon around the observed amplitude anomaly and an ellipse around the anomaly. Layer 9 represents the topmost* CO_2 *layer.*

To further develop these insights into the contacted pore space at Sleipner, we have analysed the time-lapse seismic datasets to estimate the areal sweep efficiency and the fraction of the pore volume occupied by CO_2 (at the scale of seismic resolution). Seismic resolution and signal quality allows detection of the top and base of Layer 9, giving a reasonable constraint to the pore volume contacted by CO_2. This is more challenging for deeper layers, where in some cases it can be more challenging to separate the top and base of each CO_2 layer. However, polygons indicating the lateral extent of the CO_2 can be mapped for at a least 9 intervals, and these can be used as proxies for the storage unit sizes.

It is relatively simple to show that at the scale of whole storage unit the overall storage efficiency so far is in the range of 2-5%, with the result depending very much on how the storage volume is defined. We compare methods using a box volume, a cylindrical volume or an ellipsoidal volume, respectively, corresponding to establish methods for estimating storage efficiency. However, when the effects of areal and vertical sweep efficiency are considered, the fraction of the pore space occupied by CO_2 rises to around 40%. At smaller scales, below the seismic detection limits, CO_2 saturations may well increase to higher levels (e.g., to around 60%) as determined by the pore-scale physics. Furthermore, these analyses based on the storage history do not necessarily represent the future long-term storage efficiency.

We then compare these pore-space occupancy estimates from the seismic datasets with forward models of the plume using reservoir simulations (Nazarian & Furre, 2022), which are used to estimate the fluid saturation distributions using fluid flow physics theory. It is also useful to compare the forecasts made using the gravity-dominated assumption (e.g., using the Invasion Percolation method) with full-physics multiphase flow simulations. The main insights from this analysis are in revealing how the fraction of pore volume occupied by CO_2 changes as a function of scale. The work also indicates that macroscopic storage efficiency is consistent with pore-scale measurements, if the effects of plume dynamics and rock heterogeneity are taken into account. These insights should prove useful for extracting understandings from the Sleipner site to be used as conditioning data for other CO_2 storage sites with quite different geological architectures and internal heterogeneities, while also appreciating that dominance of any particular storage mechanisms (e.g., structural closure versus residual trapping) could result in considerable variations in estimated storage efficiency.

References

Furre, A. K., Eiken, O., Alnes, H., Vevatne, J. N., & Kiær, A. F. 2017. 20 Years of Monitoring CO2-injection at Sleipner. *Energy Procedia*, 114, 3916-3926.

Furre, A-K, Alnes, H. Warchoł, M. J. and Pontén, A. S. M. 2023. Sleipner 26 years: How well-established subsurface monitoring work processes have contributed to successful offshore CO2 injection. Geological Society Special Publication, (in review).

Nazarian, B. and Furre, A.K., 2022. Simulation Study of Sleipner Plume on Entire Utsira Using A Multi-Physics Modelling Approach. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, http://dx.doi.org/10.2139/ssrn.4274191

Ringrose, P.S., 2018. The CCS hub in Norway: some insights from 22 years of saline aquifer storage. *Energy Procedia,* 146, 166-172.

Ringrose, P.S., Furre, A.K., Gilfillan, S.M., Krevor, S., Landrø, M., Leslie, R., Meckel, T., Nazarian, B. and Zahid, A., 2021. Storage of carbon dioxide in saline aquifers: physicochemical processes, key constraints, and scale-up potential. Annual Review of Chemical and Biomolecular Engineering, 12(1), pp.471-494.

A proxy model for CO2 injection during a typical storage project

L. Rijkels, S. Lindsø
ExploCrowd, Stavanger, Norway

Estimation of the quantity of CO_2 that can be safely and effectively stored in the pore space of a trap or aquifer is essential for CCUS planning at both a basin and project level. Typical approaches at the screening stage are to multiply the pore volume by an efficiency factor, which, depending on the situation, attempts to account for the final saturation of CO2 in the trap pore space, the compressibility and volume of the aquifer, or the quantity of CO2 that can be trapped residually before reaching the edge of an open aquifer. These approaches vary but all have the common feature of neglecting time, implicitly assuming equilibration of the CO_2 and aquifer pressures.

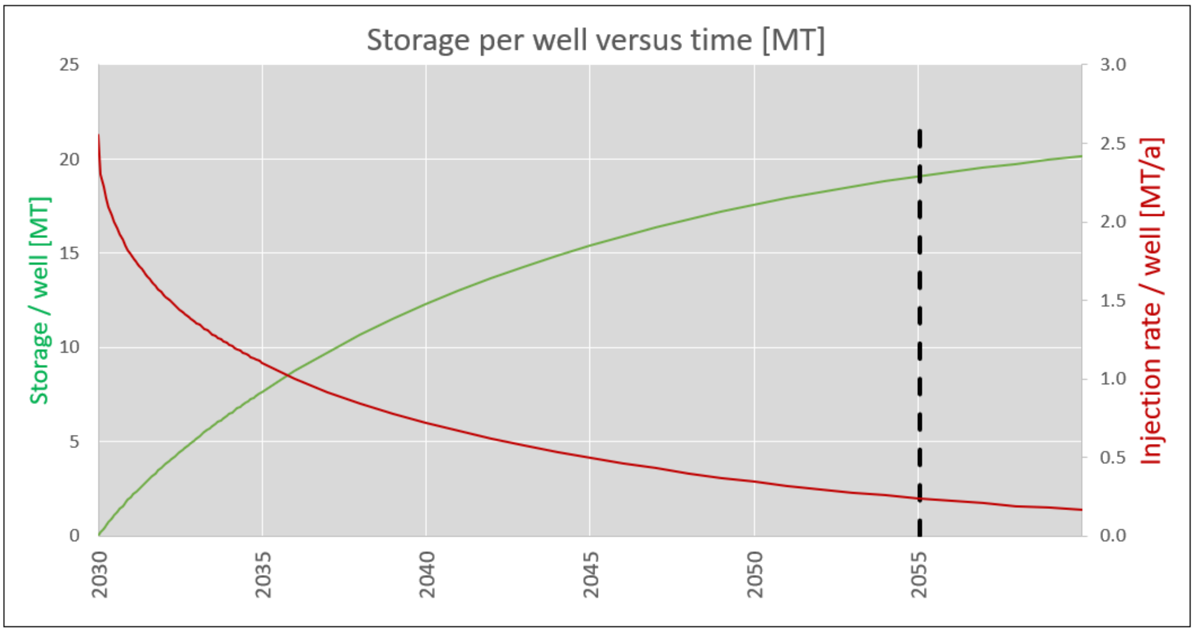
In practice the permeability of the aquifer will be a significant and often controlling factor on the quantity of CO_2 that can be stored within a project lifetime. Traditionally, incorporating permeability to assess storage capacity would involve building a full simulation model over the trap and attached aquifer, an involved and computationally intensive piece of work that is rarely performed at the screening or even early site characterisation stages. However, this paper introduces and proposes a Proxy Model that provides a time dependent estimate of CO2 storage when provided with the key geological parameters that characterise the storage site and attached aquifer.

The Proxy Model takes 8 geological parameters as input and uses these to generate a forecast for CO_2 storage through time – immediately. It does so based on maximum injection pressures calculated from top seal strength and available tubing head pressure. It can be used to screen the required number of wells to approach the maximum capacity of the trap/aquifer within a given project life.

We built this Proxy Model by running more than 1500 simulation models for various combinations of the input parameters. We then regressed functional descriptions for the initial rate, its decline, and late-time behaviour using the 8 geological parameters as input. That produced shape curves describing the injection forecast per well for up to 50 years. The proxy model takes account of well interference when it calculates total storage for a multi-well project.

We found that the screening model matched full-field forecasts to within 10-20% for a range of cases and time steps. Interestingly, many of the commercially interesting cases don’t reach the ultimate storage potential within 25 years. There is simply not enough time to push enough water out of the trap with injection wells that inject at commercial rates of about 1 MT/a. Many traps are not only aquifer-limited, but also time-limited. The proxy model makes that explicit and it links the two extremes.

We have used the Proxy Model to screen and filter potential storage sites, and to make an informed first guess of the number of wells needed in a full-field simulation model as required to model plume development and migration. Output from the proxy model for the Endeavour storage complex (East Coast Cluster) is provided below, showing that the Proxy Model is able to replicate the published capacity and injector numbers from the published aquifer data (Figure 1).



Reservoir parameters		**Trap & Aquifer**		**Wells**	
Gross thickness, m	200	Trap area, sq km	160	No. injectors	5
N/G, frac	0.85	Aquifer area, sq km	480	Total storage capcity, MT	**95**
Porosity, frac	0.22	Crest depth, m ss	1020	Effective storage efficiency	0.02
Permeability, mD	300	Max BHP, bar	193		

Figure 1: Proxy Model output using published data for Endurance structure, calculating a 95 MT storage capacity over 25 years with 5 injectors. The flattening of the storage/well curve with time indicates that capacity is limited by the effective aquifer size and that additional storage requires brine extraction. (Note that the injection rate has not been forced to a plateau in this screening run of the potential.) The 95 MT capacity requires high injection pressures, enabled by the salt seal. The storage efficiency at the end of a 25-year project life is 0.02, expressed as the pore volume occupied by CO2 divided by the pore volume in the trap.

A Compositional Numerical Model Study on the Impacts of Aquifer Formation Geological and Geochemical Properties on CO2 Injectivity and Storativity: A Case Study Cameroon Gulf of Guinea

Gregory T Mwenketishi, Nejat Rahmanian*, Hadj Benkreira
1 Department of Chemical Engineering, Faculty of Engineering and Informatics, University of Bradford,
Bradford BD7 1DP, UK
* Corresponding author: g.t.mwenketishi@bradford.ac.uk

Carbon capture and storage (CCS) has already been recognised as a critical, urgent, and essential method for reducing anthropogenic CO_2 emissions and mitigating the severe effects of climate change. CO_2 storage is the last phase in the CCS life cycle, is accomplished chiefly by the injection of CO_2 into oceanic and geological subsurface reservoir formation. This work is aimed at conducting compositional numerical simulation to investigate the impact of geological and thermo-chemical properties on CO_2 aquifer storage. A conceptual development CO_2 storage study has been considered for a deep aquifer reservoir formation Miocene Rio del Rey Basin, Cameroon Gulf of Guinea. The reservoir formations in this basin are set to have very good petrophysical and geological properties for it to be considered as a storage system.

The aquifer formation contains various amounts of mineral which in turn would alter the injection of CO_2 as the chemical and geological properties of storage system changes. Some of the chemicals may alter the CO_2 fluid and rock properties and consequently the reservoir rates and quantities of injected and stored CO_2. This present a major concern as the impact of these thermos chemical properties of CO_2 injection and storage is not well understood to date and would mean that the development and operational strategies and costing of such a project not be fully understood and ascertained.

During the study, a compositional numerical simulation was developed and the results used to evaluate the impact of aquifer chemo-physical properties on CO_2 injection and volume stored. The injection of non-associated CO_2 at constant rate and variable aquifer fluid thermo – chemical and geological properties were modelled and simulated for a period of five years CO_2 injection and 100 years of monitoring and storing.

The simulation analyses results show that aquifer reservoir formation chemo-physical and geological properties strongly affect the reservoir volume of CO_2 injected and stored at reservoir physical conditions.

Utilizing Machine Learning Power to Predict the Performance of Carbon Dioxide Trapping in Saline Aquifers

Keywords: CO2 Storage; Machine Learning; CO2 Trapping; Reservoir Simulation

Background
Subsurface carbon dioxide storage is viewed as a key pillar and a critical technology to combat and mitigate climate change in the upcoming decades. Storing carbon dioxide in deep saline formations is regarded as a promising option for geological carbon storage (GCS), but to fully comprehend the CO2 trapping processes in these formations, reliable methods must be established to evaluate the efficiency of CO2 trapping.

Methodology
A commercial numerical simulator CMG-GEM was used to simulate 30 years of CO2 injection and additional 170 years of monitoring post injection. The injection scenarios were run inside a physical reservoir model with a single well positioned at the center of a deep saline aquifer to develop the multiphase flow data set for CO2 geological storage, in which the simulation generated 48,102 data points. The dataset was then utilized to establish the machine learning (ML) workflow. Four supervised machine learning methods (Decision Tree, Random Forest, Gradient Boosting and Stacked Generalization) were applied to develop a robust model to predict CO2 trapping indices with accuracy and provide a better understanding of the physical processes occurring in reservoirs.

Results:
The developed ML models demonstrated promising results for predicting trapping indices in saline aquifers, with correlation factor R2 > 0.9. The Stacked Generalization (SG) model provided the highest correlation factor between measured and predicted values of trapping indices, with R2 = 0.99 on the testing dataset. Moreover, partial dependance plots (PDP) were utilized as a sensitivity analysis tool and it demonstrated how few variables such as salinity, temperature & time had the most effect on CO2 trapping index. The developed models, specifically RF and SG exhibited a propitious outcomes.

Innovation:
Utilizing the power of machine learning tools can speed up the development of geologic carbon storage sector to meet the decarbonization goals. Partial dependance plots also provide unique analysis that can be utilized to address the complexities associated with CO2 mineral and solubility trapping mechanisms in particular.

CO2 Storage Efficiency for Capacity Estimation – Integrating Geological and Engineering Risks in a Clastic Saline Aquifer in Central Alberta, Canada

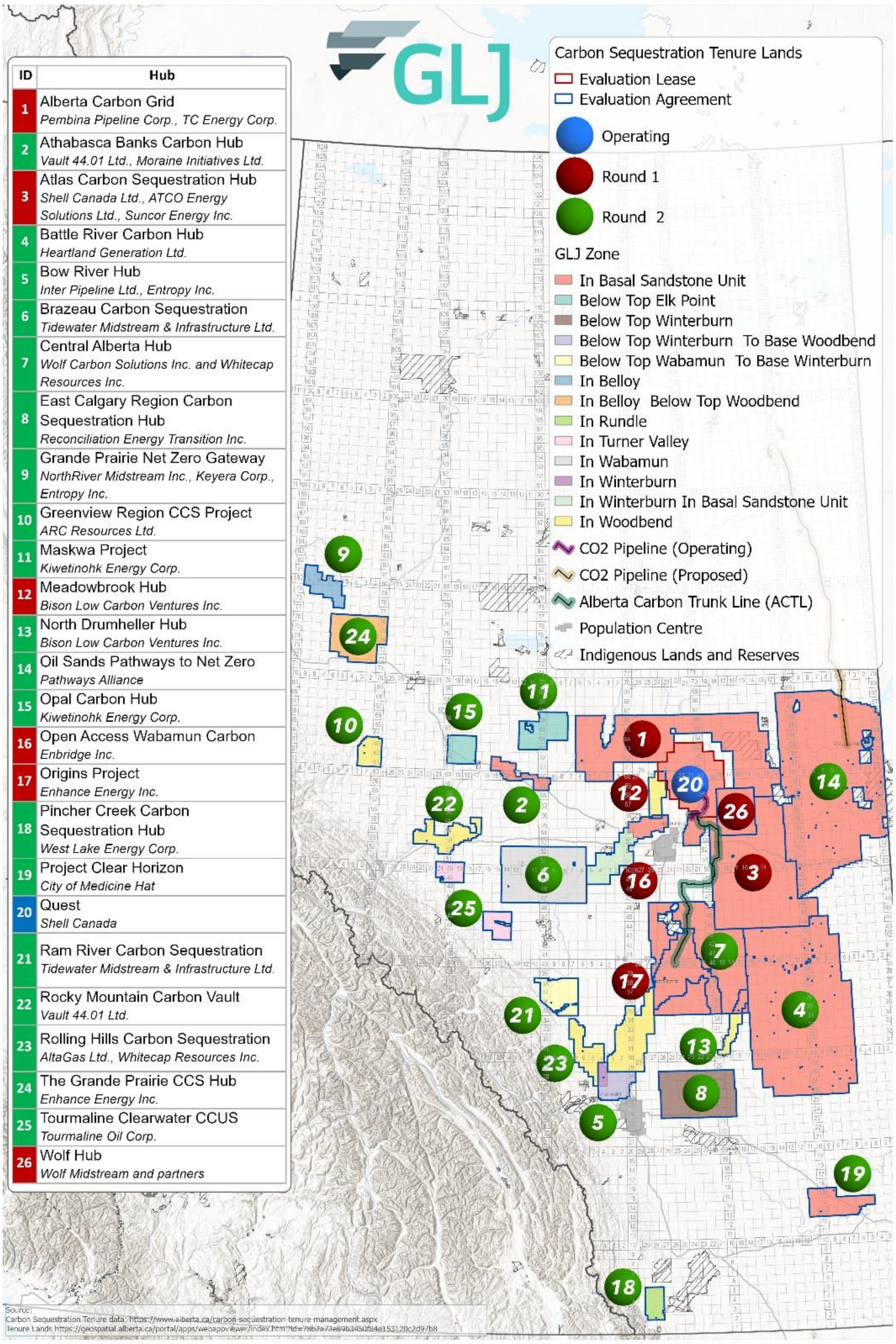
Vicky (Xiaoqi) Wang,* Suzy Chen, and Mitchell Gillrie, GLJ Ltd.
*corresponding and presenting author: vwang@gljpc.com, 1-403-266-9486, GLJ Ltd.

The US-DOE methodology for estimating CO2 storage capacity is based on volumetric methods, in situ fluid distributions, and fluid displacement processes, while assuming an open-system boundary condition or a closed system that can respond like open systems by means of managing, treating, and disposing of in situ fluids in accordance with current technical, regulatory, and economic guidelines (Goodman et al., 2011). Therefore, this methodology provides an upper limit for CO2 storage estimates. It is necessary to incorporate the geological and engineering risks when assessing the lower limit.

The Government of Alberta has entered into evaluation agreements with 25 hubs to investigate permanent CO2 sequestration options, including deep saline aquifers, as shown in Figure 1. Among the 25 approved hubs, eight hubs adjacently located plan to store CO2 in the same saline aquifer formation, which is called Basal Cambrian Sands (BCS). Although it is expected that the saline aquifer extends broadly in this region, the low compressibility of the formation water will cause pressure interference between the pore spaces when they are connected. In this case, the assumption of an open system will result in overestimating the storage capacity. Thus, the range of efficiency factors given in the US-DOE methodology will be relatively optimistic.

In this study, we built a geocellular model with reasonable representation of areal and vertical heterogeneity in BCS formation of the Quest CCS hub and then incorporated into a dynamic simulation model to test the geological and engineering uncertainties and their impact on the storage capacity. Extensive history match was performed to ensure main CO2 trapping mechanisms are captured and key properties that effect storage capacity were identified. Based on the history-matched model, the maximum injection pressure was applied to the existing CO2 injectors to simulate the carbon capture and storage (CCS) process with the consideration of geological and geomechanical safety factors and regulatory approval. Then, different boundary conditions were tested to mimic various system statuses. Subsequently, the storage efficiency factors were calculated and compared with the values from the US-DOE methodology. The results will showcase the percentages of reduction in the efficiency factor in different closed-system scenarios compared to the open-system assumption.

In summary, by taking critical geological and engineering risks into account, this study performed a comprehensive quantification of the boundary condition variation in a CCS project with real-world data. It provides an exemplary workflow to practically assess the range of the storage efficiency factor for regional CCS operations. This case study significantly narrows the uncertainty range for early-stage CCS site screening.



ID	Hub
1	Alberta Carbon Grid *Pembina Pipeline Corp., TC Energy Corp.*
2	Athabasca Banks Carbon Hub *Vault 44.01 Ltd., Moraine Initiatives Ltd.*
3	Atlas Carbon Sequestration Hub *Shell Canada Ltd., ATCO Energy Solutions Ltd., Suncor Energy Inc.*
4	Battle River Carbon Hub *Heartland Generation Ltd.*
5	Bow River Hub *Inter Pipeline Ltd., Entropy Inc.*
6	Brazeau Carbon Sequestration *Tidewater Midstream & Infrastructure Ltd.*
7	Central Alberta Hub *Wolf Carbon Solutions Inc. and Whitecap Resources Inc.*
8	East Calgary Region Carbon Sequestration Hub *Reconciliation Energy Transition Inc.*
9	Grande Prairie Net Zero Gateway *NorthRiver Midstream Inc., Keyera Corp., Entropy Inc.*
10	Greenview Region CCS Project *ARC Resources Ltd.*
11	Maskwa Project *Kiwetinohk Energy Corp.*
12	Meadowbrook Hub *Bison Low Carbon Ventures Inc.*
13	North Drumheller Hub *Bison Low Carbon Ventures Inc.*
14	Oil Sands Pathways to Net Zero *Pathways Alliance*
15	Opal Carbon Hub *Kiwetinohk Energy Corp.*
16	Open Access Wabamun Carbon *Enbridge Inc.*
17	Origins Project *Enhance Energy Inc.*
18	Pincher Creek Carbon Sequestration Hub *West Lake Energy Corp.*
19	Project Clear Horizon *City of Medicine Hat*
20	Quest *Shell Canada*
21	Ram River Carbon Sequestration *Tidewater Midstream & Infrastructure Ltd.*
22	Rocky Mountain Carbon Vault *Vault 44.01 Ltd.*
23	Rolling Hills Carbon Sequestration *AltaGas Ltd., Whitecap Resources Inc.*
24	The Grande Prairie CCS Hub *Enhance Energy Inc.*
25	Tourmaline Clearwater CCUS *Tourmaline Oil Corp.*
26	Wolf Hub *Wolf Midstream and partners*

Source:
Carbon Sequestration Tenure data: https://www.alberta.ca/carbon-sequestration-tenure-management.aspx
Tenure Lands https://geospatial.alberta.ca/portal/apps/webappviewer/index.html?id=78b2a72e89b3450f84e153120c2d97b8

Figure 1 Alberta CCS Hubs Overview – Awarded Evaluation Permits on the Proposed Pore Spaces

References

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., 972 Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., Guthrie, G., 2011. U.S. DOE 973 methodology for the development of geologic storage potential for carbon dioxide at the national 974 and regional scale. International Journal of Greenhouse Gas Control, 5, 952–965.

Rethinking Young-Laplace Capillary Pressure Conversions for CO2-Brine Systems

Jules Reed
Global Technical Manager at Premier Corex
jules.reed@premiercorex.com

The Young-Laplace equation describes how capillary pressure is a function of the interfacial tension between fluid pairs and the contact angle between those fluids and the contacted solid substrate within a capillary. Interfacial tension and contact angle are a function of temperature and pressure and thus, capillary pressure for any given series of capillaries (such as porous media) will vary as a function of the fluid pair within the system and the temperature and pressure of that system.

There are a variety of methods used for determining capillary pressure that often do not utilise either the correct fluid pair or correct conditions for the fluid pair in the subsurface system. Standard industry practice is to simply convert between fluid pairs using a ratio conversion of the Young-Laplace equation, since it is given:

$$\frac{Pc_1}{Pc_2} = \frac{2\ \sigma_1 \cos(\theta_1) / r}{2\ \sigma_2 \cos(\theta_2) / r} \quad thus \quad Pc_1 = Pc_2 \left(\frac{2\ \sigma_1 \cos(\theta_1) / r}{2\ \sigma_2 \cos(\theta_2) / r} \right)$$

where r is the capillary radius, sigma denotes interfacial tension, theta is the contact angle, subscript 1 indicates the properties values for one fluid pair and subscript 2 the properties for a second fluid pair. In this ratio equation, 2 and r are constants which cancel out leaving capillary pressure to be merely the ratio of the fluid pair properties; interfacial tension and contact angle.

This approach is correct for many reservoir systems since the fluids are either immiscible, incompressible and/or at such elevated pressure and temperature that the variance in interfacial tension and contact angle is negligible.

However, when considering injection to, and re-pressurisation of, a depleted hydrocarbon reservoir, where mass transfer between fluids and/or changes in fluid properties results in significant changes to interfacial tension or contact angle, the standard approach may require rethinking. Rather than a simple ratio conversion a matrix conversion maybe required as a function of the system, as well as iterative refining of the properties per pressure.

Geological Society
Fire Safety Information

If you hear the Alarm
Alarm Bells are situated throughout the building and will ring continuously for an evacuation.

Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms
Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid
All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of The Geological Society