CO_2 Storage Resource Catalogue

Cycle 4 Report

Global Summary

August 2024

OIL AND GAS CLIMATE INITIATIVE

GLOBAL CCS INSTITUTE

HALLIBURTON

International Association of Oil & Gas Producers

Global Amounts of CO_2 (Project and no project)

Stored

0.052 Gigatonnes

Commercial

1.7 Gigatonnes

Sub-Commercial

625 Gigatonnes

Undiscovered

13434 Gigatonnes

Global Amounts of CO_2 (Project specified)

Stored

0.051 Gigatonnes

Commercial

1.4 Gigatonnes

Sub-commercial

67 Gigatonnes

Undiscovered

55 Gigatonnes

Region	Countries
North America	2
Central & South America	2
Europe	21
Middle East & North Africa	13
Asia	13
Oceania	1
Africa	2

Document Summary			
Client	Oil and Gas Climate Initiative (OGCI)		
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Prepared by:	Halliburton: Shelagh Baines, Kate Evans, Montse Portet, Benjamin Panting, Krzysztof Drop GCCSI: Aishah Hatta, Joey Minervini		

Important notice

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1 Executive Summary

The CO_2 Storage Resource Catalogue (CSRC) has now assessed 1272 CO_2 storage resource sites from fifty-four countries against the SPE Storage Resources Management System (SRMS). Both oil and gas fields and saline aquifers are assessed.

To date, there is a total 14060 Gt aggregated global storage resource. Of this global total, 13434 Gt is classed as Undiscovered with the remaining 625 Gt as sub-commercial and the remaining 1.7 Gt as commercial

Project based resources include ~55 Gt that fall into the undiscovered category with the remaining ~66 Gt that are classed as sub-commercial and 1.4 Gt as commercial

Because CO_2 Enhanced Oil Recovery projects are not accounted for in the SRMS, the only large-scale commercial projects in operation listed in this report are in Australia, Canada, Norway, and the U.S.A.

The CO_2 Storage Resource Catalogue (CSRC) is an on-going programme aimed at building a global view of the commercial readiness of CO_2 storage resources in key markets.

The Catalogue is created by classifying the resource maturity of published storage resource evaluations using the Society of Petroleum Engineers (SPE) Storage Resources Management System (SRMS) [1]. SRMS is a project-based classification system, with progression based on commercial triggers including national/federal regulatory systems and project development milestones, as described in Section 3.0. Rigorous use of the SRMS reduces the subjective nature of resource assessment and allows comparison of resource potential and maturity.

The CO_2 Storage Resource Catalogue and CO_2 Storage Resources Management System includes CO_2 storage in saline aquifers and depleted or partially depleted oil and gas fields but excludes CO_2-Enhanced Oil Recovery (CO_2-EOR) and other storage options such as unmineable coal, 6ineralization and organic-rich shales.

The CO_2 Storage Resource Catalogue will be built up over six annual cycles. This report summarises the status at the end of Cycle 4 in July 2024, when fifty-four countries have been assessed (Figure 1-1).

A summary of the global resource base in the CO_2 Storage Resource Catalogue is presented in Table 1-1, Figures 1-2, and Figure 1-3. Aggregated global resource estimate of over 14,000 Gt in the CSRC is encouraging evidence for storage potential on a scale that will enable CCS to play an important role in reaching global net zero by 2050.

There is considerable uncertainty associated with storage estimates, so all evaluations should ideally include a range of resource estimates from either deterministic or probabilistic methodologies (see Recommendations for Evaluators, Section 4.5). Presently, uncertainty ranges are only published for 25% of the sites in the Catalogue, with the other 75% only providing a mid-case estimate. As the SRMS is a project-based system, future storage estimates should be focused on pressure-limited estimates of storage resource generated through dynamic flow models based on a realistic storage development plan.

Saline aquifers make up 96% of the aggregated storage resource. These are commonly classified as Undiscovered – Inaccessible because of inadequate data to confer discovered status and lack of a regulatory framework for CO_2 storage in most countries, meaning that this vital resource is not currently commercially accessible in most countries.

Because the CO_2 Storage Resource Catalogue is compiled purely from public domain sources, it is likely that significant additional storage resources exist (and may already be 7ineraliza in unpublished evaluations). It is possible for a country to have few published evaluations and consequently low/no storage resources in the CO_2 Storage Resource Catalogue despite having significant storage potential.

Of fifty-four countries assessed, only four (Australia, Canada, Norway, and the USA) include any commercial resource. The commercial readiness of the global storage resource remains low due to barriers to resource progression, such as the lack of CCS-specific regulation and policy support in many countries. Actions that could be taken by CCS stakeholders to aid resource progression are highlighted in Section 4.6.

Some publicly announced projects do not appear in the CSRC database because no technical evaluations of storage resources have been published. The annual 'Global Status of CCS' report published by the Global CCS Institute (GCCSI; available at https://www.globalccsinstitute.com/) provides an up-to-date summary of projects in each country. Information about CCS projects in operation or development is also available through the Institute's CO_2RE Database (available at https://co2re.co/).

This report and appendices are accompanying documents to the online CSRC database, which can be accessed and downloaded at: https://oilandgasclimateinitiative.com/CO2-storage-resource-catalogue/.

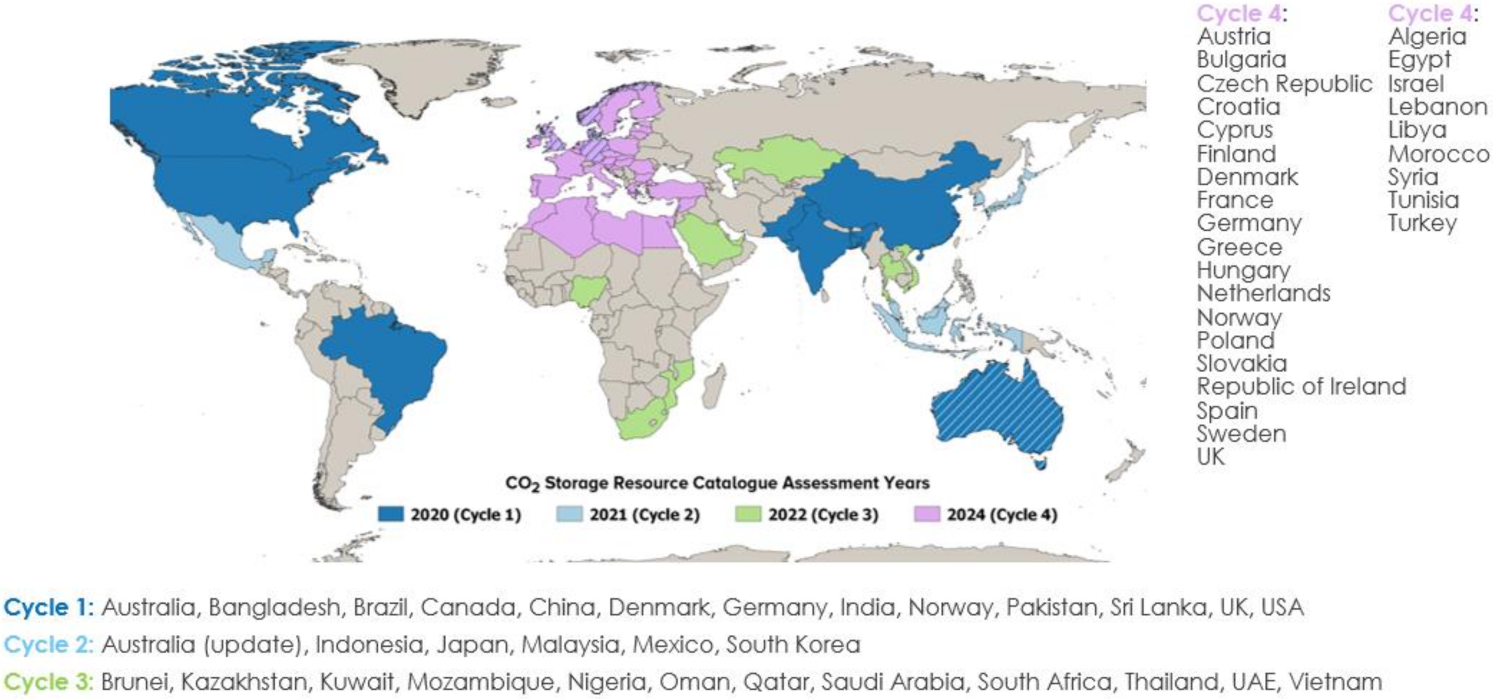

Figure 1-1: Geographic Coverage of the CO_2 Storage Resource Catalogue in July 2024

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.05194	0.05124
Capacity	1.736	1.426
Sub-Commercial	624.777	67.385
Undiscovered	13433.721	54.618
Aggregated*	14060.286	123.481

Table 1-1: Summary of storage resources in the CO_2 Storage Resource Catalogue in July 2024. Note: 'Sub-Commercial' includes 'Contingent' resources and 'Undiscovered' includes 'Prospective' resources (see Figure 3-1).

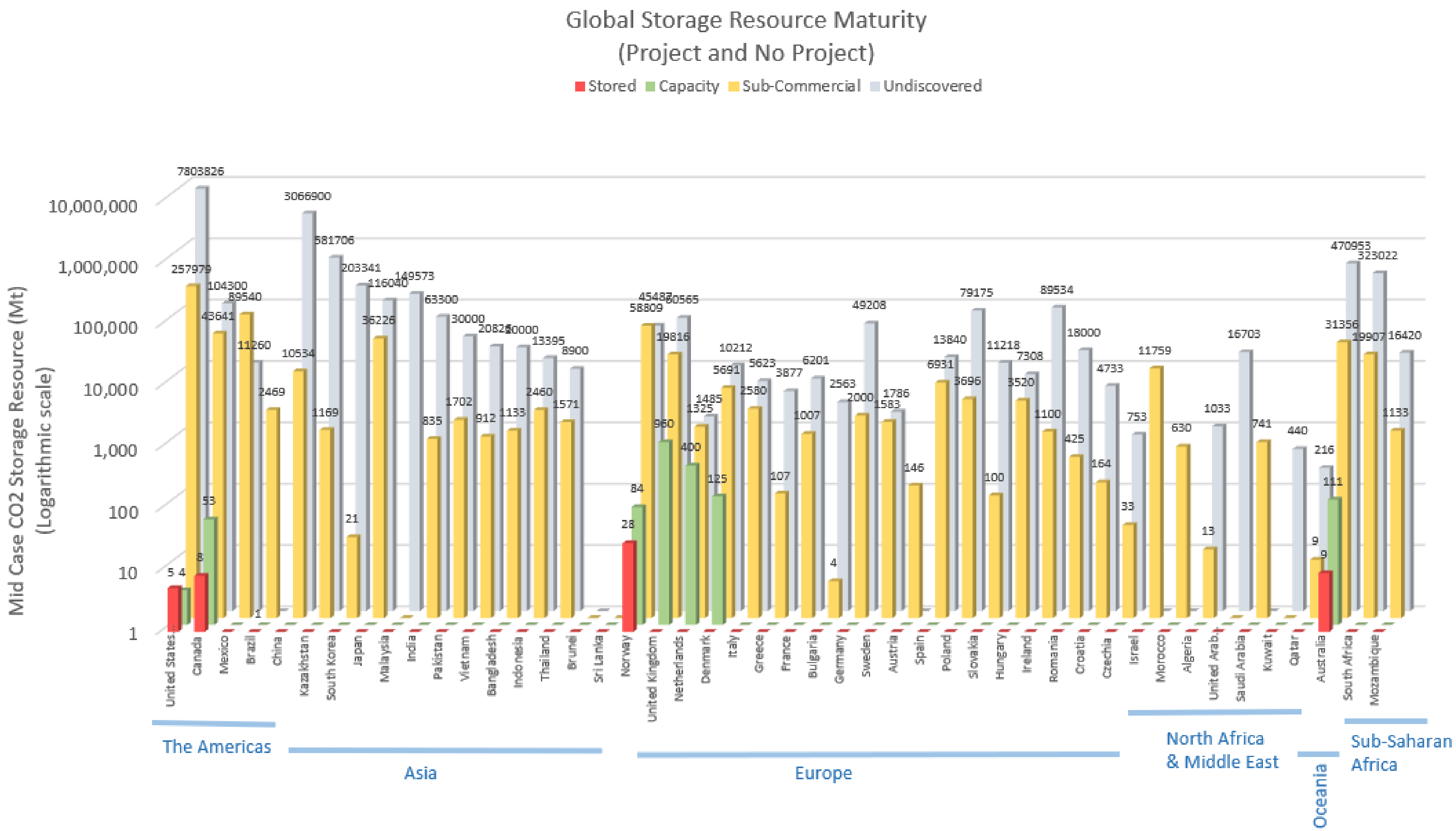

Figure 1-2: Plot of storage resources in the CSRC database by country and SRMS maturity class. (Note: the y axis is million of tonnes (Mt) on a logarithmic scale; the same data are presented on a linear scale in Figure 4-3.)

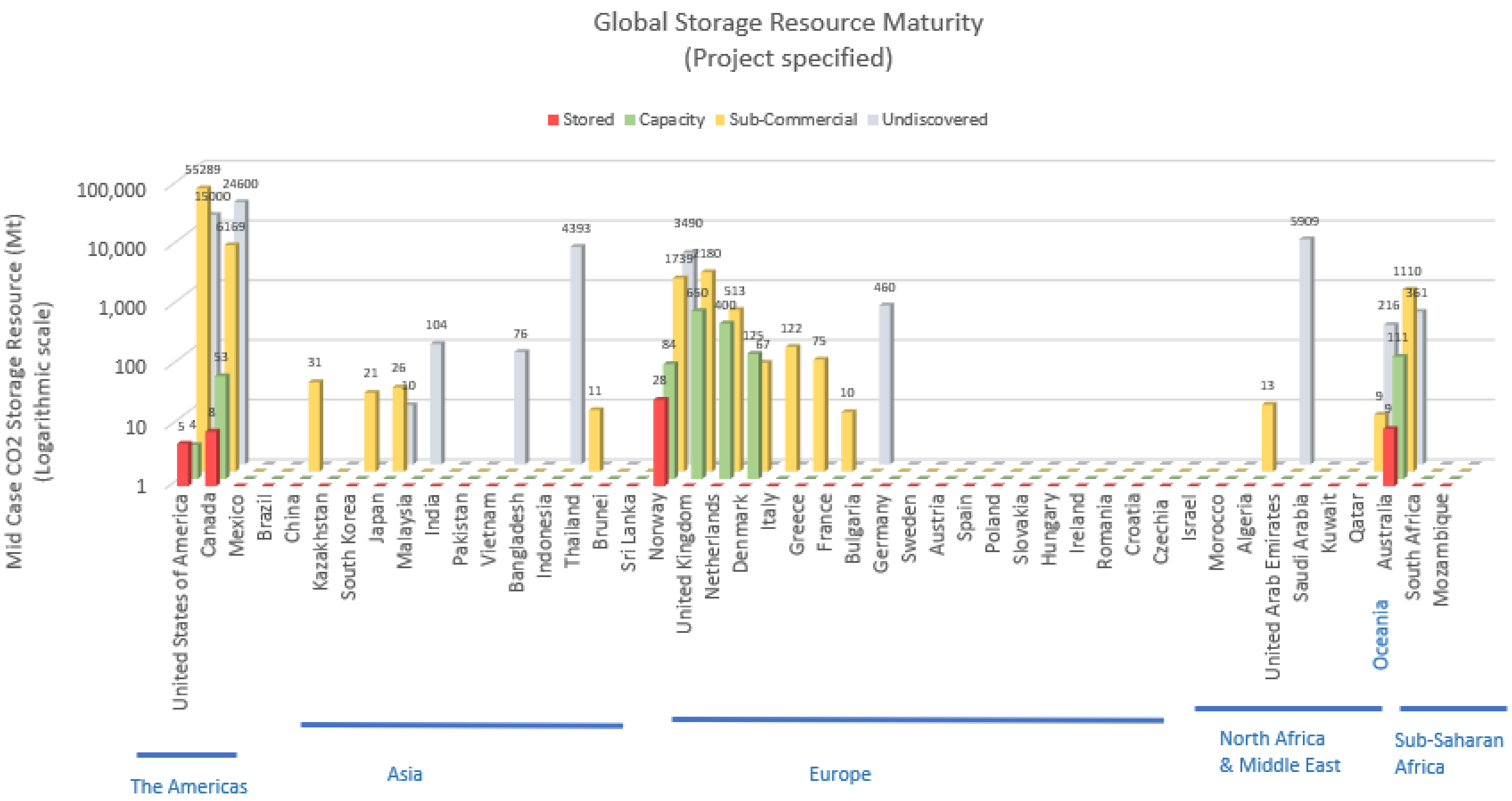

Figure 1-3 : Plot of project-specific storage resources in the CSRC database by country and SRMS maturity class. (Note: the y axis is million of tonnes (Mt) on a logarithmic scale; the same data are presented on a linear scale in Figure 4-4.)

2 Overview of the CSRC Project

This section describes the multi-year project that has been undertaken to create the CO_2 Storage Resources Catalogue (CSRC). It aims to provide clarity about the scope of the CSRC and an understanding of how to access and navigate the report and database.

2.1 Organisation

The CO_2 Storage Resource Catalogue has been commissioned by the Oil and Gas Climate Initiative (OGCI) and is led by the Global CCS Institute (GCCSI). Technical assessment, database population and reporting have been carried out by Halliburton (Cycle 4), Storegga (previously known as Pale Blue Dot Energy; Cycles 1-3) and supported by the GCCSI. Results of Cycle 4 have been co-funded by IOGP and OGCI.

2.2 Aims of the CSRC

The CO_2 Storage Resource Catalogue (CSRC) aims to build a global view of the commercial readiness of CO_2 storage resources in key markets.

The programme has four main objectives:

- Support the deployment of CCS as a sustainable low-emissions technology.
- Build confidence in CO_2 storage resources to support the deployment of CCS.
- Provide a visible platform for global storage potential.
- Establish the Storage Resources Management System as a robust reporting mechanism for CO_2 storage.

2.3 Schedule

The CO_2 Storage Resource Catalogue will be built up over six annual cycles. This report summarises the status at the end of Cycle 4 in July 2024, when fifty-four countries have been assessed (Figure 4-1).

2.4 Approach

Each cycle of work to build the CO_2 Storage Resource Catalogue uses a similar approach:

- Countries for assessment in the cycle are selected by the Storage Working Group (SWG) at the Oil and Gas Climate Initiative (OGCI).
- A bibliography of publicly available information sources and evaluations is collated by the assessment team (GCCSI and Halliburton) and approved by the OGCI SWG.
- Following a review of the evaluation documents, the assessment team assign each storage resource to an SRMS maturity class (see Section 3.0 for a description of the SRMS).

- The CSRC database is populated with key data from the evaluation, together with assessment notes to support and clarify assessment decisions.
- The updated database and supporting report are reviewed by the OGCI SWG, then made publicly available on the OGCI website at: https://www.ogci.com/CO2-storage-resource-catalogue/

2.5 Data Sources

All sources must be in the public domain.

The bibliography for each cycle typically contains a wide range of information sources, from regional-scale, national and multinational CO_2 storage resource assessments, to more detailed evaluations, often targeting a basin, sub-basin, or formation, and finally down to focused technical studies of a field or site.

The ability to 12ineralizati a site's storage resource is strongly influenced by the availability of published evaluations. It is possible for a country to have few published evaluations and consequently low/no storage resources in the CO_2 Storage Resource Catalogue despite having significant potential for CO_2 Storage.

Some publicly announced projects do not appear in the CSRC database because no technical evaluations of storage resource have been published. The annual 'Global Status of CCS' reports published by the Global CCS Institute (GCCSI; available at https://www.globalccsinstitute.com/) provide an up-to-date summary of projects in each country. Information about CCS projects in operation or development is also available through the Institute's CO_2RE Database (available at https://co2re.co/).

2.6 Terminology

In the CSRC, the terms 'evaluation' and 'assessment' are used in the following manner:

Evaluation: The geosciences, engineering, and associated studies conducted on an exploration, development, or storage project resulting in estimates of the CO_2 quantities that can be stored.

Assessment: The consideration of evaluations to classify the estimates of derived CO_2 storage resource quantities according to the SRMS guidelines, as interpreted by the Assessor / Assessment team.

Note: *The assessment team do not do any new evaluation of storage resources;* their role is to classify the resource against the SRMS based on information in the published evaluation.

2.7 Scope of the CSRC

2.7.1 Exclusion of CO_2 Enhanced Oil Recovery

The CO_2 Storage Resource Catalogue and Storage Resources Management System include CO_2

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storage in saline aquifers and depleted or partially depleted oil and gas fields but exclude CO_2-Enhanced Oil Recovery (CO_2-EOR) and other storage options such as unmineable coal, 13ineralization and organic-rich shales.

2.7.2 Minimum Threshold Resource of 10 Mt

The CSRC aims to support large, commercial-scale project development. To support this, a 'minimum threshold' of 10 Mt for a resource to be included in the Catalogue was introduced in Cycle 2. This is flexible in its application. For example, where a pilot or demonstration project has successfully injected and stored CO_2 and has potential for continued or additional injection, the site is included. A good example of this is the Tomakomai Demonstration project in Japan, where 0.3 Mt (300,000t) was injected as part of the project, but the storage aquifer holds additional potential, both Discovered and Undiscovered.

As a result of the Minimum Threshold, pilot projects are not included in the Catalogue (unless they hold additional evaluated storage potential as discussed above). However, pilot studies are recorded in the country summaries in regional appendices A-F, where significant. The Global CCS Institute also maintains a list of pilot projects (past, current, and planned) which provides the most up to date information on each project [2].

2.8 Report and Database

The main report (this document) aims to provide the reader with an understanding of:

- The aims and scope of the CSRC (Section 2.0)
- The SRMS and how it is applied by the assessment team (Section 3.0)
- Global resources in the CSRC (Section 4.0)

Summaries for individual countries are provided in separate regional appendices A – F (listed in Section 5.0).

This report and appendices are accompanying documents to the online CSRC database, which can be accessed and downloaded at: https://www.ogci.com/ccus/co2-storage-catalogue.

The CSRC database and accompanying documents are updated following each annual cycle. Each country summary states when the assessment was made and last updated.

Updates may be triggered in the following situations:

Operational Projects

- Stored and Capacity resource numbers *for operational CCS projects* listed in the CSRC are updated each cycle if new public domain information is available about the cumulative mass of CO_2 injected and/or if changes to permitted mass have been announced.

Change to policy or regulation

- Country resources may be reclassified if a significant change has been made to country regulation or policy. Information about such changes is provided by the GCCSI.

Storage resources booked

- If a storage resource is booked by a CCS developer and can be identified to a country level, it will be noted in the country summary. Resource numbers in the database may be updated if the site is in the CSRC and supporting technical data is available in the public domain.

- The first example of CO_2 storage resources being booked using the SRMS occurred when Santos included resources associated with the Moomba project in the South Australian Cooper Basin in its end 2021 reserves statement (https://www.santos.com/news/2021-reserves-statement/). (Note: The Moomba project is not included as a site in the CSRC because insufficient technical data have been published.)

EOR

The new revision to the SRMS is planning to include CO_2 EOR. This may change resources for countries based on ongoing and planned CO_2 EOR projects.

The SRMS guidance [1] recommends that Capacity projects should be developed within a 'reasonable' timeframe (generally considered to be less than five years), and Contingent projects require "active appraisal or evaluation and should not be maintained without a plan for future evaluation". Note that Capacity and Contingent for non-operational projects are not routinely reassessed in each annual cycle to ensure they remain appropriately classified, but updates can be submitted to the assessment team as described in Section 2.10.

2.9 Request for input

Authors are encouraged to publish their storage evaluations and submit the evaluation, or any update, to the CSRC assessment team using the following link: https://CO2storageresourcecatalogue.com/src-submission/

The ultimate aim is that the CSRC database matures into a fully populated and self-sustaining resource for the CCS community.

3 CO2 Storage Resource Management System (SRMS)

This section provides an overview of key aspects of the CO2 Storage Resource Management System (SRMS) and highlights some challenges encountered while assessing resources for the CO_2 Storage Resource Catalogue. It provides definitions that are used during the assessment and guidance as to how some of the challenges were handled.

3.1 Aims of the SRMS

The development of the CO2 Storage Resource Management System (SRMS) aims to provide similar support to the CCS industry as the Petroleum Resource Management System (PRMS) does for the petroleum industry.

The SRMS aims to:

- Enable nations to map the progression of storage resource maturity in a key evolving industry.
- Create consistency in the use of resource terminology to improve communication of key issues between practitioners, financiers, regulators, and policy makers.
- Improve confidence regarding resource assessments with potential customers of CCS who are unfamiliar with subsurface issues but who need to make significant business decisions.

3.2 Application of the SRMS to create the CSRC

The SRMS was originally published as a draft version in 2017 and was updated later that year to the current published version [1] which is applied in all CSRC assessments.

Work to create the CO_2 Storage Resource Catalogue initiated in 2017 with Cycle 0 [3], which tested and provided critique on the assessment of CO_2 storage sites using the SRMS. A classification flowchart (Figure 3-1) was developed from the SRMS by Storegga (formerly Pale Blue Dot Energy) to enable clear and consistent classification of storage resources.

Note that the SRMS does not separate the 'Play' classification into 'Sequence' and 'Basin', but this was recommended during Cycle 0 to distinguish sites in the Catalogue with a lower level of maturity within the Play classification.

Basin – where no storage formation was defined in the published data and the evaluation uses only the basin area and generic reservoir properties.

Sequence – where a specific storage formation was identified in the published evaluation.

3.3 Resource Progression in the SRMS

Key levers for resource progression along the SRMS are commercial, project related steps. The main levers are:

1. Discovery status of the resource, as per SRMS guidelines.
2. The status of the regulatory system in the jurisdiction area.
3. Internal project decision to proceed.
4. External regulatory consent to proceed.
5. Commencement of operations and permanent storage.

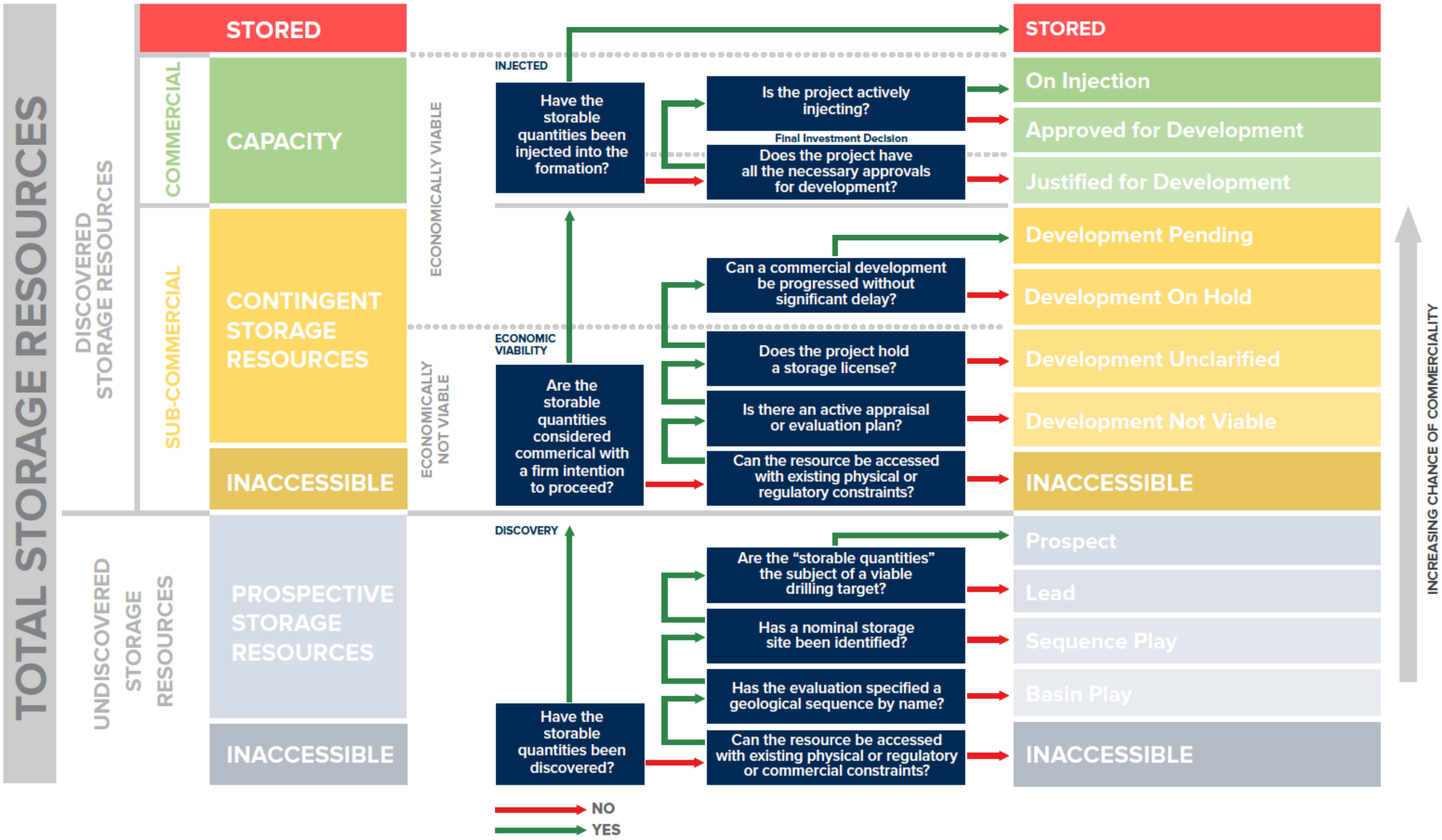


Figure 3-1 : Flowchart for the classification of storage resources based on the SRMS guidelines and terminology

3.4 Definition of a Storage Project

SRMS is a project-based classification system. The SRMS guidelines state that "to assign resources of any class, a development plan consisting of one or more projects needs to be defined." To gain 'project' status, some level of a development plan, conceptual or derived from modelling, must be available or implied, with a stated mass of CO_2 and an associated plan including the number of wells required to inject that mass of CO_2 and any associated water/brine extraction and disposal. This means that both Undiscovered and Discovered resources may be defined as projects. It is expected that the development plan, which may be based on appropriate analogues for Prospective resources, will mature as the project progresses through the SRMS. However, the reality is that due to the lack of data available in the source bibliography or due to the limitations of the evaluations, many resources do not have a published development plan. To aid in the identification of resource sites with a published development plan, each database entry records whether the site was identified as a 'Project' or not.

3.5 Resource Estimation Method

The SRMS aims to provide a method to systematically describe storage resource estimates. However, approaches used by the CCS community to calculate CO_2 storage resource estimates has varied greatly over the past couple of decades. In the CSRC database, the method used to derive the estimate or estimates for any site has been documented along with any supporting information.

Resource estimates for **saline aquifers** are reported as being derived from **volumetric or dynamic** methods.

Volumetric methods are based on pore volume estimated from either simple mapping exercises (area and thickness) or more detailed static geological models. A value for storage efficiency (denoted as 'E', defined as pore volume occupied by CO_2 divided by total pore volume, and dependent on store heterogeneity, structure, sweep efficiency, and boundary conditions) must be assumed, but the published range of 'E' varies greatly (0.01% to 25% for saline aquifers). The user should be aware that some evaluations use high 'E' values, which may not be based on detailed analysis of the specific site or lack supporting data. These evaluations are considered to potentially carry overly optimistic resource estimates.

A summary of the approach is documented where dynamic models are used; this may range from simple analytical to full simulation.

Resource estimates for **depleted oil and gas fields** commonly use a **voidage replacement methodology**. This assumes that the net volume of fluids produced/injected over field life can be replaced by an equivalent reservoir volume of CO_2. Assuming no aquifer ingress, this would return the field to original pore pressure. Decline curve analysis, or another method to estimate voidage at end of field life, should be applied if fields are still producing at the time of evaluation and resource estimation (e.g., US DOE, 2015 [4]).

A simple volumetric approach may be applied if production/injection data are not available. Note that the value of 'E' used for buoyant trapping within a depleted hydrocarbon field is often considerably higher than for saline aquifer storage and should be based on local production and/or injection experience.

3.6 SRMS Classification: Challenges & Approach

3.6.1 Discovered Status

3.6.1.1 Discovered Status – Treatment of Saline Aquifer Resources

"A discovery is a geologic formation or several geologic formations collectively, for which one or several wells have established through testing, sampling, and/or logging the existence of a significant quantity of potential CO_2 storage for a proposed project" [1]. When assessing the storage resource of open, unstructured saline aquifers, a determination must be made as to the portion of the aquifer that has been discovered (i.e., through hydrocarbon exploration).

To address this, a specified area around wells within the saline aquifers that have recognized reservoir potential and containment is considered as discovered resource. The remaining, largely undrilled portions of the site would be considered undiscovered resource. This permits the discovered proportion of the saline aquifer to be calculated from the well density where this is available. Unless otherwise specified, the reported well number is assumed to be evenly distributed across the site area. For some areas, particularly those covering a large geographic area with an unknown number of wells (e.g., USA states and Canadian provinces), no well density is available and the whole area is considered undiscovered (other than any specific projects or sites which are defined separately).

The area within the selected well radius is classed as Discovered but with the following caveats applied:

- The storage site is classified as either 'Partly Discovered' (for sites with a dynamic simulation available), or 'Discovered awaiting detailed assessment' (where no simulation is published) for the area within the well discovery zone, while the potential resource outside the zone is flagged as 'Undiscovered'.

An area of 200 km^2 (circle of 8km radius) around wells was selected following results from a study undertaken in Cycle 0 of well density in the UK Southern North Sea Bunter sandstone [3]. A smaller area is used for complex formations such as carbonates: 20 km^2 discovery area for carbonate platforms with limited diagenesis or 0.5 km^2 discovery area for carbonate reef formations (Figure 3-2).

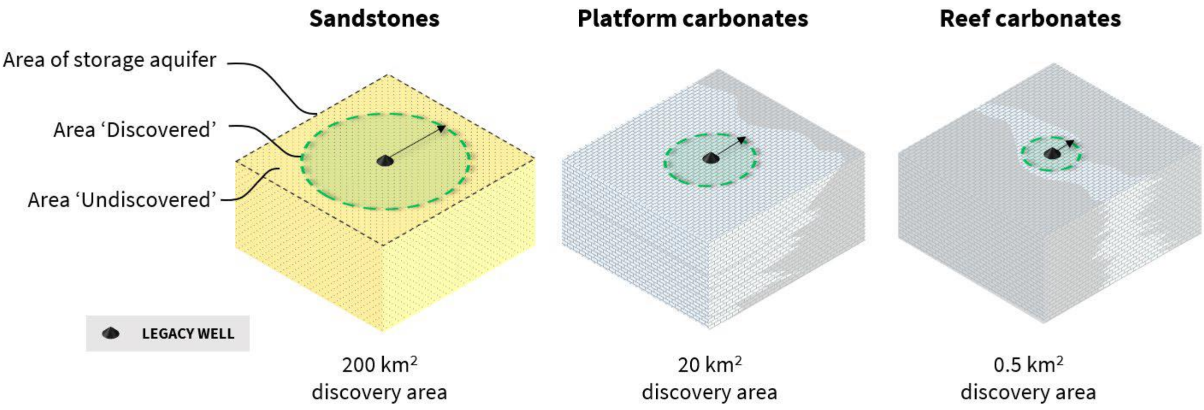


Figure 3-2: Assumed discovered areas around wells in sandstones, platform carbonate and reef carbonates.

3.6.1.2 Discovered Status – Treatment of Petroleum Accumulations

The storage resource present in depleted oil and gas fields (conventional petroleum accumulations) is considered 'Discovered' from an SRMS perspective, due to data availability (well and well tests) and the proven reservoir and containment potential.

3.6.2 Inaccessible Resources

3.6.2.1 Inaccessible Resources – Ongoing Petroleum Production

General practice to date has been to avoid CO_2 storage operations until hydrocarbon production from an oil or gas field has ceased (referred to as "cessation of production," or COP). This is due to issues of licensing (pore space ownership), materials selection, and product contamination amongst others. As a result, some countries have specific legislation to prevent negative interaction between CO_2 injection and petroleum production (e.g., Canada). The SRMS accounts for such issues through the 'Inaccessible' classification term, which is defined as the "Portion of discovered resources that are inaccessible from development as a result of a lack of physical, societal, or regulatory access at the surface or subsurface."

To aid understanding of the storage opportunity presented by depleted oil and gas fields, an "Earliest Accessible Date" (EAD) threshold has been set 30 years into the future (from the point of the storage resource assessment). Where the COP is later than the EAD, or no COP is specified, the resources are classified as Sub-Commercial but Inaccessible. For the CSRC Cycle 4, published in 2024, the EAD is set to 2054. Some supergiant fields, whose cessation of production (COP) date is far into the future, have therefore been classified as 'Sub-Commercial' but 'Inaccessible' for use.

3.6.2.2 Inaccessible Resources – Regulatory

All discovered potential storage resources have been classified as Sub-Commercial but Inaccessible in countries that have no published regulatory system covering CO_2 storage licensing. Unfortunately, this is currently the case for many countries.

3.6.3 High CO_2 Fields

Several hydrocarbon provinces contain oil and gas fields with a naturally high CO_2 content (or indeed, natural CO_2 accumulations). This includes sites in Australia, Malaysia, Indonesia, and the USA. Such sites require careful evaluation to ensure that the resource estimate provided by an evaluation does represent a storage resource, as opposed to a direct replacement of produced CO_2. To provide a standard process for assessing these types of accumulations it was decided that:

- If the evaluated resource indicates a replacement of the initial CO_2 volume through a re-injection process (i.e., re-injection into a high CO_2 gas field during production), this does not represent a storage resource and is not included in the Catalogue. If the storage volume is derived from production of hydrocarbon from a high CO_2 field, the pore volume made available is considered to represent a storage resource.

- If an evaluated storage volume is connected to a high CO_2 field but lies outside the original accumulation (i.e., water leg or surrounding aquifer), it is considered a storage resource and is included in the Catalogue if there is some degree of trapping (i.e., through residual or dissolution trapping processes) or sealing potential (i.e., it does not wholly rely field pressure depletion or on migration into the trap for containing the CO_2).

3.6.4 Double Counting

The source bibliography portfolio contains a wide diversity of published estimates of storable quantities using different approaches and methodologies which are not always documented in detail. Estimated storable quantities are often presented on a state or province basis, without the detailed information on which basins or geological formations were included in the estimate. At the same time, estimated storable quantities may be available for the same geographic region but at a Basin and/or Formation level, and not attributed to a state or province. This creates a clear risk of double counting which is acknowledged and must be appropriately managed.

Two approaches are taken in the CSRC to manage the risk of double counting:

- Subtract: The storage resource of a specific storage site is subtracted from the more regional estimate that covers the same geographical area if the resources are in the same SRMS maturity class. The condition of same SRMS maturity class is imposed because the SRMS guidance states that "Storable quantities classified as Capacity, Contingent Resources, or Prospective Resources should not be aggregated with each other without due consideration of the significant differences in the criteria associated with their classification".

- Qualify: This approach accepts that regional estimates are typically very high-level summaries and where more detailed and/or reliable technical summaries with a basin /

formation / site focus are available they have been selected as the preferred source. In these circumstances, the regional entry in the assessment database is still preserved and the estimates included in the assessor's notes, but no resources have been classified to avoid duplication of the resource entry.

The Subtract and Qualify approaches mitIgate some of the risk of double counting, but it is not possible at this stage to eliminate fully the risk of double counting within the CSRC database. Where this is identified as a significant issue, this is reported in the accompanying country assessment documentation.

3.6.5 Resource Uncertainty

All evaluations should include a range of resource estimates from either deterministic or probabilistic methodologies. These are entered in the CSRC database as low – mid – high values where they are provided. It is common for evaluations to only publish a single estimate for storage resource; in this case, the estimate is assumed to be a mid-case value unless otherwise specified.

The CSRC Includes notes from the assessor regarding the reliability of the assessment and any specific concerns that have arisen. If critical assessment evidence is not presented or is unclear, the assessor may have assigned the resources to a lower maturity SRMS class than the site may qualify for had more detailed information been provided. As a result, the storage resource assessments presented may be an underestimate of the actual maturity of the portfolio. This can be adjusted in future years as workers on each site either publish or directly submit evidence to this programme.

3.6.6 Site covered by Multiple Evaluations

Where multiple evaluations of an area or site are available the principles that have been followed are:

- Where possible, use the most recent evaluation, especially where the methodology would result in the most reliable estimate of storable quantities.
- If the most recent evaluation is considered less reliable due to the approach taken or a lack of detail published about the evaluation, then an older evaluation may be used instead with justification provided in the assessment notes.

4 Summary of Global CO_2 Storage Resources

This section provides an overview of resources contained in the CSRC database at the end of Cycle 4 (July 2024) and summarises new work done in Cycle 4. It also highlights challenges encountered by the technical assessment team, makes recommendations for professionals who work on evaluation of CO_2 storage resources, and offers ideas that could aid resource progression.

4.1 Geographic coverage of the CO_2 Storage Resource Catalogue

Geographic coverage following completion of Cycle 4 in July 2024 is shown in Table 4-1.

Europe			Pan-Mediterranean	
Austria	France	Slovakia	Algeria	Tunisia
Bulgaria	Germany	Republic of Ireland	Egypt	Turkey
Czech Republic	Greece	Romania	Israel	
Croatia	Hungary	Spain	Lebanon	
Cyprus	Netherlands	Sweden	Libya	
Denmark	Norway	UK	Morrocco	
Finland	Poland		Syria	

Table 4-1: Table 2: Geographic coverage of the CO_2 Storage Resource Catalogue in July 2024

4.2 Summary of Global Resources

The following table and discussion are most easily understood with reference to the SRMS classification flowchart shown in Figure 3-1.

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.05194	0.05124
Capacity	1.736	1.426
Sub-Commercial	624.777	67.385
Undiscovered	13433.721	54.618
Aggregated*	14060.286	123.481

Table 4-2: Summary of storage resources in the CO_2 Storage Resource Catalogue in July 2024. Note: 'Sub-Commercial' includes 'Contingent' resources and 'Undiscovered' includes 'Prospective' resources (see Figure 3-1).

A summary of the global resources in the CO_2 Storage Resource Catalogue is presented in Table 4-1, Figure 4-2, Figure 4-3, and Figure 4-4.

The aggregated global resource estimate of 14,060 Gt in the CSRC is encouraging evidence for storage potential on a scale that will enable CCS to play an important role in reaching global net zero by 2050. Global storage resources are dominated by Undiscovered (95.5%) and Sub-Commercial (4.4%) SRMS classes. Commercial projects, including those where CO_2 injection is approved for development or is already being injected and stored in the subsurface, only contribute 3.1 Gt to the overall inventory: less than 0.024%. Of the fifty-four countries assessed, only seven (Australia, Canada, Norway, UK, Denmark, Netherlands, and the USA) include any commercial resource.

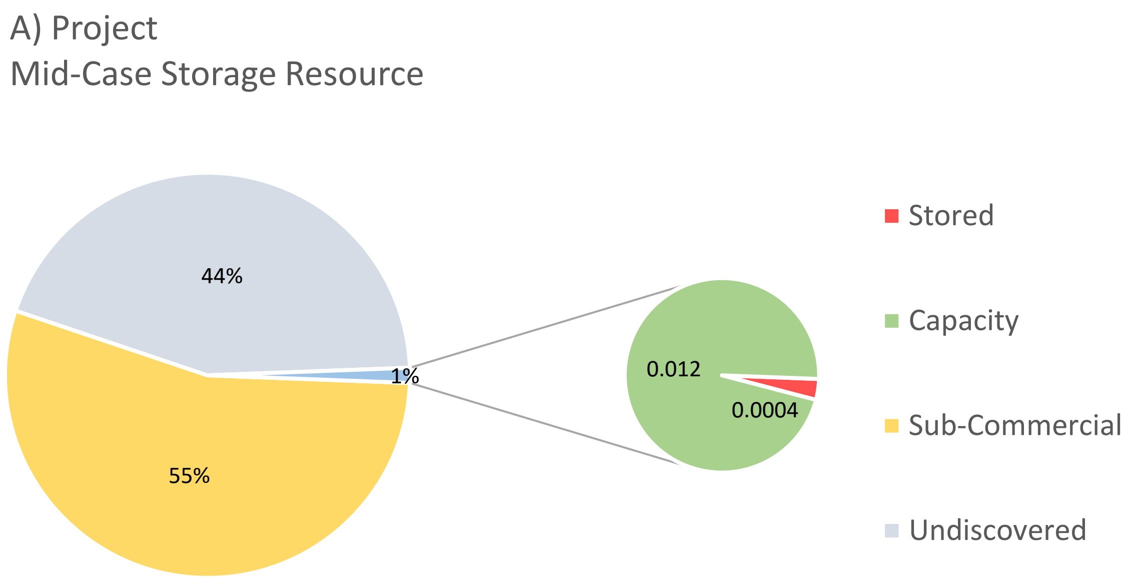
Saline aquifers dominate the resource inventory (13,485 Gt, 95.9%) mainly due to inclusion of national and regional-scale atlases and studies. However, the resource estimates for the saline aquifers rely largely on volumetric calculation and, as such, should be flagged as carrying low confidence in the estimates. Saline aquifers are commonly classified as Undiscovered – Inaccessible because of (1) inadequate data to confer discovered status and (2) lack of a regulatory framework for CO_2 storage in most countries, meaning that this vital resource is not currently commercially accessible in most countries.

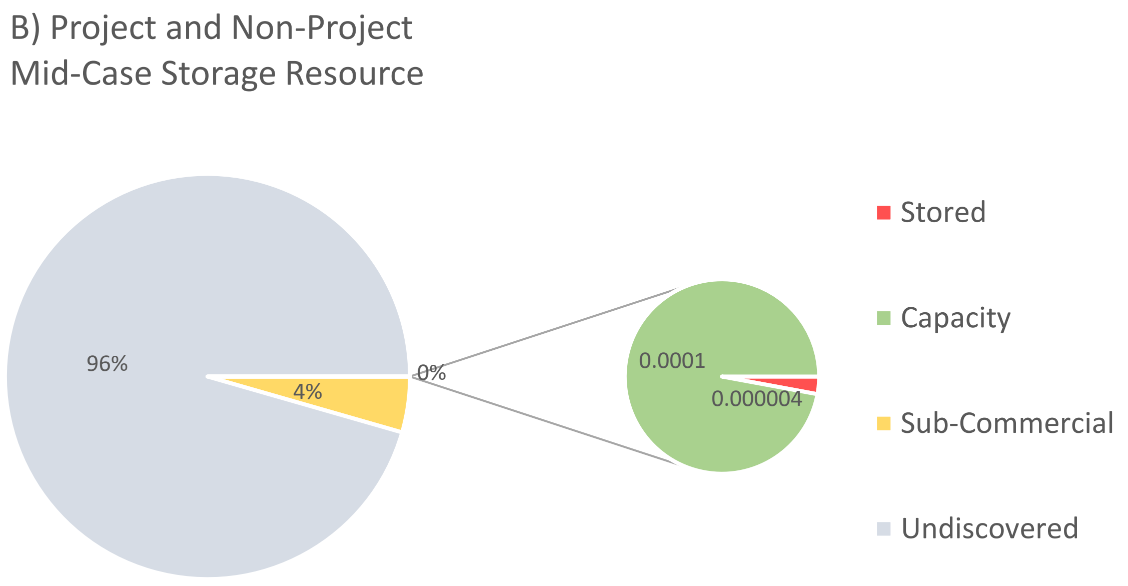
Oil and gas fields only contribute 4% (575 Gt, 3%) of the aggregated storage resource in the CSRC. Most of this resource is classed as Discovered: Inaccessible due to (1) lack of information about when the site could become available for storage and (2) lack of a regulatory framework for CO_2 storage in most countries.

116 Gt of the aggregated global resource is within the 100 sites in the CSRC that are considered to merit project status. (For the purposes of SRMS classification, a project is defined as a potential resource for which there is some level of storage development plan attached; see

Section 3.4 for further details). A historical lack of policy to actively drive investment and make CCS commercially accessible (e.g., by developing regulations for CO_2 storage) has been a barrier to project development and progression.

Actions that could be taken by CCS stakeholders to aid resource progression are highlighted in Section 4.6.


A) Project
Mid-Case Storage Resource
44%
1%
55%
0.012
0.0004
Stored
Capacity
Sub-Commercial
Undiscovered


B) Project and Non-Project
Mid-Case Storage Resource
96%
4%
0%
0.0001
0.000004
Stored
Capacity
Sub-Commercial
Undiscovered

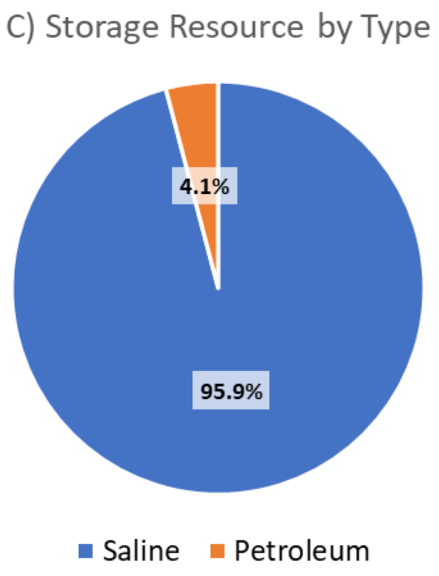


Figure 4-1: a) Spread of global storage resource across SRMS classifications, where a project has been specified. b) Spread of global storage resource across SRMS classifications, both project specified and not. c) Split of global storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

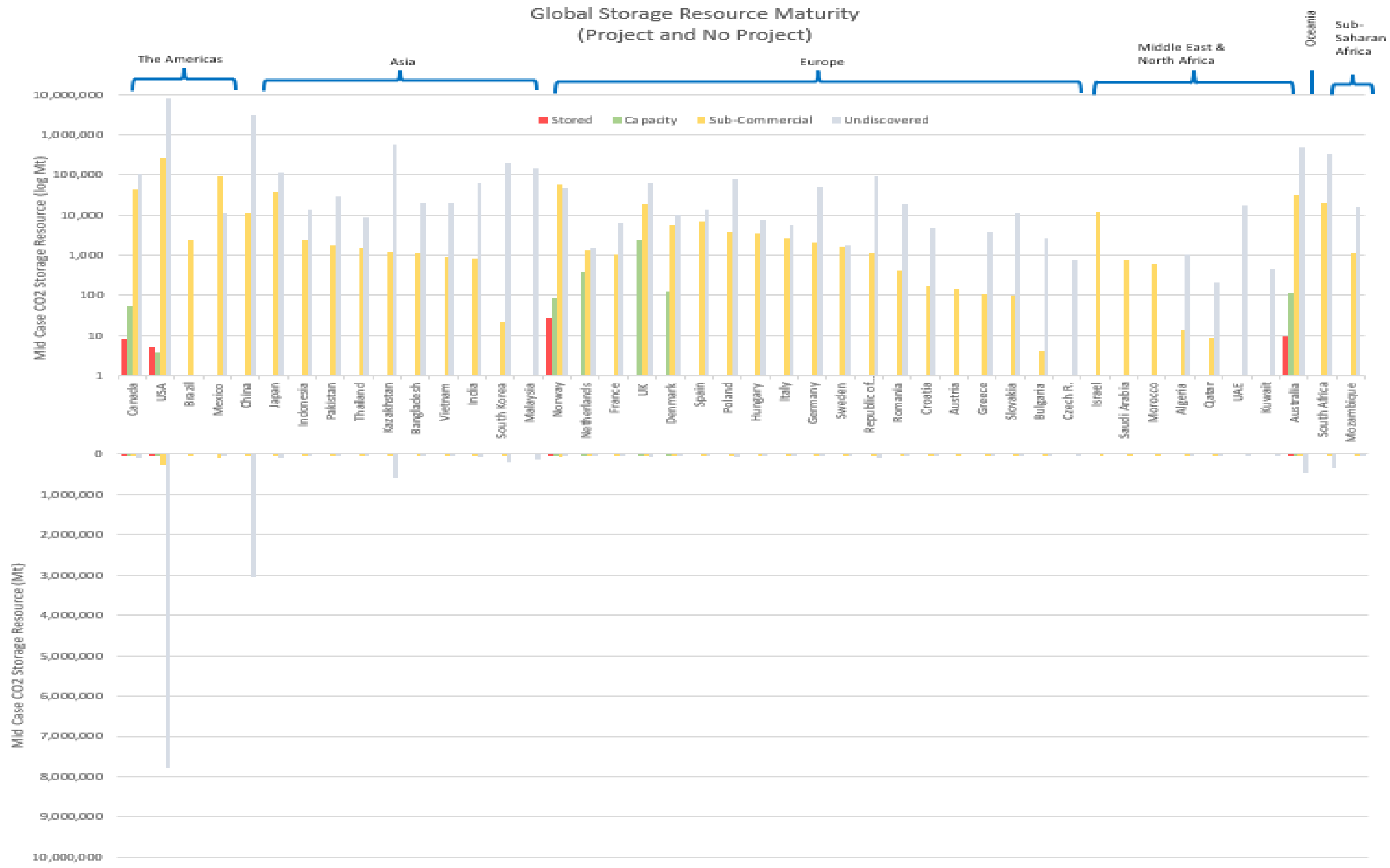


Figure 4-2: Plot of storage resources in the CSRC database by country and SRMS maturity class, showing both log and linear scales.

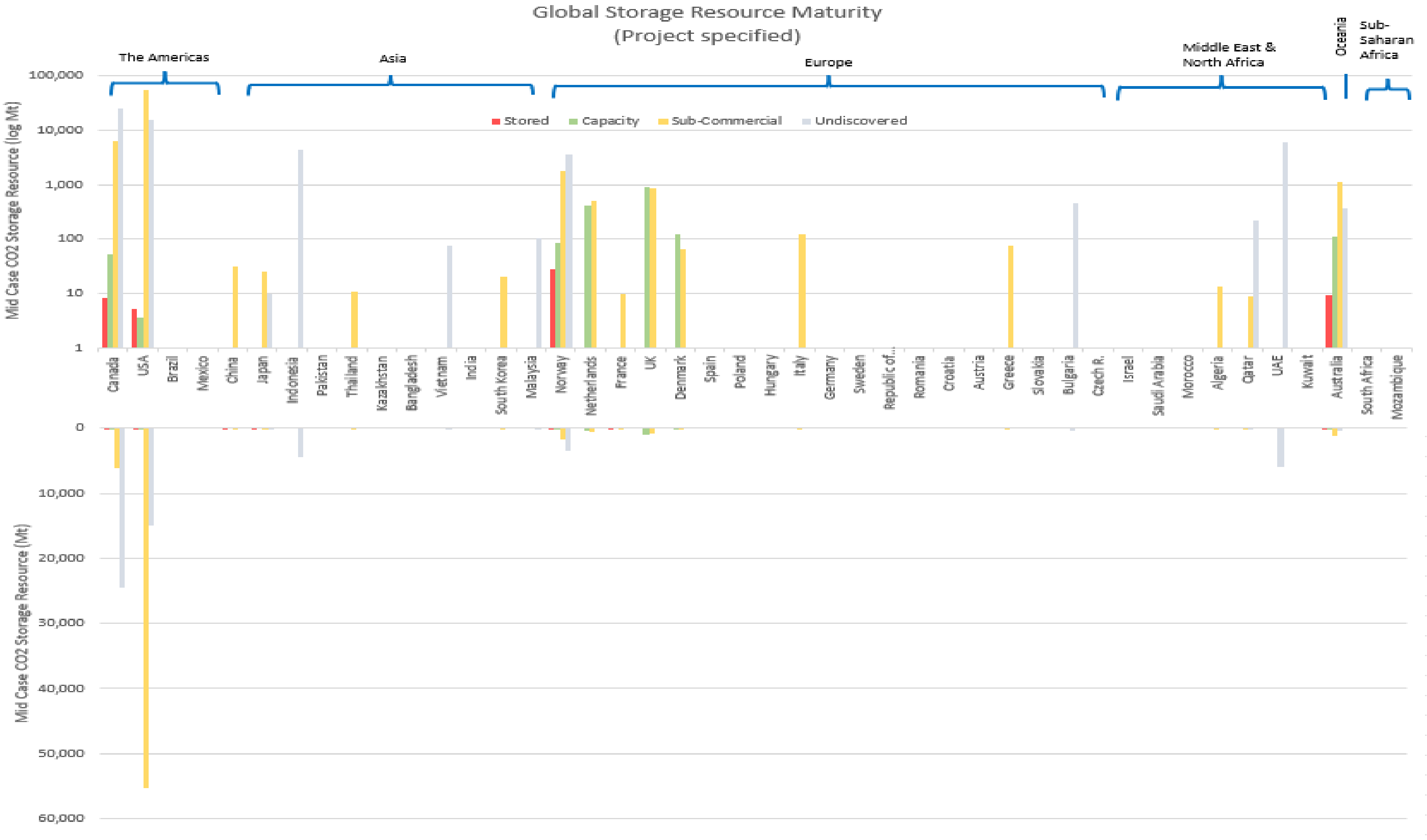


Figure 4-3: Plot of project-specific storage resources in the CSRC database by country and SRMS maturity class, showing both log and linear scales.

4.3 Overview of Cycle 4 Updates

Cycle 4 assessed the potential storage resource from 28 new countries, bringing the total number of countries in the CSRC database to 54.

Table 4-1). An additional 427 sites were added to the CSRC, adding ~362 Gt potential storage resource. This has delivered a classified inventory of 1279 potential storage sites with an aggregated storage resource of 14,060 Gt. It is of note that the revision to a Basal Cambrian entry (Cambro-Ord Saline System (COSS), Canada) in Cycle 4 resulted in a major drop in resource estimates for undiscovered resource volumes. Cycle 3 estimates were for 404 Gt and this estimate has dropped by 256 Gt to 147 Gt. This has affected the overall aggregated total significantly and has been updated in both Cycle 3 and 4 to allow for classification increases to be compared between cycles.

Overall changes resulting from new country assessments and updates in Cycle 4 are summarised in Table 4-2. Information about each country added in Cycle 4 is presented in Table 4-3.

Classification	CO_2 storage resource (Gt)	CO_2 storage resource (Gt)
	Project and no project	Project specified only
Stored	0.052 (+0.09)	0.051 (+0.08)
Capacity	1.736 (+1.52)	1.426 (+1.215)
Sub-Commercial	624.777 (+48.2)	67.385 (+1.04)
Undiscovered	13433.7 (+312.3)	54.6 (+24.5)
Aggregated*	14060.3 (+362.1)	122.388 (+25.7)

Table 4-3: Changes in the CSRC database due to addition of new countries and updates in Cycle 4 (change in Gt since Cycle 3 in brackets). Aggregated, Stored, Capacity, Sub-commercial and Undiscovered columns are resources in Gt.

Countries	Site Numbers	Saline	Petroleum	Project Specified	No Project Specified	Aggregated	Stored	Capacity	Sub-Commercial	Undiscovered
Norway	51	44	7	14	37	104.41	0.03	0.08	58.81	45.49
Republic of Ireland	35	19	16	0	35	90.96	0.00	0.00	1.10	89.86
Poland	25	25	0	0	25	82.87	0.00	0.00	3.70	79.17
UK	106	36	70	13	93	81.41	0.00	2.31	18.53	60.57
Germany	5	4	1	0	5	51.21	0.00	0.00	2.00	49.21
Spain	91	90	1	0	91	20.77	0.00	0.00	6.93	13.84
Romania	29	15	14	0	29	18.43	0.00	0.00	0.43	18.00
Denmark	43	32	11	2	41	16.03	0.00	0.13	5.69	10.21
Israel	5	5	0	0	5	11.76	0.00	0.00	11.76	0.00
Slovakia	7	6	1	0	7	11.32	0.00	0.00	0.10	11.22
Hungary	17	10	7	0	17	10.83	0.00	0.00	3.52	7.31
Italy	39	34	5	2	37	8.20	0.00	0.00	2.58	5.62
France	19	10	9	1	18	7.21	0.00	0.00	1.01	6.20
Croatia	18	12	6	0	18	4.90	0.00	0.00	0.16	4.73
Greece	7	6	1	1	6	3.98	0.00	0.00	0.11	3.88
Sweden	11	11	0	0	11	3.37	0.00	0.00	1.58	1.79
Netherlands	22	5	17	8	14	3.36	0.00	0.40	1.47	1.49
Bulgaria	10	7	3	1	9	2.57	0.00	0.00	0.00	2.56
Algeria	13	12	1	1	12	1.05	0.00	0.00	0.01	1.03
Czech R.	2	2	0	0	2	0.76	0.00	0.00	0.00	0.76
Morocco	3	0	3	0	3	0.63	0.00	0.00	0.63	0.00
Austria	6	0	6	0	6	0.15	0.00	0.00	0.15	0.00

Table 4-4: Summary of Cycle 4 CSRC data by country

Several countries (Libya, Lebanon, Syria, Tunisia, Finland, and Cyprus) did not have any published evaluations that identified sites and therefore have no entries in the CSRC; this does not mean that no storage potential exists in these countries.

The following updates were also made to previous entries in the CSRC database, consistent with the approach outlined in Section 2.9:

- Operational projects with new public domain information: 9 Mt moved from Capacity to Stored.
- Change to policy or regulation: Significant developments in CCS regulation emerged during Cycle 4; Indonesia enacted CCS-specific legislation while Brazil is awaiting confirmation of legislation which will allow CCS project development. Updates to these countries were not carried out in Cycle 4 but will be the focus on the next cycle.
- Storage resources booked: Note about Santos resource booking added to country summary for Australia.

4.4 Overview of Assessment Challenges

The CSRC has highlighted some areas where (1) the assessment of published evaluations against the SRMS is challenging or (2) lack of information impacts on assessed resource maturity. These are described in Section 3.0 and are listed here for ease of reference:

- No published development plans to underpin resource estimates (Section 3.4)
- A lack of information about the methodology used to estimate the resource (Section 3.5)
- Determining the proportion of discovered resource in large saline aquifers (Section 3.6.1.1)
- COP date for oil and gas fields not published (Section 3.6.2.1)
- The lack of CCS-specific regulatory frameworks needed for sites to be considered commercially accessible (Section 3.6.2.2).
- Managing double counting and aggregation (Section 3.6.4)
- Uncertainty not quantified (Section 3.6.5)
- The wide range in detail, quality, and consistency of published resource evaluations

These factors affect the level of confidence attached to published estimates of storage resource as well as the assessed maturity of the resource. For example, some studies at the Play level (Sequence or Basin) indicate an order of magnitude difference between resource estimates calculated from simple pore volume-based methodologies and those derived from pressure-limited dynamic simulations.

4.5 Recommendations for Evaluators

For the SRMS to be used as designed, a more complete adoption of its guiding principles and requirements is needed.

It should be noted that the SRMS is under active update, planned for completion 4Q 2024. The Evaluator should be cognizant of the fact that there may be changes that will alter the current estimates of storable quantities contained in this report.

The following recommendations are offered for professionals who work on evaluation of CO_2 storage resources:

- Any analogue parameters (e.g., storage efficiency factors) used in the evaluation should be provided, together with a clear justification for their selection.
- Where possible, high-quality maps should be included within any evaluation to increase the accuracy of site locations in the CSRC.
- It is important to describe the project that underpins the estimated storage resource, even it is just a notional development concept (see Section 3.4).
- All evaluations should include low, medium, and high case estimates of storage resource from either deterministic or probabilistic analysis.
- All workers should endeavor to use the key terms from the SRMS in a consistent manner and replace the common usage of 'capacity' with 'storage resource' (because 'capacity' is a specific SRMS maturity class).

4.6 Ideas for CCS Stakeholders to Aid Resource Progression

- Support countries to develop CCS-specific regulatory and legal frameworks.
    - Offer a regulatory toolkit, provide examples, and highlight best practice.
    - This could move a significant resource from 'Inaccessible' and is a crucial step for a CCS sector to develop in a country.
- Encourage / enable publication of storage evaluations.
    - Review existing journals and consider whether there are gaps that could be filled by a new publication.
    - This is necessary for resources of any maturity class to be added to the CSRC database and be updated thereafter.
- Continued development of the SRMS
    - Continue work to develop practical resource evaluation standards with clear guidance on key technical issues (such as definition of discovery and treatment of CO_2 injection into pore space originally occupied by natural CO_2).

- Use SRMS to make resource bookings and publish supporting information.
- Create projects that will be able to progress through the commercial milestones listed in Section 3.3.

4.7 Discussion on Storage Capacity Estimates

As discussed in Section 3.5, the CSRC contains storage resource estimates derived from both volumetric and dynamic (using analytical or flow) simulation. For saline aquifers, the resource calculation may be based on an 'open' or 'closed' system. In static, open system approaches, which dominate the published record, the pressure build-up due to CO_2 injection is not included in the resource estimate. In closed system volumetric methods, the compressibility of both water and the storage formation is accounted for, and pressure build-up limitations included through no-flow or no pressure-diffusion boundaries. This is also a static estimate of storage resource as no long-term trapping mechanisms or effects are considered. Comparison of storage estimations in saline aquifers utilising both open and closed volumetric approaches and dynamic, flow modelling methods suggest that utilising the open aquifer volumetric approach leads to significant over-estimation of storage resource [5], [6]. Figure 4-4 illustrates the significant difference between volumetric storage resource estimates and a pressure-limited flow modelling approach.

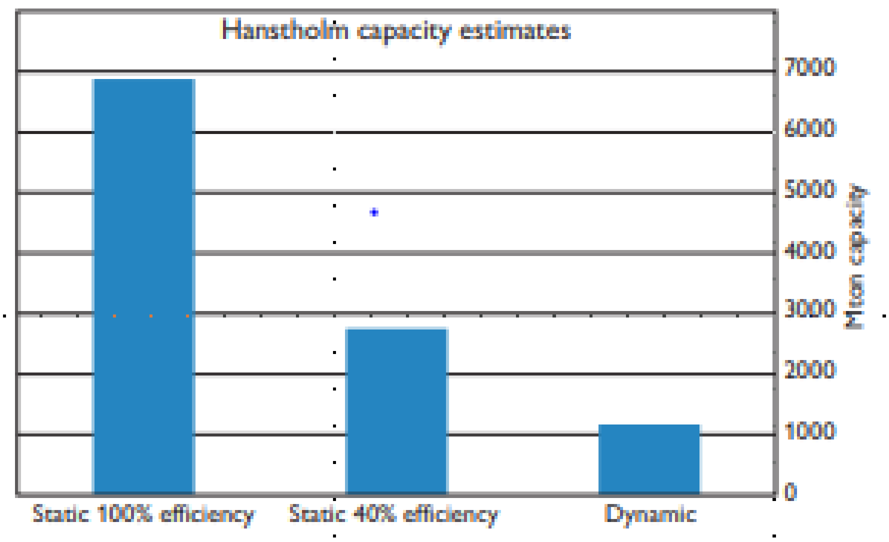


Figure 4-4: Case study illustrating the risk of storage resource over-estimation when using a static, volumetric approach. A nearly 7x reduction in storage resource was simulated in the Hantsholm structure (Denmark) when comparing maximum theoretical utilization of pore space, a storage efficiency factor of 40%, and an optimum filling dynamic simulation approach (source: Anthonsen et al., 2016).

A study [7] of the Cambrian Faludden Formation (Baltic Sea area) and Cretaceous Arnager

Greensands SW Scania area) demonstrated the risk of using theoretical storage estimates by comparing storage resource figures derived from the 2009 EU GeoCapacity project with estimates from dynamic simulation. Flow modelling generated storage estimates nearly two orders of magnitude lower than the volumetric theoretical capacity numbers (Faludden: 37271Mt was reduced to 250-500Mt; Arnager Greendsands: 26050Mt reduced to 250-400Mt).

Similarly, a study of four large saline aquifers [6] compared injected mass and pressure build-up limitations using a flow modelling approach (and accounting for CO_2 dissolution in the formation water) with static volumetric storage estimates which utilize both the open and closed approaches. This study on a Basal Cambrian site (Cambro-Ord Saline System (COSS)) has made a significant change to the resource estimates for both this site and consequentially the resource estimates for all the Basal Sand project sites. The study evaluated the resource as a notional project. The notional project had the following specifications: vertical CO_2 injectors with a maximum injection well pressure of 50% above hydrostatic pressure, pressurizing the regional formation by two values during a 50-year injection period without formation water extraction and using maximum injection rate per well of 2 Mt/yr. The project also considered only a single geologic formation. The flow modelling approach used a pressure limit of both 30 and 15%. Storage efficiencies from a combination of both volumetric and flow modelling results range from 0.46-0.52%. These are considerably lower than previous dynamic storage efficiency estimates that ranged from 7.4- 24%. Previous studies did not take into account pressure limitations; either by the assumption that storage would continue for much longer than reasonable timescales (i.e. above a realistic injection period of ~50 years) or the assumption that pressure can be reduced by large-scale formation water extraction. The results of this study by [6] provided a base case estimate of 18.6 Gt, a mid-case of 24.6 Gt and a high case of 32.0 Gt for the Cambro-Ord Saline System (COSS). For the mid case this is 256 Gt less than estimates cited in Cycle 3. These studies demonstrate the importance of having a project-based approach to resource calculations to provide a more realistic insight into resources based on potential project parameters, but also the significant effects that pressure limitations can have on a resource. In addition, to inject the high volumes indicated by the open system estimates, large-scale water production as a pressure management approach would be required to maintain pressures at a safe operating level.

Clearly, users of storage estimates should exercise caution with published numbers unless details of the calculation method is provided. Closed system volumetric methods are more closely aligned with high quality pressure-limited flow modelling derived storage resources. As new storage resource estimates are generated by applying dynamic methods which account for the realities of injecting CO2 into normally pressured systems, these should be submitted to the CSRC for inclusion and update of existing over-estimates. It should also be noted that all established CCS-specific regulatory systems demand that storage estimates are based on dynamic flow modelling approaches.

5 Appendices

The following appendices contain summaries of individual country storage resources based on evaluations in the

public domain. These documents can be downloaded from https://www.ogci.com/CO2-storage-resource-catalogue/.

Appendix A – The Americas

Countries: Brazil, Canada, Mexico, United States of America

Appendix B – Asia

Countries: Bangladesh, Brunei, China, India, Indonesia, Japan, Kazakhstan, Malaysia, Pakistan, South Korea, Sri Lanka, Thailand, Vietnam

Appendix C – Europe

Countries: Austria, Bulgaria, Czech Republic, Croatia, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, Netherlands, Norway, Poland, Slovakia, Republic of Ireland, Spain, Sweden, United Kingdom

Appendix D – Middle East and North Africa

Countries: Algeria, Egypt, Israel, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, Turkey, United Arab Emirates

Appendix E – Oceania

Countries: Australia

Appendix F – Sub-Saharan Africa

Countries: Mozambique, Nigeria, South Africa

6 Bibliography

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