EVALUATION OF BARRIERS TO NATIONAL CO_2 GEOLOGICAL STORAGE ASSESSMENTS

Report: 2016/TR1

February 2016

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Evaluation of barriers to national CO_2 geological storage assessments

Energy Programme

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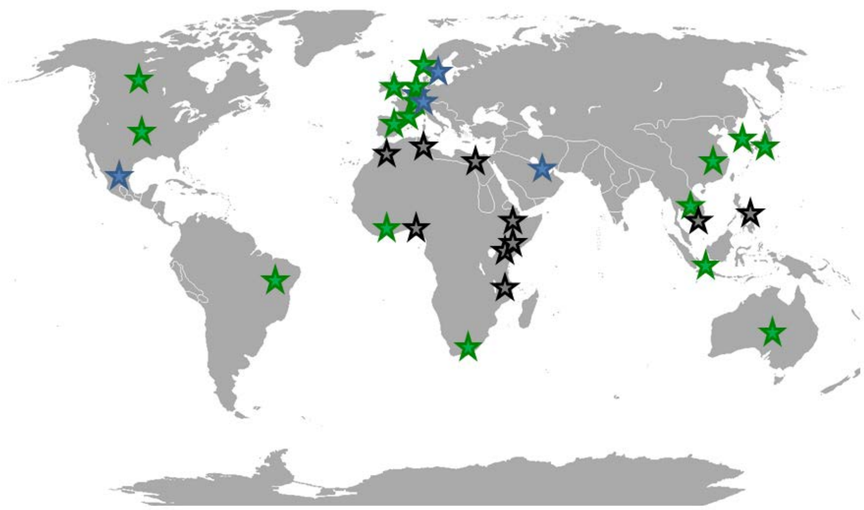

BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/15/055

Evaluation of barriers to national CO_2 geological storage assessments

C J Vincent, M S Bentham, K L Kirk, M C Akhurst and J M Pearce

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Keyworth, Nottingham British Geological Survey 2015

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Foreword

This report is the published product of a study undertaken for the Carbon Sequestration Leadership Forum (CSLF) to assess barriers to high-level geological CO_2 storage assessments for the Clean Energy Ministerial. This review was undertaken by the CO_2 Storage team of the British Geological Survey on behalf of UK Department of Energy and Climate Change and the Korean Clean Energy Ministry to support the work of the CSLF.

The review was funded by the UK Department of Energy and Climate Change and the Korean Clean Energy Ministry. The project was managed by the IEA Greenhouse Gas Research and Development Programme (IEAGHG).

The survey responses expressed and analysed in this report are based on publicly available information and the views of respondents to a questionnaire and follow-up interviews. The responses do not necessarily reflect the view of authorities or government policies for the countries included in the survey.

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Decision makers need information on their national carbon dioxide (CO_2) storage resource to assess the potential contribution that deployment of Carbon dioxide Capture and Storage (CCS) could make to national targets for reducing CO_2 emissions. The first step in assessing national CO_2 storage potential is usually the preparation of a country-level inventory of potential storage options and large sources of CO_2 emissions. This report summarises an assessment of potential barriers to national geological storage assessments and includes an analysis of common methodologies for performing such an assessment.

The main barriers were identified through responses to an online questionnaire and follow-up interviews which targeted key stakeholders in more than fifteen countries. Stakeholders were selected where the potential for CCS deployment has already been explored, to a greater or lesser extent.

Summary of key findings:

All of the fifteen countries who responded to the questionnaire had completed national 'theoretical' storage capacity assessments, of which eight countries had achieved 'matched' capacity assessments in which storage capacities were matched to potential emissions sources. In many cases, although the barriers identified in this report prevented further 'maturation' of these storage capacity estimates, these initial estimates were sufficient to allow policymakers to make informed decisions about priorities for follow-up actions.

The most commonly reported barriers to progressing national assessments of CO_2 storage capacity were:

- Data availability, either due to sparsity or absence of data, or data that is available but proprietary and so inaccessible.
- Data quality, often due to the age of the available data.
- Lack of industrial support.
- Absence of political and regulatory support.

Reported issues with data quality and accessibility did not prevent all the questionnaire respondents from achieving some level of national assessment.

Commonalities and differences between the most frequently applied methodologies for high-level storage assessments were assessed. Methodologies for estimating storage capacity varied widely in approach and showed continuous development in terms of sophistication and techniques. Significant challenges have been created in some countries by undertaking partial assessments using widely differing methodologies which prevented assessments from being made for the country as a whole. Clarity on the methodology used and underlying data is crucial.

The following key recommendations are suggested to support national storage assessments and to enable comparability between assessments:

- **National storage assessments are typically undertaken via support from the State. Without state support, national assessments seem unlikely to be prepared** though the mechanisms of delivery and sources of funding vary between countries.

- **The assessments should be undertaken at increasing levels of detail in a step-wise manner, with appropriate decision points** allowing consideration of the benefits of further detailed assessments, reflecting the likely contribution CCS might make to emissions reduction. Assessments should also consider neighbouring jurisdictions where suitable storage capacity might be accessed.
- **Where storage potential exists, policy support should ensure that there is a long-term vision for reducing greenhouse gas emissions which may include deployment of CCS.** This will encourage industrial support for CCS by reducing uncertainty in the future political and regulatory support for CCS.
- **A public organisation with a clear mandate from their national government to manage the assessment and particularly to coordinate access to, and collation of, the relevant data will support efficient national assessments.** The creation of a national body to drive CCS forward seems to greatly facilitate the speed and momentum of assessments. National storage assessments have been achieved in less than two years, where they have been undertaken by well-supported national geological surveys/geological directorates. Such relatively fast assessments have been achieved by using publically available data which has already been collated in national data repositories.
- **Data access should be facilitated at national level** (while bearing in mind commercial sensitivities). This will also be of wider benefit as sharing of geological and geophysical data is relevant to a large number of applications including strategic resource management, e.g. hydrocarbons, groundwater, gas storage and mineral reserves.
- **National assessments to the level of 'effective' storage capacity have been achieved within two years in a few countries but more typically take five to ten years to complete.** Extending these assessments to 'practical' capacities and undertaking site-specific 'matched' capacity assessments typically takes at least five years.
- **A probabilistic approach allows extension of the storage estimate to regions where there are few data.** A clear explanation of where this has been performed and the methodology used supports comparability of estimates. Clarity on uncertainties that remain in the data is critical to the assessment.
- **Those national assessments that were most rapidly completed and are most mature appear to be those undertaken by national or regional geological survey organisations.** These organisations have access to available data, of sufficient quality, and have been supported specifically by national bodies whose remit includes CCS development.
- **Developing a strategy for prioritisation of those sites for which detailed assessments should be undertaken is a crucial step** in developing a targeted and efficient approach to storage assessments.
- **A national-level database of potential sites is a good stepping-stone to detailed site surveys and flow simulations.** These are typically funded through national funding and help identify 'sweet spots' for potential storage operators.

- **Population of a well-structured database is an essential underpinning activity that will support capacity assessments and future work.** The database should facilitate clarity of understanding of the data source and accuracy of the data it contains.
- **Detailed formation or site-specific assessments can be focused on 'sweet spots' identified by the first national assessment.** These will require more detailed analyses and may require acquisition of higher-resolution data, requiring a larger investment and longer-term commitment of resources.
- **Simple volumetric estimates are a strong first stage in a national storage assessment.** These can be performed using existing data and give decision makers an early indication of the role CCS could play in reducing national CO_2 emissions. Positive results from these assessments could encourage all stakeholders to continue to improve the quality of assessments as data quality and access, and funding, increase. These simple volumetric estimates will give an order of magnitude estimate of storage capacity.
- **Flow simulations providing dynamic capacity estimates** (including the impact of site-specific dynamic factors such as injection rate, timing of injection, pressure effects at site-specific and regional scales) **are needed to fully understand the potential CO_2 storage capacity.** New data will almost certainly be required to meet this increased level of understanding.
- **A good understanding of the uncertainties and constraints in the underlying data remains critical throughout all stages of assessment.** Quality assessment and control of data deposited in repositories is essential to ensure the reliability of the data that informs future storage capacity assessments.
- **A clear and comprehensive description of the capacity assessment methodology used is essential** and critical to facilitate comparisons between estimates.
- **It is important that capacity estimates clearly describe the methodology used, as there is no agreed uniform methodology, so that the limitations of the different approaches are understood.** Creating an agreed uniform methodology would be extremely challenging as demonstrated by the wide range of approaches adopted by researchers. A clear understanding of the main approaches will allow some comparison between national capacity estimates. Storing the raw data effectively in a well-formatted database will allow the data to be reused as methodologies advance.
- **Developing countries, particularly where oil and gas resource development is still maturing, are more likely to have a greater problem finding the expertise to perform CO_2 storage assessments. However, generally, there was an interest in international collaboration and knowledge sharing so this barrier does not seem insurmountable**. Knowledge sharing projects funded by the European Commission, and the international development banks have supported initial assessments of CO_2 storage opportunities in some developing countries. Recognition of projects from established international bodies such as the Carbon Sequestration Leadership Forum (CSLF) and support from organisations such as the Global CCS Institute (GCCSI) and organisations with practical experience of undertaking capacity estimates can assist development of capacity estimates where local expertise might benefit from knowledge sharing activities.

- **If the profile of low-carbon technologies, including CCS, was increased, data access might become easier.** If it is clearer to data holders that the request for data is related to greenhouse gas (GHG) emissions mitigation and not competition for energy resources they may be more open to providing data for storage assessments.
- **The lack of modern data should not prevent storage assessments from being undertaken.** Legacy data can be used to provide an adequate national assessment and highlight areas where new data should be acquired.
- **The raw data should be made available in tabulated format**, e.g. depth, porosity, formation thickness, net sandstone to gross thickness, areal coverage, volume of hydrocarbons removed, formation compartmentalisation, pressure and temperature values**.** This will enable researchers to apply a methodology, allow comparison between different storage sites and quality control.

1 Introduction

Carbon dioxide Capture and Storage (CCS) is widely recognised as being essential to achieving the necessary reductions in atmospheric emissions of CO_2 from fossil-fuel based power generation and many industrial processes (IPCC, 2014). Decision makers need information on their national carbon dioxide (CO_2) storage resource (referred to here as the storage capacity) to assess the potential contribution that deployment of CCS could make to national targets of emissions reductions. The first step in assessing national CO_2 storage capacity is usually the preparation of a national, country-level inventory of potential storage options and large sources of CO_2 emissions.

This report describes a review undertaken by the CO_2 Storage Team of the British Geological Survey on behalf of UK Department of Energy and Climate Change and the Korean Clean Energy Ministry, to support the work of the Carbon Sequestration Leadership Forum (CSLF). The report includes a review of internationally used methodologies for estimating geological storage capacity and the analysis of results from a survey of national storage capacity assessment experience. We conclude with recommendations of practical steps that could be taken to support and improve national assessments of CO_2 storage capacity.

The report gives a high level summary of the main barriers to national storage assessments identified through the survey (Chapter 2) and discusses advantages and disadvantages of storage methodologies commonly utilised for national storage assessments (Chapter 3). Detailed results of the survey are given in Appendix 2 (questionnaire results) and Appendix 3 (summary from follow-on interviews). Detailed analysis on the storage assessment methodologies is given in Appendix 4.

1.1 DEFINITION OF NATIONAL ASSESSMENTS OF CO_2 STORAGE POTENTIAL

The level of assessment of CO_2 storage potential can be defined in a number of ways and undertaken using a range of methodologies. For the purpose of this survey, the widely recognised Carbon Sequestration Leadership Forum methodology (CSLF, 2007) was used to define the level of detail the assessments achieved.

National assessments of storage capacity identify potential opportunities where CO_2 may be securely stored in the deep subsurface over extremely long timescales. The first step usually comprises a region-by-region or sedimentary basin-by-basin assessment of potential reservoir formations combined with the identification of potential sealing formations. The coverage and quality of this national assessment is highly dependent on availability of data and other resources to complete the study.

Estimates of the availability of many geological resources, such as minerals, groundwater and fossil fuels, are commonly divided into at least two categories: *resources* (accumulations of anything that is useful and accessible to mankind) and *reserves* (that part of a resource that is available for production now, by being economically recoverable under current technological conditions).

Potential CO_2 storage capacity in geological formations should, therefore, be considered as a *resource*. Lack of widespread experience in CO_2 storage assessment, however, make estimating CO_2 storage capacity *reserves* more challenging. The Carbon Sequestration Leadership (CSLF)

Taskforce proposed that the degrees of geological and economic uncertainty associated with various parts of the resource can be considered in terms of a techno-economic resource (CSLF, 2007; please also see Appendix 1 for more detail):

1. **Theoretical Storage Capacity** is the total resource. It encompasses the whole of the resource pyramid (Figure 8). It is the physical limit of how much the geological system can accept. It assumes that the system's entire capacity to store CO_2 in pore space, or dissolved at maximum saturation in formation fluids, or adsorbed at 100% saturation in the entire coal mass, is accessible and utilized to its full capacity.
2. **Effective Storage Capacity** represents a subset of the 'theoretical' capacity and is obtained by considering that part of the theoretical storage capacity that can be physically accessed and which meets a range of geological and engineering criteria.
3. **Practical Storage Capacity** is that subset of the 'effective' capacity that is obtained by considering technical, legal and regulatory, infrastructural and general economic barriers to CO_2 geological storage. The Practical Storage Capacity corresponds to the term 'reserves' used in the energy and mining industries.
4. **Matched Storage Capacity** is that subset of the 'practical' capacity that is obtained by detailed matching of large stationary CO_2 sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate to contain CO_2 streams sent for storage from that source or sources. This capacity is at the top of the resource pyramid and corresponds to the term 'proved marketable reserves' used by the mining industry.

2 Survey to assess barriers to national high-level geological storage assessments

A survey covering 25 countries was conducted to assess the main perceived barriers to undertaking a national storage assessment (Figure 1). The purpose of the survey was to:

- explore the extent of high-level assessments of geological CO_2 storage capacity, achieved or desired,
- the potential barriers that have been faced in trying to achieve assessments for potential storage options on a country-wide level and
- learn how barriers have been overcome where national assessments have been successfully prepared.

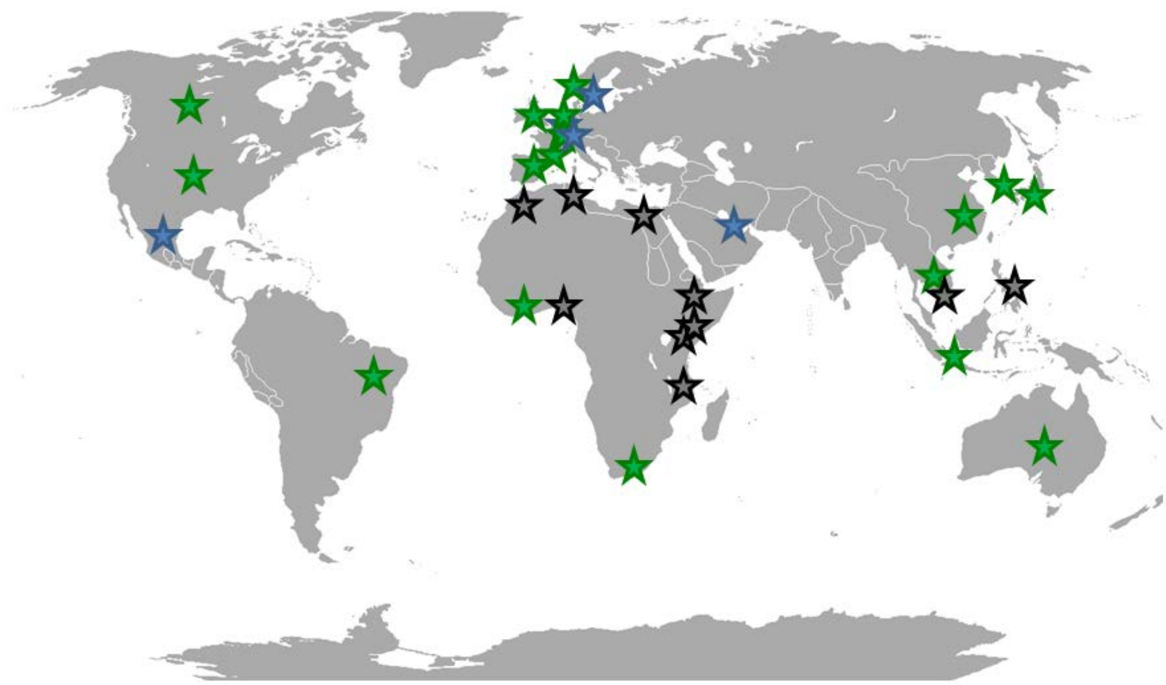

Figure 1 Countries surveyed by the questionnaire and follow-up interviews. Key: Countries represented by respondents (green); countries for whom reported information was used by BGS reviewers but with no direct respondent (grey); countries contacted with no response received (blue).

2.1 SURVEY METHOD

The survey to establish the level of CO_2 storage assessment for the countries represented by the respondents and identify barriers to geological storage assessment comprised an online questionnaire and follow-up interviews with experts in storage assessments, governmental representatives and representatives from multi-national organisations. An online resource, Survey Monkey (https://www.surveymonkey.com/r/9MGFX9F), was used to produce and distribute the questionnaire. The participants were given an overview of the reasons for the study and a description of storage assessment categories (CSLF, 2007). Participants were asked to respond to twenty three questions (listed in Appendix 2). These covered a number of topics including:

- Level of national storage assessment (using the system described by CSLF, 2007).
- Discussion of major perceived barriers (technical, financial and regulatory).
- Identification of funding routes for storage assessments.
- Description of the methodologies used.
- Future aspirations for national assessment.

Respondents were offered the option to provide additional free-text comments on nine of these topics to provide more detail or to describe additional barriers that were encountered.

2.2 ORGANISATIONS AND INDIVIDUALS CONTACTED

A request to complete a questionnaire was sent to representatives of government departments and other expert authorities who were expected to have a good overview of CCS or CO_2 storage on a national level. Participants from countries with a known interest in deploying CCS were contacted. Representatives of international funding bodies with an interest in CCS were also contacted. Individual personal emails were sent by BGS staff to known international contacts in May and September 2015. Further contacts were followed up by repeat emails and conversations held in person or by telephone from April to November 2015.

The questionnaire received 29 responses from 15 countries (Appendix 2). The countries represented were; Australia, Brazil, Canada, China, France, Germany, Japan, Netherlands, Norway, Spain, South Africa, South Korea, Thailand, UK and USA. A respondent who did not leave contact details provided information for China and Indonesia. Four countries did not provide a response. No response to the questionnaire was received from representatives from Mexico, Sweden, United Arab Emirates or Switzerland.

It should be noted that whilst we have sought to obtain a range of responses, these results may not fully represent these countries' positions. Our conclusions and recommendations should not be taken to refer to the specific actions or programmes of individual countries.

The questionnaire received responses from 79% of the number of countries contacted. Respondents represented a range of organisations but were at a sufficiently senior level to provide an overview of the status of storage assessments. Most respondents had direct experience of undertaking storage capacity assessments. All of the countries that responded to the questionnaire noted that some level of storage assessment had been undertaken in their country.

In three cases, the questionnaire was completed through telephone or face to face interviews and these results have been included in the questionnaire response results and Appendix 2.

The preparedness of the countries surveyed in terms of storage deployment has been assessed by the Global Carbon Capture and Storage Institute (GCCSI, 2015a) and is summarised in Table 1. Of those that responded to the questionnaire, four countries were considered by the Global Carbon Capture and Storage Institute (GCCSI) as being prepared for wide-scale storage, five were considered well advanced and six were making progress. There were no respondents from countries deemed by GCCSI as 'just starting' or 'yet to make a start'. In summary, we have questionnaire responses from all countries considered to be prepared, from five out of seven countries considered to be well advanced, and from six out of 31 countries considered to be making progress.

Table 1: Countries on which respondents commented and their status for large-scale storage from the GCCSI review published in May 2015 (GCCSI, 2015a).

Country that responded to survey invitation	Status as per GCCSI Storage Readiness Assessment (GCCSI, May 2015)
Australia	Well advanced
Brazil	Prepared
Canada	Prepared
China	Well advanced
France	Making progress
Germany	Well advanced
Japan	Making progress
Netherlands	Well advanced
Norway	Prepared
South Korea	Making progress
South Africa	Making progress
Spain	Making progress
Thailand	Making progress
UK	Well advanced
USA	Prepared

Follow-up interviews were conducted with representatives from national geological surveys, international funding bodies and national research organisations. The countries discussed in interview ranged from ‘not considered’ to ‘prepared for large-scale storage’ based on the assessment of storage readiness prepared by the GCCSI (GCCSI, 2015a). Some respondents discussed countries outside their own and these results have been included but may not be fully representative of the national state of play.

Questionnaire responses were received from a range of organisations (Figure 2) but the largest group of respondents were from geological surveys (37%). If national geological surveys, government bodies, national research centres/institutes and nationalised hydrocarbon companies are considered together, 70% of the national research assessments were undertaken by this group.

Figure 2 Type of organisation in which the respondents to the questionnaire are employed

The majority of respondents had a senior/principal scientist role, the second dominant group was project or programme director of a branch or programme relating to geo-resources (Figure 3). Over half of the respondents have experience in undertaking storage capacity assessments or developing methodologies. Others have experience in financing, providing advice and coordinating assessments. During the follow-up interviews, discussions were undertaken with representatives of the two main groups identified through the questionnaire and funders of CCS and energy projects.

Ten follow-up interviews were undertaken with some of the participants to the surveys, to obtain more detail in regions where the questionnaire had not been completed. These interviews included discussions with three international funding bodies which had not been invited to complete a questionnaire, as it was deemed a more general framework for discussion would be more suitable.

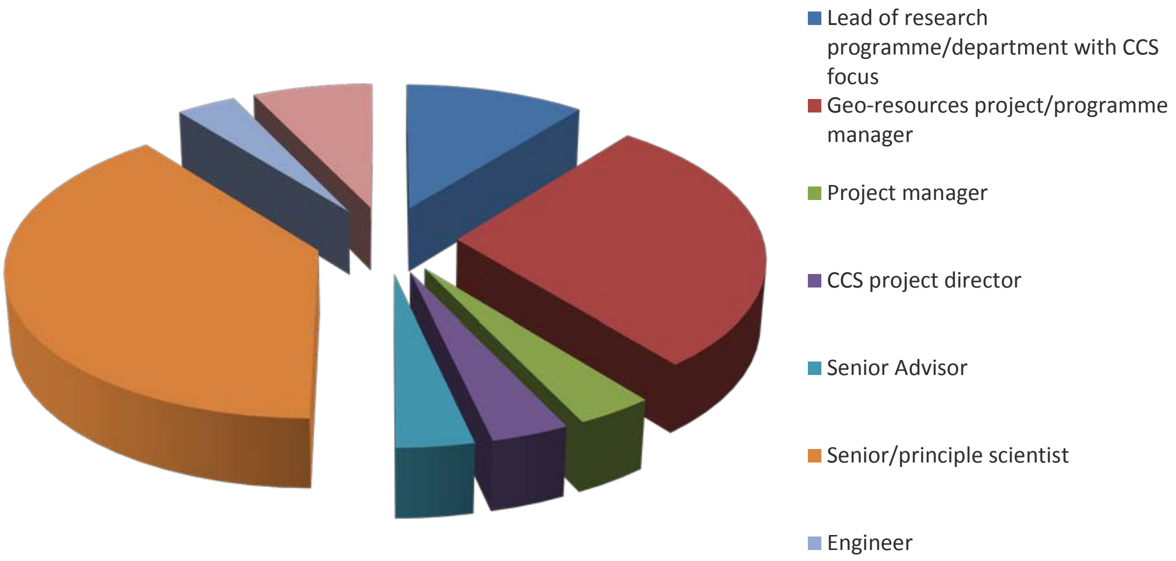

Figure 3: Role of questionnaire respondent in their organisation

2.3 THE LEVEL OF CO_2 STORAGE ASSESSMENT ACHIEVED AND AMBITIONS FOR COMPLETING STORAGE ASSESSMENTS

2.3.1 Level of Assessment

All of the 15 countries who responded to the questionnaire had completed 'theoretical' storage capacity assessments, of which 11 had undertaken 'effective' storage capacity assessments, seven countries had taken this to the next level of 'practical' storage capacity assessment. Four countries had achieved 'matched' capacity assessments. However, this latter figure is believed to be higher since Australia, Norway and Canada are also known to have full-chain CCS projects at an advanced stage of investigation (Table 2 and Figure 4).

The majority of storage assessments discussed in the questionnaire covered offshore regions (nine) and five countries have evaluated their onshore and offshore regions. Australia, Canada, Norway, South Korea and Thailand have produced sedimentary basin-level assessments. All countries have achieved a level of geographical coverage greater than one regional assessment. The level of storage assessment in each of the respondent countries is shown in Table 3.

Table 2 Summary of responses by country to questionnaire on level of storage assessment achieved

Country	Theoretical	Effective	Practical	Matched
Australia	x	x		[5]
Brazil	x[1]			
Canada	x			[5]
China	x	x	x	x
France	x	x	x	
Germany	x	x		
Japan	x			
Netherlands	x	x	x	x
Norway	x	x	x	[5]
South Korea	x	x		x [4]
South Africa	x	x[2]		
Spain		x	x	
Thailand	x			
UK	x	x	x	x[3]
USA	x	x	x	x

[1] A CCS Atlas for Brazil has been published which qualitatively points out the most suitable areas for CCS in Brazil based on point source emissions and the location of sedimentary basins. The CARBMAP project in Brazil reported national assessment at basin scale and quantified 'effective' capacities for aquifers and 'effective' and 'matched' storage capacities for hydrocarbon fields but not all results are available online

[2]Partial mapping due to insufficient data

[3]'Matched' capacities for two projects

[4]A few site specific investigations have taken place

[5] Although respondents from Australia, Canada and Norway did not mention 'matched' capacity assessments as demonstration projects are planned or underway it is assumed 'matched' capacity assessments have been carried out. Norway has two active storage demonstration projects at the time of report writing, Canada has three demonstration projects (including CO2-EOR) in the 'operate phase' and two in the 'execute' phase according to the GCCSI Global Status of CCS 2015 (GCCSI, 2015b) and Australia has at least one 'matched' capacity assessment for a demonstration project which is in the 'execution' stage according to the GCCSI Global Status of CCS 2015 (GCCSI, 2015b).

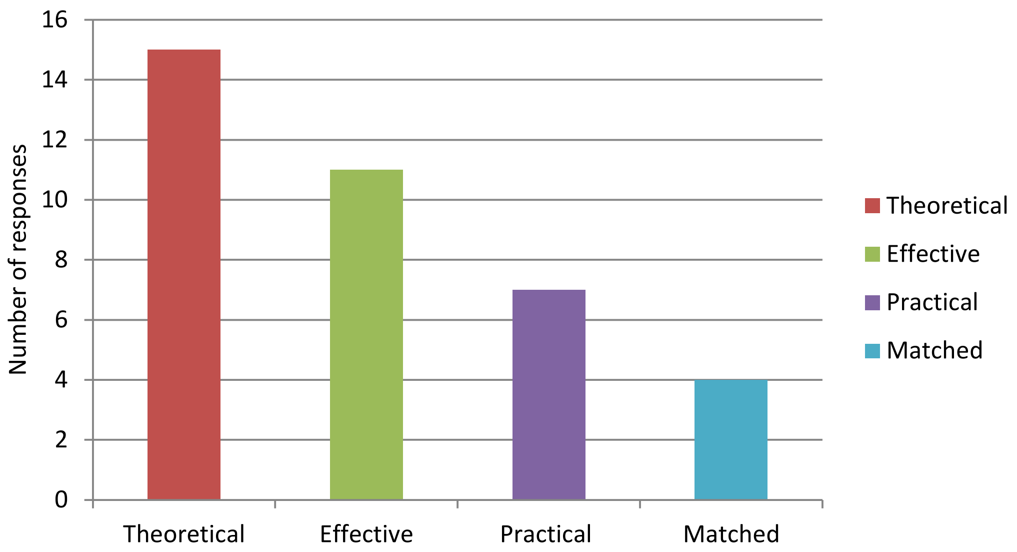

Figure 4 Responses to the questionnaire on level of national storage capacity assessment achieved

Table 3 Level of storage assessment achieved based on responses.

Country	No coverage	Onshore only (no offshore territory)	Onshore (but have offshore territory)	Onshore	Offshore	Sedimentary basin level	One regional assessment	Site-specific assessment
Australia						x		*
Brazil				x	x			
Canada					x	x		
China			x					x
France			x			x		
Germany				x	x			
Japan					x			
Netherlands				x	x			x
Norway					x	x		*
South Korea						x		x
South Africa				x	x			
Spain				x	x	x		x
Thailand						x		
UK					x			*
USA			x					

* It is worth noting that although respondents from Australia, Norway and the UK did not mention site-specific assessments, it is assumed the respondents meant to indicate that site-specific studies had not been carried out as part of the national storage assessments; Australia, the UK and Norway have demonstration projects planned or underway for which site-specific studies will have been conducted by the prospective operator.

2.3.2 Duration of Assessments

The time taken to achieve the level of ‘theoretical’ storage capacity assessment was between one and ten years, ‘effective’ storage capacity assessments between one and more than ten years, ‘practical’ storage capacity assessments five to more than ten years and ‘matched’ capacity five to more than ten years. It should be noted that in one country the answers given for time taken to get to a particular level of storage assessment varied widely, this may well reflect a differing opinion of the start time for the national storage assessment. For example, the first European discussions on CCS started in the mid-1990s with the Joule II project and if the time between that early assessment and achieving ‘practical’ storage assessment is considered, this is longer than the time required to just undertake national ‘practical’ level storage assessment.

Time taken for the storage assessment and the maximum level of storage assessment reported have been cross-referenced in Table 4 to assess the typical amount of time taken to achieve each level of storage assessment.

In summary, national assessments to the level of ‘effective’ capacities have been achieved within two years in a few countries but more typically take five to ten years to complete. Extending these assessments to ‘practical’ capacities and some site-specific ‘matched’ capacity estimates typically takes at least five years.

Table 4 Numbers of respondents who have estimated the duration in years to achieve the current levels of CO_2 storage assessment

Level of capacity assessment		Years taken to achieve assessment level			
		1 to 2 years	3 to 5 years	5 to 10 years	More than 10 years
	Theoretical	2	1	4	
	Effective	2	1	5	2
	Practical			4	2
	Matched			5	1

2.3.3 Types of organisations responsible for assessments

Countries that achieved an estimate of ‘effective’ storage capacity in the shortest time were those where the work was undertaken by national geological surveys and where existing publically available information, which had been collated in accessible data collections, was used. In both cases the results were sufficiently reliable to enable policy makers to support more advanced evaluation of storage feasibility for targeted basins.

This approach to generating a national storage capacity assessment would seem a practical first step for other countries wishing to provide an initial assessment, as this does not rely on collection of new data. In both countries where ‘effective’ capacity assessments were achieved within two years, the government also set up and provided strong funding support for a national body responsible for driving CCS forward.

In summary, those national assessments that were most rapidly completed and are most mature appear to be those undertaken by national or regional geological survey organisations, who have access to available data, of sufficient quality, and who have been supported specifically by national bodies whose remit includes CCS development.

2.3.4 Ambitions for Future Assessments

Ambitions for storage capacity assessment vary but most countries who responded to the survey desire a level of assessment above ‘theoretical’ storage capacity (respondents from four countries stated that they have not yet achieved ‘effective’ storage capacity assessments). The majority of respondents wanted to see a more advanced level of national storage assessments, as reflected in the bias towards more detailed storage assessments as shown in Figure 5. **It can be concluded that countries who responded to the questionnaire desire to achieve 'effective' capacity estimates as a minimum level and above.**

The majority of respondents from countries where CO_2 storage potential has been investigated over several years and CCS had received national policy support and funding, had the capability to complete more detailed assessments if resources (i.e. data and funding) were available. A few of the respondents had the organisational expertise to complete more detailed surveys including seismic and borehole data collection, but in most cases data collection and processing would have to be sub-contracted.

When asked for more detail on the level of storage assessment that it was hoped would be achieved in their country, nine respondents wanted to see sedimentary basin-level assessments in their country, six offshore only, three onshore only (although they have offshore territory), and three wanted to see site-specific assessments. The respondents' comments expressing the ambition for future assessments indicated that more detailed assessments in locations relevant to large CO_2 sources were desired. These responses reflect a desire to do as much as is needed to achieve commercial storage in viable regions. Several expressed a desire to achieve 'matched' capacity. In addition, several respondents supported either a wider geographical coverage of advanced national storage capacity or, in one case, to say that practical projects rather than national storage assessments are needed to drive CCS forward.

It is worth noting that some countries where it is known that at least one site-specific storage assessment has been completed, did not confirm it had been undertaken. This could reflect that site specific studies have not been conducted on a national scale or that the investigations have been conducted in confidence and/or by an industry venture. A national assessment with full site-specific studies is unlikely to be achieved, nor is it desirable due to the large budgets needed, and therefore all national assessments will require a strategic prioritisation of sites. Indeed, **developing a strategy for prioritisation of those sites for which detailed assessments should be undertaken is a crucial step in developing a targeted and efficient approach to storage assessments.**

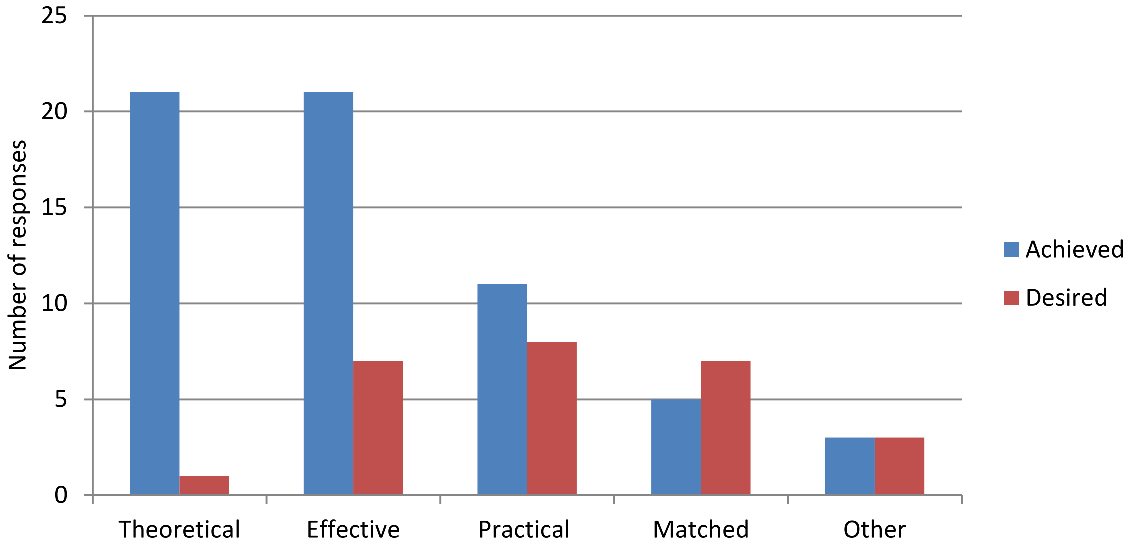

Figure 5 Number of questionnaire responses, comparing achieved and desired level of national storage assessment

The majority of respondents to the questionnaire felt that to reach the desired level of assessment would take five to ten years, although several commented that they expected site-specific surveys to take two to three years to complete.

Some countries described by GCCSI (2015a) as having storage readiness levels of 'not considered', indicated they are targeting energy efficiency and low-carbon renewable energy sources rather than CCS to keep their national emissions low. There still might be opportunities for CCS in some of these countries with (emerging) fossil fuel industries or high purity industrial CO_2 sources in the future, in support of increased energy efficiency and renewable energy generation.

2.4 FINDINGS ON PERCEIVED BARRIERS FOR NATIONAL STORAGE ASSESSMENTS

All of the countries who participated in the questionnaire have undertaken some level of storage assessment, therefore the answers to this question refer to the barriers encountered whilst planning or conducting those storage assessments. Although nine respondents reported 'other' as barriers for storage assessments, these covered variations on the main perceived barriers suggested in the questionnaire or provided more detail on the selected category so have been included in the main categories for Figure 6 (the original results are included in Appendix 2).

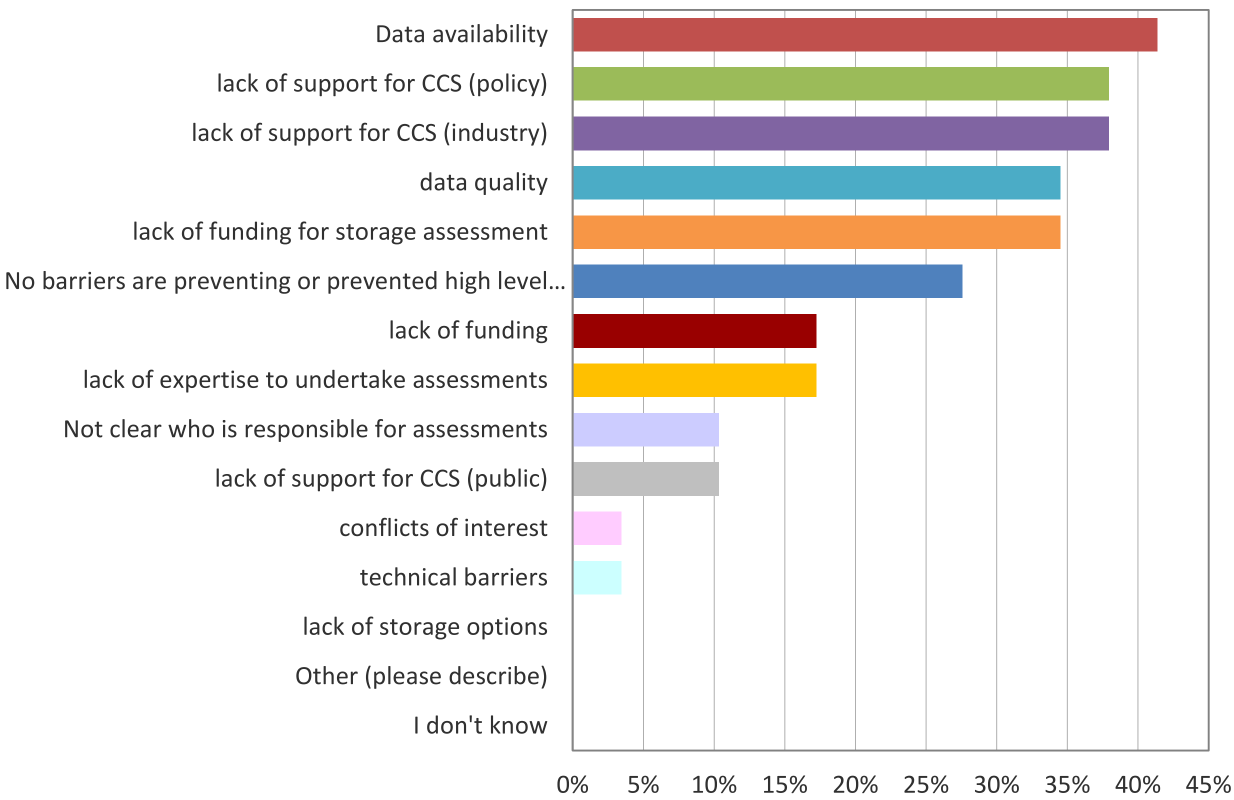

Figure 6 Barriers faced when planning or conducting storage assessments from questionnaire responses (note that the responses from the 'other' category have been included in the other responses as they fitted into the existing categories or had been used to provide more detail on the category selected by the respondent).

The main barrier topics are:

- Policy and regulatory support.
- Funding for CCS.
- National knowledge and technical expertise.
- Industrial support.
- Data access and quality.

Data availability was reported as the most significant barrier with 12 of the respondents reporting this as an issue, which is compounded with data quality being a problem (reported by 10 of the respondents).

Lack of support for CCS from a policy or regulatory point of view was also raised by several organisations along with lack of industry buy-in to CCS. The technical barrier raised was lack of understanding of reservoir and seal behaviour in response to the injected CO_2, this is quite a site specific issue and does not prevent a high-level national storage assessment but does highlight the need for practical experience from injection tests and pilot and demonstration projects in relevant geological formations.

Discussions in the follow-up interviews provided more information on the main barriers highlighted through the questionnaire responses. Data availability and quality were again identified as major issues to be overcome during preparation of national storage assessments. In the countries highlighted as CCS 'not yet considered' in the GCCSI report (GCCSI, 2015a), lack of policy and regulatory support was highlighted as a major barrier since alternatives to CCS were being given priority.

The main issues highlighted through the questionnaire and follow-up interviews are discussed in the following sections.

2.4.1 Policy and Regulatory Support

Those organisations which had responsibility for, or interest in, the development of storage assessments were typically government ministries or directorates and national geological surveys or research institutes. These organisations have been categorised to highlight which sectors are interested or responsible for storage assessments (Figure 7). The three most significant sectors considered responsible for CO_2 storage assessments reported by the questionnaire respondents are geological surveys, government bodies, and research centres or institutes.

If the geological survey, government body, state or national company and government organisations at state, provincial or local levels are considered together, these represent 65% of the questionnaire responses. This implies that national storage assessments are often undertaken by public or national organisations that are most likely to have an overview on a national level of the geology and are also likely to have access to national data collections. The remaining 35% of organisations with responsibility for, or an interest in, the development of storage assessments were universities, NGOs, non-national research institutes, oil and gas companies, power companies and 'CCS developers'.

Figure 7 Sectors perceived to be responsible for CO_2 storage assessments by the questionnaire respondents. Note that all responses are included so some institutes have been mentioned by more than one respondent.

Follow-up interviews indicated that there was strong political interest in CCS in several countries where CCS is moving forward towards demonstration and deployment, e.g. South Africa, Japan, and South Korea.

From the majority of responses, it appears that unless CCS is on the political agenda, it is very unlikely that a national storage assessment or implementation of CCS will move forward. The two exceptions to this were the USA and Indonesia. In the USA, where pilot and demonstration projects are moving forward, there is some political opposition, either on the grounds that there is no climate change or because it is perceived CCS could encourage more fossil fuel use. In Indonesia, the Asian Development Bank has undertaken a national scoping study, funded a feasibility study for a small pilot project and is processing a grant for undertaking the pilot project (though the funding for the pilot project is international not national),. Although CCS is not mentioned in the Indonesian Intended Nationally Determined Contribution (INDC) (UNFCCC, 2015) or policies, the government seemed open to the concept of CCS.

Recognition of projects from established international bodies such as the CSLF and GCCSI, as well as direct support between countries, can provide support to the development of storage assessments through facilitation of knowledge exchange, peer-review activities and sharing of best practice.

Discussion in follow-up interviews indicated that in several countries with less developed economies, government support for CCS is less certain. This is partly due to extremely low emissions per capita, low historical emissions, the need to develop basic infrastructure or greater interest in other low-carbon technologies.

2.4.2 Funding for CCS

National assessments in developed countries always involved some public or national funding for the very early stages of national assessment. National assessments in European countries were also heavily reliant on research funding; most European Countries were involved in EC-supported research projects for 'effective' level national assessments. In developing economies international funding plays an important role in early national assessments for CO_2 storage. However, all countries where CCS is moving forward (demonstration project in advanced stages of planning or active) reported a mixture of public and private funding sources and actors.

2.4.3 National knowledge and technical expertise

The availability of expertise required to carry out assessments of CO_2 storage capacity to a ‘practical’ level was generally available in all countries reviewed. However, in some countries, where assessments had not yet been carried out, the expertise was focused on exploitation of other geological commodities and therefore would need adaptation for CO_2 storage assessments. Most countries who responded have a national geological survey or government department with expertise in deep reservoir geology. The results suggest that where there is a strong oil and gas industry, useful expertise was more likely to be available, even if adaptation for CO_2 storage assessment would be needed.

Some respondents did note that if CCS rapidly accelerated towards deployment then the availability of expertise could become an issue. Other countries where political support for CCS was waning observed that although skills still existed in national or public bodies, experts had moved into other fields where research was growing. In these countries, the availability of experts was reducing which again would become an issue if CCS were to be deployed on a large scale.

Developing countries, particularly where oil and gas resource development is still maturing, are more likely to have a greater problem finding the expertise to perform CO_2 storage assessments. However, generally, there was an interest in international collaboration and knowledge sharing so this barrier does not seem insurmountable.

There appears to be a good level of knowledge sharing between forerunner countries and follower countries for national geological storage assessment. Respondents from the UK, USA and Australia mentioned working in other countries. The UK and USA have ‘practical’ and/or ‘matched’ capacity assessments, and Australia has an ‘effective’ storage capacity assessment. It is suspected that the responses to this question are not complete as, for example, it is known that Norway and the Netherlands (who both have ‘practical’ or ‘matched’ capacity assessments) have supported projects in follower countries through knowledge sharing. Representatives from ‘follower countries’ indicated that either knowledge sharing activities had been undertaken or there was interest in knowledge sharing activities.

Knowledge sharing projects funded by the European Commission, the World Bank and Asian Development have supported initial assessments of CO_2 storage opportunities in some developing countries.

2.4.4 Industrial Support

Industrial support for CCS was variable. The main controlling factors were regulatory and economic. The main reason for lack of support for CCS amongst industrial sectors was the increased cost of producing commodities (power, cement, steel, etc.). Developing countries were additionally concerned with the need to develop essential national infrastructure, implementing other low-carbon technologies and low current emissions per capita or low legacy emissions. The primary reason for supporting CCS was to reduce emissions although this was frequently tied to a concern over increased cost of emissions reduction.

Industrial ‘Champions’ for CCS were only identifiable in countries where CCS is relatively well advanced (conducting feasibility studies for pilot or demonstration projects, or implementation of demonstration projects) with the exception of Indonesia where no CCS champion was identified but a feasibility study for a pilot project has been carried out.

2.4.5 Data access and quality available for storage assessments

National inventories of subsurface data[1] for storage assessment are available for 76% of the countries who responded to the questionnaire. The data is held by a range of organisations including: Government organisations; public institutions; private companies; data release agents (who may charge for data). The majority of countries stated that at least some of the data were held in a national dataset with only a few countries where data was held by individual states or private companies.

2.4.5.1 Where is the data and who has access?

It is expected that the majority of data for storage assessments would come from national datasets, private companies and data release agents. Availability of data is further complicated through different conditions and timescales over which when proprietary data may (or may never) become available. Data access regulations vary between countries. No international inventory of data access regulations or data quality was available to the project team, but from the questionnaire responses and follow-up interviews, it was clear this was a complex topic with variable approaches. It is not known how many countries have release clauses which demand that confidential information is released after a certain period of time, though this undoubtedly facilitates more informed storage capacity estimates.

There did not seem to be a strong link between level of storage assessment and the holder of key data. The implication seems to be that although data being held in a single national database generally enabled access, data being held in several databases or by private organisations (e.g. oil and gas companies) did not always present an insurmountable barrier to national storage assessments though it was noted that this tended to increase timescales and effort required to access the data.

Following on from the questionnaire, interviews suggested that the level of difficulty in obtaining data to undertake the assessment and the barrier this presented is more subtle and depends on the relationships between institutions in the host country. In some countries, the presence of already established working relationships between geological surveys and government departments undertaking national assessments and private companies meant that obtaining the data was relatively straightforward, although often quite time consuming.

Discussion in the follow-up interviews indicated that the exception to relatively easy access to data occurred when attempting to obtain data from hydrocarbon companies in areas of active hydrocarbon exploration, which is extremely difficult due to commercial sensitivities. Overall, commercial sensitivity for access to data uniformly seemed to be a barrier to CO_2 storage assessments. In some cases this has been overcome through confidentiality agreements and existing established relationships.

[1] Subsurface data here is taken to include all geological, geophysical and geochemical data e.g. seismic data, borehole data, well log data including but not limited to depth, porosity, formation thickness, net sandstone to gross thickness, areal coverage, volume of hydrocarbons removed, formation compartmentalisation, pressure and temperature values.

Follow-up discussions suggested that if the profile of low-carbon technologies, including CCS, was increased, data access might become easier, if it was clearer to data holders that the request for data is related to GHG emissions mitigation and not competition for energy resources.

Gaps in data availability were noted as an issue, sometimes due to confidentiality of data or sometimes due to the lack of data available for some areas. Data gaps particularly seemed to be an issue in developing economies where the oil and gas industry does not exist or is less mature.

Different approaches can be observed between those countries in which relevant geological data is held centrally, typically by government departments and public institutions such as geological surveys, and those countries where data is located in a more distributed manner between public organisations and other commercial organisations including private and national oil companies. In large countries with a federal structure, data may still be held publically but at a provincial level. Although high-level national assessments can be undertaken with nationally held data, more detailed assessments of storage capacity at a regional or site level often requires more detailed and modern data that is more typically held by commercial companies actively undertaking exploration and production for hydrocarbons. In general, national storage assessments are at least facilitated and coordinated by a public organisation that is given the remit to manage the assessment and particularly to coordinate access to and collation of the relevant data.

2.4.5.2 Data vintage and quality

The lack of modern data should not prevent storage assessments from being undertaken. Whilst the use of modern datasets or, where needed, the acquisition of new seismic data can significantly enhance the quality of storage assessments, initial storage assessments can be made with data acquired for other purposes. In particular, this would include legacy seismic and well data acquired from oil and gas exploration. In our experience, limited data did not prevent the UK from undertaking useful high-level assessments, from which more detailed assessments have been built as resources and data availability and quality increases.

It is recommended that the potential impacts of the quality of the data are fully considered when providing storage estimates. Data quality was a noted issue, with old data being noted as typically being of lower quality. Depending on the age of this data, especially seismic data, the level of interpretation that can be placed upon it may be constrained by limitations in resolution, compatibility with modern interpretation tools, quality of processing and lack of geological certainty. Older well log data may be available that captures fewer characteristics for the formations of interest and may be of lower resolution. Older composite logs and well reports (e.g. engineering reports on casing quality, cementing, pressure testing) may not contain as much information as modern composite logs or may comprise lower-quality scanned versions from which it can be difficult to obtain accurate data.

Quality control is essential when the data are deposited in the repository to ensure that the data can be used later with confidence. A key issue highlighted through the follow-up discussions was that uncertainties could arise if data were not checked for quality when submitted to the national repository or collection. This applied to geological, geophysical, geochemical and CO_2 storage-related data. An awareness of any limitations on the reliability and quality of the geological data would allow later assessments to indicate the level of confidence in the new analyses. Quality was quite variable where there was no centralised repository or where a uniform Quality Control and Assurance (QC/QA) exercise had not been carried out on the data during acquisition or when it was deposited with the central repository. The issue of quality control arose for CO_2 storage-related data as well as primary data. A qualitative judgement of high, medium or low confidence in data quality is included in the UK national storage database (CO_2Stored; http://www.co2stored.co.uk/), which might also be appropriate for other national assessments.

Six questionnaire respondents replied that further advanced storage assessments would require new data to be acquired. Comments noted that government and regional partnerships deliver large-scale storage assessments whereas private companies play a bigger role in site-specific assessments. Several respondents commented that Governments have provided additional funding for data acquisition specifically to inform CO_2 storage assessments.

Through interviews, it became apparent that where assessments covered more than one country, sometimes the methodology had to be agreed and the local geological experts would apply the methodology and report the results so this meant that QC of the results on receipt was required to ensure the methodology had been applied uniformly and the results reported clearly.

2.4.5.3 Methods of output and availability

Results of storage assessments are presented in a number of ways, with most countries disseminating information via a number of formats. The majority of results were made publically available and accessible. This includes reports, databases, research papers and storage atlases. Some results remained confidential. Where questionnaire respondents answered the questions on publication of assessments, 95% anticipated that future storage assessments would be published. The follow-up interviews also supported the intention that the results of high-level national assessments would be published, even if the underlying data remained confidential.

2.4.6 Assessment methodologies

A range of methodologies were used for storage assessment with the US DOE (US DOE NETL, 2012; NACAP, 2012), CSLF (CSLF 2007) and pore volume/dynamic simulation methodologies ranking as the most used. Whilst different methodologies have been used, it is clear that most respondents felt these methods were adequate, sometimes with adaptation, to provide the necessary level of confidence in the results of the storage assessments (76% of questionnaire respondents felt the methodologies were fit for purpose). Most countries adapted the methodologies used to make them relevant to their unique geography and geology. Where problems were encountered it was often the lack of data which inhibited the application of the chosen methodology. In one case it was noted that the methodology used did not include well integrity in one particular assessment, so there may be a case for introducing risk factors to simple methodologies as implemented in more advanced methodologies applied in the UK, Norway and others (e.g. Gammer et al., 2011; Norwegian Petroleum Directorate, 2011).

National assessments would be greatly improved through the use of nationally agreed methodologies, standards and quality assurance systems. A number of respondents identified use of different methodologies at a regional or provincial level as a major barrier. This can lead to difficulties for policymakers in their ability to robustly compare results which might appear inconsistent and imply uncertainty in the capacity of the storage resource. It is clear that using different approaches at a provincial level can lead to challenges in ensuring consistency of approach, in terms of the methods adopted and in the level of access and quality of data used. Implementation of common approaches would allow robust comparisons to be made between estimates of storage capacity, to enable national and regional policymakers to determine the potential for CO_2 storage in their jurisdictions. Where different methodologies have been used clear statements of the methodologies and assumptions can allow comparison between results which would help decision makers.

2.4.7 Other barriers to national CO_2 storage assessment

Other barriers that were reported include:

- Other issues taking a higher priority in national policy.
- Prioritised interest in other low-carbon technologies.
- Need to develop energy infrastructure and enable electricity access in developing economies.
- Lack of desire to undertake CCS due to low legacy emissions or perceived ‘right to emit’ in developing economies.
- Potential protest from the public.
- Lack of detailed national regulations.
- Conflict with other industries, e.g. oil, gas, fisheries, shipping.
- Lack of acceptance of the reality of climatic change.

These barriers cover a wide range of issues from political support to public support to conflict with other national interests. They generally require more local solutions but a good starting point could be preparation of a national low-carbon roadmap to ensure that CCS is included if needed and to show how CCS can be complementary to other national interests.

2.5 SUMMARY OF IDENTIFIED BARRIERS

In the planning and conducting of storage assessments, a range of barriers were faced by the survey participants. An encouraging six respondents noted that no barriers were faced when conducting the storage assessments.

In the questionnaire, respondents could indicate multiple barriers to national storage assessment, as applicable to their experience. The three most commonly reported barriers were:

- Data availability.
- Data quality.
- Lack of industrial support.

The issues with data availability mainly related to sparsity or absence of data (especially in provinces without oil and gas prospects) or data that is available but proprietary and so inaccessible. In the follow-up interviews, it was commented that a change in the political and economic situation would mean this sort of assessment is more difficult to achieve if it hadn’t already been done. Data quality frequently related to the age of the data as older data tended to be of lower quality.

Both a lack of funding and insufficient policy support were amongst the highest-reported barriers faced in the experience of the respondents. Less commonly, an absence of expertise to conduct a storage assessment was reported, although there are models where knowledge transfer was used to assist in assessments. Experts from forerunner countries had worked with local geologists to provide expertise to prepare national storage assessments where local expertise in CO_2 geological storage had not been available. A lack of public support was noted three times and conflicts of interest recorded only once.

Absence of storage options and technical barriers were not perceived to have been issues when conducting storage assessments. Only one respondent noted that more understanding of the response of the reservoir and seal strata to CO_2 was a barrier to national storage assessments.

A range of methodologies were used for storage assessment with most countries adapting the methodologies used to make them relevant to their unique geography and geology. Where problems were encountered it was often the lack of data which inhibited the application of the chosen methodology.

3 Storage assessment methodologies review

It is important that capacity estimates clearly describe the methodology used as there is no agreed uniform methodology, so that the limitations of the different approaches are understood. To date, a wide range of methodologies have been used to assess storage capacity, representing different approaches and levels of complexity. The methodologies have different approaches to quantifying uncertainty in the calculated storage capacity. A range of factors are considered in the expected storage efficiency including geological heterogeneity, and physical and chemical response of the pore fluids and matrix. Thus far, CO_2 capacity assessments have been carried out in many countries but vary widely in their methodologies and so may not provide comparative estimates. This adds to the uncertainty associated with national geological storage potential. Agreeing a uniform methodology would be extremely challenging, however, a clear understanding of the main approaches will allow some comparison between national capacity estimates. **Storing the raw data safely in a well-formatted database will allow the data to be reused as methodologies advance.**

The availability of data for performing storage capacity assessments plays an important role in the methodology chosen. This is dependent on both national data access policies and the presence of other geological resources in the region, as pre-existing data are usually used for early capacity estimates. Where estimates are prepared using differing amounts of data, a wide range of capacity estimates can be produced, some of which are conflicting.

A short summary on the main characteristics of storage assessment methodologies is given in this chapter and a more detailed overview of methodologies used for CO_2 storage assessment studies in the UK, USA, Australia, Japan, The Netherlands, Germany, Norway and Europe is given in Appendix 4.

3.1 APPROACH TO CAPACITY ASSESSMENT

There are two main differences between the methodologies considered for this report:

1. Definition of the formation pore volume available for storage, both in terms of appropriate threshold values and accounting for geological heterogeneity, injectivity, storage volume, techno-economic considerations etc. This definition is often referred to as a static storage capacity estimate.
2. Variation in approach to accounting for the response of the reservoir and fluids to the pressure increases that result from injection of CO_2 and if this pressure increase is managed. This moves the estimate from a volumetric static capacity estimate towards a dynamic capacity estimate.

Some aspects of these factors are often included in the storage efficiency factor, others are referred to in the report text as factors requiring consideration.

3.1.1 Definition of the available pore volume

Most assessments consider storage in saline water-bearing rocks (saline aquifers), many consider depleted hydrocarbon fields and some also consider storage potential of un-mineable coal seams. Other possible options such as storage in basalt or manmade caverns are also mentioned in the CCUS Atlas (US DOE NETL, 2012) and CSLF paper (CSLF, 2007).

When considering pore volumes suitable for aquifer or hydrocarbon field storage, all relevant methodologies applied a minimum depth (ranging between 792 m and 914 m; Brennan et al., 2010, Blondes et al., 2013, US DOE NETL, 2012; NACSA, 2012 and NACAP, 2012), such that pore space that is too shallow is excluded from assessment. It is commonly recognised that below this depth CO_2 will be stored in its highly dense (or supercritical) phase and therefore have a much higher volumetric efficiency compared to storage in the gas phase at shallower depths. A maximum depth for storage varying from 2000 m (US DOE NETL, 2012; NACSA, 2012, NACAP, 2012 and Carbon Storage Task Force, 2009) to 3962 m (Brennan et al., 2010; Blondes et al., 2013 USGS) for aquifers and hydrocarbon fields is also mentioned. This is justified because at these depths or greater the reservoir quality is impaired by the effects of high temperatures and pressures within the subsurface. The depth to un-mineable coal seams is not always defined as it depends on national and technological factors; for example in the Carbon, Capture, Utilization and Storage (CCUS) Atlas the recommended upper limit is given as 305 m (US DOE NETL, 2012). It is debatable if this is suitable for storage as in addition to the difficulty in defining which coal seams can be un-mineable at such shallow depths the seals overlying the coal will be extremely important as any free CO_2 could migrate towards the surface. The CSLF methodology (CSLF, 2007) recommends storage below 700 m in the gaseous phase in coal with a relatively shallow maximum depth of 800 m.

All of the reviewed assessments also only consider pore volume where there is an adequate seal above the reservoir, which is important because even if there is plenty of space to store CO_2 within the rock pore volume, unless there is an effective sealing layer above it the CO_2 will not be retained and may reach the atmosphere. This requirement of a reservoir-seal pair is referred to as a Storage Assessment Unit (SAU) in the USGS assessment (Brennan et al., 2010; Blondes et al., 2013). In some cases, this is further refined through application of minimum porosity (Brennan et al., 2010; Blondes et al., 2013; Gammer et al., 2011), permeability or injectivity (Gammer et al., 2011; Chadwick et al., 2008; Neele et al., 2011a) cut-off thresholds.

A 'storage efficiency' factor of some description is present in most methodologies and is included for saline aquifers, except when a first step calculating the total or theoretically available pore volume is included. This 'storage efficiency' factor ranges from 0.51 – 6% of the available pore volume for regional aquifer capacity estimates and up to 40% for aquifer storage in defined closures (Chadwick et al., 2008). Depending on the methodology, this factor is used to account for geological heterogeneity, response and interaction with native pore fluids and matrix (including displacement of fluids), keeping reservoir pressure within acceptable limits and technological factors relating to location and number of injection wells. For hydrocarbon fields, it is usually assumed that the produced hydrocarbons can be replaced, sometimes with a reduction in volume to account for the net injected fluids for enhanced hydrocarbon recovery or to account for the differences in viscosity between oil and CO_2. Values for this are not generally given in the literature. For coal seam capacity assessments, 'storage efficiency' factors are included which consider how much of the coal could theoretically be contacted by the CO_2 to store CO_2 through absorption onto the coal and in the pore spaces (cleat).

3.1.2 Response of the reservoir and fluids to the pressure increase

All the assessments note that detailed studies are needed to assess potential storage sites on a case-by-case basis, including flow simulations for storage in aquifer formations or hydrocarbon fields. Flow simulations consider relative permeability of contained fluids, compressibility of the rock matrix and fluids, pressure, buoyancy (gravity) drive and many other critical factors to move from the static capacity assessment methodologies described here to full dynamic storage estimates. All assessments have estimated CO_2 density likely in the target reservoir unit though a few differing methods have been used. The static methodologies described here often include some of these factors in the ‘storage efficiency factor’.

Methodologies may assume that pressure can be managed during CO_2 injection. Theoretically, pressure can be managed by producing reservoir fluids whilst injecting CO_2 though this may be costly. Pressure managed methodologies are therefore closer to a ‘Technically Available Storage Resource’ (TASR) assessment, which is the fraction of the ‘theoretical’ storage resource that can be accessed using all currently available technologies regardless of cost.

Pressure management schemes are different for depleted hydrocarbon fields, which have had no water ingress or used injected water during production, than for saline water-bearing aquifers. In the case of depleted fields, the pressure will be lower than that recorded before production and it is generally assumed that CO_2 can be injected to re-pressurise the field as long as the original pressure is not exceeded (fluid replacement approach). Research by Li et al. (2005) states the cap rock sealing pressure should be determined before injecting CO_2 and that this should in fact be the pressure limit during a storage project to avoid volume flow into the cap rock (due to lower interfacial tension of a CO_2/water system). By comparison, for water-bearing saline aquifers, where a certain amount of pressure will be needed to displace the resident pore-water, a completely different approach will be required.

3.1.3 Scale of assessment, probabilistic approach and risk

All but two of the assessments consider national-level capacity for onshore and/or offshore storage, generally derived from regional capacity estimates. All assessments consider the need for multiple sedimentary basins. The scale of assessment is important because the methodology applied to large-scale storage, e.g. continental or basin-scale, will not be detailed enough to estimate storage capacity for an individual structural trap.

Some assessments use a probabilistic approach to estimate storage capacity whereas some use a deterministic approach. Due to a lack of data available in areas of low hydrocarbon exploration and the heterogeneous nature of geological formations, a probabilistic method of calculation is best to cope with the limitations of the assessment results (Heidung, 2013). This method uses a range of geological values based on available data and a geological model and provides a statistically sound method to make resource estimations (Heidung, 2013). A deterministic approach is applied to a region utilising known values without room for variation.

Geological uncertainty or risk is dealt with using a range of approaches over the reviewed assessments. Non-geological risks, e.g. financial project planning, are discussed in a few of the methodologies.

3.1.4 Data availability

The key driving factors in assessing the suitability of storage capacity methodologies are related to data availability. Access to data largely depends on national regulations for data access and the scale and objectives of the assessment. Basin-level storage capacity estimates can be based on relatively simple calculations. However, site-specific assessments, such as that undertaken during Front End Engineering and Design studies require very detailed data and dynamic flow simulation of CO_2 injection at the prospective storage site.

3.2 DETERMINING THE 'STORAGE ASSESSMENT UNIT'

All methodologies make some attempt to define the storage unit, setting upper and sometimes lower depth limits as a minimum constraint. The presence of a seal is always required. In addition, limits on minimum porosity, permeability and presence of closures may be set. Economic and regulatory requirements are also mentioned or utilised in most methodologies.

The CSLF (2007) methodology makes recommendations on technical factors which will impact storage capacity, such as avoiding excessively thin reservoir formations or low porosity and permeability reservoirs, but does not set limits on these factors. Other storage assessments provided specific cut-off thresholds to take techno-economic factors into account. For example, the USGS methodology (Brennan et al., 2010; Blondes et al., 2013) considers three classes of storage reservoir for residual trapping based on permeability characteristics. The Carbon Storage Task Force (2009) methodology classified the prospectivity of basins utilising their geological setting and then considered likely porosity and permeability at shallow, medium and deep depths. Ogawa et al. (2011) considers the impact of heterogeneity and defines two classes (homogeneous and heterogeneous) of storage location. The USGS method (Brennan et al., 2010; Blondes et al., 2013) only considers hydrocarbon fields that contain more than 500,000 Barrels of Oil Equivalent (BOE) as smaller fields will offer low storage capacities.

Geological and engineered hazards are also considered. For example, the CSLF (2007) methodology recommends avoiding areas affected by major or active faults or areas with steeply dipping strata, the USGS (Brennan et al., 2010; Blondes et al., 2013) and Norwegian Petroleum Directorate (NPD) (2011) methodologies specifically mention consideration of any wells which due to their location or completion history could introduce risks to storage. The Carbon Storage Task Force (2009) ranks basins with higher temperatures and a limited hydrogeological circulation to be poorer prospects for storage due to the limitations these factors place on dissolution of CO_2 into native pore waters.

National and basin-level studies generally consider regional reservoirs where reservoir-seal pairs are available. Gammer et al., 2011; NPD, 2011; Neele et al., 2011a and Chadwick et al., 2008 consider storage units in more detail and also assess if fluid migration between units is likely to be possible (formation boundary conditions as open and closed to fluid flow).

Economic limitations are applied by Gammer et al., (2011), US DOE NETL (2012), and Neele et al. (2011a). They are also considered in the Brennan et al., (2010), Blondes et al. (2013), Neele et al. (2011a) and Knopf et al. (2010) methodologies and mentioned in the CSLF (2007) methodology. These limitations usually relate to injectivity and so permeability, and the number of injector wells required to access the pore volume. In the US DOE CCUS Atlas (2012) financial modelling was used to consider the potential costs of storage. The Carbon Storage Task Force (2009) methodology includes financial modelling of the transport and storage costs for defined locations in Australia.

Regulatory restrictions are mentioned in the CSLF (2007) methodology, but as this is a general assessment, no specific limitations are set. The CO_2STOP report (Poulsen et al., 2014) and Chadwick et al. (2008) also mention regulatory restrictions. The USGS (Brennan et al., 2010; Blondes et al., 2013), US DOE NETL (2012) and Carbon Storage Task Force (2009) specify national regulatory restrictions and where case studies are given, take these considerations into account.

3.3 LESSONS LEARNED

Methodologies for estimating storage capacity vary widely in approach and show continuous development in terms of sophistication and techniques. It is unlikely that researchers can be persuaded to use only one methodology as the process is continually evolving. Therefore, the raw data should be made available in tabulated format, e.g. depth, porosity, formation thickness, net sandstone to gross thickness, areal coverage, volume of hydrocarbons removed, formation compartmentalisation, pressure, and temperature values. Data availability will enable researchers to apply a methodology and allow comparison between different storage sites. However, for some countries this may be difficult due to data sensitivity and availability. Tables for data entry were used for several of the studies, e.g. Gammer et al. (2011), Brennan et al. (2010), Blondes et al., (2013) and CO_2STOP (Poulsen et al., 2014). These tables are critical to assessing storage capacity since the raw data can be utilised by future studies as methodologies advance.

Simplified diagrams explaining the steps in capacity estimation are also useful, e.g. the CSLF (2007) pyramid and the flow diagram of steps in capacity estimation of Gammer et al., (2011). These provide the reader with a quick understanding of the methodology applied.

3.4 RECOMMENDATIONS

Key recommendations from the review of storage methodologies are given below:

- **Population of a well-structured database with clarity on data source and accuracy is an essential underpinning activity that will support capacity assessments and future work**. The database should facilitate clarity of understanding of the data source(s) and accuracy of the data it contains.
- **The raw data should be made available in tabulated format**, e.g. depth, porosity, formation thickness, net sandstone to gross thickness, areal coverage, volume of hydrocarbons removed, formation compartmentalisation, pressure and temperature values**.** This will enable researchers to apply a methodology, allow comparison between different storage sites and quality control. A good understanding of the uncertainties and constraints in the underlying data remains critical throughout all stages of assessment.
- **Simple volumetric estimates are an important first step in national storage assessments**. Simple volumetric estimates should be relatively easy to compare so that early national storage estimates can be considered in light of other national storage assessments prepared during early investigation of national potential. These assessments can be performed using existing data and give decision makers an early indication of the role CCS could play to reduce national CO_2 emissions. Positive results from these assessments could encourage all stakeholders to continue to improve the quality of assessments as data quality and access, and resources increase. These simple volumetric estimates will give an order of magnitude estimate of storage capacity.
- **A clear and comprehensive description of the capacity assessment methodology used is essential and critical** to facilitate comparisons between estimates.
- **A probabilistic approach allows extension of the storage estimate to regions where there are few data**. A clear explanation of where this has been performed and the methodology used supports comparability of estimates. Clarity on uncertainties that remain in the data is critical to the assessment.
- **A national-level database of potential sites, e.g.** http://www.co2stored.co.uk/**, is a good foundation for detailed site surveys and flow simulations**. These are typically

enabled through national funding and help identify ‘sweet spots’ for potential storage operators.

- **Flow simulations providing dynamic capacity estimates are needed to fully understand the potential dynamic capacity of a potential storage site**. New data will almost certainly be required to meet this increased level of understanding. Relatively sophisticated software and expertise in software operation will also be required.

4 Conclusions

All countries, from which responses to the questionnaire were received, have undertaken some form of national assessments of their potential storage capacities. Whilst this undoubtedly reflects a sample bias in that those countries with an interest in CCS are more likely to respond, it provides encouragement that preparation for CCS is moving forward, despite the barriers identified in our study. National and regional assessments have been undertaken in countries of varying stages of economic development, levels of policy and financial support and data accessibility.

The following overarching themes were identified:

1. National assessments require clear policy support to be in place and governmental leadership for the evaluations to achieve the greatest success, which typically was implemented as follows:
    a. A public organisation with a clear mandate from their national government to manage the assessment and particularly to coordinate access to and collation of the relevant data.
    b. Public (government) funding, or international funding, for at least early stage national storage assessments, is a prerequisite in the absence of clear, strong and stable economic incentives to develop storage.

2. The greatest barriers to storage assessments identified in our review are the sparsity or absence of data, lack of access to existing data, and the quality of available data. However this did not prevent all of the questionnaire respondents from achieving some level of national assessment. Regardless of perceived difficulties it is clear that there is still great value in undertaking preliminary assessments of ‘theoretical’ and ‘effective’ capacity. If results from these assessments are positive this can encourage all stakeholders to continue to improve the quality of assessments as data quality and access, and resources increase.

3. National storage assessments can be achieved in less than two years, where they have been undertaken by well-supported national geological surveys/geological directorates which have used publically available data which has already been collated in national data repositories and where a national body has been set up to drive CCS forward.

4. The most efficient assessments which seem to have made the most progress appear to be in those countries where the coordinating national geological surveys/geological directorates have a close relationship both with their sponsoring governmental departments and with national data holders. Government support provides an enabling environment and clear mandate including, importantly, with holders of the data. These facilitators provide

the necessary coordination and momentum to facilitate either internal or commissioned studies.

5. Assessments can give confidence in the national capacity of the potential storage resource to policy and government decision makers if they follow nationally agreed, or at least comparative, methodologies for undertaking assessments. Significant challenges have been created by undertaking partial assessments using widely differing methodologies. The potential use of these estimates in supporting policy development can be significantly undermined where apparently contradictory results are obtained. Clarity in the methodology used is essential.

6. Clear data quality assurance and understanding of uncertainties enable policy makers to make more confident, robust and informed decisions about further CO_2 storage evaluation within their jurisdictions.

4.1 RECOMMENDATIONS TO OVERCOME BARRIERS TO NATIONAL CO_2 STORAGE ASSESSMENT

We have identified in our study a number of common barriers and challenges that are discussed in more detail in Appendices 2 and 3. From our review we have identified features that are in common to successful national storage assessments to overcome the barriers noted from the survey of assessments and assessors. The following recommendations are based on our analysis of the results of our study to reduce or overcome observed barriers to national CO_2 storage assessment:

1. **Data access should be facilitated at national level**. This is of wider benefit as sharing of geological and geophysical data is relevant to a large number of applications (e.g. hydrogeological surveying, nuclear waste disposal).

2. **Quality assessment and control of data at the time of collection in repositories is essential** to ensure that any issues are corrected and that the reliability of the data is defined to inform future assessments made using the dataset.

3. **State funding for national assessments should be contingent on results of the national storage assessment being publicly available** (while of course respecting primary data confidentiality if required). This will accelerate storage assessments through knowledge sharing.

4. **Where clear storage potential exists, policy support should ensure that there is a long-term vision for reducing greenhouse gas emissions which may include deployment of CCS.** This will help to create an enabling environment in which industrial support for CCS may develop, by reducing uncertainty in the future political and regulatory support for CCS.

5. **Ideally, use of a common methodology within each country by a trusted independent body would reduce uncertainty and allow comparability across CO_2 storage**

resource estimates and at least partly answer the quality control issues highlighted by some survey respondents. The methodology used should be reported along with underlying assumptions to allow clarity and comparisons to be made.

Glossary

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BGS	British Geological Survey
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CO2CRC	CO_2 Collaborative Research Centre
CSLF	Carbon Sequestration Leadership Forum
ETI	Energy Technologies Institute
NETL	National Energy Technology Laboratory
TCE	The Crown Estate
UAE	United Arab Emirates
UK	United Kingdom
UKSAP	UK Storage Appraisal Project
US DOE	United States Department of Energy
USA	United States of America

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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Appendix 1

CSLF TECHNO-ECONOMIC RESOURCE-RESERVE PYRAMID

A summary of the techno-economic resource-reserve pyramid presented by the CSLF (2007) is presented here. Most methodologies consider a similar resource – reserve approach.

Two issues complicate the estimation of CO_2 storage capacity:

1. The economic or practical availability of storage capacity.
2. Issues due to the lack of data available and resources required to provide accurate estimates of storage capacity.

To assist in defining the accuracy of storage capacity estimates the CSLF task force adopted the concept of the Techno-Economic Resource-Reserve pyramid, described below and illustrated in Figure 8 (CSLF, 2007).

5. **Theoretical Storage Capacity** is the total resource. It encompasses the whole of the resource pyramid. It is the physical limit of what the geological system can accept. It assumes that the system's entire capacity to store CO_2 in pore space, or dissolved at maximum saturation in formation fluids, or adsorbed at 100% saturation in the entire coal mass, is accessible and utilized to its full capacity.
6. **Effective Storage Capacity** represents a subset of the 'theoretical' capacity and is obtained by considering that part of the theoretical storage capacity that can be physically accessed and which meets a range of geological and engineering criteria.
7. **Practical Storage Capacity** is that subset of the 'effective' capacity that is obtained by considering technical, legal and regulatory, infrastructural and general economic barriers to CO_2 geological storage. The 'Practical' Storage Capacity corresponds to the term 'reserves' used in the energy and mining industries.
8. **Matched Storage Capacity** is that subset of the 'practical' capacity that is obtained by detailed matching of large stationary CO_2 sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate to contain CO_2 streams sent for storage from that source or sources. This capacity is at the top of the resource pyramid and corresponds to the term 'proved marketable reserves' used by the mining industry.

TRAPPING MECHANISMS

When CO_2 is injected into a geological storage site it will migrate through the reservoir and displace some of the native pore fluids and therefore the CO_2 needs to be injected at a greater pressure than the existing reservoir pore pressure. Once in the reservoir rock the CO_2 will be retained by one or more trapping mechanisms.

There are three main types of trapping mechanism that can occur during the geological storage of CO_2: 1) physical, 2) chemical and 3) hydrodynamic (CSLF, 2007). These mechanisms occur over different timescales during the lifetime of CO_2 storage.

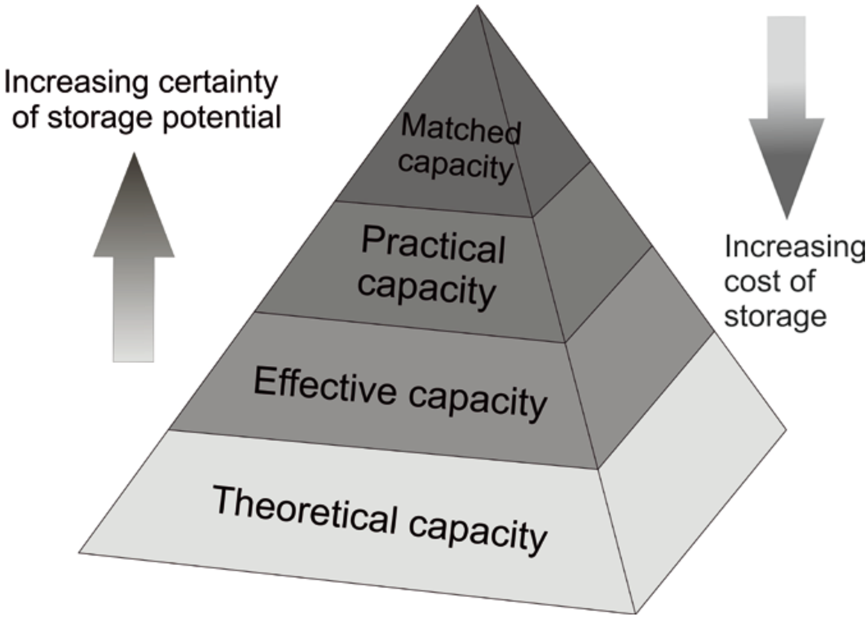


Figure 8 Techno-Economic Resource-Reserve pyramid for CO_2 storage capacity in geological media within a jurisdiction or geographic region. The pyramid shows the relationship between Theoretical, Effective, Practical and Matched capacities (from CSLF, 2007)

Physical Trapping

Physical trapping is the result of CO_2 being stored as either a free gas or supercritical fluid. There are two types of physical trapping:

1. *Static trapping* is storage within a closed trap such as a stratigraphic or structural trap that confines the CO_2 due to presence of a low permeability barrier preventing it from migrating vertically. This process is similar to the way in which hydrocarbons may be trapped by low permeability barriers. The pore space is occupied by native pore fluids that need to be displaced.
2. *Residual-saturation trapping* in pore spaces occurs as CO_2 moves through the reservoir. Some of the CO_2 remains attached to the surfaces of the grains of rock due to capillary forces. Residual –gas trapping is primarily linked with hydrodynamic trapping as CO_2 is left in the path of a migrating plume and it mainly takes place after injection has stopped (CSLF, 2007).

Chemical trapping

Chemical trapping is the result of CO_2 reaction between the CO_2 and pore fluid and reservoir matrix. There are three types of chemical trapping:

1. *Dissolution trapping* where CO_2 may dissolve into the pore water though this is dependent on the temperature, pressure and salinity of the native fluid. Once the CO_2 has dissolved it remains trapped in solution in the pore water. This highly dense pore water then sinks below unsaturated water to the bottom of the storage reservoir. There is potential for large volumes of CO_2 to be trapped in this way, but it is dependent on the solubility of the CO_2 and whether mixing occurs within the reservoir. This method of trapping can take thousands of years to dissolve the maximum amount of CO_2 within the pore water.

2. *Mineral trapping* occurs when there is a chemical reaction either between the pore water of the reservoir rock leading to the formation of new minerals. Chemical reactions with the reservoir rock will be over much longer timescales than reactions with the pore water. These chemical reactions are dependent upon the pore water chemistry, rock mineralogy and the length of the migration path.
3. *Adsorption trapping* where CO_2 is adsorbed onto coal surfaces. CSLF (2007) state that storage through adsorption is the only significant trapping mechanism for coal storage).

Hydrodynamic trapping

Under certain conditions CO_2 may migrate in the subsurface extremely slowly and could become trapped via a combination of physical or chemical trapping, this is hydrodynamic trapping (CSLF, 2007). This mechanism is active when CO_2 is injected into an unconfined aquifer (with no lateral barriers) rather than into a structural/stratigraphic trap. The CO_2 will migrate in the same direction as the natural flow in the reservoir once away from the point of injection. Hydrodynamic trapping occurs via a combination of any of the above described mechanisms which may be simultaneous but at different rates and is not specific to physical or chemical trapping. Eventually, possibly after millions of years no mobile free-phase CO_2 will remain in the system as it is trapped by residual-saturation trapping, dissolution and mineral precipitation (CSLF, 2007).

Appendix 2 Questionnaire responses

Twenty-three questions were included in the online questionnaire. Each question and the responses are presented in the following sections. The responses discussed in the following text were received by online completion (through 'Survey Monkey') of the questionnaire or by addressing the same questions in conversation.

Table 5 Responses to the email request to participate in the survey

Response	Number
Email response to request for participation	39
Returned emails as contact no longer valid	12
Survey completed online	26
Survey completed in interview	3
No response	58
Total contacted	**138**

Questionnaire outline

Question No	Question	Response	Opportunity to comment
1	Address and contact details	Required fields	No
2	What is your role in your organisation	Free text	No
3	Has a CO_2 storage assessment been done in your country?	Yes/No/NA	No
4	If you are responsible for the funding initiation or for undertaking storage assessments please describe your role and the countries you have worked in.	Free text	No
5	Level of storage assessment undertaken?	Choice given	Yes
6	What national coverage has been achieved by your countries storage assessment?	Choice given	Yes
7	Is there a plan or expectation that a high level storage assessment will be undertaken?	Yes/No	No
8	What are the perceived barriers for future storage assessment work (please tick all the potential barriers)? If storage assessment has been undertaken please tick the barrier you have encountered.	Choice given	No
9	Who are the key organisations responsible or interested in the development of storage assessment in your country?	Free text	No
10	Who was the storage assessment funded by?	Free text	No
11	Is there a national inventory of well logs, core and wellbore records?	Yes/No	No
12	Who holds national data inventories?	Free text	No
13	Where did or would key data for storage assessments come from?	Choice given	Yes
14	What level of storage assessment would you like to see in your country?	Choice given	Yes
15	Which methodology/methodologies were applied during the storage assessment work?	Free text	No
16	Were the methodologies used clear and fit for purpose?	Yes/No	Yes

17	How long did it take to get to the level of assessment your country is at now?	Choice given	Yes
18	How was the storage assessment information collated and presented?	Choice given	Yes
19	NULL		
20	What level of national coverage do you hope is achieved in your country?	Choice given	Yes
21	How long do you estimate it will take to get to this level of assessment?	Choice given	Yes
22	Will the result be published?	Yes/No	No
23	Thank you for taking time to complete this questionnaire, Would you be happy for the British Geological Survey to contact you to discuss your answers?	Yes/No	No

QUESTION 1 – CONTACT DETAILS

The questionnaire received 29 responses from 15 countries (Figure 9).

Types of organisations represented by the respondents are shown in Table 7. National geological surveys are often involved in undertaking assessments of national resources such as storage capacity and the majority of respondents were from national geological surveys (Table 6). All the countries that responded had a national geological survey or government department responsible for national geological activities. In most cases, the institutions contacted had undertaken or been instrumental in the national storage assessment (Table 6).

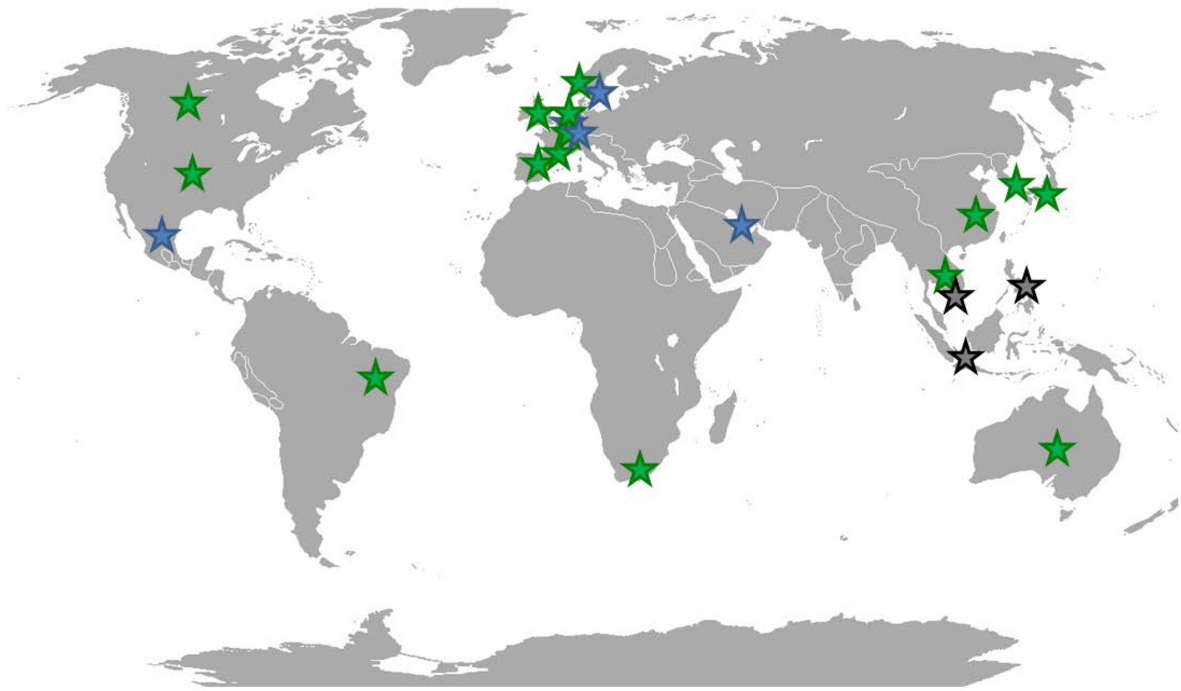


Figure 9 Countries represented by respondents to the questionnaire (green). Countries for whom reported information was used by BGS reviewers but with no direct respondent (grey). Countries contacted but not responded (blue).

Table 6 National geological assessments and storage assessment methodologies compared with reported level of storage assessment from the questionnaire

Country that responded to survey invitation	National geological survey or department in country?*	National Geological assessment completed by?	Level of storage assessment (from questionnaire)	National results published?	Level of storage assessment in published atlas	Storage assessment methodology in national assessment	Reference for storage atlas
Australia	GeoScience Australia (GA)	Australian Carbon Storage Taskforce (ACST) (including GA)	Effective	National carbon mapping and infrastructure plan – Australia	Effective	ACST	Carbon storage taskforce (2009)
Brazil	Geological survey of Brazil (CPRM)	Centre of Excellence in research and innovation in petroleum, mineral resources and carbon storage (CEPAC)	Theoretical	Brazilian Atlas of CO2 Capture and Geological Storage	Theoretical	CSLF	CEPAC (2015)
				CARBMAP (results not online)	Effective		Rockett et al (2011)
Canada	Geological Survey of Canada (GSC)	North American Carbon Atlas Partnership (NACAP)	Theoretical	North American Carbon Storage Atlas (2012)	Effective	US DOE	NACAP (2012)
China	China Geological Survey		Matched	No national atlas published in English			
France	French Geological Survey (BRGM)	BRGM	Effective	GESTCO summary report – Geological Storage of CO2 from combustion of fossil fuel	Effective	CSLF-based	Christensen et al (2003)
				GeoCapacity – Assessing European Capacity for geological storage of CO2	Effective	CSLF-based	Kirk et al (2009)
				Online database	Effective		http://www.metstor.fr/ (2009)

Germany	Federal Institute for Geosciences and Natural Resources (BGR)		Effective	GeoCapacity – Assessing European Capacity for geological storage of CO2	Effective	CSLF-based	Kirk et al (2009)
				Storage Catalogue of Germany	Effective	BGR	Knopf et al., 2010 (in Gernam)
				Storage Catalogue of Germany			Reinhold et al., 2011 (in German)
Japan	Geological Survey of Japan (AIST)		Theoretical				
Netherlands	Geological survey of the Netherlands (GDN; a section of TNO);	TNO	Matched	Offshore Atlas 2011	Practical	TNO	Neele et al (2011)
Norway	Norwegian Geological Survey (NGU)	NPD	Practical	Offshore Atlas 2011	Practical	NPD	NPD (2011)
South Korea	Korea Institutes of Geoscience and Mineral Resources (KIGAM)		Effective				
South Africa	Council for GeoScience (CGS)	CGS	Effective	Technical report on the geological storage of carbon dioxide in South Africa	Effective	CO2CRC-based	Viljoen et al., (2010)

Spain	Institute of geology and minerals (IGME)	IGME	Practical	Plan geological storage of CO2 (database)	Effective	Not stated	http://info.igme.es/algeco2/ (2010) (in Spanish)
Thailand	The Department of Mineral Resources (DMR)	Coordinating Committee for GeoScience programmes in east and southeast Asia (CCOP)	Theoretical	Prospects for south east Asia (Thailand, Indonesia, Philippines, Vietnam)	Theoretical - effective	CSLF-based	CCOP (2014)
UK	British Geological Survey (BGS)	BGS	Matched	GESTCO summary report – Geological Storage of CO2 from combustion of fossil fuel	Theoretical - effective	CSLF-based	Christensen et al (2003)
				CO_2 Stored	Practical	UKSAP	http://www.co2stored.co.uk (2011 – present)
USA	United States Geological Survey (USGS)	USGS, US DOE	Matched	CCUS Atlas IV	Effective	US DOE	US DOE NETL (2012)
				National Assessment of Geologic Carbon Dioxide Storage. Resources—Methodology Implementation	Effective	USGS	Blondes et al (2013)
				North American Carbon Storage Atlas	Effective	US DOE	NACAP (2012)

* The presence or absence of a national geological survey is indicated here as the authors were interested to examine if this could be an enabling factor for capacity assessment. The name of a national geological survey listed in this column does not necessarily indicate that a response to the questionnaire was received from that organisation.

See Chapter 3 and Appendix 4 for a comparison of national storage assessment methodologies.

Table 7 Organisations at which the survey respondents are employed

Country	Respondent organisation	Category
Australia	ANLEC R&D	Public private partnership
Australia	Geoscience Australia	Geological Survey
Australia	Global CCS Institute	Membership organisation
Brazil	PETROBRAS S.A.	State oil company
Canada	Geological Survey of Canada	Geological Survey
Canada	Alberta Innovates - Technology Futures	Research organisation
China	Energy Research Institute (NDRC)	Research organisation
France	BRGM	Geological Survey
Germany	BGR	Geological Survey
Japan	Research Institute of Innovative Technology for the Earth	Geological Survey
Japan	University of Tokyo	University
Netherlands	TNO	Research organisation
Norway	Norwegian Petroleum Directorate	Government directorate
Norway	Sintef	Oil Company
Norway	Statoil ASA	State oil company
South Korea	Research Institute of Innovative Technology for the Earth	Research organisation
South Korea	Korea Maritime and Ocean University	University
South Korea	Korea Institute of Geoscience and Mineral Resources	Research organisation
South Africa	Council for Geoscience	Geological Survey
Spain	Spanish Geological Survey (IGME)	Geological Survey
Thailand	CCOP Technical Secretariat	Membership organisation
UK	British Geological Survey	Geological Survey
UK	None	None
UK	Shell	Oil Company
USA	U.S. Geological Survey	Geological Survey
USA	World Resources Institute	Funding body

QUESTION 2 – WHAT IS YOUR ROLE IN THE ORGANISATION?

The majority of respondents were in a Programme/Project Manager role or were Senior/Principal Scientists (Table 8), providing some confidence that respondents could be expected to have a good overview of the status of storage assessments in their countries or areas of responsibility.

Table 8 Role of respondents within the organisation

Response Text	**Categories**
Formerly division chair of environmental studies	none
Senior researcher	Senior/Principle Scientist
Professor	Senior/Principle Scientist
Senior researcher, modeller	Senior/Principle Scientist
Research Manager	Project/Programme Manager
Senior Geologist	Senior/Principle Scientist
Deputy Director – Geo-resources Division	Project/Programme Manager
Deputy Director of Research on Geological Resources	Project/Programme Manager
Environmental Engineer	Engineer
Department leader CO2 Storage and EOR	CCS lead
project manager	Project Manager
Manager - R&D	Project/Programme Manager
Principal researcher of CO2 sequestration Department	Senior/Principle Scientist
Senior CCS Scientist	Senior/Principle Scientist
I do not belong to an organisation	None
Research Scientist	Senior/Principle Scientist

Project manager	Project/Programme Manager
CCS project director	CCS Project Director
CCS Deployment Leader	CCS lead
High-level Management of CCS projects	CCS lead
Senior Adviser - Storage	Senior Advisor
Project/Program Coordinator	Project/Programme Manager
General Manager - Research	Project/Programme Manager
Branch Head, Resources Advice and Promotion	Project/Programme Manager
Supervisory Research Geologist	Senior/Principle Scientist
Sub-Department Subsurface Use, Geological CO2 Storage	Senior/Principle Scientist
Research Geologist	Senior/Principle Scientist
Distinguished Scientist	Senior/Principle Scientist

QUESTION 3 – HAS A CO_2 STORAGE ASSESSMENT BEEN CARRIED OUT IN YOUR COUNTRY?

All of the respondents reported that a CO_2 storage assessment had been undertaken in their representative country. In summary therefore national assessments have been undertaken in at least 15 countries globally.

QUESTION 4 – IF YOU ARE RESPONSIBLE FOR THE FUNDING INITIATION OR FOR UNDERTAKING STORAGE ASSESSMENTS PLEASE DESCRIBE YOUR ROLE AND THE COUNTRIES YOU HAVE WORKED IN.

Twenty-three of the 28 respondents provided a text answer to this question. The responses are as follows:

Free text response	Respondent's country
Storage capacity assessments have been undertaken for offshore areas around Japan in several regions. Onshore assessments have not been undertaken. There have been some site-specific investigations for public acceptance	Japan
We are involved in three research projects on future development of CCS in China, storage assessment is one of components for these studies	China
We have done modelling of Storage assessment off shore Norway in several projects. I have also been involved in storage assessment in Sweden and Denmark	Norway
Norwegian Continental Shelf CO_2 Storage Atlas Participated in the work group	Norway
BRGM carried out a national survey on capacity assessment of CO_2 storage through different projects as GESTCO, EUGeoCapacity, METSTOR	France
I have participated in and/or directed all the main geological storage assessments carried out in Spain, including FP7 European Projects as GeoCapacity or COMET. Large participation on the national screening for identification and evaluation of geological structures for CO_2 storage carried out by IGME (2010 - 2014) which is the work of reference in this issue in Spain	Spain
As a researcher, working in PETROBRAS Research Center (CENPES) - Brazil since the beginning of my professional career, my main attributions are: evaluation of research project proposals from Universities and other partners, technical monitoring and consulting for the researches developed by partners and development of internal researches.	Brazil
Financer and contributor, Norway	Norway
I am a researcher working on CO_2 geologic storage with government funds. CO_2 storage assessments can be undertaken in higher level.	South Korea

I have worked on CO_2 storage assessments in the UK, the Indian subcontinent and elsewhere.	UK
Done assessments for other countries, acted as advisor, project manager, assurer	UK
Leading CO_2 storage assessment projects in The Netherlands	Netherlands
ADB is a multilateral financing institution that is focused on Asia and the Pacific. We have recently supported storage assessment activities in China and Indonesia.	Not given
South Africa	South Africa
Geologist, modeller and Australia	Australia
Program Coordinator of a regional capacity building program in CCS mapping, "CCOP CO_2 Storage Mapping (CCS-M) Program". This is participated by 10 member countries.	Thailand
In a previous capacity (Geoscience Australia) I led the team carrying out the resource assessment for the Australian "Carbon Storage Task Force" in 2009. I have not carried out assessments in any other country but have been involved in encouraging such assessments to be made by involvement in such projects as CAGS (China) and CCOP CCS-M workshops (SE Asia)	Australia
Lead the project within Geoscience Australia that helped create the high-level storage assessment of Australia's basins	Australia
US, China	USA
I have led a research team to conduct a CO_2 storage assessment of the onshore and State waters of the United States. I also served as an assessment geologist for various storage assessment units in the United States.	USA
We have estimated the CO_2 storage capacity for Germany	Germany
I was responsible for the Storage Assessment Methodology, and was a lead geologist for the U.S. Geological Survey's National Geologic CO_2 Storage Assessment. I was also integral in the writing of the IEA Workshop Report 2013: "Methods to assess geologic CO_2 storage capacity: status and best practice".	USA
Developing methodology and undertaking storage assessments in Canada	Canada

Of the 23 respondents, 18 people have experience in undertaking storage capacity assessments and three in developing methodologies. Participants also had experience in financing and supporting projects, advising countries undertaking assessments and coordinating assessments.

The respondents have worked in a number of countries other than their representative country including China, India and Indonesia.

QUESTION 5 – WHAT LEVEL OF STORAGE ASSESSMENT HAS BEEN UNDERTAKEN IN YOUR COUNTRY?

This question was aimed at discovering the level of storage capacity assessment that had been undertaken in the respondent’s country. Respondents were provided with a description of the levels of based on the Carbon Sequestration Leadership Forum task force methodology (CSLF, 2007) for reference, which were as follows;

1. Theoretical Storage Capacity is the total resource. It encompasses the whole of the resource. It is the physical limit of what the geological system can accept. It assumes that the system’s entire capacity to store CO_2 in pore space, or dissolved at maximum saturation in formation fluids, or adsorbed at 100% saturation in the entire coal mass, is accessible and utilized to its full capacity.

2. Effective Storage Capacity represents a subset of the 'theoretical' capacity and is obtained by considering that part of the 'theoretical' storage capacity that can be physically accessed and which meets a range of geological and engineering criteria.
3. Practical Storage Capacity, is that subset of the 'effective' capacity that is obtained by considering technical, legal and regulatory, infrastructural and general economic barriers to CO_2 geological storage. The Practical Storage Capacity corresponds to the term 'reserves' used in the energy and mining industries.
4. Matched Storage Capacity is that subset of the 'practical' capacity that is obtained by detailed matching of large stationary CO_2 sources with geological storage site that are adequate in terms of capacity, injectivity and supply rate to contain CO_2 streams sent for storage from that source or sources. This capacity is at the top of the resource pyramid and corresponds to the term 'proved marketable reserves' used by the mining industry.

High-level geological CO_2 storage assessments would be the equivalent of 'theoretical' or 'effective' storage capacity using the CSLF definition.

All of the 15 countries who responded to the questionnaire had completed 'theoretical' storage capacity assessments, of which 11 had undertaken 'effective' storage capacity assessments, seven countries had taken this to the next level ('practical' storage capacity). Four countries had achieved 'matched' capacity assessments. However, this latter figure is likely to be higher as Australia, Norway and Canada are known to have full chain CCS projects at an advanced stage of investigation.

QUESTION 6 – WHAT NATIONAL COVERAGE HAS BEEN ACHIEVED BY YOUR COUNTRY'S STORAGE ASSESSMENT?

This question was used to judge the extent of the storage assessments in the respondent's country or countries. All areas have some level of coverage (Table 9)

Table 9 Level of storage assessment achieved based on responses to questionnaire.

Country	No coverage	Onshore only (no offshore territory)	Onshore (but have offshore territory)	Onshore	Offshore	Sedimentary basin level	One regional assessment	Site-specific assessment
Australia						x		*
Brazil				x	x			
Canada					x	x		
China			x					x
France			x			x		
Germany				x	x			
Japan					x			
Netherlands				x	x			x
Norway					x	x		*
South Korea						x		x
South Africa				x	x			
Spain				x	x	x		x
Thailand						x		
UK					x			*
USA			x					

* It is worth noting that although respondents from Australia, Norway and the UK did not mention site specific assessments, it is assumed the response indicates that the respondents meant that site specific studies were not carried out as part of the national storage assessment since Australia, the UK and Norway have demonstration projects planned/underway for which site specific studies have been conducted by the project operators.

Specific comments included:

1. *Brazilian territory, encompassing both onshore and offshore areas (based on CCS Atlas)*
2. *Norway – In certain cases site-specific assessments have been done e.g. Utsira*
3. *Canada – Only a few sedimentary basins out of a few tens, but the most important ones in terms of size and vicinity of CO_2 sources. Three site-specific assessments (Weyburn-Midale, Aquistore, Shell-Quest)*
4. *Australia –Some site-specific surveys Gorgon Project (Chevron), Otway Project (CO2CRC) and SW Hub (WADMP).*

QUESTION 7 – IS THERE A PLAN OR EXPECTATION THAT A HIGH-LEVEL STORAGE ASSESSMENT WILL BE UNDERTAKEN.

Twenty-two respondents answered this question with 20 responding ‘yes’ (Figure 10). Only 7% responded ‘no’, these were representatives of Canada and Spain; it is likely that the respondents answered no to this question as high-level assessments have already been done in their country. Several respondents skipped this question, presumably for the same reason.

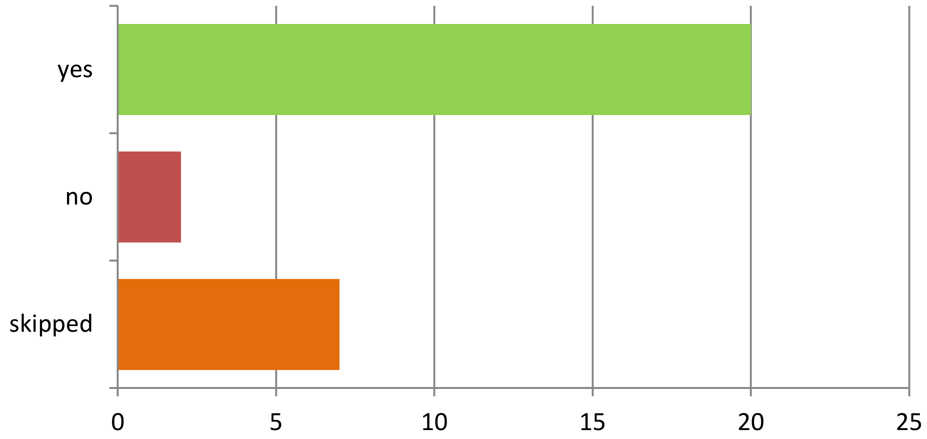


Figure 10 Plans for storage assessment

QUESTION 8 – WHAT ARE THE PERCEIVED BARRIERS FOR FUTURE ASSESSMENT WORK? IF A STORAGE ASSESSMENT HAS BEEN DONE PLEASE TICK THE BARRIERS YOU ENCOUNTERED.

All of the countries who participated have undertaken some level of storage assessment, therefore the answers to this question refer to the barriers encountered whilst planning or conducting those storage assessments (Figure 11 and Figure 12).

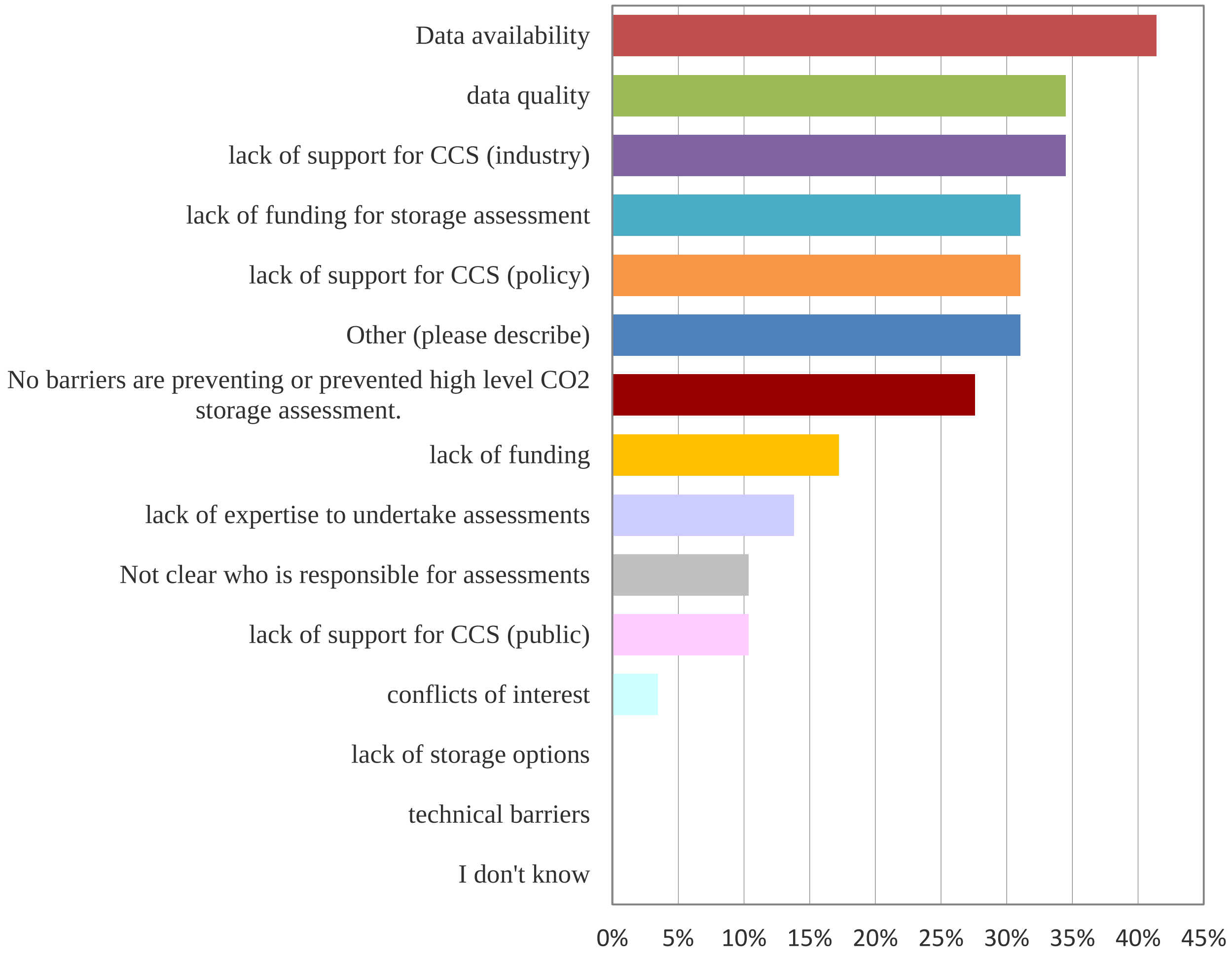


Figure 11 Original questionnaire results on barriers faced when planning or conducting storage assessments (compare with Figure 12).

Data availability was reported as the most significant barrier with eleven of the respondents reporting this as an issue, which is compounded with data quality being a problem (reported by nine of the respondents). Industrial and policy support were also seen as barriers to conducting storage assessments, reported by eight and seven of the respondents, respectively. Six of the respondents found no barriers in planning and conducting storage assessments. Lack of funding and lack of expertise was noted by four respondents. Three of the respondents found it was not clear who was responsible for storage assessments in their country. Lack of public support was only cited by two of the respondents and conflict of interest was reported by one respondent. The results from this question are given in Figure 11.

Six respondents reported ‘other’ as barriers for storage assessments; their responses are as follows:

1. *Some projects have progressed, but large-scale projects have stalled due to lack of funding.*
2. *The main issues are the lack of knowledge as to how formations will respond to injection (pressure issues) and how leak-proof cap rocks are.*
3. *If sufficient data had been available expertise may have become a limiting factor. Funds could be seen as a limiting factor else the data could be obtained. We don’t have a mature oil and gas industry and therefore the lack of data is seen as a major barrier. However, as barriers are overcome there always seem to be another.*

4. *At the time of the Carbon Storage Task-force there was a general Government and Industry support for this work, however in the current political/economic situation I believe that there would be less support for it.*
5. *Lack of funding is always an issue.*
6. *Proprietary subsurface data.*

The 'other' responses were added into the categories of potential barriers already included in the survey to allow assessment of the main reported barriers (Figure 12)

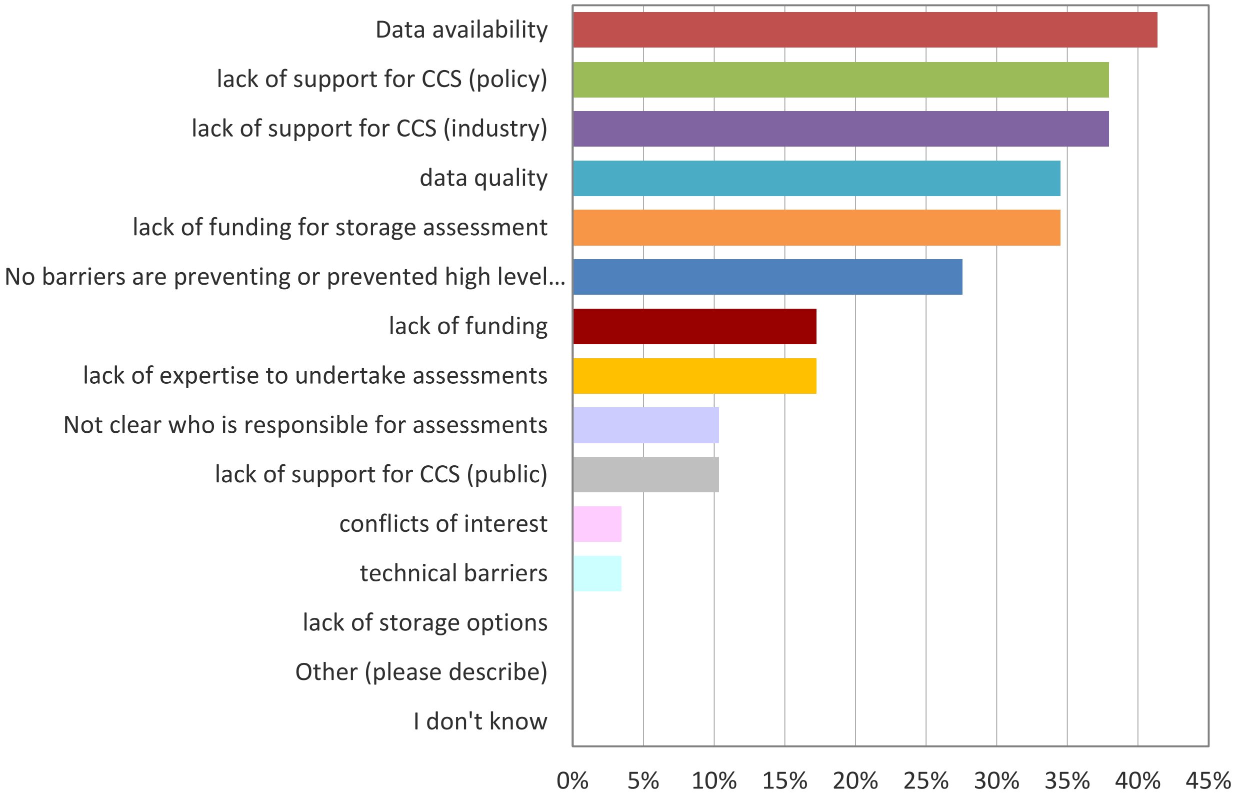


Figure 12 Barriers faced when planning or conducting storage assessments with 'other' comments included in main categories (free text response, used to provide more detail on the answer or response, so was included under the main categories already suggested in the questionnaire for easy comparison of main perceived barriers to national storage assessments).

QUESTION 9 – WHO ARE THE KEY ORGANISATIONS RESPONSIBLE OR INTERESTED IN THE DEVELOPMENT OF STORAGE ASSESSMENTS IN YOUR COUNTRY?

A range of organisations were reported to be responsible or interested in development of storage assessments in each of the countries represented by the respondents.

Countries with multiple respondents often reported a range of responsible and interested organisations (Table 10).

Table 10 Summary of key organisations who are perceived as responsible or interested in CO_2 storage assessments.

Country	Responsible organisations
Australia	Commonwealth of Australia (GeoScience Australia); Individual State Governments (State geological surveys)
Brazil	Center of Excellence in Research and Innovation in Petroleum; Mineral Resources and Carbon Storage (PUC-RS); Universities; Brazilian Geologic Survey (CPRM); Brazilian Institute of Petroleum (IBP); PETROBRAS R&D Centre (CENPES); PETROBRAS
Canada	Federal natural resources department (NRCAN), Geological Survey of Canada; corresponding provincial government agencies
China	National Development and Reform Commission (NDRC) Department of Climate Change, Huaneng Clean Energy Research Institute, Shenhua Coal Company in China, Chinese Academy of Science
France	Ministry of Sustainable Development; French Agency for Energy Management (ADEME); French Agency for Research (ANR), ClubCO2, ...
Germany	BGR in consultation with state geological surveys
Japan	Research Institute of Innovative Technology for the Earth (RITE); Japan CCS Company. (JCCS Co.); Industry, in the Japan CCS Company consortium, is responsible for development and operation of the Tomakomai demonstration CCS project in Japan; Ministry of the Environment, MOE; Ministry of Economy, Trade and Industry, METI
Netherlands	National government, industry (power), local government
Norway	Norwegian Petroleum Directorate; Gassnova; Ministry of Petroleum and Energy; Statoil; Universities; Research Institutions; SINTEF
South Korea	KIGAM for onshore; Korea Research Institute of Ships and Ocean engineering (KRISO) for offshore storage; Korea National Oil Corporation (KNOC) for offshore CO_2 storage; some universities
South Africa	The South African Energy Development Institute (SANEDI); Council for Geoscience.
Spain	Instituto Geológico y Minero de España (IGME)
Thailand	The key organisations in our member countries are the oil & gas regulatory/research agencies; national oil and gas companies; geological survey/agencies (this answer appears to refer to Committee for GeoScience Programmes in East and Southeast Asia (CCOP))
UK	Department of Environment and Climate Change (DECC) Office for Carbon Capture and Storage (OCCS); British Geological Survey (BGS); Energy Technologies Institute (ETI); The Crown Estate (TCE); CCS developers with no funding
USA	United States Geological Survey (USGS); Department of Energy Office of Fossil Energies; National Energy Technology Laboratory (NETL); various universities

There is a range of sectors that are interested and responsible for CO_2 storage assessments. The three most significant sectors responsible for CO_2 storage assessments are geological surveys, government bodies, and research centres/institutes.

QUESTION 10 – IF STORAGE ASSESSMENTS HAVE BEEN CONDUCTED WHO WAS THE STORAGE ASSESSMENT DONE OR FUNDED BY?

The responses have been amalgamated in Table 11 by country to present the organisation that funded or received the CO_2 storage assessments undertaken.

Table 11 Funding or receiving organisation of the CO_2 storage assessment by country.

Country	Recipient of storage assessment
Australia	Federal government (Commonwealth of Australia), Coal Industry, State Governments
Brazil	Brazilian Atlas of CO2 Capture and Geological Storage was organized by the Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (PUC-RS) through funding from the Global CCS Institute.
Canada	Natural Resources Canada
China	Ministry of Science and Technology (MOST); National Development and Reform Commission (NDRC)

France	At national level, done for Ministries, society and industry, funded by EU (FP6 and 7), ADEME and ANR. At site level, funded by industry and ADEME (Arcelor-Mittal, Total, GDFSuez)
Germany	Federal Government
Japan	RITE; Ministry of the Environment, MOE; Ministry of Economy, Trade and Industry, METI
Netherlands	Assessment done by TNO, funded by national and local governments, as well as by industry (power, transport)
Norway	Ministry of Petroleum and Energy; EU Projects; NFR funding
South Korea	KIGAM for onshore assessment and KNOC for offshore assessment
South Africa	The storage assessment was done for SANEDI and funded by industry and government, e.g. PetroSA, Sasol, Anglocoal, Eskom and SANEDI.
Spain	The national plan was developed by IGME in cooperation with geology and engineering consulting companies and funded by the Ministry of Industry.
Thailand	Our four-year CCS-M Program is funded up to 2.5 years, we still need additional funding to complete the regional atlas of geological storage in the region through a web GIS system. *The original atlas for Thailand, Vietnam, the Philippines and Indonesia was funded by the World Bank^.*
UK	Energy Technologies Institute, EEPR funded appraisal for White Rose project (5/42) and Shell funded appraisal for the Peterhead CCS project (Goldeneye Field)
USA	US DOE, Federal Government
No country given	for a pilot project to be funded by ADB in China and Indonesia.

^ Text in italics added by report authors

In most countries national assessments have been undertaken for national government departments, industry or petroleum departments, or organisations with a mandate to fund such activities received from national governments.

QUESTION 11 – IS THERE A NATIONAL INVENTORY OF WELL LOGS, CORE AND WELLBORE RECORDS?

The countries for the majority of respondents hold national inventories of data (Figure 13). Countries with no reported national inventory include; Brazil, Germany, China and Indonesia (respondents were not all from China or Indonesia), although this has not prevented these countries from undertaking regional or national assessments.

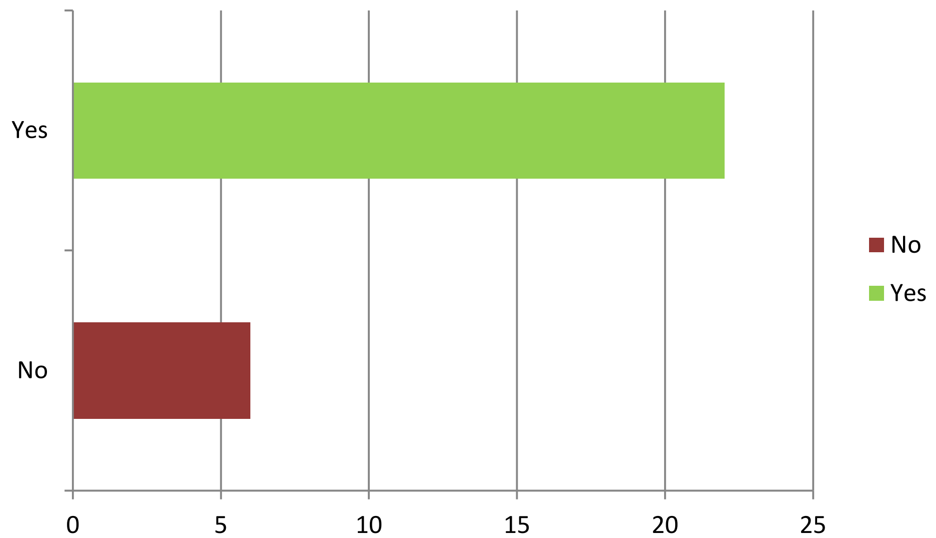


Figure 13: Percentage of countries who are perceived by respondents as holding a national inventory of well data

QUESTION 12 – WHO HOLDS NATIONAL DATA INVENTORIES?

A large number of organisations and agencies hold key data for storage assessments (Table 12)

Table 12 Perceived data owners and providers in each country represented by the questionnaire respondents

Country	Data holder
Australia	For offshore data it is Geoscience Australia while for onshore data the data resides with the individual state/national territory jurisdictions.
Brazil	Data inventories are dispersed among many private and public institutions.
Canada	There is no national data inventory. Each province holds the data within its jurisdiction, with unequal quality and categories
France	BRGM, the French Geological Survey
Germany	Individual federal states
Japan	Japanese government; Research Institute of Innovative Technology for the Earth (RITE), oil and gas companies, National Institute of Advanced Industrial Science and Technology (AIST).
Netherlands	TNO
Norway	Norwegian Petroleum Directorate
South Korea	Korea Institute for Geoscience and Mineral Resources (KIGAM) for onshore data. Korea National Oil Corporation (KNOC) for offshore data
South Africa	The Petroleum Agency South Africa (mostly) and the Council for Geoscience.
Spain	Well logs, wellbore records and other results from oil and gas exploration (for example depth maps) are available (hard copies) at the Ministry of Industry and partially on the webpage of IGME (www.igme.es) Cores are available at the IGME drill cores and cuttings repository located in Peñarroya (Córdoba)
Thailand	The member countries' regulatory and/or data management organization holds the data
UK	BGS and Data release agents (who charge for access) on behalf of DECC.
USA	States hold some data, other data are proprietary and held by private companies. These proprietary data are often available for a fee.

Data holders are a mix of oil ministries and national/provincial geological surveys, or in some cases private companies.

QUESTION 13 – WHERE DID OR WOULD KEY DATA FOR STORAGE ASSESSMENTS COME FROM?

This question captures the range of data providers required for CO_2 storage assessments. The results are provided in Figure 14 and Table 13.

Table 13: Key data holders for national storage assessments

	Australia	Brazil	Canada	China	France	Germany	Japan	Netherlands	Norway	South Korea	South Africa	Spain	Thailand	UK	USA	Not given	Number of countries
National datasets	x	x	x	x	x		x	x	x	x	x	x	x	x	x		14
Private companies		x	x	x	x	x	x		x	x	x	x	x	x	x	x	14
Data release agents			x								x			x	x		4
New data would need to be acquired	x	x									x	x		x	x		6
Other	x		x			x	x								x		5
I don't know																	

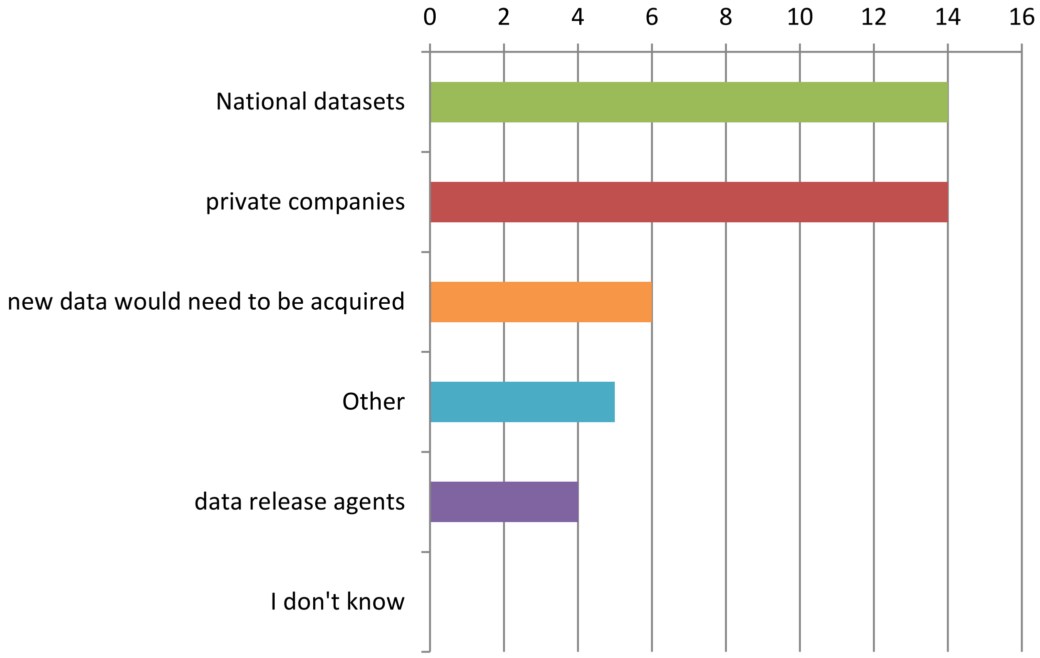


Figure 14 Data sources on which national CO_2 storage capacity is assessed (each response has been counted once for each country).

Six respondents provided additional comments on the subject of data. The comments are as follows:

1. *The regional CCS partnerships have played a significant role in the storage assessments at the regional level, private companies play a bigger role in site specific assessments (respondent from USA).*
2. *Following acceptance of the Task Force report a programme of offshore data acquisition was initiated by Federal Government (respondent from Australia).*
3. *Also from specific government funding allowing us to acquire additional data (respondent from Australia).*
4. *State surveys and research institutes (respondent from Germany)*
5. *Provincial oil and gas regulatory agencies (respondent from Canada).*
6. *The key data sets are owned by the Japanese Government (respondent from Japan)*

QUESTION 14 – WHAT LEVEL OF STORAGE ASSESSMENT WOULD YOU LIKE TO SEE IN YOUR COUNTRY?

The ambitions for CO_2 storage assessment vary from country to country. Twenty-six respondents provided an answer to this question. Most countries desire a level of storage capacity assessment above ‘theoretical’ storage capacity (Figure 15). Only one country stated ‘theoretical’ storage capacity as their ambition. Some respondents indicated they wished to extend the geographical coverage of the level that had already been achieved. Six respondents set a slightly different level of assessment, all requesting more advanced storage assessment, these are captured in the following comments:

1. *Advance site characterisation for potential CCS project sites with sufficient detail to permit a project according to regulations*
2. *Effective capacity, based on improved database.*

3. *I would like a very detailed look at prospective storage formations as the geology is quite complicated*
4. *A more detailed level of storage assessment that would include exploratory drilling*
5. *I would like to see site-level assessment of the deep offshore areas*
6. *We don't need extra studies on CO_2 storage assessment at national or regional levels, we need real projects for which practical assessments are needed*

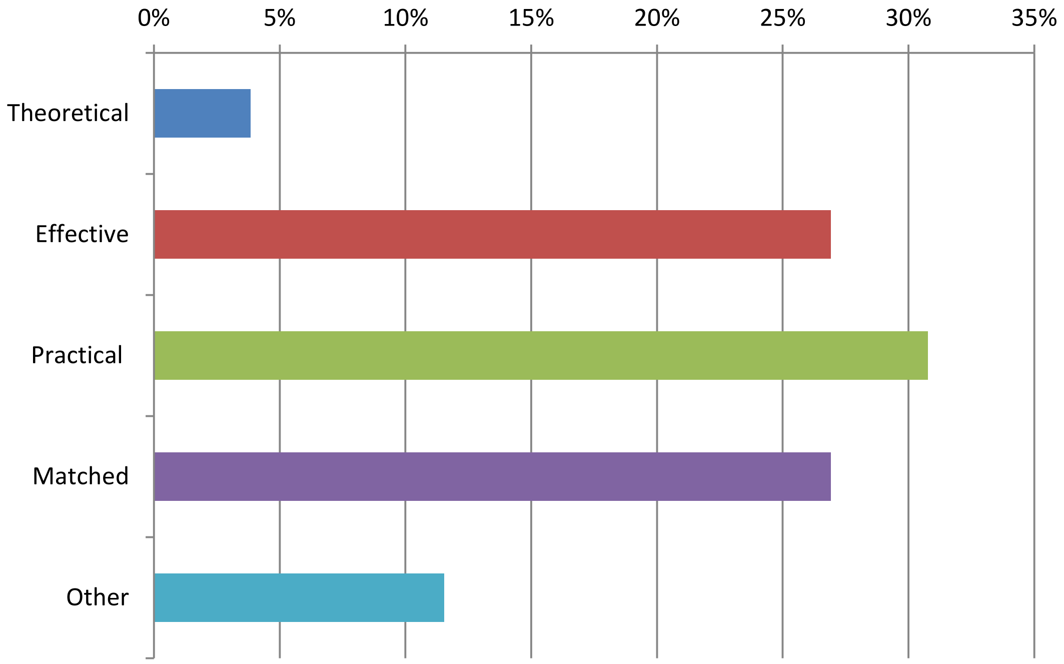


Figure 15 level of storage assessment desired by percentage of respondents

QUESTION 15 - WHICH METHODOLOGIES WERE APPLIED DURING THE STORAGE ASSESSMENT WORK?

A number of storage assessment methodologies are available (Chapter 3 and Appendix 4), the methodologies used for CO_2 storage assessment by the respondents are shown in Figure 16.

The results demonstrate there is no one dominant methodology. The respondents frequently stated in their responses that they used an adapted version of a methodology which made it relevant to their country.

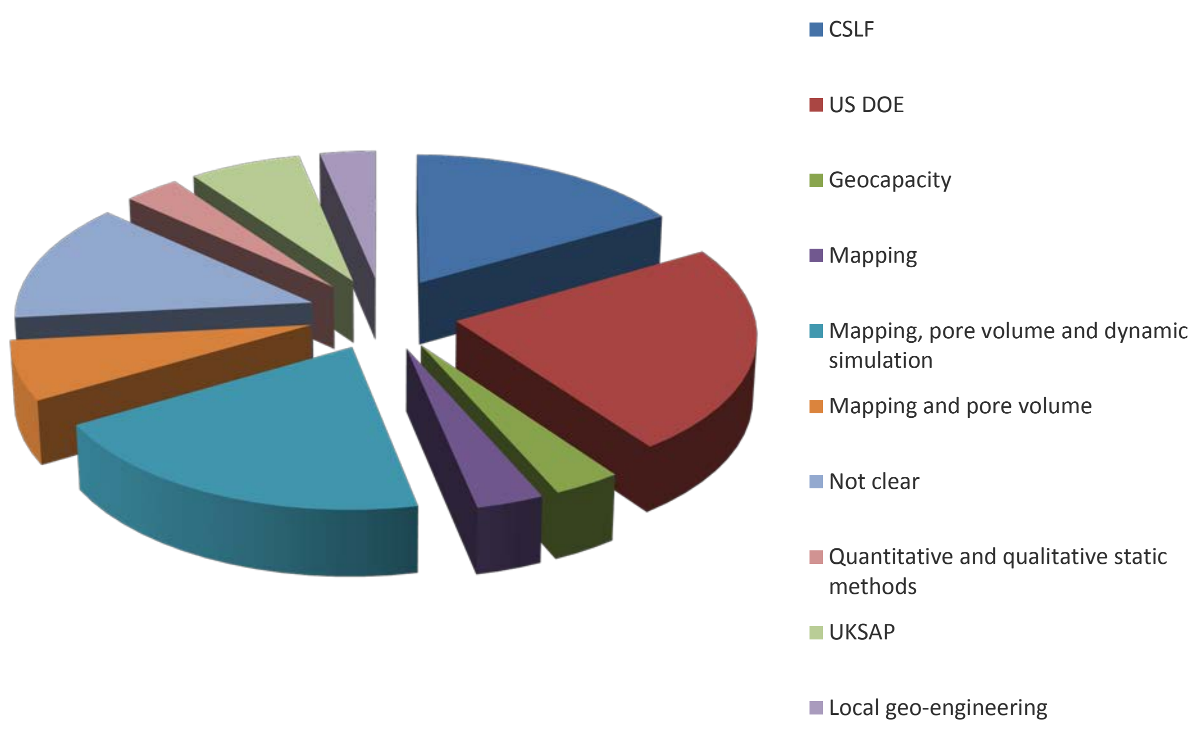


Figure 16 Methodologies followed for national storage assessments

QUESTION 16 – WERE THE METHODOLOGIES CLEAR AND FIT FOR PURPOSE?

The majority (85% of the respondents) state that the methodology used was clear and fit for purpose (Figure 17). In cases where the methodology was not clear and fit for purpose the following comments were recorded:

1. *The Atlas of CO_2 Capture and Geological Storage represents a first attempt to survey CO_2 geological storage potential and further research effort and development must be done*
2. *Lack of data*
3. *Regional assessment did not look at well integrity*
4. *We developed cut-off criteria and tested Storage efficiency factors with dynamic simulation*

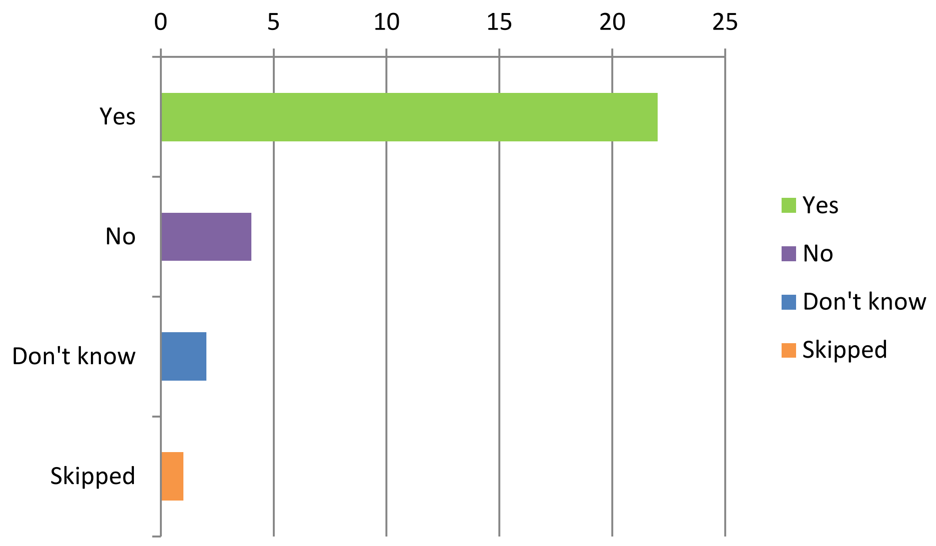


Figure 17 Number of questionnaire respondents who perceived the methodologies followed were clear and fit for purpose.

QUESTION 17 – HOW LONG DID IT TAKE TO GET TO THE LEVEL OF ASSESSMENT YOUR COUNTRY IS AT NOW?

Fifteen of the 25 respondents indicated it had taken five to ten years to reach the level of storage assessment the country had currently achieved (Figure 18).

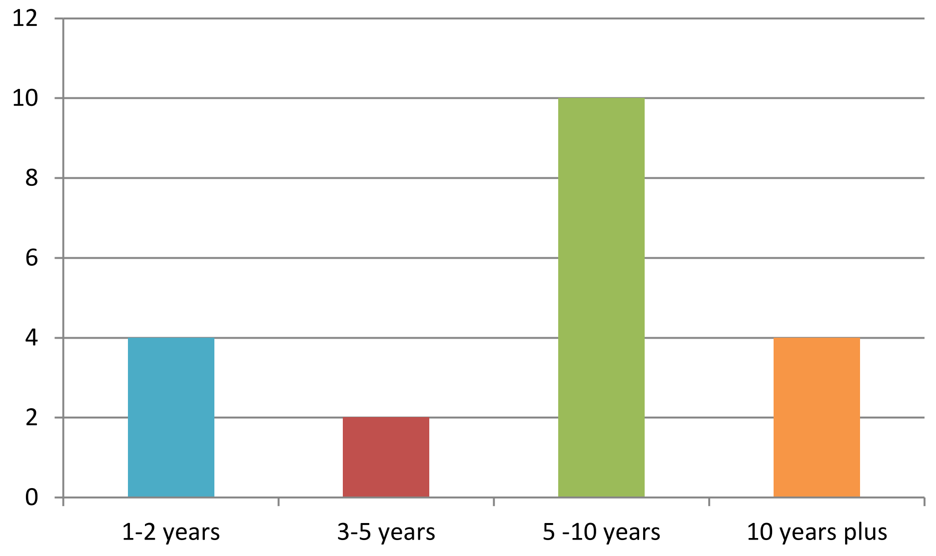


Figure 18 Time taken to reach the current level of storage assessment as reported by the questionnaire respondents.

Comments from two respondents state that the period required was three to five years.

QUESTION 18 – HOW WAS THE STORAGE ASSESSMENT INFORMATION COLLATED AND PRESENTED?

Delivery of the CO_2 storage assessment information is facilitated in a number of ways (Figure 19 and Table 14). The majority of the data is available in publically available reports, databases, research papers, storage atlases or online resources. Some of the countries represented hold storage capacity information in confidential reports or databases.

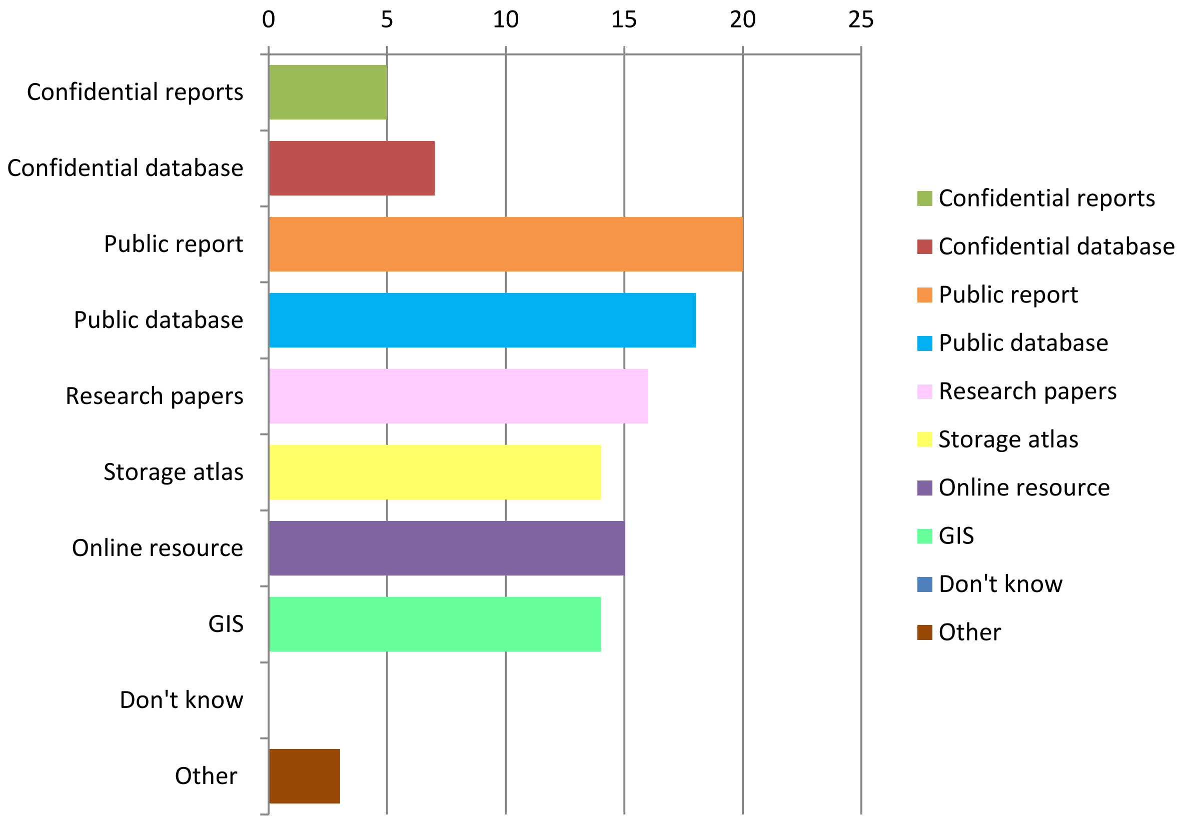


Figure 19: Number of questionnaire respondents who reported on different delivery formats of the CO_2 storage assessment results.

Two respondents noted other presentation methods were followed and made the following comments;

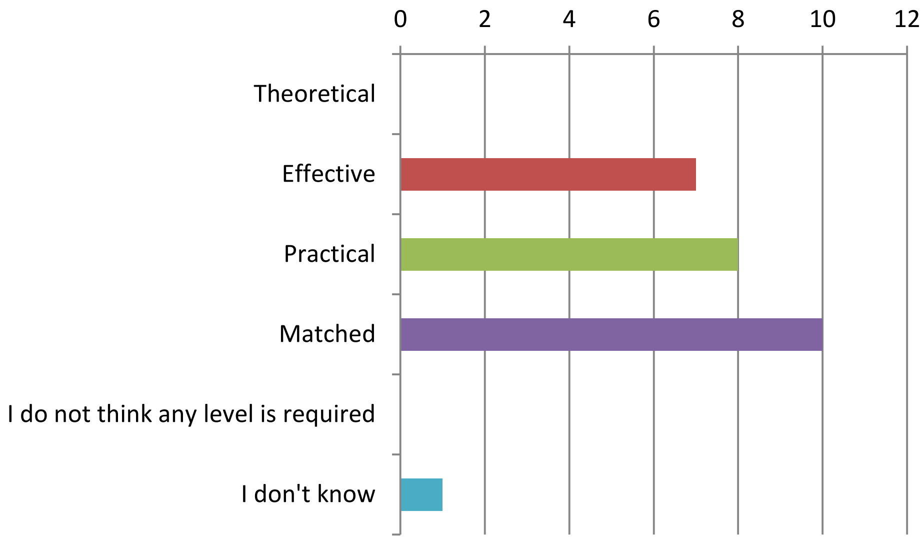
1. *Confidential databases for practical assessment at site level (respondent from France).*
2. *Database not fully publically available (respondent from UK).*

The responses indicate that there is a good amount of data in the public domain which could be used to inform future national storage assessments.

Table 14: Delivery format of the CO_2 storage assessment results by country (question 18)

	Australia	Brazil	Canada	France	Germany	Japan	Netherlands	Norway	South Korea	South Africa	Spain	Thailand	UK	USA	Not given	Number of countries
Confidential reports	x				x			x					x		x	5
Public report	x		x		x		x	x	x	x	x	x	x	x		11
Research papers	x			x	x		x	x	x	x	x		x	x		10
Confidential databases				x	x	x		x					x		x	6
Public database	x	x		x			x	x	x		x	x	x	x		10
Storage atlas	x	x	x					x		x	x		x	x		8
Online resource	x	x	x		x			x			x	x	x	x		9
GIS	x	x	x	x						x	x	x	x	x		9
Other				x									x			2
Don't know																0

QUESTION 19 – WHAT LEVEL OF STORAGE ASSESSMENT WOULD YOU LIKE TO SEE IN YOUR COUNTRY? FOR A FULL DESCRIPTION PLEASE REFER TO PAGE 1.



No questionnaire respondents indicated that a national storage assessment was not required. The 'I don't know' response was accompanied by the follow comment:

1. *It is too early to look beyond project or region specific assessment considering the very slow progress.*

QUESTION 20 - WHAT LEVEL OF NATIONAL COVERAGE DO YOU HOPE IS ACHIEVED IN YOUR COUNTRY?

This question is aimed at establishing the ambitions of coverage for CO_2 storage assessments in the represented county, i.e. the extent of the country included in the assessment. There is a range of ambition for coverage in the individual countries represented, this is likely to be due to national data availability and the unique geology and geography (Figure 20 and Figure 21).

The comments were used for a variety of purposes; to provide country-specific comments or in some cases where the respondent wanted to select more than one option. Unfortunately, this approach means the answers to question 20 are a little unclear on first collation. Many respondents have selected both 'onshore only' and 'offshore only' so interpretation of the results of this question for the survey require caution. Comments were received from seven of the respondents in the 'other' category:

1. *Combination of offshore coverage with matched storage capacity of selected sites. This response is considered as 'a 'site-specific study' for the purposes of this review.*
2. *Coal basins too (as part of sedimentary basins) This response is considered as 'sedimentary basin-level assessment' for the purposes of this review.*
3. *Coverage is already quite large but maybe in some areas offshore. This response is considered as 'sedimentary basin-level assessment' for the purposes of this review'*
4. *In specific cases we have started to look at matched capacity. This response is considered as a 'site-specific study' for the purposes of this review.*
5. *Whatever is necessary to show where commercial storage can be done. Viability will be a major problem but this might not be so in the future.*
6. *Site specific where commercial or demonstration projects are proposed. This response is considered as a 'site-specific study' for the purposes of this review.*
7. *National coverage is in place, need more detailed matched storage capacity to work and more detailed offshore assessments. This response is considered as a 'site-specific study' for the purposes of this review.*
8. *On and offshore, nationwide. This response is considered as 'sedimentary basin-level assessment' for the purposes of this review.*
9. *I think that onshore and offshore sedimentary basins should be assessed. This response is considered as 'sedimentary basin-level assessment' for the purposes of this review.*
10. *Only selected sedimentary basin located in the vicinity of large CO_2 emitters (there is no point assessing sedimentary basins in the Arctic!). This response is considered as 'sedimentary basin-level assessment' for the purposes of this review.*

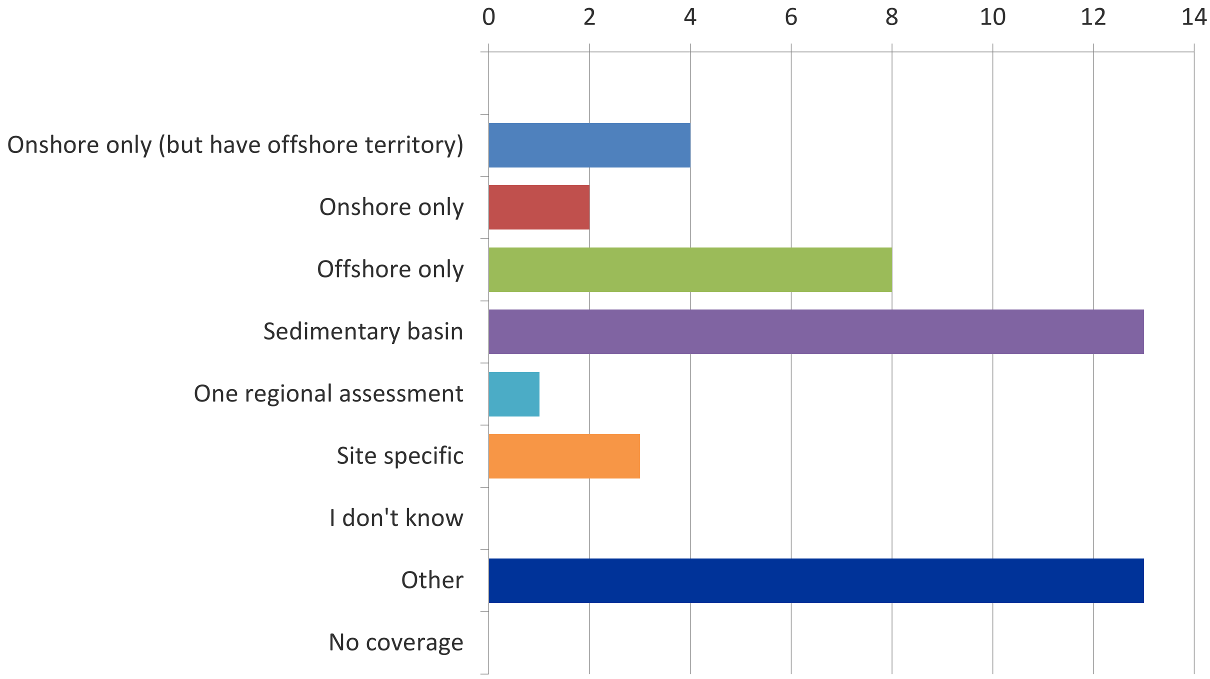


Figure 20 Number of questionnaire responses on desired level of CO_2 storage assessment coverage

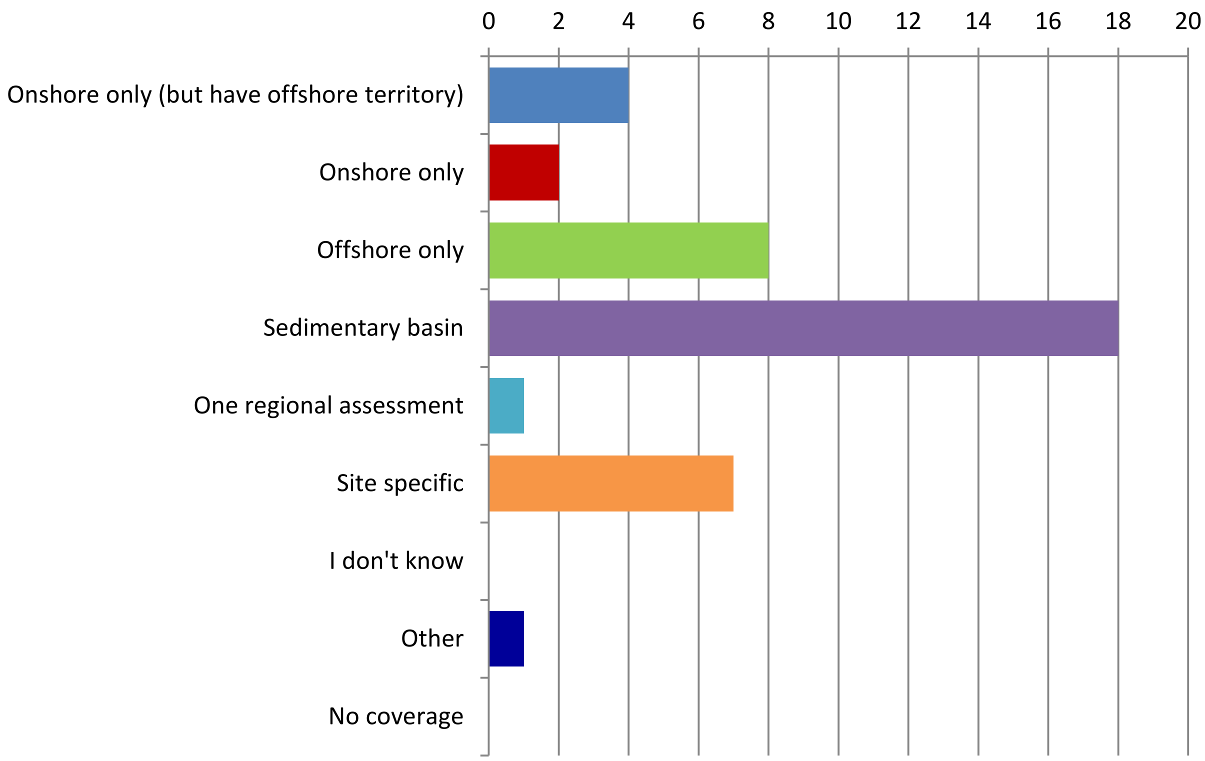


Figure 21 Interpreted results for number of questionnaire responses on desired level of storage assessment (see text in italics for interpretation)

QUESTION 21 – HOW LONG DO YOU THINK IT WILL TAKE TO REACH THIS (DESIRED) LEVEL OF STORAGE ASSESSMENT?

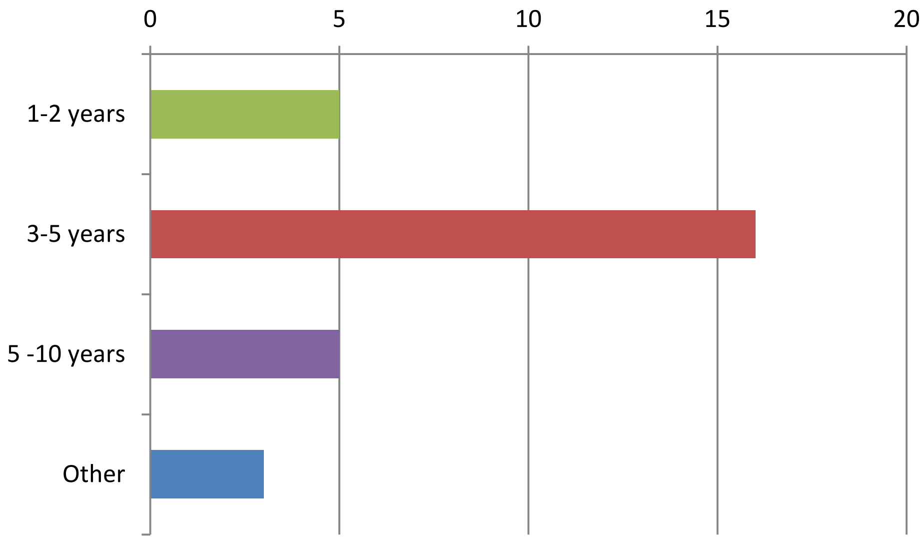


Figure 22 Estimated duration to reach the desired level and national coverage of CO_2 storage assessment.

Sixteen of the 23 respondents estimated it would take five to ten years to achieve their desired level of assessment (Figure 22). Most responders who gave the answer ‘other’ stated that the desired level of national assessment had already been achieved.

The time that it is expected to take to achieve the desired level of coverage and level of coverage described are compared in Table 15. Note that questionnaire respondents usually indicated geographical coverage desired (e.g. on or offshore) plus the level desired (e.g. sedimentary basin coverage) in their responses. The majority of responders desired sedimentary basin level coverage and felt that it would take 5 – 10 years to achieve this.

Table 15 Comparison of question 20 (desired level of storage assessment) and question 21 (estimated time taken to get to this level of assessment)

	Time taken			
	1-2 years	**5 – 10 years**	**10+ years**	**other**
Desired coverage level				
Onshore only (but have offshore territory)	1	2		
Onshore only		1	1	It has been done
Offshore only	1	3	2	It has been done (two respondents)
Sedimentary basin	3	10 Plus this comment: 3-5 years to assess sedimentary basins in the vicinity of large emitters		It has been done
One regional assessment	1			
Site specific	1		1	It has been done Undertake where commercial projects are proposed
I don't know				
Other		Extend offshore coverage Already have some matched capacities Whatever is necessary to show where commercial storage can be done. Need more detailed matched storage capacity work and more detailed offshore assessments I think that the onshore and offshore sedimentary basins should be assessed	On and offshore nationwide	
No coverage				

QUESTION 22 - WILL THE RESULTS BE PUBLISHED?

When asked if the results will be published 23 respondents said 'yes they would be published' and only one felt the results would not be published (and five skipped the question).

QUESTION 23 – WOULD YOU BE HAPPY FOR THE BRITISH GEOLOGICAL SURVEY TO CONTACT YOU TO DISCUSS YOUR ANSWERS?

All respondents were happy to be contacted by the reviewers to follow up their responses to the questionnaire by discussion with a reviewer.

Appendix 3 Follow-up interviews

Ten contacts we made to follow up key responses to the surveys and to obtain more detail in regions where the questionnaire had not been completed.

The follow-up discussions centred around the key perceived barriers identified through the questionnaire. Guidelines for topics to be covered in the follow-up discussions are given below.

FOLLOW-UP DISCUSSION TOPICS FOR BARRIERS TO CO_2 STORAGE ASSESSMENT

Objective: Given the stated ambition for storage assessment, our questionnaire and conversation are to establish if the has been achieved and if not, what were the main barriers.

The aim of the follow-up interviews is to draw out detail on perceived barriers and how barriers have been overcome.

Countries to be covered are those with advanced atlases or those countries with an interest in CCS where the stated ambitions have not been achieved.

<u>Main themes:</u>

Policy and regulatory support

- Has a national assessment been prepared (*need to check questionnaire results and what has been published before interview*). What additional support or policy would help preparation/implementation of a national assessment?
- More generally is there a lack of political/regulatory support for CCS? What drives this?
- Or is there a lack of support for national assessments?
- Has political support for CCS declined or increased over the past couple of years?
- Has a low carbon roadmap been prepared and is CCS included?
- Have other energy or other priorities, e.g. funding for national assessment, cost of implementation of CCS or lack of understanding pushed CCS off the political agenda?

Funding for CCS

- What organisations have funded CCS activities? Were activities funded through national/public funding sources or private companies? (*Need to check questionnaire response as to what stage of storage assessment has been achieved - theoretical, effective etc.*). Experience shows that often public funding comes first to achieve the early theoretical capacity estimates with private companies becoming more active later, though not always, consider Sleipner!)
- Have research, pilot or demonstration projects been funded and if so, by whom? (Again public or private funding?)
- How was funding organised? Are there specific organisations responsible for driving CCS and national assessments? Who are these organisations?
- What motivates companies, institutions and the government to work on or drive forward CCS/national assessments? (e.g. taxes or subsidies or desire to lower GHG emissions?)

National knowledge and technical expertise

- Is there sufficient expertise available to perform storage assessments? (Are there enough people and does the expertise exist?)

- Does this relate to funding or lack of engagement with organisations who have the expertise or data?
- Would the offer of international expertise to support national scientists in the assessment method be welcome
- Would national funds be available to support international experts or would international funds be needed?

Industrial support

(Types of companies/organisations/consortia include oil companies, CCSA, Tees Valley Unlimited, Carbon Sequestration Partnerships in the USA)

- Has the interviewee's company/organisation engaged with industrial companies?
- Is CCS getting support from (large) industrial companies or consortia?
- Has the level of support from (large) industrial companies or consortia increased or decreased in recent years?
- What kind of industrial companies are active (or opposing) in CCS?
- Has expertise from industrial companies been applied to CCS? What level of effort?
- What made these companies/consortia active in CCS or what made them oppose CCS? Have any stepped back and if so, why? (e.g. oil companies and power are involved in the UK, the former has storage expertise, the latter probably due concern about being perceived as 'green' or paying for emissions. The Teesside capture cluster is interested in providing low carbon plastics etc as their customers are asking for it)
- Are there active CCS 'champions', either consortia of interested parties or bodies formed to support CCS or clean energy? (e.g. in the UK there is CCSA, Tees Valley Unlimited, Caledonian Clean Energy Group.)
- Have other energy-related activities influenced CCS? Positive or negative? (e.g. small scale CO_2-EOR seems to have helped support CO_2 storage in the USA in terms of confidence in the technology and experience)

Data access and quality

(note that data availability was reported as the most significant barrier by the respondents)

- Do national data collections exist and if yes what do they comprise?
- Do they provide all the data needed?
- Do other sources of data exist and how accessible are they?
- If data are dispersed what level of resources would be needed to compile them?
- How easy is it to access to national data collections? Are all data for a national assessment held centrally and is the data of sufficient quality?
- Is there a cost to access national data collections?
- Who is responsible the national data collection and how is sending data to this repository regulated? (e.g. in the UK oil and gas companies have to lodge data with BGS)
- What are the barriers to accessing data and how has the interviewee's company worked around these barriers (e.g. we have confidentiality agreements and show the modelling results but not the original data; we have involved the operator in the project; financial support is needed to obtain data; involving regulators can help data access)

- For the national assessment, how long did it take and how much did it cost? What part of this activity took the longest and what part cost the most? (*Check what stage has been reached in terms of theoretical, effective in questionnaire response, also check their response to question 12 on how long it took to get to current level of assessment*)
- Have other subsurface activities influenced data availability/access? (e.g. in the North Sea we have lots of data from the oil and gas industry and our established relationship with oil companies has helped with data access)
- Are there any other barriers not previously discussed that you think have been overcome or still need to be tacked to reach the stated level of ambition?

Additional notes for discussion

After interview will send notes for them to check to ensure they are happy we have captured discussion.

DISCUSSION RESULTS

Policy and regulatory support

This discussion section aimed to assess the importance of political and regulatory support in overcoming perceived barriers to national CO_2 storage assessments.

Representatives from Spain, South Africa, Japan, Korea and Indonesia all commented positively on political and regulatory support for CCS (comments in no particular order):

- *There is ministerial support for CCS. The minister announced a few years ago after publication of the storage atlas that CCS is a flagship program for the government.*
- *When the national strategy against climate change was approved the government charged a research institution with developing a storage (screening) assessment at a national level (study was paid for by Ministry). The national CCS assessment was carried out with the aim of reducing greenhouse gas (GHG) emissions as the wanted to ensure continuation of the national coal industry and thermal (coal fired) power plants. It was perceived at the time that the national coal industry and thermal coal fired power plants could only continue while meeting the Kyoto GHG targets if CCS were utilised.*
- *The level of political support has remained static over the last couple of years, neither an increase nor a decrease. We have prepared a low-carbon road map and CCS is included within it. There are no energy or other priorities that are pushing CCS off the political agenda. There are, however, concerns from environmentalists. Although this is not a serious barrier, the concern about CCS is that it may be perceived as being damaging effect on the environment.*
- *The government has given financial support for some regional CO_2 storage capacity assessments to be undertaken. The government has money assigned for CCS and will support investigation for implementation. Politically, there is governmental support for CCS as a climate change mitigation technology. Political support by the government for CCS has increased over the last couple of years. We have a low-carbon roadmap and CCS is included, although it may not be very obvious.*
- *Memoranda of Understanding (MoUs) had been signed with national governments (and nationalised hydrocarbon companies) during the regional storage assessment study to facilitate data access.*

In contrast, in one country, although there are storage pilots and demonstrations moving forward, a geological survey respondent observed that there is actually almost uniform political opposition by all political parties to CCS on the grounds that '*there is no need for CCS because there is no such thing as global warming*' or '*introducing CCS will encourage more fossil fuel use and we need to move away from that'*. There seems to be more local government support for CCS although the use of CCS for enhanced oil recovery seems a stronger driver than reducing CO_2 emissions.

In some developing economies, government interest was apparently less certain in some countries, for example where legacy emissions are low, current GHG emissions per capita are low and basic infrastructure is still being developed. In some cases, there was more interest in energy efficiency and developing a low-carbon energy supplies so that the need for CCS could be avoided. In addition, the Intended Nationally Determined Contributions (INDCs) for emissions reduction (UNFCCC) did not include CCS. However, a respondent from one developing country observed that there seems to be relatively good support from the national government and discussions with the local government in the region of the proposed pilot project seem positive at this time.

In some developing economies, it was observed that high-purity industrial sources might be of interest in a few years, particularly if climate negotiations went well in Paris (COP21, UN climate change discussions in November and December 2015), raising the profile of GHG targets and starting discussions on the most appropriate mitigation/low carbon technologies.

Funding for CCS

For Spain, Japan and South Korea, public funding was extremely important for national assessments and early work on CO_2 storage assessments (comments in no particular order):

- *Regional groups undertaking basin level and site specific assessments are co-funded by government and industry groups.*
- *Public funding was strong during the early phases of CCS research. Financial support from the government has been reduced over the last two to three years due to the tough economic conditions.*
- *To date, funding for national CCS assessments and activities have come only from the government.*
- *National funding has supported national CO_2 storage assessment activities. Government funding has supported pilot projects and a demonstration project.*

In South Africa, a combination of national and international funding supported national CCS assessment:

- *National assessment was supported by government funding supplemented by international and other funders. Funders supporting national assessment included the World Bank, Norwegian Embassy, UK Government, EuropeAid as well as private sector organisations such as Anglo-American, Eskom and Sasol.*

In Indonesia, the Philippines, Thailand and Vietnam, international funding dominated:

- *In Indonesia, funding for the national assessment mainly came from the Asian Development Bank, UK Government and GCCSI. Japanese companies and oil and gas majors appeared to have an interest in CO_2-EOR. Two small private Japanese trading companies undertook early work on CCS in Indonesia as well, these companies were interested in EOR or in undertaking work to obtain carbon credits for Japan for offsetting their emissions through bilateral Environment Orientated Cost Management (EoCM) offset through joint crediting mechanism (JDM).*

- *In Vietnam, the Agence française de développement (AFD) supported an initial assessment and the national hydrocarbon company in collaboration with a Japanese industrial company assessed CO_2-EOR potential for two oil fields.*
- *In the Philippines and Thailand, funding for national assessments came from the ADB.*

National knowledge and technical expertise

The availability of expertise to assess CO_2 storage potential was generally good. However, in some countries, the expertise was focused on exploitation of other geological commodities and therefore would need adaptation for CO_2 storage. In other countries where the national assessment had been carried out some time ago, skills loss to other sectors was noted. In countries where CCS had not yet been considered or where oil and gas industries were just emerging, there was some debate as to whether interest in CCS would develop in the future:

- Expertise in CO_2 storage is still available in public centres. However, due to the reduction in CCS activities over the last few years, many experts have moved into other fields (e.g. gas storage, other energy technologies such as renewables) and it may be difficult to bring these experts back if CO_2 storage moves forward again.
- There is sufficient expertise available to perform storage assessments though additional expertise would have been welcome to work on the extensive national assessment project.
- We have the national expertise to undertake a national assessment of CO_2 storage capacity. The knowledge and capability is held by the national geological survey and in oil and gas companies. Where specific additional expertise is needed, recognised international specialist organisations within a technical field could be approached.
- We have a sufficient level of expertise available to assess our national CO_2 storage capacity. However, global collaboration is welcome, particularly for very specific high-level expertise on specific subjects.
- The national geological survey led on preparation of the national storage atlas. There isn't much oil and gas exploration being carried out, there is more expertise in mineral exploration. Expertise and expertise in CO_2 storage assessment is somewhat limited. Expertise in offshore basins is more limited.
- Data was provided through collaboration between national government departments and nationalised hydrocarbon companies. These institutes had expertise on the subsurface. The national geological storage assessment was carried out by an external international expert.
- Countries with (emerging) fossil fuel industries might be interested in CCS in the future but at this stage cannot know if this will be the case. Many countries have been investigated for mineral wealth but not oil and gas. National geological surveys are only just discovering oil and gas reserves in some countries. Some countries may not have the expertise to seek out geological CO_2 storage repositories.

Industrial support

Industrial support for CCS was variable. This seemed to depend strongly on regulatory requirements for CCS and financial factors:

- *Initially there was a lot of support from the large industrial companies, particularly power companies. Cement companies became interested in CCS a little later. Other industrial sectors (steel, paper, glass) are quite small here and have not yet shown much interest in CCS. Presently, cement companies are more interested in CCS than power companies. The power companies were interested in CCS as the national inventory of GHG for 2005 and 2006 was much higher than the Kyoto targets and the power companies expected the price of* CO_2 *emissions to be high.*
- *Major opposition from oil companies over how they are going to store the* CO_2 *due to differing regulatory regime.* CO_2 *emitters may fight regulation because of the uncertainty (there was similar opposition to scrubbing out SOx and NOx emissions). The downturn in oil prices has affected interest from oil companies – they are trying to reduce their own footprint in any CCS research or projects. Power providers are also pulling back due to the decrease in CCS activities from oil companies and the decrease in political will. Lack of sites to put* CO_2 *that they may capture into the subsurface.*
- *There was good support for the atlas including from private sector sponsors. Our state owned energy institute are an agency active in reducing impacts of the energy industry. The oil and gas industry are also active (though not all their CCS studies have been made public). No industrial companies opposed but there are two Non-Governmental Organisations opposed to CCS.*
- *Industrial companies have been contacted but large industrial companies have not given support for CCS development although interest has increased over the last couple of years. The industry sectors that have an interest in CCS are oil companies, manufacturing, heavy industry and shipping. Industry has provided data and research personnel for* CO_2 *storage appraisal. CCS is seen by industry as key to the reduction of* CO_2 *emissions and also a possible future new business.*
- *The level of interest in CCS by industry has increased alongside the increase in funding levels from the government. The additional funding has been made available from an increased environmental tax. The oil and gas sector has been active in its support for CCS with the motivation of a business opportunity and to broaden the scope of its work. Electricity companies have been reluctant and have opposed because of the additional cost to implement CCS but this is balanced by the perceived need for 'clean' energy generation.*
- *Some support from oil and gas sector but focused on* CO_2*-EOR not reducing emissions. Not on the radar for power or industrial sectors. Some international oil majors and industrial companies are interested in CCS due to emission trading crediting mechanisms.*
- *No industrial interest in CCS. Focus is on building national energy infrastructure and a low-carbon power network which includes hydroelectric power generation. Chemical plants might be current or future candidates for CCS for more advanced economies but don't know if the plants are large enough to be worth investing in infrastructure for CCS.*

A few 'CCS champions' were identified:

- *USA - DoE fill this role in many ways and National Defence Resources Council are a proponent of CCS. There are more groups that for example support EOR.*

- *South Africa - SANEDI could be classed as a CCS champion in South Africa as the only mandated agency in the country to do CCS work.*
- *Korea - The organisations that are 'champions' for the development CCS in Korea are research institutions: KIER, Korea Institute of Energy Research; KCRC, Korea Carbon Capture and Sequestration R&D Centre; KEPCO, Kansai Electric Power Company.*
- *Japan - The Japan CCS Company (government and industry consortium) is the champion body for the implementation of CCS.*

Data access and quality

Data availability and quality formed a large part of the telephone discussions. Data access was highly variable, in many developing countries there was not a centralised repository, data was not easily available and there were issues with data quality. Similar issues were raised in all countries. Despite these issues, national assessments had been produced in all countries discussed except the North African countries (though Egypt, Morocco, Kenya and Tunisia are described as 'just starting' in the GCCSI Storage Readiness Assessment; GCCSI, 2015a).

DATA AVAILABILITY

One of the stipulations from the government for the national CCS assessment was that the results and data should be publicly available (includes maps, seismic and borehole data etc.). Fewer data were accessible in regions where there are current oil and gas activities. Now, with the interest in unconventional oil and gas, there are a lot of small companies collecting data and it would probably be difficult to access these data since the small companies will want to sell them to the large energy companies. It is likely to be easier to obtain information from larger companies based on past experience. Large companies have already contributed to storage assessments and have an established working relationships and common areas of work with research organisations. For a specific study, research organisations would usually be able to obtain access to data from large companies, particularly where already have a working relationship. Field operators are generally happy to share geological data (including models) on fields or regions which have been investigated, but data on production or daily activities are more difficult to obtain.

The following notes reflect some of the discussion on data availability in the follow-up interviews:

- *Open data sources put together by national energy department. Well data resides at state level. There are formation data, such as tops, thickness, and well logs. You would have to pay for access to the primary data.*
- *Much of the data for the assessment was provided as an in-kind contribution by the national data holder who were involved in the project.*
- *The data used to make an assessment of CO_2 storage offshore is held by government ministries and the data is available to research bodies. There are other sources of data, some is held by oil companies. Access to data acquired by oil companies is available only to research partners to whom the information is available at no cost. The terms of access by research partners is by careful negotiation and agreement of the terms and so could be regarded as a barrier to CO_2 storage assessment. The length of negotiations needed to agree access to data owned by oil companies by research partners could also be perceived as a potential barrier.*

- *Access to data is likely to be an issue if CCS does develop here in the future. National oil and gas companies may not want to share data, particularly in countries where oil and gas is just being discovered, the seismic and borehole data is likely to be highly confidential and commercially sensitive at the moment. Working with state oil and gas companies has proved challenging in the past. Oil majors who have joint ventures etc. with the government will also have data but the data is likely to be highly sensitive. Access to data might improve if there is progress on [UN] climate talks in Paris (November and December 2015) and it becomes more obvious that there are other uses for the data, not just for oil and gas prospecting and exploitation.*
- *The regional report is public but the country reports are marked as confidential. For the regional report, anonymisation of the geological data was required (e.g. removal of well names). Country partners wouldn't allow publication of all the geological data. The main reason for issues accessing data were that oil and gas exploration and exploitation were being undertaken in those areas. There were lots of issues getting access to data for the regional report, e.g. it took almost a year to sign MoUs with the national government agencies and even after MoUs signed, often still couldn't get data released or data wasn't available.*

These comments indicate that there are a range of issues relating to data access, most of which could be overcome given enough time and resources. The main issues which could not be mitigated were lack of data and access to commercially sensitive data. It should be noted that all these countries, some level of national storage assessment had been achieved, so even issues with data access did not preclude an initial assessment utilising available data. The comments given above all come from countries where some level of national storage assessment had been achieved, so access to data had not prevented an initial assessment of storage potential.

CENTRALISED REPOSITORY:

The following notes reflect discussions on the presence of a centralised repository for seismic and borehole data:

- *The national authority for oil and gas resources holds data from the oil and gas industry (seismic and borehole data). Seismic and borehole data are generally easy to access. It is a legal requirement for oil and gas companies to deposit data with this ministry. However, the database is not always complete as sometimes companies did not deposit all data with the ministry and as some of the exploration was carried out decades ago, additional data cannot be recovered from the companies.*
- *Data are held on several online sources. The government does not have rights to all subsurface data. However, offshore data has to be provided to a government organisation and this is available through subscription.*
- *The data was collected some time ago and the organisation has now split into an onshore and offshore section, who are responsible for the well and seismic data. Unfortunately during division of the organisation, some data as lost. Maps of available offshore seismic and borehole data are available online. National geological survey also holds some data and cores. Relevant data is now held by these two national organisations and the national geological survey. The national energy research institute will be responsible for curation of all geological storage related data. Offshore data is much more abundant than the onshore data.*

- *There are national data collections to inform storage assessment. National geological datasets are held by national research institution. There are also some other sources of data that are privately held by oil and gas companies.*
- *The data used to make an assessment of CO_2 storage offshore is held by the government and the data is available to research bodies.*
- *No centralised repository (two countries).*
- *There is a centralised repository, held by the state owned oil and gas company.*
- *Even where there was a centralised repository, some data was often held by several entities so it was challenging to find out what data existed and then to obtain data.*

The common themes identified from these discussions are: data is often held in a centralised repository; but this does not guarantee that all data will be available or that the data will be of good quality. Even if data are available in a centralised repository, obtaining newer data may still require negotiation with the field operator.

DATA QUALITY

The following notes reflect discussions on the impact of data quality on national storage assessments:

- *Much of the data used for the CCS assessment was acquired during the 1970s and 1980s, a lot of work had to be carried out to update the format.*
- *National data held by one organisation. Much of data collected in the 1960s and 1970s so the data is old and not the best quality – core has been disaggregated and many logs have incomplete records. New data is required due to incomplete or missing records and this is a stumbling block in particular in a country with a small oil and gas industry.*
- *A range of quality issues relating to Quality Control and Quality Assurance (QC and QA) were highlighted by the national assessment, there was no uniform standard and different units etc. were used.*

The main issue appeared to be age of the data as techniques for seismic and borehole/logging data are constantly evolving and improving.

Other barriers to national CO_2 storage assessment

Other barriers included:

- Interest in other low carbon technologies (though this is not necessarily an issue in terms of the overall picture as this will still ensure low emissions).
- The need to develop infrastructure/enable electricity access in developing economies. CCS would have an energy penalty and increase cost of electricity.
- Lack of desire to undertake CCS due to low legacy emissions or perceived ‘right to emit’ in developing economies.
- Potential protest from the public.
- Lack of detailed national regulations.
- Conflict with other industries (usually due increased cost - electricity generators and cement, steel and other commodity producers frequently have cost objections. Fisheries and shipping industries may also have conflicts of use with CCS).
- Lack of global acceptance of climate change.

- Desire to implement local technologies.
- Unfavourable onshore geology for a pilot project.

These barriers require a range of responses to overcome, frequently relating to specific national actions.

Appendix 4 Comparison of current national CO_2 resource assessment methodologies

Through a literature search, a wide range of methodologies were identified for comparison. These included storage in the pore space of saline aquifers and hydrocarbon fields, dissolution into native pore fluids and storage through adsorption onto coal. The methodologies consider a range of trapping mechanisms by which the CO_2 is stored in the subsurface and vary from simple volumetric calculations to those which consider the physical and chemical response of the pore fluids and matrix to the highly dense CO_2 injected under pressure, including flow simulations.

METHODOLOGIES ASSESSED

The IEA published a report comparing methodologies for assessing storage potential in saline aquifers (Heidung, 2013) which provides a useful summary for saline aquifer storage. Heidung, (2013) also notes a range of methodologies for capacity estimation in hydrocarbon fields and coal seams. Additional methodologies identified during the literature search carried out by the BGS team were also assessed for this report. Enhanced hydrocarbon recovery (EHR) utilising CO_2 to increase the amount of oil (enhanced oil recovery; EOR) or gas (enhanced gas recovery; EGR) is mentioned in a few studies but rarely quantified.

The methodologies used in the following CO_2 storage potential assessments/methodologies were considered for this report:

1. UKSAP; United Kingdom CO_2 Storage Appraisal Project (Gammer et al., 2011).
2. USGS; United States Geological Survey (USGS) (Brennan et al., 2010, Blondes et al., 2013).
3. US DOE; The United States 2012 Carbon Utilization and Storage Atlas IV (US DOE NETL, 2012; NACSA, 2012, NACAP, 2012).
4. ACST; Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009).
5. Ogawa; Saline-aquifer CO_2 Sequestration in Japan (Ogawa et al., 2011).
6. Tanaka; Possibility of underground CO_2 sequestration in Japan (Tanaka et al., 1995).
7. TNO; Geological Survey of the Netherlands (TNO) – Independent Storage Assessment of Offshore CO_2 Storage Options for Rotterdam (Neele et al., 2011a, b; 2012).
8. BGR; Federal Institute for Geosciences and Natural Resources (BGR), Germany – Recalculation of Potential Capacities for CO_2 Storage in Deep Aquifers (Knopf et al., 2010).
9. NPD; CO_2 Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011, Vangkilde-Pedersen, 2009).

10. CO_2STOP – a project mapping both reserves and resources for CO_2 storage in Europe (Poulsen N. 2012, Schuppers et al., 2003; CSLF Task Force, 2007; Frailey, 2007).
11. BPM; Best Practice for the storage of CO_2 in saline aquifers (SACS and CO_2STORE projects, 2008).
12. CSLF; Estimation of CO_2 Storage Capacity in Geological Media (CSLF Task Force, 2007).
13. Silva; A study of methodologies for CO_2 storage capacity estimation of coal (Silva et al., 2012.

Table 16: Comparison of storage options considered by methodologies

Methodology	**Saline aquifers**	**Depleted oil & gas fields**	**EHR**	**Unmineable coal seams**	**ECBM**	**Other options mentioned/excluded from report**
UKSAP (1)	x	x				-
USGS (2)	x	x				EHR excluded
US DOE (3)	x	x	x	x	x	Organic-rich shales and basalt
ACST (4)	x	x	EOR in one case study			Unmineable coals or chemical trapping in reactive rocks such as serpentine mentioned but excluded
Ogawa (5)	x	x		x (doesn't specify must be unmineable)		-
Tanaka (6)	x	x				-
TNO (7)	x	x				Salt caverns, empty coal mines and coal beds mentioned. EHR mentioned.
BGR (8)	x					-
NPD (9)	x	x				EHR discussed
CO_2STOP (10)	x	x		x		Notes that EHR could result in larger storage than current estimate. Coal seams mentioned.
BPM (11)	x					-
CSLF (12)	x	x		x		Underground in manmade caverns and basalt
Silva (13)				x		Storage in saline aquifers and hydrocarbon fields mentioned

APPROACH TO CAPACITY ASSESSMENT

All assessments except Silva et al. (2012) consider storage in saline water-bearing rocks (saline aquifers), many consider (depleted) hydrocarbon fields and some also consider storage potential of unmineable coal seams. Other possible options such as storage in basalt or manmade caverns are also mentioned in the CCUS Atlas (US DOE NETL, 2012) and CSLF paper (CSLF, 2007).

There are two main differences between the methodologies considered for this report:

1. Definition of the pore space available for storage, both in terms of appropriate cut-offs and accounting for geological heterogeneity, injectivity, storage space, techno-economic considerations etc.
2. Variation in approach to accounting for the response of the reservoir and fluids to the pressure increases that result from injection of CO_2 and if this pressure increase is managed. This moves the estimate from a volumetric static capacity estimate towards a dynamic capacity estimate.

Some aspects of these factors are often included in the storage efficiency factor, others are referred to in the report text as factors requiring consideration.

When considering pore volumes suitable for aquifer or hydrocarbon field storage all relevant methodologies applied a minimum depth cut-off (ranging between 792 m and 914 m), therefore pore space that is too shallow is excluded from assessment. It is commonly recognised that below this depth CO_2 will be stored in its highly dense (or supercritical) phase and therefore have a much higher volumetric efficiency compared to storage in the gas phase at shallower depths. A maximum depth for storage varying from 2000 m (ACST) to 3962 m (USGS) for aquifers and hydrocarbon fields is also mentioned, this is justified because at these depths or greater the reservoir quality is impaired by the effects of high temperatures and pressures within the subsurface. The depth to unmineable coal seams is not always defined as it depends on national and technological factors, in the Carbon, Capture, Utilization and Storage (CCUS) Atlas the recommended upper limit is given as 305 m (US DOE NETL, 2012). It is debatable if this is suitable for storage as in addition to the difficulty in defining which coal seams can be unmineable at such shallow depths the seals overlying the coal will be extremely important as any free CO_2 could migrate towards the surface. The CSLF methodology recommends storage below 700 m in the gaseous phase in coal with a relatively shallow maximum depth of 800 m.

All of the reviewed assessments also only consider pore space where there is an adequate seal above the reservoir, this is important because even if there is plenty of space to store CO_2 within the pore space of a rock, unless there is an effective sealing layer above it the CO_2 will not be retained and may reach the atmosphere. This requirement of a reservoir-seal pair is referred to as a Storage Assessment Unit (SAU) in the USGS assessment (Brennan et al., 2010; Blondes et al., 2013). In some cases, this is further refined through application of minimum porosity (USGS, UKSAP), permeability or injectivity (UKSAP, BPM and TNO methodology) cut-offs.

A 'storage efficiency' factor of some description is present in most methodologies and is always included for saline aquifers (except when a first step calculating the total or theoretically available pore space is included). This 'storage efficiency' factor ranges from 0.51 – 6% for regional aquifer capacity estimates and up to 40% for aquifer storage in defined closures. Depending on the methodology, this factor is used to account for geological heterogeneity (including topography at top of reservoir), response and interaction with native pore fluids/matrix (including displacement of fluids), keeping reservoir pressure within acceptable limits and technological factors relating to location and number of injection wells. For hydrocarbon fields, it is usually assumed that the produced hydrocarbons can be replaced sometimes with a reduction to account for the net injected fluids for enhanced hydrocarbon recovery or to account for the differences in viscosity between oil and CO_2, but a value is not generally given in the literature. For coal seam capacity assessments, ‘storage efficiency’ factors are included which consider how much of the coal could theoretically be contacted by the CO_2 to store CO_2 through adsorption onto the coal and in the pore spaces (cleat).

All the assessments note that detailed studies are needed to assess potential storage sites on a case by case basis, including flow simulations for storage in aquifers or hydrocarbon fields. Flow simulations consider relative permeabilities, compressibility of the rock matrix and fluids, pressure, buoyancy (gravity) drive and many other critical factors to move from the static capacity assessment methodologies described here to full dynamic storage estimates. The static methodologies described here often include some of these factors in the ‘storage efficiency factor’.

Some methodologies assume that pressure can be managed during CO_2 injection. Theoretically pressure can be managed by producing reservoir fluids whilst injecting CO_2 though this may be costly. Pressure managed methodologies are therefore closer to a ‘Technically Available Storage Resource’ (TASR) assessment which is the fraction of the ‘theoretical’ storage resource that can be accessed using all currently available technologies regardless of cost.

Pressure management schemes are different for depleted hydrocarbon fields than for saline water-bearing aquifers which have had no water ingress or used injected water during production. In the case of depleted fields, the pressure will be lower than that recorded before production and it is generally assumed that CO_2 can be injected to re-pressurise the field as long as the original pressure is not exceeded (fluid replacement approach). Research by Li et al. (2005) states the caprock sealing pressure should be determined before injecting CO_2 and that this should in fact be the pressure limit during a storage project to avoid volume flow into the caprock (due to lower interfacial tension of a CO_2/water system). When you compare this to water-bearing saline aquifers where a certain amount of pressure will be needed to displace the resident pore-water a completely different approach will be required.

All but two of the assessments consider national-level capacity for onshore and/or offshore storage, generally derived from regional capacity estimates. All assessments consider the need for multiple sedimentary basins. The scale of assessment is important because the methodology applied to large scale storage e.g. continental or basin-scale will not be detailed enough to estimate storage capacity for an individual structural trap.

Some assessments use a probabilistic approach to estimate storage capacity whereas some use a deterministic approach. Due to a lack of/little data being available in areas of low hydrocarbon exploration and the heterogeneous nature of geological formations, a probabilistic method of calculation is the best technique to cope with the limitations of the assessment results (Heidung, 2013). This method uses a range of geological values based on available data and a geological model and provides a statistically sound method to make resource estimations (Heidung, 2013). A deterministic approach is applied to a region utilising known values without room for variation.

A few differing methodologies were used to estimate CO_2 storage density. All assessments utilise an estimated CO_2 density likely in the target reservoir unit.

Geological uncertainty or risk is dealt with using a range of approaches over the reviewed assessments. Non-geological risks (e.g. financial project planning) are discussed in a few of the methodologies.

The key driving factors in assessing the suitability of storage capacity methodologies are data availability (which largely depends on national regulations for data access) and the scale and objectives of the assessment (basin-level estimates can utilise simple calculations, site specific assessments during Front End Engineering and Design studies require detailed data and dynamic flow simulation).

DETERMINING THE 'STORAGE ASSESSMENT UNIT'

All methodologies make some attempt to define the storage unit, setting upper and sometimes lower depth limits as a minimum constraint. The presence of a seal is always required. In addition, limits on minimum porosity, permeability and presence of closures may be set. Economic and regulatory requirements are also mentioned or utilised in most methodologies.

The CSLF methodology makes recommendations on technical factors which will impact storage capacity (avoiding excessively thin reservoirs or low porosity or permeability reservoirs) but does not set limits on these factors. Other storage assessments provided specific cut-offs to take techno-economic factors into account: For example, the USGS methodology considers three classes of storage reservoir for residual trapping based on permeability characteristics. The ACST methodology classified the prospectivity of basins utilising their geological setting and then considered likely porosity and permeability at shallow, medium and deep depths. Ogawa considers the impact of heterogeneity and defines two classes (homogeneous and heterogeneous) of storage location. The USGS method only considers hydrocarbon fields that contain more than 500,000 BOE as smaller fields will offer low storage capacities.

Geological and engineered hazards are also considered. For example, the CSLF methodology recommends avoiding areas affected by major or active faults or areas with steeply dipping strata, the USGS and NPD methodologies specifically mention consideration of any wells which due to their location or completion history could introduce risks to storage. The ACST ranks basins with higher temperatures and a limited hydrogeological circulation to be poorer prospects for storage due to the limitations these factors place on dissolution of CO_2 into native pore waters.

National and basin level studies generally consider regional reservoirs where reservoir-seal pairs are available. More detailed studies such as the UKSAP, NPD, TNO and BPM consider storage units in more detail and also assess if these fluid migration between units is likely to be possible (boundary conditions; open and closed).

Economic limitations are applied in the UKSAP, US DOE, TNO methodologies, considered in the USGS, TNO and BGR methodologies and mentioned in the CSLF methodology. These limitations usually relate to injectivity (permeability) and the number of injectors required to access the pore space. In the US DOE CCUS Atlas financial modelling was used to consider the potential costs of storage. The ACST methodology includes financial modelling of the transport and storage costs for defined locations in Australia.

Regulatory restrictions are mentioned in the CSLF methodology, but as this is a general assessment, no specific limitations are set. The CO_2STOP report and BPM also mention regulatory restrictions. The USGS, US DOE and ACST specify national regulatory restrictions and where case studies are given, take these considerations into account.

APPROACH TO AQUIFER CAPACITY ASSESSMENT

Most of the existing assessment methodologies produce estimates of CO_2 storage resources/reserves that fall into one of five groups:

1. The total amount of storage space available ('theoretical' storage capacity/resource estimate). If included this is usually used as a first step which is then refined. This step is mentioned here as in some cases few data are available and only very simple capacity estimates can be calculated.
2. The fraction of the 'theoretical' storage resource that can be accessed using all currently available technologies regardless of cost (Technically Accessible Storage Resource Assessment, TASR; Brennan et al., 2010; Heidung, 2013).
3. The storage resource available in structural or stratigraphical traps including mappable reservoir units with seals.
4. Capacity that can be accessed considering injectivity of the storage reservoir and the storage resource available without increasing reservoir pressure to unacceptable levels (with a sub-set of methodologies assuming pressure management wells will not be used).
5. The storage resource available considering impact on other potential uses of the sub-surface (for example, subsurface volumes where CO_2 storage will not affect hydrocarbon production or exploration, potable water etc).

The definition of pore volume suitable for storage in individual assessments within any one of these groups may vary slightly, either due to policy constraints or the methodologies employed (Heidung, 2013). A summary of key factors relating to aquifer storage is provided in Table 17. In addition, political and socio-economic considerations are often not included as factors within the calculations but are instead described within the documents outlining the methodologies.

Additional potential alternative uses of sub-surface resources and other limiting factors specifically mentioned/considered are;

- Potable water (e.g. USGS, regions where pore water has <100,000 mg/L TDS are ignored unless hydrocarbon fields are present due to regulatory requirements).
- Hydrocarbon resources (e.g. NPD; avoid sterilising energy resources).
- Cost of utilising storage (e.g. UKSAP, point to point costs, number of injectors etc).

All the methodologies consider buoyant trapping. Residual, dissolution and mineral trapping are considered to varying degrees.

A key advantage of simple methodologies such as the CSLF, USGS, US DOE, ACST, Ogawa, NPD (Vangkilde-Pedersen methodology), BPM (regional methodology) is that these can be applied with relatively sparse data to give a first-pass assessment. More detailed assessments where TASR are mapped (e.g. UKSAP, TNO, NPD) are obviously more accurate but require access to seismic and well data to define and characterise the storage sites and to assess the acceptable pressure increase for each reservoir. Consideration of regulatory factors improves the accuracy of capacity estimates by excluding regions where it will not be permitted and also helps communicate restrictions of which non-nationals may not be aware.

Table 17: Storage criteria for saline aquifer and hydrocarbon field storage

	Type and scale of assessment	Depth constraints	Reservoir quality constraints	Seal quality constraints
UKSAP (1)	National offshore resource for UK	CO_2 in highly dense phase, minimum depth ~ 800 m	Sandstone and carbonate stratigraphical units considered for storage	Each unit assessed for security of containment and excluded if no seal
USGS (2)	National onshore resource for USA	CO_2 in highly dense phase, depth ~ 914 - 3962 m (may consider deeper depending on reservoir)	Notes injectivity should be considered	Any area not beneath a seal formation is excluded
US DOE (3)	High level storage assessment onshore and offshore USA, Canada, Mexico	CO_2 in highly dense phase, minimum depth ~ 792 - 800 m. Maximum 2500 m depth for assessment in Mexico	Sandstone and carbonate stratigraphical units considered for storage. Reservoir quality and pore fluid mentioned but no limits specified	Seal to prevent migration required
ACST (4)	National, top-down assessment of storage potential with qualitative determination of most promising basins	CO_2 in highly dense phase ~ 800 to 2000 m depth	Sandstone and carbonate stratigraphical units considered for storage.	Seal required to trap CO_2
Ogawa (5)	National resource assessment for onshore and offshore Japan	CO_2 in highly dense phase, minimum depth ~ 800 m	Porous & permeable formations considered	Seal required to trap CO_2
Tanaka (6)	National resource assessment for onshore and offshore Japan	CO_2 in highly dense phase or liquid phase	Porous & permeable formations considered	CO_2 must be trapped securely to avoid unwanted migration
TNO (7)	Offshore resource assessment for the Netherlands, relates to ROAD demonstration requirements	CO_2 in highly dense phase, minimum depth ~ 800 - 1000 m	Porous & permeable formations considered	Seal must retain CO_2 for geological period of time
BGR (8)	Onshore and offshore resource assessment to expand previous work for Germany	CO_2 in highly dense phase, minimum depth ~ 800 - 1000 m. Maximum studied 5500 m but no recommendation on maximum depth	Reservoir porosity ≥20%, thickness ≥10 – 20 m.	Seal required to trap CO_2
NPD (9)	Bottom up resource assessment for Norwegian Sector of North Sea	CO_2 in highly dense phase, minimum depth ~ 800 m Maximum recommended 2500 m	Reservoir properties; net thickness >50 m, average porosity in net reservoir >25%, permeability >500 mD. Low reservoir scores with net thickness <25 m, porosity <15%, permeability <10 mD	Seal quality evaluated (thickness, fractures, composition). Good seal >100 m thick. Low seal score if thickness <50 m.
CO_2STOP (10)	Bottom up assessment for much of onshore and offshore Europe	CO_2 in highly dense phase, minimum depth ~ 800 – 914 m	Porous & permeable formations considered	Effective caprock required

BPM (11)	Case studies in offshore/onshore Europe	Positive indicators depth >1000 m and < 2500 m, cautionary indicators depth < 800 m and >2500 m	Positive indicators; net reservoir thickness >50 m, porosity > 20%, permeability >500 mD, salinity >100000 mg/L. Cautionary indicators; net thickness <20 m, porosity <10%, permeability < 200 mD, salinity < 30000 mg/L TDS	Seal integrity critical factor. A good seal is a prerequisite for storage. Positive indicators thickness >100m, small or no faults, homogenous stratigraphy. Cautionary indicator <20 m.
CSLF (12)	Methodology study with specific case studies from across the globe	CO_2 in highly dense phase, minimum depth ~ 800 m	Porous & permeable formations considered	Low permeability seal overlies reservoir

Highlights from specific aquifer methodologies

Some of the studies (TNO, UKSAP, NPD, CO_2STOP, BPM) take into account the likelihood of pressure rises limiting CO_2 injection to varying degrees. Pressure being an important limiting factor on injectivity is mentioned in the CSLF methodology. Some cases assume that the pressure will dissipate due to natural migration of fluids out of the storage unit because there is good connection to the seabed (e.g. for a few storage units in the UK assessment), in these instances a storage efficiency factor has been applied to calculate the volume of CO_2 that can be stored. The storage efficiency factor reduces the theoretical total capacity estimate to the amount of accessible pore volume that will host the injected CO_2. The assessments in the Netherlands and the UK do not consider pressure management by fluid extraction for economic reasons. The assessments that have assumed that pressure can be managed will ultimately result in larger storage estimates than those methods that do not agree that pressure can be effectively managed (Table 18).

The reviewed assessments generally have assigned different explanations of what the storage efficiency is and even those with similar meaning use different methods to calculate it. The time at which storage efficiency is evaluated is also important, e.g. whether to apply to the bulk volume of a regional aquifer (where storage efficiency may vary greatly across a large area) or whether to apply to a specific trap. Storage efficiency is very site specific and should ideally be calculated using numerical simulation for individual sites. Examples of where a storage efficiency factor has been applied to a bulk volume of regional aquifer estimates can be found in the assessments by the USDOE, ACST, BPM and CO_2STOP where they apply a factor of 0.51 – 8%. In some cases where closures have been defined or flow simulations with reservoir data run, a higher storage efficiency is considered acceptable. A consistent method for estimating storage efficiency would be extremely helpful, but given the variable level of available data for different countries and sites, this would be very challenging to define.

The USGS methodology divides storage estimates into buoyant and residual trapping (Brennan et al., 2010), and specifies storage efficiencies for both types of storage (Blondes et al., 2013). The buoyant trapping efficiency is determined probabilistically and is expected to be lower than oil/gas saturation due to the inability of a low viscosity fluid (e.g. highly dense CO_2) to efficiently displace a high viscosity fluid (e.g. pore water) without exceeding the fracture pressure of the storage or seal formation (Brennan et al., 2010). The method employed for buoyant storage efficiency is described using the mobility factor and the irreducible water fraction, without taking into account the residual gas saturation since the CO_2 would be held in place by a trap. The USGS methodology utilises 'injectivity categories' for residual trapping. This methodology suggests that residual trapping will play an important role since the pore volume in closures is expected to be much smaller than the total pore volume available in aquifers though the authors also note that there is much greater uncertainty for residual storage in general as it is less well understood. The USGS report uses a method advised by MacMinn et al. (2010) to calculate residual storage efficiency. A capillary trapping number and a mobility factor demonstrate how much CO_2 may be trapped and how much of the pore space will be occupied by CO_2 respectively. Both residual and buoyant estimation methods assume that pressure management will be employed.

The two USA studies exclude pore space due to strict requirements to protect sources of underground drinking water. Two studies (UK and Germany) apply a minimum storage unit capacity cut-off value while the study in Germany also excludes using sites outside known traps for buoyant fluid (e.g. structural and stratigraphic).

Tanaka et al. (1995) consider that CO_2 injected into aquifer structures/traps should be estimated by taking into consideration the amount of CO_2 that will dissolve into the pore water. This is achieved by multiplying results of the effective storage capacity by the CO_2 solubility in water, (a 50 % sweep efficiency is assumed). However, there is ongoing debate on the rate of dissolution and how rapidly this will occur during injection and therefore the contribution dissolution trapping will make to storage capacity.

Table 18: Summary of storage assessment considerations for aquifers

	Determination of storage units	**Trapping mechanisms**	**Storage efficiency considerations**	**Techno-economic, regulatory and financial considerations**
UKSAP (1)	Potential storage sites selected based on mapping from seismic and borehole data. Divided into parent and daughter units on basis of pressure regime and structural barriers (or arbitrary division on licensing blocks where insufficient data)	Buoyant trapping, residual/capillary trapping	Dynamic behaviour of candidate reservoirs through flow models. Sensitivity analysis of parameters. Limiting pressure for storage was defined as 90% of the minimum of either the assessed fracture pressure or lithostatic pressure in closed scenarios. Expected 1 – 6% storage efficiency	Excluded where initial estimates suggest <50Mt. Single source-single store costs included in database.
USGS (2)	Pore space within mappable subsurface reservoir units is Technically Accessible Storage Resource (TASR)	Buoyant trapping, residual/capillary trapping (residual trapping potentially large but high uncertainty)	Probabilistic buoyant trapping efficiency determined, expected to be lower than oil/gas saturation. 20 – 80% sweep efficiency anticipated in storage units.	Saline aquifers outside hydrocarbon provinces excluded where < 10,000 mg/L TDS
US DOE (3)	Pore space accessible to injected CO_2	Volumetric approach, mechanisms not specified	An efficiency factor is derived from local experience or reservoir simulations. P_{10}, P_{50}, and P_{90} percent confidence intervals are 0.51 percent,	Saline aquifers outside hydrocarbon provinces excluded where < 10,000 mg/L TDS

			2.0 percent, and 5.5 percent, respectively	
ACST (4)	Three representative locations in each of the top ranked basins were selected to represent a shallow, mid and deep injection location. High level assessment.	Volumetric approach, mechanisms not specified	Efficiency factor of 4% and 0.5% used at P10, P50, and P90 percent confidence intervals. Reservoir simulation used to assess gas saturation post injection	Financial modeling utilises statistical model for number of wells needed. Transport and storage costs vary widely depending on location. Proximity to sources and future capture hubs mentioned.
Ogawa (5)	Saline aquifers divided into two classes, (A) saline aquifer in structural traps and (B) aquifers with alternative trapping mechanisms	Buoyant trapping and residual trapping	Storage efficiency factor of 2.5 – 5% and up to 12.5 % or 25% used depending on geological heterogeneity and type of storage. Ratio of immiscible CO_2 to pore volume and CO_2 saturation included in this factor.	Proximity to sources included in screening criteria
Tanaka (6)	Saline aquifers divided into four categories; 1) in water leg associated with hydrocarbon fields, 2) in traps and 3) and 4) in monoclinal structures	Buoyant, residual and dissolution trapping in traps (categories 1) and 2)). Residual and dissolution trapping in monoclinal structures	Sweep efficiency assumed to be 50%. CO_2 saturation assumed to be 20% in traps.	-
TNO (7)	Sites screened, specific sites considered for hydrocarbon fields. Some aquifers are basin-level assessments. Aim of study was to improve certainty in availability, of capacity and cost of utilizing prospective CO_2 storage sites	Volumetric approach, mechanisms not specified but need to displace pore fluids noted	Assumed that acceptable pressure increase is 10 – 20% but must not fracture reservoir or seal which authors suggest means 1% of available pore space can be used. Achievable injection rate a major controlling factor.	Production of fluids could be used to control pressure. Must be able to store 1.1 Mt/yr and minimum 50 Mt recommended)
BGR (8)	Basin-level study of saline aquifer storage in Germany where previous studies indicate presence of potential storage formations	Volumetric approach, mechanisms not specified	Assumes 5% of regional aquifer will be in traps. Flooding efficiency factor 5 – 20% in calculation. Noted that 20% could be an underestimate in some structures. Storage capacity calculated at P90, P50 and P10.	Proximity to sources mentioned
NPD (9)	Potential storage sites selected based on mapping from seismic and borehole data and simplified simulations	Buoyant trapping, residual trapping and dissolution trapping	Storage efficiency depends on boundaries of reservoir (open/closed), ranges from 0.4 to 10%. Injectivity controlled by reservoir boundaries and pressure increase, it was assumed a pressure increase of 50 to 100 bar for a closed system would be acceptable but it was noted this would need careful assessment on a site by site basis. Simulations	Storage sites where there might be a conflict of interest with the petroleum industry excluded. Only aquifers of reasonable size and quality evaluated.

			suggest 10 – 20% of CO2 will dissolve in pore water.	
CO_2STOP (10)	Sites screened and parent and daughter units defined	Buoyant trapping and residual trapping. Dissolution and precipitation excluded	Assumed that acceptable pressure increase is 20%, could be changed if found to be less than optimal. Storage efficiency expected to be 1 – 2%	Excludes regions where pore water has <10,000 mg/L TDS
BPM (11)	Screening criteria defined based on case studies. Regional calculations and specific case studies included. Comparison of static methodology and dynamic simulations where CO_2 has been injected	Buoyant, residual trapping and dissolution trapping	Boundaries of reservoir (open/closed) important for injectivity because of pressure increase, storage capacity factor controlled by pore space available, viscosity of brine and CO_2, geological heterogeneity, buoyancy forces. 0.00009 – 40% mentioned; regional aquifers at the lower end of this range	National regulations mentioned including Norwegian tax on emissions
CSLF (12)	Development methodology for estimating storage capacity. Case studies mentioned	Buoyant trapping and residual trapping.	Pressure an important constraint on injectivity	Consideration of regulatory frameworks mentioned, including exclusion on storage in some countries in regions where water is <10,000 mg/L TDS

The TNO approach differentiates between saline aquifers connected to hydrocarbon fields and 'virgin' saline aquifers, although the same initial storage volumetric methodology is used, the uncertainties in reservoir characteristics are expected to be higher for 'virgin' saline aquifers.

The BGR methodology includes not only geological heterogeneity but also technical factors such as number and location of injection wells in the storage efficiency factor.

Petroleum exploration and production is expected to continue on the Norwegian continental shelf for some time to come and therefore any areas that may be prospective have been excluded from their assessments. The UK assessment excludes the onshore prospective areas and also remote offshore areas.

Comparison of the methods used to estimate the CO_2 storage capacity of saline aquifers reveal that seven of the assessments used deterministic methods and five used probabilistic methods (Table 19). Three of the assessments (CSLF, BPM and Silva) haven't provided any nationwide/jurisdictional estimates.

Table 19 Table summarising methods used to estimate CO_2 storage capacity in aquifers

	Probabilistic	**Deterministic**	
UKSAP (1)	x		Confidence in assessment of unit recorded and Monte-Carlo simulations used to expand to national assessment

USGS (2)	x		Fully probabilistic. Monte Carlo simulations. Permeability used to determine injectivity classes (only deterministic input entered into Monte Carlo simulations)
US DOE (3)	x		Statistical approach to storage efficiency. Pore volume for buoyant storage calculated from a 'geologically determined, probabilistic-distribution of the volume fraction of the storage formation' (Brennan et al., 2010). Residual pore volume calculated as total pore volume less buoyant pore volume, 'it is calculated during iterations of the Monte Carlo simulator after a value from the buoyant trapping pore volume distribution is chosen' (Brennan et al., 2010)
ACST (4)	x		Monte Carlo simulations used to derive probabilistic storage estimates.
Ogawa (5)		x	Numerical simulation studies for case studies carried out and a Monte Carlo simulation tool developed to account for the effects of uncertainties in key parameters (no further details are given on this simulation tool). For aquifers where there are no well data, national scale geological surveys were used identify promising aquifers. Classified as deterministic as the paper mainly describes using data from hydrocarbon fields.
Tanaka (6)		x	Data taken from oil and gas fields and where available, onshore aquifer data used to populate offshore aquifers where no data
TNO (7)		x	'The model computed the response of the storage reservoir, using a limited set of geological data and production data' (Neele et al., 2011).
BGR (8)	x		Monte Carlo simulation to consider uncertainties in factors entered in the capacity calculation
NPD (9)		x	Numerical simulation performed on potential storage sites
CO_2STOP (10)	x		Minimum and maximum storage capacity usually calculated from Monte Carlo simulations.
BPM (11)		x	Numerical simulation performed on potential/existing storage sites
CSLF (12)		x	Factors should be based on laboratory experiments, numerical simulations and field experience and measurements

The CO_2STOP assessment builds on the deterministic results produced by the EU GeoCapacity project with a calculation engine capable of providing probabilistic estimates (Poulsen, 2012). It uses a similar approach to the USGS methodology but the storage available in saline aquifers and depleted hydrocarbon fields are considered together as stratigraphical-base units.

Although the CSLF Task Force (2007) doesn't provide a CO_2 storage estimate for a specific country or region it does provide theoretical methodologies (as described by their resource-reserve pyramid, see Figure 8 in Appendix 1) to be able to calculate CO_2 storage capacity in deep saline aquifers by:

- Physical trapping:
    - Static (at site-, basin- and regional-scale assessments).
    - Residual-saturation (only in local- and site-scale assessments).
- Chemical trapping:
    - Dissolution (only in local- and site-scale assessments).
    - Mineral (only in local- and site-scale assessments).

CO_2 can also be trapped using any combination of the above mechanisms and is referred to as 'hydrodynamic trapping' for which estimates can be calculated at local- and site-scale. These trapping mechanisms are described in more detail in Appendix 1.

The CSLF Task Force also provide calculation methodologies from 'theoretical' through to 'practical' CO_2 storage capacity estimates (as illustrated by their resource-reserve pyramid, see Figure 8 in Appendix 1) for oil and gas fields. They provide calculation methods based on:

1. Original reserves in place.
2. Geometry of the reservoir.
3. Undiscovered hydrocarbon reservoirs.
4. Enhanced oil recovery.

The BPM methodology consider two possible methodologies for calculating storage potential, one for regional aquifers (which uses a storage coefficient to consider geological heterogeneity and techno-economic limitations) and another for aquifers within structural traps which considers the permissible pressure increase, matrix and native pore fluid compressibility.

APPROACH TO HYDROCARBON CAPACITY ASSESSMENT

There are two main approaches to calculating storage capacity:

1. Assuming part or all of the hydrocarbons (produced and/or unproduced) can be replaced by CO_2.
2. Calculating the available pore volume and assuming a fraction can store CO_2 (equivalent to the volumetric aquifer storage approach).

Most studies take the approach of assuming that all (USGS, UKSAP) or part of the extracted hydrocarbons from depleted oil and gas fields can be replaced by injected CO_2 less the volume of water (or other enhanced hydrocarbon recovery fluids) injected (UKSAP). The USGS method additionally uses data from a national resource estimate to consider likely untapped hydrocarbon volumes which could be replaced by CO_2. Various assumptions are made about water influx during hydrocarbon production (natural flow), in that all this water will be expelled during storage (UKSAP) or that some fraction of this water can be expelled. A summary of key factors for hydrocarbon storage are provided in Table 17 and Table 20.

The CSLF methodology suggests that the same volumetric methodology used for estimating available pore space in aquifers can be utilised where hydrocarbon production data are not available. The CCUS Atlas (US DOE NETL, 2012) assumes that a percentage of the pore space in the hydrocarbon reservoir can be utilised with an efficiency factor derived from local experience or reservoir simulation.

Most methodologies focus on depleted fields for storage with only regional carbon sequestration partnerships (RCSP) in the CCUS Atlas (US DOE NETL, 2012) calculating potential for EOR, EGR and ECBM. Utilisation of CO_2 for Enhanced Hydrocarbon Recovery is mentioned in several other studies but not explored.

Again for hydrocarbon fields, simple methodologies (CSLF, US DOE, USGS) can be applied with relatively sparse data to give a first-pass assessment. More detailed studies assessing storage units (e.g. UKSAP, TNO, NPD) are obviously more accurate but require access to detailed reservoir data. Assessments of enhanced oil recovery potential seem to be limited to individual field assessments in the reviewed reports, though some regional assessments have been made utilising arbitrary factors based on USA EOR experience applied to field resource estimates (e.g. COACH project, *pers. comm*. Ceri Vincent). Consideration of regulatory factors to improve accuracy of capacity estimates also helps communicate restrictions of which non-nationals may not be aware.

Highlights from specific hydrocarbon field methodologies

The UKSAP methodology assumes that all the produced hydrocarbons can be replaced by CO_2 less the volume of injected water. This assumes that any water that intrudes into the reservoir during hydrocarbon production by natural aquifer flow can be expelled during CO_2 injection.

A minimum cut-off for the size of fields considered for storage was applied by the USGS method. The methodology is based on the recoverable volume of hydrocarbons and considers the relative viscosity of oil vs. CO_2 (a low viscosity fluid, such as supercritical CO_2, will not be able to efficiently displace a high viscosity fluid, such as oil or water, without exceeding the fracture pressure of the storage or seal formation). Dry traps were included in the USGS CO_2 storage resource estimate.

The CCUS Atlas (US DOE NETL, 2012) considers how much CO_2 can be stored in depleted fields by assuming most of the volume occupied by hydrocarbons can be replaced, with the volume of water present in the reservoir subtracted and a storage efficiency factor derived from local experience/reservoir simulation to account for how much of the pore space can be utilised. In the CCUS Atlas (US DOE NETL, 2012), all the RCSPs have assessed the potential for EOR and some also considered the possibility for EGR and ECBM. Additionally, in the CCUS Atlas the authors note that Advanced Resources International and MGSC are developing an improved methodology for a generalised CO_2-EOR performance model.

The TNO method considers depleted oil and gas fields and aquifers in hydrodynamic contact with these fields. The net volume of produced fluids is considered (i.e. the produced oil/gas less the volume of injected fluids) where the field is not connected to an aquifer with active water drive. EOR and EGR are mentioned but not quantified.

The NPD methodology assumes the net volume of fluids produced (oil, gas, condensate, water) can be replaced by CO_2 with the caveat that this volume should be reduced to account for water influx and the pressure in the reservoir at the end of production. EOR is mentioned but not quantified.

CO_2STOP utilises the CSLF methodology for calculating storage capacity utilising the recoverable hydrocarbon reserves, assuming this fluid can be replaced by CO_2 with factors to accommodate injected and produced fluids. It is worth noting that due to limited data, in the database, the CSLF 'theoretical' (i.e. all pore space utilised) and CSLF 'effective' (i.e. a proportion of the pore space utilised) estimates are not distinguished. Where insufficient data are available, an alternative approach (Schuppers et al., 2003) assuming the ultimately recoverable reserves can be completely replaced with CO_2 is used by CO_2STOP.

The CSLF methodology has two options for assessing storage capacity; 1) assumes the recoverable reserves can be replaced with CO_2 with factors to accommodate injected and produced fluids and 2) calculates the pore volume from the reservoir extent and assumes the pore volume saturated with hydrocarbons less net injected fluids, can be utilised.

Four of the assessments have used a probabilistic approach in their storage capacity methodology for the hydrocarbon fields whereas five of the assessments have used a deterministic approach

(Table 21). With hydrocarbon fields there are more certainties about the available data and more known values so that it may be possible to move towards a deterministic methodology.

Table 20: Assessment considerations for storage in hydrocarbon fields

	Determination of storage units	**Trapping mechanisms**	**Storage efficiency considerations**	**Techno-economic, regulatory and financial considerations**
UKSAP (1)	Potential storage sites selected based on mapping from seismic and borehole data. Divided into parent and daughter units on basis of pressure regime and structural barriers (or arbitrary division on licensing blocks where insufficient data)	Replacement of fluids	Assume net quantity of fluids withdrawn during hydrocarbon activities can be replaced (and assume any natural water that migrates into the field during hydrocarbon extraction can be displaced)	Excluded where initial estimates suggest <50Mt. Single source - single store costs included in database.
USGS (2)	Pore space within mappable subsurface reservoir units is Technically Accessible Storage Resource (TASR)	Replacement of fluids and buoyant storage where no hydrocarbon field data	Assume a fraction of the resources in place can be replaced. In addition, undiscovered hydrocarbon resources (based on USGS study) included as possible buoyant trapping opportunity.	Regions where no proven hydrocarbon accumulations present with aquifers < 10,000 mg/L TDS excluded. Only hydrocarbon fields with >500,000 BOE and traps of similar size included.
US DOE (3)	Pore space accessible to injected CO_2	Volumetric approach for USA. Study for Canada used CSLF fluid replacement method. No oil or gas field information for Mexico	An efficiency factor is derived from local experience or reservoir simulations.	Regions where no proven hydrocarbon accumulations present with aquifers < 10,000 mg/L TDS excluded.
ACST (4)	High level assessment based on existing hydrocarbon field data	Replacement of fluids	None mentioned	Financial modeling utilises statistical model for number of wells needed. Transport and storage costs vary widely depending on location. Proximity to sources and future capture hubs mentioned.
Ogawa (5)	Saline aquifers including depleted fields included in class (A) saline aquifer in structural traps of study	Volumetric approach	Storage efficiency factor of 25% assumed though noted as possibly optimistic	Proximity to sources included in screening criteria
Tanaka (6)	Oil and gas fields included in category 1)	Volumetric approach	Sweep efficiency assumed to be 50% for CO_2, CO_2 saturation assumed to be 20%	-

TNO (7)	Sites screened, specific sites considered for hydrocarbon fields. Aim of study was to improve certainty in availability, of capacity and cost of utilizing prospective CO_2 storage sites	Replacement of fluids	Assume net quantity of fluids withdrawn during hydrocarbon activities can be replaced	Production of fluids could be used to control pressure. Must be able to store 1.1 Mt/yr and minimum capacity 5 Mt
BGR (8)	Basin-level study of saline aquifer storage (including depleted fields) in Germany where previous studies indicate presence of potential storage formations	Volumetric approach	Flooding efficiency of between 5% and 20% suggested	Proximity to sources mentioned
NPD (9)	Potential storage sites selected based on mapping from seismic and borehole data and simplified simulations	Replacement of fluids	Storage efficiency depends on net produced fluids, 5 – 10% suggested (largely dependent on permeability and pressure buildup which is in turn controlled by boundary conditions). If reservoirs have been water flooded where pressure has built up to original then storage efficiency will be low (~1% suggested) due to pressure increase.	Injectivity controlled by reservoir boundaries and net produced fluids
CO_2STOP (10)	Sites screened and parent and daughter units defined	Replacement of fluids	Storage efficiency depends on net produced fluids or proven ultimate recoverable reserves (second method is alternative for regions where few data are available)	-
CSLF (12)	Development methodology for estimating storage capacity. Case studies mentioned	Replacement of fluids or volumetric (volumetric includes factors describing injected and produced water)	Storage efficiency depends on net produced fluids provided not in hydrodynamic contact with an aquifer and where secondary and tertiary recovery techniques have not been utilised	Consideration of regulatory frameworks mentioned, including exclusion on storage in some countries in regions where water is <10,000 mg/L TDS

Table 21 Summary of methods used to estimate CO_2 storage capacity in hydrocarbon fields

	Probabilistic	Deterministic	
UKSAP (1)	x		Confidence in assessment of unit recorded and Monte-Carlo simulations used to expand to national assessment
USGS (2)	x		Fully probabilistic. Monte Carlo simulations. Permeability used to determine injectivity classes (only deterministic input to Monte Carlo simulations)
US DOE (3)		x	Storage resource estimated for many mature oil and gas fields

ACST (4)	x		Monte Carlo simulations used to derive probabilistic storage estimates.
Ogawa (5)		x	Numerical simulation studies for case studies carried out and a Monte Carlo simulation tool developed to account for the effects of uncertainties in key parameters (no further details are given on this simulation tool). Depleted fields are treated as aquifers in terms of storage capacity. Classified as deterministic as the paper mainly describes using data from hydrocarbon fields.
Tanaka (6)		x	Data from oil and gas fields used
TNO (7)		x	A simplified model of the different subsurface reservoirs (depleted gas fields) was used for basic injection rate calculations. 'The model computed the response of the storage reservoir, using a limited set of geological data and production data' (Neele et al., 2011).
BGR (8)	x		Monte Carlo simulation to consider uncertainties in factors entered in the capacity calculation
NPD (9)		x	Numerical simulation performed on potential storage sites
CO_2STOP (10)	x		Minimum and maximum storage capacity usually calculated from Monte Carlo simulations
CSLF (12)		x	Factors should be based on laboratory experiments, numerical simulations and field experience and measurements

APPROACH TO COAL SEAM CAPACITY ASSESSMENT

Coal seam storage capacity is infrequently assessed. The USGS method does not include it on the grounds that 'unmineable' resources cannot be clearly defined.

The CCUS Atlas (US DOE NETL, 2012), CSLF methodology (CSLF, 2007) and Silva methodology (Silva et al., 2012) consider how much CO_2 can be adsorbed onto unmineable coal seams. It should be noted that the definition of unmineable includes seams (i.e. those too deeply buried and/or too thin for economic exploitation as an energy reserve) is highly dependent on national and technological factors (for example, the cut-off for uneconomic depth for mining is given as 305 m in the CCUS Atlas (US DOE NETL, 2012) and is therefore very difficult to define, particularly as technological advances and economic factors constantly change which seams would be considered unmineable.

Enhanced coalbed methane recovery is mentioned by both the CSLF (2007) and US DOE (2012) methodologies. Both methodologies consider the coal composition, ash and moisture content in order to derive the theoretical maximum storage capacity. To calculate the 'effective' capacity the CSLF methodology recommends utilising the reservoir gas deliverability to consider how much gas is likely to be producible. The US DOE NETL (2012) methodology utilises a storage efficiency factor based on the fraction of the total pore volume that will be occupied by the CO_2 at P10, P50 and P90.

A more detailed methodology is given in Silva et al. (2012) requiring data on the coal composition, moisture, ash content, volatile matter and vitrinite reflectance. The main storage mechanism is adsorption but displacement of free coalbed methane is also considered.

Calculation of storage capacity in coal generally requires more detailed data on the response of the coal to CO_2 than is required for aquifer or hydrocarbon field capacity calculations. This, along with the lack of practical experience (including on the impact of reduced permeability due to reaction with the injected CO_2), means that calculating storage capacity in coals is generally quite challenging.

Highlights from specific coal seam methodologies

The US DOE methodology (US DOE NETL, 2012) for calculating storage capacity in coalbeds is the equivalent of the effective storage capacity calculated by the CSLF (CSLF, 2007). Both assessments recommend depths above the point at which permeability of coal reaches less than 1 mD. The CCUS Atlas and CSLF methodologies also mention exclusion of coals where groundwater has TDS<10,000 mg/L.

Both the CCUS Atlas (US DOE, 2012) and the CSLF methodology recommend storing CO_2 in permeable coals (both note that the adsorption of CO_2 onto the coal will reduce permeability through coal swelling). The US DOE recommends storage in permeable unmineable coals in the gaseous phase, above 800 m (US DOE NETL, 2012). The CSLF recommends that only coal beds where CO_2 will be in gaseous phase (due to in-situ temperature and pressure conditions) should be used at depths of around 700 – 800 m and that the coal permeability should be above 1 mD. These recommendations greatly limit the depth ranges suitable for use of coal seams. The CSLF methodology also notes that in some regions regulatory restrictions on storage where aquifers have <10,000 mg/L TDS apply, reducing the possible volume of coal seams available for storage (Table 22).

Table 22: Storage criteria for storage in unmineable coal seams

	Type and scale of assessment	Depth constraints	Reservoir quality constraints	Seal quality constraints
US DOE (3)	High level storage assessment onshore and offshore USA, Canada, and Mexico	CO_2 need not be in highly dense phase, minimum depth ~ 200 m	Permeability	Seal to prevent migration required
Ogawa (5)	National resource assessment for onshore and offshore Japan	No details	No details	No details, but seals defined as critical for storage
CO_2STOP (10)	Bottom up assessment for much of onshore and offshore Europe	No details	No details	No details, but seals defined as critical for storage
CSLF (12)	Methodology study with specific case studies from across the globe	Recommend CO_2 in highly gaseous phase, preferably at depths between 700 – 800 m depth	Coal permeability should be above 1 mD	Low permeability seal overlies reservoir
Silva (13)	Review of storage methodologies for coal. Case studies utilised	No details	Coal permeability should be above 1 mD	No details

More advanced equations for calculating storage on coal through adsorption and displacement of desorbed and free coalbed methane are given in Silva et al. (2012) where an empirical relationship between storage through adsorption and pressure is defined by type of coal (low, medium and high volatile bituminous coal). It was noted that further investigation to consider the impact of coal swelling in response to adsorption is required.

No details of the methodology for assessing storage potential in coals are given in Ogawa et al. (2011) or in the CO_2STOP methodology report (Poulsen et al., 2012). A summary of the methodologies described in the reports assessed is given in Table 23.

All the methodologies utilise deterministic approach (Table 24).

Table 23: Summary of storage assessment considerations for coal seams

	Determination of storage units	**Trapping mechanisms**	**Storage efficiency considerations**	**Techno-economic, regulatory and financial considerations**
US DOE (3)	Unmineable coal seams	Absorption and pore space (cleat)	Coal preferentially adsorbs CO_2 over at a ratio of 2 to 13 times. Absorption of CO_2 can impact permeability. Storage efficiency depends on volume of coal seam, CO_2 absorption capacity and total pore volume occupied by injected CO_2 (P10, P50, and P90 percent confidence intervals are 21 percent, 37 percent, and 48 percent, respectively)	ECBM potential assessed
Ogawa (5)	No details	Absorption	No details	No details
CO_2STOP (10)	No details	Absorption	No details	No details
CSLF (12)	Development methodology for estimating storage capacity. Case studies mentioned	Absorption	Depends on producible gas in place. This depends on initial gas in place multiplied by the completion factor (the amount of coal contacted by CO_2) and the recovery factor (expected to be more than 20 – 60%)	ECBM mentioned
Silva (13)	Review of storage methodologies for coal. Case studies utilised.	Absorption, in cleat and displacement of free methane	Absorption of CO_2 can impact permeability by an order of magnitude of two or more. Storage efficiency depends on producible gas, exchange ratio of CH_4:CO_2, completion factor and recovery factor. Dissolution into pore water is mentioned in one of the methodologies.	No details

Table 24:Table summarising methods used to estimate CO_2 storage capacity in unmineable coal seams

	Probabilistic	Deterministic	
US DOE (3)		x	Storage resource estimated for many mature oil and gas fields
Ogawa (5)	No details	No details	No details
CO_2STOP (10)	No details	No details	No details
CSLF (12)		x	Factors should be based on laboratory experiments, numerical simulations and field experience and measurements
Silva (13)		x	Empirical method for assessing absorption capacity tested

OTHER STORAGE RESERVOIRS DISCUSSED

Storage in basalt is mentioned in the CCUS Atlas (US DOE NETL, 2012) and one of the Regional Carbon Sequestration Partnerships (Big Sky Carbon Sequestration Partnership) is planning a small scale injection test. In addition, alternative 'unconventional CCUS' reservoirs are mentioned in the CCUS Atlas (US DOE NETL, 2012) including gas shales with enhanced gas recovery.

LESSONS LEARNED

Methodologies for estimating storage capacity vary widely in approach and show continuous development in terms of sophistication and techniques. It is unlikely that researchers can be persuaded to use only one methodology as the process is continually evolving. Therefore, making the raw data available (e.g. depth, porosity, formation thickness, net to gross, areal coverage, volume of hydrocarbons removed, compartmentalisation, pressure, temperature) in tabular form to enable researchers to apply their own methodology and to allow comparison between different storage sites is probably a good first step. However for some countries this may be difficult due to data sensitivity and availability. Tables for data entry were used for several of the studies (e.g. UKSAP, USGS, CO_2STOP). These tables are critical to assessing storage capacity since the raw data can be utilised by future studies as methodologies advance.

Simplified diagrams explaining the steps in capacity estimation are also useful (e.g. the CSLF pyramid, the UKSAP flow diagram of steps in capacity estimation) in providing the reader with a quick understanding of the methodology applied.

RECOMMENDATIONS

Following on from this review, a few key recommendations are given below:

- A well-structured database with clarity on data source, accuracy etc is an essential underpinning activity that will support capacity assessments and future work.
- Simple volumetric estimates are a strong first step. These will be comparable with the early national storage estimates typically prepared during early CCS development stages. These simple volumetric estimates will give an order of magnitude estimate of storage capacity.
- Clarity on the methodology used is critical to comparability of estimates.

- A probabilistic approach allows extension of the storage estimate to regions where there are few data. A clear explanation of where this has been performed and the methodology utilised supports comparability of estimates. Clarity on uncertainties in the data remain critical.
- A National level database of potential sites (CO_2Stored; http://www.co2stored.co.uk/) provides a good stepping stone towards detailed site surveys and flow simulations. These are typically funded through national funding and help identify 'sweet spots' for potential storage operators.
- Flow simulations are needed to really understand dynamic capacity. New data will almost certainly be required. Relatively sophisticated software and expertise in software operation will also be required.

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