NATIONAL CO_2 STORAGE ASSESSMENT GUIDANCE

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Executive Summary

This guide provides information on where to find the material required to undertake initial national scale storage assessments. It is designed to help government bodies and policy makers with limited prior carbon capture and storage (CCS) experience find information regarding the methodology of conducting an assessment. A nationwide storage estimate is fundamental to progress CCS as a climate mitigation technology as it will determine how suitable the regional geology is for CO_2 storage and provide an initial indication of capacity.

This guidance document includes definitions of technical terminology, proposed steps to establishing a national storage assessment and recent up to date case studies from a variety of countries focussing on Africa and Asia. A variety of methods for capacity estimation have been used and this report provides explanations of where to find these studies and sources of information including websites, papers and organisations. Most companies and organisations engaged in CCS development have stated their ambition to share knowledge and experience; and they actively collaborate at an international level to aid future projects. This guide provides a link with current expertise in CO_2 storage to help facilitate new CCS projects especially in developing countries.

Many detailed storage assessments have been conducted and published in the past decade. A wide variety of techniques and technologies have been used to complete them given the varying nature of each country and individual sites. Although a standardised method has yet to be established, this guide aims to provide links to the most developed methodologies providing a direction on the most suitable approach to adopt.

At the conclusion of this guide there is a nine point summary of the key stages that are recommended for the establishment of a national CO_2 storage assessment (see Section 7).

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1 Introduction

1.1 Background

Carbon dioxide (CO_2) capture and storage (CCS) has been identified as a key technology in mitigating climate change with rapid deployment required globally by 2050. CO_2 is captured and stored at over 800m depth in geological formations for safe long-term (millennial) retention. The geological formations required for the storage of CO_2 can have variable properties which dictate the amount of CO_2 the can be potentially stored. Decision makers initially require CO_2 storage assessments to evaluate the potential contribution that CCS could make to reach national CO_2 emission reduction targets.

Following a survey completed by the British Geological Survey (BGS), with UK and South Korean Government funding, entitled ‘Evaluation of Barriers to National CO_2 Geological Storage Assessments’ (IEAGHG, 2016), the lack of available data was identified as a major barrier to completing an initial storage assessment in some of the countries questioned.

Methodologies for producing storage assessments have been published from a variety of sources such as the Carbon Sequestration Leadership Forum (CSLF) and the United States Department of Energy (USDOE). Feedback from the BGS barrier paper implied that countries trying to conduct an initial assessment for the first time are unaware of these documents and guidance is needed.

1.2 Guide Content

The purpose of this document is to provide a reference guide on national storage assessments including where to find previous work on methodologies to conduct capacity estimations for geological formations. Section 2 describes the technical terminology that defines storage capacity. In the following section (3) barriers to national storage assessments are outlined. Section 4 highlights how capacity estimates should be made in a step wise fashion from basin-scale to prospective target formations, to give some indication on how the complexities influence capacity. Sections 5 and 6 give case studies, firstly by looking at methodologies used for different formations (coal beds, saline formations and depleted oil and gas fields) then by specific countries that have conducted these assessments and published reports. Section 7 summarises the steps to establish a national CO_2 storage capacity.

A number of national surveys have already been conducted at a variety of levels. Some notable assessments have been conducted for the Norwegian Shelf, the UK Shelf, US Regional Carbon Sequestration Partnerships, South Africa and the Asian Development Bank (ADB) South-Asian Assessment. Although these assessments were conducted at a high-level their initial surveys and characterisation provide an initial insight into methodologies that allow these assessments to be conducted. The South African and South-East Asian assessments are of specific relevance for this guide given the interest and status in the development of low-carbon technologies including CCS in these countries. The UK reference is included as an example of how a country with a mature oil and gas industry can preferentially select candidate storage sites.

This report is aimed at countries with either limited or no previous CO_2 storage assessment experience to help structure a route to develop reliable national storage capacity estimates. Absence or low quality data has been highlighted as the greatest barrier to CO_2 storage assessment. By providing a synthesis on case studies, methodologies and procedures already conducted and published this report can help to reduce this obstacle.

2 Technical Terminology

Differentiation between the following technical terms is essential to understand the development of a CO_2 storage assessment. The definitions are taken from a variety of sources but predominantly CSLF, USDOE and IEAGHG documents. Definitions may vary between texts but the following definitions are widely accepted.

A description of volumetric versus dynamic storage assessments is outlined below (IEAGHG 2014):

Volumetric storage assessments are conducted by calculating or estimating the pore volume of the storage target (a portion, such as a defined field, or all of a saline formation within a geologic basin) and then multiplying the volume by an appropriate storage efficiency term (E). The pore volume of an area is estimated by multiplying the porosity by the average thickness and total area of a specific formation. The efficiency term (E) represents the fraction of the pore volume that CO_2 can occupy and is affected by boundary conditions, sweep efficiency, heterogeneity, etc. Volumetric estimates do not consider factors such as number of wells, timing or length of injection, pressure build-up over time, or injection rate.

Dynamic storage assessments are conducted by investigating the effective of dynamic variables such as the number of wells, length of injection, rate of injection, and the time required to inject a given mass of CO_2 into a target storage volume. This is typically accomplished by constructing geo-cellular models of the injection volume and running numerical simulations where different scenarios evaluate variables such as number and type of wells, rate of injection, length of injection, formation water extraction, and other optimization techniques. The storage efficiency term can be estimated at any time by dividing the mass of CO_2 injected by the total mass of CO_2 that could have been stored if all of the pore space of the target storage volume had been filled with CO_2. It should be noted that, in a dynamic estimate, the storage efficiency changes with time, starting at a low level and increasing over time, as long as the total storage volume remains the same.

The following terms refer to different assessment scales as identified and defined in the CSLF Phase II Report (CSLF, 2007; Bachu et al., 2007):

Country-scale assessment which is a high level of assessment performed for a contiguous geographic area defined by national jurisdiction (country) and which usually encompasses several sedimentary basins.

Basin-scale assessment which is a more detailed level of assessment focusing on a particular sedimentary basin to evaluate and quantify its storage potential and to identify the best regions for CO_2 storage and the types of storage that might take place there, often in relation to the major stationary CO_2 sources in the basin or in its proximity.

Regional-scale assessment which is performed at an increasing level of detail for a large, geographically-contiguous portion of a sedimentary basin, usually defined by the presence of large CO_2 sources and/or by its known large potential for CO_2 storage.

Local-scale assessment which is very detailed, usually performed at a pre-engineering level when one or several candidate sites for CO_2 storage are examined to determine site capacity, injectivity and containment prior to site-selection decisions.

Site-scale assessment which is performed for the specific storage unit (hydrocarbon reservoir, deep saline aquifer or coal bed), usually to model the behaviour of the injected CO_2.

As illustrated in Figure 1, a Techno-Economic Resource-Reserve Pyramid for CO_2 Storage Capacity was proposed by CSLF, 2008; (Bachu et al., 2008). It shows the various capacities, described below in ascending order, which are nested within the resource-reserves pyramid:

Theoretical Storage Capacity is the total resource. It encompasses the whole of the resource pyramid (Figure 1). 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.

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.

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.

Matched Storage Capacity is that subset of the 'practical' capacity that is obtained by detailed matching of large point-sources of CO_2 with geological storage sites that are adequate in terms of capacity, injectivity and supply rate to contain CO_2 streams sent for storage from a defined source or multiple sources. This capacity is at the top of the resource pyramid and corresponds to the term 'proved marketable reserves' used by the mining industry.

3 Barriers to National Storage Assessments

The BGS produced a questionnaire, with responses from 15 countries, assessing potential barriers to conducting national storage assessments (IEAGHG, 2016). The report was jointly funded by the former UK Department for Energy and Climate Change (DECC) and the Korean

Institute of Energy Technology, Evaluation and Planning (KETEP), the conclusions of which prompted the development of this guidance document.

All the countries from which responses were taken (including Thailand and South Africa) had undertaken some form of national assessment of their potential storage capacities. The feedback received has helped to show how national assessments have been successfully prepared and how barriers have been overcome. The following are overarching themes which were identified as possible/ encountered barriers to progressing national assessments of CO_2 storage capacity:

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

The feedback also gave an indication of the typical timeframe for conducting an assessment. National assessments to the level of 'effective' capacities (Figure 1) can take two years but typically take 5-10 years. Extending these assessments to 'practical' capacities and some site-specific 'matched' capacity estimates takes at least 5 years depending on data availability and quality.

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. Section 4 provides a synthesis on where to find information on how to conduct these assessments and Section 5 gives examples of methods used in real-world scenarios.

The greatest barrier identified was the sparsity or absence of data, however, this did not prevent all of the questionnaire respondents from achieving some level of national assessment. The recommendations from the report highlighted the need for these assessment to be facilitated at a high level with sharing of public information and co-ordination at a country-wide level. National scale databases need to be facilitated at a higher level and a common methodology within each country should be developed by a trusted independent body such as a country's geological survey. A long-term vision is also required to enable industrial support for CCS to develop, supported by government policy. It was noted that the most rapidly completed and most mature assessments were completed by countries with a national or regional geological survey, as this allowed for better access to a wider variety of high quality data.

The survey also concluded that assessments should be taken in a step-wise manner to allow for incremental manageable steps towards a more detailed assessment. Population of a well-structured database is also essential as an underpinning activity that will aid the efficient development of storage assessments. The initial stage of a capacity estimate is a volumetric assessment of specific formations. Once this stage is completed a dynamic assessment based on more detailed criteria can be made to provide a more accurate estimate of storage capacity.

4 Steps to the Establishment of National Storage Assessments

Storage assessments should be undertaken in a step-wise manner, gradually increasing in complexity with appropriate decision points. Assessments should also consider neighbouring jurisdictions where suitable storage capacity might be accessed. Alongside conducting a national storage assessment, as highlighted in the BGS paper, the following points are also considered important for conducting an assessment:

- A public organisation with a clear mandate from each national government to manage the assessment particularly the co-ordination and collation of relevant data to support efficient national assessments.
- Development of a strategy to prioritise those sites where detailed assessments should be undertaken. This is a crucial step in developing a targeted and efficient approach to storage assessments.
- 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. Part of any national programme should review large point-sources of CO_2, such as coal-fired power stations, and their proximity to potential storage sites.

4.1 Database

Data quality and accessibility were both highlighted as barriers that needed to be overcome. For countries without a national geological survey, an initial step will be to develop a geology database at a country-wide level and preferably basin-wide level, which needs to include seismic data to improve the quality of data available. A database that includes well density and location, especially with respect to potential target formations, is also highly beneficial. This should include wellbore integrity, casing and cementation completion records and plugged/abandoned wells. The extent and quality of wireline logs through prospective storage and cap-rock formations and cores should also be recorded.

A 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. The database needs to be facilitated at a national-level, as multiple databases can hinder data access as relationships between organisations can be time consuming.

Key factors that need to be considered for basin storage assessments is the quality and vintage of legacy seismic and well log data from oil and gas exploration. Older composite logs and well reports on casing quality, cementation and pressure testing might lack sufficient detail or be inaccurate. When initial storage assessments are made data quality needs to be ascertained and the degree of reliance that can be placed on it. Data compilation for storage assessments should categorise data according to its quality. For example the UK national storage database includes qualitative rankings of high, medium and low depending upon the level of confidence that can be placed on it.

The BGS have a good variety of open source data available for public use. The geological survey is well established and hence the database is developed and well resourced. Their website is available for review (http://www.bgs.ac.uk/opengeoscience/) and is a good example of how geological data can be collated.

The Indonesian Geological Survey (Badan Geologi, http://www.bgl.esdm.go.id/) is another good example of how to develop such a database. The group was founded in 2005 and within 10 years has developed an extensive geological database with public information on energy, minerals, groundwater, geological hazards and environment and spatial planning. Roadmaps are available on their website showing the development of the survey from 2005-2016.

OneGeology is a current international effort to produce a ‘world map’ of current known geology. It has had contributions from 113 countries, UNESCO and large global geoscience bodies. The website was launched in 2008 with the aim of helping to locate the porous rocks suitable for the storage of greenhouse gases. The map is currently available at http://portal.onegeology.org/OnegeologyGlobal/ but is a currently a work in progress.

4.2 Simple Volumetric Estimate

Simple volumetric estimates are recommended as the first stage in a national storage assessment. A comparison of methodologies for conducting volumetric storage assessments is included in CSLF’s report ‘Comparison between Methodologies Recommended for Estimation of CO_2 Storage Capacity in Geological Media’ (CSLF, 2008). This compares two previous reports published by the USDOE Sequestration Partnerships Program (Atlas I, USDOE 2007) and an original report by CSLF (Phase I report, 2005). The aim was to bring together the two reports to help define one standard method for conducting assessments. The report classifies the methodologies into three main groups: coal beds; oil and gas fields; and deep saline aquifers (Section 5).

Figure 1 (from the CSLF Report) shows the relationship between the capacities described in Section 2 and how detail increases the certainty of potential and decreases the cost of storage. Theoretical capacity can be calculated by conducting a simple volumetric estimate. Calculating pore volume and reservoir size allows an estimate of the highest theoretical potential volume that can be stored.

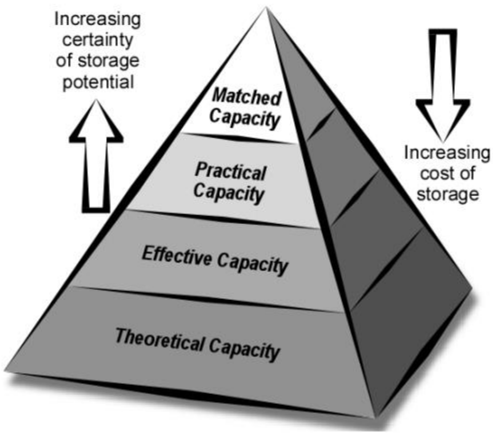

Figure 1 “Techno-Economic Resource-Reserve pyramid for CO2 storage capacity in geological media within a jurisdiction or geographic region” CSLF, 2008.

All equations recommended for making volumetric storage assessments are included in the report and how to use them for each type of possible geological storage scenario. To date, there is not one standard method used for calculating these estimations but this report provides a review and comparison of the most regularly used. The fundamental concept behind the equations is:

Volumetric estimate = volume of pore space x efficiency

The methods vary on how the efficiency is calculated and how to define the reservoir boundaries that define the total pore volume.

4.3 Dynamic Estimate

Although initial volumetric assessments are valuable, flow simulations providing dynamic capacity estimates (including the impact of site-specific dynamic factors such as injection rate, timing of injection, and pressure effects at site-specific and regional scales) are needed to fully understand the potential CO_2 storage capacity. Dynamic estimates are more specific and hence their methodologies are more varied. They can also take into account injection pattern, location and number of wellbores, overall formation pressure build up and water (brine) extraction.

Recent studies have been conducted by IEAGHG to assess the difference in storage estimates based on volumetric and dynamic methods. A study completed in 2014 compared these two methods of calculating storage efficiencies and concluded that over very long timescales (thousands of years) the estimates produced roughly the same results, as the dynamic assessment asymptotically reaches the volumetric estimate (IEAGHG 2014). Importantly though, within the first decades of injection, the estimates were very different.

The study compared volumetric to dynamic storage in two distinct and contrasting basins. An open system, the Minnelusa Formation from the Power River Basin in the western United States, was compared with the Qingshankou and Yaoju Formations of the Songliao Basin of north-east China, which is representative of a closed system. The effects of dynamic storage were modelled over a period of 2,000 years. The study also investigated the effects of geological uncertainty, boundary conditions, numbers and types of well and water (brine) extraction. A second stage, currently approaching completion, is also contrasting dynamic storage in two different formations in contrasting basins: the Minnelusa Formation and the Bunter Sandstone located in the southern North Sea Basin. The dynamic storage has been modelled over a shorter timescale of 50 years to produce a more refined capacity estimate.

The concept of dynamic storage, and the ability to make estimates of CO_2 storage at a national scale, have been the subject of generic research for over a decade. There are five key references listed at the back of this report which explain this topic in some depth i.e. Birkholzer, J.T et.al. (2015), Goodman, A., et.al. (2013), Dooley, J.J., (2013), Hosa, A., et.al. (2011) and Bachu, S. (2015).

5 Geological Formation Examples

5.1 Storage in Deep Saline Formations

The term ‘deep saline formations’ (DSF) refers to a body of porous rock that contains saline water with total dissolved solids greater than 10,000 mg/l (ppm). The reservoir must be below a depth of 800m where suitable conditions required for the injection of super critical CO_2 storage occur. More than one aquifer may be present at a given location.

Structural and stratigraphic trapping (volumetric) are the only trapping mechanisms taken in to account in the USDOE and CSLF volumetric methods as other mechanisms (e.g. residual trapping, solubility trapping, mineral precipitation) are time-dependant processes and depend on site-specific parameters (i.e. would be included in a dynamic estimation model).

Some discrepancies between CSLF and DOE capacity estimate methodologies for DSFs still remain. The USDOE assessment is purely volumetric whereas the CSLF considers the dissolution of CO_2. The USDOE also considers the whole aquifer as a storage site whereas CSLF estimates only include areas of the aquifer with a stratigraphic or structural trap. Generally though the two methodologies are computationally equivalent (if an average CO_2 density is used, not a minimum and maximum value).

5.2 Storage in Oil and Gas Reservoirs

Storage capacity estimates for oil and gas fields are the simplest to conduct given the amount of characterisation data available because of their defined cap-rocks, stratigraphic and structural traps. They are also considered discrete media compared to saline aquifers and coalbed storage sites.

Volumetric estimates are made simpler with the assumption that volume previously occupied by hydrocarbons becomes available for CO_2 storage. This is generally true unless the reservoir has been used for secondary/ tertiary oil recovery or is in hydrodynamic contact with an underlying reservoir. Another assumption in these volumetric estimates is that the CO_2 can be injected to meet the pre-production reservoir pressures. Given the production history of the reservoir the cap-rock may have been affected and hence lower pressures may be required.

No methodology was provided by the CSLF or USDOE for EOR sites. Any capacity estimates would need to be produced at a site specific scale. USDOE also recommends excluding potentially water-bearing units for storage estimates (although these are expected to be classified as unpotable due to hydrocarbon contamination).

5.3 Storage in Coal beds

USDOE and CSLF methods for volumetric capacity estimation in coal beds largely coincide. When calculating the volume of coal available the focus in both methods is on classifying the types/ areas of coal suitable for CO_2 storage. Both methods define the depth boundaries of coal available as shallow enough for permeability to be above 1md and deep enough to be below groundwater protection zones. The CSLF then go on to highlight that coal beds also need to be classified on in-situ pressure and temperature to only classify coal beds where CO_2 would be in gaseous phase.

6 Case Studies by Country

6.1 South Africa

The development of a South African CCS storage atlas was completed in 2010 with the aim of starting a test injection pilot project by 2020. An assessment of the potential for CCS in Africa was initially published in 2004 by the CSIR (Council for scientific and Industrial research, South Africa). The study concluded that there was enough storage capacity to make CCS feasible with further detailed dynamic estimations required. By April 2012 the World Bank – South African Department of Energy CCS study developed two separate stakeholder plans (Beck, B. et.al., 2013). These focused on local and national level engagement issues to help communicate the concept of CCS within the context of national priorities such as access to energy and job creation.

The technical report conducted by Viljoen et al., 2010 describes how the storage capacity estimations were undertaken. The report highlights the relatively small capacities estimated for the Karoo Supergroup and depleted oil and gas reservoirs. New storage potential is evident from oil and gas exploration and development in the offshore Mesozoic basins that fringe the coast of South Africa. Between the three storage types 150Gt of potential storage were identified (98% of which is offshore). The first step of the report was to identify CO_2 sources in South Africa, the character of the CO_2 and the potential types of geological storage (depleted fields, sedimentary saline aquifers, coal bed methane etc.). Next a review of previous storage capacity estimates was undertaken and data availability. The screening criteria for assessing basins was then outlined including tectonic setting, fault intensity, onshore or offshore and twelve other critera. Major deposits such as the Mesozoic basins and Karoo Supergroup were then studied separately.

The 2010 technical report followed the CO2CRC 2008 storage assessment methodology, working up from country to basin scale assessments to then developing geological and engineering characterisations. The study concluded that a majority of the storage potential for South Africa lies within the oil and gas bearing sequences of the Ousteniqua, Orange and

Durban/Zululand basins of the Mesozoic, approximately 150Gt. Depleted oil and gas fields are beneficial as previous characterisation data (seismic surveys, borehole logs) are available which reduces cost. There is the possible economic advantage of enhanced oil and gas recovery. It was previously assumed the Karoo Supergroup would provide the largest onshore group but borehole data provided geological characterisation that proved permeability and porosity would be too low for large-scale CO_2 storage.

The report highlighted in 2010 that the way forward for CCS in South Africa was for collaborations between major stakeholders, industry and government if funding could be secured. Although commercial scale CCS was not studied in the report it identify a series of further studies including the use of existing boreholes for CO_2 injection tests.

The 2010 South African study is a good example of a well-planned reconnaissance assessment for CO_2 storage which provides clear evidence of storage potential and a strategy for a future direction.

6.2 Asia (Indonesia, Philippines, Thailand and Vietnam)

A report written by the Asian Development Bank (ADB), Global CCS Institute and Department of Energy and Climate Change in September 2013 outlined the future prospect for CCS in Southeast Asia. The report included Indonesia, Thailand, the Philippines and Vietnam as they represent a dynamic group of economies. A strong increase in energy demand has developed in these countries within the last decade. A rapid increase in industrialisation provides the need for CCS to reduce emissions with a concomitant increased in natural gas and oil production and consumption. Overall it was concluded that each country did have enough resources to store CO_2 to make CCS viable, with natural gas processing and power plants as the capture sources.

A two stage ranking process was utilised to assess 143 oil and gas fields to determine the best storage options in each country. As shown in Figure 2, the approach for estimating storage capacity used separate screening processes for each type of storage reservoir (saline, coal and depleted hydrocarbon field). The ranking process for storage suitability was only conducted for oil and gas fields during this study as industry data allowed reservoir characteristics to be established and volumetric estimates to be made. For other sites data was sparser and estimates were not as easily established. Some estimates were made for coal bed methane although as there is no current commercial production in south-east Asia these were hypothetical estimates. Oil and gas reservoirs were considered the best options for storage as more data was available and the potential for CO_2-EOR could give a potential financial incentive.

Volumetric estimates for saline aquifers were only considered for basins at 1km or greater depth and storage efficiencies were calculated using average porosity using typical temperature and pressure data for the given depth. The coal bed methane estimates were calculated for deposits at 300m or deeper. The measurements included the assumption that CO_2 sorption would be preferential to methane and an efficiency factor of 0.2 was used.

The Asian Development Bank report also discusses capture sources and the source-sink matching process and results. Costs analysis, legal/ social issues and recommendations are also published.

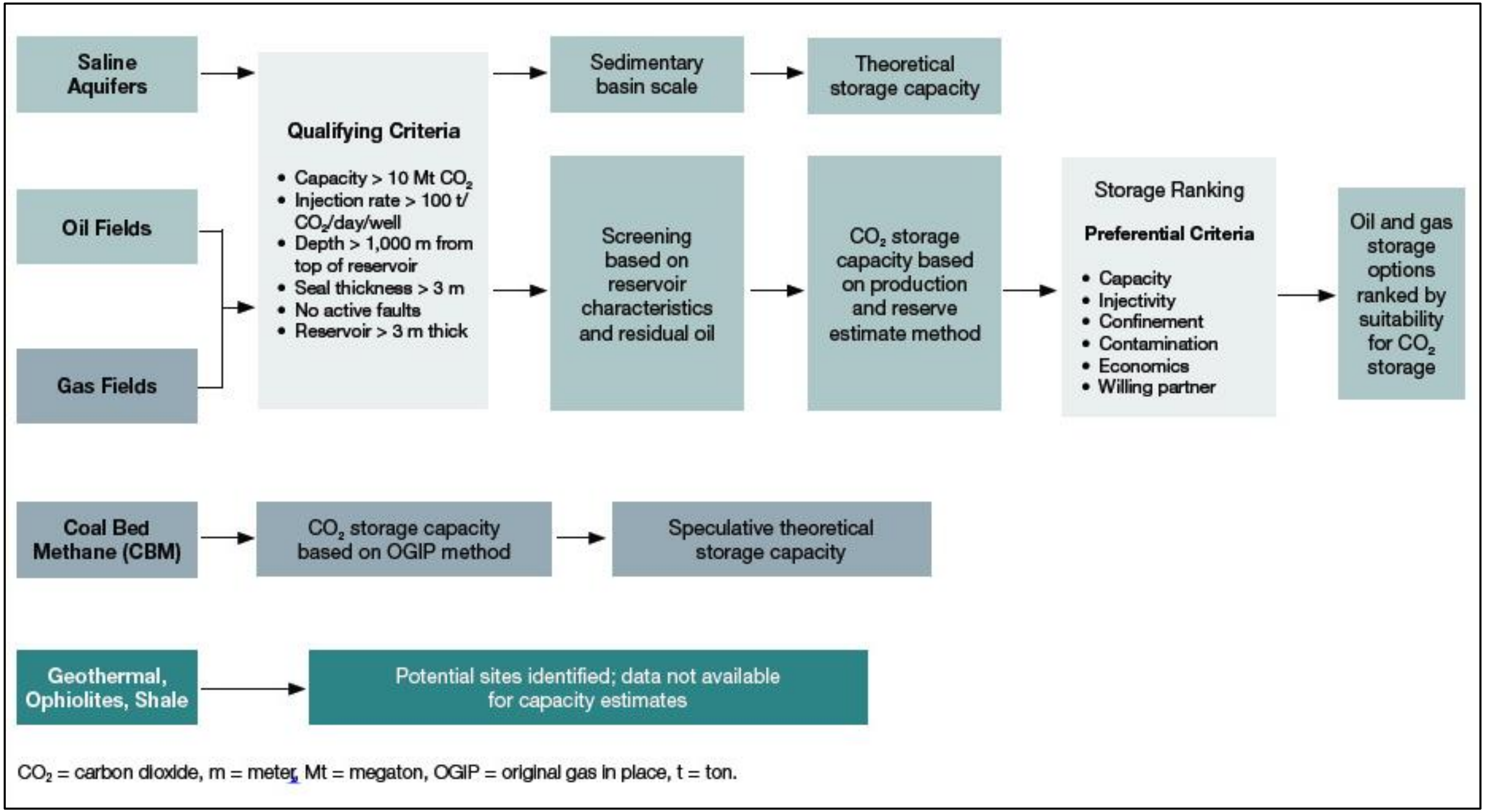

Figure 2 Approach for Estimating CO2 Storage Capacity (ADB, 2013)

6.3 South Korea

South Korea has rapidly industrialised in the last 60 years and is now actively developing CCS. The Korea Institute of Geoscience and Mineral Resources (KIGAM) initiated a research programme in 2009 to identify a site for a pilot storage project. A systematic and quantitative evaluation method (Bachu 2003) was used to evaluate the storage potential of sedimentary basins in Korea (Kim, A.R. et.al., 2013). 15 criteria including geological characteristics and maturity were weighted according to their suitability for CO_2 storage. This exercise showed that the offshore Ulleung Basin is the most suitable for CO_2 storage in Korea. A theoretical CO_2 storage capacity has been estimated for this basin using 2D/3D multi-channel seismic and wellbore data compiled from offshore oil and gas exploration since the 1980s (Yulle et.al., 2012). This exercise identified five different seismic units. The total volumes were converted with a time-depth relation inferred from the surveys before porosity and density were used to compute the potential storage capacity. The estimated capacity for all five units is approximately 5,100M tonnes.

There are few onshore conditions in the country that are suitable for CO_2 storage particularly deep sedimentary aquifers with impermeable cap-rock that are also tectonically stable and lack faults. Initial screening identified three candidates: the Paleozoic Taebaksan Basin, the much larger Gyeonsang Basin which occupies the south east of the Korean peninsula and the much small Miocene Pohang Basin.

Attention has focussed on the onshore Gyeonsang Basin which has also undergone geothermal exploration that has provided borehole data and temperature profiles. The geological storage capacity of CO_2 in sandstones of the Sindong Group within the Gyeonsang Basin was initially investigated by quantification and characterisation of spatial and stratigraphic distributions of sandstones within the basin (Kosuke Egawa et.al., 2009). Detailed field descriptions and porosity measurements of samples from three areas were used. Spatial variance of channel sandstone bodies were geostatisitically calculated to estimate storage capacity. The volume of these channel sandstones between 800 – 2,000m depth in the Sindong Group is estimated to be 1,960 and 1,081 km^3 which equates to a capacity estimate of between 535 - 1,011M ton.

Oil and gas exploration in the Pohang Basin has generated a suite of borehole logs. The KIGAM survey of this basin identified three prospective sites for the pilot: Euiseong; Gunwi; and Heunghae. Magneto-telluric surveys were conducted across Euiseong and Gunwi in the summer of 2008. A Nationwide evaluation concluded in 2013 that onshore basins have a collective capacity of 1.8B tonnes of CO_2, but offshore basins could store as much as 10B tonne (Current status of CCS in Korea, 2013).

This example of a country-wide CO_2 storage assessment shows a clear progression beginning in 2003 with a high level evaluation to basin-specific initiatives that have built from earlier resource exploration. Targeted field research and geophysical surveys orientated at CO_2 storage, have complemented background geological data to provide better capacity estimates and to identify an onshore pilot scale CO_2 storage site. South Korea has also benefited from KIGAM participation in the CO2CRC Otway Pilot Project in Australia.

6.4 United Kingdom

The UK has recently completed a strategic CO_2 storage appraisal (ETI, 2016). This is a good example of a selection process to identify five key prospective storage sites from a number of offshore basins characterised from over 40 years of oil and gas exploration and development. Five strategic storage sites were selected from an initial list of almost 600 candidates. The study covers detailed interpretation and analysis of subsurface information for each site and preparation of an outline storage development plan, budget and detailed risk assessment. The study has concluded that only two of the five sites require any further appraisal drilling before an investment decision. This example provides an insight into a selection process for candidate storage sites for a country with a mature oil and gas industry.

7 Key Stages for setting up a National CO_2 Storage Assessment

The joint UK / South Korean funded survey clearly shows that building a national CO_2 storage assessment should be compiled in a series of incremental steps:

1 Develop a national strategy to produce a CO_2 storage capacity estimate. The strategy should first review whether there are existing national institutions that are capable of conducting an assessment.

2 Appointment of a designated organisation, probably the national geological survey, to co-ordinate and collate key data on a country's geology and geotechnical background.

3 Set up a dedicated database that acts as a national repository for all key data that can be used to identify and characterise CO_2 storage sites.

4 Categorise data sets according to the level of confidence that can be accrued to the quality of data and reliance that can be placed on it.

5 Depending on the level of data categorise a national CO_2 storage resource based on an accepted terminology and scale, for example, basin-wide or regional-scale.

6 Target specific formations such as DSFs that have some evidence of pressure / temperature, depth and structural characteristics that are suitable for CO_2 storage.

7 Initial capacity estimates can be volumetric, bearing in mind these can only provide a general indication of capacity.

8 Apply dynamic estimates based on modelled projections of capacity that take account of pressure effects and numbers of wells.

9 Dynamic estimates can be further refined, depending on the quantity and quality of data available. Features such as the presence of faults, facies variations and other forms of geological heterogeneity are known to affect CO_2 storage especially migration rates and distribution and therefore capacity.

8 Directory of Leading Global Research Centres

International Centres on CCS:

- Carbon Sequestration Leadership Forum (CSLF) – Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation https://www.cslforum.org/cslf/
- Global Caron Capture and Storage Institute (GCCSI) http://www.globalccsinstitute.com/
- International CCS Research Centre (BIGCCS) http://bigccs.no/
- CCS Association (CCSA) http://www.ccsassociation.org/
- IEAGHG – IEA Greenhouse Gas R&D Programme http://ieaghg.org/

National CCS Centres:

- Australia –CO2CRC http://www.co2crc.com.au/
- Australia - Commonwealth Scientific and Industrial Research Organisation (CSIRO) http://www.csiro.au/en/Research/EF/Areas/Coal-mining/Carbon-capture-and-storage
- UKCCSRC (UK CCS Research Centre) https://ukccsrc.ac.uk/
- Japan CCS Company - http://www.japanccs.com/?lang=en
- Japan - Research Institute of Innovative Technology for the Earth (RITE) http://www.rite.or.jp/co2storage/en/
- Korea - KCCSA (Korean CCS Association)

Geological surveys:

- British Geological Survey http://www.bgs.ac.uk/
- French Geological Survey - Bureau de Recherches Géologiques et Minières (BRGM) http://www.brgm.eu/activities/geological-storage-of-co2/geological-storage-of-co2
- German Research Centre for Geosciences – GeoForschungsZentrum (GFZ) http://www.gfz-potsdam.de/en/section/fluid-systems-modelling/projects/complete/
- Norwegian Geological Survey (Norges Geologiske Undersøkelse, NGS) http://www.ngu.no/en/node
- Indonesian Geological Survey (Badan Geologi) http://www.bgl.esdm.go.id/
- South Africa – Council for Geoscience – Applied Geoscience Solutions http://sageoscience.maps.arcgis.com/home/index.html

North America:

- U.S Regional Carbon Sequestration Partnership Program – Capacity and Fairways Subgroup (USDOE) http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships
- National Energy Technology Laboratory (NETL, part of USDOE) http://www.netl.doe.gov/
- Energy & Environmental Research Center (EERC) https://www.undeerc.org/

- Bureau of Economic Geology (BEG) http://www.beg.utexas.edu/
- Battelle - http://www.battelle.org/search?indexCatalogue=basic&searchQuery=CO2+Storage+with+EOR+Project&wordsMode=0

Other:

- Intergovernmental Panel on Climate Change (IPCC) https://www.ipcc.ch/

Oil companies actively engaged in CO_2 storage:

- Statoil http://www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2CaptureStorage/Pages/default.aspx
- Shell http://www.shell.com/sustainability/environment/climate-change/carbon-capture-and-storage-projects.html
- Total http://www.total.com/en

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