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Methods to assess geologic CO_2 storage capacity: status and best practice

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INTERNATIONAL ENERGY AGENCY

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Table of contents

List of Figures

List of Tables

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Executive Summary

To understand the emission reduction potential of carbon capture and storage (CCS), decision makers need to understand the amount of carbon dioxide (CO_2) that can be safely stored in the subsurface and the geographical distribution of storage resources. Estimates of storage resources need to be made using reliable and consistent methods. This report offers recommendations for an internationally shared approach to quantifying this potential.

Previous estimates of CO_2 storage potential for a range of countries and regions have been based on a variety of methodologies, with access to widely differing amounts of data, resulting in a correspondingly wide range of capacity estimates. Some of these estimates have even been in conflict with others. Consequently, there has been uncertainty about which of the methodologies were most appropriate in given settings, and whether the estimates produced by these methods were useful to policy makers trying to determine the appropriate role for CCS.

In 2011, the International Energy Agency (IEA) convened two workshops, which brought together experts from six national geological survey organisations to review geologic CO_2 storage assessment methodologies and make recommendations on how to harmonise CO_2 storage estimates worldwide.

This workshop report presents the outcome of the workshops. It first gives an overview of factors to consider before undertaking a CO_2 storage assessment on saline aquifers. This is followed by a comparison of ten of the more recently published CO_2 storage resource assessment methods and resource estimates, which are characterised according to ten parameters and the results tabulated.

The method comparison is then followed by a set of steps that can be used to assess geologic CO_2 resources. As the overall goal of the workshops was to harmonise CO_2 storage estimates, the participants identified best practice in the form of steps that can be followed to conduct a thorough assessment of storage resource, throughout the world, across geologic settings, regardless of the amount of available geologic data.

The following statements reflect the consensus of the workshop participants:

- Strata within a basin should be subdivided into storage assessment units (SAUs). These are defined as mappable volumes of rock that consist of a porous flow storage unit and an overlying regional sealing formation.
- Estimation methods should be probabilistic. The benefit of a probabilistic methodology is that it allows the resource to be assessed with any given level of uncertainty in the input data.
- Pore volumes in SAUs should be estimated.
- The application of any additional constraints should be clearly stated.
- Methodologies should identify the total accessible storage resource (TASR), defined as the mass of CO_2 that may be injected and stored using present-day geologic and hydrologic knowledge of the subsurface and engineering practices.
- Jurisdictions should use a common methodology to estimate storage efficiency factors, which are the fraction of available pore space that will be occupied by CO_2 within an SAU.

One of the most important points of agreement was that jurisdictions should assess and report the TASR alongside any other estimates that are subject to further jurisdiction-specific constraints. TASR estimates are solely determined by geological considerations, and thus country-level TASR estimates could be easily compared and aggregated. Following the approaches and procedures outlined in this report would ensure that jurisdictional CO_2 storage resource assessments are comparable, thereby allowing decision makers to understand the distribution of global geologic CO_2 storage resources.

To further support the aim of harmonising international storage assessments, workshop participants agreed on the need:

- to conduct further research into storage efficiency to develop robust and generically applicable calculation methods; and
- to enhance international co-operation between organisations that have attempted or completed CO_2 storage resource assessments and those that are looking to begin assessments.

Introduction

To understand the emission reduction potential of carbon capture and storage (CCS), decision makers need to understand the size and distribution of carbon dioxide (CO_2) storage resources. Prerequisites for this are a clear and widely shared definition of CO_2 storage potential and an agreed method for its calculation.

In 2011, the International Energy Agency (IEA) invited experts from the geological surveys of Australia, Canada, Germany, the Netherlands, the United Kingdom and the United States to two seminars to explore ways to improve the consistency of geologic storage resource estimates, and develop a shared understanding of what constitutes a resource estimate. This report presents the outcomes of the two seminars.

The objective of the first seminar, entitled "CO_2 Storage Capacity Estimation: Towards a Common Framework", was to review and compare assessment frameworks currently used by different IEA member countries. As part of this, participants compared ten of the more recently published CO_2 storage resource assessments to understand:

- common aspects of the methods;
- differences in the underlying geological assumptions and methods used; and
- policy constraints on the areas and rock volumes they cover, *i.e.* what sections of the total resource of pore space in a jurisdiction are considered in a particular assessment and why.

These insights provided input to the second seminar, "CO_2 Storage Capacity Estimation: Developing Guidelines", in which participants considered best practice for storage resource assessment and suggested ways in which storage assessment methodologies could be harmonised.

The workshops focused on methods used to estimate the storage capacity in saline water-bearing parts of reservoir rocks, which are widely described in the CO_2 storage literature by the shorthand term "saline aquifers" (*e.g.* Benson and Cook, 2005), as that is where the majority of the technically accessible CO_2 storage potential resides (Benson and Cook, 2005; Bradshaw *et al.*, 2007).

This report first outlines key considerations in the estimation of a storage resource, contrasting estimation approaches used today, and then proceeds to present the participants' shared view of best practice for storage resource estimation. The information in the report is intended to support future national or regional-scale storage assessments, to produce robust and internationally meaningful results.

The implementation of the recommendations from the workshops, which are a consensus of the participating experts, would ensure that jurisdictional or national-scale CO_2 storage resource assessments could be comparable with each other and would provide a meaningful estimate of the global geologic CO_2 storage resource.

Background

The last two decades have seen a proliferation of proposed classification schemes for CO_2 storage potential and methods to estimate CO_2 storage resources, with none being uniformly adopted around the world. These methods have been used to make estimates of storage potential that, in some cases, conflict with each other, despite being of similar vintages and covering comparable areas. For example, some estimates of potential for individual countries or regions were larger than those for the entire world (Benson and Cook, 2005; Bradshaw *et al.*, 2007). Consequently, there remains uncertainty about what different methods to estimate potential are actually measuring, which methods are most appropriate in given settings, and whether the estimates produced by these methods provide a sound basis for policy making.

Several organisations independently saw a need to develop classification systems that clearly differentiate between measures of storage potential, and methods to estimate storage resources (*i.e.* the largest, most inclusive measure of storage potential). These organisations included the Carbon Sequestration Leadership Forum (CSLF) (Bachu *et al.*, 2007; Bradshaw *et al.*, 2007), the US Department of Energy (US DOE) National Energy Technology Laboratory (NETL) (2008), and the IEAGHG Programme (IEAGHG, 2009). In particular, the CSLF and US DOE proposed methods for CO_2 storage resource assessments that could be applied in any jurisdiction given certain minimum levels of data availability. Comparisons (Bachu, 2008; Gorecki *et al.*, 2009) of the CSLF and US DOE methodologies found that these two methodologies were basically identical, with minor differences in computational formulation.

Since the publication of the CSLF and US DOE methods, several other organisations have published and applied methods for determining geologic CO_2 storage potential. A review of six CO_2 storage atlases for different countries and regions indicates that there are significant differences between the six methods and the way in which they have been applied (Prelicz, Mackie and Otto, 2012). The storage estimates are not all based on the same scientific assumptions and thus cannot be accurately compared or summed to provide regional or global estimates of CO_2 storage potential. Moreover, the estimates generally do not cover the entire technically accessible CO_2 storage resource, because a range of local policy constraints have been applied to them, to make them relevant to a particular jurisdiction (Prelicz, Mackie and Otto, 2012). It is these discrepancies that this report seeks to begin to address.

Defining geologic CO_2 storage resources and assessment types

Classification of CCS capacity

As in other industries (*e.g.* oil and gas), CO_2 storage classification schemes delineate between estimates of resources and reserves (or, in the case of CO_2 storage, capacity) on the basis of technology, cost and certainty. A resource can be described as anything useful and potentially available to mankind that can be exploited with available technology; however, the presence of a resource does not imply that any part of it can be exploited economically now or in the future. The portion of a geologic resource that has economic value now, and is thus a commodity, is referred to as a "reserve", whereas resource estimates that take into account economic factors are typically referred to as contingent resources.

A geologic CO_2 storage resource comprises pore space that can safely and permanently hold CO_2. Therefore the geologic formation must have properties that allow CO_2 to be injected and, once injected, retained through one or more trapping mechanisms. Four trapping mechanisms are generally recognised (Benson and Cook , 2005; Bradshaw *et al.*, 2007):

- buoyant (also referred to as structural and stratigraphic);
- residual;
- solubility; and
- mineral.

While all four mechanisms play an important role in ensuring that CO_2 is retained over long time scales, given anticipated injection rates and current technology, the most relevant trapping mechanisms for resource assessments are residual and buoyant trapping. Residual CO_2 trapping is defined as "Discrete droplets, blobs, or ganglia of CO_2 as a nonwetting phase, essentially immiscible with the wetting fluid, trapped within individual pores [or group of pores] where the capillary forces overcome the buoyant forces" (Brennan *et al.*, 2010). Buoyant CO_2 trapping is defined as "CO_2 in communication across pore space creating a column that is held in place by a top and lateral seal, either a seal formation or a sealing fault" (Brennan *et al.*, 2010). This document only covers assessments of buoyant and residual trapping mechanisms.

Constraints on CCS capacity

Any geologic CO_2 storage resource assessment estimate is based on the mass of CO_2 that can be stored within the pore space of subsurface rocks. However, the differences between classes of resource estimate, and indeed, the disparity among estimates of any single class, are the result of constraints placed on what constitutes "available" pore space. Assessments of subsurface CO_2 storage potential are constrained by:

- geology and our understanding of the subsurface (*e.g.* geologic data and models);
- engineering considerations (*i.e.* technologies available to exploit the available pore space and our ability to implement them);
- economics (*e.g.* storage resources that are infinitely expensive to access are not useful); and,
- socio-political factors (*e.g.* acceptance of use of the subsurface for CO_2 storage, or regulatory limitations on the use of certain technologies).

The advantages of probabilistic assessments

Our limited understanding of the subsurface and its inherent variability can be addressed by gathering more geologic data and the use of probabilistic methods to quantify uncertainty. Given that gathering more data is not always feasible and may not necessarily reduce variability, workshop participants focused on probabilistic methods. Probabilistic methods use a range of geologic values, based on available data and a geologic model. Probabilistic resource assessment requires careful integration of a geologic model of the resource with the statistical analyses of results (Ahlbrandt and Klett, 2005; Charpentier and Klett, 2005).

Because rocks are heterogeneous, data sets for large areas are rarely complete. Storage capacity estimates thus need to rely on geological models to fill gaps in the data. Uncertainties could be addressed by generating a large number of Monte Carlo simulations with input parameters that are statistically distributed in accordance with the geological model. The statistical analysis of results can provide resource estimates at differing confidence intervals or fractiles.

Probabilistic methods traditionally provide a statistically sound method to make resource approximations (Ahlbrandt and Klett, 2005; Charpentier and Klett, 2005). The benefit of a probabilistic methodology is that it allows for the resource to be assessed with any given level of uncertainty in the input data. If the basin or basins within a jurisdiction are mature petroleum provinces, then there will likely be abundant well data that can be used for the assessment. By contrast, if the data are sparse, then there will need to be some geologic interpretation to estimate the input parameters. And if there are no data, then an analogue must be used. All data density scenarios, however, require the establishment of a geologic model that describes the basin's depositional, burial, diagenetic and structural history. The geologic uncertainty increases as the amount of data decreases; the resource estimates will reflect the geologic uncertainty. Therefore the range of possible storage assessment resource values will widen with increasing geologic uncertainty. Regardless of the output of the probabilistic models, the ranges of resource estimates still hold significant value as a prospective tool and for adding to the understanding of the global CO_2 storage endowment.

Engineering, economic and socio-political constraints

Engineering, economic and socio-political constraints can be applied to the input values used for the initial estimation (upstream) or to output values based on how much of that pore space will be made available for CO_2 storage (downstream). They are informed by scientific, technological or economic factors, and may often be imposed by government policy; the minimum depth requirements in many methodologies are one such example. Therefore, before a jurisdiction or organisation attempts to estimate the geologic CO_2 storage resource of any particular area, they need to determine the constraints that will be involved in their estimates and how they will be applied.

Upstream constraints limit the amount of pore space available for storage. Depending on the jurisdiction, these constraints could limit pore space to:

- storage formations overlain by a sealing formation;
- off-shore storage;
- petroleum-bearing strata;
- a certain distance from point sources of CO_2 emissions;
- stratigraphic or structural closures where CO_2 will be trapped as an immobile column;
- reservoirs associated with enhanced oil recovery; or
- depth at which CO_2 exists as a dense liquid or supercritical fluid.

Examples of downstream constraints are:

- assumptions about whether reservoir pressure control is practical (in essence this is an economic constraint); and
- the minimum total dissolved solids (TDS) values of groundwater in potential storage formations, to protect underground drinking water resources.

Several factors come into play when determining the goal of an assessment, and ultimately the assessment geologist must decide what constraints to apply before choosing or developing their own geologic CO_2 storage assessment methodology.

Storage efficiency

A key component necessary to estimate CO_2 storage is typically referred to as storage efficiency. The storage efficiency represents the fraction of accessible pore volume that will be occupied by free-phase CO_2. The time at which storage efficiency is evaluated affects its value. For example, Gorecki *et al.* (2009) performed a comprehensive study on storage efficiency as a function of lithology, describing a model that estimated the efficiency based on the time at which CO_2 injection stopped, but the CO_2 plume was still mobile. Szulczewski *et al.* (2012) issued a method to estimate efficiency numerically in two scenarios: (1) migration-limited efficiency factor, which expresses the amount of CO_2 that can be injected such that it all becomes sequestered by residual trapping and solubility trapping before reaching the boundary of the aquifer; and, (2) pressure-limited efficiency factor, which expresses the amount of CO_2 that can be injected over a given time period without fracturing the seal. The type of trapping influences the magnitude of storage efficiency, with buoyant trapping being the most efficient.

There is considerable uncertainty over what storage efficiency factor should be used in assessment methodologies. Current analytical techniques for estimating the storage efficiency (Juanes, MacMinn and Szulczewski, 2010; Okwen, Stewart and Cunningham, 2010) allow for the storage efficiency of an entire geological unit to be estimated given temperature and pressure gradients, depth ranges, estimates of the irreducible water saturation at the leading edge of a mobile CO_2 plume, the residual gas saturation at the trailing edge of the plume, and the relative permeability between the CO_2 and the ground water. These estimates come primarily from experimental data (*e.g.*, Bennion and Bachu, 2005, 2008; Burton, Kumar and Bryant, 2008; Okabe and Tsuchiya, 2008; Okabe *et al.*, 2010; Akbarabadi and Piri, 2013).

The controls on storage efficiency are:

- the volume of rock contacted by the CO_2 plume, also known as the sweep efficiency;
- how easily CO_2 will move relative to the water present within the pore space, also known as relative permeability;
- the amount of water that will be displaced by the leading edge of the CO_2 plume, also known as drainage;
- how much water re-enters the pore space at the trailing edge of the CO_2 plume, also known as imbibition;
- a ratio of the viscosity of the CO_2 to the viscosity of the water, which estimates how much water can be displaced by the lower viscosity CO_2;
- a ratio of the density of the CO_2 to the density of the water, to determine the control of gravity forces, or buoyancy, on how the CO_2 plume moves, and the shape of that plume from the injection well through the storage formation; and

- whether any pressure management methods will be allowed during CO_2 injection – the lack of pressure management might significantly reduce the storage efficiency values (Zhou *et al.*, 2008).

Further research into storage efficiency factors would be extremely beneficial to the development of a more robust and generically applicable set of storage efficiency factors.

Overview of current CO_2 resource assessment methodologies

The methodologies used in the following ten CO_2 storage potential assessments were compared:

- United Kingdom CO_2 Storage Appraisal Project (Gammer *et al.*, 2011);
- United States Geological Survey (USGS) (Brennan *et al.*, 2010, Blondes *et al.*, 2013);
- US DOE – The United States 2012 Carbon Utilization and Storage Atlas IV (US DOE NETL, 2012);
- North American Carbon Atlas Partnership (NACAP, 2012);
- Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009);
- Queensland CO_2 Geological Storage Atlas (Bradshaw *et al.*, 2009);
- Saline-aquifer CO_2 Sequestration in Japan (Ogawa *et al.*, 2011);
- Geological Survey of the Netherlands (TNO) – Independent Storage Assessment of Offshore CO_2 Storage Options for Rotterdam (Neele *et al.*, 2011a, b; 2012);
- Federal Institute for Geosciences and Natural Resources (BGR), Germany – Recalculation of Potential Capacities for CO_2 Storage in Deep Aquifers (Knopf *et al.*, 2010); and
- CO_2 Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011).

The comparison is summarised in Annex 1. The methodologies were compared according to a set of criteria, covered in Annex 1 in rows 1-20.

The type of assessment and the area of jurisdiction covered by the resource assessments vary (row 1). All but the Queensland CO_2 Geological Storage Atlas are national-level resource assessments for onshore or offshore territory, or both.

The geographical scale of the assessment ranges in the reviewed studies from the continental to state or province in extent (row 2). They all consider multiple sedimentary basins. The scale of the assessment can be important because more resources are needed to assess larger areas at a given level of detail. Thus the methodology applied to a continental or basin-scale CO_2 storage resource assessment is unlikely to be sufficiently detailed to determine the CO_2 storage capacity of an individual structural trap at the project level.

In all of the studies reviewed, the data are stored in a database and are displayed and queried using a geographic information system (GIS) (row 3).

All the assessments reviewed consider the storage potential of saline water-bearing reservoir rocks (saline aquifers) (row 4). Most (nine out of ten) also consider the storage potential of hydrocarbon fields and four also consider the storage potential of coal seams.

The criteria in rows 5-11 describe the pore volumes that were considered unsuitable for CO_2 storage in the reviewed assessments. None of the assessments reviewed considers the entire pore space in reservoir rocks within the area that they cover, for a range of technical, policy-driven and economic reasons. All the studies exclude:

- pore space at shallow depth, where stored CO_2 is not likely to be in the dense phase;[1] and

[1] The minimum depth requirement is commonly justified on the grounds that (a) the CO_2 should be stored in the dense (supercritical) phase, because storage density would be much greater than in the gas phase, and (b) because it is more likely to leak or interact with other uses of the subsurface (including the present or future use of potable groundwater resources) at shallower depths. The actual minimum depths quoted vary from 762 m to 914 m.

- pore space in inadequately sealed reservoir rocks. This is justified because although such rocks could retain a residual saturation of CO_2, creating a residual saturation of significant mass would cause significant volumes of CO_2 to leak out of the reservoir.

Of the eight studies that include onshore areas, the two US studies (USGS and US DOE) explicitly exclude pore space because of policy requirements to protect underground sources of drinking water. One study (Germany) excludes pore space outside known traps for buoyant fluids (*i.e.* structural and stratigraphic traps). Two studies (United Kingdom and Germany) exclude a fraction of the available pore space by applying minimum storage unit capacity cutoffs. Three studies (United Kingdom, Queensland, and the Netherlands) exclude pore space by applying minimum permeability or injectivity cutoffs. The Norwegian study excludes pore space in the rock volume where petroleum may have migrated, because they expect that petroleum exploration and production will continue on the Norwegian continental shelf for the foreseeable future. The UK study excludes onshore pore space and some remote areas offshore.

The basis of all CO_2 storage resource assessments reviewed in Annex 1 is a reservoir-seal pair (row 12), which is referred to as a Storage Assessment Unit (SAU) in the USGS assessment. An SAU is there defined as a mappable subsurface body of rock into which CO_2 can be injected and trapped (Brennan *et al.*, 2010; Blondes *et al.*, 2013).

Rows 13-17 describe the methods used to estimate the CO_2 storage resource. Row 13 indicates whether the assessments use probabilistic or deterministic methods. Four of the ten assessments use probabilistic methodologies (USGS, Australia, Germany and United Kingdom). Row 14 indicates that all assessments estimated CO_2 density; however, different methods were employed to estimate those density values or ranges.

Eight of the assessments (all except those of the Netherlands and United Kingdom) assume that reservoir pressure rise does not limit CO_2 injection (row 15). These eight methods assess resources that are technically available, as they do not take any economic factors into account in their estimates. In cases where the assumption is that pressure can dissipate through the migration of fluids out of the SAU (*e.g.* due to a good hydraulic connection between the affected pore space and the seabed) or be actively managed through engineering measures, a storage efficiency factor is applied to the pore volume of the assessment unit to derive the volume of CO_2 that could be stored in the SAU. The storage resource is then obtained by multiplying the stored volume of CO_2 by the density of CO_2 at the estimated storage temperature and pressure.

Although the equations used in the various assessments differ in minor respects (Prelicz, Mackie and Otto, 2012; Goodman *et al.*, 2013), the main differences between the assessments, which are based on the assumption that pressure can be managed, are in the storage efficiency factors that are applied. Understanding and calculating storage efficiencies where pressure management is allowed is a subject where further research would be advantageous and would likely lead to further harmonisation.

In cases where the assumption is that pore fluid pressure in the reservoir cannot be managed by withdrawal of reservoir fluids or by migration of reservoir fluids out of the SAU, pressure is considered to be the factor that limits storage capacity. Details are provided in rows 16-17. For example, the Netherlands and UK studies assume that pressure management (by producing reservoir fluids from wells) will not be used. This assumption is made because of the perception that pressure management is costly. Accordingly, they estimate the contingent storage resource, which is a resource estimate limited by economic considerations. The storage potential of a few of the UK units of assessment are estimated on the basis that they are well connected to the seabed and thus pressure build-up in the reservoir will naturally dissipate into the sea over the typical lifetime of an injection project (*i.e.* reservoir pressure build-up will equilibrate during injection).

Row 18 describes the way in which geological uncertainty (sometimes described as geological risk or the level of confidence in the resource in a particular SAU) is treated in each assessment. The treatment of uncertainty varies considerably in these assessment methods.

Rows 19 and 20 describe the method for storage resource assessment in hydrocarbon fields. In the majority of assessments that include the storage resource in hydrocarbon fields, it was assumed that all or part of the hydrocarbon fluids that have been removed from the field could be replaced with CO_2. In one method (the Netherlands) the pressure capacity of the total affected space is used. Row 20 indicates if the method is deterministic or probabilistic.

Significance of the differences between the assessment methodologies

Methodological differences

The main difference between the assessment methodologies is whether there is an underlying assumption that pressure management techniques can be used. In a purely technical sense, reservoir pressure *can* be managed through the production of reservoir fluids from the storage reservoir, though this may occur at significant cost. Therefore methodologies in which it is assumed that pressure can be managed are closer to a technical resource assessment than those in which it is assumed that pressure cannot be managed. The former are constrained by what is technically possible (regardless of current cost), whereas the latter are contingent upon the (potentially prohibitive) cost of pressure management.

Assessments in which it is assumed that pressure can be managed result in larger storage potentials than those in which it is assumed that pressure cannot be managed, because the storage efficiency factors used are typically larger than the pressure-limited storage efficiencies derived in the latter.

Storage efficiency factors

The various assessments by and large attach different meaning to the concept of storage efficiency and, in cases where a similar meaning is assumed, use different methods to estimate storage efficiency. Comparing the storage resource estimates from the various assessments is therefore difficult, and leads to the wide range of values mentioned earlier in this document. Therefore, a consistent definition and method for estimating storage efficiency is needed.

Policy constraints

Policy constraints, applied in all the methodologies, can significantly reduce the pore volume considered in the assessment compared to the total pore volume in the jurisdiction. This is not necessarily a disadvantage for policy makers, because the net result is a realistic assessment of the available resource in each jurisdiction studied. The policy constraints applied in each study are shown in Annex 1 in row 1, "Type of assessment and area covered", and rows 5-11 "Pore volumes considered unsuitable for CO_2 storage".

Grouping of CO_2 storage assessment methodologies

Most of the existing assessment methodologies produce estimates of CO_2 storage resources that fall naturally into one of four groups:

1. technically accessible storage resources;
2. the storage resource in structural or stratigraphic traps;
3. the contingent storage resource assuming pressure management wells will not be used; or
4. the contingent storage resource in subsurface volumes where CO_2 storage will not affect hydrocarbon production or exploration.

Individual assessments within any one of these groups may vary slightly, either due to policy constraints or the methodologies employed. Nonetheless, from a policy maker's perspective, their results are broadly comparable. Table 1 shows how the resources from each of the reviewed methodologies fit into these various categories.

Table 1 • Categorisation of reviewed storage resource assessment methodologies

Name of assessment	Technically accessible storage resource assessment	The resource in structural or stratigraphic traps	The resource assuming pressure management wells will not be used	The resource in subsurface volumes where CO_2 storage will not affect hydrocarbon production or exploration
UK CO_2 Storage Appraisal Project		•	•	
USGS	•	•		
US DOE Carbon Utilization and Storage Atlas	•			
North American Carbon Atlas Partnership	•			
Australian Carbon Storage Taskforce	•			
Queensland CO_2 Geological Storage Atlas	•			
Japan – Saline-Aquifer CO_2 Sequestration	•			
TNO – Offshore CO_2 Storage Options for Rotterdam			•	
BGR – CO_2 Storage Potential in Deep Aquifers		•		
Norwegian CO_2 Storage Atlas				•

Guidelines for CO_2 storage assessment methods

A key goal of international collaboration on storage assessment methods is to create a uniform and coherent process that would facilitate the comparison of storage assessment results between countries. Given that subsurface storage space is finite, and so represents a scarce natural resource, this initiative raises issues that are similar to the ones encountered with the assessment and categorisation of subsurface hydrocarbon resources (IEA, 2013). Since society and policy makers can make choices that limit (or expand) the amount of storage resource that will be accessed, the fundamental question that must first be answered is: how much storage resource is there in total? The answer to this question is the technically available storage resource (TASR) in a country. TASR comprises the pore space that can be reasonably expected to retain CO_2 over a long period of time without adverse environmental impact; in this sense it represents an "upper limit". Since the TASR is not constrained by economic or policy considerations, it can be used to gain a better understanding of the trade-offs that are often made when developing policies to control access to resources. Furthermore, the TASR allows comparison of the endowments of countries with storage space.

For these reasons, the initial assessment of a country's endowment with storage space should aim to quantify its TASR. In line with this objective, this section discusses first the guidance for assessing TASR provided by the USGS. After an initial assessment of the TASR using this approach, a further, more focused assessment can be performed to reflect country-specific policy requirements. In this document, examples of such focused assessments are illustrated by the German (BGR) and the Dutch (TNO) methodologies. Further detail on these USGS, BGR and TNO methodologies can be found in Annex 2.

Conducting TASR assessments

A TASR assessment provides an evaluation of all the accessible storage resource, regardless of non-technical (*e.g.* economic, political) constraints. The guidance for assessing TASR provided by the USGS (Brennan *et al.* 2010, Blondes *et al.* 2013) represents a comprehensive and versatile assessment framework that could be applied globally. It is based on four steps that can be applied to all assessments.

Step 1 – Subdivision into geological units of assessment

The basis of geologic CO_2 storage resource assessments is characterisation of the subsurface. All the studies considered here use reservoir and seal pairs as their units of assessment. In general it is advantageous to break down the assessment into 'storage assessment units' (SAUs) each of which comprises a mappable subsurface body of rock into which CO_2 can be injected and trapped, and which is overlain by a regional sealing formation (Brennan *et al.*, 2010). This regional seal formation is needed to retard the upward migration of a mobile CO_2 plume, and ensures that buoyant and residual trapping can be maximised in the storage formation. Therefore, SAUs do not include either those parts of storage formations that are technically unsuitable or inaccessible for the injection or trapping of CO_2, and might not include technically suitable and accessible portions of the storage formations due to policy requirements. In some cases an SAU might consist of a series of stacked geological reservoir formations (or parts thereof) and their single overlying seal. The advantages of breaking down the assessment into SAUs are:

- each SAU is spatially limited (and thus can be included in a GIS);
- detailed assessments and reports can be compiled for individual SAUs; and

- SAUs are treated individually in a potential aggregation step.

Step 2 – Estimation of the total volume of accessible pore space in each SAU using probabilistic methods

The total volume of accessible pore space in each SAU is needed so that a range of storage efficiencies can be applied. The recommendation of the IEA workshops is that this total volume of pore space in each SAU is estimated in all new assessments.

Because geologic properties are inherently heterogeneous and data are typically sparse and have associated errors, probabilistic methods are best at considering these limitations and capturing the uncertainty in the assessment results. Therefore, ranges for all input estimates should be used rather than fixed values. These ranges, and the extent of the ranges, provide the data distribution, with some assumptions made about the shape of that data distribution (normal, logarithmic, Beta, PERT, etc.) (Olea, 2011).

Step 3 – Use consistent storage efficiency ranges

To generate repeatable CO_2 storage assessment results, a consistent method to estimate storage efficiency ranges is recommended. The USGS methodology splits storage estimates into buoyant and residual trapping (Brennan *et al.*, 2010), and documents unique storage efficiencies for both types of storage (Blondes *et al.*, 2013).

For calculating residual storage efficiency, the USGS method uses the approach suggested by MacMinn, Szulczewski and Juanes (2010), which quantifies the residual storage efficiency of a sloping reservoir (interface of storage formation and sealing formation is not horizontal) using an equation that employs the capillary trapping number divided by an approximation involving the mobility factor. The capillary trapping number explains how much CO_2 will be trapped and the mobility factor describes how much of the pore space the CO_2 will enter. A brief description of the equations is given in Annex 3; they are explained in much further detail in Blondes *et al.* (2013), with explanations as to how to determine the storage efficiency of any SAU.

Within geologic closures, where CO_2 will be kept in place by relatively impermeable rocks, the storage efficiencies can be much higher. In the case of CO_2 within a closure, the primary trapping type is buoyant trapping. Though some residual trapping will occur within the closure, residually trapped CO_2 is a minor constituent. Buoyant storage efficiency is controlled primarily by 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. For example, the USGS has assumed a buoyant storage efficiency of one minus the irreducible water fraction, less an estimate of the mobility factor, resulting in buoyant storage efficiency values of 20%, 30%, and 40% (minimum, most likely, maximum) (Blondes *et al.*, 2013). These buoyant storage efficiency values, like the residual efficiency estimation method above, assume that pressure management will be allowed.

Step 4 – Convert the volume of CO_2 to a mass of CO_2

The TASR is defined as the mass of CO_2 that can be stored in the pore volume of the SAU, while taking into account present-day geologic knowledge and engineering practice and experience (Blondes *et al.*, 2013; Brennan *et al.*, 2010). Therefore, the unit volume of CO_2 storage, as determined by steps 2 and 3, must be converted to a unit mass by estimating the density of CO_2 within the SAU. The CO_2 density can be determined for the thermal and pressure ranges present across the SAU on the basis of a suitable equation of state (Blondes *et al.*, 2013).

Methods to estimate subsets of the TASR

In many jurisdictions there will be specific constraints on the amount of the TASR that will be available for CO_2 storage. For example, in the United States, water that has less than 10 000 milligrams per litre (mg/L) of TDS is protected as a potential source of underground drinking water; no fluid injection is allowed in rocks that contain low salinity groundwater (US EPA, 2009; 2010). Therefore, the USGS methodology excludes capacity in parts of an SAU containing water with a salinity equal to or less than 10 000 mg/L TDS.

Depending on the policy constraints of a given jurisdiction, it is possible that application of other constraints would provide policy makers with storage resource assessment values that assess the contingent fraction of the TASR available for storage. One such constraint might be on the type of trapping allowed; if only buoyant trapping is acceptable, then a methodology that focuses only on buoyant trapping would be expedient. An example of only assessing buoyant trapping is the methodology developed by BGR to assess the storage potential in Germany (Knopf *et al.*, 2010). Another common constraint is excluding the application of pressure management during storage, which limits injection of CO_2 beyond pressure maxima. One such method for pressure-limited storage assessment is the methodology used by TNO for assessing the storage potential in the Netherlands (Neele *et al.*, 2011a). Both methodologies are characterised below.

Recommended steps for buoyant-limited storage assessment

Follow all the steps for TASR assessments, and then follow these subsequent steps:

Step 5 - Identify closure type

The types of closures need to be defined, *e.g.* as stratigraphic, structural, or a combination of both. Stratigraphic traps involve the way in which the rocks were initially deposited, whereas structural traps are the result of folding or faulting of the rocks post-depositionally. Stratigraphic traps will not show up on structural maps, and are more difficult to find and predict in areas where undiscovered traps might occur. If possible, spill points should be identified or estimated. Spill points are the locations on the margins of a trap where a buoyant fluid will migrate out of the trap; spill point depths are the maximum fill depths for a trap.

Step 6 - Identify geologic models for existing traps

Geologic closures are caused by a variety of factors, involving stratigraphic relationships between rock deposits, burial history, structural history and diagenetic history. These factors will lead to a set of closures that can be described with similar geologic models. These models can be used to consolidate petrophysical data into groups, which can then provide ranges for estimating distributions of area, thickness, porosity and permeability for that specific closure type. These distributions can then be used as inputs into probabilistic assessment methodologies.

Step 7 - Use geologic models as analogues

The geologic models created in step 6 can then be used as analogues for assessing formations or basins with little to no data. These analogues can help to identify promising storage potential in formations or basins that do not have hydrocarbon production.

Recommended steps for pressure-limited CO_2 storage assessments

If no pressure management is allowed, follow the same steps as in the TASR methodology, and then follow these subsequent steps:

Step 5– Determine present pore pressure

The present pressure of the injection site or formation can be determined from well measurements or from modelling.

Step 6 – Identify injection rate to stay below maximum allowable pressure increase

The requirement to limit the increase in pressure above its present value to remain below a specified maximum allowable value imposes constraints on the CO_2 injection rate. The injection rate controls how quickly CO_2 enters the formation from the well, how the plume migrates in the formation, and how the pressure front propagates.

Step 7 – Identify extent and depth of the pressure front

The extent and depth of the pressure front should be identified based on the injection rate, to keep within jurisdictional limits. Through engineering practices, the CO_2 plume migration is typically expected to stay within regions of the storage formations where the CO_2 will remain in the supercritical state. However, there is no similar limitation on the propagation limit for the pressure front. The controls on where the pressure front limits are will be up to the jurisdiction. But the injection rate and the geologic model for the storage formation will help determine how far the pressure front will be in front of the CO_2 plume.

Whichever assessment methodology is chosen, it is important that all constraints are explicitly stated in order to facilitate comparisons of assessment between jurisdictions that are subject to contrasting restrictions.

Looking Ahead

This report is the first step of an international collaborative effort to compare national storage assessments, and ultimately aggregate them into a worldwide storage estimate. It highlights several challenges that need to be met.

On a technical level, there is a need to identify a uniform method for calculating storage efficiency ranges and how that method might be used for future assessments. To stimulate further discussion on this issue the USGS sponsored a CO_2 Storage Efficiency Workshop in July 2012. Its results could form a basis for follow-up work.

There is also a need to enhance the co-operation between organisations that have attempted or completed CO_2 storage resource assessments and those that are looking to begin assessments. This co-operation could be fostered via agreements between national organisations or through workshops or training by those with experience in assessing CO_2 storage resource. The IEA may continue to facilitate this co-operation. However, in order to have the best, up-to-date estimate of global CO_2 storage resources, and the geographical distribution of those resources, some sort of formalised international co-operation would be desirable.

Conclusions

This report reflects the consensus reached at two workshops organised by the IEA in 2011 and attended by the geological surveys of Australia, Canada, Germany, the Netherlands, the United Kingdom, and the United States, together with the IEA. At these workshops, the need for a common procedure was identified to allow for a transparent and robust assessment of geologic CO_2 storage resource, throughout the world, across geologic settings, regardless of the amount of available geologic data.

Participants agreed that the initial objective of any storage assessment should be to identify the total TASR available for a country. Given that estimates of TASR are essentially determined by geological considerations, and are not constrained by country-specific policies regarding the use of the subsurface, TASR estimates for different countries or jurisdictions can then be easily compared and aggregated. Therefore, TASR estimates from jurisdictions worldwide, following the approaches and procedures outlined in this report, would be of relevance for international policy making in relation to CCS.

Also, to honour the political or economic constraints and regulations of jurisdictions, it would be helpful to have estimates of contingent resources. Contingent resources, unlike conventional resources, take these constraints into account. An aggregation of the contingent resources would also be helpful to policy makers as an worldwide estimate of the total storage resource that jurisdictions will allow to be used. This goal can be reached using the approach presented in this report as well.

The general consensus of the workshop participants was the need for uniformity in the methods used to estimate storage efficiency values. The storage efficiency estimates are the major controlling and uncertain variable in determining the storage resources (Brennan *et al.*, 2010; Blondes *et al.*, 2013). The methods described in this report can be a starting point for a uniform storage efficiency estimation method.

The workshop participants agreed that any storage assessment method should seek to make estimates of the storage resource that consider both the variability inherent in the subsurface and uncertainty that results from our limited knowledge of the subsurface.

Annex 1: Comparison of CO_2 storage capacity and resource assessment methodologies

Table 2 • Comparison of CO_2 storage capacity and resource assessment methodologies for the United Kingdom, the United States, North America and Australia

	UK CO_2 Storage Appraisal Project (Gammer *et al.*, 2011)	**USGS (Brennan *et al.* 2010, Blondes *et al.*, 2013)**	**US DOE The United States 2012 Carbon Utilization and Storage Atlas (US DOE NETL, 2012)**	**North American Carbon Atlas Partnership (NACAP, 2012)**	**Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009)**
1. Type of assessment and area covered	Offshore resource estimate for the United Kingdom	National onshore resource estimate for the United States	High-level inventory of onshore and offshore capacity in the United States and Canada	High-level inventory of onshore and offshore capacity in Canada, the United States, and Mexico	Top-down assessment of CO_2 storage resources in offshore and onshore Australia.
2. Scale of the assessment	National	National	Continental	Continental	National
3. How is underpinning data held and queried?	Database and GIS	Database and GIS	Database and GIS	Database and GIS	Data utilised derived from national and state petroleum well databases. No GIS data base included with the report
4. Classes of storage reservoirs assessed	Saline aquifers, hydrocarbon fields	Saline aquifers, hydrocarbon fields	Saline aquifers, hydrocarbon fields, coal seams	Saline aquifers, hydrocarbon fields, coal seams	Saline aquifers, hydrocarbon fields
Pore volumes considered unsuitable for CO_2 storage					
5. Pore volumes at shallow depths*	Yes (cutoff 800 m)	Yes (cutoff 914 m)	Yes (cutoff 762 m)	Yes (cutoff 800 m)	Yes (cutoff 800m, implicit in good reservoir being between 800 m and 2 000 m)
6. Pore space in inadequately sealed reservoir rocks	Yes	Yes	Yes	Yes. Sealing unit is explicit criterion for storage suitability	Storage region defined by area of seal above reservoir
7. Excludes pore volumes containing water with potable water**	Not explicitly, but not relevant to an offshore assessment	Yes	Yes	Yes	Not considered in assessing total volumes
8. Pore volumes not in mapped buoyancy traps	No	No	No	No. Structural/ stratigraphic and residual gas trapping are all considered	Based on saline aquifer storage not buoyancy trapping
9. Minimum storage unit size cutoff	Yes	No	No	1 $MtCO_2$	No
10. Minimum reservoir quality (porosity-permeability) cutoff	Yes	No	No	No	Not defined, P10 - P90 distribution for each basin picked on permeability depth-plots

	UK CO_2 Storage Appraisal Project (Gammer *et al.*, 2011)	**USGS (Brennan *et al.* 2010, Blondes *et al.*, 2013)**	**US DOE The United States 2012 Carbon Utilization and Storage Atlas (US DOE NETL, 2012)**	**North American Carbon Atlas Partnership (NACAP, 2012)**	**Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009)**
11. Pore volumes within an area of potential petroleum migration	No	No	No	No	No
12. Unit(s) of assessment - definition	Storage unit - a sealed saline water-bearing part of a reservoir formation that is suitable for CO_2 storage, Daughter unit - hydrocarbon field or mapped saline water-bearing trap within a storage unit	Storage assessment unit - a mappable subsurface body of rock that consists of a porous flow storage unit into which CO_2 can be injected and trapped and a bounding regional sealing formation	Saline formations, hydrocarbon fields, unminable coal beds	Saline formation, hydrocarbon field, unminable coal	Area of storage region
Methods used to estimate CO_2 storage capacity in saline water-bearing reservoir rocks					
13. Probabilistic or deterministic estimate	Probabilistic	Probabilistic	Deterministic	Deterministic	Probabilistic
14. CO_2 density calculation for storage units	Yes	Yes, calculated for each basin based on pressure/temperature curves (Blondes *et al.*, 2013)	Yes	Yes	Yes, triangular distribution 0.5-0.6-0.7 tonne/m^3
15. Storage efficiency method (assumes capacity of some or all storage units not pressure-limited)	Yes - for the minority of storage units with a good connection to other reservoirs or the seabed (so-called open units)	Yes (Blondes *et al.*, 2013)	Yes	Yes, *E* estimates of 1%-4% (2.4% average) based on Monte Carlo simulations by US DOE (2007)	Yes - uniform storage efficiency factor of 4% used
16. Pressure capacity method (assumes capacity of some or all aquifer storage assessment units pressure-limited)	Yes - for the majority of storage units, which are not thought to have a good connection to other reservoirs or the seabed (so-called closed units)	No	No	Pressure must be less than some fraction of fracture pressure	Not considered in assessing total volumes
17. Treatment of pressure management	Estimates CO_2 storage resource that is technically accessible without recourse to pressure management or chase water injection	Estimates technically accessible CO_2 storage resource (TASR). Underlying assumption that pressure can be managed	Unencumbered CO_2 storage capacities calculated on sub-regional (Partnership) basis. Underlying assumption that pressure can be managed	Underlying assumption that pressure can be managed. Qualitative assessment of sedimentary basins; quantitative assessment of best potential basins subject to data availability. Unencumbered CO_2 storage capacities	Qualitative assessment of sedimentary basins. Quantitative assessment of basins considered highly suitable or suitable

	UK CO_2 Storage Appraisal Project (Gammer *et al.*, 2011)	**USGS (Brennan *et al.* 2010, Blondes *et al.*, 2013)**	**US DOE The United States 2012 Carbon Utilization and Storage Atlas (US DOE NETL, 2012)**	**North American Carbon Atlas Partnership (NACAP, 2012)**	**Australian Carbon Storage Taskforce (Carbon Storage Taskforce, 2009)**
				calculated on regional basis. Confidence in capacity estimates to be specified using confidence matrix (US DOE, 2007)	
18. Treatment of geological uncertainty	Risk data collected for each assessment unit. Not convolved with resource estimate. Chance of success and economics of each storage unit assessed	The probabilistic assessment of the potential storage resource in each assessment unit takes account of geological uncertainty	Produces a high and low estimate of storage resource, mainly based on a high and low storage efficiency estimate	Produces a high and low estimate of storage resource, mainly based on a high and low storage efficiency estimate	The probabilistic assessment of the potential storage resource in each assessment unit takes account of geological uncertainty
19. Assessment method for storage resource in hydrocarbon fields	Calculation based on fluid replacement. Mass of CO_2 that could be stored = mass that occupies the reservoir volume of net fluids produced at initial pressure and temperature of hydrocarbon reservoir	Hydrocarbon fields treated as potential buoyancy traps for CO_2. Minimum size of approximately 50 000-60 000 tonnes storage resource, based on a minimum reservoir size of 0.5 million boe.	Calculation based on fluid replacement. Mass of CO_2 that could be stored = mass that occupies the reservoir volume of the produced fluids at initial formation pressure or a pressure considered a maximum CO_2 storage pressure~~.~~	Calculation based on fluid replacement. Mass of CO_2 that could be stored = mass that occupies the reservoir volume of the produced fluids at initial formation pressure or a pressure considered a maximum CO_2 storage pressure~~.~~	Estimated by the Petroleum and Greenhouse Gas Advice Group of Geoscience Australia. Methodology not explicitly stated. Based on high-level reserve estimates~~.~~
20. Probabilistic or deterministic estimate of hydrocarbon field storage potential	Probabilistic	Probabilistic	Deterministic	Deterministic	Deterministic

Notes: boe = barrel of oil equivalent; m = metre; m^3 = cubic metre; $MtCO_2$ = million tonnes of carbon dioxide.

* Where the CO_2 is not likely to be in dense phase.

** Water with <10 000 ppm TDS.

Table 3 • Comparison of CO_2 storage capacity and resource assessment methodologies for Queensland, Japan, the Netherlands, Germany and Norway

	Queensland CO_2 Geological Storage Atlas (Bradshaw *et al.* 2009)	**Japan Saline-Aquifer CO_2 Sequestration in Japan – methodology of storage capacity assessment (Ogawa *et al.* 2011)**	**TNO Independent Storage Assessment of Offshore CO_2 Storage Options for Rotterdam (Neele *et al.*, 2011a, 2011b)**	**BGR Recalculation of Potential Capacities for CO_2 Storage in Deep Aquifers (Knopf *et al.*, 2010)**	**Norway CO_2 Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011)**
1. Type of assessment and area covered	Onshore resource assessment for Queensland (Australia)	Onshore and offshore resource assessment for Japan	Offshore resource assessment for the Netherlands	Onshore and offshore resource assessment for Germany	Offshore resource assessment for Norway
2. Scale of the assessment	State	National	National	National	National
3. How is underpinning data held and queried?	Database and GIS	Data utilised derived from national petroleum well databases. No GIS data base included with the report	Database and GIS	GIS / spreadsheets	Database and GIS
4. Classes of storage reservoirs assessed	Saline aquifers - hydrocarbon fields and coal seams as regional summaries	Saline aquifers, hydrocarbon fields, coal seams	Saline aquifers, hydrocarbon fields	Saline aquifers, hydrocarbon fields (mainly natural gas, some oil fields)	Saline aquifers, hydrocarbon fields
Pore volumes considered unsuitable for CO_2 storage					
5. Pore volumes at shallow depths*	Yes (cutoff 800 m)	Yes (cutoff 800 m)	Yes, CO_2 must be supercritical (800-1 000 m recommended)	Yes (cutoff 800 m)	No
6. Pore space in inadequately sealed reservoir rocks	Storage region defined by area of seal above reservoir	Yes, implied in description of suitability assessment	Seal required where buoyant plume	Yes	Yes
7. Excludes pore volumes containing water with potable water**	Not considered in assessing total volumes	Not considered in assessing total volumes	Not considered in assessing total volumes	Not explicitly; sweet water occurs usually at depths < 400 m below surface	Not explicitly but not relevant to an offshore assessment
8. Pore volumes not in mapped buoyancy traps	Based on "migration assisted storage" not buoyancy traps	No	No	Yes	No
9. Minimum storage unit size cutoff	No	Not stated	No	Various, depending on context of regional assessment	No
10. Minimum reservoir quality (porosity-permeability) cutoff	>5mD, >10%	Not stated	Yes (via injectivity criterion)	No	No
11. Pore volumes within an area of potential petroleum migration	No	No	No	No	Yes

	Queensland CO_2 Geological Storage Atlas (Bradshaw *et al.* 2009)	**Japan Saline-Aquifer CO_2 Sequestration in Japan – methodology of storage capacity assessment (Ogawa *et al.* 2011)**	**TNO Independent Storage Assessment of Offshore CO_2 Storage Options for Rotterdam (Neele *et al.*, 2011a, 2011b)**	**BGR Recalculation of Potential Capacities for CO_2 Storage in Deep Aquifers (Knopf *et al.*, 2010)**	**Norway CO_2 Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011)**
12. Unit(s) of assessment - definition	Potential storage area (maximum known extent of reservoir-seal intervals within a basin that are evaluated as having potential for geological storage)	Sealed saline formations in geographical areas	Affected space (total space affected by storage in a reservoir including the resulting pressure footprint)	Reservoir rock units (*e.g.* Middle Bunter in the North German Basin)	Geological formations (with reservoir potential and overlying seals)
Methods used to estimate CO_2 storage capacity in saline water-bearing reservoir rocks					
13. Probabilistic or deterministic estimate	Deterministic	Deterministic	Deterministic	Probabilistic	Deterministic
14. CO_2 density calculation for storage units	Yes, calculated for each basin based on pressure/temperature curves	Yes (via CO_2 volume factor)	Yes	Yes but in some regional studies only	Yes
15. Storage efficiency method (assumes capacity of some or all storage units not pressure-limited)	Storage efficiency based on reservoir thickness vs. plume thickness. High for thin reservoirs, low for thick, determined on a reservoir-by-reservoir basis using precalculated RGS Storage Efficiency curves for various plume thicknesses	Yes (described as storage factor)	No	Yes (distribution of storage efficiency factor between 5% and 20% for Monte Carlo simulations)	Yes
16. Pressure capacity method (assumes capacity of some or all aquifer storage assessment units pressure-limited)	Discussed, but not explicitly factored into calculations	Not considered in assessing total volumes	Yes	No	No
17. Treatment of pressure management	Technical resource estimate. Evaluates technical suitability of basins for storage. Risk of basin suitability included via simple risk matrix and score. Reliability of estimate for each storage area derived from a data quality assessment	Technical resource estimate. Reliability of estimate for each storage area derived from a data quality assessment process	Resource assumed to be limited by pore fluid pressure build-up fluid conductivity in the total affected space and injectivity. Reliability of data limits reliability of estimate so propose system for rating data quality	No	No

	Queensland CO_2 Geological Storage Atlas (Bradshaw *et al.* 2009)	Japan Saline-Aquifer CO_2 Sequestration in Japan – methodology of storage capacity assessment (Ogawa *et al.* 2011)	TNO Independent Storage Assessment of Offshore CO_2 Storage Options for Rotterdam (Neele *et al.*, 2011a, 2011b)	BGR Recalculation of Potential Capacities for CO_2 Storage in Deep Aquifers (Knopf *et al.*, 2010)	Norway CO_2 Storage Atlas: Norwegian Sea (Norwegian Petroleum Directorate, 2011)
18. Treatment of geological uncertainty	Ranking of storage options partially based on quality of available data	Primarily accounted for with the storage efficiency estimate	Yes, capacity assessment must include the uncertainties in geological properties	The probabilistic assessment of each structure takes account of geological uncertainty	Ranking of storage options partially based on quality of available data
19. Assessment method for storage resource in hydrocarbon fields	Estimated by calculating the maximum theoretical CO_2 replacement volume for all hydrocarbon fields using reserves estimates and production data	Tanaka *et al.* (1995) included saline aquifers in hydrocarbon fields, but only saline aquifers in the vicinity of CO_2 emission sources are considered in the current report	Pressure capacity of total affected space	Production history approach; assuming, that the produced gas volumes can be replaced by the equivalent volume of CO_2 (1:1)	Only within abandoned fields, but no fields are abandoned within the Norwegian North Sea. Estimated which fields might cease production by 2050 and determined CO_2 storage within those abandoned fields via volumetric calculation
20. Probabilistic or deterministic estimate of hydrocarbon field storage potential	Deterministic	Deterministic	Deterministic	Probabilistic	Deterministic

Notes: m = metre; mD = millidarcy.

* Where the CO_2 is not likely to be in dense phase.

** Water with <10 000 ppm TDS.

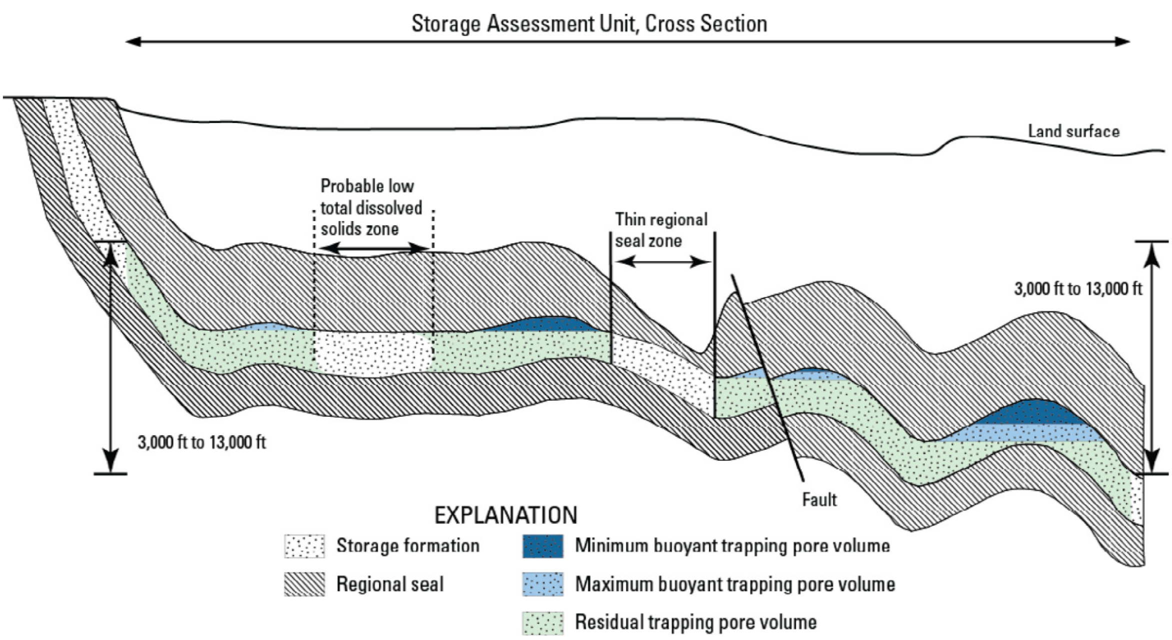
Annex 2: Best practice examples of methodologies

TASR assessment methodology example (USGS methodology)

The methodology used by the USGS (Brennan *et al.*, 2010; Blondes *et al.*, 2013) is described below as an example of best practice in TASR assessment. The initial step is to identify potential SAUs, which must have regional seals that have the potential to retain CO_2 within the underlying storage formation (Figure 1). The seal should have several metres, typically tens of metres, of very low permeability (microdarcy) rock that will stop the upward flow of CO_2. When such an acceptable regional seal formation has been documented for an SAU, and the boundary of the SAU is agreed upon by a review panel, then the geologic data is then vetted to assess the storage resource.

Figure 1 presents a schematic cross section through an SAU. The hatched pattern represents the regional seal, whereas the stippled pattern represents the storage formation. The colours within the storage formation illustrate the relation between buoyant and residual trapping styles (Blondes *et al.*, 2013, modified from Brennan *et al.*, 2010). SAU depth limits of 914 m and 3 962 m (3 000 ft and 13 000 ft), in accordance with Brennan *et al.* (2010), are included.

Figure 1 • A schematic cross section through an SAU



The data are put into an input form (Figure 2), which collects the most critical data for assessing the TASR within the SAU. Critical geologic assessment data include the area and the net porous thickness of the storage formation, porosity, depth from land surface to storage formation top, and permeability. The area, net porous thickness, and porosity are used to estimate the total pore volume of the SAU. The depth from surface is used to estimate the range of potential density and the storage efficiency values for each SAU. The storage efficiency is estimated using the relative viscosities of the CO_2 and groundwater, which are calculated using temperature and pressure data from the formation as well as the salinity of the groundwater, or using analogue data from a similar basin. The salinity of the groundwater can affect its viscosity, which can affect the storage efficiency estimates. The storage efficiency and density, which allows for volume to be converted to mass, can be plotted versus depth to estimate the overall range of the values, which are then entered into the probabilistic assessment.

Figure 2 • USGS CO_2 storage assessment input form

STORAGE ASSESSMENT UNIT INPUT DATA FORM

Identification Information

Assessment geologist:	____________	Date:	______
Assessment region:	____________		
Province:	____________	Number:	______
Basin:	____________	Number:	______
Storage Assessment Unit (SAU):		Number:	______
	____________		
SAU relationship to NOGA AU:			
	____________		
Notes from assessor:			
	____________		

Characteristics of the Storage Assessment Unit

Lines 1-9 concern data for the SAU at depths of (check one):				3,000-13,000 ft		______
				> 13,000 ft		______
(1) SAU depth from surface (ft):	minimum:	______	most likely:	______	maximum:	______
(2) Area of the SAU (acres):	minimum:	______	most likely:	______	maximum:	______
(3) Mean total SAU thickness (ft):	minimum:	______	most likely:	______	maximum:	______

(4) SAU water quality (check one):

Most of the water in the SAU is saline (greater than 10,000 mg/L TDS).	______
Water in this SAU is both saline and fresh.	______
Most of the water in the SAU is fresh (less than 10,000 mg/L TDS).	______

(5) Area fraction available for storage (generally, the area where SAU pore water has more than 10,000 mg/L TDS):

	minimum:	______	most likely:	______	maximum:	______
(6) Mean thickness net porous interval (ft):	minimum:	______	most likely:	______	maximum:	______
(7) Mean porosity net porous interval (fraction):	minimum:	______	most likely:	______	maximum:	______

Buoyant Trapping Probabilistic Calculation Inputs

(8) Buoyant trapping pore volume (MMbbl):

	minimum:	______	most likely:	______	maximum:	______

Residual Trapping Probabilistic Calculation Inputs

(9) Permeability of the net porous interval (mD):	minimum:	______	most likely:	______	maximum:	______

Source: Blondes *et al.*, 2013; modified from Brennan *et al.*, 2010.

The permeability is a proxy to estimate injectivity, which is an estimate of how easily, at some given flow rate, CO_2 will enter the pore space (Brennan *et al.*, 2010). The USGS methodology assigns three injectivity classes, comprising class 1, which is the percentage of the rock that has permeability greater than 1 000 millidarcy (mD); class 2, which is the percentage between 1 000 mD and 1 mD; and class 3, which is the percentage less than 1 mD. The different injectivity classes have different storage efficiencies. The storage efficiencies for the three injectivity classes for each SAU assessed were determined using the method described in Blondes *et al.* (2013).

The USGS uses a minimum depth of about 914 m for CO_2 storage, as below that depth CO_2 will be a high-density, supercritical fluid (Figure 1), and thus, in the USGS methodology, the area of an SAU is the area of the storage formation where the top is deeper than 914 m. This specific minimum depth is a USGS requirement; the participants of the IEA workshop recommended no specific depth requirement.

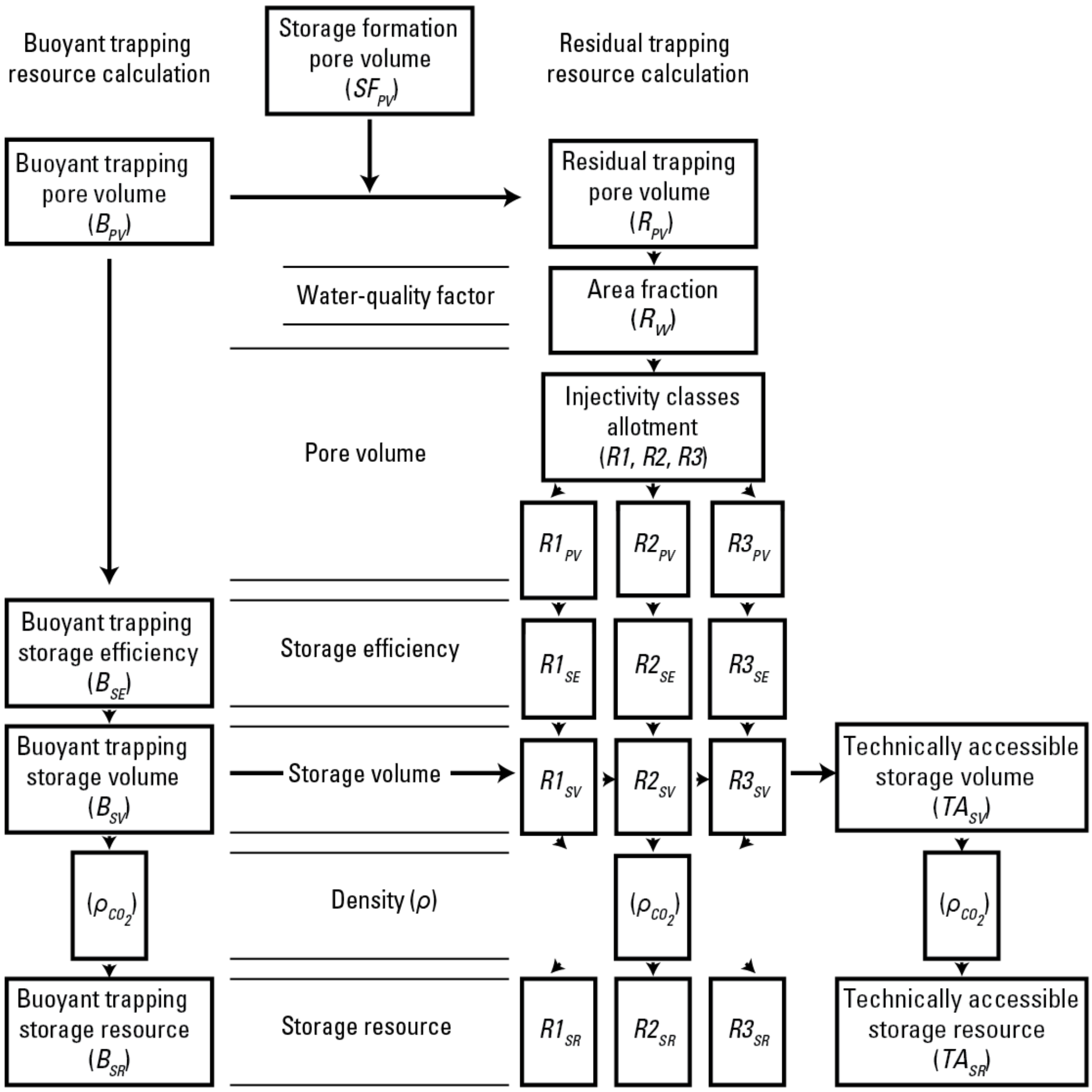
The tops of formations as identified in well logs are plotted in a GIS, which allows the assessment geologist to map where the storage formation top is deeper than this minimum depth. The area is then calculated using the GIS, and is given a basic uncertainty range, because mapping the outline of the SAU has uncertainty depending on the sparseness of the data. The USGS methodology does not require the storage formation to have a lateral seal; instead there is an assumption that the injection of CO_2 could be engineered to become neutrally buoyant at that depth.

In addition to the above inputs, the methodology also requires an estimate of the range of the potential for buoyant trapping of CO_2 within the SAU. The USGS methodology requires that single buoyant traps used to estimate these parameters be greater than 500 000 boe. This value is equivalent to 50 000 to 60 000 tonnes of CO_2, depending on the density of the CO_2 within the trap. To estimate the pore space available for buoyant trapping, the assessment geologists typically use the volume of hydrocarbons produced from the SAU, corrected by formation volume factors (FVF), which converts the surface hydrocarbon volumes to the original subsurface volume, as a minimum value. The most likely buoyant pore space value is typically an estimate based on the volume of the produced hydrocarbons plus the volume of undiscovered hydrocarbons, estimated by previous USGS oil and gas assessments. The maximum buoyant storage volume is at the discretion of the assessment geologist in agreement with the review panel; this maximum buoyant value estimate is typically based on either mapping the large closures within the storage formation from structural contour maps, or geologic models of the trap geometry and potential for more similar traps within the formation.

These values are all used to create distribution shapes for a Monte Carlo model that runs thousands of iterations. During each iteration of the Monte Carlo run (Figure 3), the total pore volume and the total buoyant pore volume are calculated. The buoyant volume is subtracted from the total pore volume, and the difference becomes the residual pore volume. The residual pore volume is then apportioned into the three injectivity classes described above – class 1 (R1), class 2 (R2), and class 3 (R3). Respective storage efficiencies are then applied to the volume of each injectivity class, and to the buoyant volume, to determine a CO_2 storage volume. These CO_2 volumes are then multiplied by the basin-average density value to determine the storage resource as a mass of CO_2. The governing equations are given in Brennan *et al.* (2010) and Blondes *et al.* (2013).

In the United States, most sedimentary CO_2 storage formations are located within mature hydrocarbon-producing basins. These basins tend to have a substantial amount of the subsurface data needed for assessments. Where there are sparse data, geologic analogues may be used, either from similar formations within the basin, or in nearby basins, or from formations that have similar depositional and burial histories in basins worldwide. The prudent use of analogues allows the assessment geologist to estimate input values. However, assessments based solely on analogues, without any data from the storage formation, inherently have greater uncertainty.

Figure 3 • Flow diagram of USGS CO_2 TASR assessment methodology



Source: Blondes *et al.*, 2013; modified from Brennan *et al.*, 2010.

Buoyant-limited assessment methodology example (BGR methodology)

The methodology used by the BGR (Knopf *et al.*, 2010) follows a static, volumetric approach for the estimation of CO_2 storage capacities in known structural or stratigraphic traps. The approach considers neither potential interactions of pressure fields between storage sites or any time-dependent reservoir processes and injection scenarios. The capacity assessments are solely based on geological and/or physical parameters. Further technical, economic or social parameters are not accounted for. The uncertainties of geologic input parameters are accounted for by performing Monte Carlo simulations.

The first step in this approach is a review of the geologic conditions in the investigated area to identify potentially suitable storage and seal rock units. This includes the screening for existing data *(e.g.* wells and seismic). The following step is to analyse distribution and contour maps of the storage and seal rock units. For each reservoir rock unit, areas are outlined that fulfil a predefined minimum depth of 800 m at the top of the storage rock unit to ensure that the CO_2 is a supercritical fluid.[2] The extent of a potentially suitable storage and seal rock unit pair below 800 m is outlined within a GIS.

Potential storage structures (traps) such as anticlines are identified and mapped within this outlined area based on the interpretation of contour maps. The area of each structure is defined by the deepest structural contour (spill-point). The spill-point is defined as the location at the base of a trap where the buoyant CO_2 will escape from, or "spill out" of, the trap and upwards to more shallow portions of the storage unit. Further specific parameters applied for characterisation of potential storage structures for CO_2 are:

- areal extent of the structure;
- depth range between crest of structure and spill-point;
- net thickness of reservoir rocks; and
- porosity of the reservoir rock.

Based on the findings, the CO_2 storage capacity of each trap is estimated by calculating the average pore volume of each trap, and multiplying that value by a site-specific storage efficiency and the density values.

Considering the nature of regional geological assessments, some calculation parameters (especially porosity values) cannot be determined accurately for each storage structure. The calculations are therefore partly based on analogues. In order to account for parameter uncertainties on the calculated storage capacities, Monte Carlo simulations are performed. For each potential storage structure 10 000 runs of capacity calculations have been performed. To determine the pore volume within structures a normal or uniform distribution was assumed. For the CO_2 density, a constant distribution of 625 ± 75 kilograms per cubic metre (kg/m^3) is used for all calculations. Storage efficiencies are assumed to range between 5% and 20%, exhibiting a triangular distribution pattern and a median value of about 10%. For each storage structure the Monte Carlo simulation results in 10 000 capacity values, and are plotted as a frequency distribution. Three capacity values with simulated probabilities of 90%, 50% and 10% are listed for each structure.

In the final step, individual storage capacities of all structures are summed into the CO_2 storage capacity of the investigated area.

Pressure-limited assessment methodology example (TNO methodology)

The methodology used by the TNO (Neele *et al.*, 2011a) incorporates the concept of total affected space, *i.e.* the entire space whose state or qualities change during the total storage time as a result of the storage operation, to estimate CO_2 storage resource. The total affected space, in combination with a maximum allowable average pressure increase in the affected space, determines the ultimate storage potential (Meer and Egberts, 2008).

In this methodology, three types of pressures are defined: local injection pressures (bottom-hole pressure), regional storage pressures (reservoir pressures), and finally the total average pressure

[2] Again, the IEA makes no recommendation about minimum depth. The minimum depth many methodologies require is to ensure that CO_2 is a supercritical fluid.

increase in the affected space. The maximum allowable regional storage pressures are site-specific and related to the mechanical properties of the seal, while the maximum allowable average pressure increase in the affected space depends on the geological conditions of the total system. During the injection cycle of the storage activity, the pressures near the injection location are higher than those at the edge of the affected space. The former will be controlled by the injectivity, whereas the dynamic development of the latter is the result of pressure conductivity of the formation.

The intended storage location for the CO_2 must have enough storage space and enough sealing capacity to contain the free CO_2 and prevent it from migrating to the surface. In the TNO method, storage capacity can be limited by either the total affected space (which, combined with pressure increase and total system compressibility gives the total storage capacity of the system), or the buoyant trapping capacity (the volume of the traps in the total affected space).

Annex 3: The USGS method for calculating residual storage efficiencies

The USGS methodology calculates residual trapping storage efficiencies (Blondes *et al.*, 2013) using the equation suggested in MacMinn, Szulczewski and Juanes (2010, page 349), which is defined as an approximation of the storage efficiency of a sloping reservoir (interface of storage formation and sealing formation is not horizontal), and provides a simple calculation of residual storage efficiency:

$$\varepsilon_s = \Gamma^2/[0.9M + 0.49] \quad (1)$$

where Γ is the capillary trapping number and *M* is the mobility factor (MacMinn, Szulczewski and Juanes, 2010). The capillary trapping number and mobility factor are defined (MacMinn, Szulczewski and Juanes, 2010, pages 333, 334) as:

$$\Gamma = S_{gr}/(1-S_{wc}) \quad (2)$$

$$M = (k_{rg})(\mu_w)/\mu_g \quad (3)$$

where S_{gr} is the residual gas saturation after imbibition and S_{wc} is the connate water saturation, or irreducible water saturation; k_{rg} is the relative permeability of CO_2; μ_g is the viscosity of CO_2; and μ_w is the viscosity of the brine. Values for k_{rg}, S_{gr}, and S_{wc} are found in experimental (Bennion and Bachu, 2005, 2008; Burton, Kumar and Bryant, 2008; Okabe *et al.*, 2010) and modelling studies (Kopp *et al.*, 2009a,b; Juanes, MacMinn and Szulczewski, 2010; Okwen, Stewart and Cunningham, 2010; Szulczewski *et al.*, 2012). Values for μ_g are calculated using the equation of state of Span and Wagner (1996). Values for μ_w are calculated using the Mao and Duan (2008) model, which can determine the viscosity of brines of varying salinities.

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Acronyms, abbreviations and units of measure

Acronyms and abbreviations

B_{PV}	buoyant trapping pore volume
B_{SE}	buoyant trapping storage efficiency
B_{SR}	buoyant trapping storage resource
B_{SV}	buoyant trapping storage volume
BGR	German Federal Institute for Geosciences and Natural Resources
CCS	carbon capture and storage
CO_2	carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
FVF	formation volume factor
GIS	geographic information system
IEA	International Energy Agency
k	permeability
NACAP	North American Carbon Atlas Partnership
NETL	National Energy Technology Laboratory
R1	residual trapping class 1
R2	residual trapping class 2
R3	residual trapping class 3
R_{PV}	residual trapping pore volume
R_{SE}	residual trapping storage efficiency
R_{SR}	residual trapping storage resource
R_{SV}	residual trapping storage volume
SAU	storage assessment unit
SF	storage formation
SF_{PV}	storage formation pore volume
TASR	technically accessible storage resource
TA_{SR}	technically accessible storage resource
T_{pi}	net porous thickness
TA_{SV}	technically accessible storage volume
TDS	total dissolved solids
TNO	Geological Survey of the Netherlands
US DOE	United States Department of Energy
USGS	United States Geological Survey
Φ	porosity

Units of measure

boe	barrel of oil equivalent
ft	feet
kg/m^3	kilograms per cubic metre
m	metre
m^3	cubic metre
mD	millidarcy
mg/L	milligrams per litre
$MtCO_2$	million tonnes of carbon dioxide
t	tonne

Glossary

The following definitions are modified from Brennan *et al.* (2010) and Blondes *et al.* (2013) and other sources indicated.

barrels of oil equivalent (boe)	A unit of petroleum volume in which the gas part is expressed in terms of its energy equivalent in barrels of oil. For this assessment, the energy equivalent (not the volume equivalent) of 6 000 cubic feet of natural gas equals 1 barrel of oil equivalent (Klett *et al.*, 2005).
buoyancy	Upward force on one phase (for example, a fluid) produced by the surrounding fluid (for example, a liquid or a gas) in which it is fully or partially immersed, caused by differences in density.
buoyant trapping	A trapping mechanism by which CO_2 is held in place by a top and lateral seal (either a sealing formation or a sealing fault), creating a column of CO_2 in communication across pore space.
downstream constraints	The policy-based constraints applied to the output values from initial estimation of CO_2 storage resource.
enhanced oil recovery	Injection of steam, gas or other chemical compounds into hydrocarbon reservoirs to stimulate the production of usable oil beyond what is possible through natural pressure, water injection, and pumping at the wellhead.
geologic storage of CO_2	A type of carbon sequestration that uses the long-term retention of CO_2 in subsurface geologic formations.
injectivity	The rate at which fluid can be injected into an aquifer per unit of pressure applied to inject the fluid.
net porous thickness (T_{pi})	Defined as the net stratigraphic thickness of the portion of the storage formation that the assessment geologist determined contained an appropriate lithology with sufficient porosity to store CO_2. This determination was dependent on the geology of the storage formation, which did not allow for a fixed threshold.
permeability (k)	A measure of the ability of a rock to permit fluids to be transmitted through it; it is controlled by pore size, pore throat geometry, and pore connectivity. Permeability is typically reported in darcies.
porosity (Φ)	The part of a rock that is occupied by voids or pores. Pores can be connected by passages called pore

	throats, which allow for fluid flow, or pores can be isolated and inaccessible to fluid flow. Porosity is typically reported as a volume, fraction or percentage of the rock.
pressure gradient	The change in pore pressure per unit depth, typically in units of pound-force per square inch per foot (psi/ft), kilopascals per metre (kPa/m), or bars per metre (bar/m).
residual trapping	A mechanism by which CO_2 is trapped as discrete droplets, blobs, or ganglia of CO_2 as a nonwetting phase, essentially immiscible with the wetting fluid, within individual pores where the capillary forces overcome the buoyant forces.
seal	A geologic feature that inhibits the mixing or migration of fluids and gases between adjacent geologic units. A seal is typically a rock unit or a fault; it can be a top seal, inhibiting upward flow of buoyant fluids, or a lateral seal, inhibiting the lateral flow of buoyant fluids.
seal formation	The confining rock unit within the SAU. The seal formation is a rock unit that sufficiently overlies the storage formation and where managed properly has a capillary entrance pressure low enough to effectively inhibit the upward buoyant flow of CO_2.
storage assessment unit (SAU)	A mappable volume of rock that includes two main components: (1) the storage formation (*SF*), which is a reservoir flow unit for CO_2 storage, and (2) a regional seal formation.
storage efficiency factor (B_{SE} and R_{SE})	Values representing the fraction of the total available pore space that will be occupied by free-phase CO_2. Ranges of storage efficiency are specific to trapping types. The two used in this assessment were buoyant trapping storage efficiency (B_{SE}) and residual trapping storage efficiency (R_{SE}).
storage formation (*SF*)	The reservoir component of the storage assessment unit. The sedimentary rock layers that are saturated with formation water having TDS greater than 10 000 mg/L. In the CO_2 assessment methodology, the storage formation resource calculation is the main resource calculation and consists of two parts: a buoyant trapping resource and a residual trapping resource.
storage formation pore volume (SF_{PV})	The available pore space in the storage formation calculated from area, net porous thickness and porosity. This value was used in the calculation of the R_{PV}.

technically accessible storage resource (TASR and TA_{SR})	The mass of CO_2 that may be injected and stored using present-day geologic and hydrologic knowledge of the subsurface and engineering practices. This term is analogous to the term "technically recoverable resource" used in USGS oil and gas assessments.
technically accessible storage volume (TA_{SV})	The volume of CO_2 that may be injected and stored using present-day geologic and hydrologic knowledge of the subsurface and engineering practices.
total dissolved solids (TDS)	The quantity of dissolved material in a sample of water, usually expressed in mg/L.
trapping	The physical and geochemical processes by which injected CO_2 is retained in the subsurface.
upstream constraints	The policy-based constraints can be applied to the input values used for the initial estimation of CO_2 storage resource.

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