GLOBAL CCS INSTITUTE

GLOBAL STORAGE READINESS ASSESSMENT

AN APPROACH TO ASSESSING NATIONAL READINESS FOR WIDE-SCALE DEPLOYMENT OF CO_2 GEOLOGICAL STORAGE PROJECTS

MAY 2015

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ISBN

978-0-9871863-7-9

Acknowledgements

The authors would like to acknowledge the assistance of the many research and government bodies who have published CO_2 storage assessments. A special thanks to members of the CGS Europe Project in providing information and reviewing the original country scoring.

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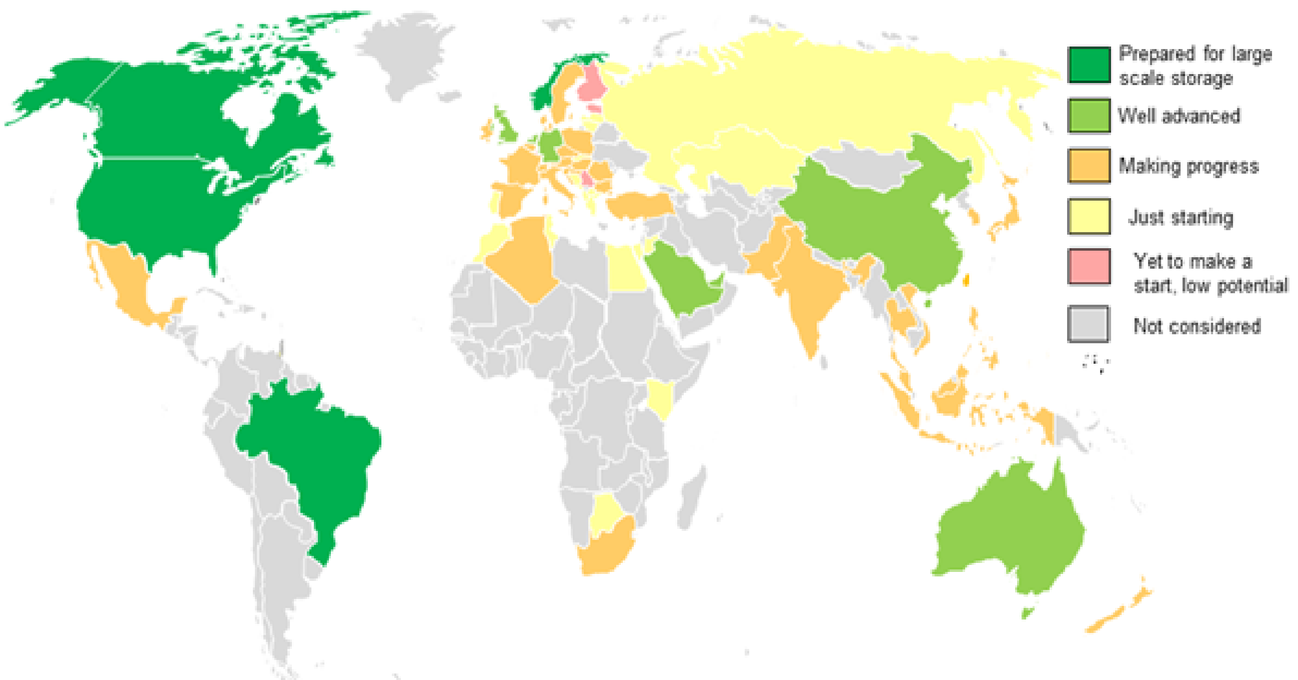
Executive Summary

The Global CCS Institute has devised a methodology to assess any given nation's readiness for large-scale carbon dioxide (CO_2) geological storage projects, as part of the wide-scale deployment of carbon capture and storage (CCS) projects. Our assessment method enables a consistent and repeatable framework using a weighted set of criteria for transparency and accountability that can be updated as necessary to revise assessments and to include new nations.

- An assessment of 61 countries shows in 2014, 11 nations are ready or well advanced for the CO_2 geological storage and 31 countries are making significant progress.
- Brazil, Canada, Norway and the United States (US) are ranked highest in this assessment and are considered ready for the wide-scale deployment of storage.
- Government action on climate change, fossil fuel resources or high emissions are the main factors that result in a country's high ranking.
- An advanced hydrocarbon industry for data and expertise also strongly influences a country's ranking in their ability develop storage assessments.
- Regional to country-scale assessments are an important step to help de-risk early storage exploration programs.

This assessment is a living document designed to reflect the evolution of CCS and be updated regularly.

Figure 1: World map showing countries colour coded by storage readiness



1

Introduction

CCS can reduce greenhouse gas emissions from the power industry and other energy intensive industries. Twenty two large-scale integrated CCS projects (LSIP[1]) are now operational or under construction globally, with the potential to capture around 40 million tonnes per annum (Mtpa) of CO_2 (Global CCS Institute, 2014). International Energy Agency (IEA) (2015) analysis indicates 120 gigatonnes of CO_2 will need to be stored between now and 2050 to keep within its two degree scenario. To achieve this goal many countries need to be prepared for large scale CO_2 geological storage (herein referred to as storage) to support a significant number of new large-scale CCS projects over the coming decades.

One of the first steps in deploying CCS in any nation is to understand the geological resources available for storage. A global analysis of how countries are progressing in the exploration of their storage potential and ability to host storage projects was created by the Global CCS Institute, termed the *Global Storage Readiness Assessment*.

The methodology of this assessment is transparent and updatable as countries progress their knowledge of storage resources. The assessment may be used as a living document with periodic updates maintaining a systematic, repeatable approach that can, in the future, show a changing worldwide situation.

This storage assessment complements the *CCS Policy Indicator* (CCS-PI) previously published by the Global CCS Institute in 2013 to compare levels of national policy support for CCS. Together, these two assessments work to highlight the global progression of CCS.

2

Methodology

The goal of the *Global Storage Readiness Indicator* is to consistently define and assess a country's preparedness for wide-scale deployment of large storage projects over time. In 2013, an initial literature review was completed by Rick Causebrook, which was updated by the Institute authors in 2014. The findings of this review can be found in Appendix 1. The many organisations and authors that contributed to those publications have advanced the global understanding of storage prospectivity and capacity estimates. That literature is the basis of this assessment and the findings of this review.

The Global Storage Readiness method follows a generalised approach presented by Bachu (2003) for the screening and ranking of basins for their suitability for storage. That method involves judging a series of criteria with a set of values. The criteria are not equally critical so the scored criteria are weighted based on their importance to the assessment. Providing the underlying definitions and weighting assigned to the criteria do not change, consistent assessments can then be updated over time. The Global Storage Readiness uses a similar method to Bachu (2003) with eight criteria being adapted to assess country's storage knowledge and advancement and this incorporates a series of geological, technical and development criteria to give an overall ranking on a country's preparedness (Table 1). The procedure is as follows:

1. A first screening criteria determines if a country has significant storage potential. Only nations with 'Yes' proceed.

2. Thereafter, each criterion grades from A to E, where A is high or advanced and E is low or poor.

3. The graded criterion is then converted to a numerical score and weighting applied. The weighting is based on the criteria's importance, as judged by the authors in consultation with storage community

4. The final score groups countries across five categories from 'Yet to make a start or very low potential' through to 'Prepared for wide-scale storage' (Table 2).

Table 1: Criteria for grading storage readiness

Criterion		Grades				
		E	D	C	B	A
		Low				High
1	Has the country any conventional storage potential? Yes/No					
Standard of country storage assessment						
2	Regional potential	Extremely limited		Limited		Extensive
3	Regional assessment	None	Limited	Partial	Detailed	Full
4	Dataset	None	Sparse	Moderate (Appropriate)	Detailed	Extensive
Maturity of the science						
5	Assessment maturity	Regional, Country-scale/ Theoretical capacity		Basin-scale/ Effective capacity		Site-scale/ Practical capacity
6	Pilot project	No	Preliminary planning	Active preparation	Injection has occured in one project	Injection has occured in several projects
7	Commericial project	No	Active planning	Passed final investment decision	Injection has occured	Mature project
Outreach						
8	Knowledge dissemination	Does not engage in any known dissemination activities	Attends knowledge sharing activities	Actively participates in knowledge dissemination activities organised by others	Has organised/ held some knowledge sharing activities	Has active targeted program of knowledge sharing and/or dissemination

Providing the underlying definitions of the criteria do not change, this method allows for consistent assessments over time and the addition of new nations. For further details on the criteria and the weighting of the criteria please see Appendix 1.

2.1

Assumptions and limitations

- The countries selected for this study have either: completed previous CCS studies; geographically close to a high emissions region; or a strategic country for their region.
- The assessment includes storage potential in deep saline formations, depleted oil and gas fields and in association with CO_2-enhanced oil recovery (EOR).
- Only storage within the borders (including the marine exclusive economic zone) of a country is considered. Storage in neighbouring or even distant countries may become a reality in the near future for many countries with low quality or inaccessible storage sites.

3

2014 Assessment

The results of the 61 countries are summarised in Table 2 and figures 1 and 2.

The key conclusions are:

- Brazil, Canada, Norway and the US are 'prepared for wide-scale storage'.
- Seven countries are 'well advanced'
- 31 countries are 'making progress' and a further 18 are 'just starting' on the CCS pathway.

Table 2: Storage readiness assessment results

Prepared for wide-scale storage					
Brazil	Canada		Norway		USA
Well advanced					
Australia	China		Germany		Netherlands
Saudi Arabia		United Arab Emirates		United Kingdom	
Making progress					
Algeria	Austria	Belgium	Bulgaria	Croatia	Czech Rep.
Denmark	France	Hungary	India	Indonesia	Italy
Japan	Malaysia	Mexico	New Zealand	Pakistan	Philippines
Poland	Rep. Ireland	Romania	Slovenia	South Africa	South Korea
Spain	Sweden	Switzerland	Taiwan	Thailand	Turkey
Vietnam					
Just starting					
Albania	Bosnia & Herzegovina	Botswana	Egypt	Greece	Jordan
Kazakhstan	Kenya	Latvia	Lthuania	Macedonia	Montenegro
Morocco	Portugal	Russia	Slovakia	Trinidad/Tobago	Tunisia
Yet to make a start, or very low potential					
Serbia					

4

Discussion

An analysis of the results highlights some critical aspects towards the global deployment of CCS. The most striking is only four countries are currently prepared for wide-scale storage, including Brazil, Canada, Norway and the US. All of these countries have a CCS research and development program, extensive storage potential, an innovative and advanced oil and gas industry and, with the exception of Norway, CO_2 for enhanced oil recovery (CO_2-EOR) projects. Norwegian industries are leaders in dedicated storage with two operating large-scale CCS projects.

'Well advanced' nations are generally countries with high CO_2 emissions (per capita or total) including Australia, China, Germany, Saudi Arabia, United Arab Emirates (UAE), and the United Kingdom, with the exception of Netherlands. Almost all of these nations, in the top two rankings have LSIPs in operation, under construction or in an advanced planning stage.

The 'Making progress' category holds the largest number of nations. Collectively, they understand their storage resource, have undertaken some level of storage research or progressed to an injection project. However, they do not meet all criteria. Firstly, it is important to identify that some nations have a low storage potential but are leading nations in other part of the CCS value chain, such as capture research. This study focuses only on storage factors within jurisdictional boundaries and therefore is not a reflection of CCS advancement. South Korea and Japan as examples, at this point, have comparatively low readily-identified storage capacity (this does not necessarily preclude wide-scale CCS deployment in their nation). They have, however, completed storage evaluations, potentially at several sites. On the other hand, a large number of nations also ranked as 'Making progress' have extensive storage resource potential, but their research and development of that resource is low. Nations including India, Malaysia, Mexico, Poland and South Africa fall into this group. Finally, there are nations that have not progressed their storage resource assessments to an advanced stage, but have completed a few limited site storage evaluations or even injection projects. France, Italy and Spain all fit into this group.

Nations in the 'Just starting' category generally have not pursued any extensive storage studies, or explored CCS in detail. The majority of countries in this category are developing nations and are not obliged to pursue climate change mitigation.

4.1

Priority areas

This review found regional and country-wide assessments lead to successive studies and storage knowledge maturity. Countries with regional, or country-wide assessments, more often than not, have mature basin or site-scale assessments with dynamic simulations completed. To date though, almost half of the countries assessed have not completed full national assessments or been part of regional studies. Regional studies such as on the Baltic Sea (Elfosrk, 2014), or the Asian Development Bank report on CCS in Southeast Asia (ADB, 2014) promote a country's storage readiness level even if the assessment is at a broad level. Multi-national reports are especially important for developing nations, or nations with little oil and gas industry experience as they enable the sharing of limited data, technical expertise and methodologies to those countries. Using this data and knowledge, national, or even basin-scale studies could follow the regional studies. An example is the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) CO_2 Storage Mapping Program which will produce a regional atlas and provide the training and exchange of data for national studies to proceed.

With regards to data availability, this study has found nations without access to subsurface geologic data (seismic and well) and/or low development of oil and gas resources had limited knowledge of their storage potential. Pre-competitive data acquisition and research programs focusing on storage reservoirs are important for these nations to evaluate their storage resources. Such data opens up the utilisation of the storage pore space as a resource and enhances our understanding of the global storage capacity.

For a country's technical development, the construction of a pilot project is highly beneficial for the deployment of CCS, especially those in the 'Making progress' category. Pilot injection projects can greatly enhance the technical capacity of a country (in regards to CCS technology), and also educate the public on CCS. The majority of the countries assessed have not completed a pilot project.

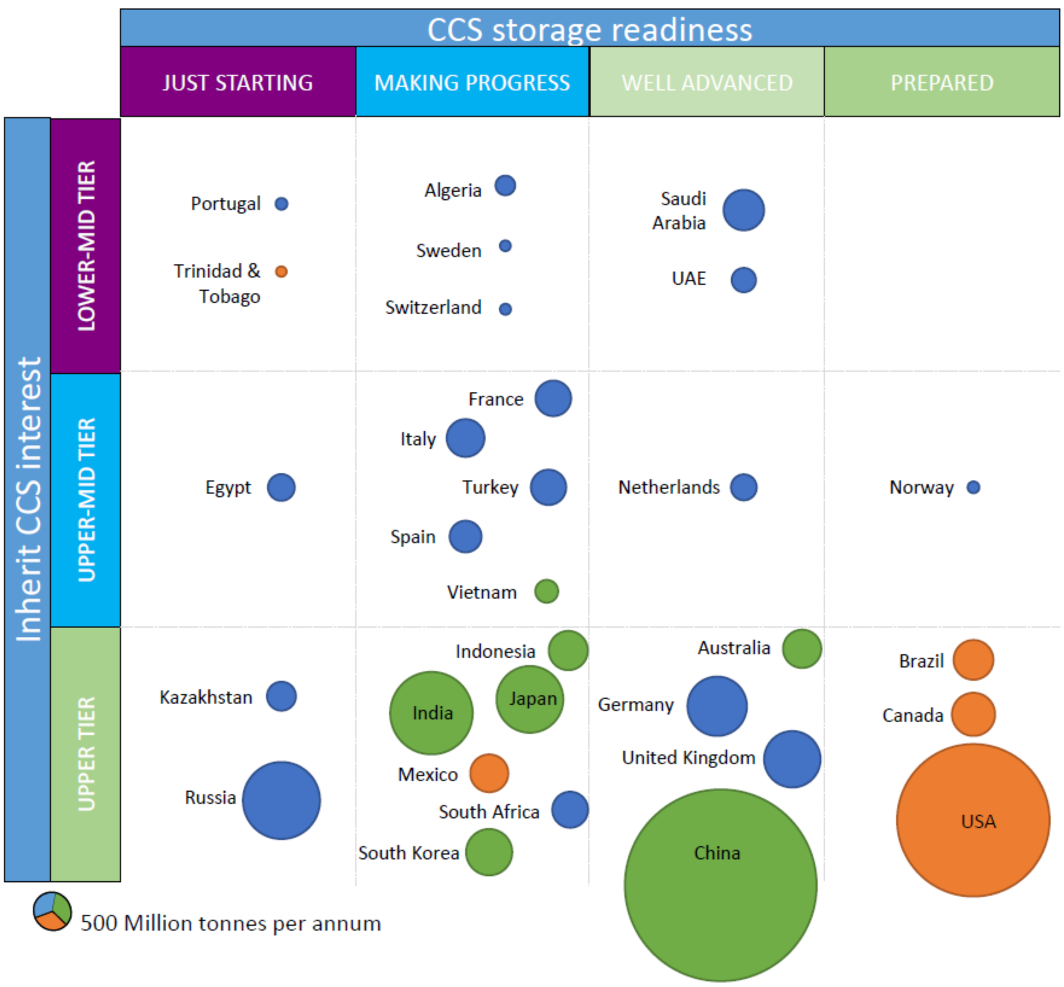
4.2

CCS Interest

A country's CCS interest can be expressed as their *Inherent CCS Interest Index*, previously published in the *CCS Policy Indicator* (Global CCS Institute, 2013). The index is based on a series of indicators such as fossil fuel production and consumption. For example, countries heavily reliant on fossil fuel exports (eg Poland) or are large fossil fuel users (eg India) will rate high, whereas countries with low fossil fuel use or exports will not. When comparing the storage readiness and CCS interest, the countries with a higher interest in CCS are also more advanced in their storage preparedness (Figure 2). In terms of progress on climate change, several nations with high emissions are also focusing on CCS and are prepared, or well advanced for storage, including China and the US. In addition, key fossil fuel exporting nations have also recognised the importance of CCS and sit in the well advanced and prepared categories.

Figure 2: Assessment of the 2014 storage readiness assessment versus the CCS interest

Ball size relates to 2012 CO_2 emissions from fuel combustion (Source: CO_2 emissions from fuel combustion (IEA, 2014)). Green: Asia-Pacific, Orange: Americas, Blue: Europe, Africa, Middle East, Eurasia.



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Conclusion

This report summarises the first Global Storage Readiness assessment using a systematic and replicable methodology for the 61 countries included. The state of play in 2014 is discussed here, but this storage readiness assessment is designed to be updated regularly as CCS progresses. The assessment found that:

- Brazil, Canada, Norway and the US are ranked highest in this assessment and are considered ready for the wide-scale deployment of storage. Seven countries are 'well advanced'
- Many nations are progressing to a stage where their storage readiness can be potentially accelerated, with emission intensive countries dominating this ranking, most notably Japan, South Korea, China, UAE and Saudi Arabia.
- The drive for government action on climate change, fossil fuel resources or high emissions are the main factors according to this assessment that drives a country's high ranking.
- The importance of the hydrocarbon industry for data and expertise also strongly influences a country's ranking in their ability develop storage assessments.

The *Global Status of CCS: 2014* report stated it can take up to ten years to appraise a storage site. Knowing where suitable storage sites are located and how much space is available for storage are the two storage-related uncertainties in the early stages of a project's life. Regional to country-scale assessments are an important step to help de-risk early storage exploration programs through recognising knowledge or data gaps, as well as identifying basins with the highest (or most practical) potential for storage. Upon further advancement of a country's storage program, pilot projects are cost effective, advanced technical platforms to show that CCS is achievable in a country, fostering wider-scale CCS deployment. There are no technical barriers to the deployment of multi-million tonne storage operations, yet despite a few countries being storage ready and many advancing towards storage readiness, the deployment of large-scale projects is currently slow. This report is intended to help countries identify gaps as well as strengths to shape their future storage programs and to help accelerate CCS deployment.

6

Recommendations

This report recommends regional collaboration on multi-country assessments for several reasons. They enable:

- Transfer of knowledge and methodologies
- Solutions for nations with low or no storage potential, and allow collaborative planning for storage in neighbouring countries
- Advanced nations to assist less resourced neighbours. Many of the countries in the 'Just starting', or 'Yet to make a start' category are developing nations.

A second recommendation is that nations which have completed regional and national studies, especially those in the 'Making progress' ranking, complete site-scale evaluations and progress to a comprehensive, detailed understanding of their storage resources and the realistic practical storage capacity in their nation. Site-scale studies assist nations to identify barriers to deployment such as legal and regulatory issues, and they enable national planning, including source-to-sink matching.

This report recommends that countries at an advanced stage of CCS development either initiate or participate in a small-scale storage injection project in their region. A pilot project results in many benefits including public awareness of CCS and addressing country-specific challenges. Participating in a pilot project in their region will enable local scientists and technical experts to understand the processes and fundamentals of enabling a storage project, with potential knowledge flow-on effects in their country.

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Appendix I: Framework for systematic assessment of geological storage readiness: summary of contractual report

1. Introduction

The Global CCS Institute (the Institute) contracted the development of a protocol for the systematic assessment of a country's preparedness for the geological storage of carbon dioxide (CO_2), based on publically available information.

2. Assessment Development

The first stage of the project has been the development of the protocol and a mechanism for a consistent approach to the assessment of the available data. The basis of the methodology chosen was broadly based on one proposed in 2003 by Dr Stefan Bachu of the Alberta Research Centre (now called Alberta Innovates – Technology Futures) for the screening and ranking of basins for their suitability for geological storage (Bachu, 2003). The Bachu method involves judging the subject of the assessment against weighted criteria under a set of clearly established values. The method allows for a rapid and consistent assessment of a group of units and, providing the underlying definitions or weighting of the criteria are not changed, allows for consistent assessments over time. New entries can be added to the database or pre-existing entries can be revised without necessarily needing to revisit the previously agreed criteria and weightings.

3. Assessment Methodology

The assessment methodology was documented in a spreadsheet-based workbook. Previous experience has shown this to be the best method to record data and the ongoing decision-making progress that actual underpins the assessment methodology.

Assessment was against eight criteria documenting how far a nation has progressed towards wide-scale geological storage of CO_2 and falls into four general categories.

3.1. Geological Factors

3.1.1 Internal criterion: Has the country any conventional storage potential?

The initial criterion, is a Yes, or No answer. A "no" answer precludes any further scoring in this assessment. Countries identified as having no storage potential are generally in geologically-young, mountainous or igneous provinces lacking deep sedimentary basins.

3.1.2 Criterion 1: Regional potential

The first scoring criterion grades from *extremely limited* to *extensive* and has the highest weighting as without potential to store CO_2, wide-scale CCS in that country will be difficult. Most geological storage will be in sedimentary basins. Countries with geologically younger, relatively deep, but undisturbed sedimentary basins are often the most prospective for extensive storage capacity.

Basins with the highest potential for the geological storage of CO_2 are found in basins which also host extensive volumes of oil or gas. That is, the conditions necessary for trapping oil and gas are precisely those which are required for the storage of anthropogenic CO_2. However, the converse is not necessarily true as sedimentary basins which have not held oil and gas may still have potential for storage if the absence of oil and gas is primarily due to the absence of suitable source rocks. An example is the Mount Simon Sandstone, interior the US, the target formation of pilot and commercial storage projects.

In contrast, basins which have undergone deep burial and subsequent uplift and possibly extensive folding will most likely have seen the qualities of the potential reservoir rocks degraded to the point that they are not suitable for storage. In addition, those countries which lie areas of new or ancient fold mountain belts, or with large areas of ancient rocks, often with a high occurrence of valuable mineral deposits, have a reduced potential for the identification of suitable storage sites.

3.2 Storage capacity assessment

3.2.1 Criterion 2: Regional assessment

Regional assessment criterion is concerned with the level of detail the country has completed in their national assessments and ranges from limited to full. The criterion is highly weighted as it directly reflects the country's progression in understanding their storage potential and what studies/exploration have been completed to date. However, it does not necessarily inhibit the deployment of CCS as is seen in the case of Algeria, which has a limited regional assessment ranking, but a mature commercial CCS project, In Salah, operated by BP.

Nevertheless, it is an assertion of this study that in order to be fully prepared for wide-scale geological storage a country should have conducted a detailed review of its storage potential using all available data. Published regional assessment examples include North American Carbon Storage Atlas 2012, the Brazilian CARBMAP Project, the Atlas on Geological Storage of Carbon Dioxide in South Africa, or the CO_2 Storage Atlas of the Norwegian North Sea. In general, such atlases are comprehensive and cover all potential storage basins within the area under study. Optimally, they would include all potential basins within the national jurisdiction and this would warrant the "full" rating.

In other cases, assessments that consist of individual studies dealing with only selected basins or even just particular depleted oil or gas fields would have a lower score. The extent to which information is available on the assessed storage capacity of a country's sedimentary basins varies widely and studies may have been known to have been carried out but not been publically released for one reason or another. In making an assessment such as the present one, credit can only be given for information that is in the public realm.

3.2.2 Criterion 3: Dataset

The existence and amount of deep sedimentary basin data available grades from none to extensive, however, it does not preclude a country's ability to wide-scale CCS activity and therefore has a low weighting in this assessment.

For regional assessments to be of value it is important to consider the amount and quality of the technical data on which it was based. Generally, due to the depths under consideration for storage, these data are derived from the exploration for oil and gas. Importantly, the availability of such technical data can vary widely from country to country. In some cases, data is privately held by the exploration companies and/or national oil companies and may be unavailable for use by outside bodies (eg Malaysia). In other cases exploration data may become available (normally after a withholding period), for a fee or sometimes simply for the cost of transfer. In such cases, the data is held in a National Data Repository that has been set up to preserve resource data, particularly relating to oil and gas exploration and production, and to promote further resource exploration within the country (eg Australia). The availability of data is a major consideration when assessing the level of confidence placed in a capacity assessment, particularly as assessments have a high degree of uncertainty, especially when evaluating saline aquifer storage.

3.3 Maturity of the science

3.3.1 Crierion 4: Assessment maturity

Assessment maturity grades from *Regional, Country-scale/ Theoretical capacity* to *Site-scale/ Practical capacity* and is moderately weighted, as it reflects a country's understanding of their storage potential and level of knowledge.

A number of methodologies for assessing regional capacity have been published over the past 10 years. They range from the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program methodology (2006), CSLF methodology (2007) to the recent publication by the IEA, *Methods to Assess Geological CO_2 Storage Capacity: Status and Best Practice* which develops a methodology first proposed by the US Geological Survey (USGS) in 2010. The latter relies on detailed examination of the geological data available from each basin.

All of these methodologies recognised that, particularly in deep saline formations, an understanding of the pore space available to CO_2 needs to progress from broad-scale national, or basin studies through to site-scale development. Throughout this ascent of knowledge, the amount of time, data used and detail of the reservoir and seal increases. At the broadest level, a desktop study will utilise highly extrapolated data with broad assumptions to calculate the reservoir and seal quality as well as storage capacity based on averaged data. It is a critical first pass in understanding a country's storage potential. At the most detailed level, that is the most precise way of calculating the storage capacity for a specific site, prior to actual injection, is completed through a detailed mathematical modelling (usually using a dynamic reservoir simulator). This often will be applied at the site of injection, targeting specific reservoir(s) with precise reservoir properties.

3.3.2 Criterion 5: Pilot project and Criterion 6: Commercial project

A pilot, or commercial injection project are the final steps to storage readiness. It shows that a country has progressed to the point of enabling deployment of CCS projects. In order to progress to this point, the project has met technical, economic, social and regulatory hurdles through expertise and knowledge of CCS requirements. A pilot or commercial project shows that CCS is possible in their nation and this is important for public perception. Pilot injection criterion grades from none to *several projects*, and commercial-scale storage project grades from *none* to *mature project*. Both criteria are heavily weighted as they provide actual deployment of storage. The two criteria have intermediate stages of active planning, but it should be emphasised that this only refers to projects which have a high likelihood of being achieved. Experience in many countries has shown that numerous projects in active planning, often disappear early in the process.

3.3.3 Criterion 7: Knowledge dissemination

Grades from *Does not engage in any known dissemination activities* to *Has active and targeted program*. A proxy for the maturity of the science within a country could be the readiness of research institutions within that country to engage in the dissemination of technical knowledge. It has been observed that whereas some countries readily engage in knowledge dissemination others may be more reticent, especially about their own capacity for storage which may be regarded as commercially or politically sensitive. Given the ultimate aim of geological storage is climate change mitigation, which is a global issue, the free exchange of knowledge is an important aspect of the development of the science. However, it is recognised there might be an objection made and this criteria does not directly relate to storage readiness and therefore it is given a reduced weighting in the final scoring.

4. Scoring

Each country was graded against the eight criteria on a scale of A (high) to E (low) which were converted to a numerical score before being weighted and converted to a total out of 100 (Table 1). The resultant score was used to allocate the country to one of five status levels (Table 2): from 'Prepared for wide-scale storage' to 'Yet to make a start or very low potential'. The boundaries between the levels are to some extent arbitrary and may be revised in future iterations.

Table 1: Criterion weighting for this study

Criterion	Weighting (%)
Has the country any conventional storage potential?	Y/N
Regional potential	22
Regional assessment	18
Dataset	8
Assessment maturity	15
Pilot project	15
Commericial project	20
Knowledge dissemination	2

Table 2: Scores for the five status levels

Grading		
Stage1	Yet to make a start or very low potential	<10
Stage 2	Just starting	10 to 30
Stage 3	Making progress	30 to 70
Stage 4	Well advanced	70 to 90
Stage 5	Prepared for wide-scale storage	over 90

5. Source Documents and References

5.1 Regional, Country and Basin Assessment

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5.5 Web resources

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http://www.cslforum.org/index.html

CO_2CRC
http://www.co2crc.com.au/

Geocapacity
http://www.geology.cz/geocapacity

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http://www.geus.dk/programareas/energy/denmark/co2/GESTCO summary_report_2ed.pdf

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