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Global Storage Resource Assessment – 2019 Update
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1.0 Executive Summary

The Global CO$_2$ Storage Resource Assessment (GSRA) 2019 update has assessed 525 CO$_2$ storage resource sites from 12 countries/regions against the SPE Storage Resources Management System (SRMS). Both oil and gas fields, and saline aquifers are assessed.

To date, 84.8 Gt storage resource is held within defined storage projects, only a small portion of the total 12,267 Gt project and non-project, aggregated global storage resource. Of this global total, only 3.3% is classed as Discovered (408.6 Gt) with less than 0.001% assessed as Commercial resource (106 Mt).

Since CO$_2$ Enhanced Oil Recovery projects are not accounted for in the SRMS, active commercial projects are only operating in Australia, Canada, Norway and the U.S.A.

Whilst this assessment has identified several challenges with the SRMS framework, future resource evaluations should comply with SRMS guidelines to build a more robust global picture of CO$_2$ storage potential and maturity.

The Global CO$_2$ Storage Resource Assessment (GSRA) 2019 update is the first of a six-year programme aimed at building a global view of the commercial readiness of CO2 storage resources in key markets. Funded by the Oil and Gas Climate Initiative (OGCI) with oversight by the Storage Working Group (SWG), published results of potential resource evaluations are classified against the Storage Resource Management System (SRMS). This system is based on the Petroleum Resource Management System (PRMS) and provides a consistent set of definitions and a classification system for CO2 storage resources. It aims to reduce the subjective nature of resource assessment and allow sensible comparison of resource potential. The GSRA 2019 Update comprises a web-based database of assessed storable quantities accompanied by this report, the annual summary of resource classification. Unless otherwise stated, all resource quantities stated are mid case values close to P50 estimates.

The 2019 Update reviewed published evaluations of potential storage resources from 525 sites across 12 countries or regions (Figure 1-1). This includes both oil and gas fields and saline aquifers but excludes CO$_2$-Enhanced Oil Recovery projects (CO$_2$-EOR) and other storage options such as unmineable coal, basalts and organic-rich shales. The aggregated storage resource across all SRMS maturity classes is 12,267 Gigatonnes (Gt) but this combined figure masks the wide range of data availability, approaches, and methodologies applied across the resource evaluations. Over 97% of this aggregated figure is currently classed as 'Undiscovered (Prospective)' meaning that further drilling or enhanced reporting is required before discovered resource can be declared. Only 3%, or 408 Gt, of the aggregated storage resource is classified as being Discovered but Sub-Commercial or Contingent resource. Here, the current level

of understanding, economic, or regulatory conditions are not yet mature enough for commercial development. While the scale of these estimates is encouraging, suggesting that significant storage potential exists globally, the commercial readiness of the global resource remains very low due largely to business model and economic constraints. As of the end of 1st quarter 2020, only 0.1 Gt of the resources assessed was classed as Commercial with a further 0.03Gt as Stored. The assessment highlights the disparity in maturity of the reported storage resource on a global scale (Figure 1-2). Of the twelve countries assessed, only four (Australia, Canada, Norway and the USA) carry any commercial resource, but even in these countries where regulatory and legal frameworks exist to allow CCS, the lack of policy to actively drive investment and deployment means that the country-wide resource is still dominated by Sub-Commercial and Undiscovered resources.

The SRMS is designed as a project-based classification system with progression based on commercial triggers including national/federal regulatory systems and financial investment to drive project progression. Currently only six countries in the GSRA 2019 Update have identified projects (Figure 1-3) but these are still dominated by Sub-Commercial and Undiscovered storage resources. The GSRA 2019 Update has highlighted some areas where the assessment of published evaluations against the SRMS is challenging. Determining the proportion of discovered resource in large saline aquifers, the wide range in detail and quality of published resource evaluations, a lack of development plans linked to resource estimates, overcoming double counting and aggregation, and the adherence of the evaluations to the SRMS, were key issues identified. These factors also affect the level of confidence attached to published estimates of storage resource, particularly at the Play level (sequence or basin) where some studies indicate an order of magnitude difference between

estimates calculated from simple pore volume based methodologies and those derived from numerical simulations where subsurface constraints such as

Figure 1-1. Number of potential storage resource sites assessed in the 2019 Update, by country or region. N = 525.

pressure change during injection can be taken into account.

For the SRMS to be used as designed, a more complete adoption of its guiding principles and requirements is needed across the global CO_2 storage resource evaluation process. All evaluations should include a range of resource estimates from either deterministic or probabilistic methodologies. Furthermore. in the absence of numerical simulations to assess the impact of pressure on storage potential, any analogue parameters (e.g. storage efficiency factors) should be provided together with a clear justification for their selection.

As a result, all countries or regions probably carry a significant commercial maturity understatement and improving this should be a focus of future

assessment cycles. Similarly, on-going injection operations and projects under active evaluation should be re-assessed annually to monitor progression or resource maturity. At present the GSRA 2019 Update is currently underpopulated in this class. Workers on CO2 storage resources around the world are encouraged to submit a summary resource statement for consideration and inclusion in future annual updates.

This work has been commissioned by OGCI and led by the Global CCS Institute and supported by Pale Blue Dot Energy.
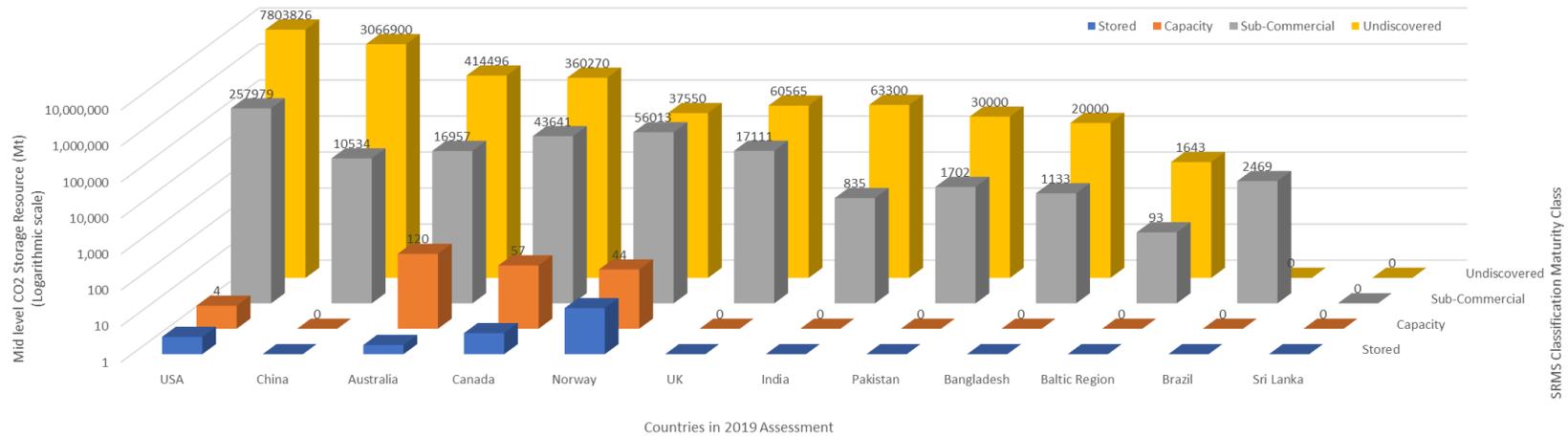
Figure 1-2. Both project and non-project specified storage resource summary for the countries assessed by the GSRA 2019 update. Data labels represent the assessed potential storage resource by SRMS maturity class in millions of tonnes (Mt) (Note: the z scale on this plot is logarithmic)
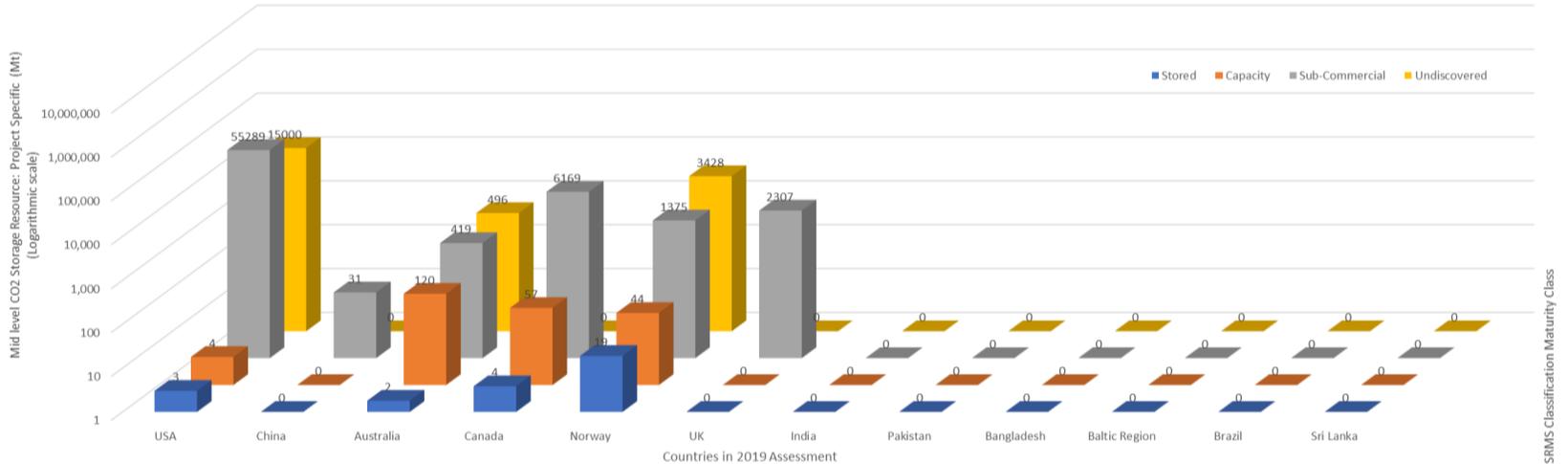
Figure 1-3. Project-specific storage resource summary for the countries assessed by the GSRA 2019 update. Data labels represent the assessed potential storage resource by SRMS maturity class in millions of tonnes (Mt) (Note: the z scale on this plot is logarithmic)

2.0 Objectives & Approach

Figure 2-1 Map showing countries included in the GSRA 2019 Update Assessment.

2.1 Objectives

This GSRA 2019 Update report fulfils the delivery of an annual programme of the classification of published storage resource evaluations using the SPE SRMS (Society of Petroleum Engineers (SPE) 2017). This project supports the Oil and Gas Climate Initiative Storage Working Group (OGCI SWG) in identifying the availability of CO_2 storage resource in key markets. The current programme builds on the work of Pale Blue Dot Energy's interim assessment, produced for the OGCI in 2017. This Update represents the first in a six-year programme, which aims to capture advances in CO_2 storage resource evaluation during this period.

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 SPE's SRMS as robust reporting mechanisms for CO_2 storage

Each objective is met through a series of work packages.

Work Package 1

Objective: to complete CO_2 storage resource assessments by classifying published CO_2 storage resource evaluations from around the world, against the SRMS. The 2019 Assessment both updates the 2017 Interim Assessment (PBDE, 2017) and focuses on a 'priority' country selected by the OGCI SWG. In 2019, the priority country was Canada.

Work Package 2

Objective: to build, populate and deliver the *Global CO₂ Storage Resource*s website based on the outputs of Work Package 1. This work package is delivered by the Global CCS Institute (GCCSI).

Work Package 3

Objective: to develop and publish a summary of the current classification of the target regional CO_2 storage resource assessments against the SRMS system (this report).

Work Package 4

Objective: to establish an outreach programme to selected stakeholders. The first level of engagement will focus on senior budget holders in major institutions responsible for regional resource estimation. The objective with these stakeholders is to build support for the SPE SRMS reporting system and its implementation. The second group of stakeholders will include technical resource estimators. The goal of this engagement level will focus on showing how to use the SPE SRMS reporting system.

Note: As the first cycle of the programme was ending, the global Covid-19 pandemic resulted in the cancellation and/or long-term postponement of many of the events identified as candidates for implementing the Work Package 4 outreach programme. In response, the Assessment Team proposed replacing the outlined programme with a webinar designed to meet the goals of the work package.
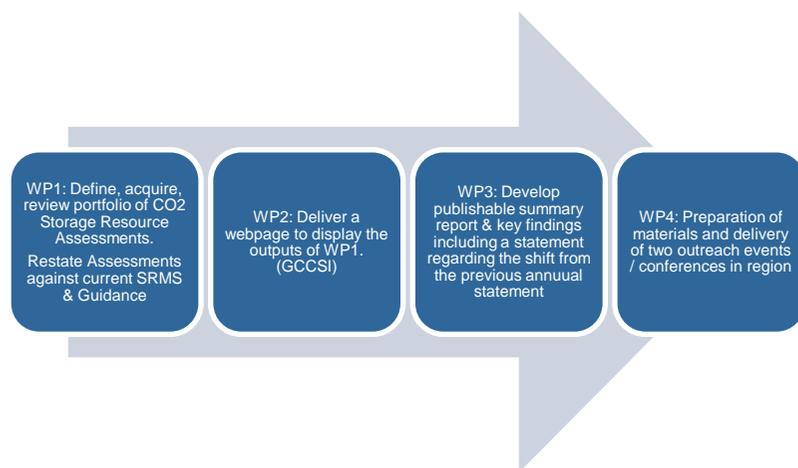
Figure 2-2. Work flow for Work Packages 1, 2, 3 and 4 of the GSRA – 2019 Update

2.2 Approach

The GSRA 2019 Update deployed the SRMS against a library of publicly available information sources and evaluations collated by the assessment team and the Storage Working Group. The effort in Work Package 1 of this project was focussed in two main areas:

- A review and update of the preliminary storage resource classification undertaken in 2017 by PBDE (PBDE, 2017) which targeted Australia, the Baltic Region (Denmark and Germany), Bangladesh, Brazil, China, India, Norway, Pakistan, United Kingdom, and the United States of America.
- A detailed assessment of the 'priority' country for the 2019 assessment cycle: Canada.

In order to align fully with the current SRMS, only depleted or partially depleted oil and gas fields, and saline aquifers were included in the assessment; alternative storage resources such as CO_2-Enhanced Oil Recovery (EOR) operations, basalts, unconventional organic-rich shales, and deep unmineable coals seams were excluded.

A comprehensive bibliography of papers and web-based datasets, all available in the public domain, was built and reviewed prior to being approved by the OGCI SWG for use. This formed the basis of the assessment and is presented in Section 5.0. The bibliography contains a wide range of information sources, including regional scale national and multinational CO_2 storage resource assessments, more detailed evaluations, often targeting a basin, sub-basin, or formation, and focussed technical studies of a field or site.

Following review of the evaluation documents, each storage resource was taken through the SRMS classification process (see Section 3.0 for additional information). Key data for the resource were collated, where available, and assessment notes to support and clarify assessment decisions were documented in the GSRA database.

The Assessment Team met regularly to perform due diligence and consistency reviews on both the data and the classification process. Additional feedback and guidance were provided by the OGCI SWG. Once Work Package 1 was complete, the database was uploaded to the website developed in Work Package 2.

This report is the deliverable for Work Package 3 and is a summary report to accompany the 2019 cycle of the annual assessment. It should be viewed as an accompanying document to the Global CO_2 Resources database (Work Package 2 deliverable).

2.3   Report Organisation

The report is organised into four key sections. **Section 3.0** provides an overview of key aspects of the SRMS and highlights some challenges encountered while deploying the system during the GSRA 2019 Update. It also provides a description of the terminology applied during this assessment and guidance as to how some of the challenges were handled. **Section 4.0** provides a summary of the 2019 Assessment and gives recommendations for future assessment cycles. The classification process has been applied to all sites identified from the bibliography in **Section 5.0. Section 6.0 (Appendix A)** provides the 2019 Country Assessments, where further details of each country's storage resource can be found.

3.0 Storage Resource Management System (SRMS)

The development of the 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, supporting petroleum project development through resource classification for investment. More specifically to CCS, 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 important business decisions.

Key levers for resource progression along the SRMS are commercial, project related steps. In contrast to many current approaches to maturing potential CO_2 storage sites, neither the type of resource nor the methodology of evaluating the resource are the key drivers. The main levers are:

- Discovery status of the resource, as per SRMS guidelines
- The status of the regulatory system in the jurisdiction area
- Internal project decision to proceed
- External regulatory consent to proceed
- Commencement of operations
- End of injection

- The point of handover of long-term responsibility for the injected CO2 to the state

The SRMS was originally published as a draft version in 2017 and was updated later that year. The approach to applying the SRMS in this 2019 Assessment uses this updated version (SPE, 2017) and has attempted to rigorously apply the published guidance and terminology throughout the assessment to ensure a consistent approach. There are several terms used throughout the work which are highlighted below.

A classification flowchart (Figure 3-1), derived from the SRMS documentation, has also been developed and updated, and has been used to aid the classification process throughout the assessment. Note that the SRMS does not separate the 'Play' classification into 'Sequence' and 'Basin', however during the interim assessment undertaken in 2017 (see 2.1), it was recommended to distinguish the following:

- *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.

Although not distinguished by the SRMS, the classification was split in the GSRA 2019 Update to separate sites with a lower level of maturity within the Play classification.
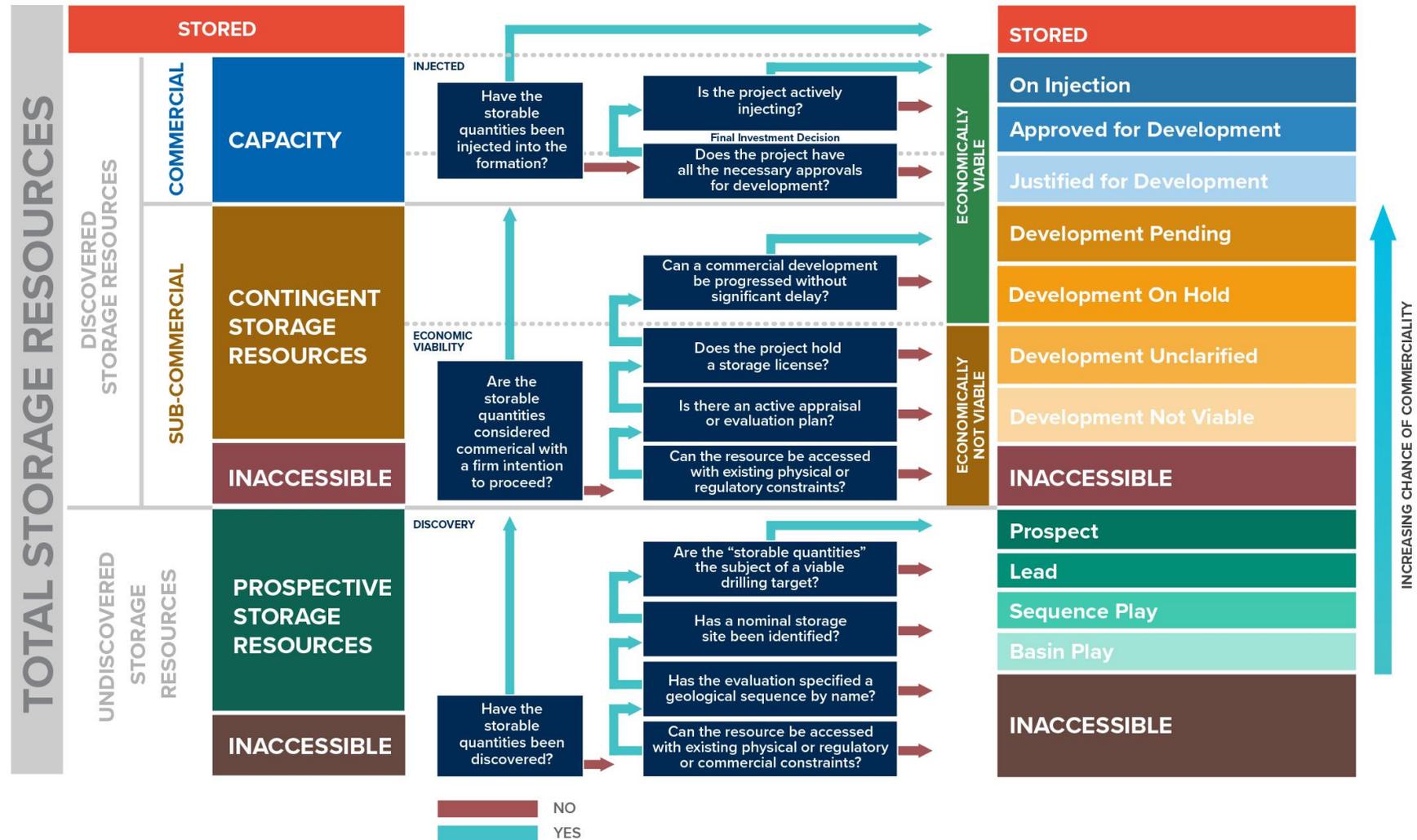
Figure 3-1. Flowchart for the classification of storage resources based on the SRMS guidelines and terminology.

3.1 Terminology

In the SRMS guidelines, 'evaluation' and 'assessment' have the same meaning. In the GSRA 2019 update, these terms are used in the following manner:

Evaluation: The geosciences, engineering, and associated studies, including economic analyses, conducted on an exploration, development, or storage project resulting in estimates of the CO_2 quantities that can be stored and the associated cash flow under defined forward conditions.

Assessment: The consideration of any Evaluations for the purpose of classifying the estimates of derived CO_2 storage resource quantities according to the SRMS guidelines, as interpreted by the Assessor / Assessment team.

Total Storage Resource: This is the equivalent of Total Petroleum in Place in the PRMS and represents the maximum conceivable theoretical storage resource. The Total Storage Resource is the sum of: -

1. Storage resource assuming pore volume water is fully saturated in dissolved CO_2
2. Storage resource assuming pore space in unstructured saline aquifers is fully occupied with CO_2 to the maximum residual saturation level (after CO_2 flood with 100% sweep efficiency)
3. Storage resource assuming pore space in structured saline aquifers & oil/gas fields is fully occupied with CO_2 leaving only irreducible water saturation

3.1.1 Storage Project

The SRMS is a project-based 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'. 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, many resources do not have a published development plan. To aid in the identification of resource sites which have a published development plan each database entry is coded as either identified as a 'Project' or not. In order to gain 'project' status, some level of development plan, conceptual or derived from modelling, must be available or implied with a stated volume of CO_2 with an associated plan including the number of wells required to inject that volume of CO_2. This means that both Undiscovered and Discovered resources may be defined as projects.

3.1.2 Treatment of Discovered 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" (Society of Petroleum Engineers (SPE) 2017). When determining the discovery status of open, unstructured, clastic saline aquifers a problem arises, when part of the aquifer may have been discovered through hydrocarbon exploration, while another part may be largely undrilled. To overcome this, an area of 200 km^2 (circle of 8km radius) around wells within the site that have proven reservoir potential and containment was considered as discovered. This permitted the discovered proportion of the saline aquifer to be calculated from the well density where this was available. Unless otherwise

specified, the reported well number was 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 of 200 km^2 was selected, following results from a study of well density in the UK Southern North Sea Bunter sandstone (PBDE, 2017). The area within the selected well radius is classed as Discovered but with the following caveats applied:

- The analogue used for the storage efficiency factor linked with the discovered contingent resource is clearly identified, where possible.
- 'The storage site is flagged as 'Discovered awaiting detailed assessment' for the area linked to the exemplar or analogue while the potential resource outside the well discovery zone is flagged as 'Undiscovered'. Together this represents a partly discovered site.
- A smaller area was considered for use in complex formations such as carbonates:- 20km^2 discovery area for carbonate platforms with limited diagenesis or 0.5km^2 discovery area for carbonate reef formations. In practise, the data availability in the published sources precluded the use of this approach for carbonate formations and a 200km^2 area around discovery wells was adopted.

3.1.3 Treatment of Petroleum Accumulations

By definition, conventional petroleum accumulations are considered to be Discovered from an SRMS perspective, due to the proven reservoir and containment potential, and having been characterised as having a structural or stratigraphic trap.

It is recognised that the simultaneous production of hydrocarbons and injection of CO_2 in the same site, is commercially problematic outside a pilot or full field deployment of a CO_2-EOR programme. This is due to issues of licensing, materials selection, and product contamination amongst others. As a result, many countries have specific legislation to prevent negative interaction between CO_2 injection and petroleum production. This lack of regulatory access may lead to the classification of certain storage resources as Sub - Commercial but Inaccessible for use, yet may change if there is a date forecast with reasonable confidence, at which that negative interaction will cease and that that date is within a reasonable timeframe. This classification is consistent with the SRMS, which defines Inaccessible resource 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." This approach will leave supergiant fields, whose cessation of production (COP) date is far into the future, and other accumulations which have no published estimation of the COP date as Sub - Commercial but Inaccessible.

To manage this situation, 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, the resources are classified to be Sub - Commercial but Inaccessible at the time of assessment, due to regulatory/commercial issues preventing the sanctioning of CO_2 injection in the vicinity of petroleum productions sites. If no COP is specified (as is the case with many producing properties) then it is assumed that production will continue past the EAD and therefore the storage resources are also Sub - Commercial but Inaccessible. Whilst this may be considered a harsh threshold, petroleum Operators should be encouraged to think beyond the production cycle for the use of the subsurface resources. Indeed, the SRMS notes that Inaccessible

resources "may be used for storage in the future as commercial or regulatory circumstances change". As such, should a COP for a specific producing field become known and published then, subject to this being earlier than the EAD, the associated storage resource could progress into a contingent storage resource classification.

For the GSRA 2019 update, to be published in 2020, the EAD is set to 2050.

In countries which have no published regulatory system covering CO_2 storage licensing, then all discovered potential storage resources (whether former petroleum producing properties or not) have been classified as Sub - Commercial but Inaccessible, regardless of knowledge or status of COP as these are constrained by the lack of regulatory system.

It is noted that the SRMS could be clearer in its definition of Inaccessible storage resources. Currently the glossary contains the following definitions:

Inaccessible: 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.

Inaccessible Contingent Storage Resources: Portion of Contingent Storage Resources' storable quantities that is identified but is not considered available for storage. *(Note this definition is in direct conflict with Figure 2.1 of the SRMS document which clearly shows that Discovered Inaccessible Storage Resources are not part of the Contingent Storage Resources class)*

Inaccessible Resources: That portion of Contingent (Discovered) or Prospective (Undiscovered) Storage Resource quantities, which are estimated as of a given date, not to be used for storage. A portion of these quantities may become storable in the future as commercial circumstances change, technological developments occur, or additional data are acquired. *(Note this definition is in direct conflict with Figure 2.1 of the SRMS document which clearly shows that Discovered Inaccessible Storage Resources are not part of the Contingent Storage Resources class and that Undiscovered Inaccessible Storage Resources are not part of the Prospective Storage Resources class)*

Inaccessible Storage: Storable quantities for which a feasible project cannot be defined by use of current, or reasonably forecast improvements in, technology.

Clearly, from Figure 2.1 in the SRMS guidelines (and incorporated into the SRMS Flowchart in Figure 3-1 in this report), Inaccessible storage resources contribute to the Total Storage Resource, but lie outside both Contingent and Prospective storage resource classifications. This contradiction should be resolved by the SRMS committee soonest.

It is appreciated that the terminology and guidance of how this may be applied in the SRMS may change in the future; the 2019 assessment is designed to conform to the 2017 published SRMS, together with its glossary of definitions and guidance.

3.2 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. Often, as with the US DOE CO_2 Storage Atlas, estimated storable quantities are presented on a state or province basis, without the detailed information on which basins or geological formations,

or which portions of these 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.

Ideally, estimated storable quantities should be presented on the basis of basin, formation, state, and storage site to enable appropriate countrywide assessment, however, this is currently only available in countries with no requirement for state or provincial resource breakdowns, such as the UK and Norway.

Four potential strategies for handling this concern have been considered: -

1. Calculate

This would involve the refinement of the estimated storable quantities by the Assessor, such that each was divided by basin, formation, state, and storage site using the published materials. Such allocation is likely to either:

- Degrade the quality of the regional storage resource estimate
- Lend more credibility, maturity and confidence to early regional evaluations than is appropriate
- Introduce additional error to the evaluation by using an inappropriate allocation algorithm
- Falsely suggest that adequate definition was available for the important early, regional evaluations to allow reliable and representative allocation

As such, where there is an evaluation which covers more than one state, region, province, or basin within the same country, no attempt to allocate resources between the various areas has been made.

The 'calculate' approach was tested but it was rarely possible to complete in a manner acceptable to the assessment team and is beyond the scope of this assessment.

2. Ignore

This option accepts and acknowledges that the issue is real, but simply make no attempt to estimate its impact. Whilst the Calculation Option is not possible, this approach was not viable since it would undermine the Global Storage Resource Assessment programme objectives.

3. Subtract

This approach subtracts the storage resource of a specific storage site from the more regional or state-wide estimate that covers the same geographical area. This option has some potential to manage the double counting issue. The SRMS however presents very clear guidance on the aggregation of resource estimates, which it is felt should apply equally to subtraction of resource estimates as well as summation. Specifically, the SRMS guidance is 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". With single state-wide estimates being classed here as 'Undiscovered', the subtraction of the 'Discovered' contingent resources from a specific site is problematic. Subtraction has been used in some cases where it was considered appropriate but only for storage resources within the same major SRMS maturity class.

4. Qualify

Another approach is to accept the state-wide estimates as 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 state-wide entry in the assessment database is still preserved and the estimates included in the assessor's notes, but no resources have been classified.

The Subtract and Qualify approaches outlined noted here have been used to manage the Double Counting issue to some extent. Whilst these approaches mitigate some of the risk of double counting, it is not possible at this stage to eliminate fully the risk of double counting within the GSRA database. Where this is identified as a significant issue, this is reported in the accompanying country assessment documentation.

3.3 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.

3.4 Single Evaluations

Where a single evaluation of an area or site is available then this evaluation has been used as input to the assessment. The assessment will include a note from the assessor regarding the reliability of the assessment and any specific concerns that have arisen from the available reports of the evaluation. 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 actually qualify for if more detailed information were available. As a result, the storage resource assessments presented will 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.

3.5 SRMS Evolution Draft to Approved July 2017

There was some evolution of the SRMS between the draft deployed in the OGCI 2017 assessment and this GSRA 2019 update. One specific change was in the definition of Contingent Resource sub-classes and is outlined in the table below:

	SRMS - Draft	SRMS - Approved July 2017
Development Pending	Discovered storable quantities where project activities are ongoing to justify commercial development in the foreseeable future.	Discovered storable quantities where project activities are ongoing to justify commercial development in the foreseeable future.
Development on Hold	Discovered storable quantities where project activities are on hold and/or where justification as a commercial development may be subject to significant delay.	Discovered storable quantities where project activities are on hold and/or where justification as a commercial development may be subject to significant delay.
Development Unclarified		Discovered storable quantities where project activities are under evaluation and where justification as a commercial development is unknown on the basis of available information.
Development Not Viable	Discovered storable quantities for which there are no current plans to develop or to acquire additional data at the time due to limited storage potential.	Discovered storable quantities for which there are no current plans to develop or to acquire additional data at the time as a result of limited storage potential.

Of particular note is the clarification of the Development Unclarified sub class in the SRMS - Approved July 2017. The guidance for this sub class is that "it requires active appraisal or evaluation and should not be maintained without a plan for future evaluation." The implications of this change are that many potential CO_2 storage sites which have demonstrable storage resource potential including many depleted petroleum fields, for which no current plans for future evaluation are available must now be assessed as Development Not Viable rather than Development Unclarified. This is despite the SRMS definition of Development Not Viable referring to "limited storage potential" which is interpreted here as limited technical or commercial potential at the time of assessment. This includes sites which have good technical potential but limited commercial potential due to limited demand from storage developers to progress at the current time.

4.0 Summary & Recommendations

4.1 Summary

The GSRA 2019 update has assessed the potential storage resource from twelve countries against the 2017 SRMS (Society of Petroleum Engineers (SPE) 2017). This has delivered a classified inventory of over 525 potential storage sites with an aggregated storage resource of 12267 Gt*.

Classification	CO$_2$ storage resource (Gt) Project and no project	CO$_2$ storage resource (Gt) Project specified
Stored	0.028	0.028
Capacity	0.106	0.106
Sub-Commercial	408	65.59
Undiscovered	11859	18.92
Aggregated*	12267	84.77

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 4-1. Storage resource classification summary for the GSRA-2019 Update

As shown by Table 4-1, the resource base is dominated by the pre-commercial Undiscovered (97%) and Sub-commercial (3%) classes of storage resource. Commercial projects and those where CO$_2$ is approved for development or already being injected and stored in the subsurface only contribute 0.13 Gt to the overall inventory; less than 0.001%. Only 84.6 Gt (0.7%) of the aggregated potential resource is within defined projects.

The skewed distribution of the storage resource classification highlights one of the key issues with current storage potential evaluations; most are not reported with storage resource classification in mind and often do not provide the detail required to fully assess the discovery status of a site. However, the large resource estimate is encouraging evidence for significant storage potential on a scale which matches the industrial and societal requirements. This observation is tempered both by the small number of projects (52) identified by the GSRA 2019 update and by the classification of many projects as Development Not Viable as, although the projects demonstrate storage potential, none are either currently being progressed or under active evaluation.

a) Project and Non-Project Summed Mid Case Storage Resource
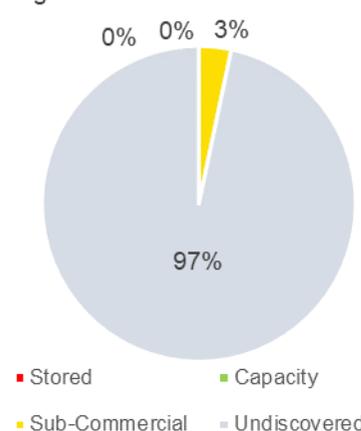
b) Project Specified Summed Mid Case Storage Resource
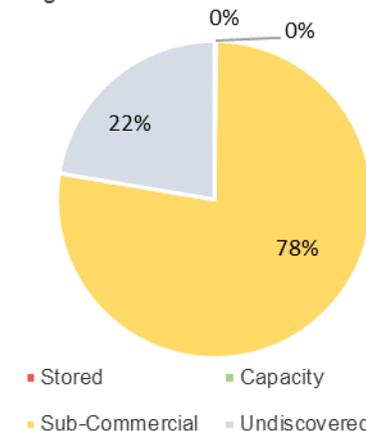
c) Saline Aquifers vs Petroleum
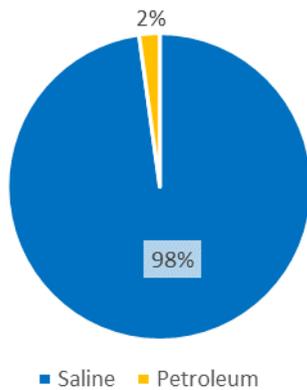
Figure 4-1. a) Spread of global storage resource across SRMS classifications, both project specified and not. b) Spread of global storage resource across SRMS classifications, where a project has been specified. c) Split of global storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

Saline aquifers dominate the resource inventory (11,999 Gt: 98%) mainly due to the large storable quantities from the national and regional atlases and studies. The resource estimates for the saline aquifers rely largely on volumetric calculation, however, and, as such, should be regarded as very high-level estimates of storage potential.
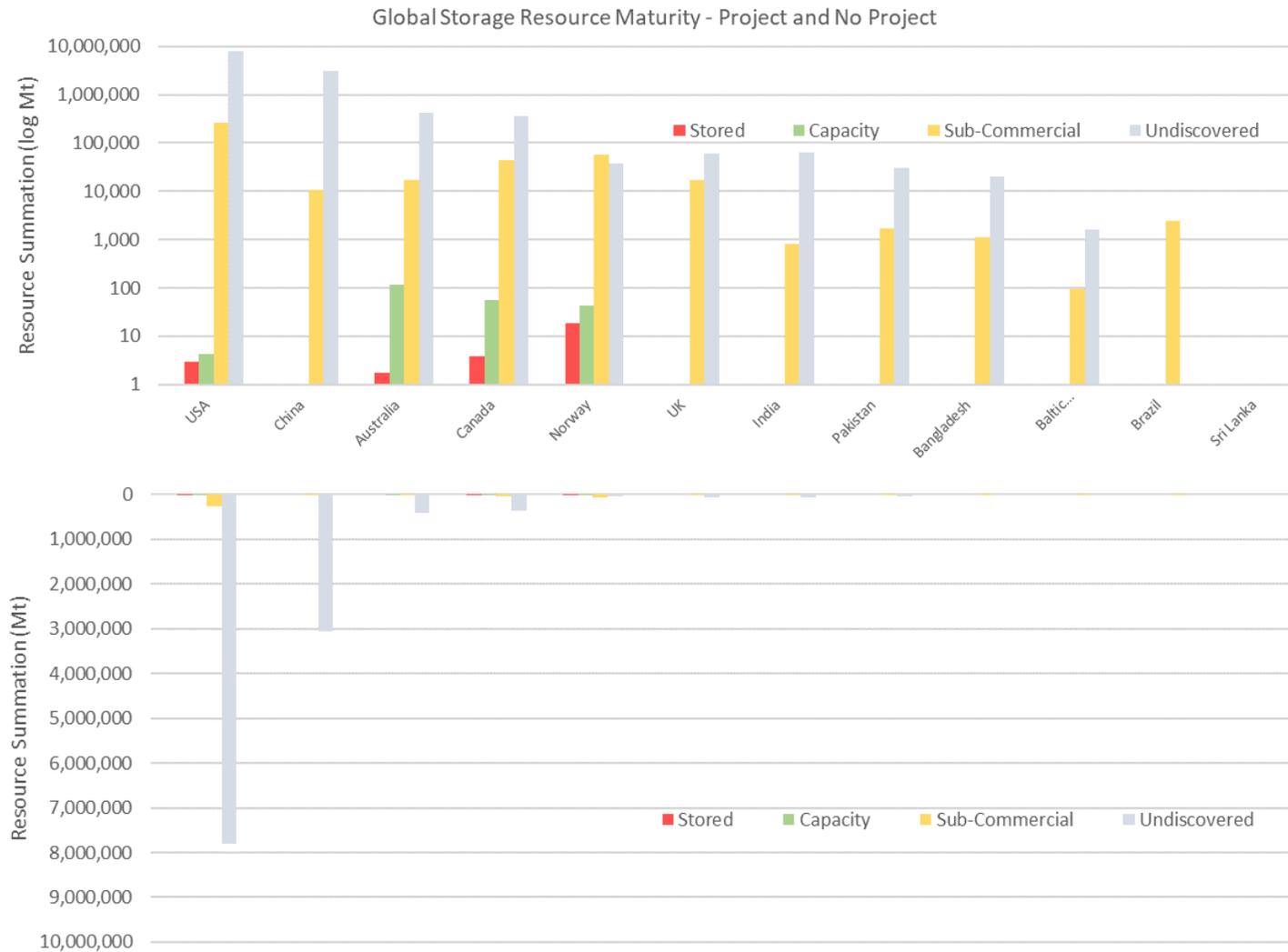
Figure 4-2. Storage resource summary for the countries assessed in the GSRA 2019 update, both project specified and not.

Figure 4-3. Storage resource summary for the countries assessed in the GSRA 2019 update, project specified only.

Oil and gas fields only contribute 2% (268 Gt) of the aggregated storage resource for this assessment. Most of this resource is classed as Discovered: Inaccessible as only Norway and the UK provide COP or EAD dates with the published reserves data

Significant volumes of CO_2 are being injected into depleted fields for enhanced oil recovery, particularly in North America, but CO_2-EOR is not currently covered by the SRMS and so was not considered in the GSRA.

Figure 4-2 displays the storage resource for all the sites that have been placed in the SRMS classification system. Norway and Canada are the most mature with significantly greater resource sitting in the Commercial class. However, there are only four countries in which CO_2 has been stored in the subsurface with projects currently classed as being commercially mature. In all countries, except Norway, the Undiscovered resource dominates the inventory, however it is acknowledged that the maturity of some countries such as the UK is understated.

4.2 Issues

In general, there is a wide variation in data quality and quantity in the evaluations in the bibliography. This can be split into two key areas:

1. a lack of breakdown of resource at the basin or formation level,
2. and a lack of consistency in the approach to resource estimation.

Many countries, even those seen to be advancing CCS (e.g. USA), are dominated by high level, data-light, published resource estimates due to the huge geographic areas to be covered. In others, e.g. Australia, the problem lies with current resource estimates being over a decade old and in need of update with more up-to-date methodologies. Some countries have yet to be rigorously

evaluated, providing only single estimate, poorly defined storage resource values. A consistent and benchmarked methodology is essential for maintaining a balanced overview of available potential resources in a region.

As discussed in Section 3.0 of this report, double counting remains as issue within this assessment. To adhere to SRMS guidelines on aggregation, there are several examples where Prospective (often regional) and Contingent (often local) resources are carried for the same basin or formation. The large size of the Prospective resource relative to the Contingent means the double counting is not numerically significant but this again emphasises the issue with poorly constrained resource evaluations.

Only 10% of the 525 sites in the GSRA 2019 update are defined projects and only 9% have a numerical simulation providing the resource estimate. Given the example of the Basal Sand in Canada where there is an order of magnitude difference between the volumetric estimate of storage potential derived from a 3D static model, and that from the simulated (using an equivalent 3D static model) injection of CO_2 taking pressure build-up during active injection into account, the validity of the very large volumetric estimates must be questioned.

As discussed in Section 3.0, many evaluations only provide a single resource estimate. The data available for the GSRA 2019 update suffer from a lack of probabilistic analysis; most studies do not provide a range of estimates of storage resource. An additional issue lies with the active storage projects where often the storage resource value is the permitted value for the operation, not the simulated storage resource.

Oil and gas fields offer a well-defined storage option, albeit for often smaller volume of CO_2, however, other than the UK and Norway, it is unusual to have published COP or EAD available. This means that many large, potentially

commercial storage resources are currently classified as Inaccessible and cannot be moved through the SRMS system until the necessary data are made available.

While several countries in the 2019 update currently have CCS-specific regulatory and legal frameworks either federally or at a state/province level, most are still lacking a comprehensive policy to drive investment and actively encourage deployment of CCS. This is a major obstacle to development of potential storage resources at the rate considered necessary to meet the industrial and societal requirement.

4.3 Recommendations

- All storage assessments should include low, medium, and high estimates of storage resource from either probabilistic or Monte Carlo methodology.
- Specific sources of any analogue parameters used in estimation such as storage efficiency should always be provided.
- All workers in the CO_2 storage and CCS space should endeavour to use the key terms from the SRMS in a consistent manner and replace the common usage of 'capacity' with 'storage resource'.
- Further systematic assembly of storage exemplars and their storage *efficiency characteristics should be developed as a global resource* tool to support accelerated storage resource assessment.
- Active pilots and projects should be re-assessed in each assessment cycle to monitor the progression of the project.
- Countries such as the USA which are at risk of significant under-statement of commercial maturity should be considered for on-going assessment in future. In the USA large data resource sits with the

Regional Partnerships and should be accessed. In addition, the DOE Carbon SAFE projects should be added to the database as information becomes more readily available.

5.0 Bibliography

Note: The following bibliography contains all the references considered during the GSRA 2019 update. They may be referenced directly in this report, used as a source of storage resource in the accompanying GCCSI website database, or may have been excluded from this study due to a more recent evaluation of a site. In the latter case, the reference may not be cited in either this report or the website database.

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6.0 Appendix A – Country Assessments

6.1 Australia

6.1.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for Australia as follows:

Classification	CO$_2$ storage resource (Gt) Project and no project	CO$_2$ storage resource (Gt) Project specified only
Stored	0.002	0.002
Capacity	0.12	0.12
Sub-Commercial	17	0.42
Undiscovered	414	0.5
Aggregated*	431	1

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-1. 2019 Storage resource classification summary for Australia

- There are currently 29 sites at both a local and regional scale, located across a minimum of 14 basins, both onshore and offshore. Five of these evaluations have a project defined.
- As of February 2020, over 1.8 Mt of CO_2 has been injected to deep geological storage. 1 Mt in the Chevron-operated Gorgon project and 0.8 Mt in the CO2CRC Otway Research Facility.

- Australia remains the most highly-ranked country in the world for CCS specific legislation, according to the GCCSI Legal and Regulatory Indicator (Global CCS Institute 2018).

a) Project Specified
Mid-Case Storage Resource
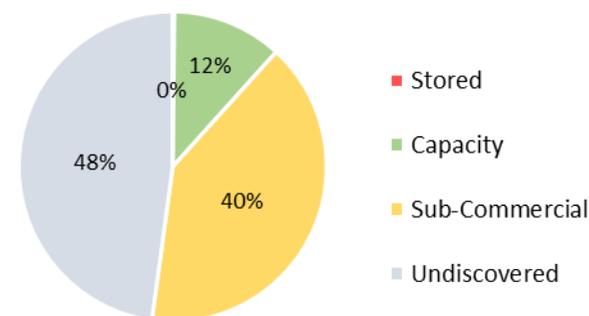
b) Project & Non Project
Mid-Case Storage Resource
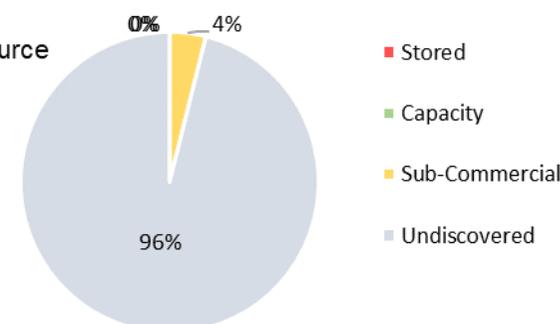
c) Saline Aquifers vs Petroleum
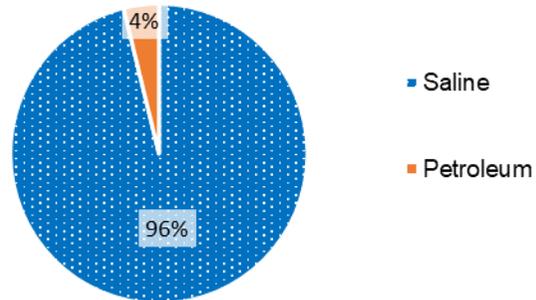
Figure 6-1. a) Spread of storage resource in Australian sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Australian sites across SRMS classifications; both project specified and not. c) Split of Australian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.1.2 Resource Statement

Figure 6-2. Storage resource summary for Australia compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double counting.

6.1.3   Evaluation History

The potential CO_2 storage resources of Australia were summarised as part of the GEODISC programme of research completed by the Australian Petroleum Cooperative Research Centre, Geoscience Australia and the University of New South Wales in 2004 (Bradshaw, et al. 2004). The project screened over 300 geological basins down to 48 before some 65 "potentially environmentally sustainable sites for CO_2 injection" (ESSCIs) were identified. This report was at the time a ground-breaking piece of work and one of the first attempts at a regional CO_2 resource evaluation. To navigate the lack of globally published reservoir simulation studies at the time, a "risked based" calculation method was developed. A chance factor was assigned to each potential ESSCI, describing its chance of being capable to deliver a viable development. This ESSCI chance accounted for storage resource, injectivity potential, site details, containment, and existing natural resources. In general, depleted fields had the highest ESSCI chance, followed by structural traps with no hydrocarbons and finally hydrodynamic systems with no structures.

The study concludes that Australia has a potential risked storage resource (ESCCI storage potential x ESCCI Chance factor) of 720 Gt. Whilst the evaluation included the identification of specific formation and seal pairs through regional review and highlighted the significant potential available, the document does not support a useful classification against the SRMS system. Furthermore, the CO_2 storage resource was presented as "Risked Resource" rather than the un-risked resource required by the SRMS.

In 2009, the Carbon Storage Taskforce (CST) compiled the National Carbon Mapping and Infrastructure Plan – Australia on behalf of the Australian Government, which provided the storage resource estimations included in this report (Australian Government 2009). The Taskforce is composed of members from key industry sectors which have an expertise or interest in CCS. The Plan aims to map both the potential storage resource and carbon sources in Australia to accelerate industrial CCS development. The report considered the storage resource within saline aquifers, petroleum fields and EOR projects. Theoretical, probabilistic storage capacities were calculated for saline aquifers, based on the probability of the resource being able to be utilised. The reported results used a storage efficiency factor (E) of 4%.

The methodology to evaluate the storage within hydrocarbon fields was not defined in the CST report.

Since 2009, the Australian Government has undertaken several research projects on specific sites or basins that are considered priority areas for CCS development in Australia. Of these, two provide storage resource estimations, one for the Gippsland Basin and one for the Petrel Sub-basin (Australian Government: Geoscience Australia 2016) (Australian Government: Geoscience Australia 2014). Both these reports use simulation modelling to prove CO_2 containment, built using well and seismic data from nearby hydrocarbon exploration activity. As such, they provide project-based evaluations.

6.1.4   Resource Review

6.1.4.1   *Major Projects*

The Australian commercial storage resource documented in this report is sourced from two projects: Chevron's Gorgon LNG project and the CO2CRC Otway Research Facility.

Operating since 2009, Gorgon is an LNG site where naturally occurring CO_2 is separated from the natural gas before compression. Up to 3.8 Mt/yr is expected

to be injected over a 25-year period, and in February 2020, the project surpassed 1 Mt CO_2 injected. A total CO_2 volume of 120 Mt has been approved for injection (M. Trupp, Chevron, *pers. comm*), representing the expected volume of captured CO_2. A suite of CO_2 injection, water injection and surveillance wells are used in the project to manage CO_2 containment in the Jurassic-age reservoir (Macdonald-Smith 2020).

The Otway Research Facility was established in 2008 by the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) under the Australian Government's Cooperative Research Centres (CRC) program. Following the cessation of funding in 2014, the facility now operates as a not-for-profit research centre with the aim of developing CCS injection and monitoring techniques to lower industrial GHG emissions. It has successfully stored 80,000 tonnes of CO_2 and aims to drill up to 5 injection and/or monitoring wells from 2017 onwards (CO2CRC n.d.).

No estimations for the total storage resource potential at either site could be found within the published literature.

6.1.4.2   Depleted Oil & Gas Fields

The CST (Australian Government 2009) reports a total of 16.5 Gt storage potential within Australian depleted hydrocarbon fields. The report does not, however, note the methodology used to calculate this resource.

By definition, all hydrocarbon fields can be classified as discovered. The CST Report (Australian Government 2009) notes that in the NW shelf, petroleum activity is currently forecasted to extend beyond 2050 and are therefore considered Discovered Inaccessible storage resources at this time. This holds a total of 13.4 Gt of storage resource.

Outside the NW Shelf, in both offshore and onshore locations, the aggregated storage resource is 3.1 Gt. This portion has been classified as Discovered Development Not Viable, as the resource is not constrained by the Australian regulatory system, however while the storage resource is accessible before the AED of 2050, no sites currently undergoing appraisal were found during the GSRA 2019 update.

6.1.4.3   Saline Aquifers

The saline aquifer resource comprises the largest proportion of potential storage resource in Australia. The majority, 414 Gt, of this resource lies at the 'Undiscovered Basin Play' level as no formation has been specified for many of the basin-level evaluations (Australian Government 2009). In the recent projects undertaken by the Australian Government, where a formation was specified, the resource was classified as 'Undiscovered Sequence Play', however this only accounts for 0.4 Gt, highlighting the overall low maturity of the saline aquifer resource (Australian Government: Geoscience Australia 2014), (Australian Government: Geoscience Australia 2016).

In areas where the reservoir had been discovered through the drilling and logging of hydrocarbon wells, a portion of the site could be classified as 'Discovered Not Viable', calculated as a proportion to the well density.

The total 'Stored' saline aquifer resource is 2 Mt, from the Gorgon and CO2CRC projects, as detailed in 6.1.4.1.

6.1.5   Regulatory Framework

CCS legislation in Australia is defined either by the state, or by the Commonwealth, when in Commonwealth Marine Protection Zones. There is currently legislation established covering a number of states and areas in the

Commonwealth waters, giving Australia the highest global Legal and Regulatory Indicator rating from the GCCSI (Global CCS Institute 2018). The CST Report notes, however, that the regulation is not consistent between states, particularly in the areas surrounding long-term liability and any pre-existing rights for resource exploitation of specific sites (Australian Government 2009).

The CCS-supportive legislation and policy framework in Australia has led to industry CCS operations at Gorgon, in addition to numerous government-backed research facilities and pilot-projects (Global CCS Institute 2018).

6.1.6   Issues for the 2019 Assessment

While the National Carbon and Infrastructure Mapping Plan made significant progress in identifying and quantifying CO_2 storage resource in Australia, the report is now more than a decade old and would benefit from modern evaluation, accounting for the significant changes in the CCS industry over the last 10 years and also learnings from the petroleum industry.

There is a risk of double counting in the Bonaparte and Gippsland Basins between the regional, theoretical evaluation made in the National Carbon Mapping and Infrastructure Plan (Australian Government 2009) and later studies that considers injection on a local scale into the basins (Australian Government: Geoscience Australia 2014) (Australian Government: Geoscience Australia 2016). In accordance with the SRMS guidelines on aggregation of resources, the double counting cannot be avoided as due to the different maturity of the sites against the SRMS classification system (Society of Petroleum Engineers (SPE) 2017).

6.1.7   Future Updates

Further work should also focus on evaluation at a site or even formation level, to progress the maturity of the Australian resource along the SRMS classification system.

6.2 Baltic Region (Denmark & Germany)

6.2.1 Summary

During the course of the assessment, a series of Triassic age closures in the western Baltic region were reviewed from a GHGT-12 publication (Anthonsen, Bernstone and Feldrappe 2014). Whilst this does not portray a complete picture of the resource profile for the Baltic region, which includes countries surrounding the Danish North Sea and the Baltic Sea, it points to the availability of significant resource in that region and so has been included here. The GSRA 2019 update has identified a CO_2 storage resource for the Baltic region as follows:

Denmark

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	0.093	0
Undiscovered	1,5351.643	0
Aggregated*	1.628	0

Germany

Classification	CO_2 storage resource (Gt) DENMARK	CO_2 storage resource (Gt) GERMANY
Stored	0	0
Capacity	0	0
Sub-Commercial	0	0
Undiscovered	0.11	0
Aggregated*	0.11	0

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-2. 2019 Storage resource classification summary for Baltic Region (Denmark & Germany)

The aggregated storage potential for the Baltic region is 1.74 Gt and is entirely held within saline aquifers within closed structures. These are classified mostly as Undiscovered Prospective Resource. No projects are defined.

The published evaluations identified 13 closures of Triassic Bunter Sandstone in the North West German Basin; 12 sit within in Denmark and 1 in Germany.

a) Project & Non-Project
Mid Case Storage Resource

b) Saline Aquifers vs Petroleum
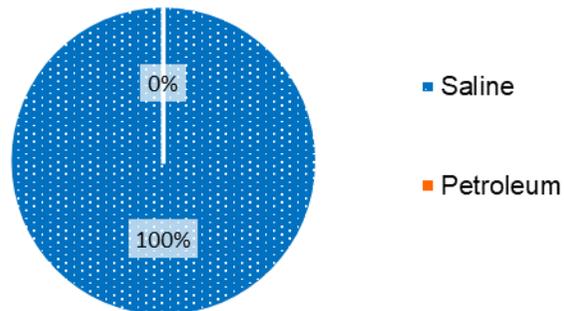
*Note: None of the Baltic sites have an associated project specified.

Figure 6-3. a) Spread of storage resource in all Baltic sites across SRMS classifications. b) Split of Baltic storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.2.2 Resource Statement

Figure 6-4. Storage resource summary for Baltic region compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Projects were not specificed for any of these sites. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double counting.

6.2.3 Evaluation History

The storage resources of the Baltic region were reviewed, and a preliminary assessment carried out, during the GSRA 2019 Update. The basis of the assessment is the Screening study of sites in the Southern North Sea and Southwest Baltic Sea areas (Anthonsen, Bernstone and Feldrappe 2014). This document is based on petroleum research project called Petrobaltic.

The GSRA reviewed the potential storage resource offered by saline aquifers, both onshore and offshore. In the huge offshore area considered, only 11 wells were available to the study,

6.2.4 Resource Review

6.2.4.1 *Major Projects*

No active or developing carbon storage projects have been assessed.

6.2.4.2 *Depleted Oil & Gas Fields*

No depleted oil and gas fields have been considered.

6.2.4.3 *Saline Aquifers*

The published evaluation considered static resource assessments of large closed structures containing Jurassic and/or Triassic formations. This included a review of reservoir and caprock potential.

6.2.5 Regulatory Framework

As the Baltic area is covered by the EU CCS Directive, the area is covered by jurisdictions which are generally at an advanced state of deployment readiness. Denmark, Germany and Poland are all classed as a 'moderately performing' nations by the 2018 GCCSI CCS Readiness Index. Of these, Germany leads with the highest combination of scores for both CCS interest and readiness and

with increased focus after a 2019 shift on the government position regarding underground CO_2 storage. Poland carries a moderate readiness with a high interest due to the countries large domestic coal resource and dependent on fossil fuels. Denmark is also at a moderate readiness, but with advanced renewable energy deployment and net zero policy ambitions.

6.2.6 Issues for the 2019 Assessment

The single source of storage resource evaluation provides a very early and incomplete view of Baltic storage resource potential. The sites specified are materially immature, although large subsurface structures have been identified using seismic data.

6.2.7 Future Updates

Future assessment updates should review and check for published evaluations of storage progress across the Baltic states.

6.3 Brazil

6.3.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for Brazil as follows:

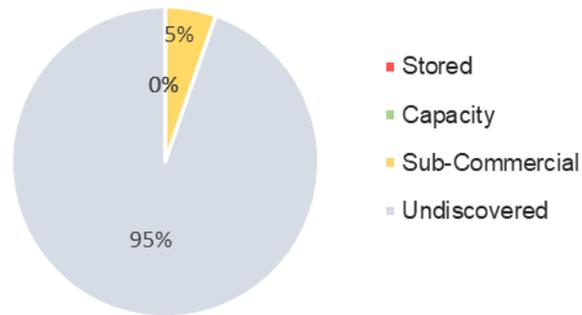| Classification	CO₂ storage resource (Gt) Project and no project	CO₂ storage resource (Gt) Project specified only
Stored	0.001	0.0006
Capacity	0	0
Sub-Commercial	2.47	0
Undiscovered	0	0
Aggregated*	2.47	0.0006

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-3. 2019 Storage resource classification summary for Brazil

The storage potential is Brazil has been summed to 2.47 Gt and is entirely held within oil and gas fields. These are classified as Discovered but Inaccessible due to the lack of cessation of production dates, an EAD date, or a CCS-specific regulatory and legal framework.

The Assessment has identified 17 oil and gas fields in the Campos Basin with a storage potential evaluation, plus a small CO_2-EOR operation (Buracica, Reconcavo Basin) which has injected a reported 0.0006 Gt CO_2. Storage

potential has also been evaluated at the basin-scale, providing an additional 0.7 Gt across 9 geological basins.

a) Non-project*
Mid-Case Storage Resource

b) Saline Aquifer vs Petroleum
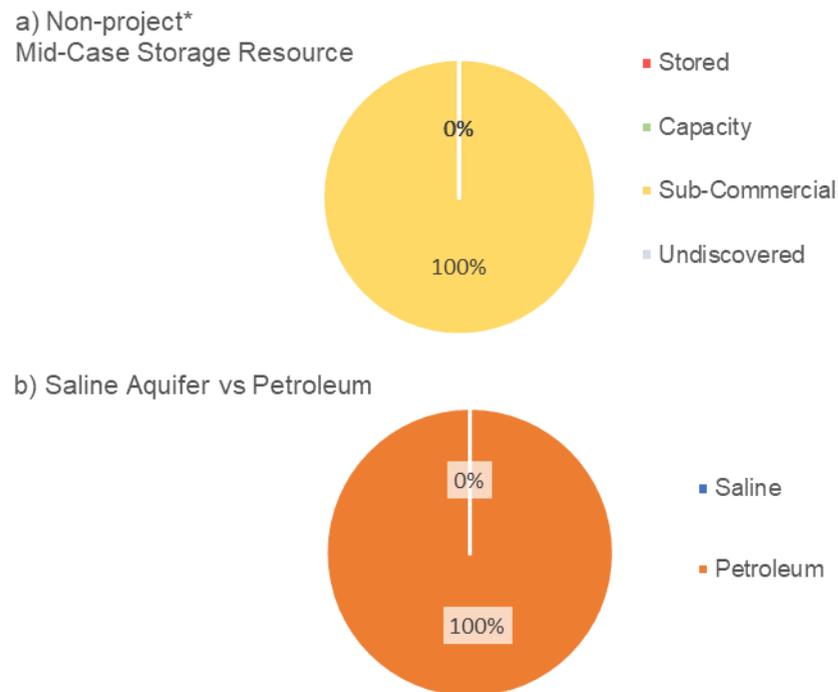
*Note: None of the Brazilian sites have an associated project specified.

Figure 6-5. a) Spread of storage resource in all Brazilian sites across SRMS classifications. b) Split of Brazilian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.3.2   Resource Statement

Figure 6-6. Storage resource summary for Brazil compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double counting..

6.3.3　Evaluation History

Brazil's storage resources were reviewed, and a preliminary assessment carried out, during the 2019 Assessment. The basis of the assessment is the 2016 Brazilian Atlas of Carbon Capture and Storage. This document is based on research by the Centre of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) and was funded by the Global Carbon Capture and Storage Institute (GCCSI).

The 2019 Assessment also accessed information from the Brazilian Carbon Geological Sequestration Map Project (CARBMAP; 2011), an effort to create a geographic information system (GIS) to facilitate matching of CO_2 sources and sinks. These two documents currently provide the only information on storage resource potential in Brazil.

The Assessment has reviewed the potential storage resource offered by oil and gas fields, both onshore and offshore. Coalfields and basalts are also evaluated by the Atlas but do not form part of this Assessment. Currently 24 hydrocarbon fields, covering 10 geological basins, have been evaluated and considered by the assessment. All storage resources are classified as Discovered as they are oil and gas fields, however the absence of both a Cessation of Production (COP) date, or an EAD, indicating when the resource may become accessible for CO_2 injection, and the lack of a CCS-specific regulatory system limits them to "Inaccessible Storage Resources". It should be noted that even though a CCS regulatory framework is lacking, CO_2 continues to be injected underground for enhanced oil recovery under the existing petroleum regulatory system.

6.3.4　Resource Review

6.3.4.1　_Major Projects_

No major carbon storage projects were identified by the 2019 Assessment. However, the Pre-Salt oilfields in the Campos and Santos offshore basins contain high levels (8-12%) CO_2 in the produced fluids (Iglesias et al., 2014). Petrobras operate an active project which captures CO_2 from the hydrocarbon processing facilities and re-injects the CO_2 into the supergiant Lula field in the Santos Basin. This operation is utilising a 'hub and cluster' development which, uniquely, deploys 10 FSPO's. The primary focus is on CO_2-EOR however the reported aim is to cumulatively inject 40 Mt by 2025. By January 2019, 10 Mt had successfully been injected. Future assessments should re-visit this operation.

6.3.4.2　_Depleted Oil & Gas Fields_

Quantitative information is available from the Brazil Atlas on the large, offshore post-salt oil & gas fields within the Campos basin region. The Campos region potential storage resource is estimated to be 950Mt (CARBMAP; Rockett et al. 2011) but the published resource only represents a subset of 17 fields out of 50 in the basin and excludes the large Pre-Salt oilfields. The approach to evaluating storage potential uses the replacement methodology proposed by Bachu et al. (2007).

Further basin-wide storage resource estimates are available for 9 additional onshore basins. The data are derived from the CARBMAP project and also apply a cumulative production/replacement methodology for resource evaluation.

In addition, the Reconcavo Basin project, a CO_2 storage pilot project in fields undergoing EOR, has evaluated the impact of 20 years CO_2 injection into the

onshore Buracica oilfield where a small 600,000t inventory has been injected for enhanced oil recovery.

6.3.4.3 *Saline Aquifers*

The 2019 Assessment found no specific published details of CO_2 storage potential in saline aquifers. A 2009 pilot project in which 12,000 t CO_2 was injected into the Rio Pojuca saline aquifer represents the only reported carbon storage.

6.3.5 Regulatory Framework

Brazil is classed as a 'moderately performing' nation by the 2018 GCCSI CCS Readiness Index with moderate scores for both CCS Readiness and Inherent Interest. Although Brazil's energy mix is 90% renewables, due to a large share of hydropower in the country, it is supportive of CCS and recognizes it as an important energy technology in its energy strategy. The government National Energy Plan 2030, which identifies CCS technology as one of the tools to reduce CO_2 emissions from fossil fuel, was issued on 2007. CCS is also recognized as a technology capable of boosting Brazil's energy security. However, there is currently no clear policy environment which encourages investment in CCS and no development of a regulatory or legal framework to enable deployment. This is exemplified by the Santos Basin CCS facility which has developed into a commercial-scale operation through implementation of CO_2-EOR, not carbon storage.

6.3.6 Issues for the 2019 Assessment

Both the Brazil Atlas and CARBMAP provide an early high-level overview of the potential storage resource and links basins to emissions centres to minimise transportation burden. However, the overall resource potential remains unquantified and, as such, the 2019 Assessment is significantly incomplete with regards to the classification.

6.3.7 Future Updates

Future assessment updates should review and check for published evaluations of storage progress across Brazil. As the Pre-salt operations develop in the Campos and Santos offshore basins, additional resource potential may be identified.

6.4 Canada

6.4.1 Summary

The GSRA 2019 Update has identified a CO_2 storage resource for Canada as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.004	0.004
Capacity	0.057	0.057
Sub-Commercial	43.6	6.2
Undiscovered	360.3	0
Aggregated*	399	6.2

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-4. 2019 Storage resource classification summary for Canada

- Storage resource potential is present in both saline aquifers and oil and gas fields.

- Potential storage resource has been identified in 4 geological basins with 56 sites or regional locations identified. All together, 11 projects have been defined. High level, province-scale resource estimates are also included in the Assessment for those provinces where a more detailed break-down of the storage resource is unavailable.

- As of December 2019, 3.84 Mt of CO_2 has been reported injected and stored by two CCS projects operating in Canada: Quest (3.7 Mt) and Aquistore (0.14 Mt).

- Five site characterisation projects have been undertaken over the past decade, but these have not been progressed since completion.

- Most published information on potential storage resource is geographically centred on the provinces of Alberta and Saskatchewan within the Western Canada Sedimentary and Williston basins, with additional potential identified in British Columbia, Ontario, and Quebec.

- The current regulatory system is moving towards a CCS-specific framework with most progress at the provincial level. Alberta and Saskatchewan have both approved CO_2 injection legislation to support the active Quest and Aquistore projects.

- There are currently no well-publicised plans for any future large-scale CCS project in the pipeline, although opportunity may exist with the Alberta Trunk Line (ACTL) CO_2 pipeline project which is expected to come online during 2020.

a) Project Specified
Mid-Case Storage Resource
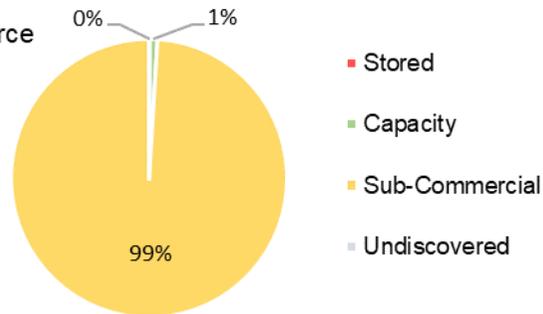
Split of Canadian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

b) Project and Non-Project
Mid-Case Storage Resource
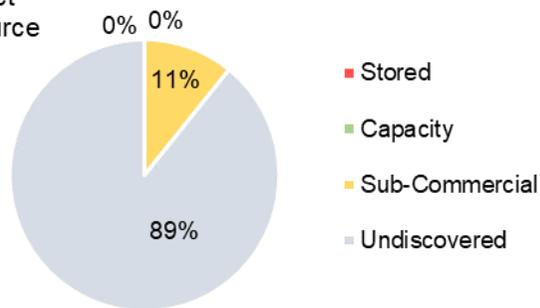
c) Saline Aquifer vs Petroleum
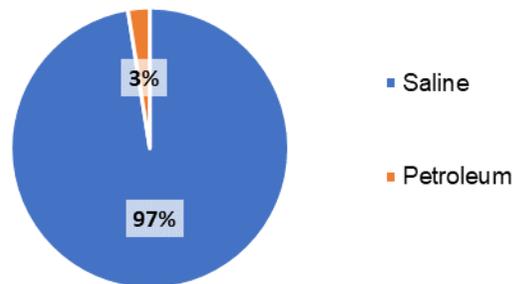
Figure 6-7. a) Spread of storage resource in Canadian sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Canadian sites across SRMS classifications; both project specified and not. c)

6.4.2 Resource Statement

Figure 6-8. Storage resource summary for Canada compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.4.3 Evaluation History

Canada was selected as the priority country for review during the 2019 Assessment. The approach taken was to review the published national and regional evaluations of storage potential, followed by a more detailed study of specific projects at the basin and local scale. As a starting point, both the North American Carbon Storage Atlas (NACSA, 2012) and the 2015 DOE Atlas V were used to derive high level estimates of the storage resource at the Country- and Province level. US-DOE-funded projects, through the Regional Carbon Sequestration Partnerships (specifically the Plains CO_2 Reduction Partnership; PCOR), provided additional data and information. The storage potential in unmineable coals seams (Enhanced Coalbed Methane, or ECBM), basalt deposits, and organic-rich shale units has also been investigated by both the country-level atlases and the regional studies, but has **not** been included in this Assessment, as these resource types do not fall within the current SRMS.

6.4.4 Resource Review

6.4.4.1 *Major Projects*

In 2006, Canada's National Round Table on the Environment and Energy (NRTEE, 2006), a now defunct independent advisory board to the Canadian Government, reported that CCS technology had the potential to offer up to 40% of the required reductions in CO_2 emissions in Canada (NRTEE, 2006). In the following decade, various task forces created a case for CCS implementation in Canada, leading to over $3 billion in government and provincial support for CCS through a range of programs. As a result, several large-scale CCS demonstration projects, designed to inject at least 1 Mt CO_2 / year, were advanced. These included:

- Boundary Dam Carbon Capture project: a coal-fired electricity-generation project (SaskPower, Saskatchewan).
- Alberta Carbon Trunk Line (ACTL): a CO_2 pipeline project (Enhance Energy, Alberta).
- Quest CCS: Scotford oil sands upgrader (Shell, Alberta).
- Pioneer project: coal-fired electricity generation (TransAlta, Alberta).
- Swan Hills project: underground coal gasification and syn-gas electricity generation (Alberta).
- Fort Nelson CCS: shale gas processing plant (Spectra Energy, NE British Columbia).
- Weyburn: commercial CO_2 -EOR (Whitecap Resources (formerly owned by Cenovus Energy), Saskatchewan).
- Midale: commercial CO_2-EOR (Apache Energy, Saskatchewan).

Of these, only Boundary Dam, Quest, and Weyburn-Midale are actively either capturing or injecting CO_2; albeit predominantly for EOR, using CO_2 captured from the Boundary Dam site, or piping CO_2 from the Dakota Gasification syn-fuels plant in North Dakota (Weyburn-Midale fields).

As of the 2019 Assessment, only the Quest CCS project and the Aquistore project, which acts as a 'overflow' store for CO_2 captured at Boundary Dam, are currently injecting CO_2 into saline aquifers as part of fully integrated and monitored CCS projects. The Fort Nelson project completed initial site characterisation studies and is currently on-hold. The Pioneer CC project collapsed in 2012 for economic reasons related to the absence of either a national carbon trading market, or a method for capturing value from emissions credits (Petroleum Economist, 2012). Swan Hills Syn-Fuels ran a demonstration project (the ISCG project) in 2009 but has since shifted the company focus.

Site Studies

Several saline aquifer site characterisation projects were carried out during the period 2004 – 2014. These attempted to identify or technically progress potential storage sites:

- WASP
- HARP
- Athabasca area
- St Lawrence Lowlands basin, Quebec (Becancour project)
- Michigan Basin, Ontario
- PCOR (Plains CO_2 Reduction Partnership Basal Cambrian System

These are included in the 2019 Assessment.

6.4.4.2   *Application of the SRMS in North America*

North America raises some of the issues discussed in Section 3.2, which are particular to both Canada and the USA. National atlases (e.g. 2015 DOE Atlas V and the 2012 NASCA Atlas) have been used as a starting point for reviewing the resource potential of each country. These publications report state-wide or province-wide resource estimates for USA and Canada. These estimates are generally large numbers for which there is no detail explaining source or geographic distribution of the data inputs. Both atlases do, however, provide an explanation of how the resource estimate was calculated, including providing low/mid/high values for the storage efficiency factors applied to saline aquifers.

The GSRA 2019 Update uses the 2015 DOE Atlas V resource estimates in preference to the earlier 2012 NASCA data. According to the Atlas V, the data presented is derived from the DOE-funded Regional Carbon Sequestration Partnerships. These partnerships have distinct study areas which are defined

by geological basins, i.e. not state or province boundaries, and therefore there is often no clear alignment between the state and province-level reporting by the Atlases, and the Regional Partnership evaluation reports.

The GSRA 2019 Update has reviewed studies undertaken by the PCOR and Big Sky Regional Partnerships. The PCOR study area crosses the USA/Canada national boundary and covers those parts of British Columbia Alberta, Saskatchewan and Manitoba which sit within the Alberta and Williston basins. The partnerships also include several USA states: Montana (North-Central and Williston Basin), North Dakota, South Dakota, NE Wyoming (Powder River Basin) and NW Nebraska (Denver Basin). These are reviewed in Section 4.8 of this report.

For saline aquifers, the Regional Partnerships provide two levels of storage resource evaluation: DOE Phase I and II studies which provide high level resource estimates at the formation-level, and DOE Phase III studies which evaluated specific sites as detailed site characterisation studies or demonstration projects. As per the SRMS guidelines, formation level resource estimates have been classified as Undiscovered: Prospective Sequence Play due to the generally large area covered by the resource, and the lower level of confidence in the resource estimate. Site specific or demonstration studies have been classified as Discovered and then further classified based on their level of development (e.g. Not Viable).

These saline aquifer resource evaluations have been handled according to the level of published data available:

1. Where the Sequence Play resource estimates are considered to fully represent the State- or Province-wide resource estimate provided by the Atlas V, the GSRA 2019 Update has nulled

the State- or Province-wide resource estimate and a note has been attached to the assessment.

2. Where there is insufficient data available to fully supersede the State- or Province-wide resource estimate, the Atlas-derived estimate has been held and classified as Undiscovered: Prospective Basin Play.

3. If a resource estimate for a Sequence Play can be shown to only partly contribute to the State- or Province-wide resource estimate, the Sequence Play estimate is subtracted from the Basin Play estimate to avoid double counting within the Undiscovered SRMS maturity class.

4. Where no resource estimate is available in the 2015 DOE Atlas, the 2012 NASCA report has been used (this applies to the eastern Canada provinces which are not covered by the DOE Regional Partnerships).

5. Where storage resource estimates are available and classified as Discovered, the resource estimate has not been subtracted from the Sequence or Basin Play resource estimate to avoid aggregation across SRMS maturity classes. This has been noted in the 2019 Assessment notes for that site.

This approach has highlighted some issues:

- Mismatch of resource estimate values between different Atlases, e.g. the Atlas V estimate is significantly different to the equivalent NASCA estimate. This occurs for both oil and gas fields, and saline aquifers. Where possible the DOE Atlas has been used in preference to the NASCA Atlas to provide consistency of data inputs and volumetric calculations.

- Multiple evaluations of the same saline aquifer formation reporting quite different resource estimates. This is particularly true for the Cambro-Ordovician Basal Sand for which there are 3 different static volumetric estimates which use mid-range storage efficiency factors (E) of 2%, 9.1% and 14%. In this case, preference has been given to estimates derived from 3D static models which use the lower value of E, which here is 9.1% as opposed to 14% (while 14 % is used by PCOR for clastic lithologies where all net-to-gross terms are known (Goodman et al., 2011), a more recent study (Craig et al., 2014) suggests that on a 50 year injection time-scale values of E greater than 2% may be overly optimistic). The alternative estimates are noted in the Assessment.

- Resource estimates are provided for a geological basin, i.e. they are not sub-divided by federal nation, or state/province. For the Basal Sand, which covers an international boundary, the approach taken is to use a percentage value of the resource estimate derived from a 2D model which did apportion the resource between USA and Canada and apply to the 3D static estimate.

- Aggregated Sequence Play resource estimates for a region do not equal the Basin Play resource estimates for that region. This suggests that either the Basin Play resource estimates contain additional data, which is not apparent from the regional studies available, or that the range of storage efficiency factors applied are quite different. This highlights the need for a consistent approach to storage resource calculation.

- Studies which use a simulation to evaluate the impact of pressure on the storage potential of a formation indicate that the storage

resource is up to 1 magnitude lower than the equivalent volumetric estimate. Where this occurs, it is noted in the assessment and the country report and suggests that the volumetric resource estimate is likely to be invalid.

6.4.4.3   Depleted Oil & Gas Fields

The aggregated depleted field resource identified by the 2019 Assessment is 11.2 Gt. This Sub-commercial resource is assumed Discovered but is classed as currently Inaccessible due to a lack of information on abandonment dates for the fields. 7.1 Gt storage potential sits within identified oil and gas fields with the remaining 4 Gt derived from high level, province-scale studies which do not provide any level of detail on data source or distribution.

The 2012 NASCA report states that over 50,000 oil and gas reservoirs, plus oil reservoirs with a gas cap, existed at the time of reporting in north-eastern British Columbia, Alberta, Saskatchewan, and Manitoba. Additional fields are also present in Ontario (below Lake Erie), Northwest Territories, and in the Canadian offshore (Nova Scotia and Newfoundland). Twenty-three (23) depleted fields have been included in the 2019 Assessment. Inclusion was based on a few key criteria: a published evaluation of storage potential for an individual field or pool, having greater than 20 Mt reported storage potential, and appearing in a publicly available, searchable reserves database. None of the oil or gas fields in the 2019 Assessment have an abandonment date or an EAD (Earliest Accessibility Date) assigned as the necessary information is not available in the public domain. A significant number of oil fields in Canada are currently, or have previously undergone, secondary or tertiary recovery and are flooded with the water or natural gas injected to enhance oil production, leaving little available pore volume for CO2. These are typically not included in published storage resource estimates.

Most of the identified storage resource is in oil pools (5.9 Gt) which are located predominantly in Saskatchewan and Manitoba. Oil pool size in Alberta is generally small. Of nearly 8500 oil reservoirs under primary production in 2004 only 98 have a calculated storage resource > 1Mt (Bachu, 2004), and only 1 oil pool was identified as having a resource greater than the 20 Mt cut-off applied by this study. Similarly, gas pools in Canada are typically small. Out of nearly 25,800 fields studied in the published literature, only 9 fields in Alberta and 7 in British Columbia qualify for the >20Mt cut-off; Saskatchewan and Manitoba do not contain any identified resource potential in gas fields. The total storage resource reported for gas pools is 1.2 Gt.

Regarding commercial readiness of the depleted field resource identified, no projects with a stated aim of injecting CO_2 directly into depleted fields for storage have been identified. CO_2-EOR is taking place in several locations but these projects and injected volumes do not form part of the SRMS at this stage. At the province level, British Columbia is least commercially mature with most of the stated storage resource sitting within the Undiscovered Province-wide classification.

Additional data included in the SRMS database were taken from online reserves data maintained by each province. In some cases, e.g., Saskatchewan, these publications are not exhaustive and only provide data from a selection of active projects (i.e., high activity, new projects/pools, or changes to existing projects/pools).

6.4.4.4   Saline Aquifers

Most of the saline aquifer resource (360 Gt; 93%) is within Undiscovered resource, split between Sequence Play (83%) and Basin Play (10%). Sub-commercial resources make up a much smaller proportion (25.6 Gt; 6.6%) of

the summed saline storage resource. Storage projects form only 15% (3.9 Gt) of the Sub-commercial resource however the only reported, non-EOR stored CO_2 in Canada is within the Cambro-Ordovician Basal Sand formation saline aquifers at the Quest and Aquistore projects in Alberta and Saskatchewan respectively where a total of 61 Mt is either already Stored, or is permitted for injection (On-Injection).

Saline aquifers identified as holding storage potential in Canada include the diachronous Cambro-Ordovician Basal Sand clastic formation in the Williston and Alberta basins, and it's temporal equivalent, the Mt Simon Sandstone in Ontario, Devonian carbonates located predominantly within the West Canadian Sedimentary Basin, and the Lower Cretaceous Viking Formation in the Alberta Sub-basin.

In terms of commercial maturity of saline aquifer storage potential, Alberta is significantly more advanced than other provinces, with identified potential resources at several stages of maturity. Saskatchewan is dominated by storage resource estimates for the Basal Sand, but only the Aquistore project is currently demonstrating successful injection. In comparison, British Columbia, Manitoba, and the eastern provinces of Ontario and Quebec contain significantly lower resource volume and are less commercially (and technically) advanced, except for the Fort Nelson CCS site in British Columbia.

Basal Sand Storage Potential. The Cambro-Ord Basal Sand (or Basal Aquifer) is one of the most widely studied aquifers. As such there are several different estimates of storage potential for the unit; all of which use different values for storage efficiency:

- Province-wide estimates of storage potential provided by the DOE Atlas V using a mid-range storage efficiency factor of 2.0%.

- A 2013 PCOR 2D static volumetric estimate which provides a split between the Canadian (75.2%; 85 Mt) and US (24.8%) portions of the Williston and Alberta basins and uses a P50 storage efficiency factor of 2.4%.

- Two (2014 and 2015) PCOR 3D static (geocellular) models for the combined USA & Canada area (373 Mt) which use P50 values for storage efficiency of 9.1% and 14% to calculate a volumetric estimate of storage (note: as discussed above, 14% is considered an unrealistically high storage efficiency factor on a 50 year injection timescale and so is not used in this assessment).

- Two numerical simulation studies which both look at injecting a set volume (63 Mt and 94 Mt) of CO_2 into the Basal Sand over a period of 50 years. Both use the 3D geocellular static model (or equivalent using the same dataset) developed for the 2014 volumetric case. By optimising injection location in areas of highest modelled transmissivity within Saskatchewan and eastern Alberta, the model was able to successfully able to simulate injection of 3100 Mt (63 Mt/year) without exceeding set pressure constraints using 5 injection locations (including the Quest site). It should be noted that the pressure map of the Basal Sand model indicates that there is little pressure space remaining in the high transmissivity areas of the aquifer following injection of this volume of CO_2 and, as such, may represent a near-capacity resource value. The alternative (94 Mt/year) simulation attempt focussed injection at the Duffield-Warburg power generation facility (Alberta) but only achieved a maximum injected volume of between 298 Mt and 1280 Mt over the 50-year period. Detail is limited in both studies but it appears from

maps of the simulated subsurface pressure increase that the 2 study areas do not overlap as the 63 Mt/year study discarded the Warburg site as it failed to achieve the injection volume of 23 Mt/year set in that model for the Warburg site.

- Active injection operations which target the Basal Sand are currently operating at the Shell Quest CCS project (Alberta) and the Aquistore project (Saskatchewan)

The Basal Sand is classified as a Sequence Play (Undiscovered) and assigned a summed storage resource estimate of 75.2% of the 2014 3D static model volumetric calculation (284 Gt). It is noted that this is a very high estimate of storage resource potential given the numerical simulations which achieved almost one order of magnitude lower injection volumes.

The Basal Sand project sites are classed as Discovered Sub-commercial: Contingent (Development Not Viable) resources for those where no current project evaluation is occurring, or Commercial: Capacity (Stored or On Injection) where CO_2 injection is taking place or permitted. By carrying the Prospective, Contingent and Capacity resource estimates in the database, there is a degree of 'double counting', however this only amounts to 6500 Mt (6.5 Gt) out of the high level volumetric estimate of 284,000 Mt (284 Gt) and as such only represents 2.8 % of the volumetric estimate. It also raises the question of whether any credence should be given to the static volumetric resource estimate given the issue of available pressure space for a 50-year injection project.

Devonian Aquifers Potential. The mid-upper Devonian section of the foreland basin is best developed in the Alberta sub-basin of the West Canadian Sedimentary Basin. At the basin scale, the section has been evaluated by the PCOR group with a summed storage resource of 14.2 Gt. The Devonian

aquifers have also been targeted by several studies including the Athabasca area identifying possible storage resource associated with the oil sands operations in the area, large reefal build-up structures (HARP) and regional carbonates (WASP).

Lower Cretaceous Aquifer Potential: The Viking Formation, which sits within the Alberta Basin, has been evaluated by PCOR as having some storage resource potential. No storage projects have been identified within the formation.

The 2019 Assessment carried an assumption that the DOE Atlas V (2015) province-wide estimates for saline aquifers represent the sum of any reported regional evaluations (e.g. by PCOR). As per the discussion in Sections 3.2- 3.6, the SRMS entries at the province-level for Alberta, Saskatchewan and Manitoba have therefore been assigned a null value.

6.4.5 Regulatory Framework

Canada is the top-ranking nation in the GCCSI CCS Readiness index, meaning that it has been identified as a leader in promoting and deploying CCS. It is only lacking a strong policy to help drive investment for rapid deployment on a commercial scale. The regulatory competence for developing CCS legislation in Canada is shared between several national and provincial bodies. Regulatory development, in the form of design and implementation of CCS-specific legislation, has principally occurred at the provincial level in Canada. Several provinces have undertaken reviews and scoping studies to consider their existing regimes potential to manage CCS activities and, in some instances, this has resulted in the promotion of CCS-specific frameworks. The provincial governments of Alberta, Saskatchewan, and Nova Scotia have all made attempts towards the deployment of CCS-specific legislation in recent years,

however it is the province of Alberta that has developed the most comprehensive CCS-specific model.

6.4.6   Issues for the 2019 Assessment

6.4.6.1   Data Validation

While the NASCA (2012) report provides a useful early snapshot of storage resource potential in Canada, it has been superseded by province-wide resource statements published in the 2015 DOE Atlas V. In addition, the NASCA Viewer and website which provided web-based access to all NASCA data is no longer live. Information is provided on the method of calculation of storage potential in both reports, however there is little to no supporting detail as to the source of the data. However, the DOE Atlas also has significant shortcomings for application to the SRMS. The data presented as state-wide storable quantities are derived from studies carried out by the DOE Regional Partnerships. For Canada, this only includes information from the PCOR group (the WestCarb group does not appear to have published any studies for the west coast of Canada). For example, PCOR studies provide back-up for the overall, basin-wide storage potential reported for the Cambro-Ord Basal Sand, but this not reported at the province-level.

6.4.6.2   Probabilistic Assessments

The data available for the 2019 Assessment suffer from a lack of probabilistic analysis; most studies do not provide a range of estimates of storage resource. For studies which provide a storage resource estimate derived from a volumetric methodology, a range of storage efficiency factors may be used but these are applied to a single static model pore volume. Numerical simulations are rarely available for the sites reviewed by this report, and often only give a single

storage resource value, assessing whether the site meets the stated benchmark resource.

Projects (sites with dynamic simulations which specify an injection volume and a development plan) may only report a single 'base case' resource value. At the only actively injecting projects, Quest and Aquistore, the resource classified as Stored or On-Injection refers to the permitted injection volume, not the maximum storage potential which is not reported.

6.4.6.3   National Atlas Data Discrepancy

There is a significant discrepancy between the storage resource figures provided in the 2015 DOE Atlas V and the 2012 NASCA report. For example, the Alberta saline aquifer storage resource in the NASCA report is given as 28 Gt, but the DOE report gives a mid-estimate value of 76.74 Gt, over 2x greater. Similarly, the values for Saskatchewan saline aquifer storage vary between 75 Gt in the NASCA report but greatly increase to 285.22 Gt (mid estimate; 149.72 Gt as the low estimate) in the DOE report.

The discrepancies cannot be wholly attributed to differing methodologies for calculating storage resource as both studies use the same volumetric equation and efficiency factors for saline aquifers. Discussion with the DOE-NETL team responsible for generating the Atlas V numbers suggests that the regional PCOR study data are not included in the NASCA numbers, as NASCA Canada generated their own estimates. It is suggested here that any figure for saline aquifers derived from the 2012 NASCA study should be considered a low estimate for those provinces which are covered by the DOE Regional partnerships.

By contrast, the depleted field storage resource estimates are higher (for each province) in the NASCA report relative to the DOE Atlas, for example, the

Alberta depleted field resource is 12 Gt in NASCA but only 1.49 Gt in the DOE Atlas. The reasons for the discrepancies are not clear, NASCA (2012) states that the CSLF approach of using original oil or gas in place plus a recovery factor (and an efficiency factor based on local experience or simulations) was applied. The DOE Atlas applied two methods depending on the available data. Either an efficiency factor to convert produced volumes to CO_2 storage volumes, or a straight replacement (on volume-for-volume basis) of hydrocarbon by CO_2 was used (DOE, 2015). Given the fact that only 3 years separates the publication of each report, the difference in values for storage resource at the Province-scale should be used with caution.

In all cases, the 2015 DOE Atlas V data are used in preference to the 2012 NASCA data as they are the most recent storage estimate available. NASCA data are used if the Atlas V does not report for a province (this mainly applies to the eastern provinces).

6.4.6.4   *Data Mismatch for Oil and Gas Fields*

Following on the above discussion, there is also an issue with data mismatches between the high level, province-scale resource estimates, and the estimates based on site-specific resources, e.g., in Saskatchewan the province-wide total of 960 Mt reported is significantly less than the 4857 Mt resource reported in depleted fields in the public literature. In such cases, the province-wide resource has been entered as a null value in the database.

6.4.6.5   *Availability of Resource Estimates*

Storage resource potential in oil and gas reservoirs is only quoted for British Columbia, Alberta, Saskatchewan, Manitoba and Ontario as, while oil and gas reservoirs are present outside of these provinces, they are considered by the

major reports to be too distant from major emissions sources and therefore not reported.

6.4.7   Future Updates

Required updates to the 2019 Assessment should include:

- **Annual adjustments to account for continued injection and any model updates at Quest and Aquistore**. Annual reports are released for both projects (end-first quarter) and should be reviewed when released for database update.
- **Update following any future release of DOE Carbon Storage Atlas, or equivalent publication**. This should include any further information as to the source of the data used to generate the high, Province-level, estimates of storage potential. According to the team at the US DOE responsible for the Atlas, an updated edition is currently in-progress, but no release date was provided (M Sullivan, *pers. comm*, January 2020).
- **Additional release of information on depleted field availability and storage resource calculations**. All depleted field resource data are currently classes as Discovered - Inaccessible due to the absence of a published field abandonment date.

6.5 China

6.5.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for China as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.0003	0.0003
Capacity	0	0
Sub-Commercial	105	0.031
Undiscovered	3067	0
Aggregated*	3077	0.03

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-5. 2019 storage resource classification summary for China

- There is a total of 72 sites in this GSRA 2019 update, largely at a regional scale or a high-level evaluation, with only two sites associated with a project. The storage resource is located across a minimum of 21 geological basins, both onshore and offshore.
- China boasts numerous CCUS projects, of which 8 of the key projects currently are, or will reach large-scale operations in the 2020s.
- Government policy has led to numerous pilot- and large-scale CCUS facilities being developed, however, this is largely to support

enhanced oil recovery operations (EOR). The lack of CCS-specific legislation means more needs to be done to incentivise geological storage and true decarbonisation.

a) Project Specified Mid-Case Storage Resource

b) Project and Non-Project Mid-Case Storage Resource
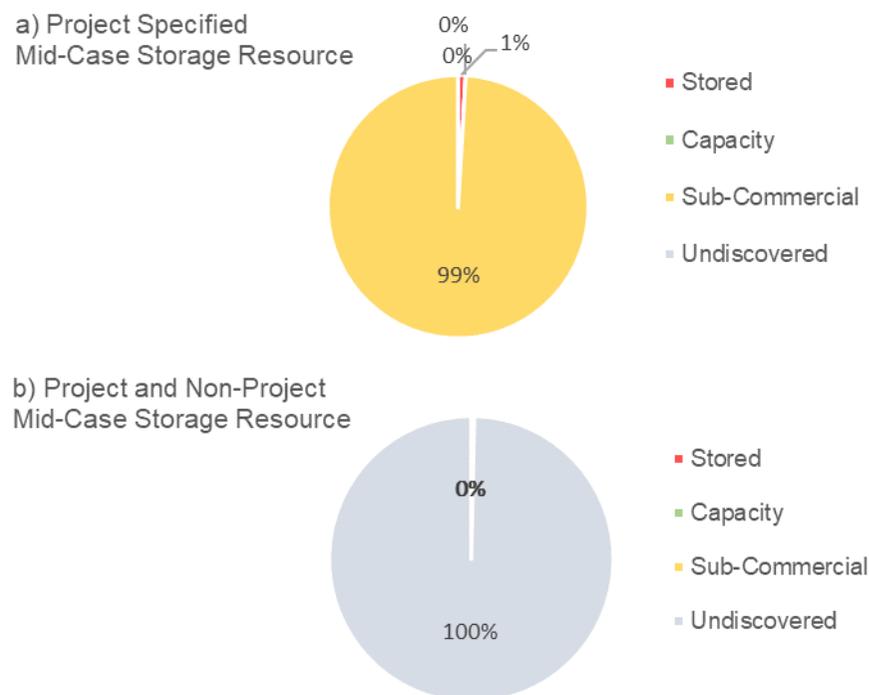
c) Saline Aquifer vs Petroleum
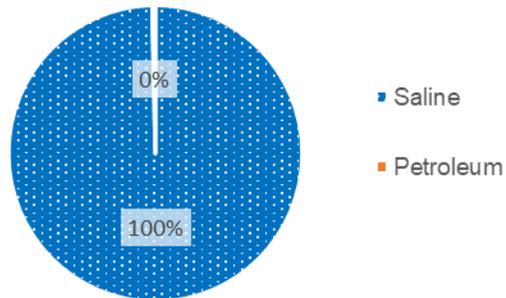
Figure 6-9. a) Spread of storage resource in Chinese sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Chinese sites across SRMS classifications; both project specified and not. c) Split of Chinese storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.5.2 Resource Statement
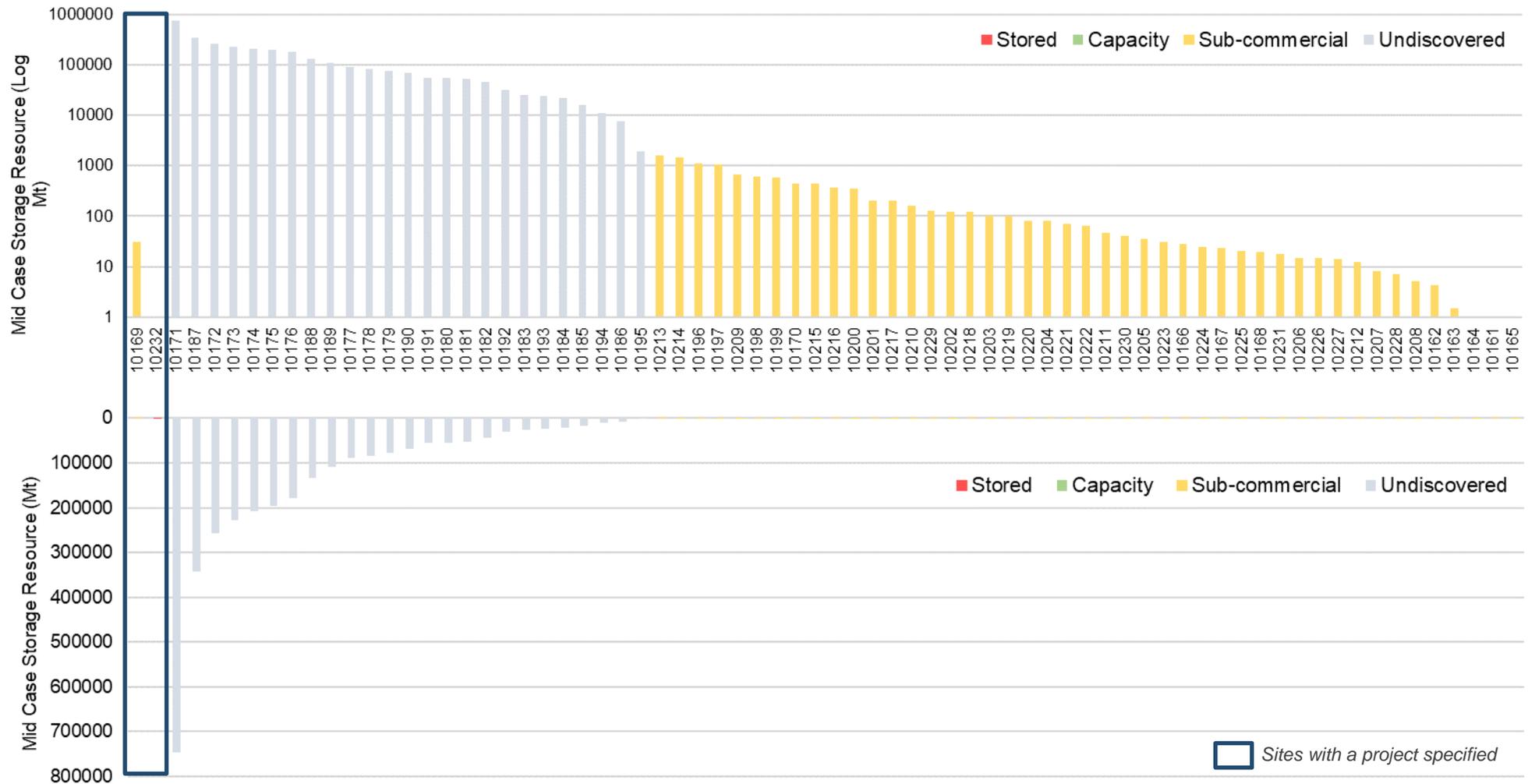
Figure 6-10. Storage resource summary for China compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.5.3 Evaluation History

The regional evaluation by the Pacific Northwest National Laboratory in 2009 (PNNL 2009), of the potential CO_2 storage resource available within the onshore and offshore territory of China was a first of its kind. It was produced as a collaboration between US and Chinese researchers and was commissioned by the US Department of Energy. The report evaluates a large and diverse geographic portfolio of potential CO_2 storage resource within oil and gas fields, deep saline formations and coal seams. It is only intended to provide a starting point for finer resolution analysis. The majority of the Chinese sites are sourced from this PNNL report.

The estimation of the storage resource within saline aquifers was considered only through theoretical calculation of 100% dissolution of CO_2 within reservoirs deeper than 800-1000m. Whilst acknowledging the clear potential for hydrodynamic and residual trapping, these storage mechanisms are not specifically included within the assessment. The authors PNNL suggest that this approach of ignoring the potential of "free CO_2" phase storage will result in a very conservative resource estimate.

For the evaluation of gas fields, a modified replacement method was adopted which assumes that only 75% of the pore volume once occupied by produced gas could be filled with CO_2. This would seem to make provision for some loss of storage efficiency perhaps resulting from water ingress into the reservoirs from underlying water legs.

Unlike the other regional assessments, the PNNL study only considers the storage in oilfields when linked to enhanced oil recovery. Instead of deploying a simple replacement method for the assessment of storage potential, the regional assessment has considered this potential using guidance and analogues from well-established CO_2 EOR provinces such as the West Texas area of the US. This together with pre-published assessments of initial oil in place for Chinese oilfields has enabled an initial assessment of potential storage resources associated with EOR to be made. It should be noted that the CO_2 EOR performance of the primary analogues is drawn from an environment where the oil producer must purchase CO_2 from a provider. As a result, the operators have become extremely efficient at using the purchased CO_2 inventory to optimise oil recovery. Of course, this approach also minimises CO_2 Storage resource by definition and so this does represent a conservative view of potential storage resource.

Updates to this report include the stored volume at the Shenhua Group CCS Demonstration project (Diao 2018), plus theoretical storage resource evaluations for hydrocarbon fields within the Dagang oilfield complex (Vincent 2010).

6.5.4 Resource Review

6.5.4.1 *Major Projects*

China hosts a plethora of CCS and CCUS projects, ranging from pilot and demonstration right up to large-scale projects. Many of these projects are not well publicised and as such, this study may be an under-representation of the full scale of commercial and research operations currently being undertaken in China. The GCCSI (2018) recognises 18 key CCUS projects in China, including:

- 10 enhanced oil recovery (EOR) projects; 5 of which are demonstration projects and 5 of which are currently or are developing towards large-scale operations by the 2020s
- 3 projects capturing carbon dioxide for use in industrial or beverage applications

- 2 projects currently under evaluation. There are large-scale facilities with power and coal-to-liquids applications.
- 3 projects are dedicated geological storage servicing the power and coal-to-liquids industries. One of these projects came to completion in 2014.

As carbon utilisation is outside the scope of this study, only projects utilising permanent geological storage of CO_2 were considered in this GSRA 2019 update. These projects include:

Shenhua Group CCS Demonstration project in the Ordos Basin. It was the first deep saline aquifer storage in China. The project started in 2011, injecting 0.1 Mtpa until completion in 2014, reaching a total of 0.302 Mt CO_2 stored. The full-chain CCS project captured CO_2 from a coal liquefaction plant and injected the CO_2 into a tight carbonate reservoir using fracking to enhance secondary porosity.

China Resources Power (Haifeng) Integrated CCS Demonstration Project, Shanwei. A capture test platform has been running since 2018 capturing 0.025 Mtpa from the power industry, aiming to scale up to large-scale operations (1 Mtpa) in 2020s. Due to the small volumes, this project is not included in the website database.

Guohua Jinjie CCS Full Chain Demonstration, Shaanxi Province. Demonstration-scale operations capturing CO_2 from a coal-to-liquids facility at 0.15 Mtpa since 2017. Due to the small volumes and lack of publicly available literature, this project is not included in the website database.

6.5.4.2 _Depleted Oil & Gas Fields_

The natural gas fields represent a small portion of the storage resource in China, with an aggregated storage resource of 5.2 Gt. Similarly, oilfields comprise a more minor component, with an aggregated storage resource of 4.8 Gt for oilfields including EOR. In this GSRA 2019 update, evaluations for geological CO_2 storage, rather than CO_2 EOR, could only found for the Dagang Oilfield Complex. This highlights the need for the country-wide evaluation of hydrocarbon fields, to avoid the underestimation of storage resource, as detailed in 6.5.3.

All storage resource within depleted hydrocarbon fields is classified as discovered. As the SRMS classification places a significance on the presence of a CCS regulatory system for classification, the absence of such a system in China currently limits the classification of discovered resources to "Inaccessible". For the oilfields evaluated with EOR operations (PNNL 2009), however, the resource could be classified as "Development Not Viable" as CO_2 injection for EOR can take place under existing petroleum regulatory systems.

6.5.4.3 _Saline Aquifers_

As in many countries, deep saline formations represent the largest storage target in China, with an Aggregated Storage Resource for Undiscovered sites in this GSRA 2019 update of 3067 Gt (PNNL 2009). The PNNL regional evaluation does not present any information regarding the discovery status or the geological formations of the potential CO_2 storage resource. As a result, the entirety of the saline aquifer potential has been classified as Undiscovered Basin Play, even though significant tracts of this potential resource will undoubtedly have been discovered through exploration for petroleum and groundwater resources.

A small volume (0.302 Mt) has been stored in the Shenhua Group CCS Project (Diao 2018), while 31.4 Mt is classified as Discovered Inaccessible (Wen 2018), due to the lack of a CCS-specific regulatory system in China. The evaluation by (Wen 2018), uses simulation modelling to estimate the storage resource of the Donggou Formation, in the Junggar Basin, and represents one of only two sites in this 2019 report with a project specified. In a country where there are numerous CCS and CCUS projects being undertaken, this highlights the lack of detailed published literature on the Chinese CO_2 storage resource.

6.5.5 Regulatory Framework

China has numerous pilot- and large-scale CCUS facilities supporting the cement, coal-to-liquids and steel industries. These have been developed through state-supported research and development funding. The GCCSI recognise the strong focus on government incentives for EOR activities but encourage a stronger emphasis to be placed to incentivising storage through policy and CCS-specific regulation (Global CCS Institute 2018).

6.5.6 Issues for the 2019 Assessment

The calculation of depleted oil fields in the PNNL report was only considered when in EOR applications, which not only contrasts the methodology of other regional reports, but also doesn't provide a true reflection of CO_2 stored, as described in 6.5.3. Indeed, due to these complications, EOR studies are out of the scope for this GSRA 2019 update, however the values from the PNNL report were included, in the absence of other significant estimations.

6.5.7 Future Updates

Further work should focus on evaluation at a site or even formation level, to progress the maturity of the Chinese resource along the SRMS classification system. The current evaluations of Chinese storage provide an under-representation of the storage potential in China.

In the 2018 GCCSI review of Chinese decarbonisation facilities (Global CCS Institute 2018), two key projects are highlighted as planned operations:

- Shanxi International Energy Group CCUS, Shanxi Province. Planned large-scale facility aiming to capture 2 Mtpa in the 2020s from power generation.
- Shenhua Ningxia CTL, Ningxia Province. Another large-scale facility is planned to be operational in the 2020s, aiming to capture 2 Mtpa from the coal-to-liquids industry.

A further two projects are identified by (H. J. Liu 2017) as 'in preparation' for geological storage:

- IGCC Clean Energy pilot-project in Lianyungang. Aims to capture 1 Mtpa using pre-combustion capture.
- Oxy-fuel combustion sequestration in Zhongyan Yingcheng of Hubei. The project aims to capture 0.1 Mtpa for storage in salt rock.

If evaluations for the above projects are published, they should be included in future updates.

(K. A. Jiang In press), provide a critique on the status of CCUS policy in China in a recent paper, which could also be included.

6.6 Bangladesh, India, Pakistan, and Sri Lanka

6.6.1 Summary

The GSRA 2019 update has identified CO_2 storage resources for Bangladesh, India, and Pakistan as follows:

Bangladesh

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	1.13	0
Undiscovered	20.0	0
Aggregated*	21.13	0

India

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	0.84	0
Undiscovered	63.3	0
Aggregated*	64.14	0

Pakistan

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	1.7	0
Undiscovered	30.0	0
Aggregated*	31.7	0

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-6. 2019 storage resource classification summary for Bangladesh, India and Pakistan

- Bangladesh has 23 sites in the 2019 Assessment: 1 saline aquifer (Undiscovered; 20.0 Gt) and 22 gas fields (Discovered; 1.13 Gt).
- India has 15 sites in the 2019 Assessment: 11 saline aquifers (Undiscovered; 63.3 Gt) and 4 oil and gas fields (Discovered; 0.84 Gt)
- Pakistan has 17 sites in the 2019 Assessment: 2 saline aquifers (Undiscovered; 30 Gt), 14 gas fields and 1 site representing 56 small oilfields (Discovered; summed resource 1.7 Gt).
- No resources in Sri Lanka were reported.
- All sites in Bangladesh, India and Pakistan are classed as Inaccessible for both the Sub-Commercial oil and gas fields and the Undiscovered saline aquifers due to the lack of a CCS regulatory

framework in any of these South Asian countries. No projects are defined.

- There are no defined storage projects in the region.

India: Non Project* Mid-Case Storage Resource
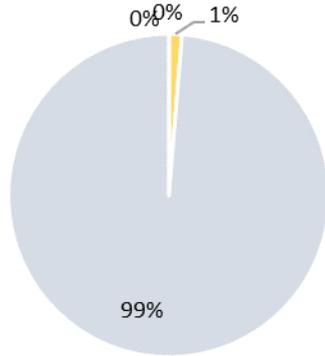
Pakistan: Non-Project* Mid-Case Storage Resource
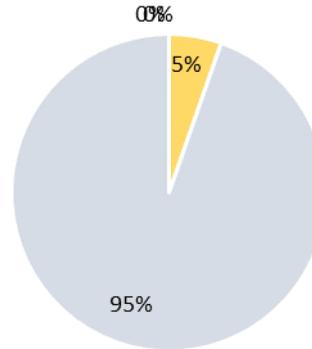
Bangladesh: Non-Project* Mid-Case Storage Resource
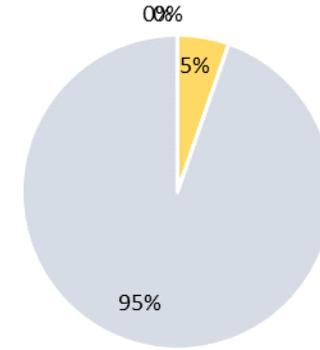
Note: No sites with a project specified were identified for the South Asian countries.

India: Saline Aquifer vs Petroleum
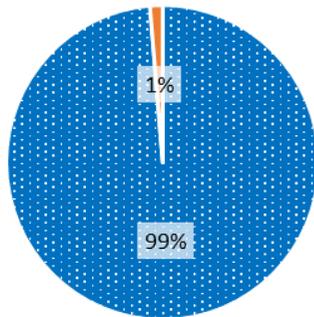
Pakistan: Saline Aquifer vs Petroleum
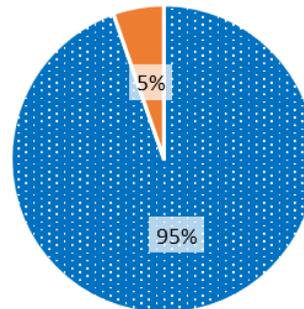
Bangladesh: Saline Aquifer vs Petroleum
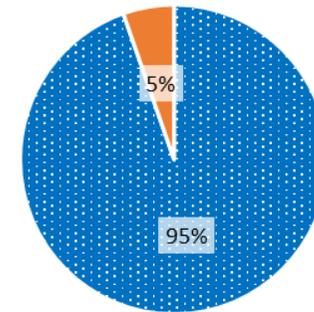
Figure 6-11. Above: Spread of all storage resource across SRMS classifications. Below: Split of storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.6.2 Resource Statement

Figure 6-12. Storage resource summary for the Indian Sub-Continent compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting..

6.6.3 Evaluation History

Bangladesh, India, and Pakistan underwent a preliminary assessment as part of the 2019 Assessment. A regional evaluation of the CO_2 storage potential of the Indian subcontinent was completed in 2008 by the British Geological Survey (BGS) on behalf of the IEAGHG. Its purpose was an early stage evaluation to gauge the potential for CO_2 storage in geological reservoirs across the region. It includes a review of all major emissions points of over 1Mt/yr. and considered depleted oil and gas fields, saline aquifers and deep unmineable coal seams. It excludes the potential storage resource within salt caverns and the subcontinents extensive basalt formations in the Deccan and Raajmahal Traps. The national storage potential of India, Pakistan, and Bangladesh all evaluated independently. Although there is some evidence for offshore resource potential to the north and west of Sri Lanka, no resource base has been quantified at this time.

The methodology used in the BGS evaluation included the replacement method for the depleted oil and gas reservoirs, but for India this has been based upon state by state petroleum reserves figures (excluding oil already recovered). Elsewhere many fields had statements of projected ultimate recovery. Further challenges with data availability have resulted in reasonable assumptions having to be made about CO_2 density, water influx, gas production and oil properties. All these factors contribute to the assessment of potential storage resources in depleted oil and gas fields as being both "highly provisional".

For Saline aquifer resource estimation, an analogue method has been adopted where it is assumed that the potential CO_2 storage resource potential could be estimated as: Total potential saline aquifer storage resource potential = Area of Basin in square kilometers x 0.5 x 0.2. This equates the CO_2 storage resource potential in Mt as 10% of the basin area in square kilometers.

6.6.4 Resource Review

Overall, it is only possible to identify two classes of quantified CO_2 storage resource potential within the region:

- Depleted oil and gas fields - these have been classified as discovered storage resource, but also as "inaccessible" at this time due to the absence of a CCS regulatory system within any of the countries in the region
- Saline aquifer systems - these have been classified as undiscovered storage resources, although it is accepted that there will be a small number of wells drilled into these systems which establish discoveries, the location and details of these wells are not available within the regional assessment. Due to the absence of a CCS regulatory framework, the resources have been classified as 'Inaccessible' at the time of assessment.

The regional assessment is an early and indicative assessment of storage resources. Over 95% of the stated resource is held within very poorly defined saline aquifers.

6.6.5 Regulatory Framework

None of the countries have developed policies or CCS-specific regulatory or legal frameworks and only India has been evaluated under the GCCSI CCS Readiness framework. India is classed as a high opportunity country in that it would benefit from CCS deployment but has no system in place to encourage this. India has a legally non-binding CO_2 emissions reduction target of 20-25%

by 2020. In its Mission Innovation submission India indicated its interest in CO_2 capture and utilization (CCU) beyond EOR but there has been no significant action from the federal government to advance its deployment.

6.6.6   Issues for the 2019 Assessment

There is currently little information available to build a true picture of the storage potential of any of the countries in the region. Where data are available, the depth and generally low quality of the information make assessment difficult and so several assumptions have had to be made during resource estimation.

As a result of the low maturity of the resource estimation, there is only a single value provided for each resource. This has been recorded as the 'Mid-Range' estimate of resource potential. As future studies are planned in the region, effort needs to be made to move towards generating probabilistic assessments.

6.6.7   Future Updates

Any update should be made as and when concrete, useful improvements to the understanding of storage potential in the region become available.

6.7 Norway

6.7.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for Norway as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.019	0.019
Capacity	0.044	0.044
Sub-Commercial	56	1.4
Undiscovered	37.5	3.4
Aggregated*	93.6	4.9

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-7. 2019 Storage resource classification summary for Norway

- There is currently a total of 42 sites at both local and regional scale, located across 5 geological basins in the offshore sector. Most of the Norwegian storage resource is located in the Norwegian North Sea.
- There is a total of 11 project-specified sites, the majority of which also contain a simulation model.
- As of 2017, a total of 18 Mt of CO_2 has been injected to deep geological storage, at Sleipner (17 Mt) and Snøhvit (1 Mt).

- The Norwegian government has created strong foundations for a CCS market in Norway, through the introduction of a high carbon tax for fossil fuel extraction and the GHG Emission Trading Scheme. Gaps still remain, however, in CCS-specific legislation according to the GCCSI Legal and Regulatory Indicator Report (Global CCS Institute 2018).

a) Project Specified Only
Mid-Case Storage Resource
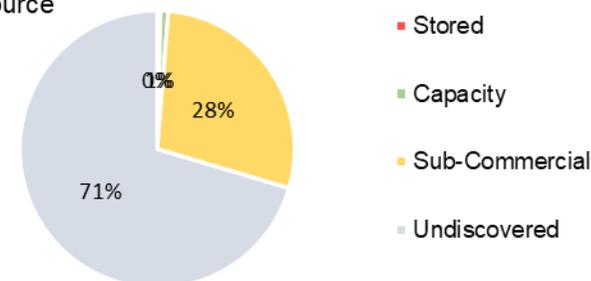
b) Project and Non-Project
Mid-Case Storage Resource
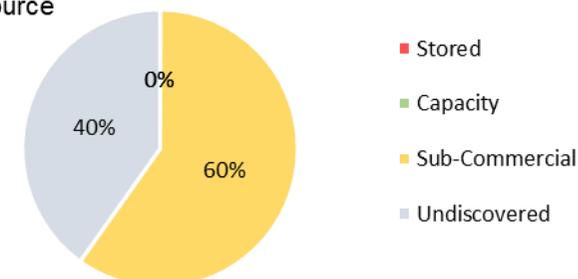
c) Saline Aquifer vs Petroleum
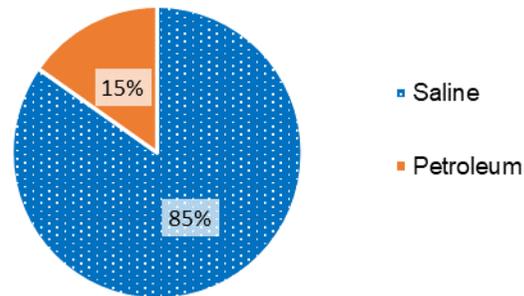
Figure 6-13. a) Spread of storage resource in Norwegian sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Norwegian sites across SRMS classifications; both project specified and not. c) Split of Norwegian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.7.2　Resource Statement
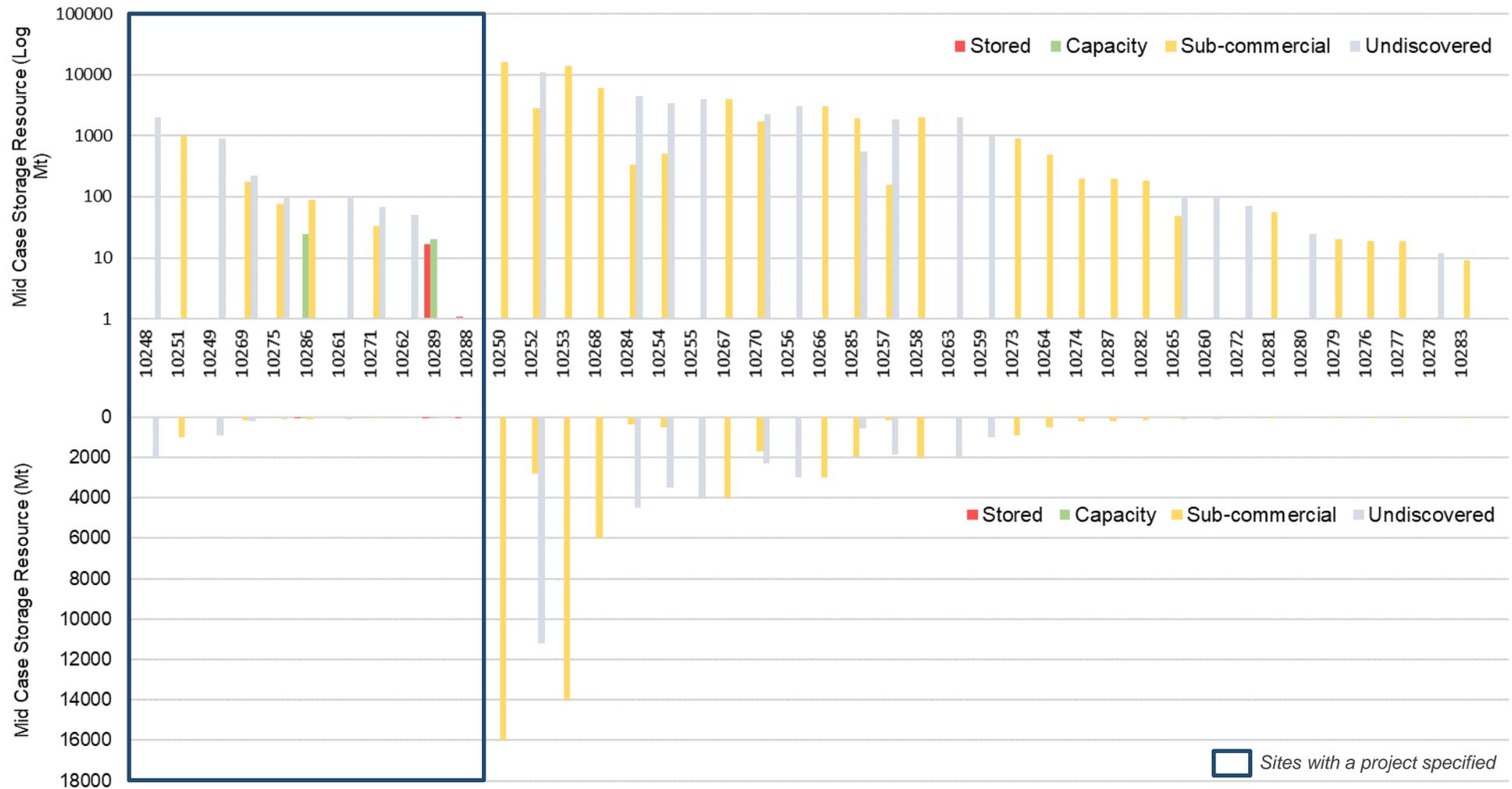
Figure 6-14. Storage resource summary for Norway compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.7.3 Evaluation History

The Norwegian CO_2 Storage Atlas is a key document for evaluation of the storage resource in Norway (Norwegian Petroleum Directorate 2014). It was prepared by the Norwegian Petroleum Directorate (NPD) at the request of the Ministry of Petroleum and Energy and forms the data source for the majority of the Norwegian sites within this assessment. The Atlas is compiled from both site-specific evaluation in published literature and regional evaluation by the NPD and is composed of three regional basin atlases: the Norwegian North Sea, the Norwegian Sea and the Barents Sea. Papers published following the release of the Atlas were included to supplement and update the Norwegian assessment.

Whilst Norway has a similar overall resource character to the UK, it enjoys larger areas of undrilled potential and therefore storage resource prospectivity. It also has operational and developing CO_2 injection projects, which together creates a spread of resource across the SPE SRMS classifications. Significant storage resource is recognised in the numerous supergiant petroleum fields within the Norwegian sector. However, as they have the potential to continue production beyond 2050, the storage resources in these petroleum provinces have been classified as discovered but inaccessible at this time.

In general, a volumetric method was adopted to estimate potential storage resource. For a limited number of sites, a more detailed evaluation was made, sometimes including a simulation model. Where possible, the pore volume has been estimated using seismic and well data. Storage efficiency has been either evaluated using a bespoke reservoir simulation model, based upon a reasonable development plan, or sourced from a representative analogue. For hydrocarbon fields, a fluid replacement methodology was adopted.

In the Norwegian Atlas, the maturity of a site, and the subsequent methodology used to evaluate the storage potential of that site, is dictated by data availability. This approach is described by the maturation pyramid, where the evaluation of a site only moves up the pyramid and becomes more mature when more data becomes available for the evaluation. When the site reaches a different maturity level, a different methodology will be deployed to estimate the site's storage resource. In Norway, the vast amount of data and experience built through the petroleum industry allows some sites to be placed high up in the pyramid.

The maturity pyramid methodology adopted in the Atlas is only weakly mappable to the SRMS, which uses an increase in chance of commerciality to mature a site. Furthermore, the storage resource nomenclature within the Norwegian Atlas contrasts with the SRMS. It defines "Prospectivity" as the potential to find a commercially viable CO_2 storage project, rather than as the potential to find "accessible pore volume being suited to containment", as described in the SRMS. As a result of this, structures with reservoirs already proven by wells are held as "Prospects" rather than "Discoveries". Finally, in saline aquifers, the presence or absence of structures is not always clear, however sites described as "Prospects" have been considered as structures in this assessment.

No probabilistic work was reported within the Atlas.

6.7.4 Resource Review

6.7.4.1 *Major Projects*

In Norway, there are two commercial-scale CCS projects currently injecting CO_2: Sleipner and Snøhvit. Operated by Equinor since 1996, Sleipner was the world's first offshore CCS facility. Natural gas produced at the site contains naturally occurring CO_2, which is separated and stored within the Utsira Formation, in the

Norwegian North Sea. Sleipner has a stored CO_2 volume of 17Mt, up until 2017 (S. S. Thibeau 2018).

Snøhvit is an LNG facility, that is similarly operated by Equinor but located in the Barents Sea. The natural gas produced from the Snøhvit, Albatross and Askeladd fields contains CO_2 which is separated and injected into the Stø Formation.

Both projects are referenced in the Atlas, however evaluations focus largely on additional storage potential within their respective saline aquifers.

The Snøhvit project is evaluated in more detail in the Atlas, however at the time of publication (2014), operations at Snøhvit has ceased due to an unexpected and rapid pressure build-up in the Tubaen Formation. It is reported that 1 Mt of CO_2 was stored during this time (Norwegian Petroleum Directorate 2014). The asset has since been developed in the Stø Formation, which is believed to have greater hydraulic connectivity which should allow sufficient dissipation of pressure. No recent publications were found in the GSRA 2019 update that provide up-to-date stored volumes at Snøhvit, however the Atlas estimated a mid-case storage resource of 24 Mt.

6.7.4.2   _Depleted Oil & Gas Fields_

The Aggregated Storage Resource within hydrocarbon fields in the Norwegian sector is 14 Gt, where 13 Gt lies in the Norwegian North Sea and 1 Gt in the Norwegian Sea. A small volume (0.2 Gt) lies in the Barents Sea, however as no date for the cessation of production (CoP) was provided for these fields, the resource has been classified as Discovered Inaccessible in this GSRA 2019 update. The fields within the Norwegian North Sea and Norwegian Sea are either abandoned or are due to be abandoned by 2050, however no sites are reportedly undergoing active appraisal for CO_2 storage in the published

literature. As such, they have been classified as Discovered Development Not Viable.

These data are all sourced from the Atlas, as no further publications were identified for depleted hydrocarbon fields in this GSRA 2019 update.

6.7.4.3   _Saline Aquifers_

The storage resource for saline aquifers in Norway is spread across a range of the SRMS classifications, with Aggregated Storage Resource as follows; 37.6 Gt Undiscovered, 41.7 Gt Sub-commercial, 0.044 Gt Capacity and 0.019 Gt Stored. The Undiscovered portion is largely classified as Sequence Play, with some sites classified as Lead where a nominal storage site was identified, or Prospect where a drill-ready target was present. The Capacity and Stored storage resource is from Sleipner and Snøhvit, where CO_2 has already been stored and further CO_2 is licensed for injection.

The storage resource is spread across a wide range of formations, however the majority of the storage resource identified in the GSRA 2019 update lies within the formations: Bryne and Sandnes, Utsira and Skade, and Sognefjord Delta.

Similar to the depleted hydrocarbon fields, little has been published assessing the storage resource of Norwegian saline aquifers since the Atlas was published. Recent work has been focussed on the Utsira Formation and Garn Formation, where simulation modelling has identified optimal locations for CO_2 injection, across the regional aquifers (Nilsen 2015), (Lothe 2014).

6.7.5 Regulatory Framework

Norway has the highest CCS Policy-Indicator of the countries within the GCCSI Carbon Policy Indicator Report (Global CCS Institute 2018). This is the result of the high level of carbon tax and Greenhouse Gas Emission Trading Act

implemented by the Norwegian government in 1991, which has facilitated the permanent storage of CO_2 at both Sleipner and Snøhvit (Norwegian Petroleum 2020). Additionally, the Norwegian government has funded several R&D projects and facilities, including the initiation of Gassnova, a state-owned CCS enterprise, and the Technology Centre Møngstad, an R&D facility to test CCS technologies.

Norway has a lower rating of Band B (40/87) in the GCCSI Legal and Regulatory Indicator Report (Global CCS Institute 2018). The rating shows that Norway has "CCS specific laws or existing laws that are applicable across parts of the CCS cycle".

6.7.6   Issues for the 2019 Assessment

There is a risk of double counting in the Utsira Formation between the regional, theoretical evaluation made in the NPD Atlas and a later study that considers injection into optimal structures within the aquifer (Nilsen 2015). In accordance with the SRMS guidelines on aggregation of resources, the double counting cannot be avoided as due to the different maturity of the sites against the SRMS classification system (Society of Petroleum Engineers (SPE) 2017).

6.7.7   Future Updates

It is recommended that future publications should focus on:

- **Probabilistic storage resources**. It states in the SRMS, that published volumes should provide a range of capacities, where possible, to account for variability. The leading work in the Atlas could be enhanced by including the range of storage resource to highlight the uncertainty of the estimation.

- **Current stored volumes for Sleipner and Snøhvit.** The recent release of 4D seismic data and simulation models over the Sleipner field may help stimulate further research in this area.

- **Published storage resource estimates for the Northern Lights project.** Following the successful drilling the Northern Lights injection well, updates on the storage resource of the site in the published literature would be welcome for future updates to this study.

6.8 United Kingdom

6.8.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for the United Kingdom as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	17	2.3
Undiscovered	60.6	0
Aggregated*	77.6	2.3

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-8. 2019 Storage resource classification summary for United Kingdom

- There is currently a total of 87 sites at both local and regional scale, located across 5 geological basins in the offshore sector. There are currently no evaluated storage sites onshore UK.
- There is a total of 11 project-specified sites, the majority of which also contain a simulation model developed.
- There are numerous active projects in the UK all at different stages of development, however as there is no record of this within the

published literature, they could not be included in the GSRA 2019 update.

- The UK Government has outlined strong ambitions for CCUS deployment in the Clean Growth Strategy released in 2017 and has released funding for CCS research and development.

a) Project Specified Only
Mid-Case Storage Resource
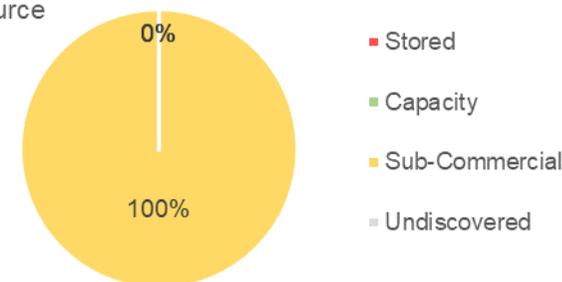
b) Project and Non-project
Mid-Case Storage Resource
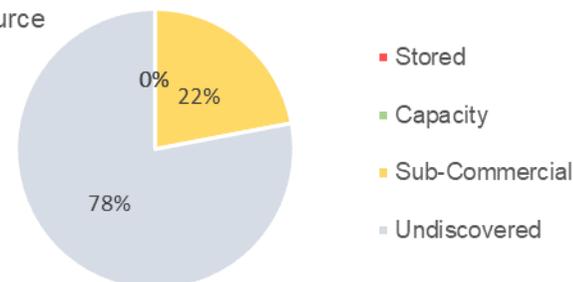
c) Saline vs Petroleum
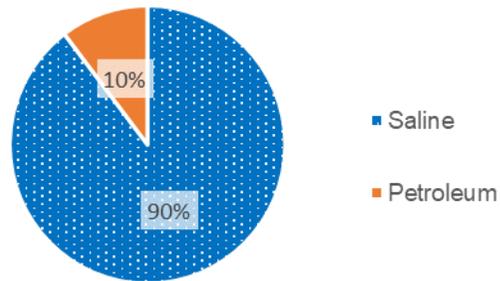
Figure 6-15. a) Spread of storage resource in UK sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all UK sites across SRMS classifications; both project specified and not. c) Split of UK storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.8.2 Resource Statement
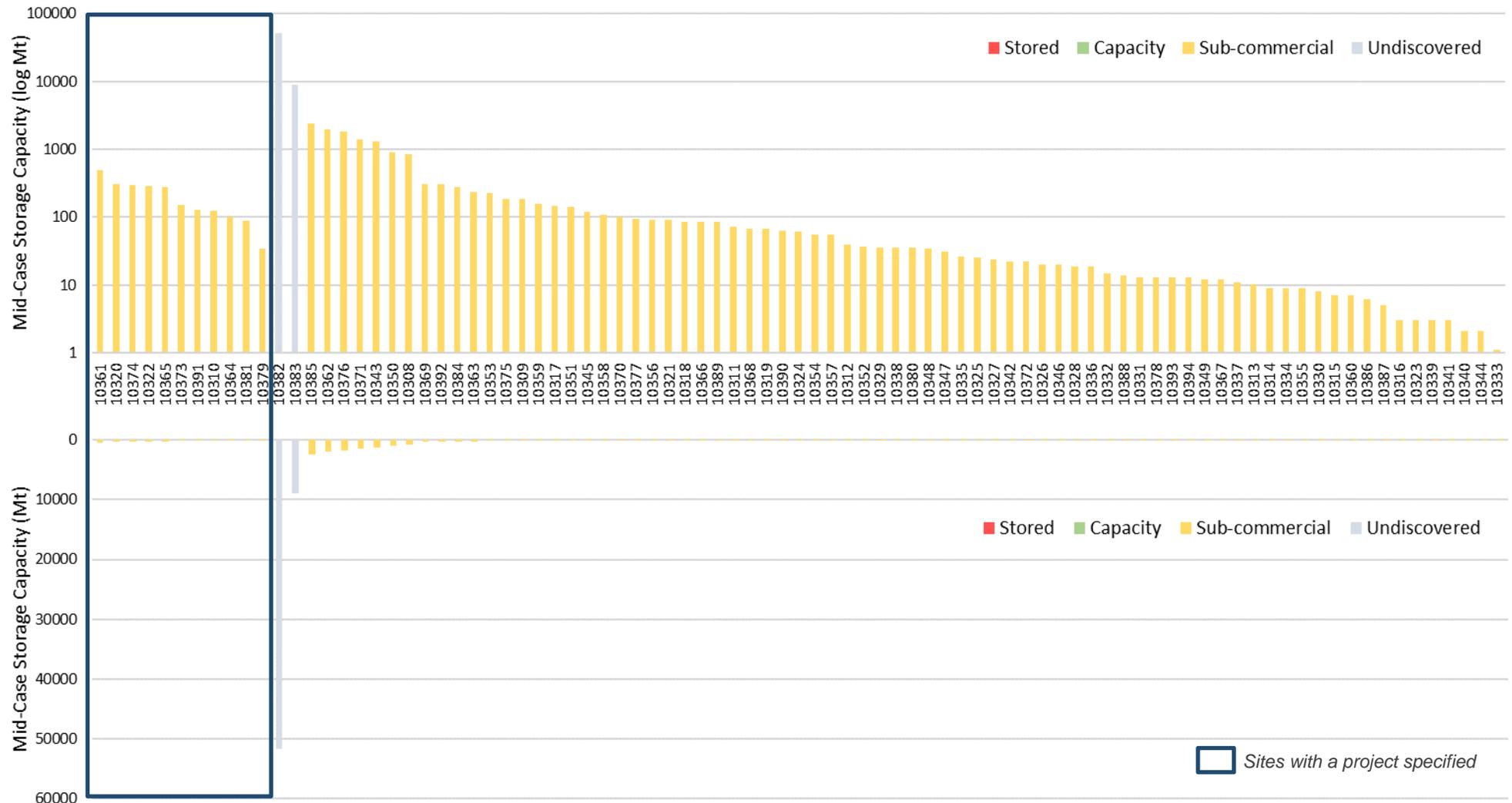
Figure 6-16. Storage resource summary for the UK compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.8.3 Evaluation History

The most widespread source for the estimation of CO_2 storage resource within the UK is from CO2Stored, the UK CO2Storage Evaluation Database, hosted and under development by the British Geological Survey and The Crown Estate and under license from the Energy Technologies Institute (ETI). The original data in CO2Stored was developed by the UK Storage Appraisal Project (UKSAP), which was commissioned and funded by the ETI. CO2Stored provides an overview of CO_2 storage data for over 500 potential CO_2 storage sites around offshore UK. To date the database excludes the large tracts of acreage to the west of the Shetland Islands and in the South-Western Approaches. The East Irish Sea is included. Unfortunately, due to the restriction of the CO2Stored license to non-commercial use, it could not be used directly in this GSRA 2019 update. As such, the UK individual entries are restricted to sites where the database is referenced in the published literature, including resource summaries created by the Energy Technologies Institute (ETI). To account for this and ensure that the storage resource for the UK is not under-represented, the remaining storage resource not captured in individual entries, is included in the GSRA database as four aggregated entries under the groupings: 'Sandstone aquifers', 'Chalk aquifer's, 'Oil fields' and 'Gas fields'.

6.8.4 Resource Review

6.8.4.1 Major Projects

To date three carbon storage licenses have been, or are being, held in the UK Continental Shelf (UKCS). These are:

1. CS001 Endurance License. Held by National Grid. Active from November 2012 till present. Storage site for the previous White Rose Project and now a potential target site for both the Humberside and Teesside projects. No published updates since the cancellation of the White Rose Project in 2015.
2. CS002 Peterhead License (Goldeneye field) held by Shell U.K. Limited. Active between July 2013 and August 2016. License terminated by Shell U.K. following the withdrawal of government funding in 2015. The evaluated area is now part of the current Acorn License.
3. CS003 Acorn License. Active from January 2018 till present. The license combines both the Goldeneye field and ACT Acorn Storage Site which have both been subject to extensive study during many phases, but most recently the CCS Commercialisation Programme, funded by the UK Government. The Acorn Project is currently in Concept Select Phase and is due to enter FEED mid-2020. There are currently no published evaluations of the storage resource within the newly defined Acorn site and as such, it could not be included in the GSRA 2019 update.

In addition to the projects with a storage license, there are also several other industrial clusters developing around the UK, notably the HyNet Project which is in Detailed Design and Engineering Phase 1. The project is currently evaluating the Hamilton Gas Field as a potential storage site, amongst others, however no details of the project could be found in the published literature so was not included in the GSRA 2019 update. This absence of reporting for active projects results in the notable absence of Commercial Storage Resources within the UK. Should any of the active project publish updated evaluations of the storage sites, they will be included in future assessments.

6.8.4.2   Depleted Oil & Gas Fields

All oil and gas fields can be classified as Discovered due to the presence of a proven reservoir. In the UK the majority of the hydrocarbon fields are further classified as "Development Not Viable" due to the absence of an active appraisal program. The two exceptions to this are the Hamilton Gas Field where the resources are classified as "Development Unclarified" as an active appraisal is being undertaken however no storage license is held for the site and Goldeneye, where resources are classified as "Development on Hold" as the retraction of government funding has caused significant delay.

It has been assumed that the UKCS hydrocarbon fields in the GSRA 2019 update will reach the end of their productive life before 2050 and therefore become available for CO_2 storage before that time, due to the maturity of the North Sea basin.

The majority of sites have been assessed using a fluid replacement methodology, with the exception of the sites; Goldeneye Gas Field, Viking A Storage Site, Hewett Gas Fields Storage Site, and Hamilton Gas Field, which have a simulation model and published results.

6.8.4.3   Saline Aquifers

The UK, like many other countries within the North Sea region, benefits from a wealth of experience and data acquired through a well-established hydrocarbon industry. Furthermore, the requirement for operators to share key subsurface data through the National Data Repository, have allowed both academia and industry to accelerate the assessment of many UK sites for CO_2 storage. Consequently, the reasonably high well density in many of the UK saline aquifers has allowed many of the sites to be classified as Discovered.

The overwhelming majority of the discovered resource is classified as "Development Not Viable", due to the lack of an active appraisal or evaluation plan presented for any of the sites. The two aggregated entries for sandstones aquifers and chalk aquifers, mentioned in 6.8.3, are all classified as "Undiscovered Basin Play", due to the aggregated nature of the entry. It is noted that this is not a true reflection of the maturity of the storage resource and portions of it will undoubtedly be Discovered due to significant hydrocarbon exploration in the North Sea. Should the licensing conditions for the CO2Stored database change, or should evaluations be published for sites included in these aggregations, then the resource can be classified more appropriately.

The two sites 'Endurance Bunter Closure' and 'Goldeneye Storage Site' have been classified as "Development On Hold" following the retraction of government funding detailed in 6.8.4.1, which has led to significant delay in the projects.

6.8.5   Regulatory Framework

The UK has the second most highly rated country in the GCCSI Policy Indicator Report (Global CCS Institute 2018) due to the ambitions for CCUS deployment outlined in the Clean Growth Strategy in 2017. Additionally, there are a range of policies which support emission performance standards and CCS research and development projects.

6.8.6   Issues for the 2019 Assessment

Lack of commercial access to the CO2Stored database. Due to restrictions on the database for commercial usage, the data for the UK sites was restricted to publications that reference the database. Many of the sites in CO2Stored could not be found in other publications, leading to the undesirable work around

detailed in 6.8.3, to prevent significant under-representation of the storage resource in the UK.

Lack of reporting on active projects. As detailed in 6.8.4.1.

6.8.7 Future Updates

Published evaluations for the sites currently active in the UK would be welcome for future updates to the GSRA. This would better represent the maturity of the storage resource associated with these projects.

6.9 United States of America

6.9.1 Summary

The GSRA 2019 update has identified a CO_2 storage resource for the United States of America as follows:

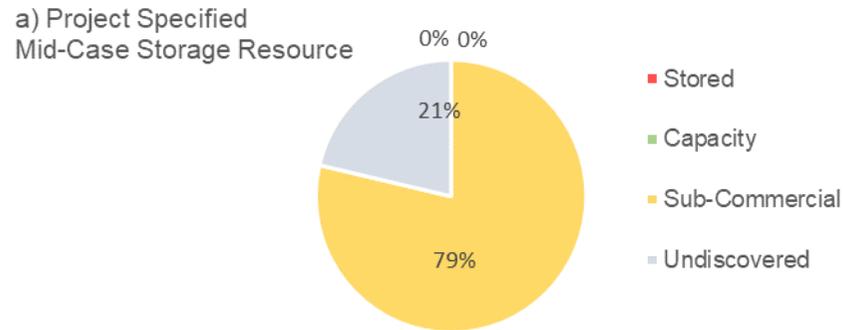| Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.003	0.003
Capacity	0.004	0.004
Sub-Commercial	258	55
Undiscovered	7804	15
Aggregated*	8017	70

* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-9. 2019 Storage resource classification summary for United States of America

- Storage resource potential is present in both saline aquifers and oil and gas fields.
- Potential storage resource has been identified in 36 US States with 12 projects and 14 regional studies included in the 2019 Assessment. High level, state-wide estimates are also provided by the DOE Atlas V, but these have no detail in terms of individual resource location or estimate attached.
- As of December 2019, 4.36 Mt of CO_2 has been reported injected and stored, or permitted for injection by 4 CCS projects operating in the USA: Illinois Basin Decatur project (1Mt), Illinois: ICCS (5 Mt), the Citronelle Project (0.1 Mt), and the Michigan Basin Niagaran Pinnacle Reef Trend project (0.14 Mt). A significant volume of CO_2 has also been injected into oilfields via EOR operations, but this figure is not included in the SRMS.
- While the US storage resource is distributed across the Lower 48, the regional saline aquifer studies are dominated by the northern states within the Williston, Michigan, Illinois, Powder River, and Denver basins. Future assessments should focus on updating with the vast potential in other parts of the country, including California, the southern states, the Gulf of Mexico region, and the Federal Offshore.
- The current regulatory system is positive to CCS with recent changes to the tax system (45Q) to incentivise both CO_2-EOR and geological storage. California leads the way with state-level credit-based systems. Permitting for existing CCS projects provides a way-forward for future projects.
- The DOE-funded CarbonSAFE initiative is currently funding thirteen Phase I 'Pre-Feasibility' studies and six Phase II 'Feasibility' programs with the aim of identifying several saline aquifer sites with proven potential to store at least 50 Mt/site with an anticipated injection start-date of 2026.

a) Project Specified
Mid-Case Storage Resource

0% 0%

21%

79%

- Stored
- Capacity
- Sub-Commercial
- Undiscovered

b) Project and Non-Project
Mid-Case Storage Resource

0% 0% 3%

97%

- Stored
- Capacity
- Sub-Commercial
- Undiscovered

c) Saline Aquifer vs Petroleum

3%

97%

- Saline
- Petroleum

U.S. storage resource between saline aquifers and hydrocarbon fields, both project specified and not.
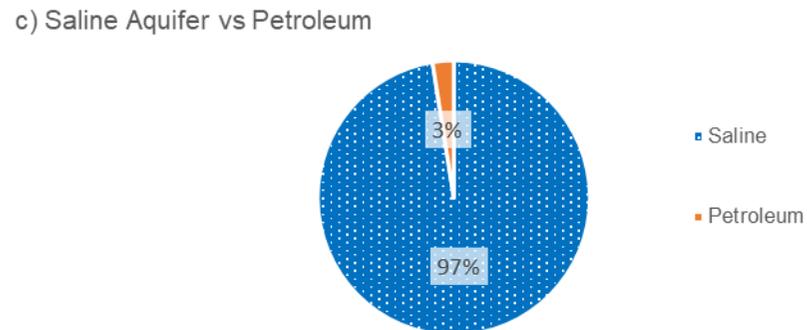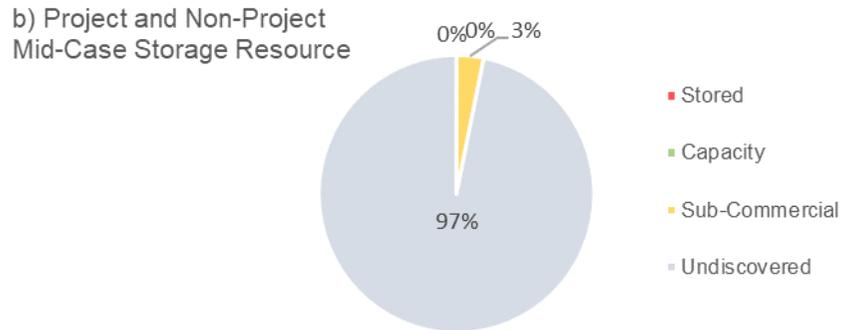
Figure 6-17. a) Spread of storage resource in U.S. sites across SRMS classifications, where a project has been specified. b) Spread of storage resource in all U.S. sites across SRMS classifications; both project specified and not. c) Split of

6.9.2   Resource Statement

Figure 6-18. Storage resource summary for the U.S. compiled in the GSRA 2019 update. Graph above is log scale and graph below is linear. Blue box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.9.3 Evaluation History

The initial basis for the 2019 Assessment was the 2015 US and North America Carbon Storage Atlas - fifth edition produced by the National Energy Technology Laboratory and commissioned by the US DOE Office of Fossil Energy. The storage information in Atlas V was developed to provide a high-level overview of the immense CO_2 storage potential of the North America region and was intended to provide developers with a starting point for further investigation. The Atlas considers a full range of sequestration options including oil and natural gas reservoirs (with or without EOR), saline aquifers, deep unmineable coal seams, unconventional organic rich shales, and basalt formations. Data and information in the Atlas are based on input from the DOE-funded Regional Sequestration Partnerships, research groups delivering evaluations of sequestration potential across the USA and parts of Canada. The Atlas V provides a state by state breakdown of potential CO_2 storage resources available in both saline formations, and oil and gas fields. These are referred to as 'State-wide Evaluations' for both saline aquifers and petroleum fields to highlight the fact that very little is known about the origin and geographic location of the data presented. In addition, the Atlas delivers short case studies on the major evaluation and demonstration projects taking place across North America between 2005 and 2015 which points to the detail that is available but remains unpublished.

The State-wide saline aquifer evaluations have been further broken down into regional studies carried out by the Regional Partnerships. These are generally presented as estimates of storage resource potential at the sequence play level for a geological basin and, as such often cross state or as in the case of the Cambro-Ord Basal Sand, national boundaries. In such cases, it has been assumed that the regional studies by the partnerships represent the summed resource reported at the state level by the Atlas V and so the State-wide evaluation for those states is nulled.

In the 2019 Assessment, the demonstration project sites identified from the Atlas V were reviewed and updated, where possible, to populate the SRMS database. The nature of the Atlas V has presented some challenges for the storage resource classification due to its extensive scope, but high-level overview approach; the data collated by the 2019 Assessment is in no way intended as a substitute for site-specific characterisation, testing and assessment.

The calculation methods used to assess resource potential are essentially volumetric methodologies for the State-wide assessments, with local variations at the local/Project-scale provided where information is available.

For oil and gas fields, Potential CO_2 Storage Resources have been estimated by the replacement method where suitable records are available and the volumetric method where production and injection records are unavailable.

6.9.4 Resource Review

Despite the volume, quality, and progression of CO_2 storage in North America, the current classification of potential storage resource is significantly limited due to the mismatch between the lack of detail available and the very large resource base, particularly for saline aquifers. The approach taken here is to adopt a minimum maturity level approach to classification and only elevate resources to more mature classes when there is both evidence and quantification available. This has led to an understatement of the maturity of the resource potential with 97% held within the Undiscovered: Prospective maturity class; the USA represents a strong candidate for re-classification.

The Sub-Commercial resource class contains both the oil and gas fields (203 Gt, classified as 'Inaccessible' at this stage due a lack of knowledge on field accessibility dates), and those storage projects (55 Gt), classified as 'Development Not Viable) for which detailed data are not published, or where their current activity status is on-hold, cancelled, or unknown.

6.9.4.1   Major Projects

The USA has amassed a huge amount of information through the Regional Carbon Sequestration Partnerships. These have informed the location and potential scale of storage through high level screening studies through to the selection of pilot projects. The US DOE is now developing the next generation of large-scale, integrated CCS projects: the CarbonSAFE Initiative.

At the time of assessment, the only projects reporting stored CO_2 in the subsurface (non-CO_2 EOR) are the Alabama Citronelle Project (0.114 Mt), the Illinois IBDP, injecting 1Mt over 3 years, and the IL: ICCS project, injecting up to 5Mt over 3 years.

6.9.4.2   Depleted Oil & Gas Fields

While there is a large inventory of CO_2 injection into commercial oil properties for enhanced oil recovery, there are very few studies which have evaluated the injection of CO_2 into depleted oil and gas fields for carbon storage without an uplift in hydrocarbon production. The DOE Atlas V does however report large resource estimates in oil and gas fields for some states, e.g., Texas: 17180 Mt, West Virginia: 9840 Mt, New Mexico: 9710 Mt, Louisiana: 5700 Mt, and California: 4850 Mt, but the source evaluations for these figures are unknown. The National Energy Technology Laboratory (NETL) has indicated that an additional demand of 10 to 45 Gt CO_2 for enhanced oil recovery operations may exist across the Lower 48 states, Alaska and Offshore Gulf of Mexico. This could significantly increase the available storage potential of depleted oil fields but a more detailed breakdown of where and which fields could be targets for CO_2 storage is needed, and a mechanism for including this resource into the SRMS.

6.9.4.3   Saline Aquifers

The storage resource in the USA is currently dominated by the state-wide (Basin Play) saline aquifer resource estimates provided by the DOE Atlas (7803 Gt), and regional studies (e.g. COSS (Basal Sand), and the Lower Cretaceous and Mississippian aquifers; 416 Gt) reported by the DOE Regional Partnerships. These regional estimates are assigned Undiscovered: Sequence Play status due to the immense scale of the aquifers and the lack of published detail which would move them into the 'Discovered' resource category. The scale of this resource suggests that the USA 'Discovered' portfolio is heavily under-estimated.

The 2019 Assessment focused the PCOR partnership studies which cover Montana, North and South Dakota, NW Nebraska, and NE Wyoming and focus on the Williston, Powder River and Denver basins. As discussed earlier (Section 6.3.4.2: Application of SRMS to North America), this region has required some careful treatment to avoid double counting. Those states wholly covered by the PCOR study area (MT, ND, SD) have had the State-wide saline aquifer evaluation nulled in the database to avoid double counting, however, there is a mismatch between the summed state-wide evaluations for these three states, and the summed regional sequence play resource estimates reported. This is likely to be at least partly a result of re-calculation using a different storage efficiency factor by the DOE before incorporation into the Atlas, making direct comparison of reported data difficult.

The state-wide saline aquifer evaluations in other areas of the USA point to extremely large, gigatonne-scale, potential storage resources, for example, Texas: 1505.8 Gt, California: 1311.1 Gt, Louisiana: 734.6 Gt, Wyoming: 550.3 Gt, Mississippi: 459.2 Gt, and Alabama: 304.1 Gt. These regions require further evaluation to breakdown the resource for proper assessment against the SRMS. Future evaluations should also work towards validating, if appropriate, such large resource estimates.

6.9.5 Regulatory Framework

According to the GCCSI CCS Readiness Index 2018 (GCSSI, 2018), the USA ranks in the highest category, second only to Canada, indicating that, as a country the USA is well placed to enable CCS deployment, though long term investment and commitment to CCS. Positive regulatory developments include a 2018 revision to the 45Q CCS tax incentive increasing the tax credit for dedicated geological storage to $22.66/ton (increasing linearly to $50/ton by 2026), and incorporation of a CCS Protocol into the California Low Carbon Fuel Standard (LCFS; a credit-based emissions reduction system). LCFS can also be stacked with 45Q. US states are looking to simplify CCS guidelines and provide regulatory clarity to help enable CCS deployment (Beck, 2019). However, the USA also scores maximum points on the GCCSI Inherent CCS Interest as a nation which relies heavily on fossil fuels and therefore is most likely to have a need for a robust CCS policy to achieve any future deep emissions reduction targets.

6.9.6 Issues for the 2019 Assessment

The 2019 Assessment recognises that the resource statement significantly understates the Sub-Commercial storage resource within the USA saline aquifer systems due to the lack of detail on discovery status. The expectation is that there are large tracts of saline aquifer that should be considered as discovered resource. Sub-Commercial storage resources are classified at this time as "Development Not Viable" due to the lack of information on this portfolio. The classification status of the commercial and active projects could also be improved through achieving more clarity regarding the progression and status of pilot projects with many projects only reporting very limited consents for injection at this time.

Several large, commercial-scale carbon capture facilities have either captured anthropogenic CO_2, or have commenced operations, however most are delivering to EOR operations. Large-scale capture and geological storage operations have not yet started-up in the USA. Future opportunities exist with the CarbonSAFE Initiative – see 'Future Updates' below.

6.9.7 Future Updates

- The USA is expected to deliver several projects into the CCS pipeline in the next 5 years:
- **IL: ICCS Project:** this project follows (but is administratively separate to) the pilot IBDP project in Decatur, Illinois. CO_2 injection and monitoring continues through 2020. The final injection volume needs to be updated when it becomes available.
- **CarbonSAFE Initiative** (the Carbon Storage Assurance Facility Enterprise) is a DOE-funded program focused on the development of geological storage sites with the potential to store at least 50 Mt CO_2. The timeframe for deployment is 2025-2035. Currently there are 13 projects at the 'pre-feasibility' stage and 6 being funded to better establish the 'feasibility' of a project. The funding cycle for many of these ends in during 2020-2021 and so results should be

available for update in the next two assessment cycles. It is anticipated that the projects which succeed at the 'Feasibility' stage will be the major projects with the best chance of progressing to the FEED study stage and onward to project commerciality.

- **Gulf Coast Offshore** opportunity: a key area which is under-represented in the current SRMS database is the offshore zone and the offshore Gulf Coast. The region is represented by two Pre-Feasibility CarbonSAFE projects, but any future country update should include published reviews of the offshore potential.