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CO2 Storage Resource Catalogue – Cycle 2

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1.0 Executive Summary

The CO_2 Storage Resource Catalogue (CSRC) Cycle 2 has assessed 715 CO_2 storage resource sites from 18 countries/regions against the SPE Storage Resources Management System (SRMS). Both oil and gas fields, and saline aquifers are assessed.

To date, 89.9 Gt storage resource is held within defined storage projects, only a small portion of the total 12,958 Gt project and non-project, aggregated global storage resource. Of this global total, only 4.3% is classed as Discovered (551Gt) with less than 0.002% assessed as Commercial resource (254 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.

While 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 CO_2 Storage Resource Catalogue (CSRC) Cycle 2 update is the second of an on-going programme aimed at building a global view of the commercial readiness of CO_2 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 CO_2 storage resources. It aims to reduce the subjective nature of resource assessment and allow sensible comparison of resource potential. The CSRC 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.

The CSRC contains commercially assessed evaluations of published potential storage resources from 715 sites across 18 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 12,958 Gigatonnes (Gt) but this combined figure masks the wide range of data availability, approaches, and methodologies applied across the resource evaluations. Nearly 96% of this aggregated figure is currently classed as 'Undiscovered (Prospective)' meaning that further drilling or enhanced evaluation and reporting is required before discovered resource can be declared.

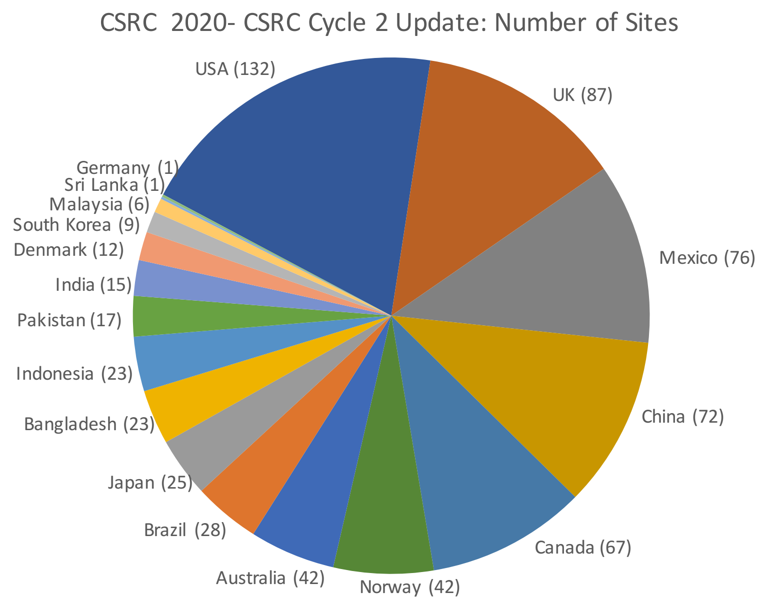

Figure 1-1. Number of potential storage resource sites assessed in the CSRC, by country or region. N =715.

Only 4.3%, or 551 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 2021, only 0.25 Gt of the resources assessed was classed as Commercial including 0.04 Gt as Stored. The assessment highlights the disparity in maturity of the reported storage resource on a global scale (Figure 1-2). Of the 18 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 (for the purposes of the SRMS classification, a project is defined as a potential resource for which there is some level of storage development plan attached; see Section 3.2 for further details). Currently only 10 countries in the CSRC have identified projects, as highlighted by the comparison between Figure 1-2 and Figure 1-3, and these are still dominated by Sub-Commercial and Undiscovered storage resources. The CSRC 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 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. On-going injection operations and projects under active evaluation are re-assessed at least annually to monitor progression or resource maturity. At present, the CSRC is currently underpopulated in this class. Workers on CO_2 storage resources around the world are encouraged to submit a summary resource statement for consideration and inclusion in future annual updates. The website link is: https://oilandgasclimateinitiative.com/co2-storage-resource-catalogue/.

This work has been commissioned by OGCI and led by the Global CCS Institute. Technical assessment, database population and reporting were carried out by Pale Blue Dot Energy.

Note: this report uses both gigatonnes (Gt; 10^9 t) and megatonnes (Mt; 10^6 t) as units of measure for the storage resources. The CSRC database uses Mt but where the value of this number is so high as to risk confusion Gt is the preferred written unit.

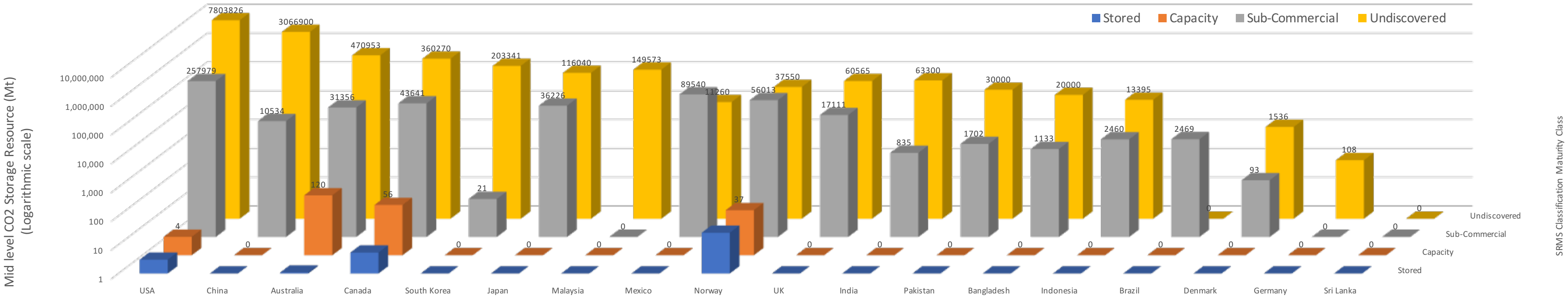

Figure 1-2. Both project and non-project specified storage resource summary for the countries assessed by the CSRC. Data labels represent the assessed potential storage resource by SRMS maturity class in millions of tonnes (Mt). Numerical values on the plot represent values currently entered in the Global Storage Catalogue; a value of '0' indicates no storage resource assigned to that maturity class. (Note: the y axis on this plot is logarithmic)

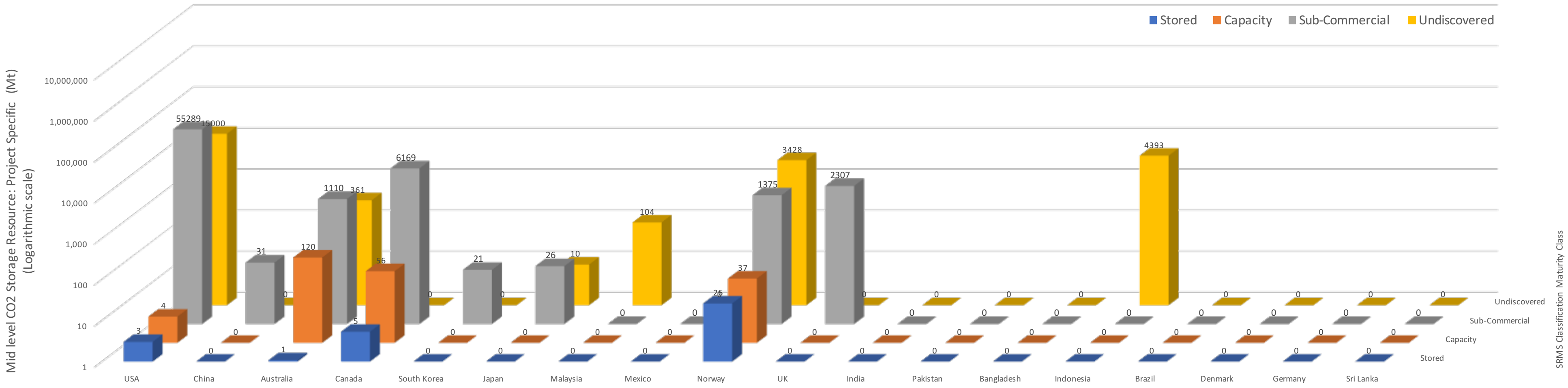

Figure 1-3: Project-specific storage resource summary for the countries assessed by the CSRC. Data labels represent the assessed potential storage resource by SRMS maturity class in millions of tonnes (Mt). Numerical values on the plot represent values currently entered in the Global Storage Catalogue; a value of ‘0’ indicates no storage resource assigned to that maturity class. (Note: the y axis on this plot is logarithmic)

2.0 Objectives & Approach

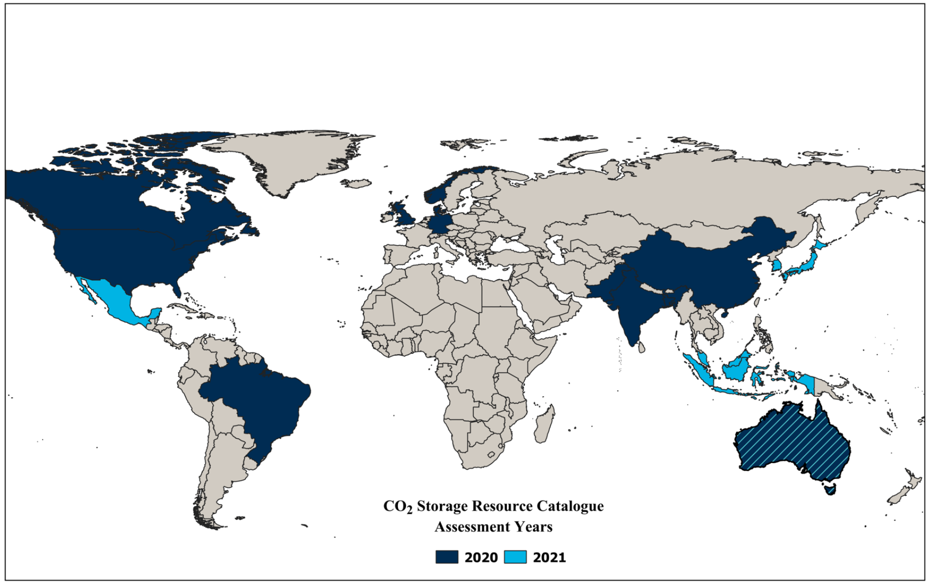

Figure 2-1 Map showing countries included in the CSRC.

2.1 Objectives

The CO_2 Storage Resource Catalogue (CSRC) forms an on-going programme of classification of published storage resource evaluations using the Society of Petroleum Engineers (SPE) SRMS [1]. 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. In 2017, the programme was initiated with Cycle 0 which identified data sources and provided critique on the assessment of CO_2 storage sites using the SRMS. Following this, a series of six cycles of resource assessment was initiated in 2019, as outlined in Table 2-1 and Figure 2-1. Currently the CSRC and SRMS includes depleted oil and gas fields and saline aquifers.

This Cycle 2 report fulfils the delivery of the second in the 6-year programme and provides an update to Cycle 1 [2]. The programme aims to capture advances in the evaluation of CO_2 storage resource 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. A summary of countries assessed in each cycle is provided in Table 2-1.

Work Package 2

Objective: to build, populate and deliver the *CO_2 Storage Resource Catalogue* 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: Both the first and second cycles of the programme were impacted by the global Covid-19 pandemic which 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 has proposed replacing the outlined programme with a webinar designed to meet the goals of the work package.

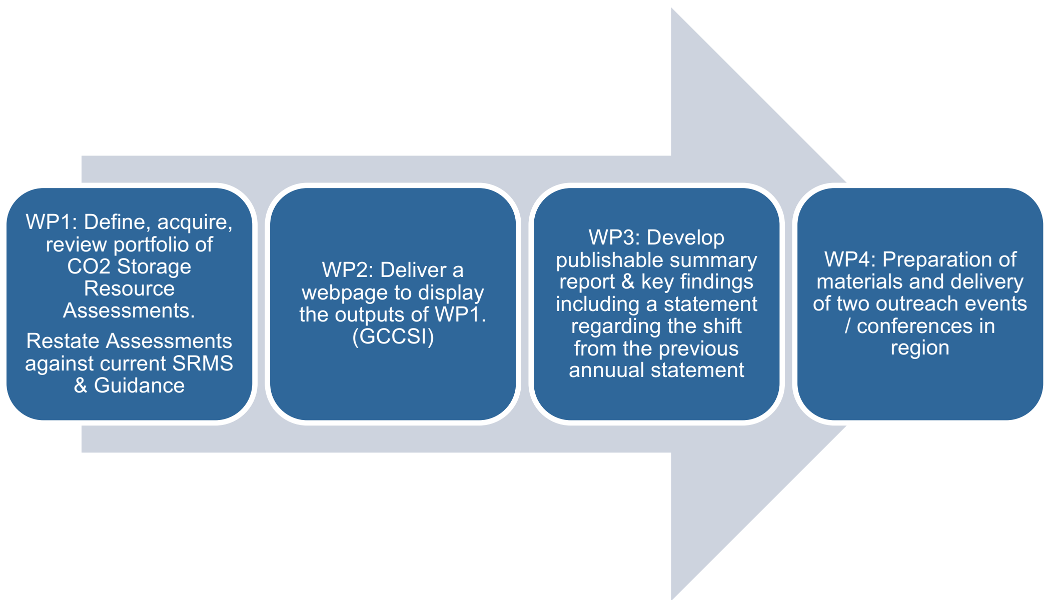

Figure 2-2. Work flow for Work Packages 1, 2, 3 and 4 of the CSRC.

2.2 Assessment Cycles

Cycle	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
Period	**2017**	**2019-2020**	**2020-2021**	**TBC**	**TBC**	**TBC**	**TBC**
Countries Assessed	Australia	Australia	Australia[2]	TBC	TBC	TBC	TBC
	Baltic Region (Denmark and Germany)	Baltic Region (Denmark and Germany)	Indonesia				
	Bangladesh, India, Pakistan, Sri Lanka	Bangladesh, India, Pakistan, Sri Lanka	Japan				
	Brazil	Brazil	Malaysia				
	China	Canada[1]	Mexico				
	Norway	China	South Korea				
	United Kingdom	Norway					
	U.S.A	United Kingdom					
		U.S.A					

Table 2-1: Summary of assessment cycles to date. Each cycle reviews a set of countries selected by the OGCI Storage Working Group. Countries for Cycles 3-6 have not yet been selected. Note: In Cycles 0-2 Denmark and Germany were combined under the 'Baltic Region'.

[1] In Cycle 1, Canada was selected as a priority country for assessment.

[2] In Cycle 2, Australia underwent an assessment update and refinement

2.3 Approach

The CSRC deployed the SRMS against a library of publicly available information sources and evaluations collated by the assessment team and the OGCI SWG. The effort in Cycle 2, under Work Package 1 was focused in two main areas:

- A review and assessment of the storage resource of five new countries: Mexico, South Korea, Indonesia, Japan, and Malaysia.
- A review and update of published evaluations of storage resource in Australia from the Cycle 1 assessment.

Note: Cycles 0-2 combined the limited number of sites assessed in Denmark and Germany into the 'Baltic Region' and Bangladesh, India, Pakistan, and Sri Lanka into a similar regional grouping. As the CSRC is refined and updated for these countries, individual nations will be assessed separately.

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 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, from regional scale national and multinational CO_2 storage resource assessments, to more detailed evaluations, often targeting a basin, sub-basin, or formation, and finally down to focused technical studies of a field or site. Data from the United States Geological Survey [3] was used to assign sites to basins.

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 CSRC.

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 Cycle 2 of the CSRC. It should be viewed as an accompanying document to the online CSRC database (Work Package 2 deliverable). This database can be accessed here: https://oilandgasclimateinitiative.com/co2-storage-resource-catalogue/.

As an 'evergreen' document, this report is updated following each Cycle or significant update to the CSRC. All country-specific summaries are maintained in the Appendix of this report. Previous versions of the report are retained by Pale Blue Dot Energy.

2.4 Minimum Threshold Resource

While storage resource evaluations exist globally within the published literature, the CSRC aims to support large, commercial-scale project development. To support this, a 'minimum threshold' for a resource to be included in the Catalogue has been set. After discussion with the OGCI SWG, the threshold was set during Cycle 2 at 10Mt. This is open to review in future cycles and it can be flexible in its application. For example, where a pilot or demonstration project has successfully injected and stored CO_2 and has potential for continued or additional injection, the site is included. A good example of this is the Tomakomai Demonstration project in Japan where 0.3 Mt (300,000t) was injected as part of the project, but the storage aquifer holds additional potential, both Discovered and Undiscovered.

2.4.1 Pilot Projects

As a result of the Minimum Threshold, pilot projects are not included in the Catalogue (unless they hold additional evaluated storage potential as discussed above). Under European Union guidelines, a pilot project would be considered one to which the CCS Directive [4] does not apply; where the total intended CO_2 storage is below 100 kilotonnes and the project is undertaken for research, development or testing of new products and processes.

Where appropriate, pilot studies are recorded in the Country Summaries in Appendix A (**6.0**). The Global CCS Institute also maintains a list of pilot projects (past, current, and planned) which provides the most up to date information on each project [5].

2.5 High CO_2 Fields

During Cycle 2 the challenge of handling hydrocarbon fields with high CO_2 content (or indeed, natural CO_2 accumulations) presented itself. This includes sites in Australia, Malaysia, Indonesia, and the USA. To provide a standard process for assessing these types of accumulation it was decided that:

1. If the evaluated resource indicates a replacement of the initial CO_2 volume through a re-injection process (i.e., re-injection into a high CO_2 gas field during production), this does not represent a storage resource and is not included in the Catalogue.
2. If the evaluated storage resource is connected to the high CO_2 field, the storage volume which lies outside the original accumulation, (i.e., water leg or surrounding aquifer) and is considered to have some degree of trapping (i.e., through residual or dissolution trapping processes) or sealing potential (i.e. it does not wholly rely on migration into the trap or field draw down for containing the CO_2), the storage estimate is considered a storage resource and is included in the Catalogue.

One additional type of resource that may become available is that of storage voidage through the production of hydrocarbon from a high CO_2 field. An example where this may become an opportunity in the future is at the East Natuna field, where 80% of the field gas volume is naturally occurring CO_2. However, the very large size of the field (46 TCF; [6]) means that potentially 500 Mt (using a basic conversion calculation) of 'additional' storage resource may be created through the voidage from methane production.

2.6 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 assessments. It also provides a description of the terminology applied during this assessment and guidance as to how some of the challenges were handled. The classification process has been applied to all sites identified from the bibliography in **Section 5.0**. **Section 6.0 (Appendix A)** provides the 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 significant 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:

1. Discovery status of the resource, as per SRMS guidelines.
2. The status of the regulatory system in the jurisdiction area.
3. Internal project decision to proceed.
4. External regulatory consent to proceed.
5. Commencement of operations.
6. End of injection.
7. The point of handover of long-term responsibility for the injected CO_2 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 the CSRC assessments uses this updated version [1] 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 Cycle 0 (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 is split in the CSRC updates to separate sites with a lower level of maturity within the Play classification.

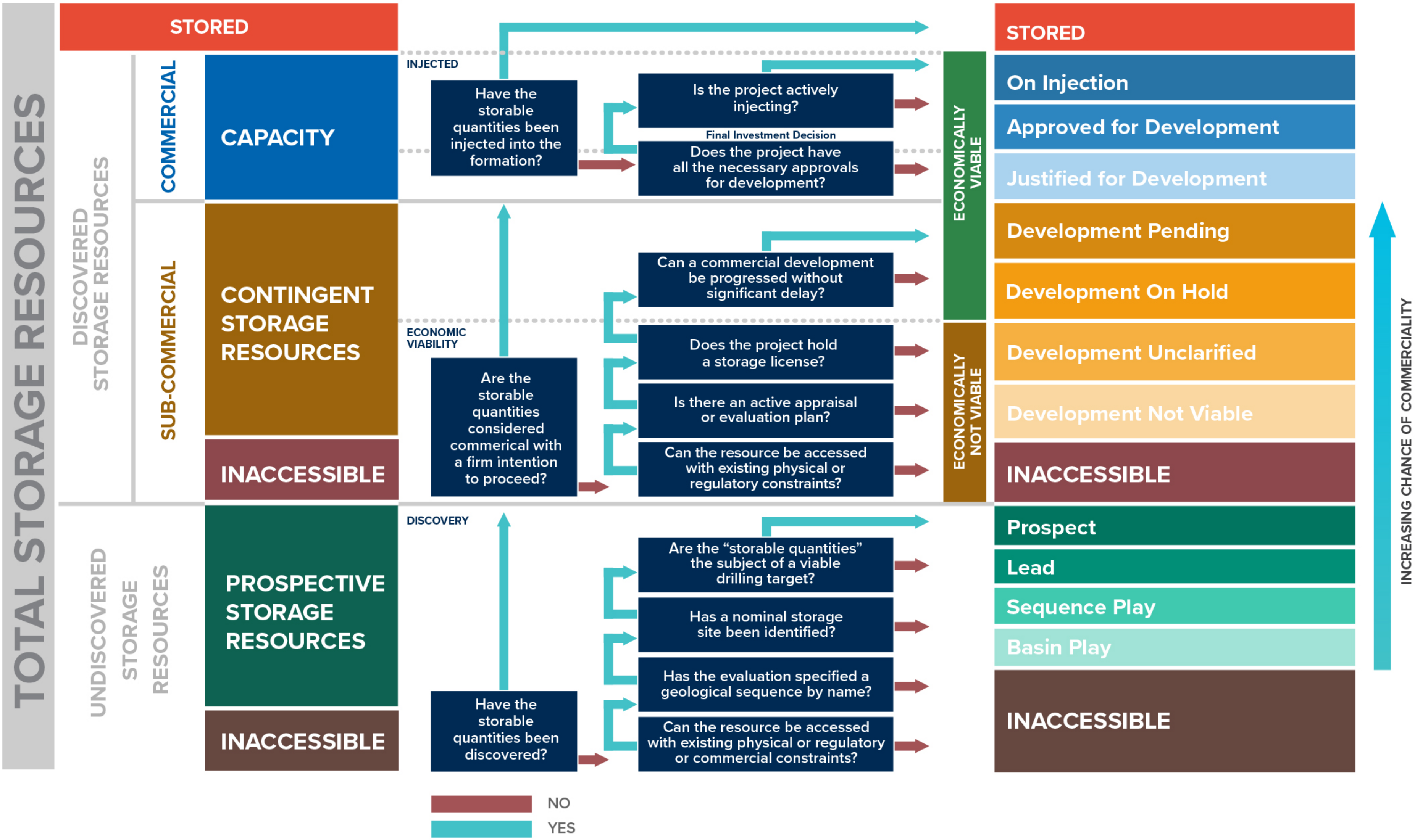

Figure 3-1: Flowchart for the classification of storage resources based on the SRMS guidelines and terminology.

3.1 Terminology

In the SRMS guidelines, ‘evaluation’ and ‘assessment’ have the same meaning. In the CSRC, 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.

3.2 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. 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.

3.3 Resource Estimation Method

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

Resource estimates are reported as being derived from **Volumetric** or **Probabilistic** methods. Volumetric methods include both simplistic ‘theoretical’ estimates based on pore volume derived from mapping exercises (area and thickness), or from more detailed static geological models. A value for storage efficiency (derived from effects of trap heterogeneity, gravity, sweep efficiency) is assumed but the range of ‘E’ varies greatly (0.01% to 25%) and the user should be aware that some evaluations use potentially unrealistically high values and/or values selected from ranges based on broad depositional environment descriptors (i.e., not site-specific) resulting in overly optimistic resource estimates. An additional issue is that it is common for volumetric estimates to only provide a single estimate of resource size.

The deterministic volumetric approaches do not consider the effects of changing temperature or pressure. Where probabilistic dynamic models are used (ranging from simple analytical, semi-analytical to full simulation) as much detail on the approach used is documented.

3.4 SRMS Classification: Challenges & Approach

3.4.1 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" [1]. 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 sites 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 undertaken in Cycle 0 of well density in the UK Southern North Sea Bunter sandstone [7]. 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 classified as either 'Partly Discovered' (for sites with a dynamic simulation available), or 'Discovered awaiting detailed assessment' (where no simulation is published), for the area within the well discovery zone, while the potential resource outside the zone is flagged as 'Undiscovered'. 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.

3.4.2 Treatment of Petroleum Accumulations and Inaccessible Resources

3.4.2.1 *Petroleum Accumulations*

The storage resource present in depleted oil and gas fields (conventional petroleum accumulations) is considered to be 'Discovered' from an SRMS perspective, due to data availability (well and well tests), the proven reservoir and containment potential, and having been characterised as having a structural or stratigraphic trap.

3.4.2.2 *Inaccessible Resources - Petroleum*

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. 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. 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 CSRC Cycle 2, published in 2021, the EAD is set to 2051.

Where hydrocarbon fields were described as depleted, it was assumed that extraction of hydrocarbons had ceased and that the site is accessible for CO_2 storage.

3.4.2.3 *Inaccessible Resources - Regulatory*

In countries that 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.

3.4.2.4 *Inaccessible Resources - SRMS Definitions*

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 because 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 Cycle 1 and 2 CSRC assessments are designed to conform to the 2017 published SRMS, together with its glossary of definitions and guidance.

3.5 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 based on 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 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 CSRC database. Where this is identified as a significant issue, this is reported in the accompanying country assessment documentation.

3.6 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.

3.7 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.

3.8 SRMS Evolution: Resource Updates

It is anticipated that the current resource base in the CSRC database will mature as the commercial interest in CCS increases. Regular refinement and updating of the storage resource at the country or regional level will enable the database to represent the most up to date status of global storage potential. Evaluator updates and new entries to the database should also keep the resource content current. Individual projects will be reviewed on an annual basis and updated as appropriate. Capacity and Contingent projects should be re-assessed regularly to ensure they remain appropriately classified. Capacity projects should be developed within a ‘reasonable’ timeframe (generally considered to be less than five years [1] . For Contingent projects, 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". As a result, several 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 are assessed as Development Not Viable rather than Development Unclarified. It should be noted that this terminology does not necessarily imply limited technical potential.

Any future updates or refinements of the SRMS may lead to a need for changes to the CSRC site entries. As such, the status of the SRMS should be regularly reviewed.

4.0 Summary & Recommendations

4.1 Summary

The CSRC Cycle 2 update has assessed the potential storage resource from five new countries and reviewed the potential storage resource of Australia, bringing the total number of countries assessed against the 2017 SRMS [1] to 18. Cycle 2 saw an additional 190 sites added to the CSRC, adding 680 Gt potential storage resource. This has delivered a classified inventory of 715 potential storage sites with an aggregated storage resource of 12958 Gt*.

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified
Stored	0.037	0.037
Capacity	0.217	0.217
Sub-Commercial	551	66.33
Undiscovered	12407	23.3
Aggregated*	12958	89.88

* 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. Total storage resource classification summary following Cycle 2

As shown by Table 4-1, the resource base is dominated by the pre-commercial Undiscovered (95.7%) and Sub-commercial (4.3%) classes of storage resource. Commercial projects and those where CO_2 injection is approved for development or is already being injected and stored in the subsurface only contribute 0.25 Gt to the overall inventory: less than 0.002%. Only 89.9 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 (72) identified by the CSRC and by the classification of many projects as Development Not Viable as, although the projects demonstrate storage potential, none are currently being progressed, or under active evaluation.

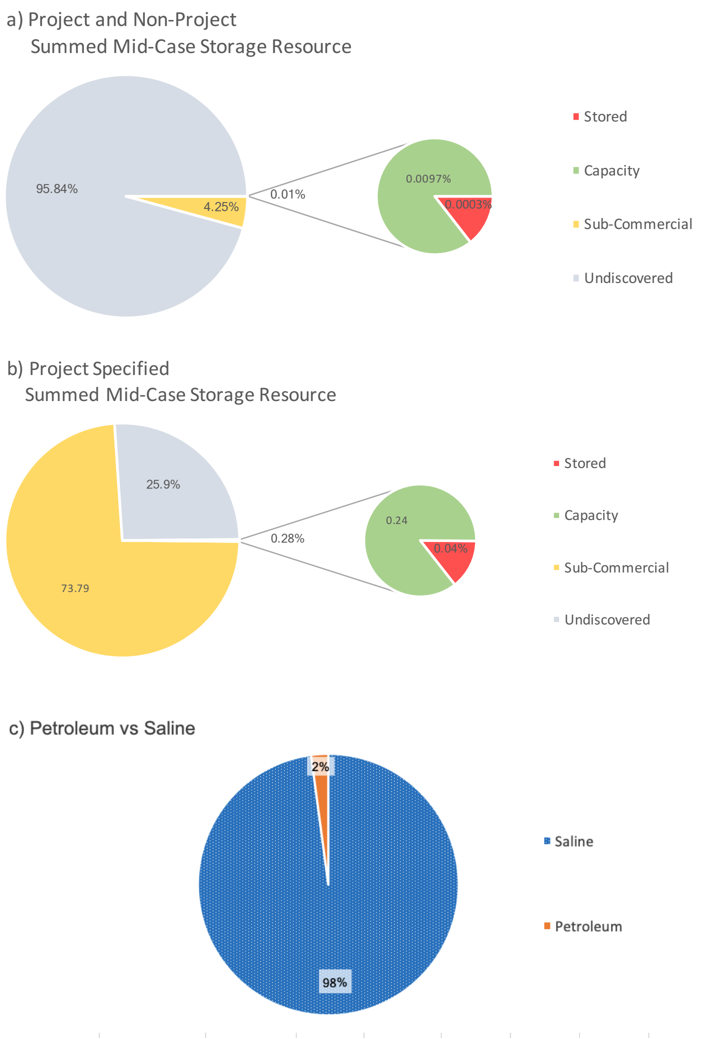

Figure 4-1: a) Spread of global storage resource across SRMS classifications, both project specified and not. b) Spread of global storage resource across SRMS classifications, where a project has been specified. c) Split of global storage resource between saline aquifers and hydrocarbon fields, both project specified and not. Note: due to the large variance in size of values, numbers in pie plots do not add up to 100.

Saline aquifers dominate the resource inventory (12,684 Gt: 98%) mainly due to the large storable quantities from national and regional-scale 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 and be flagged as carrying low confidence in the estimates.

Oil and gas fields only contribute 2% (274 Gt) of the aggregated storage resource for this assessment. Most of this resource is classed as Discovered: Inaccessible due to only Norway and the UK providing COP or EAD dates with the published reserves data and due to the lack of a regulatory framework for CO_2 storage in some other countries (e.g., Indonesia, Malaysia and Mexico).

Significant volumes of CO_2 are being injected into depleted fields for enhanced oil recovery, particularly in North America, but CO2-EOR is not currently covered by the SRMS and so was not considered in the CSRC.

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 five 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.

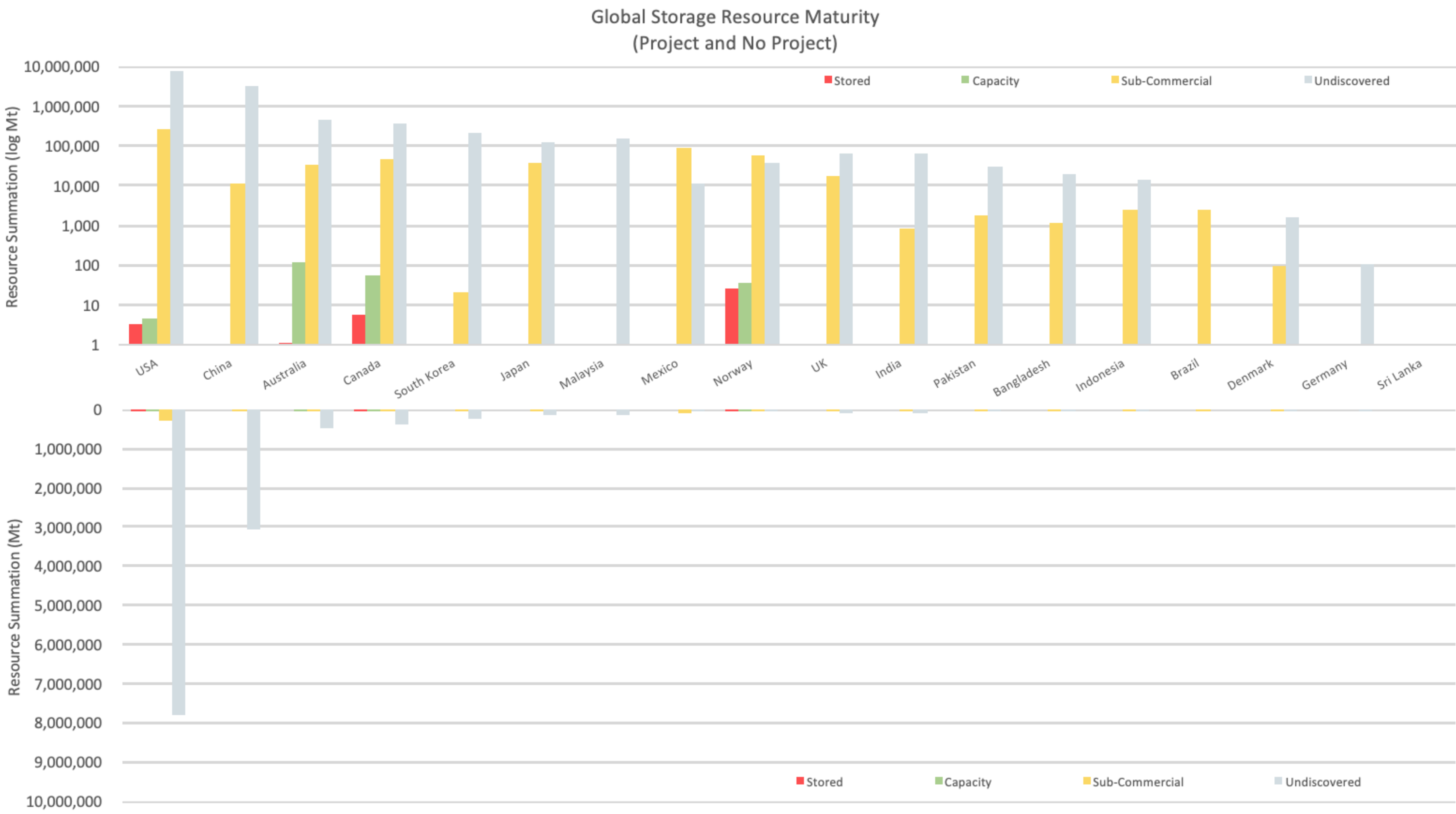

Figure 4-2 Storage resource summary for the countries assessed in the CSRC, both project specified and not.

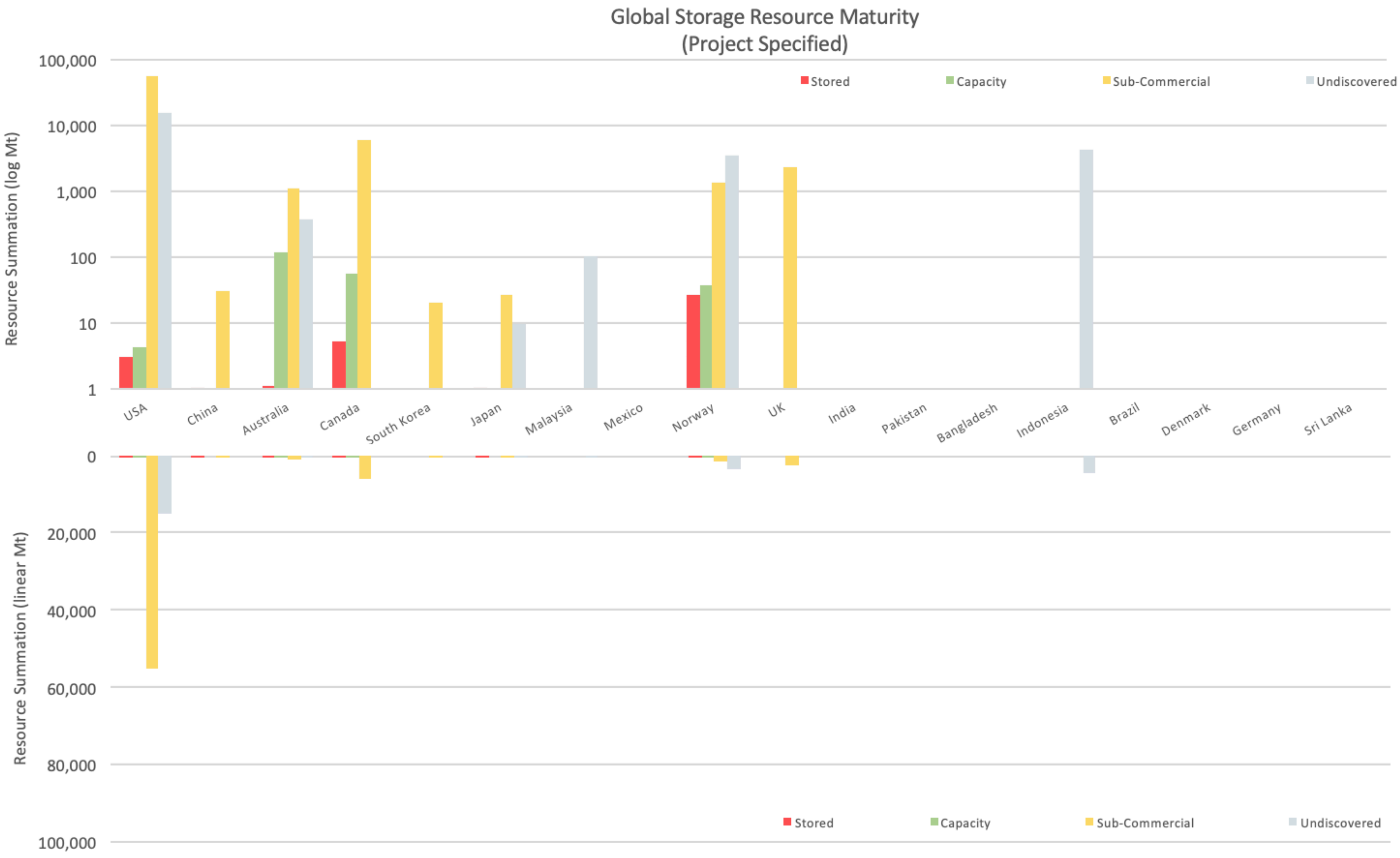

Figure 4-3: Storage resource summary for the countries assessed in the CSRC, project specified only.

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 three key areas:

1. A lack of detail reported and depth of the evaluation.
2. A lack of consistency in the approach to resource estimation
3. A lack of established CCS regulatory framework

Detail and depth of evaluation

Many countries, even those seen to be advancing CCS (e.g., USA and Japan), are dominated by high level, data-light, published resource estimates due to the huge geographic areas to be covered. Often the currently available resource estimates may be 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 (e.g., India). This frequent reporting of only a single resource estimate, which is sometimes described as a 'high' estimate (e.g., Australia Bowen and Surat basins) means that the CSRC suffers from a lack of probabilistic analysis, as most studies do not provide a range of estimates of storage resource. An additional issue lies with active CCS projects where the reported storage resource value is the permitted value for the operation, not the simulated storage resource, resulting in an under-representation of the 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.

Consistency of reporting

As discussed in Section 3.5 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. A consistent and benchmarked methodology is essential for maintaining a balanced overview of available potential resources in a region.

Only 10% of the 715 sites in the CSRC are defined projects (n= 72) and only 10% 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 large volumetric estimates must be questioned.

Regulatory framework

While several countries in the CSRC 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 and from a CSRC perspective, an entire country's potential storage resource could be classified as Inaccessible under the SRMS (e.g., Indonesia).

4.3 Recommendations for Evaluators

The following recommendations are suggested for Evaluators carrying out storage evaluations:

- All storage assessments should include low, medium, and high case estimates of storage resource from either deterministic or probabilistic analysis.
- 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.
- Where possible, high quality maps should be included with any evaluation to enhance the accuracy of site locations in the CSRC.

4.4 Recommendations for Assessors

The following recommendations are suggested for Assessors for future cycles and updates to the CSRC:

- Active projects should be re-assessed in each assessment cycle to monitor the progression of the project.
- Countries which are at risk of significant under-statement of commercial maturity should be considered for on-going assessment in future. Several countries assessed during Cycles 1 and 2 report large resource estimates assigned at the basin level with little to no refinement. Where this is a result of existing data not being readily available to the public (i.e., Japan 'Mission 2' data; see Appendix for details), efforts should be made to gain access to the data. In the USA, a large data resource sits with the Regional Partnerships and should be accessed to help refine and mature storage resource potential. In addition, the US DOE Carbon SAFE projects should be added to the database as information becomes more readily available.
- A decision should be made, with guidance from the OGCI SWG, for how to handle projects that undertake CO_2-EOR, but also store the CO_2 afterwards.

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Note: An extended bibliography (CSRC Extended Bibliography), containing all publications reviewed by this project is available to accompany this report.

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6.0 Appendix A – Country Assessments

6.1 Australia

6.1.1 Summary

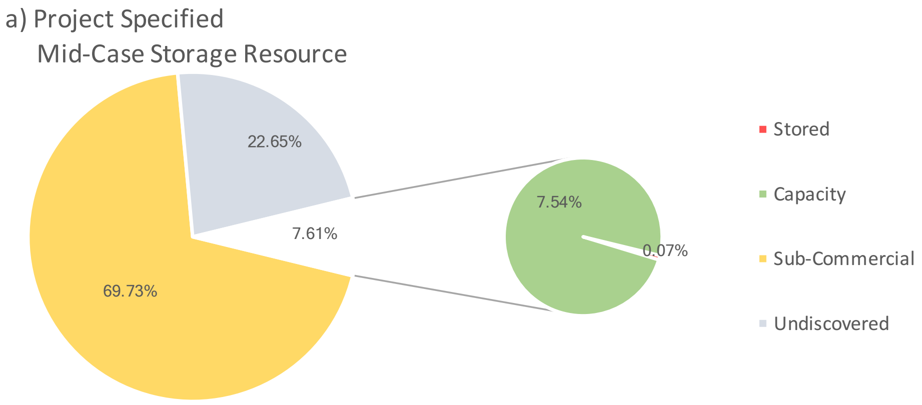
Australia was assessed during Cycle 1 and updated during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for Australia as follows:

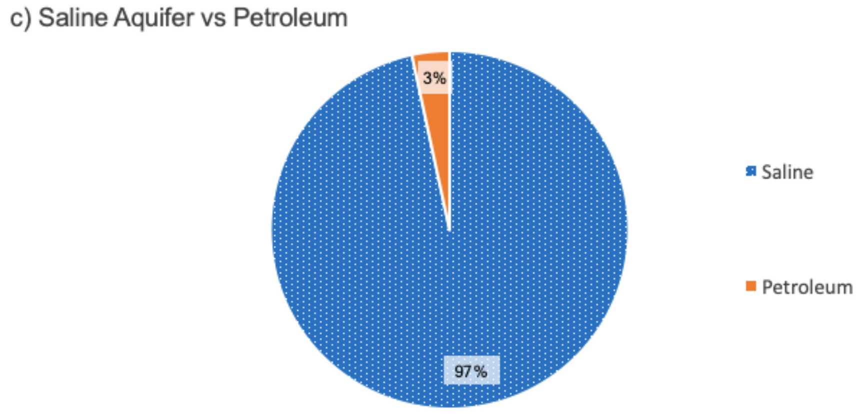
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.001	0.001
Capacity	0.12	0.12
Sub-Commercial	31.4	1.11
Undiscovered	471.0	0.36
Aggregated*	502.4	1.59

* 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. Storage resource classification summary for Australia

- There are currently 69 sites at both a local and regional scale, located across a minimum of 14 basins, both onshore and offshore. 13 of these evaluations have a project defined.
- As of February 2021, over 1.8 Mt of CO_2 has been injected to deep geological storage. 1 Mt (published data) in the Chevron-operated Gorgon project and 0.8 Mt in the CO_2CRC 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.





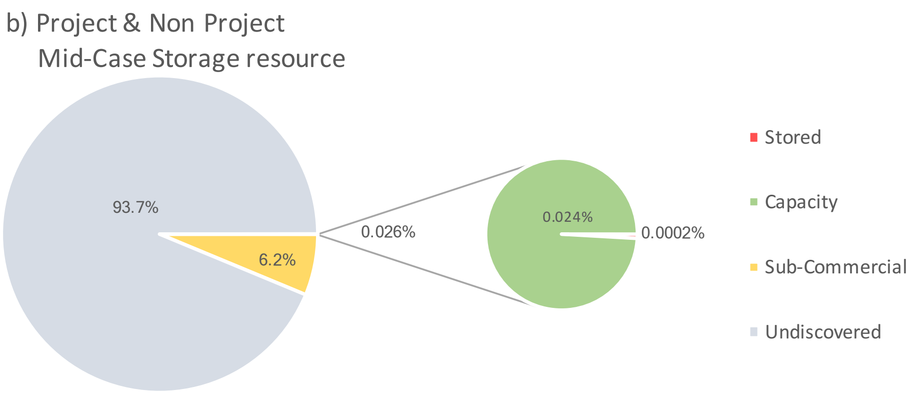


Figure 6-1. a) Spread of storage resource in Australian sites (69) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Australian sites across SRMS classifications; both project specified and not. c) Split of Australian storage resource between saline aquifers and hydrocarbon fields, both project specified and not. Note: due to the large variance in size of values, numbers in pie plots do not add up to 100.

6.1.2 Resource Statement

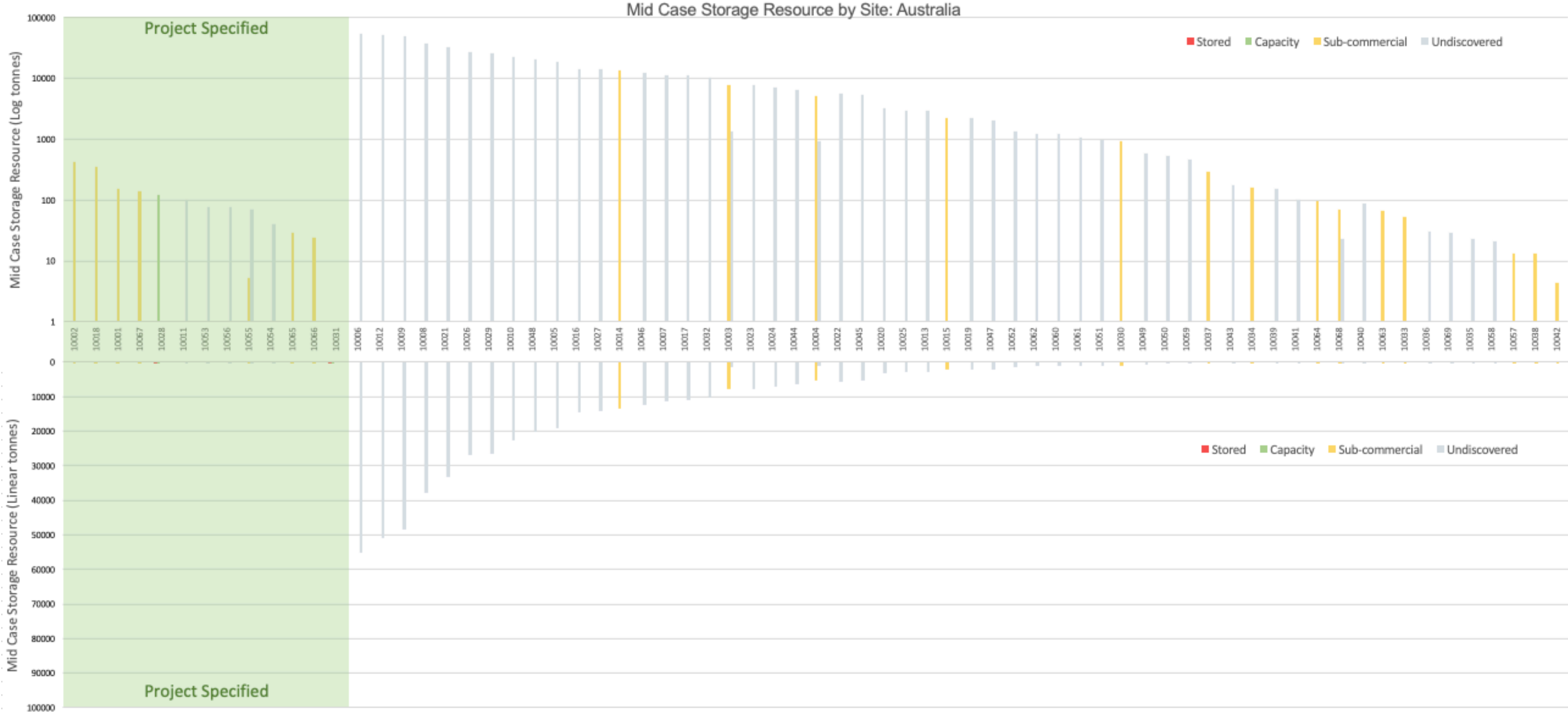


Figure 6-2. Storage resource summary for Australia compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double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

6.1.3 Evaluation History

The potential CO_2 storage resources of Australia were initially 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 [8]. 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 concluded 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 [9]. The Taskforce is composed of members from key industry sectors and Governments 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 [10] [11]. 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.

The storage resource potential for Australia was updated in Cycle 2. Cycle 1 data was a limited update of the Cycle 0 dataset which was used to test the SRMS classification process and create the initial version of the CSRC. As much of the data included in this early version was from country-wide and regional basin scale evaluations dated from the Geodisc 2003 [7] and the National Carbon Storage Taskforce 2009 [9] studies, much of the original data have been superseded by studies carried out in the subsequent decade.

The major changes to the resource entries and classification are:

- Refinement of the ‘undiscovered’ resource in eight basins resulting in a re-classification of 49% of the Basin Play resource to Sequence Play and Lead most of this data was published in Bradshaw et al [12].
- Overall, 40 new sites have been added to the Catalogue, ranging from Sequence Play to Development Unclarified on the SRMS classification. This includes six sites which changed classification and six new Projects.
- 15 new Sub-commercial (Discovered) sites (10 new saline aquifer sites and five new depleted fields).
- Most sites sit within the onshore basins (Bowen, Eromanga, Surat, Galilee, and Perth basins, including depleted fields in Queensland), with the Gippsland, Browse and Bonaparte basins containing offshore potential opportunities.
- Volumes of Stored CO_2 have been updated at the Otway facility and at the large-scale, commercial Gorgon project.

Cycle 2 updated the resource review of Australia using the detailed evaluations of the Queensland-based Zerogen project which looked at storage potential in the Bowen and Surat basins, and the Wandoan project which also evaluated the Surat Basin [13]. Additional studies also evaluated the Eromanga Cooper and Galilee basins. In the North West Shelf area, evaluations of the opportunities in the saline aquifers of the Browse and Bonaparte basins offer potential support for the development of the high CO_2 gas field sin that area. The SW Hub project has evolved over the past decade and provides refinement of the Perth Basin area resource potential. Resource potential of the onshore and offshore Gippsland Basin and Otway Basin was also updated.

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 CO_2CRC 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 [14].

The Otway Research Facility was established in 2008 by the Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC) 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 [15].

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

The Global CCS Institute has provided updates on several CCS projects in Australia [16]:

- The Cooper Basin Project has commenced FEED for the 1.7 Mtpa CCS project taking CO2 produced from the Moomba natural gas processing plant to depleted hydrocarbon fields (via a 50 km pipeline) for storage.
- The Carbon Transport and Storage Company (CTSCo) is planning a demonstration project capturing up to 120,000 T/y CO_2 from a coal-fired power station with storage in the Surat Basin.
- The CarbonNet project (Victoria) has completed appraisal drilling and is developing plans with stakeholders for commercialisation in the future.

6.1.4.2 *Depleted Oil & Gas Fields*

The CST [9] 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 [9] 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 CSRC Cycle 1.

6.1.4.3 *Saline Aquifers*

The saline aquifer resource comprises the largest proportion of potential storage resource in Australia. The majority, 485 Gt of this resource lies at the 'Undiscovered Basin Play' level as no formation has been specified for many of the basin-level evaluations [9]. 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 [11], [10].

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 CO_2CRC 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 [17]. In 2020 the Offshore Petroleum and Greenhouse Storage Act 2006 (OPGGSA) was updated to allow cross-boundary CO2 injection (i.e., between Commonwealth and state/Territory jurisdictions; [16]. 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 [9].

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 [18]. [16].

6.1.6 Issues for the 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 [9] and later studies that considers injection on a local scale into the basins [11] [10]. 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 [1].

6.1.7 Future Updates

6.1.7.1 *Future evaluations*

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

The Baltic region was assessed during Cycle 1 and was not updated during Cycle 2 (Table 2-1). During the Cycle 1 assessment, a series of Triassic age closures in the western Baltic region were reviewed from a GHGT-12 publication [19]. 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 CSRC 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	1.535	0
Aggregated*	1.628	0

Germany

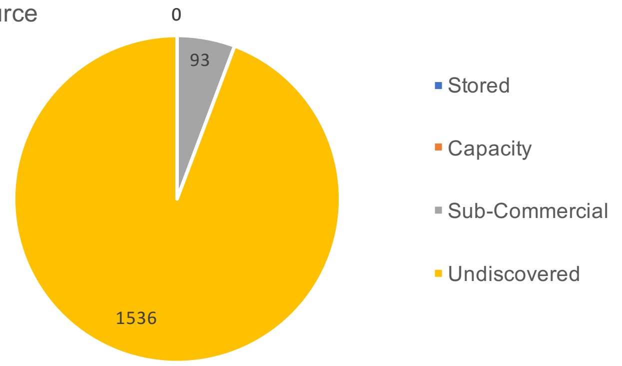
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0	0
Capacity	0	0
Sub-Commercial	0	0
Undiscovered	0.11	0
Aggregated*	0.11	0

* 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.

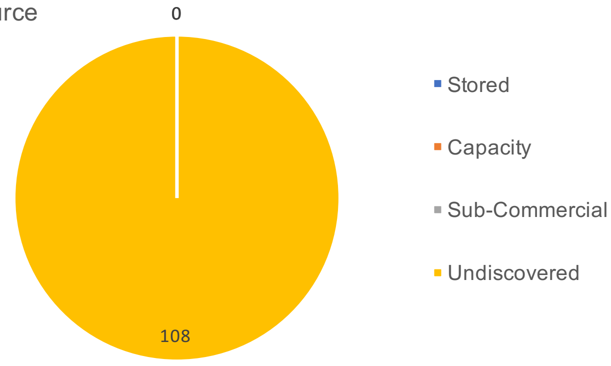
Table 6-2. Storage resource classification summary for Baltic Region (Denmark & Germany)

- The published evaluations identified 13 closures of Triassic Bunter Sandstone in the North West German Basin; 12 sit within in Denmark and one in Germany.
- The aggregated storage potential for the Baltic region is 1.74 Gt (1.628 Gt for Denmark and 0.11 Gt for Germany) and is entirely held within saline aquifers within closed structures. These are classified mostly as Undiscovered Prospective Resource.
- No projects are defined.

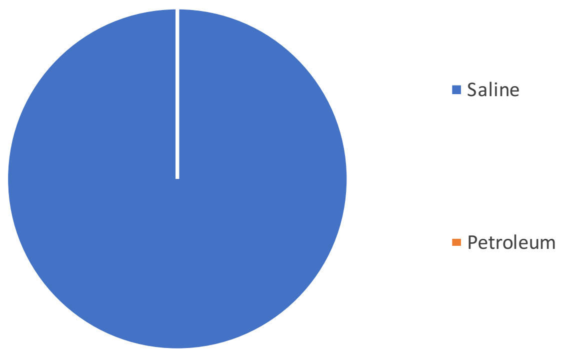
a) **Denmark** Project and Non-Project
Mid-Case Storage Resource



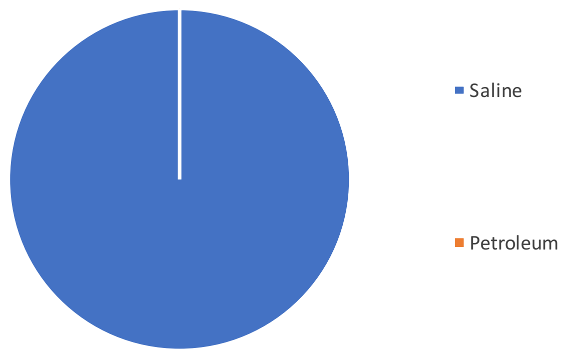
a) **Germany** Project and Non-Project
Mid-Case Storage Resource



b) **Denmark** Saline vs Petroleum



b) **Germany** Saline vs Petroleum



*Note: None of the Baltic sites have an associated project specified.

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

6.2.2 Resource Statement

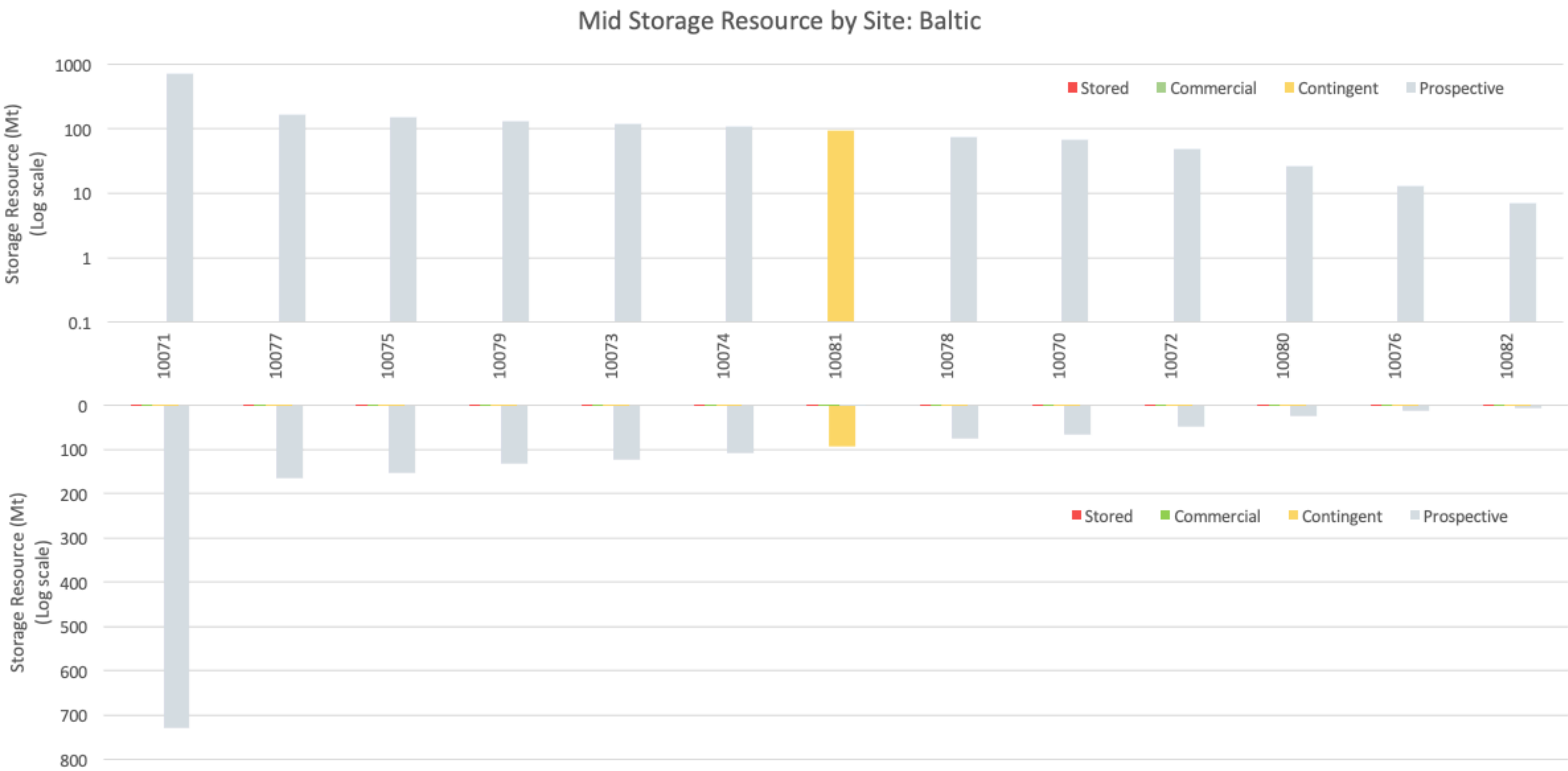


Figure 6-4. Storage resource summary for Baltic region compiled in the CSRC. Graph above is log scale and graph below is linear. Projects were not specificed for any of these sites. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double counting.

6.2.2 Evaluation History

The storage resources of the Baltic region were reviewed, and a preliminary assessment carried out, during the CSRC Cycle 1. The basis of the assessment is a screening study which evaluates sites in the Southern North Sea and Southwest Baltic Sea areas [19]. This document is based on petroleum research project called Petrobaltic, which 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.

6.2.3 Resource Review

6.2.3.1 *Major Projects*

No active or developing carbon storage projects have been assessed.

6.2.3.2 *Depleted Oil & Gas Fields*

No depleted oil and gas fields have been considered.

6.2.3.3 *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.

6.2.4 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 shift in 2019 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.

6.2.5 Issues for the 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.

6.2.6 Future Updates

6.2.6.1 *Future CSRC cycles*

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

6.3 Bangladesh, India, Pakistan, and Sri Lanka

6.3.1 Summary

Bangladesh, India, Pakistan and Sri Lanka were assessed during Cycle 1 and were not updated during Cycle 2 (Table 2-1). The CSRC 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

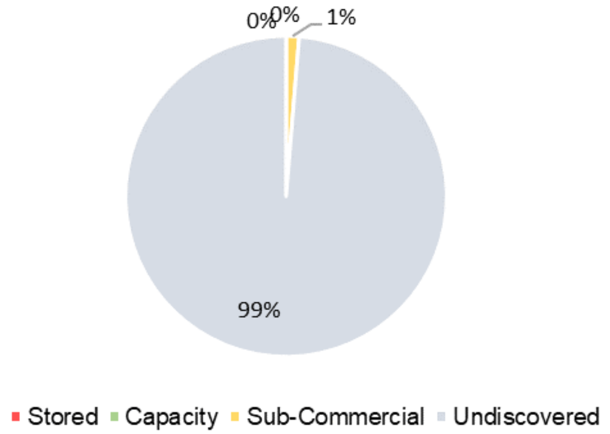
* The aggregated resource represents the summed storage resource across all maturity classes and as such should not be viewed as representative of the potential of the country.

Table 6-3. Storage resource classification summary for Bangladesh, India and Pakistan

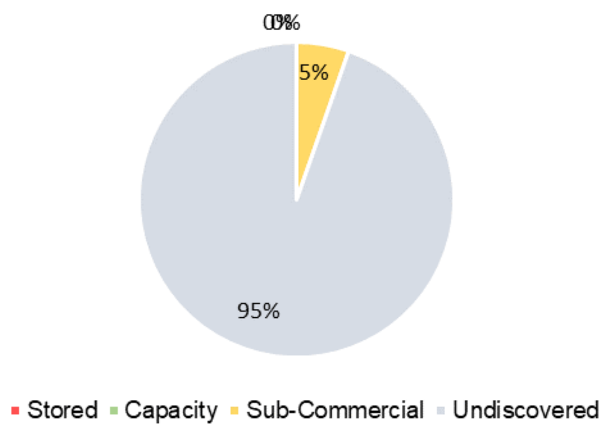
- Bangladesh has 23 sites in the CSRC: 1 saline aquifer (Undiscovered; 20.0 Gt) and 22 gas fields (Discovered; 1.13 Gt).

- India has 15 sites in the CSRC: 11 saline aquifers (Undiscovered; 63.3 Gt) and 4 oil and gas fields (Discovered; 0.84 Gt)
- Pakistan has 17 sites in the CSRC: 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 countries. No projects are defined.
- There are no defined storage projects in the region.

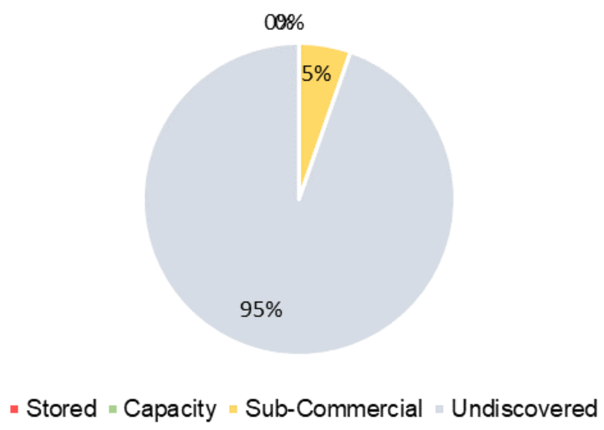
India: Non Project* Mid-Case Storage Resource



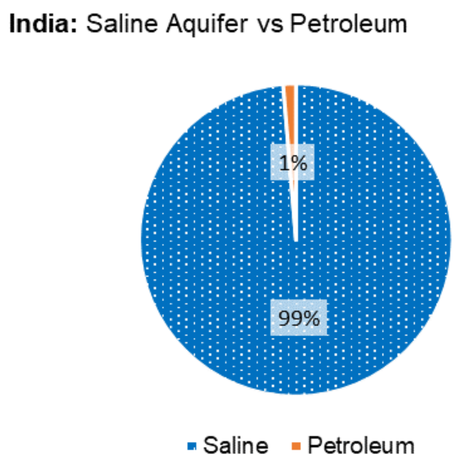
Pakistan: Non-Project* Mid-Case Storage Resource

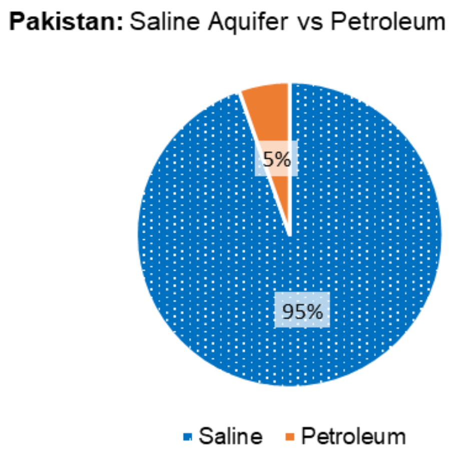


Bangladesh: Non-Project* Mid-Case Storage Resource



**Note: No sites with a project specified were identified for India, Pakistan and Bangladesh.*





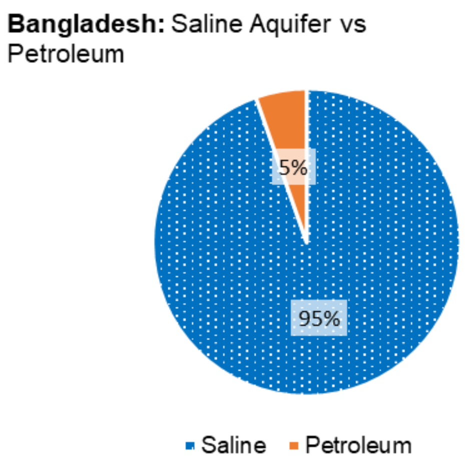


Figure 6-5. Above: Spread of all storage resource across SRMS classifications. Below: Split of storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.3.2 Resource Statement

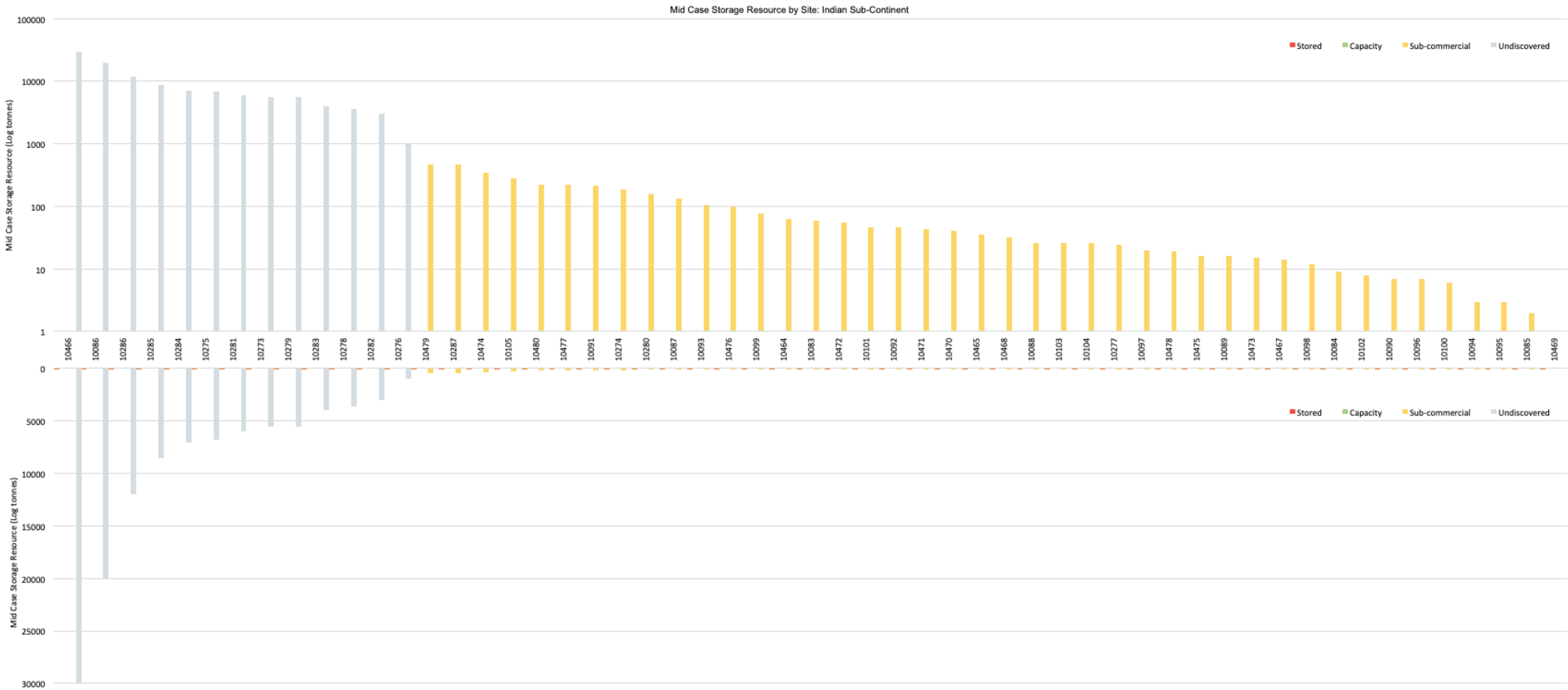


Figure 6-6. Storage resource summary for India, Bangladesh and Pakistan compiled in the CSRC. Graph above is log scale and graph below is linear. No project specified sites were identified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.3.3 Evaluation History

Bangladesh, India, and Pakistan underwent a preliminary assessment as part of the CSRC Cycle 1. 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 [20]. 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 were 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 BGS evaluation used the replacement method for calculating storage resource for 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 CO_2 storage resource potential could be estimated using the following assumptions:

4. “That one or more deep saline aquifers suitable for CO_2 storage were present over 50% of the basin.”
5. “0.2×10^6 tonnes CO_2 could be stored per km^2 of the area above.”

This equates the CO_2 storage resource potential in Mt as 10% of the basin area in square kilometres.

6.3.4 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.

6.3.5 Regulatory Framework

None of the countries in this region 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.

6.3.6 Issues for the 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.

6.3.7 Future Updates

6.3.7.1 *Future CSRC cycles*

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

6.4 Brazil

6.4.1 Summary

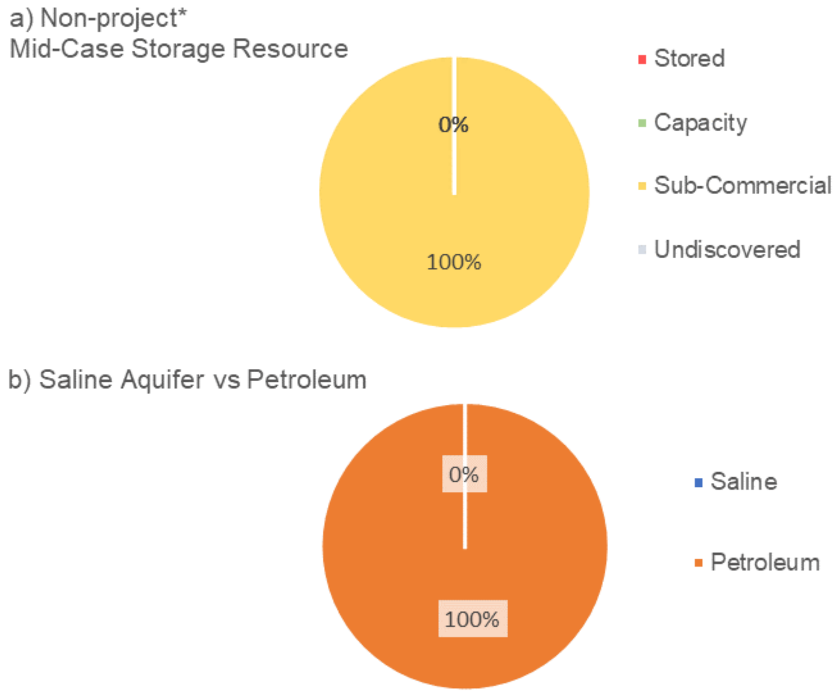
Brazil was assessed during Cycle 1 and was not updated during Cycle 2 (Table 2-1). The CSRC identified a CO_2 storage resource for Brazil as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 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 6-4. Storage resource classification summary for Brazil

- The aggregated storage potential in Brazil is 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 CSRC has identified 17 oil and gas fields in the Campos Basin with a storage potential evaluation, plus the summed evaluation of hydrocarbon fields in a further 10 geological basins.



*Note: None of the Brazilian sites have an associated project specified.

Figure 6-7. a) Spread of storage resource in all Brazilian sites (28) across SRMS classifications. b) Split of Brazilian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.4.2 Resource Statement

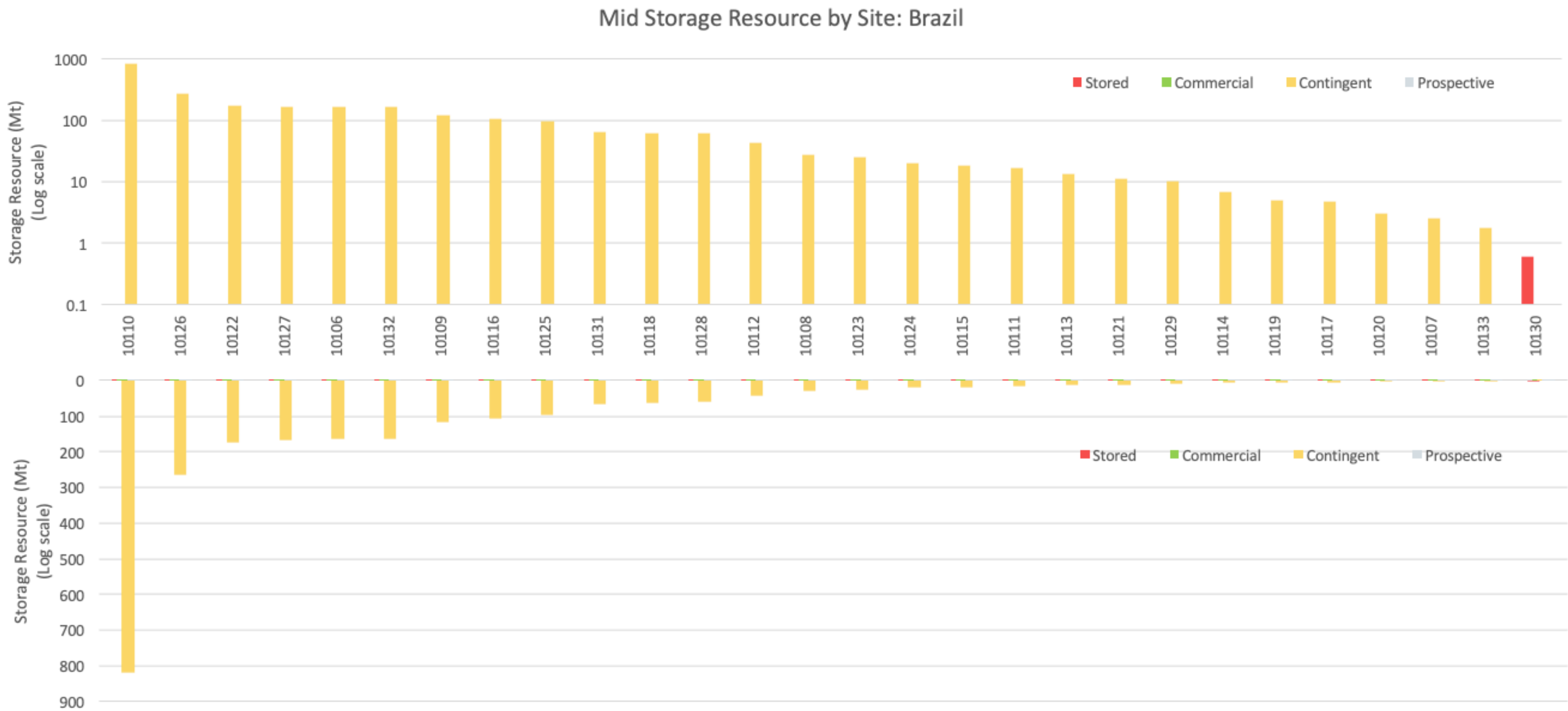


Figure 6-8. Storage resource summary for Brazil compiled in the CSRC. Graph above is log scale and graph below is linear. No project specified sites were identified. Where possible the data have undergone due diligence checks, identifying potential repeat entries to avoid double counting..

6.4.3 Evaluation History

Brazil's storage resources were reviewed, and a preliminary assessment carried out, during Cycle 1. The assessment draws from three documents which currently provide the only information on CO_2 storage resource potential in Brazil.

The first 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 Brazilian Atlas evaluated the storage potential in oil and gas fields, both onshore and offshore, however quantitative evaluations were only available for fields in the Campos Basin. In addition, coalfields and basalts were evaluated but do not form part of this assessment [21].

The second is the Brazilian Carbon Geological Sequestration Map (CARBMAP) Project [22], an effort to create a geographic information system (GIS) to facilitate matching of CO_2 sources and sinks. Here the storage potential of Brazilian oil and gas fields in 11 basins was evaluated using the hydrocarbon reserve volumes.

The final source, published in 2013, evaluated the storage potential in 17 of approximately 50 hydrocarbon fields in the Campos Basin, using a voidage replacement method by Bachu et al (2007) [23].

6.4.4 Resource Review

6.4.4.1 *Major Projects*

No major carbon storage projects were identified that could be assessed against the SRMS, during Cycle 1. 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.

6.4.4.2 *Depleted Oil & Gas Fields*

The Campos region potential storage resource is estimated to be 0.95 Gt [23] 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 CARBMAP Project identified a further 1.52 Gt in hydrocarbon fields across Campos and a further 10 basins [22].

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. For example, in the Reconcavo Basin, a CO_2 storage pilot project, 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 [21].

6.4.4.3 *Saline Aquifers*

The CSRC 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 [24].

6.4.5 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 was issued in 2007 and identifies CCS technology as one of the tools to reduce CO_2 emissions from fossil fuels. 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.

6.4.6 Issues for the 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 due to the lack of saline aquifer storage resource, and as such, the CSRC is significantly incomplete with regards to the classification.

6.4.7 Future Updates

6.4.7.1 *Future evaluations*

Future evaluations should focus on the potential for saline aquifer storage which is likely to be significant but is not represented currently in the CSRC. As the Pre-salt operations develop in the Campos and Santos offshore basins, additional resource potential may be identified.

6.5 Canada

6.5.1 Summary

The CSRC has identified the following CO_2 storage resource for Canada. It has been updated in Cycle 2 to reflect continued injection of CO_2 in active projects.:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.005	0.005
Capacity	0.056	0.056
Sub-Commercial	43.6	6.2
Undiscovered	360.3	0
Aggregated*	404	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 6-5. 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 67 sites or regional locations identified. Altogether, 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 March 2021, 5.33 Mt of CO_2 has been reported injected and stored by two CCS projects operating in Canada: Quest (5 Mt) and Aquistore (0.33 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 exists with the Alberta Trunk Line (ACTL) CO_2 pipeline project. This 240km pipeline, capable of transporting up to 14.6 Mt CO_2/annum across Alberta, became operational in June 2020.

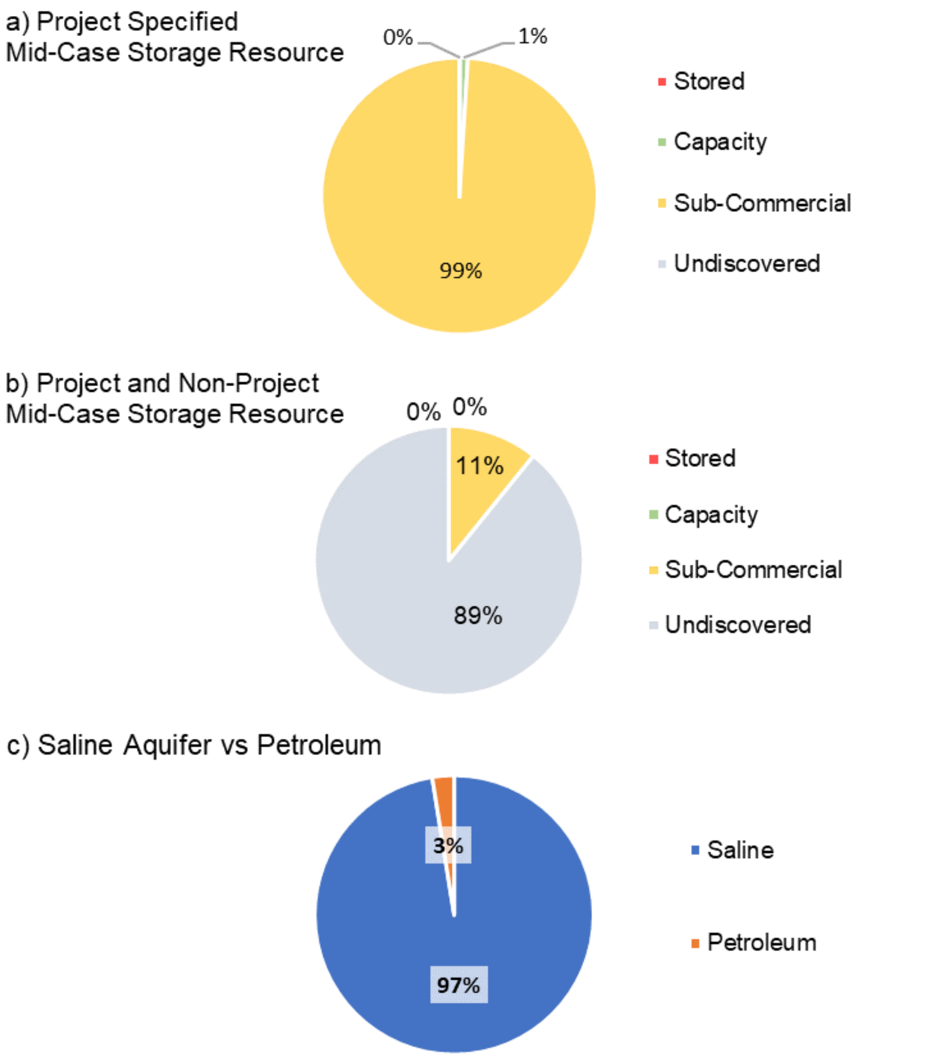


Figure 6-9. a) Spread of storage resource in Canadian sites (67) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Canadian sites across SRMS classifications; both project specified and not. c) Split of Canadian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.5.2 Resource Statement

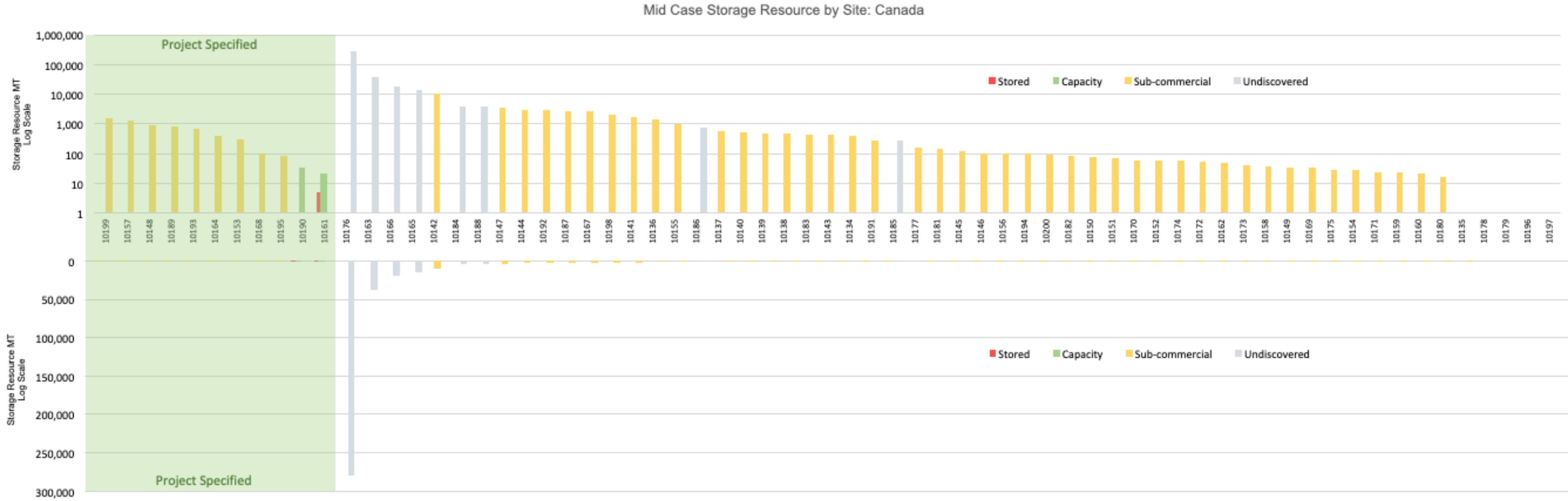


Figure 6-10. Storage resource summary for Canada compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.5.3 Evaluation History

Canada was selected as the priority country for review during the Cycle 1 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 [25] and the 2015 DOE Atlas V [26] 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.

6.5.4 Resource Review

6.5.4.1 *Major Projects*

In 2006, Canada's National Round Table on the Environment and Energy, 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. 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 Cycle 2 Assessment, only the Quest CCS project (5 Mt by mid-2020) and the Aquistore project (325,000t by October 2020), 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. 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 Cycle 1 assessment.

6.5.4.2 *Application of the SRMS in North America*

North America raises some of the issues discussed in Section 3.5, which are particular to both Canada and the USA. National atlases [26] and [25] 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 Cycle 1 used the 2015 DOE Atlas V [26] resource estimates in preference to the earlier 2012 NASCA [25] 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 CSRC Cycle 1 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).

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 CSRC Cycle 1 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 [27], a more recent study [28] 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.

6.5.4.3 *Depleted Oil & Gas Fields*

The aggregated depleted field resource identified by the Cycle 1 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 [25] 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 Cycle 1 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 Cycle 1 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 CO_2. 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 [29], 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).

6.5.4.4 *Saline Aquifers*

Most of the saline aquifer resource (3 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 its 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 Cycle 1 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.

6.5.5 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.

6.5.6 Issues for the Assessment

6.5.6.1 *Data Validation*

While the 2012 NASCA [25]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.

6.5.6.2 *Probabilistic Assessments*

The data available for the Cycle 1 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.

6.5.6.3 *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 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 [26]. 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).

6.5.6.4 *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.

6.5.6.5 *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.

6.5.7 Future Updates

6.5.7.1 *Future CSRC cycles*

Required updates in future Assessment cycles 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.

6.6 China

6.6.1 Summary

China was assessed during Cycle 1 and was not updated during Cycle 2 (Table 2-1). The CSRC 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	10.5	0.03
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 6-6. Storage resource classification summary for China

- There is a total of 72 sites in the CSRC, 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.

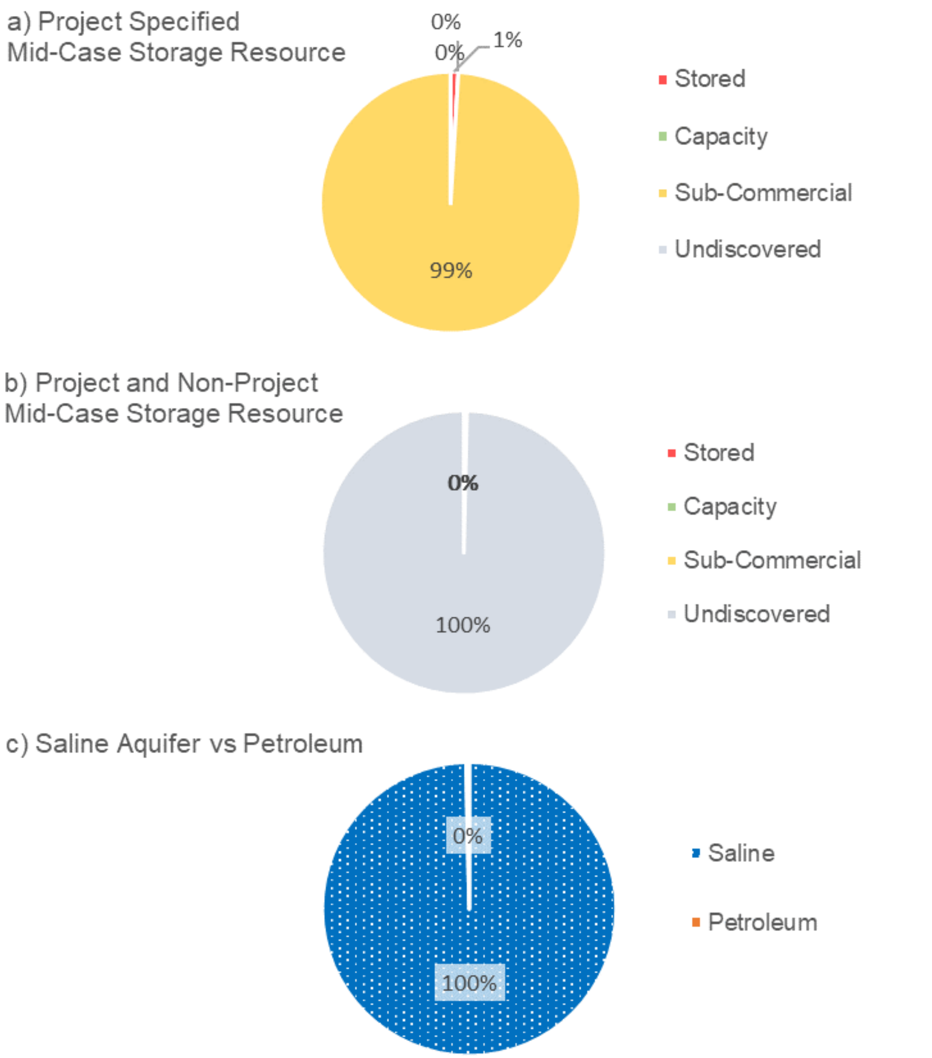


Figure 6-11. a) Spread of storage resource in Chinese sites (72) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Chinese sites across SRMS classifications; both project specified and not. c) Split of Chinese storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.6.2 Resource Statement

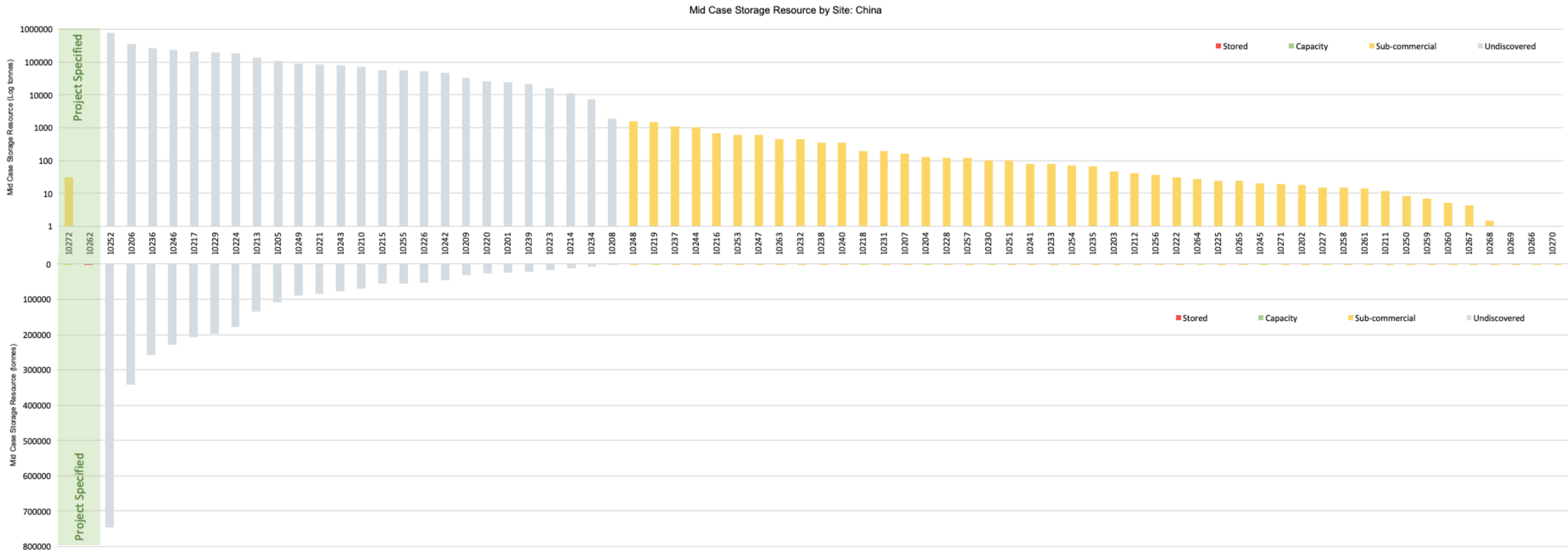


Figure 6-12. Storage resource summary for China compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.6.3 Evaluation History

The regional evaluation by the Pacific Northwest National Laboratory in 2009 [30], 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 leg.

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.

The PNNL reported volumes are supplemented by the stored volume at the Shenhua Group CCS Demonstration project [31], plus theoretical storage resource evaluations for hydrocarbon fields within the Dagang oilfield complex [32].

6.6.4 Resource Review

6.6.4.1 *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 the CSRC 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 MtCO_2/yr 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.

6.6.4.2 *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. Evaluations for dedicated geological CO_2 storage within oilfields, 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 6.6.3.

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 [30], however, the resource was classified as “Development Not Viable” as CO_2 injection for EOR can take place under existing petroleum regulatory systems.

6.6.4.3 *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 the CSRC of 3067 Gt [30]. 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 [31], while 31.4 Mt is classified as Discovered Inaccessible [33], due to the lack of a CCS-specific regulatory system in China. The evaluation by [33], 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 CSRC 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.

6.6.5 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 [17].

6.6.6 Issues for the 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 6.6.3. Indeed, due to these complications, EOR studies are out of the scope for the CSRC, however the values from the PNNL report were included, in the absence of other significant estimations.

6.6.7 Future Updates

6.6.7.1 *Future evaluations*

Further work for evaluators 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.

6.6.7.2 *Future CSRC cycles*

In the 2018 GCCSI review of Chinese decarbonisation facilities [34], 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 [35] 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 to the CSRC.

A critique is provided in [36], on the status of CCUS policy in China in a recent paper, which could also be include

6.7 Indonesia

6.7.1 Summary

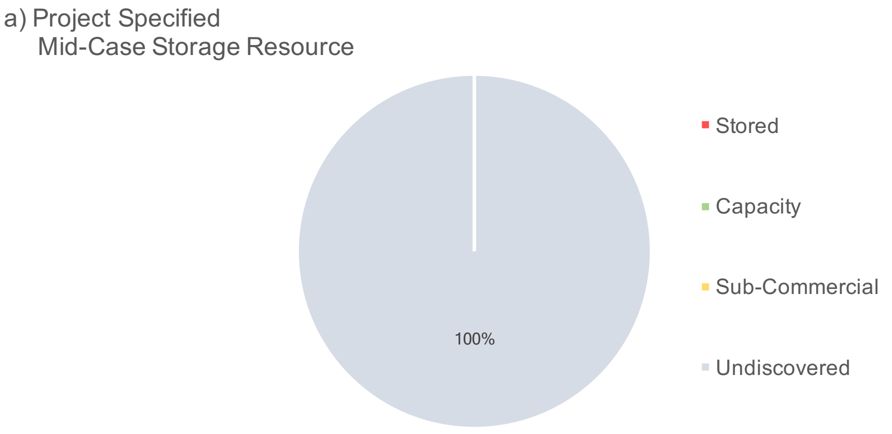
Indonesia was assessed during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for Indonesia as follows:

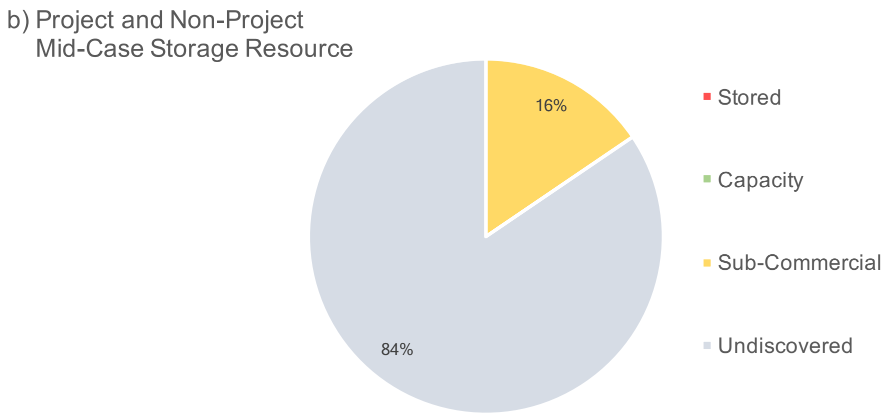
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.00	0.00
Capacity	0.00	0.00
Sub-Commercial	2.46	0.00
Undiscovered	13.40	4.39
Aggregated*	15.85	4.39

* 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: Storage resource classification summary for Indonesia.

- Storage resource potential (33 sites) is present in both saline aquifers and oil and gas fields, with saline aquifers accounting for 84% of Indonesia's storage resource. Six sites are considered 'projects'.
- Potential storage resource has been identified in 11 sedimentary basins, with published oil and gas storage resource available for seven basins.
- Due to the lack of regulatory framework for CCS, all storage resource for Indonesia is classified as *Inaccessible* under the SRMS.
- The only discovered resource for Indonesia is in oil and gas fields.
- One known pilot project, the Gundih CCS Pilot, has support through state research and development funding and from the state-owned company Pertamina. It is yet to undergo the design and construction phase. This shows that the government clearly has an interest in potentially growing the CCS industry.
- Indonesia has several high CO_2 gas fields, many of which were studied in the CO_2CRC (2010) [6] report, with their associated saline aquifers proposed for CO_2 injection sites. Please see Section 2.5 for a discussion on high CO_2 fields.





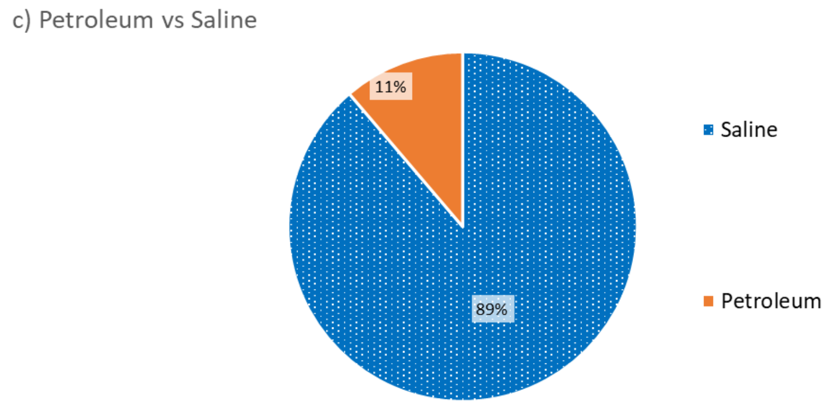


Figure 6-13: a) Spread of storage resource in Indonesia. Sites (33) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Indonesia. sites across SRMS classifications; both project specified and not. c) Split of Indonesia storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.7.2 Resource Statement

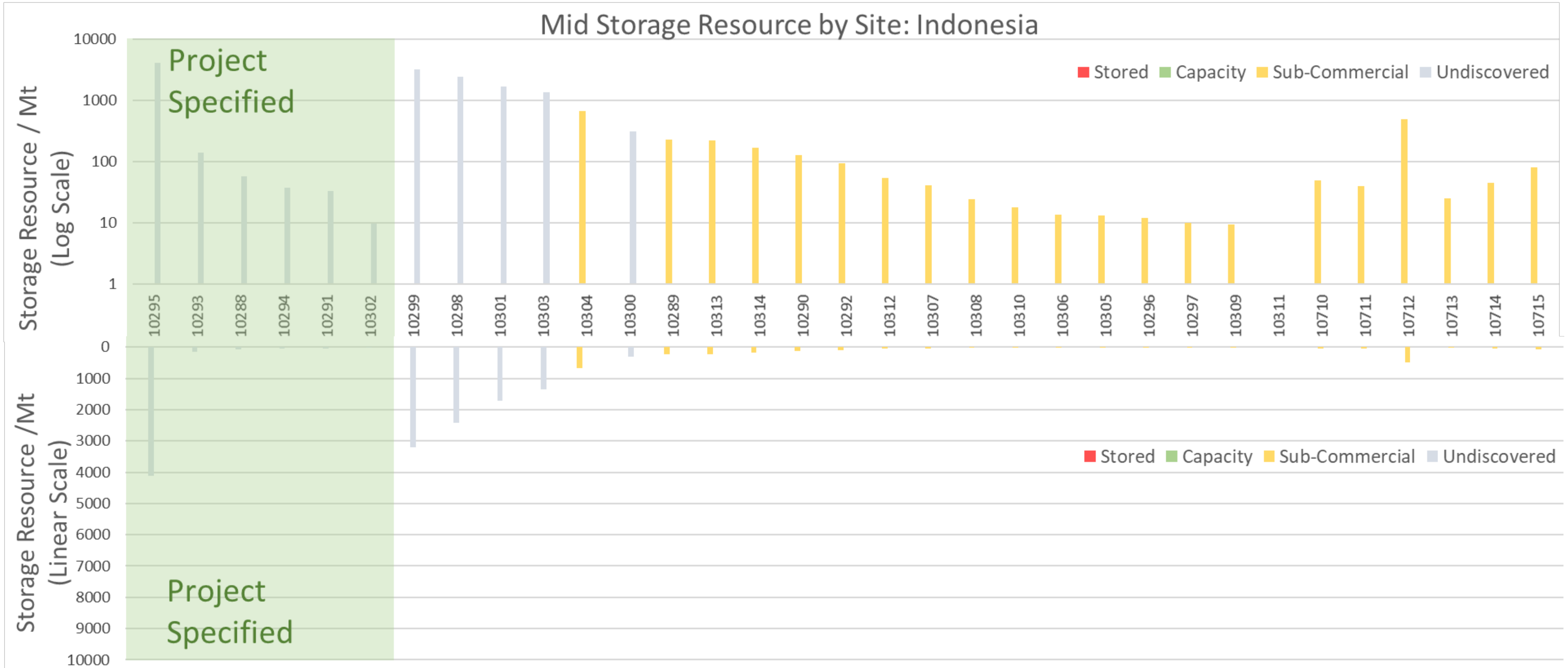


Figure 6-14: Storage resource summary for Indonesia compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.7.3 7.7.1 Evaluation History

The Cycle 2 storage resource assessment was based on five papers: Hedriana et al (2017) [37], World Bank (2015) [38], Iskandar et al (2013) [39], Asian Development Bank (2013) [40] and CO_2CRC (2010) [6]. All additional papers that were reviewed either provided no storage resource value, had been superseded by later studies, were based on CO_2-EOR or referred to the Gundih CCS Pilot, which is not included as a site in the CSRC as it is below the minimum threshold of 10 Mt.

Hedriana et al (2017) [37] built on the World Bank (2015) [38] study and both used equivalent approaches for calculating saline aquifer resource. The Hedriana et al (2017) [37] paper is more recent and uses a more realistic value for storage efficiency factor, therefore the saline aquifer resource from this paper was used in the CSRC.

The Asian Development Bank (2013) [40] report looked at a broad range of gas field resources in South Sumatra, which were split down to individual fields with attached resource numbers, and locations shown on a map. The World Bank (2015) [38] paper also includes a list of gas field resources in South Sumatra. The individual gas fields identified in the report have different names and resource numbers than the Asian Development Bank (2013) [40] report and do not appear to be duplicates so are included in the CSRC.

The CO_2CRC (2010) study for the Asia-Pacific Economic Cooperation [6] looked at high CO_2 gas fields and produced development plans for the saline aquifers associated with these fields. The resource values were included in the CSRC as projects.

6.7.4 Resource Review

6.7.4.1 *Introduction*

Indonesia has 11 sedimentary basins which have been identified (to date) as having storage potential and are included in the CSRC. Basin-wide saline aquifer resource data is available for the larger South Sumatra and West Java Basins, and smaller Bintuni, East Natuna, South and North Sumatra, and Kutai basins. Published data for depleted oil and gas storage is available for seven of Indonesia's sedimentary basins. Saline aquifers account for the majority (84%) of Indonesia's resource.

6.7.4.2 *Pilot Projects*

The only known pilot project in Indonesia is the Gundih CCS Pilot located in Blora district, Central Java province. Key players include Indonesia's state-owned oil and gas company Pertamina, the Ministry of Energy and Mineral Resources and the Asian Development Bank among others. The development plan is to capture CO_2 from the Gundih gas field and inject this into an uneconomic oil field at a rate of 30 tonnes per day. A total of 20 kt is to be injected during the two years of the project. According to the Global CCS Institute's database for pilot plants [5], the design and construction phase of the project is due to begin by the early 2020s.

6.7.4.3 *Depleted Oil & Gas Fields*

The only discovered storage resource in Indonesia are depleted oil and gas fields. The data coverage ranges from resources associated with individual fields to cumulative resources for entire basins. The South Sumatra Basin has resource values for 13 individual gas fields, which could be located on a map. The total resource between all 13 fields is 875 Mt, which is greater than any cumulative South Sumatra data that has been assessed. All together, these fields represent 49% of the discovered resource throughout the entire country.

Resource for the West Java Basin is divided into offshore and onshore fields and totals 395 Mt, representing 22% of the discovered resource.

All other basins do not have individual field values, the only subdivisions present are between cumulative oil fields and gas fields. Other basins with depleted oil field resource are: East Kalimantan, North Sumatra, South Sumatra and Barito. Other basins with depleted gas field resource: Salawati and North East Java. All these other basins hold a total resource of 528 Mt, 29% of Indonesia's discovered resource.

All oil and gas fields are classified as discovered, but inaccessible as the country has no regulatory framework present for CCS activities.

6.7.4.4 *Saline Aquifers*

As mentioned in the introduction, Indonesia has a small range of basin-wide saline aquifer data. All basin-wide storage resources exist within the South Sumatra and West Java basins – this is because they were included in multiple studies that aimed to identify sites for storage of CO_2 emissions from coal power stations in the area. Overall, three published values for each basin-wide resource were assessed, but only the resources from Hedriana et al. (2017) [37] were included as they were most recent, and in the case of south Sumatra, the values were more refined. The other two studies considered were a 2015 study by the World Bank [38] and a 2013 study by the Asian Development Bank [40]. There is a nulled entry in the storage assessment database to represent this.

The small saline aquifer sites mentioned above are associated with nearby high CO_2 fields [6] and represent 31% of the undiscovered resource. They are spread over five basins compared to just two for basin-wide resources. It should be noted that these sequence plays were only assessed based on their potential to store CO_2 from nearby high CO_2 gas fields. Therefore, they may not be in a good location, nor have the desirable properties for injection of anthropogenic CO_2 from power stations.

All saline aquifers are classed as undiscovered and inaccessible as the country has no regulatory framework present for CCS activities. If a regulatory framework became available, these resources would be promoted to the Basin Play and Sequence play maturity classes.

6.7.5 Regulatory Framework

Although Indonesia has a petroleum industry, there are not currently any laws specific to CCS. To deploy CCS in Indonesia, a legal and regulatory framework is required, however, the Global CCS Institute's CCS Readiness Index [17] states that "Indonesia is not taking the necessary steps to advance deployment at the required rate."

Due to this lack of regulatory framework for CCS, all storage resources for Indonesia are classified as *Inaccessible* under the SRMS.

The Gundih pilot project is yet to undergo the design and construction phase, but it has support through state research and development funding and from the state-owned company Pertamina. This shows that the government clearly has an interest in potentially growing the CCS industry. The Global CCS Institute's CCS Readiness Index also ranks Indonesia within the top 5 countries for inherent CCS interest, meaning that it has a high fossil fuel dependency and therefore will need CCS projects to meet future climate goals. Currently, interest in EOR projects appears to be greater than that for storage, since they provide financial incentives. The government needs to incentivise CO_2 storage through policy and CCS-specific regulation.

6.7.6 Issues for the Assessment

6.7.6.1 *Oil and Gas Fields*

The most recent data for gas fields in South Sumatra and West Java are given as cumulative basin numbers by Hedriana et al. (2017) [37], however the data in the CSRC are from World Bank 2015 [38] and Asian Development Bank (2013) [40] as these sources presented data for individual fields that could be located on a map. Therefore, the gas field data presented here is not the most recent but is the most refined.

The depleted oilfield storage that is given by Iskander et al. (2013) [39] does represent CO_2 storage as opposed to CO_2-EOR. However, due to the high incentives for EOR activities in the region, this can't be ruled out in any of these fields.

6.7.6.2 *Saline Aquifers*

To calculate the resource for the West Java Basin saline aquifer, the methodology presented in the World Bank 2015 report [38] used volumetric data from 15 gas fields before scaling up by a factor of 3 to represent the full extent of the basin. This is a different method than that which is used to calculate resource for most other saline aquifers.

In the CO_2CRC (2010) study for APEC [6], saline aquifers associated with high CO_2 fields were the planned CO_2 injection sites, and therefore included as storage resource in the CSRC. For each of these sites, a simple simulation was conducted to determine the maximum rate of CO_2 that could be injected over the injection period without the pressure in the reservoir exceeding its fracture pressure. Sensitivities were carried out on the number of wells required. Due to the sites having development plans, they have been included as projects in the CSRC.

6.7.7 Future Updates

6.7.7.1 *Future Updates for Evaluators*

- There is good detail on storage resource for depleted gas fields within the South Sumatra Basin, however the low resolution of the map images in the reports makes the field names challenging to read. For future evaluations, providing higher resolution map images is recommended.
- In other basins out with South Sumatra, acquiring, analysing and publishing new resource data that would divide up the cumulative depleted gas and oil field resource into individual field values with an attached location would be a good next step to mature the storage resource in Indonesia.
- For the West Natuna Basin, no data was uncovered in this cycle. The Natuna gas field and associated saline aquifer storage is East of Natuna Island and so not located within the West Natuna basin.
- The only basin wide saline aquifer data assessed in this cycle came from the West Java Basin, Java Sea Basin and the South Sumatra Basin. Future assessments should look to uncover basin wide saline aquifer resource data from other basins.

6.8 Japan

6.8.1 Summary

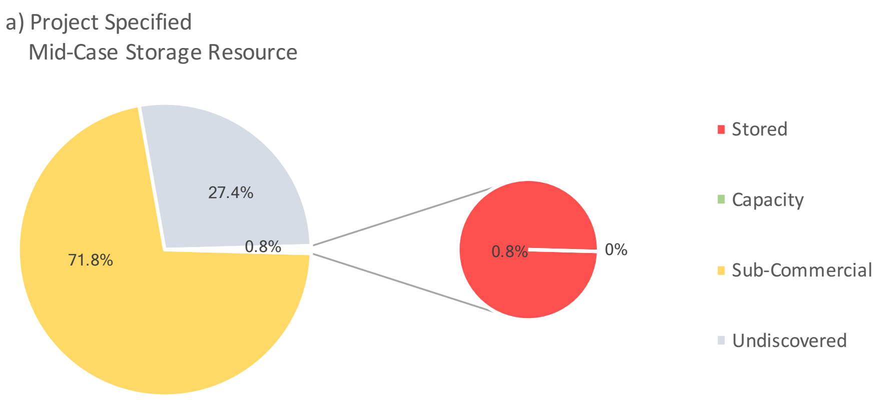
Japan was assessed during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for Japan as follows:

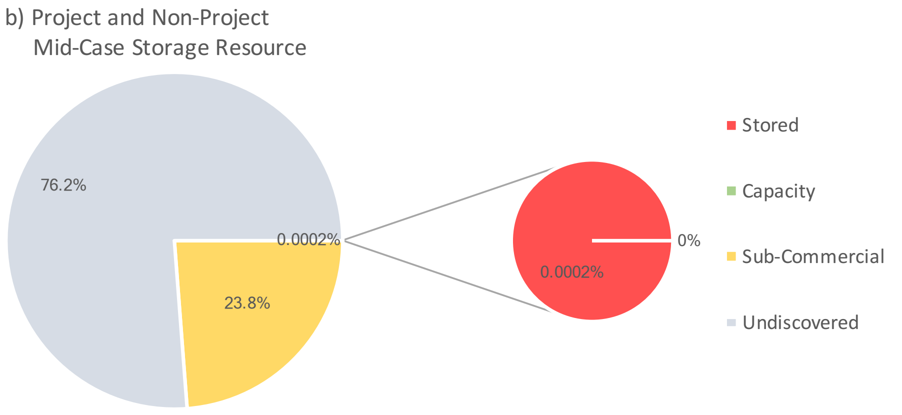
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.0003	0.0003
Capacity	0.00	0.0
Sub-Commercial	36.23	0.03
Undiscovered	116.04	0.01
Aggregated*	152.27	0.04

* 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 6-10. Storage resource classification summary for Japan

- Although storage resource is reported as being present in both saline aquifers and oil and gas fields, the greatest potential lies in saline aquifers.
- Evaluation of potential storage sites began in the late 1990's. Japan has developed one pilot project (10,000t) and one demonstration project (300,000 t) to date.
- Early studies reviewed sites using available data from hydrocarbon exploration ('Mission 1' study), follow-up evaluation of saline aquifers close to emissions sources ('Mission' 2 study) indicate significant storage potential, but the data are not readily available in the published literature.
- 25 sites with storage potential were identified in the Cycle 2 assessment, however only 13 have a storage resource estimate attached to it due to the difficulty in accessing data.
- The demonstration project, Tomakomai, is the first project in which CO_2 injection wells are directionally drilled from onshore to an offshore (subsea completion) injection point. Additional resource potential is available at the project site.
- Japan has no current CCS-specific current regulatory system, but CCS is embedded in its long-term Low Emissions Development strategy. The Tomakomai demonstration project was permitted using existing laws.





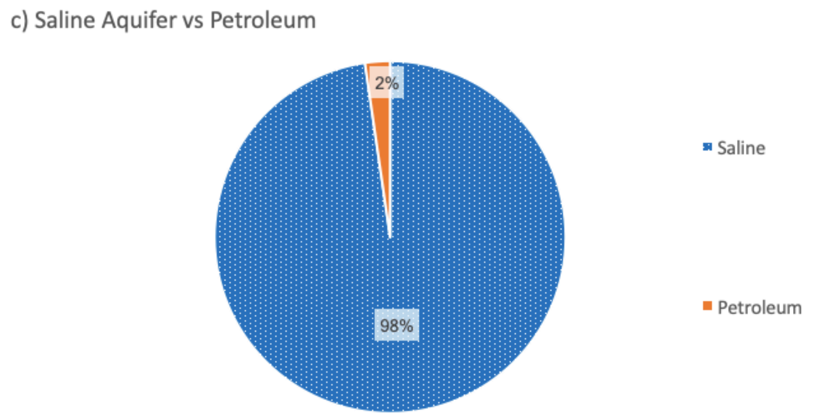


Figure 6-15. a) Spread of storage resource in Japan. Sites (25) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Japan. sites across SRMS classifications; both project specified and not. c) Split of Japan storage resource between saline aquifers and hydrocarbon fields, both project specified and not. Note: due to the large variance in size of values, numbers in pie plots do not add up to 100.

6.8.2 Resource Statement

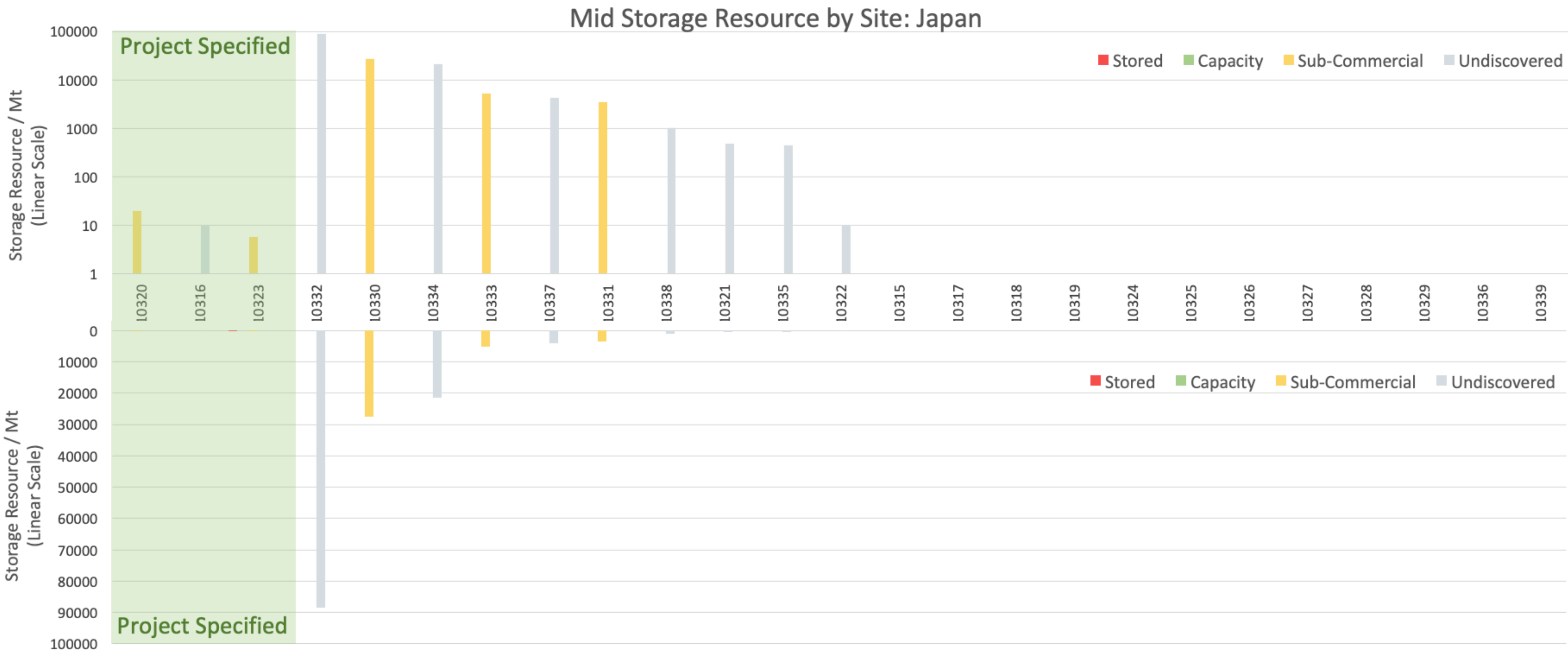


Figure 6-16. Storage resource summary for Japan compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.8.3 Evaluation History

Evaluation of potential storage resources in Japan began in the mid-nineties with an initial review of the storage opportunity using available hydrocarbon exploration and field data. All identified sites were subdivided by trapping style, data availability, and whether injected CO_2 could be 100% dissolved. A volumetric -based estimate of 91.5 Gt storage resource was published [41]. This initial review was followed by a 5-year national R&D project, 'Underground Storage of CO_2', which was then extended in 2005 to cover site selection for large-scale demonstration projects and future commercial projects. 'Mission 1' of the national project involved the Research Institute of Innovation Technology for the Earth (RITE) and the Engineering Advancement Association of Japan (ENAA) publishing a review of the 1995 data and an updated (volumetric) storage resource of 146.1 Gt [42], although the storage efficiency factors used are considered high (25% for structural traps; 12.5% for stratigraphic traps and open aquifers). 'Mission 2' studies continued the storage review work but focused on non-hydrocarbon-bearing basins close to major CO_2 emission sources (areas not covered by the Mission 1 studies). This work was used to build a database of 'promising areas' [43]. This Japanese language database is not readily available in the public domain, although attempts have been made to access the data during this 2020 Cycle (see 'Future Work'). Ogawa et al. [44] describe 27 candidate storage aquifers of which between 14 and 17 were down selected for detailed (although still at a regional level) study. In the absence of access to the Mission 2 database, estimates of storage potential in this assessment cycle are derived from a published bubble plot [44].

In 2008 [45] a comprehensive evaluation of potential storage sites identified 3 candidate sites: Nakoso-Iwaki Oki, a depleted gas reservoir 40km off the east coast of Honshu; Kitahyushu, a saline (open, no structure) aquifer; and Tomakomai, a pair of saline aquifers with some closure. Following the Great East Japan Earthquake, the Iwaki-Oki site was no longer considered as a candidate site. The Kitakyushu site was under a very early stage of evaluation having only limited 2D seismic data available. The more data-rich (3D seismic and 2 survey wells available) Tomakomai site was selected as Japan's first CCS Demonstration project.

In 2017, Japan CCS Co. Ltd. was commissioned by the Ministry of Environment (MOE and the Ministry of Economy, Trade and Industry (METI) to conduct an 'Investigation of Potential CO_2 Storage Sites' with the aim of selecting prospective sites by around 2021. At the Miakwa project (coal or biomass-fired power station), the search is underway to identify and evaluate potential transport and storage options for the project. The JCCS project is thought to be linked to this effort.

First deployment of CCS occurred at the pilot Nagaoka Project (2003 – 2005 where 10,400t CO_2 was injected into an onshore saline aquifer. This was followed by a successful demonstration scale project at Tomakomai.

As of 2020, Japan has a GCCSI Indicator score of 71/100 [16], an evaluation of a country's geological storage potential, maturity of their storage assessments and progress in the deployment of CO_2 injection sites.

Additional studies which provide discussion and storage estimates for microbubble CO_2 storage in Japan have not been included in this assessment cycle on the basis that they represent a more unconventional and untested approach to storage.

6.8.4 Resource Review

Although there is some identified storage potential in depleted fields in Japan (3.5 Gt), most of the storage resource potential lies in saline aquifers in the Neocene section of the subsurface; the older, deeper geological section is considered too structurally complex for CO_2 storage [46]. [47]

6.8.4.1 *Major Projects*

Following the success of the pilot Nagaoka project, the Tomakomai Demonstration Project, operated by Japan CCS Co. Ltd., commenced in 2012 and ran until late 2020. Tomakomai and Nagaoka remain the only projects in Japan to have injected CO_2 for storage purposes.

At Tomakomai (Hokkaido Prefecture), gaseous CO_2 (99% purity) sourced from a hydrogen production unit (pressure swing adsorption off-gas) at an oil refinery near the port area is injected 3-4 km offshore into 2 offshore saline aquifers via 2 reservoir-dedicated, deviated injection wells. Between April 2016 and November 2019 300,110 tonnes CO_2 (approximately 100,000t/year) was injected for permanent storage. Extensive post-injection monitoring will continue. The majority (300,012t) of the CO_2 has been injected into the higher permeability Moebetsu Formation (1.1km subsea), with only 98t injected into volcanic rocks of the Takinoue Formation (2.7km). CO_2 injection was not impacted by the 2018 Hokkaido Eastern Iburi Earthquake. Current dynamic models indicate that up to 5.73 Mt CO_2 may be injected into the Moebetsu Formation using the existing injection well, while the Greater Moebetsu Formation is calculated (volumetric method) to hold a storage resource in the region of 486 Mt (P50; [47]). Future development plans include looking at the potential for using Tomakomai as a storage reservoir for CO_2 from other emission sources across Japan (Tanaka, *pers.comm.).*

A new pilot project, the Miakwa Pilot, broke ground in 2018. The Miakwa Power Plant is a biomass fed plant where over 500t CO_2/day will be captured and stored (making it carbon negative). The storage site for the pilot has yet to be determined but potential sites are being reviewed, including those involving transport of the captured CO_2 to distant locations.

6.8.4.2 *Depleted Oil & Gas Fields*

No detailed review of storage potential in depleted oil and gas fields is available in the public domain. Both Tanaka [41] and Takahashi et al [42] used data derived from hydrocarbon activities, which included oil and gas exploration data, with Takahashi et al. reporting 3.5 Gt total storage potential in 13 unnamed oil and gas fields. The offshore Iwaki-Oki depleted gas field (ceased production in 2007) was a candidate site for a demonstration project [45] with a numerically simulated 20Mt potential resource (at an injection rate of 1 Mt/year), but further evaluation and consideration was discontinued following the ‘Great East Japan Earthquake’, in 2011. Other technical issues including low reservoir pressure and legacy wells were also considered problematic. An additional 27.5 Gt is reported in onshore dissolved gas fields by the same authors. The large (368 BCM) Southern Kanto gas field is included in this resource, but no further breakdown of these storage resources is available in the public domain.

6.8.4.3 *Saline Aquifers*

Both Mission 1 and Mission 2 evaluated the storage potential on non-hydrocarbon bearing saline aquifers across Japan. The Mission 2 study (as reported in Ogawa et al. [44] focussed on areas close to major emission sources, with particular focus on Tokyo Bay, Ise Bay, Osaka Bay and Northern Kyushu. Of these, a more detailed evaluation of Osaka Bay and, to a more limited extent, Tokyo Bay are published, but are still on a regional scale. In addition to these areas, an additional 10 or 11 areas (out of the total 27 areas reviewed) were reviewed to assess the accuracy of the volumetric estimate of storage. Analyses of data availability and quality were made but unfortunately actual target formations and calculated resource estimates are only provided for 3 areas. All other estimates have had to be derived from a 'bubble' plot which limits the accuracy of the Catalogue data entries.

The volumetric resource calculation methodology uses a 'storage factor' derived from the ratio of immiscible CO_2 plume volume to total plume volume which, when multiplied by a value for the supercritical CO_2 gas phase volume fraction of the injected plume is considered to equate to the US DOE [26] 'storage efficiency factor'. However, in the examples published, the storage efficiency equivalent factor was an optimistic 12.5%, almost certainly resulting in an overestimation of the storage resource estimate (US DOE, [26] P50 confidence interval storage efficiency factor for clastic reservoirs is 2.0%.

The estimated resource total for these Mission 2 aquifers is in the region of 23.9 Gt but care should be taken with this figure for the reasons described above. If a 2% storage efficiency factor were used the total resource estimate would be closer to 4Gt.

6.8.5 Regulatory Framework

In the 2018 GCCSI CCS Readiness Index [17], Japan ranked as a 'Progressive Nation', or one which is actively advancing deployment of CCS in the country but still has some 'gaps in legislation policy and/or storage resource development which must be addressed before widespread deployment can proceed'. As of 2020, Japan has no CCS-specific regulatory system. However, it has continued to be a leader in future clean energy development. Japan is one of 15 countries which includes CCS in a long term low GHG emission development (LED) strategy under the UN Framework Convention on Climate Change (UNFCCC) [16]. CCS is embedded in the countries 2020 Environmental Innovation Strategy with an expectation that CCS will contribute 14% of cumulative CO_2 reduction by 2060. Japan also has the stated aim of being carbon neutral by 2050. Regulatory precedent is held through the CO_2 stored by the Nagaoka (pilot) and Tomakomai (demonstration) projects under the current regulatory system. To permit the Tomakomai project Japan amended a domestic law reflecting the London Protocol (1996) and awarded a 5-year permit allowing offshore storage of CO_2 but required an accompanying marine environment survey plan [48].

6.8.6 Issues for the Assessment

Lack of ready access to site-specific data was the main issue for this assessment cycle. Since 1995 Japan has undertaken several country-wide evaluations of storage potential however much of the detail of these is not in the accessible public domain. This means that the Catalogue risks an underestimation, or at a minimum a poor representation, of the details of the available resource.

6.8.7 Future Updates

6.8.7.1 *Future CSRC cycles*

Should any further development at the Tomakomai storage system occur, this should be reviewed on an annual basis to ensure the Global Storage Catalogue is up to date.

The RITE/ENAA storage resource database could provide additional, in-depth resource summaries which are currently not readily available in the public domain.

If Japan CCS Co. Ltd. publish the results of their 2017 study 'Investigation of Potential CO_2 Storage Sites', any new sites should be added to the Catalogue.

6.9 Malaysia

6.9.1 Summary

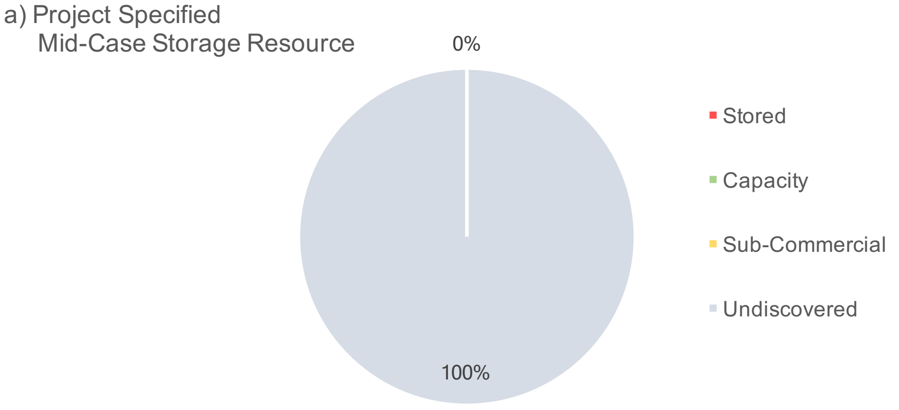
Malaysia was assessed during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for Malaysia as follows:

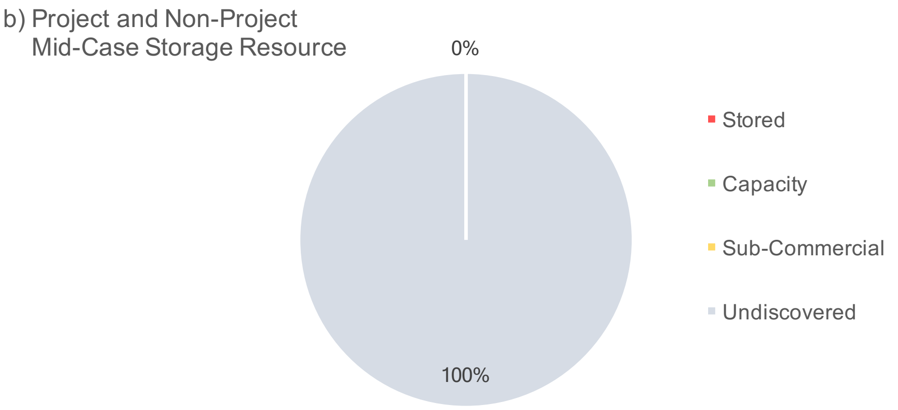
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.0	0.0
Capacity	0.0	0.0
Sub-Commercial	0.0	0.0
Undiscovered	149.6	0.10
Aggregated*	149.6	0.10

* 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 6-10. Storage resource classification summary for

- Malaysia has six sites in the Cycle 2 Assessment: two basin scale saline aquifers (undiscovered) and one project where the resource will be used to store CO_2 that is co-produced with natural gas (undiscovered).
- All sites are undiscovered as there is no published information on wells that may have been drilled in the formation.
- In the absence of any CCS-specific regulatory system, all resources are currently classified as 'Inaccessible'.





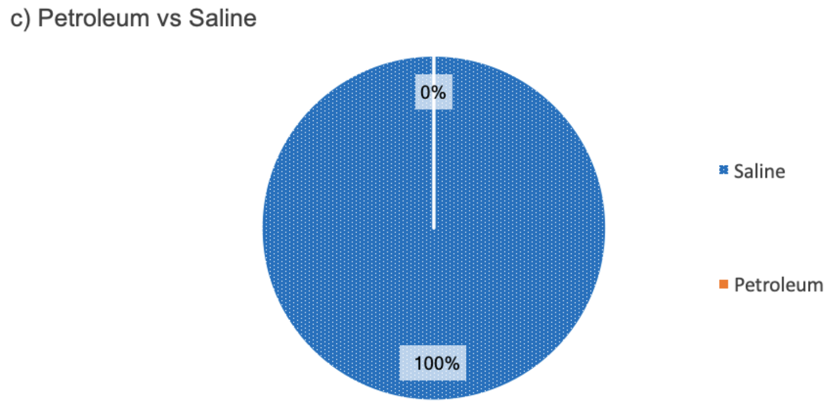


Figure 6-17. a) Spread of storage resource in Malaysia. sites (6) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Malaysia. sites across SRMS classifications; both project specified and not. c) Split of Malaysia storage resource between saline aquifers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

6.9.2 Resource Statement

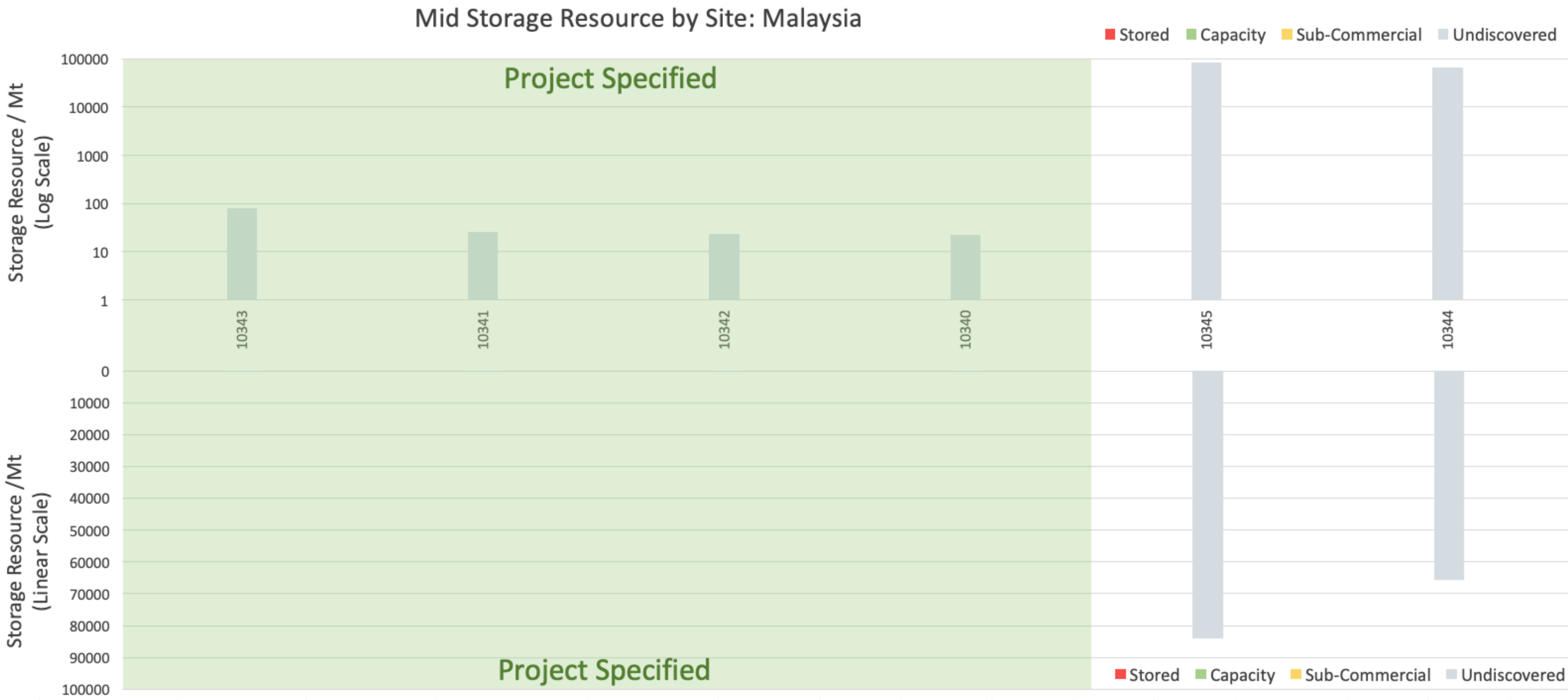


Figure 6-18. Storage resource summary for Malaysia compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double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

6.9.3 Evaluation History

The oldest evaluation of Malaysia's carbon storage potential was carried out by the Asia-Pacific Economic Cooperation in partnership with CO_2CRC. This assessment solely focused on storage of CO_2 co-produced with natural gas in south east Asia using a case study on CO_2 capture and storage from the cumulative gas stream of the undeveloped Tangga Barat cluster, Malay basin, although all estimates appear to have been generated using a simple volumetric methodology.

A regional study was undertaken by Junin and Hasbollah. [49], in which a dynamic spreadsheet (using geological and economic inputs) was used to assess 14 of Malaysia's sedimentary basins on their potential for carbon storage. This spreadsheet down selected to just two basins that are most suitable for CO_2 storage. The assessment criteria did not include proximity of the resource to large CO_2 emissions sources. The storage resource was calculated by the US-DOE [50]volumetric method for the two "high scoring" basins, these numbers are given as part of the 2020 Assessment. Junin and Hasbollah. [49] carried out this study in recognition of the fact that Malaysia's CO_2 emissions have been increasing by 1.9% per year since 1990, and if not acted on will continue to rise as Malaysia undergoes rapid economic growth.

Both of the above studies calculate storage resource using basic volumetric calculations. Based on lithology and depositional environment, all reservoirs presented will have a large variation in properties resulting in the resource estimates having low confidence.

6.9.4 Resource review

All storage resources assessed in this region are saline aquifers, however they can be subdivided into two different classes:

- Storage of CO_2 co-produced with natural gas: sites selected because of their close proximity to undeveloped natural gas fields with high percentage CO_2 content. These were classified as undiscovered as, although there are hydrocarbon exploration wells in the area, there is no direct mention of wells within the formation nor any indication of proximity to the storage resource site.

Basin wide storage resource – these have been classified as undiscovered as, although the basins have an active hydrocarbon exploration and production, there is no mention or location of any wells within the basins. Potential storage sites are mapped onto cross-sections, but these are not geographically-located.

6.9.5 Regulatory Framework

Malaysia has been evaluated under the 2018 GCCSI CCS readiness index [17]. However, there are no CCS-specific regulatory or legal frameworks that could directly assist a project in Malaysia. The readiness index gives Malaysia a high score for inherent interest; this means that based on the nation's economic dependence on fossil fuels, it would benefit from implementing CCS as a carbon emissions reduction strategy. However, the index shows that law and policy changes are needed to give more incentives for CCS project development.

An APEC (2010) study outlines a range of incentives that Malaysia has in place for environmental management, some of these may be relevant for CO_2 transport and storage practices. Incentives include: varying tax exemptions for companies providing energy conservation services; facilities to store, treat and dispose of toxic waste; or companies using environmental protection equipment. While CO_2 transport and storage practices do not currently qualify for these, it would be possible to make a case for their inclusion.

Malaysia has committed to reduce its emissions intensity by 40% by 2020 and 45% (relative to 2005 emissions) by 2030 as part of the Paris Agreement (UNFCCC, 2015). By 2011 they had already reduced emissions by 33% and, a recent announcement from the Malaysian state-owned energy company Petronas, states their aim of becoming a net zero emitter of greenhouse gases by 2050.

6.9.6 Issues for Assessment

The biggest issue with classifying all the Malaysia storage resources, was a lack of detail on data availability and location; no well numbers or locations were given despite some sites being in or near areas with significant ongoing petroleum exploration. This means that most of the resources have had their maturity downgraded.

Accuracy of resource estimates for most sites is limited by both the volumetric methodology used and the assumption of one set of reservoir properties for all estimates at all sites.

For all but one of the storage resources presented, there is only a single value for resource estimation. In cases where the resource estimation only reflects the volume of emissions over lifetime of project, the resource estimate has been recorded as the ‘Low-Range’ value. In all other cases the resource estimation has been recorded as the ‘Mid-Range’ value.

6.9.7 Future Updates

6.9.7.1 *Future CSRC cycles*

- Any updates on current potential storage sites should align with SRMS approach and methods to allow progress (maturation) up the classification system.
- Updates should be made if Petronas and other petroleum’s companies release any well location data for the area’s which contain storage resources in the Malay Basin and Greater Sarawak Basin. This would promote several storage resources from undiscovered to discovered.

6.10 Mexico

6.10.1 Summary

Mexico was assessed during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for Mexico as follows:

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.0	0.0
Capacity	0.0	0.0
Sub-Commercial	89.5	0.0
Undiscovered	11.3	0.0
Aggregated*	100.8	0.0

* 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 6-8. Storage resource classification summary for Mexico

- There are currently a total of 76 sites across nine basins in Mexico.
- There are no project-specified sites in the Mexican dataset.
- There are no active CCS projects operational in Mexico, however pilot capture plants have been proposed.
- The Mexican Government has recognised the requirement for CCS in meeting its commitments to the Paris Agreement, yet lacks a developed CCS policy to allow projects to progress.

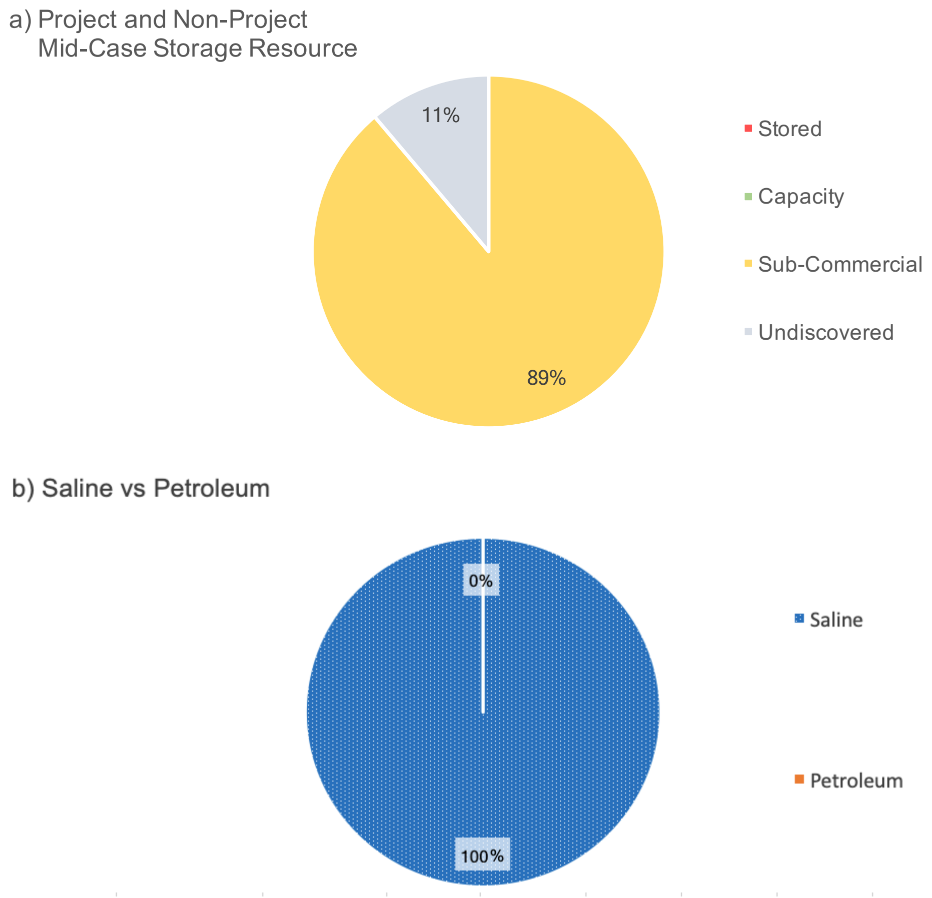


Figure 6-19. a) Spread of storage resource in all Mexican sites (76) across SRMS classifications. No sites have a project specified. b) Split of Mexican storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.10.2 Resource Statement

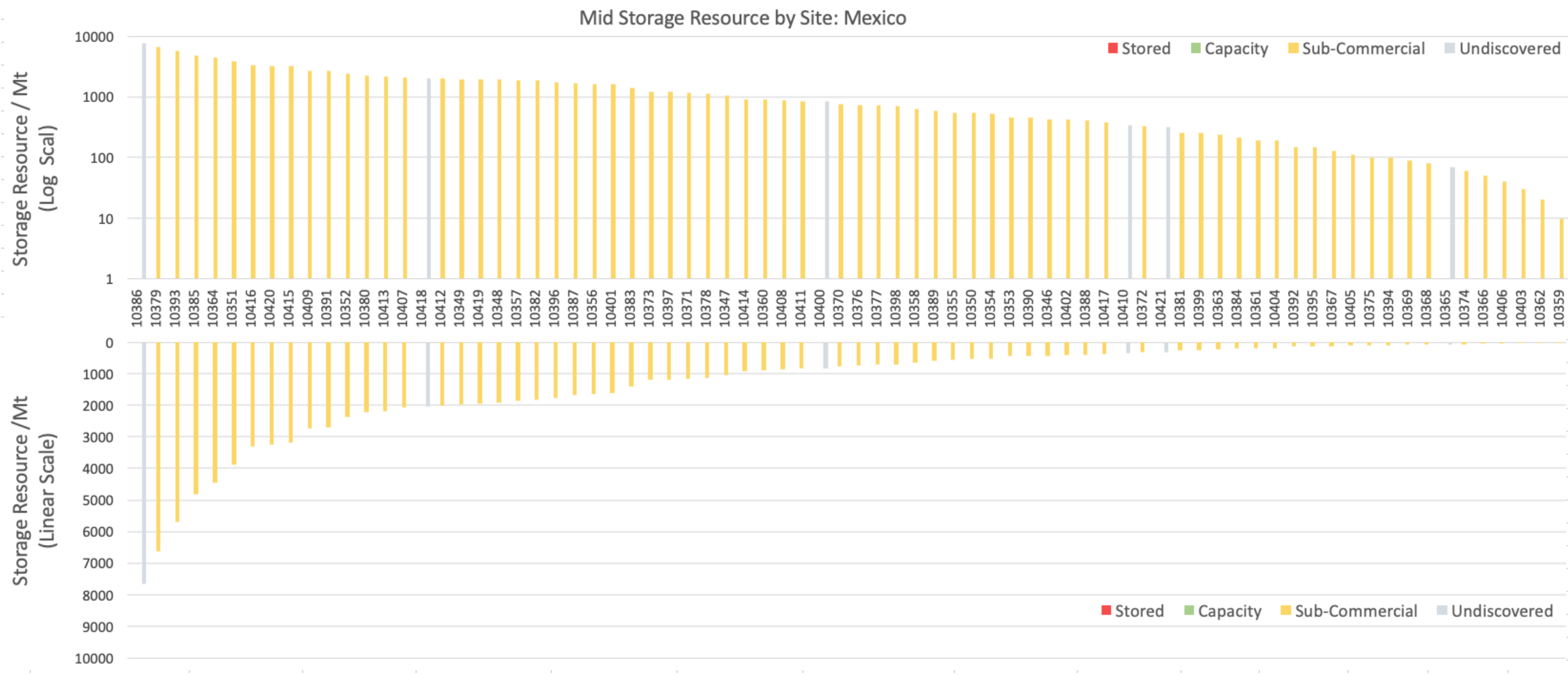


Figure 6-20: Storage resource summary for the Mexico compiled in the CSRC. Graph above is log scale and graph below is linear. No project specified sites were identified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting

6.10.3 Evaluation History

Only two sources were available for the estimation of CO_2 storage resource within Mexico; where the North American CO_2 Storage Atlas (NASCA) [51] is the main source, with supplementary information provided by Moja (2016) [52]. Both sources reference the same storage resource evaluations for 76 sites across nine basins. These evaluations were conducted in two phases:

In the first phase, the basins were separated into the exclusion or inclusion zones, where excluded basins exhibited high seismicity, geothermal or volcanic activity and thus are not recommended for geological storage.

In the second phase, a theoretical storage resource was calculated for prospective sectors within basins in the inclusion zone. Maps displayed in the Appendix of the NASCA suggest that this evaluation was largely undertaken in areas around existing wells. The CSLF equation for saline aquifer storage was used to calculate the potential storage resource for geological formations at depths between 800 to 2,500m. The equation does not consider geological constraints to storage resource, injectivity, hazards, or solubility and mineral trapping, and importantly does not apply a storage efficiency factor. As such, the authors consider the calculated storage resource to be a theoretical maximum.

The evaluations were published in 2012 and no further work has been completed to assess Mexico's CO_2 storage potential, with the exception of EOR feasibility projects.

6.10.4 Resource Review

6.10.4.1 *Major Projects*

No major CCS projects were identified in Mexico during Cycle 2.

Pilot capture plants were noted to be in development in the coming year by Heras (2018) [53], however no further details of either project could be sourced in the public domain. These capture pilots were to be located in Poza Rica and CO_2 EOR in Minatitlan, both the in Veracruz area.

6.10.4.2 *Depleted Oil & Gas Fields*

No CO_2 storage evaluations for Mexican depleted hydrocarbon fields were identified in the CSRC. Due to the wealth of fields in the country, it is likely that any future evaluations of storage resource in depleted fields would benefit the apparent potential within Mexico.

6.10.4.3 *Saline Aquifers*

The NASCA (2012) identified a total of 101Gt of storage resource, split across 9 basins which line the eastern coastline of Mexico [51]. Largely, this resource was calculated for an area surrounding a legacy well, and as such, could be classified as "Discovered". A smaller portion, 11.3Gt, was classified as "Undiscovered" due to its distance from well data points. The lack of a developed CCS policy in Mexico, means the identified storage resource cannot be developed under the current regulatory constraints. Consequently, all storage resource potential in Mexico is classified as either "Undiscovered Inaccessible" or "Discovered Inaccessible". Should this position change, the storage resource can mature from the Inaccessible classification.

6.10.5 Regulatory Framework

Mexico's rating in the GCCSI Policy Indicator Report 2018 [18] increased significantly since the previous assessment in 2015. This is due to Mexico attracting funding from the World Bank to complete feasibility studies for demonstration projects, and for the establishment of the Mexican CCUS Centre, through which two pilot capture plants have been proposed.

In October 2019, the Secretaría de Medio Ambiente y Recursos Naturales (SENERNAT) introduced a carbon market pilot program which includes stationary sources of CO_2 from the energy and industrial sectors, whose emissions exceed 100,000 tonnes per year. The pilot program is to last for 36 months, from 1st January 2020, and will transition into an Emissions Trading Scheme from 2022 [18].

6.10.6 Issues for the Assessment

Lack of recent and detailed reporting of CO_2 storage resource. The maturity of the CO_2 storage resource in Mexico is very low due to the lack of detailed reporting and developed CCS policy.

The reported resource also suffers from a lack of development since the initial evaluation published in 2012. An update to this work should be considered to build on the important work completed to date.

6.10.7 Future Updates

6.10.7.1 *Future evaluations*

A focus of future evaluations on CCS rather than CCUS for EOR would be welcome to allow inclusion in the Global CO_2 Storage Catalogue. Far more detailed reporting and evaluation of the CO_2 storage resource is also required to accurately represent Mexico's full potential.

A significant amount of subsurface data is likely to be available in Mexico, due to its active hydrocarbon industry. Further use of this data for CO_2 storage evaluations and more detailed reporting of these evaluations, would significantly benefit the reported resource and help to increase its maturity.

6.11 Norway

6.11.1 Summary

Norway was assessed during Cycle 1 and was updated in Cycle 2 to reflect continued injection of CO_2 in active projects.: (Table 2-1). The CSRC 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	0.025	0.025
Capacity	0.036	0.036
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 6-9. Storage resource classification summary for Norway

- There is currently a total of 42 sites at both local and regional scale, located across five geological basins in the offshore sector. Most of the Norwegian storage resource is in the Norwegian North Sea.
- There is a total of 11 project-specified sites, the majority (10) of which also contain a simulation model.
- As of 2019, a total of 25.1 Mt of CO_2 has been injected to deep geological storage, at Sleipner (18.6 Mt) and Snøhvit (6.5 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 [17].

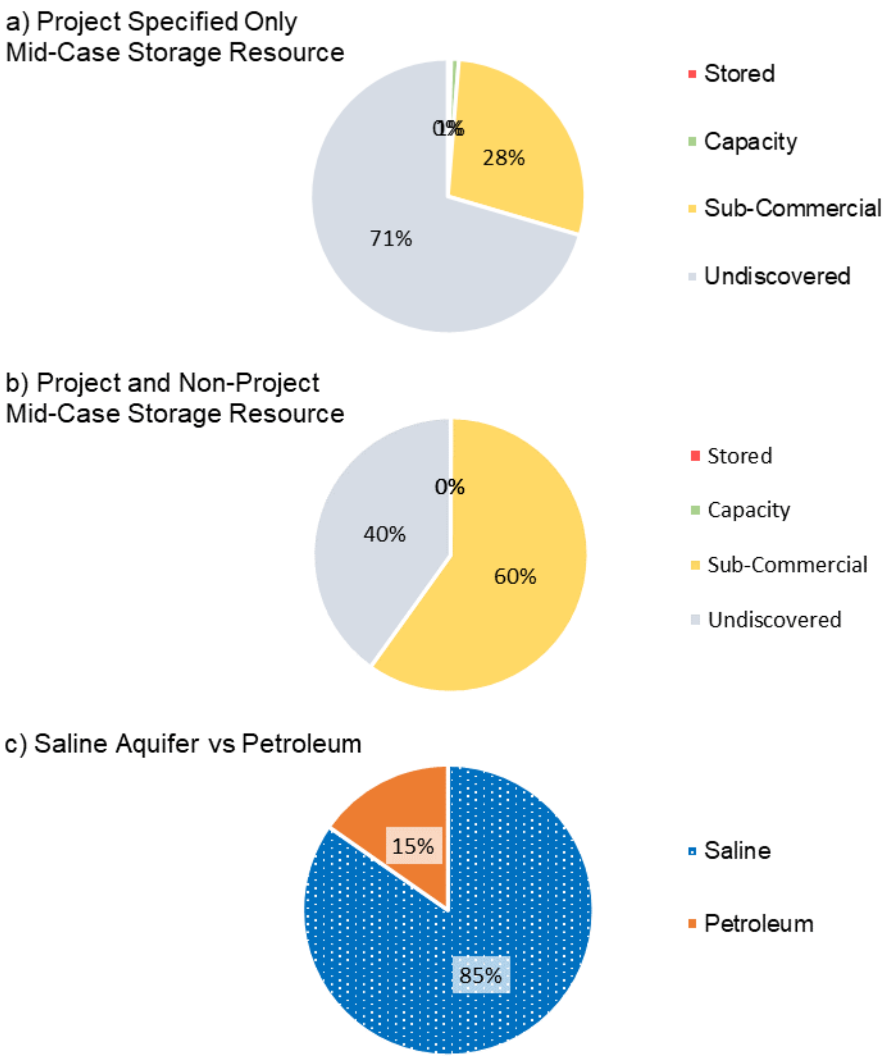


Figure 6-21. a) Spread of storage resource in Norwegian sites (42) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all Norwegian sites across SRMS classifications; both project specified and not. c) Split of Norwegian storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.11.2 Resource Statement

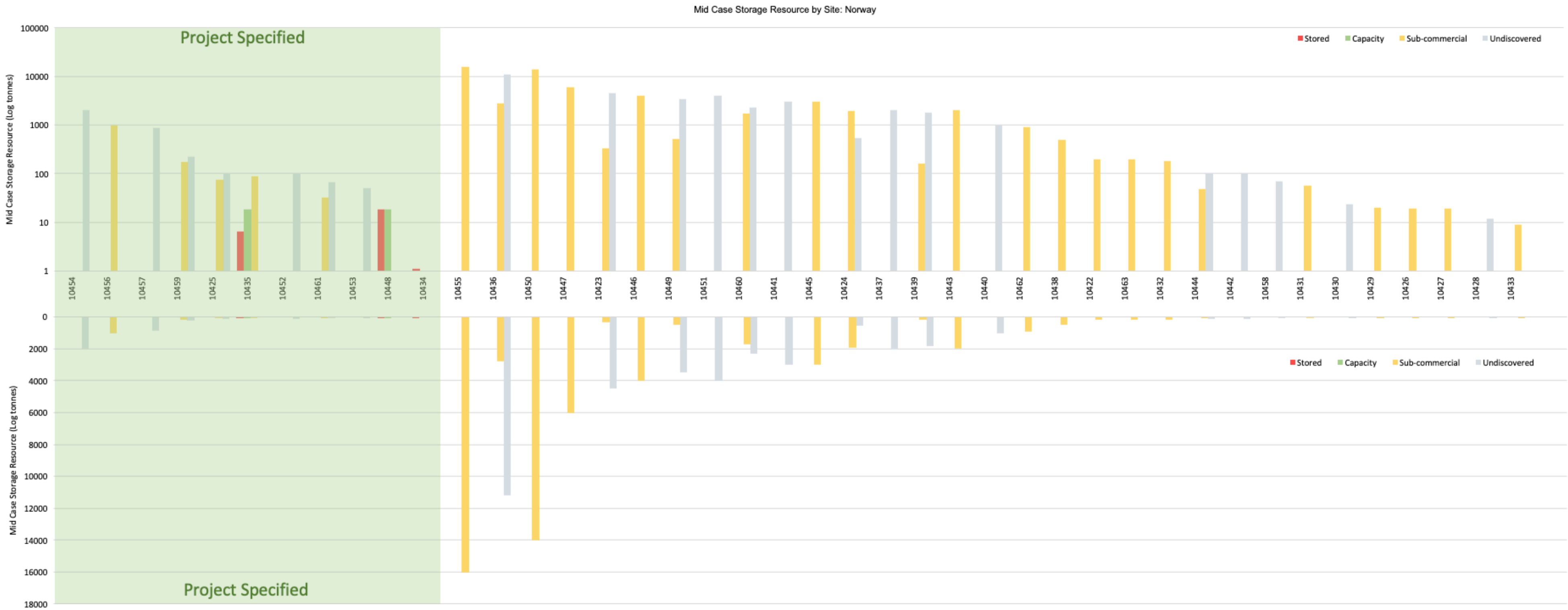


Figure 6-22. Storage resource summary for Norway compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.11.3 Evaluation History

The Norwegian CO_2 Storage Atlas is a key document for evaluation of the storage resource in Norway [54]. 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.

6.11.4 Resource Review

6.11.4.1 *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 18.6Mt, (end-2019; P Ringrose, *pers. comm;* [55]) [56].

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 had 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 [54]. 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 CSRC Cycle 1 that provide up-to-date stored volumes at Snøhvit, however the Atlas estimated a mid-case storage resource of 24 Mt.

6.11.4.2 *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 the CSRC Cycle 1. 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 the CSRC.

6.11.4.3 *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 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 [57], [58].

6.11.5 Regulatory Framework

Norway has the highest CCS Policy-Indicator of the countries within the GCCSI Carbon Policy Indicator Report [18]. 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 [59]. 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 [17]. The rating shows that Norway has "CCS specific laws or existing laws that are applicable across parts of the CCS cycle".

6.11.6 Issues for the 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 [57]. 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 [1].

6.11.7 Future Updates

6.11.7.1 *Future evaluations*

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.

6.12 South Korea

6.12.1 Summary

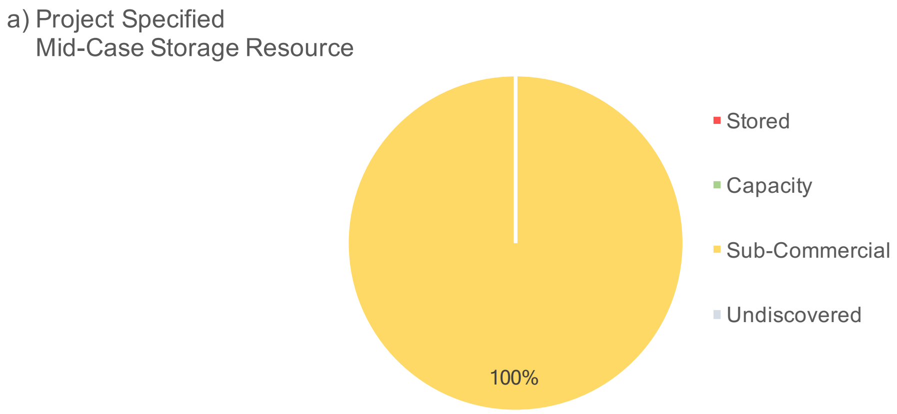
South Korea was assessed during Cycle 2 (Table 2-1). The CSRC has identified a CO_2 storage resource for South Korea as follows:

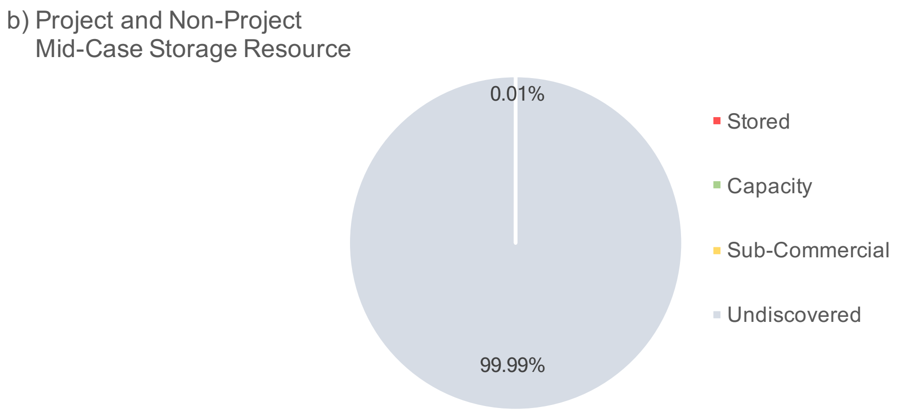
Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified only
Stored	0.0	0.0
Capacity	0.0	0.0
Sub-Commercial	0.02	0.02
Undiscovered	203.3	0.0
Aggregated*	203.4	0.02

* 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 6-10. Storage resource classification summary for South Korea

- Storage resource potential is dominated by Undiscovered resource in saline aquifers in offshore basins. Only one gas field has been evaluated (Donghae-1).
- Potential storage resource has been identified in three offshore basins marginal to the Korean peninsula. Limited resource potential may exist in onshore basins, but these are generally too shallow and tight for large scale storage.
- As of February 2021, 203.4 Gt of potential resource has been reported from nine sites however all but one site is a basin-scale play and resource number should be flagged as carrying low confidence. No projects have been identified.
- The Ulleung Basin (East Sea) is considered to have the greatest commercial potential due to its location near the SE coast, however the Jeju Basin (northern East China Sea) holds greater resource potential. Data to support the resource statements is lacking.
- No current regulatory system exists with respect to CCS however South Korea has stated an ambitious Intended National Contribution (2015) and a Draft Korean CCS Act has been circulated.





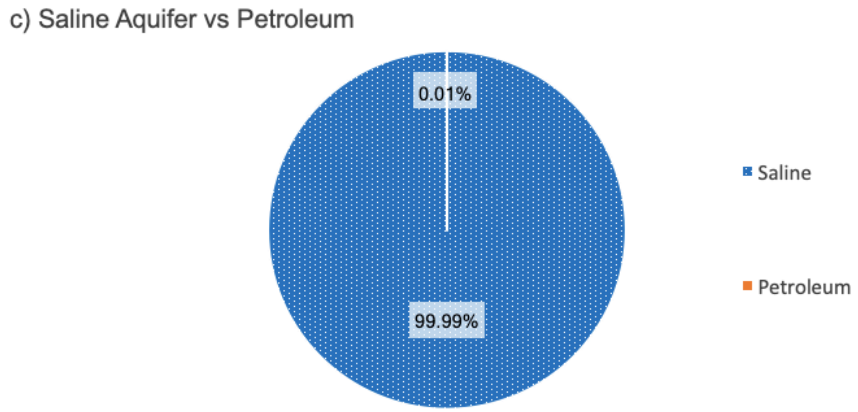


Figure 6-23. a) Spread of storage resource in South Korea. Sites (9) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all South Korea. sites across SRMS classifications; both project specified and not. c) Split of South Korea storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.12.2 Resource Statement

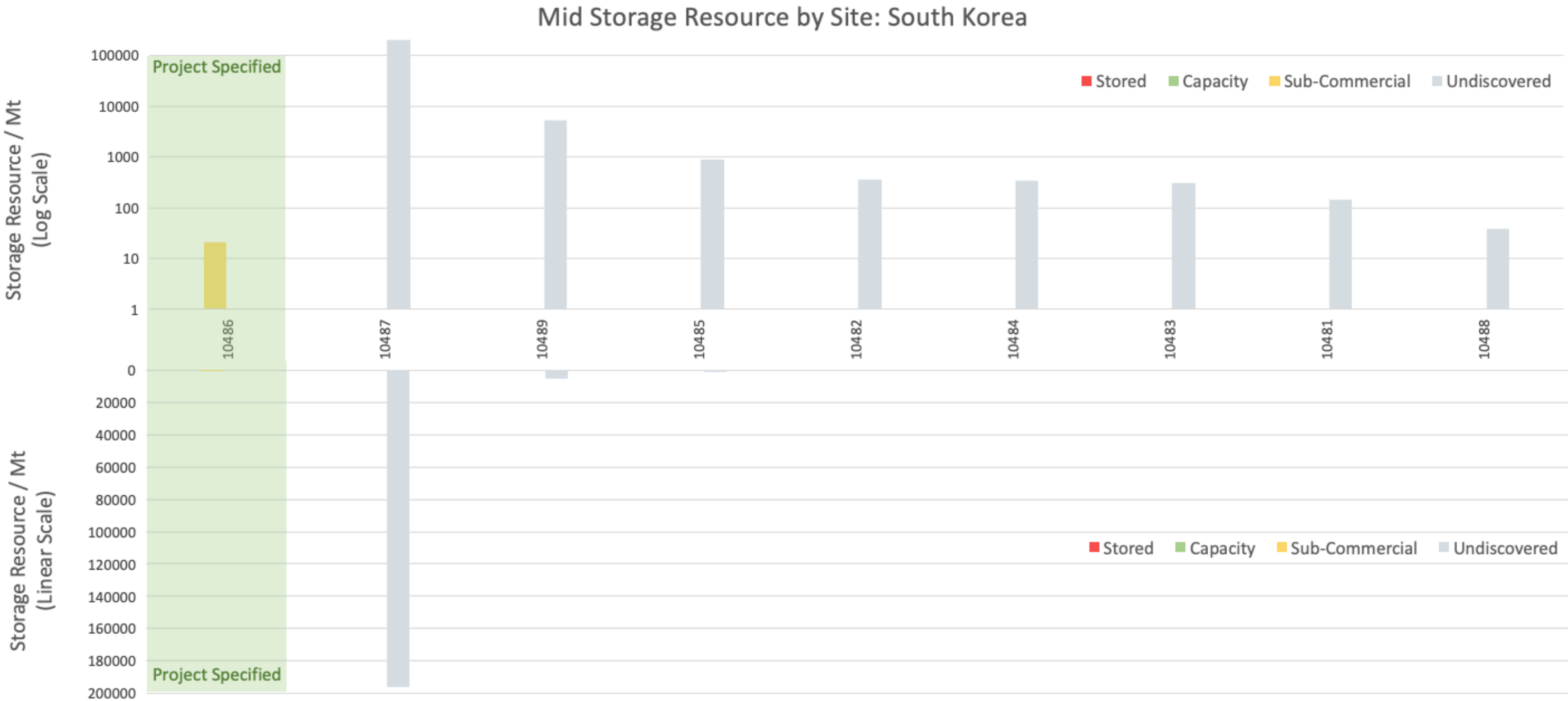


Figure 6-24. Storage resource summary for South Korea compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.12.3 Evaluation History

In general, the onshore geology of South Korea is considered unsuitable for commercial-scale CO_2 storage. According to Park et al. [60], Kim et al. ([61], Lee et al [62], and Huh and Yoo [63] the onshore basin geology is unfavourable for CO_2 injection and storage, being too shallow with low permeability. Saline aquifer storage is considered to hold the most potential due to the lack of a local hydrocarbon industry [61]. In addition, a 2017 5.4 magnitude earthquake in Pohang City (in the largest onshore basin) caused cessation of all fluid injection activities (both CO_2 and geothermal). Post-event analysis suggests the earthquake was induced by water-injection in an enhanced geothermal system [64].

Studies have been undertaken in both the onshore and offshore areas in South Korea. Of the three offshore basins (the Ulleung basin in the East Sea, the Jeju basin in the East China Sea to the south of the peninsula, and the Kunsan basin in the Yellow Sea to the west). The Ulleung basin has been considered the most feasible due to the presence of gas-bearing structures [65] [64] and closer proximity to major emissions sources. Further developments made be possible as KNOC and Woodside began exploration in the Ulleung Basin in 2019 and new drilling contract (awarded February 2021) for the area may lead to further data availability. The data availability in the Yellow Sea (6 wells, plus 2D and limited 3D) and the Jeju Basin (14 wells plus 2D and some 3D surveys) is more restricted.

The calculation methods used to assess resource potential are essentially volumetric methodologies using the DOE/NETL [66] approach. No projects have been identified which meet the Global catalogue threshold of 10 Mt for inclusion.

6.12.4 Resource Review

The current classification of potential storage resource in South Korea is significantly limited due to the lack of robust data sets for evaluating the saline aquifers. The approach taken here is to adopt a minimum maturity level approach to classification; resources can progress to more mature classes when there is both evidence and quantification available. The stated resource for South Korea is considered an overestimation as it represents a theoretical value based on limited data.

All resource entries (both saline aquifer and the single gas field) are classified as 'Inaccessible' at this stage due the lack of a regulatory system for CCS and any knowledge on gas field accessibility dates).

6.12.4.1 *Major Projects*

No major storage projects have been announced by South Korea. The Korea 2020 project was a major national plan controlling technology development, R & D, and promotion of CCS facilities. Although the projects identified are heavily focused on carbon capture the project did carry the goal of selecting a storage site suitable for the injection of 10,000 t CO_2. Two potential sites are discussed in the literature, the Yeong-Il Bay site in the offshore Pohang Basin and the Noeseongsan block in the onshore Janggi Basin. Although start-up of injection was due to be in 2016-2017, no mention of these pilot projects was found in the public literature or on the Korea 2020 website. Simulation of injection at the Yeong-Il Bay site indicated a maximum injection volume of between 40,000 t [67] and <1 Mt [68] before maximum allowable pressures were reached.

6.12.4.2 *Depleted Oil & Gas Fields*

The Ulleung Basin (East Sea) contains the only identified gas-bearing structures and the only active hydrocarbon field in South Korea. The Donghae-1 gas field

(Gorae structure) and the attached aquifer has been evaluated for a range of injection scenarios, with post-depletion CO_2 injection with brine extraction giving the most optimistic resource (24.3 Mt; [65]). Additional gas-bearing structures in the Ulleung Basin (e.g., Dolgorae) may hold potential but no evaluations are available to this cycle of assessment.

6.12.4.3 *Saline Aquifers*

The storage resource in South Korea is dominated by the basin-scale saline aquifer resource estimates. Few publications provide sufficient back-up detail to support the published resource estimates, for example, the Taebaek Basin (onshore) has a published resource estimate of 3 Mt (sandstones; [69]) but presentations by the KCCSA [70] quote 180 Mt. In the absence of supporting information for this estimate, the Taebaek Basin resource is not included in the Cycle 2 Assessment. The greatest onshore resource potential is held in the Gyeongsang (Kyoungsang) Basin in which up to 1 Gt resource [71] was calculated in sandstones units from 3 separate locations. The highest potential, 535 Mt, was identified in channel sandstones from these locations. An alternative estimate of 680 Mt for the basin are given by KCCSA [70] but with no supporting data. In the absence of more detailed analysis, these sites may warrant further evaluation. In the south east of the peninsula, the onshore Janggi Basin was evaluated as a potential pilot project location with emphasis on the Janggi Conglomerate and the clastic Seondongri Formation, both of which show significant theoretical resource estimates (142 Mt and 26 Mt respectively [67]; [72] but probabilistic estimates of the effective resource (fluid phase) do not meet the Catalogue threshold (1 Mt and 0.2 Mt respectively).

Three offshore basins have undergone evaluation of their storage resource. The most advanced is the Ulleung Basin where subsurface data (seismic and well) is available. The Jeju Basin to the south has been evaluated but used a simplistic approach dividing the study area into a layer model (cross-cutting geological/lithological boundaries). The estimated resource range of 24 – 690 Gt (average: 196 Gt) is considered a significant overestimation. To the west, the Gunsan (Kunsan) Basin was evaluated by MEST (2008; in Korean) with a reported 254 Mt resource, although this has also been linked to EOR [61] and as such is not currently included in the Catalogue.

6.12.5 Regulatory Framework

Following an initial GHG reduction goal of 30% (243 Mt) of 2020 BAU emission (813 Mt), with 2Mt of the total to be achieved through CCS, the South Korean government announced an Intended Nationally Determined Contribution (INDC) of a reduction of 37% of GHG emissions compared to 2030 BAU. CCS is seen as a key technology to achieve low carbon growth [73] but currently has no CCS-specific regulatory system, although a Draft Korean CCS Act has been circulated. As a result, all resource entries in the Global Catalogue are currently (Cycle 2) sitting in the Inaccessible category. This may be changed as soon as any legal and regulatory system is adopted. South Korea did test an emissions trading scheme (started in 2010), with the goal of the scheme taking effect in 2015.

6.12.6 Issues for the Assessment

While South Korea has been proactive at setting up national plans (e.g., Korea 2020) for R&D and technology development, most of the focus to date has been capture technology. The proposed 10,000t storage pilot has not been reported on in the literature although this may relate to cessation of activities following the 2017 Pohang earthquake. Current published evaluations of storage resource potential are high level, basin scale estimates with no projects (except for the Yeong-Il Bay pilot study which is <1Mt) available for inclusion in the Global Catalogue.

6.12.7 Future Updates

6.12.7.1 *Future CSRC cycles*

There is limited information on future carbon storage development in South Korea, however it is anticipated that this may change if the country looks to CCS to help meet its current INDC. Future assessment cycles should check for developments.

6.13 United Kingdom

6.13.1 Summary

The United Kingdom was assessed during Cycle 1 and was updated in Cycle 2 only to reflect recent changes in licensing and UK Government funding announcements (Table 2-1). The CSRC 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 6-10. Storage resource classification summary for United Kingdom

- There is currently a total of 87 sites at both local and regional scale, located across five 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 CSRC.
- The UK Government has outlined strong ambitions for CCUS deployment in the Energy White Paper, and also announced the intention to provide £1 billion to support the development of several CCS hubs and clusters across the UK by the end of the decade.

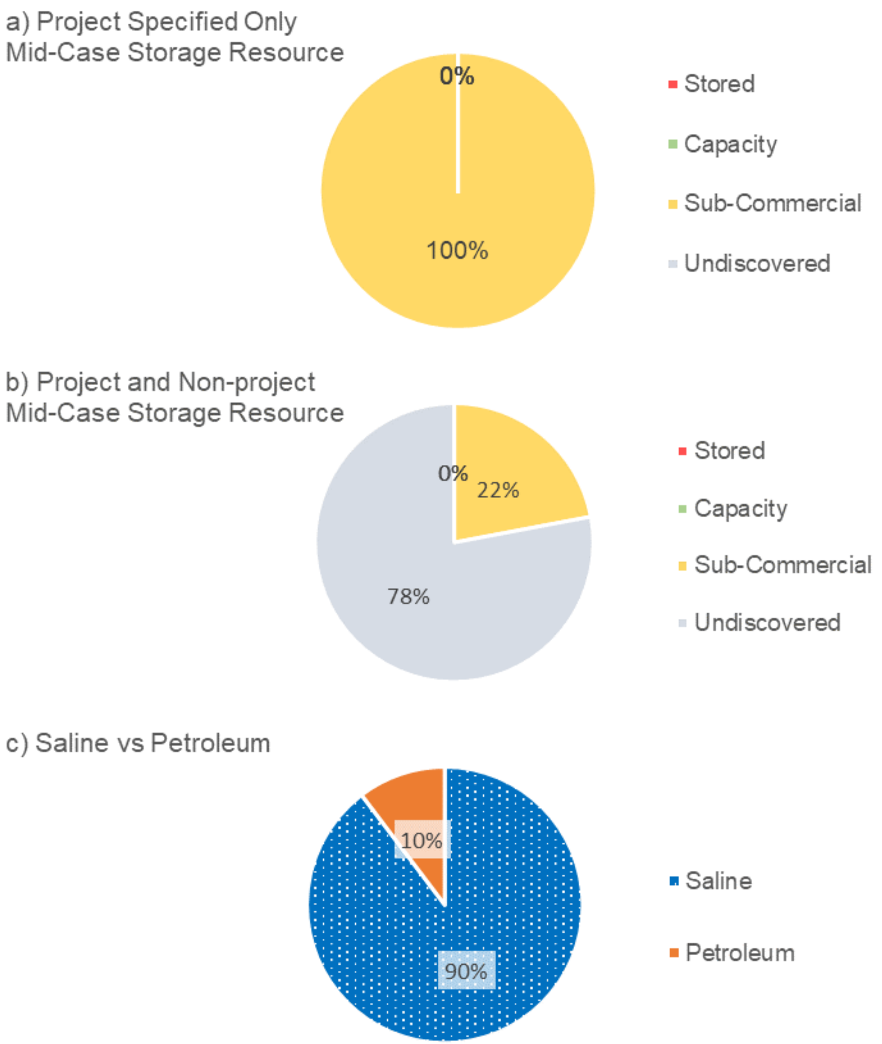


Figure 6-25. a) Spread of storage resource in UK sites (87) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all UK sites across SRMS classifications; both project specified and not. c) Split of UK storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.13.2 Resource Statement

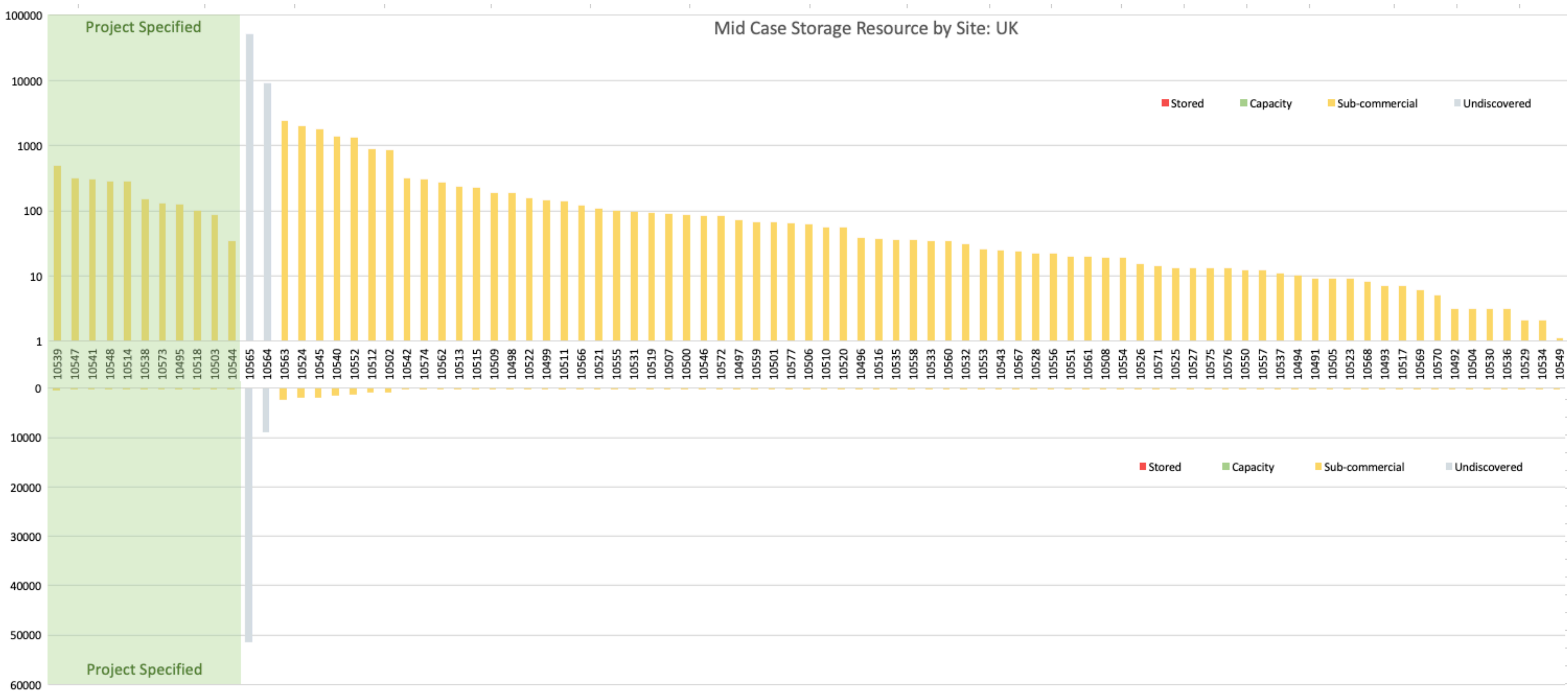


Figure 6-26: Storage resource summary for the UK compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.13.3 Evaluation History

The most widespread source for the estimation of CO_2 storage resource within the UK is from CO_2Stored, the UK CO_2Storage 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 CO_2Stored was developed by the UK Storage Appraisal Project (UKSAP), which was commissioned and funded by the ETI. CO_2Stored 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, however the East Irish Sea is included. Unfortunately, due to the restriction of the CO_2Stored license to non-commercial use, it could not be used directly in the CSRC. 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 CSRC database as four aggregated entries under the groupings: 'Sandstone aquifers', 'Chalk aquifer's, 'Oil fields' and 'Gas fields'.

6.13.4 Resource Review

6.13.4.1 *Major Projects*

To date four carbon storage licenses have been, or are being, held in the UK Continental Shelf (UKCS), in addition to one further licence application made in 2021 which is currently undergoing review. The past and current licences are:

1. CS001 Endurance Licence. 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 Licence (Goldeneye field) held by Shell U.K. Limited. Active between July 2013 and August 2016. Licence terminated by Shell U.K. following the withdrawal of government funding in 2015. The evaluated area is now part of the current Acorn Licence.
3. CS003 Acorn Licence. Active from January 2018 till present. The licence is held by Pale Blue Dot Energy and 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 FEED. 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 CSRC Cycle 1.
4. CS004 Hamilton and Lennox Licence. Active from October 2020 till present. The licence is held by Eni and covers the depleted hydrocarbon fields Hamilton, Hamilton North and Lennox. It is the potential storage site for the HyNet Project which is currently under development.

The 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.

6.13.4.2 *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 On Hold" a storage licence is held for the site but suffers from a developed UK CCS business model, 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 CSRC Cycle 1 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.

6.13.4.3 *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 6.13.3, 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 CO_2Stored database change, or should evaluations be published for sites included in these aggregations, then the resource can be classified more appropriately.

The site 'Endurance Bunter Closure' has been classified as "Development On Hold" following the retraction of government funding detailed in 6.13.4.1, which has led to significant delay in the projects.

6.13.5 Regulatory Framework

The UK has the second most highly rated country in the GCCSI Policy Indicator Report [18] 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. In 2020 and 2021, the UK Government released their Energy White Paper detailing how UK energy supply will meet Net Zero ambitions and also pledged £1 billion towards the development of a series of clusters and hubs across the UK, further demonstrating their commitment to the UK CCS industry.

6.13.6 Issues for the Assessment

Lack of commercial access to the CO_2Stored 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 CO_2Stored could not be found in other publications, leading to the undesirable work around detailed in 6.13.3, to prevent significant under-representation of the storage resource in the UK.

Lack of reporting on active projects. As detailed in 6.13.4.1.

6.13.7 Future Updates

6.13.7.1 *Future evaluations*

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

6.13.7.2 *Future CSRC cycles*

A full update for the UK storage resource potential is recommended for future updates to the CSRC to capture changes in the rapidly advancing CCS industry.

6.14 United States of America

6.14.1 Summary

The CSRC Cycle 1 assessment identified the CO_2 storage resource for the United States of America as shown in the table below. This was not updated in Cycle 2.

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 6-11. 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 Cycle 1 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.

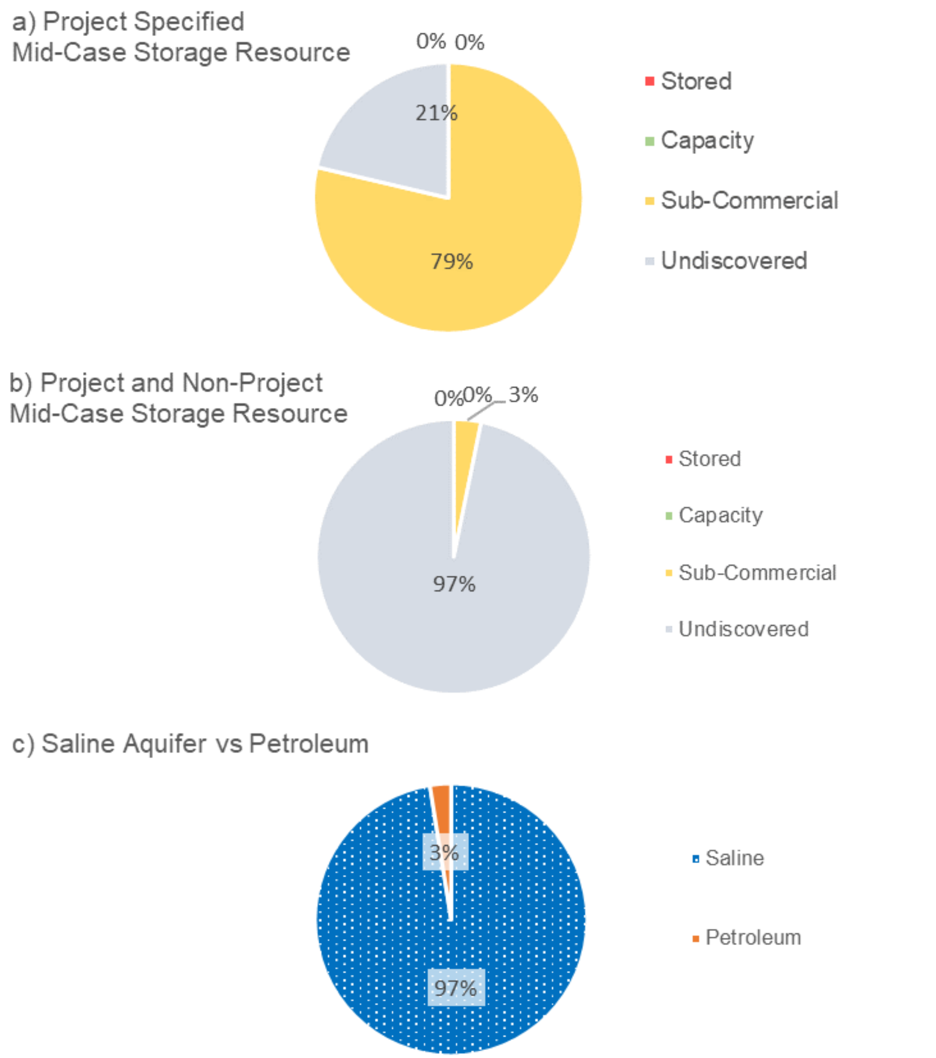


Figure 6-27. a) Spread of storage resource in U.S. sites (132) across SRMS classifications, where a project has been specified. b) Spread of storage resource in all U.S. sites across SRMS classifications; both project specified and not. c) Split of U.S. storage resource between saline aquifers and hydrocarbon fields, both project specified and not.

6.14.2 Resource Statement

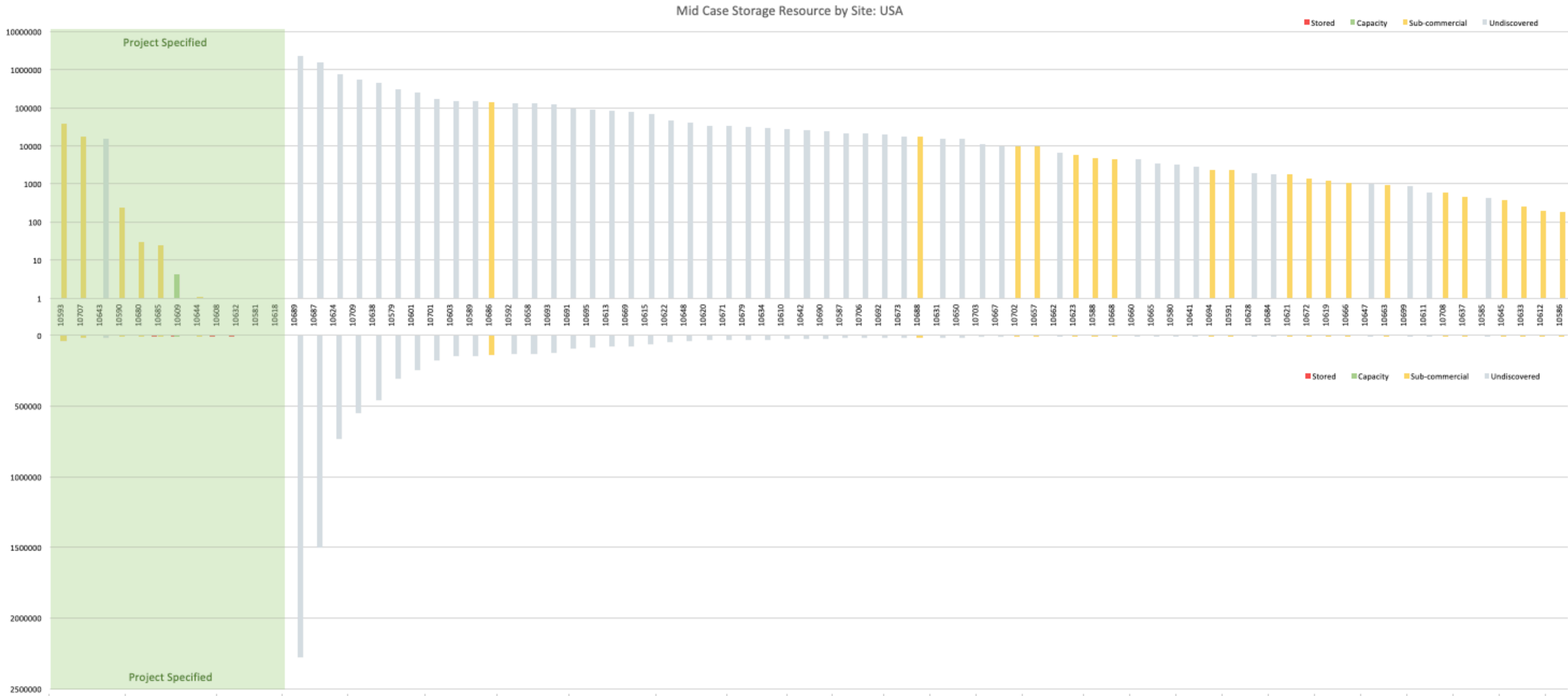


Figure 6-28. Storage resource summary for the U.S. compiled in the CSRC. Graph above is log scale and graph below is linear. Green box highlights sites where a project has been specified. Where possible, the data have undergone due diligence checks identifying potential repeat entries to avoid double counting.

6.14.3 Evaluation History

The initial basis for the Cycle 1 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 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 Cycle 1 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 Cycle 1 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.

6.14.4 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.

6.14.4.1 *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.

6.14.4.2 *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.

6.14.4.3 *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 Cycle 1 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.

6.14.5 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. The final rules and a 2 year extension of 45Q was passed in December 2020. Several US states are looking to simplify CCS guidelines and provide regulatory clarity to help enable CCS deployment (Beck, 2019). The USA does, however, score 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.

6.14.6 Issues for the Assessment

The Cycle 1 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.

6.14.7 Future Updates

6.14.7.1 *Future assessments*

- 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.