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Comparison between Methodologies Recommended for Estimation of CO_2 Storage Capacity in Geological Media by the CSLF Task Force on CO_2 Storage Capacity Estimation and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program

- Phase III Report -

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The document on "Methodology for Development of Geologic Storage Estimates for Carbon Dioxide", prepared for the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Carbon Sequestration Program by the Capacity and Fairways Subgroup of the Geologic Working Group of the DOE Regional Carbon Sequestration Partnerships, was prepared in 2007 and, at the time of presenting this Task Force Phase III report to the Technical Group at the CSLF meeting in Cape Town, South Africa, April 13-17, 2008, was still in the process of being externally reviewed. As such it is not yet a public document and it was accessible only to Stefan Bachu and Robert Burruss, who were members of the Capacity and Fairways Subgroup. The document was not available to the other members of the CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation. The author assumes sole responsibility for the content of this report.

Executive Summary

Implementation of CO_2 capture and geological storage technology at the scale needed to achieve a significant and meaningful reduction in CO_2 emissions requires knowledge of the available CO_2 storage capacity. The CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation produced, in March 2007, a report in which a consistent set of methodologies for estimating CO_2 storage capacity in coal beds, oil and gas reservoirs and deep saline aquifers was recommended. In parallel, the United States Department of Energy (USDOE) Capacity and Fairways Subgroup within the Geologic Working Group of the Regional Carbon Sequestration Partnerships Program developed standards for CO_2 storage capacity estimation for a Carbon Sequestration Atlas of the United States and Canada. At the March 2007 CSLF meeting the CSLF Task Force proposed and was given approval to conduct a comparison of the methodologies developed in parallel by the CSLF Task Force and the USDOE Subgroup.

The methodologies proposed by the CSLF Task Force and the USDOE Subgroup are basically identical, with minor differences in computational formulation. In both cases the methods are based on volumetrics and are applicable to country-, regional- and basin-scale CO_2 storage capacity estimates. Local and site-specific storage capacity estimates should be based on numerical modeling that takes into account the dynamic aspect of CO_2 injection and of CO_2 plume evolution. The only difference of significance is that the CSLF Task Force proposed to estimate static CO_2 storage capacity in deep saline aquifers by considering only stratigraphic and structural traps present in these aquifers, while the USDOE Subgroup proposes to consider the entire aquifer, not only the traps. In addition, through Monte Carlo simulations of CO_2 storage in coal beds and in deep saline aquifers for conditions characteristic to North America, the USDOE Subgroup obtained a range of values for these storage efficiency coefficients for the 15% and 85% confidence intervals, which are between 0.28 and 0.40 for coal beds, and between 1% and 4% for deep saline aquifers.

The proposed methodologies are useful in estimating the effective CO_2 storage capacity, before applying regulatory, land use, economic and other constraining overlays. The only regulatory constraint explicitly considered by the USDOE Subgroup is that CO_2 storage should be at depths greater than the depth of protected groundwater, defined by water salinity less than 10,000 mg/l (ppm). This constraint has been recognized also by the CSLF Task Force, but no specific value has been recommended, allowing for each jurisdiction to establish its own.

The match, or identity, of the methodologies for CO_2 storage capacity estimation at the country, regional and basin scales proposed independently by both the CSLF Task Force and the USDOE Subgroup indicates that these methodologies are robust and science-and-engineering based, increasing the degree of confidence in their use and in the results obtained by using them. Application of these methodologies at various appropriate scales should provide decision makers in governments and industry with the information needed to assess the potential for CO_2 geological storage and in focusing further work for site screening and selection.

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1. Introduction

Carbon dioxide capture and sequestration in geological media, also known as Carbon Capture and Storage (CCS), is one among several means of reducing atmospheric emissions of anthropogenic CO_2. This is a technology that: 1) is immediately applicable as a result of the experience gained mainly in oil and gas exploration and production, deep waste disposal and groundwater protection; 2) has large capacity, although unevenly distributed around the world, and 3) has retention times of centuries to millions of years (IPCC, 2005). In regard to CCS, the Carbon Sequestration Leadership Forum (CSLF) is an international climate change initiative that was established in 2003 and that is focused on the development of improved cost-effective technologies for the separation and capture of CO_2 for its transport and long-term safe storage. It comprises 22 members, including 21 countries and the European Commission, that are significant producers and/or users of fossil fuels and that have a commitment to invest resources in research, development and demonstration activities in CO_2 capture and storage technologies. The Forum has recognized that geological storage is an important element of the CCS chain and that it is critical for CSLF members to have a good assessment of the CO_2 storage potential and capacity within their national jurisdictions.

The Technical Group of the CSLF has identified early on that the lack of consistent and sound methodologies for estimating CO_2 storage capacity represents a barrier to CCS deployment and has established at its meeting in Melbourne, Australia, in September 2004 a *Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation*. In its Phase I report (CSLF, 2005), delivered in September 2005 at the CSLF meeting in Berlin, Germany, the Task Force has identified and critically analyzed the issues associated with various methodologies used to date for estimating CO_2 storage capacity (see also Bradshaw et al., 2007). At the meeting in Paris, France, in March 2007, the Task Force submitted a Phase 2 report (CSLF, 2007) that presented definitions, concepts and methodologies to be used in estimating CO_2 storage capacity (see also Bachu et al., 2007). It is hoped that the concepts, definitions and methodologies presented in the Phase II report would serve as a basis in CSLF member countries for collecting the necessary data and properly estimating the CO_2 storage capacity in geological media in their jurisdiction, and indeed the proposed methodologies have been and are being applied for estimating CO_2 storage capacity in various European countries, in the Indian sub-continent and in Brazil.

During the same period, starting in 2003, the United States Department of Energy (USDOE) established seven Regional Carbon Sequestration Partnerships across the United States, with the goal of advancing and demonstrating the CCS technology. During Phase I of the Regional Carbon Sequestration Partnership Program (2003-2005), the partnerships independently produced quantitative estimates of the CO_2 storage capacity within their respective areas, which were subsequently compiled into a Carbon Sequestration Atlas of the United States and Canada[1] (USDOE, 2007), hereafter labelled Atlas I. The Atlas presents information about CO_2 storage capacity in the U.S. and parts of Canada both by geological medium (unmineable coal seams, oil and gas reservoirs and deep saline aquifers), and by individual partnerships. However, some inconsistencies in the evaluation of CO_2 storage capacity by various Regional Partnerships subsequently became apparent, and in 2006 USDOE established a Capacity and Fairways Subgroup within the Geologic Working Group of the Regional Carbon Sequestration Partnerships for developing standards for CO_2 storage

[1] The four western Canadian provinces are also members of two Regional Partnerships, PCOR and WestCarb, and as such they are included in the Atlas.

estimation, with the intent of producing an updated *2008 Carbon Sequestration Atlas of the United States and Canada (Atlas II)*. The primary focus of the update is to "add basins and formations to the CO_2 storage portfolio, document procedures completely, and provide definitions of CO_2 resource versus CO_2 capacity that reflect the uncertainty of geologic storage estimates across the Regional Carbon Sequestration Partnership Regions".

Mindful of the similarity between the efforts of the CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation, and of the Capacity and Fairways Subgroup of the U.S. Regional Carbon Sequestration Partnership Program, the CSLF Task Force has proposed and was given approval at the CSLF meeting March 2007 that was held in Paris, France, to proceed to a Phase III of the Task Force that would include coordination of methodology for CO_2 storage capacity estimation with other national and international groups working on this subject, including the Capacity and Fairways Subgroup of the USDOE Regional Carbon Sequestration Partnership Program.

In June 2007 the Capacity and Fairways Subgroup of the Geologic Working Group of the Regional Carbon Sequestration Partnerships in the U.S. initiated an effort to inventory and review the methods used in Atlas I to estimate CO_2 storage potential and capacity, to generate consistent methods and assumptions across a wide range of data for estimating the geologic resource for storing CO_2 in the U.S. in unmineable coal seams, oil and gas reservoirs, and deep saline aquifers. The author of this Task Force Phase III report has been invited to be a member of, and participate in the work of the Capacity and Fairways Subgroup. Through various meetings, conference calls and e-mail exchanges, a consensus emerged within the Subgroup for an updated approach towards producing Atlas II, summarized in October 2007 in a draft document titled "Methodology for Development of Geologic Storage estimates for Carbon Dioxide" that is currently under review.

This Phase III Report of the CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation presents a review of the methodologies proposed by the CSLF Task Force in its Phase II report, and those proposed by the Capacity and Fairways Subgroup of the U.S. Regional Carbon Sequestration Regional Partnership Program, with the aim of identifying commonalities and differences in proposed methodologies, leading hopefully to improved and harmonized methodologies for estimating the potential and capacity for CO_2 storage in geological media.

2. Concepts and Definitions

The methodologies for estimating CO_2 storage potential and capacity are based on widely accepted assumptions about geological trapping mechanisms, storage media and operating timeframes reviewed previously (e.g., IPCC, 2005; CSLF 2007). Only concepts relevant to this comparison between CSLF and USDOE methodologies will be reviewed here.

2.1 Assessment Scale

Five different assessment scales have been identified in the CSLF Phase II Report (CSLF, 2007; Bachu et al., 2007):

1) **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.
2) **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.
3) **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.
4) **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.
5) **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.

The relationship between basin-scale and regional-scale assessments may reverse in the case of large, continental-size countries where a region may contain several sedimentary basins.

The purpose and envisaged GIS-based structure of the Carbon Sequestration Atlas of United States and Canada is to provide quantitative estimates of the geologic resource for CO_2 storage in each of the three media under consideration and in aggregate for individual sedimentary basins, States (Provinces in Canada), the seven regions covered by the Regional Partnerships, and the United States as a whole. As such, the CO_2 storage capacity estimates correspond to the country-, regional- and basin-scale assessments defined by the CSLF Task Force (note that in this case the order of regional and basin scales is reversed). Local- and site-scale assessments are explicitly excluded from the Carbon Sequestration Atlas of United States and Canada.

2.2 Resource-Reserve Pyramid Concept

Carbon dioxide storage capacity constitutes a geological resource (commodity) whose availability can be expressed using the concepts of resources and reserves, in the same way as other energy and mineral commodities such as oil and gas, coal, uranium, iron, gold, etc., are classified[2]. ***Resources*** are those quantities of a commodity that are estimated at a given time to exist within a jurisdiction or a geographic area. Resources are of two types: *discovered, or in-place* (i.e., an existing commodity whose location and characteristics are known, being assessed on the basis of scarce data), and *undiscovered, or inferred* (i.e., not found yet but assumed to exist based on inferences from geological knowledge and/or various analyses). ***Reserves*** are those quantities of a commodity that are known to exist and that are commercially recoverable. Their assessment integrates technical, economic, environmental, societal and regulatory factors available at the time of the assessment. Reserves are a subset of resources, and usually accessibility, technology and economic cutoffs are used to define and delineate reserves.

Using the concept of resources and reserves, the CSLF Task Force proposed a ***Techno-Economic Resource-Reserve Pyramid for CO_2 Storage Capacity*** (CSLF, 2007; Bachu et al., 2007), illustrated in Figure 1. The various capacities, described below in ascending order, are nested within the resource-reserves pyramid:

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

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[2]http://www.spe.org/specma/binary/files/4675179GuidelinesEvaluationReservesResources05Nov.pdf#search=%22Classification%20and%20Nomenclature%20Systems%20for%20Petroleum%20and%20Petroleum%20Reserves%22
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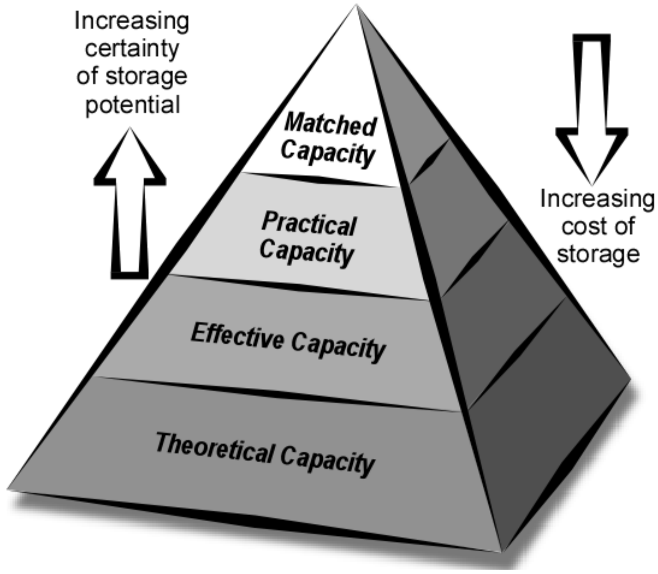

Figure 1. Techno-Economic Resource-Reserve pyramid for CO_2 storage capacity in geological media within a jurisdiction or geographic region. The pyramid shows the relationship between Theoretical, Effective, Practical and Matched capacities.

The Capacity and Fairways Subgroup of the U.S. Regional Carbon Sequestration Regional Partnership Program proposes to provide CO_2 resource estimates and, where possible, CO_2 capacity estimates. A **CO_2 Resource Estimate** is defined as the volume of porous and permeable sedimentary rocks that is most likely accessible to injected CO_2 via drilled and completed wellbores, and includes all volumetric estimates of geologic storage reflecting physical and chemical constraints or limitations, but does not include current or projected economic constraints, regulations, or well and/or surface facilities. A **CO_2 Capacity Estimate** includes economic and regulatory constraints, such as groundwater protection, land use, minimum well spacing, (maximum) injection rate and pressure, number and type of wells, operating costs and proximity to a CO_2 source.

From the above definitions it appears that the USDOE *CO_2 Resource Estimate* corresponds to the CSLF *Effective Capacity*, and the USDOE *CO_2 Capacity Estimate* corresponds to the CSLF *Practical Capacity*. The CSLF-defined Theoretical Capacity is not considered in the USDOE Carbon Sequestration Atlas of United States and Canada, and commercial-scale assessments, which would correspond to the CSLF Matched Capacity, are excluded from the USDOE Atlas.

3. Estimation of CO_2 Storage Capacity

The USDOE Capacity and Fairways Subgroup defines static and dynamic methods for estimating subsurface volumes. These are widely used in the oil and gas industry, and in underground natural gas storage, groundwater and the underground disposal of fluids. The static methods are volumetric and compressibility-based; the dynamic methods are decline/incline curve analysis, material balance and reservoir simulations. The dynamic methods can be applied only after the start of active injection (although one may argue that numerical simulations without history matching can be applied also prior to injection), hence only the static methods were and will be used in producing the Carbon Sequestration Atlas of United States and Canada (Atlas I and II). The approach taken by the Regional Partnerships in the U.S. is basically consistent with the methodology proposed by the CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation, which is also based on static methods.

3.1 Coal Beds

Carbon dioxide storage in coal beds occurs when CO_2 is preferentially adsorbed onto coal. Coal has higher affinity for *gaseous* CO_2 than for methane, which naturally occurs in coals, the volumetric ratio between the two ranging from as low as 1 for mature coals such as anthracite, to as high as 10 for younger, less altered coals. Thus, CO_2 storage in coal beds is based on the concept that the injected CO_2 will replace the methane in coal and stay adsorbed onto the coal surface as long as the coal is undisturbed (i.e., the pressure doesn't drop).

CSLF-Proposed Methodology. The methodology proposed by the CSLF Task Force is based on two steps, consistent with the resource-reserves pyramid (Figure 1). The theoretical storage capacity M_{CO2t} for a given coal bed is calculated first according to:

$$M_{CO2t} = \rho_{CO2s} \times A \times h \times \tilde{n}_C \times G_C \times (1 - f_a - f_m) \qquad (1)$$

where $\rho_{CO2s} = 1.873$ kg/m^3 is CO_2 density at standard (surface) conditions, A and h are the area and effective thickness of the coal zone, respectively, $\tilde{n}_C$ is the bulk coal density (generally $\tilde{n}_C \approx 1.4$ t/m^3), G_{CS} (in units of volume of gas per unit of coal mass) is the coal gas content (dry, ash free) at saturation assuming that the coal will be 100% saturated with CO_2, and f_a and f_m are the ash and moisture weight fraction of the coal, respectively. The coal gas content at saturation, G_{CS}, is generally assumed to follow a pressure-dependent Langmuir isotherm of the form:

$$G_{CS} = V_L \times \frac{P}{P + P_L} \qquad (2)$$

although other isotherm functions can be used. In relation (2), V_L and P_L are Langmuir volume and pressure, respectively. The Langmuir volume, V_L, represents the maximum gas adsorption capacity of a particular coal at the given temperature, and is usually given in cc/g, which is equivalent to m^3/t. The Langmuir isotherm expressed by eq. (2) displays an increase in adsorption capacity with increasing pressure as the gas content G_{CS} tends asymptotically towards V_L with increasing pressure P.

The **effective** storage capacity, M_{CO2e}, is obtained according to:

$$M_{CO2e} = R_f \times C \times M_{CO2t} \tag{3}$$

where R_f is the recovery factor and C is the completion factor, and together they express the reservoir gas deliverability. The completion factor C represents an estimate of that part of the net cumulative coal thickness within the drilled coal zone that will contribute to gas production or storage, it strongly depends on the individual thickness of the separate coal seams and on the distance between them, and is lower for thin coal seams than for thick ones. The recovery factor R_f represents the fraction of gas that can be produced from, or stored in, the coal seams.

USDOE-Proposed Methodology. The methodology proposed by the Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships is consistent with the definition of CO_2 resource estimate, which is equivalent with the effective storage capacity defined by the CSLF Task Force. The proposed relationship for calculating CO_2 storage capacity in coal beds is:

$$M_{CO2} = \rho_{CO2s} \times A \times h \times C \times E \tag{4}$$

where C is CO_2 concentration (standard volume) per unit of coal volume (Langmuir or alternative), and E is CO_2 storage efficiency factor reflecting the fraction of the total coal bulk volume that is contacted by CO_2. The concentration C assumes 100% coal saturation with CO_2. If C is for dry, ash-free (daf) conditions, then A and h have to be corrected accordingly.

Monte Carlo simulations produced a range for E between 28 and 40% for a 15 to 85% confidence range, with an average of 33% for 50% confidence. In the Monte Carlo simulations that produced the recommended range for E, various calculation components have been varied as follows:

- Fraction of the coal bed that is suitable for CO_2 storage: 0.6 to 0.8
- Fraction of coal seam thickness that has adsorption capability: 0.75 to 0.90
- Areal displacement efficiency: 0.7 to 0.95
- Vertical displacement efficiency: 0.8 to 0.95
- Fraction of net coal thickness contacted by CO_2 as a result of CO_2 buoyancy compared with the water in coal cleats: 0.9 to 1.0
- Pore-scale displacement efficiency, reflecting the achievable degree of saturation for in-situ coal compared with the theoretical maximum predicted by the adsorption isotherm: 0.75 to 0.95.

These ranges of values were chosen to reflect various coals, with the maximum and minimum meant to be reasonable high and low values for each parameter.

Comparison of relations (1)-(3) and (4) indicates that the two proposed methodologies are practically identical, where:

$$C = \tilde{n}_C \times G_C \times (1 - f_a - f_m) \quad \text{and} \quad E = R_f \times C$$

Applicability/Screening Criteria. Both the CSLF Task Force and the USDOE Capacity and Fairways Subgroup propose some screening criteria for identifying coal beds suitable for CO_2 storage.

Both the CSLF Task Force and the USDOE Capacity and Fairways Subgroup recommend the depth where coal permeability, which generally decreases with depth, becomes less than 1 mD as the maximum depth for coal beds to be considered for CO_2 storage. Similarly, a minimum depth is suggested by both as the depth dictated by water-quality standards to ensure that potentially freshwater-bearing coals are not included (i.e., only coals deeper than the depth of groundwater protection should be considered). The USDOE Capacity and Fairways Subgroup recommends considering only coal seams with a water TDS concentration of 10,000 mg/l (ppm) and higher. Although this is a regulatory constraint, which moves the effective storage capacity estimate into the practical storage capacity estimate (or, in USDOE parlance, moves the resource estimate into capacity estimate), it is believed that regulations will always be in place to protect potable groundwater and, therefore, this criterion should be applied from the beginning to avoid including in assessments coal beds that will never be available for CO_2 storage. Thus, only coals in this depth interval, between the depth of groundwater protection and the depth where coal permeability is less than 1 md, should be considered for CO_2 storage. In addition, the CSLF Task Force proposed to consider only coals where, based on in-situ pressure and temperature, CO_2 is in gaseous phase, and this criterion may reduce further the coal beds considered for CO_2 storage, but this is a screening criterion that can be debated.

In regard to coal mineability, within the depth interval established above, the USDOE Capacity and Fairways Subgroup recommends that coal mineability should be established based on today's standards of technology and economic profitability. This criterion implies use of economic criteria, which again would move the estimate in the resource-reserves pyramid from effective to practical (or from resource estimate to capacity estimate); however use of this constraint is necessary because of safety and regulatory concerns for mining coals that have been used to store CO_2. Thus, coal reserves should be excluded from CO_2 storage capacity estimates. These recommendations are generally consistent with the recommendations made by the CSLF Task Force.

This analysis shows that there is complete identity between the methodologies and the applicability criteria proposed by the CSLF Task Force and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships for estimating CO_2 storage capacity in coal beds.

3.2 Oil and Gas Reservoirs

Estimation of the CO_2 storage capacity in oil and gas reservoirs is the simplest, relatively speaking, and most straightforward of the three media considered for CO_2 geological storage. This is because, unlike coals and aquifers, oil and gas reservoirs are better known and characterized than the other two as a result of exploration for and production of hydrocarbons. Also unlike coal beds and deep saline aquifers, oil and gas reservoirs are discrete rather than continuous, such that the capacity for CO_2 storage in hydrocarbon reservoirs in any particular region at any scale is given by the sum of the capacities of all reservoirs in that area, calculated on the basis of reservoir properties such as original oil or gas in place, recovery factor, temperature, pressure, rock volume and porosity, as well as in situ CO_2 characteristics such as phase behaviour and density.

In the case of oil and gas reservoirs, the fundamental assumption is that the volume previously occupied by the produced hydrocarbons becomes, by and large, available for CO_2 storage. This assumption is generally valid for reservoirs that are not in hydrodynamic contact with an aquifer, or that are not flooded during secondary and tertiary oil recovery. In reservoirs that are in hydrodynamic contact with an underlying aquifer, formation water invades the reservoir as the pressure declines because of production, leading to a decrease in the pore space available for CO_2 storage. Carbon dioxide injection can partially reverse the aquifer influx, thus making more pore space available for CO_2. However, not all the previously hydrocarbon-saturated pore space will become available for CO_2 because some residual water may be trapped in the pore space due to capillarity, viscous fingering and gravity effects. Another important assumption is that CO_2 will be injected into depleted oil and gas reservoirs until the reservoir pressure is brought back to the original, or virgin, reservoir pressure. In some cases reservoir depletion may damage the integrity of the reservoir and/or caprock, in which case the pressure cannot be brought back to the initial reservoir pressure and the capacity would be lower, while in other cases the pressure can be raised beyond the original reservoir pressure as long as it remains safely below the lesser of the capillary entry pressure and the threshold rock-fracturing pressure of the seal (caprock), in which case the CO_2 storage capacity would be higher due to CO_2 compression. In many cases the structure that hosts a hydrocarbon reservoir is not filled with oil and/or gas to the spill point, and the additional pore space down to the spill point can also be used for CO_2 storage, but, to achieve this, the pressure has to be increased beyond the original reservoir pressure. However, raising the storage pressure to or beyond the original reservoir pressure, and evaluating the effects of water invasion, reservoir heterogeneity, mobility contrast and buoyancy require a case-by-case reservoir analysis that is not practical for country-, regional- and basin-scale evaluations. In this respect there is complete agreement between the CSLF and USDOE proposed approaches, assumptions and methodologies.

CSLF-Proposed Methodology. Consistent with the resource-reserves pyramid concept, both theoretical and effective CO_2 storage capacities are calculated according to:

$$M_{CO2t} = \rho_{CO2r} \times R_f \times (1 - F_{IG}) \times OGIP \times [(P_s \times Z_r \times T_r) / (P_r \times Z_s \times T_s)] \qquad (5)$$

for gas reservoirs, and by:

$$M_{CO2t} = \rho_{CO2r} \times [R_f \times OOIP / B_f - V_{iw} + V_{pw}] \qquad (6)$$

for oil reservoirs.

An alternate equation for calculating the CO_2 storage capacity in oil and gas reservoirs is based on the geometry of the reservoir (areal extent and thickness) as given in reserves databases:

$$M_{CO2t} = \rho_{CO2r} \times [R_f \times A \times h \times \phi \times (1 - S_w) - V_{iw} + V_{pw}] \quad (7)$$

In the above equations *OGIP* and *OOIP* are the initial gas and oil in place, respectively, R_f is the recovery factor, F_{IG} is the fraction of injected gas, *P*, *T* and *Z* denote pressure, temperature and the gas compressibility factor, respectively, B_f is the formation volume factor that brings the oil volume from standard conditions to in-situ conditions, V_{iw} and V_{pw} are the volumes of injected and produced water, respectively (applicable in the case of oil reservoirs), and *A*, *h*, ϕ and S_w are reservoir area, thickness, porosity and water saturation, respectively. If gas or miscible solvent is injected in oil reservoirs in tertiary recovery, then the mass balance of these should be added to eq. (6) or (7). The subscripts "*r*" and "*s*" in eq. (5) denote reservoir and surface conditions, respectively. The volumes of injected and/or produced water, solvent or gas can be calculated from production records. In the case of reservoirs with strong aquifer support (water drive), the volumes of injected and produced water may be negligible by comparison with the amount of invading water.

All the processes and reservoir characteristics, such as buoyancy, gravity override, mobility, heterogeneity, water saturation and strength of the underlying aquifer if present, that reduce the actual volume available for CO_2 storage can be expressed by capacity coefficients ($C < 1$) in the form:

$$M_{CO2e} = C_m \times C_b \times C_h \times C_w \times C_a \times M_{CO2t} \equiv C_e \times M_{CO2t} \quad (8)$$

where M_{CO2e} is the **effective** reservoir capacity for CO_2 storage, the subscripts *m*, *b*, *h*, *w* and *a* stand for mobility, buoyancy, heterogeneity, water saturation, and aquifer strength, respectively, and the coefficient C_e is a single effective capacity coefficient that incorporates the cumulative effects of all the other.

USDOE-Proposed Methodology. The volumetric relationship proposed by the Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships is consistent with the definition of CO_2 resource estimate (i.e., effective storage capacity):

$$M_{CO2t} = \rho_{CO2r} \times A \times h \times \phi \times (1 - S_w) \times B \times E \quad (9)$$

Where *E* is a CO_2 storage efficiency factor that reflects the fraction of the total reservoir pore volume from which oil and/or gas has been produced and that can be filled by CO_2. The CO_2 storage efficiency factor E involves the original oil or gas in place and recovery factor, and can be derived based on experience or reservoir simulations. Factors not explicitly considered include CO_2 miscibility into oil, dissolution of CO_2 into residual and associated water, hysteretic effects during hydrocarbon production and CO_2 injection, waterflooding, and solution gas. Most of these factors were not considered by the CSLF Task Force either because they can be evaluated only on a case-by-case basis at the site-specific scale.

Comparison of the methodologies proposed by the CSLF Task Force and the USDOE Capacity and Fairways Subgroup indicates that the two are equivalent. Basically, relation (9) is equivalent to relations (7) and (8) if injected and produced water are not considered, and where $E = R_f \times C_e$.

In the cases where good production (and injection) records are available, and particularly when cumulative production is greater than the original oil or gas in place, a production-based method can be used to estimate CO_2 storage capacity, in which basically the product $R_f \times OGIP$ or $R_f \times OOIP$ in relations (5) and (6) is replaced by the produced gas or oil, respectively.

Neither the CSLF Task Force nor the USDOE Capacity and Fairways Subgroup recommends any methodology for estimating CO_2 storage capacity in CO_2 enhanced oil recovery (EOR) operations because these are based on reservoir simulations at the site-specific scale.

Applicability/Screening Criteria. While the CSLF Task Force did not recommend any specific screening criteria in the case of oil and gas reservoirs, the USDOE Capacity and Fairways Subgroup recommends excluding from CO_2 resource and capacity estimates those oil and gas reservoirs whose water has a salinity less than 10,000 mg/l (ppm), to ensure that potentially freshwater-bearing units are not included, although it is recognized that the reservoir water is very likely to be classified as non-potable due to oil and/or gas contamination. The number of oil and gas reservoirs thus excluded from the CO_2 resource and capacity estimation is expected to be very small.

In addition, the USDOE Capacity and Fairways Subgroup recommends aggregating reservoir CO_2 resource or capacity estimation to the field scale. Field-scale estimates can then be easily summed up at either the basin or state scale, depending on interest by geological entity or by jurisdiction.

3.3 Deep Saline Aquifers

Both the CSLF Task Force and the USDOE Capacity and Fairways Subgroup recognize that a deep saline aquifer is a body of porous rock that meets the depth conditions for CO_2 storage and that contains water with total dissolved solids (TDS) greater than 10,000 mg/l (ppm), and that it may include more than one geological formation or be defined only as part of a formation. Furthermore, more often than not more than one deep saline aquifer is present within a sedimentary succession at a given location.

The CSLF Task Force differentiated between the various CO_2-trapping mechanisms that operate in deep saline aquifers: structural and stratigraphic (volumetric) trapping, residual-gas saturation trapping, dissolution, precipitation and hydrodynamic trapping. Because CO_2 storage through residual gas trapping, mineral precipitation and hydrodynamic trapping are time-dependent processes, and because CO_2 storage capacity can be evaluated in these cases only at the local and site-specific scales using numerical simulations (CSLF, 2007; Bachu et al., 2007), they are not discussed in this comparative analysis. The USDOE Capacity and Fairways Subgroup also does not consider these trapping mechanisms in calculating CO_2 storage resources and capacity at the basin and regional scales.

CSLF-Proposed Methodology. Storing CO_2 in structural and stratigraphic traps is similar to storing CO_2 in depleted oil and gas reservoirs. If the geometric volume V_{trap} of the structural or stratigraphic trap down to the spill point is known, as well as its porosity ϕ and the irreducible water saturation S_{wirr}, then the theoretical volume available for CO_2 storage, V_{CO2t}, can be calculated with the formula:

$$V_{CO2t} = V_{trap} \times \phi \times (1 - S_{wirr}) \equiv A \times h \times \phi \times (1 - S_{wirr}) \qquad (10)$$

where A and h are the trap area and average thickness, respectively.

The effective storage volume, V_{CO2e}, is given by:

$$V_{CO2e} = C_c \times V_{CO2t} \qquad (11)$$

where C_c is a capacity coefficient that incorporates the cumulative effects of trap heterogeneity, CO_2 buoyancy and sweep efficiency.

Calculating the mass of CO_2 that corresponds to the effective storage volume is more difficult because CO_2 density, ρ_{CO2}, depends on the pressure in the trap once it is filled with CO_2, and this pressure is not known *a priori* but depends on permeability, relative permeability to formation water and CO_2, dimensions and volume, and the nature of trap boundaries, and may vary with the injection strategy (number and/or inclination of injection wells, etc.). However, this pressure has to be higher than the initial water pressure in the trap, P_i, in order to achieve CO_2 injection, but it has to be lower than the maximum bottomhole injection pressure, $P_{max,}$ that regulatory agencies usually impose in order to avoid rock fracturing or breaching of the capillary seal. Thus, the mass of CO_2 that would be stored in a structural or stratigraphic trap would be between these two limits:

$$\min M_{CO2e} = \rho_{CO2}(P_i, T) \times V_{CO2e} \leq M_{CO2e} \leq \max M_{CO2e} = \rho_{CO2}(P_{max}, T) \times V_{CO2e} \qquad (12)$$

where T is the average temperature in the trap. The mass capacity of a trap may vary in time if pressure varies because, although the volume of the trap remains constant, CO_2 density varies with varying pressure.

Relations (10) – (12) can be applied to both theoretical and effective storage capacity estimates for basin- and regional-scale assessments by applying them individually to all the structural and stratigraphic traps identified as potential candidates for CO_2 storage and summing the resulting individual capacities. They can be applied also to the case of a plume of CO_2 that is not necessarily contained in a stratigraphic or structural trap.

Solubility trapping is based on CO_2 dissolution into formation water, which depends on pressure, temperature and water salinity. Solubility trapping is a continuous, time-dependent process estimated to be most effective over time periods in the order of centuries. Therefore, the CO_2 storage capacity through solubility trapping has to be evaluated for a specified period or periods of time. The rate at which solubility trapping occurs depends principally on the amount of free-phase CO_2 coming into contact with formation water unsaturated with CO_2. Generally, the CO_2 storage capacity through solubility trapping has to be determined through numerical modeling at the local and site-specific scales. However, at the basin- and regional-scale, the theoretical CO_2 storage capacity in solution can be estimated using the relation (after Bachu and Adams, 2003):

$$M_{CO2t} = \iiint \phi(\rho_S X_S^{CO2} - \rho_0 X_0^{CO2})\,dxdydz \qquad (13)$$

where ϕ is porosity, ρ is the density of formation water, X^{CO2} is the carbon dioxide content (mass fraction) in formation water and the subscripts 0 and S stand for initial carbon dioxide content and carbon dioxide content at saturation, respectively. The initial carbon dioxide content and carbon dioxide content at saturation depend on the pressure, temperature and salinity distributions in the aquifer, and, because of their continuous variation, a process of volumetric integration needs to be used. If average values are being used for aquifer thickness and porosity, and for carbon dioxide content in aquifer water (initial and at saturation), then the following simpler relation can be used:

$$M_{CO2t} = A \times h \times \phi \times (\rho_S X_S^{CO2} - \rho_0 X_0^{CO2}) \qquad (13')$$

where A and h are aquifer area and thickness. The effective storage capacity, M_{CO2e}, is determined using a relationship similar to relation (3) for storage capacity in coal beds, and relation (8) for storage capacity in oil and gas reservoirs:

$$M_{CO2e} = C \times M_{CO2t} \qquad (14)$$

where C is a coefficient that includes the effect of all factors that affect the spread and dissolution of CO_2 in the whole aquifer volume under consideration. Given the strong time-dependence of CO_2 dissolution, the coefficient C should arguably be time-dependent. It may be possible to evaluate through numerical simulations a functional expression for the coefficient C, or even just a single value.

USDOE-Proposed Methodology. The USDOE Capacity and Fairways Subgroup proposes the following relation for calculating the volumetric CO_2 storage resource (equivalent to effective storage capacity) in deep saline aquifers:

$$M_{CO2} = A \times h \times \phi \times \rho_{CO2} \times E \qquad (15)$$

where ρ_{CO2} is the average CO_2 density evaluated at pressure and temperature that represents storage conditions anticipated for a specific deep saline aquifer, and E is a storage efficiency factor that reflects the total pore volume filled with CO_2. No distinction is made between CO_2 stored by various mechanisms. Monte Carlo simulations produce a range for E between 1 and 4% of the bulk volume of a deep saline aquifer for a 15 to 85% confidence range, with an average of 2.4% for 50% confidence. In the Monte Carlo simulations that produced the recommended range for E, various calculation components were varied as follows:

- Fraction of the saline aquifer that is suitable for CO_2 storage: 0.2 to 0.8
- Fraction of the geological unit that has the porosity and permeability required for CO_2 injection: 0.25 to 0.75
- Fraction of interconnected porosity: 0.6 to 0.95
- Areal displacement efficiency: 0.5 to 0.8
- Vertical displacement efficiency: 0.6 to 0.9
- Fraction of net aquifer thickness contacted (occupied) by CO_2 as a result of CO_2 buoyancy: 0.2 to 0.6
- Pore-scale displacement efficiency: 0.5 to 0.8.

These ranges of values were chosen to reflect various lithologies and geological depositional systems that occur in North America, with the maximum and minimum meant to be reasonable high and low values for each parameter.

Comparison of the methodologies proposed by the CSLF Task Force and the USDOE Capacity and Fairways Subgroup indicates several analogies and differences:

1) Only volumetric (static) storage of CO_2 in free phase is considered and discussed by the USDOE Capacity and Fairways Subgroup (no CO_2 in solution);
2) On the other hand, unlike the CSLF Task Force, the USDOE Capacity and Fairways Subgroup does not limit the volumetric trapping in deep saline aquifers only to stratigraphic and structural traps; rather the entire aquifer is considered;
3) The effect of irreducible water saturation is not taken into account explicitly in relation (15) proposed by the USDOE Capacity and Fairways Subgroup, but is included in the efficiency factor E through the pore-scale displacement efficiency;
4) The two methodologies are computationally equivalent if $E=C_c \times (1 - S_{wirr})$ and if an average CO_2 density at in-situ conditions is used in relation (12) rather than minimum and maximum values.

Applicability/Screening Criteria. The USDOE Capacity and Fairways Subgroup explicitly recommends considering only saline aquifers (TDS greater than 10,000 ppm) deeper than 800 m (or the necessary depth to ensure that CO_2 is in dense liquid or supercritical phase) that are confined by aquitards or aquicludes (caprock) which include shale, anhydrite and evaporite. The CSLF Task Force did not make any specific recommendations in this regard, these screening criteria being implicit on the basis of the IPCC Special Report on CO_2 Capture and Storage (IPCC, 2005).

4. Conclusions

Carbon dioxide capture and geological storage is a means for reducing greenhouse gas emissions into the atmosphere that, technologically, is immediately available, as demonstrated by analogue commercial-scale operations in CO_2 enhanced oil recovery (EOR), natural gas storage and acid gas disposal, and by several commercial and pilot projects such as Sleipner and In Salah. However, for implementation of this technology at the scale needed to achieve a significant and meaningful reduction in CO_2 emissions, governments and industry need to know more about CO_2 storage capacity within their respective jurisdictions or within economic distance from large CO_2 emitters.

Previous attempts to assess CO_2 storage capacity used a variety of approaches and methodologies, and data sets of variable size and quality, resulting in widely varying estimates of inconsistent quality and reliability. The CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation produced in March 2007 a report in which a consistent set of methodologies for estimating CO_2 storage capacity in coal beds, oil and gas reservoirs and deep saline aquifers was recommended. In parallel, the USDOE Capacity and Fairways Subgroup within the Geologic Working Group of the Regional Carbon Sequestration Partnerships Program developed standards for CO_2 storage estimation for producing a Carbon Sequestration Atlas of the United States and Canada. At the March 2007 CSLF meeting the CSLF Task Force proposed and was given approval to conduct a comparison of the methodologies developed in parallel by the CSLF Task Force and the USDOE Subgroup.

The methodologies proposed by the CSLF Task Force and the USDOE Subgroup are basically identical, with minor differences in regard to computational formulation. In both cases the methods are based on static volumetrics and are applicable to country, regional and basin scale storage capacity estimates. Local and site-specific storage capacity estimates should be based on numerical modeling that takes into account the dynamic aspect of CO_2 injection and of CO_2 plume evolution.

The only difference of significance is that the CSLF Task Force proposed to estimate static CO_2 storage capacity in deep saline aquifers by considering only stratigraphic and structural traps present in these aquifers, while the USDOE Subgroup proposes to consider the entire aquifer, not only the traps (i.e., storage in open systems).

The proposed methodologies are useful in estimating the effective CO_2 storage capacity, before applying regulatory, land use, economic and other constraining overlays. The only regulatory constraint explicitly considered by the USDOE Subgroup is that CO_2 storage should be at depths greater than the depth of protected groundwater, defined by water salinity less than 10,000 mg/l (ppm). This constraint has been recognized also by the CSLF Task Force, but no specific value has been recommended, allowing for each jurisdiction to establish its own.

In certain respects the work of the USDOE Capacity and Fairways Subgroup represents an advance on the work of the CSLF Task Force. Both the CSLF Task Force and the USDOE Subgroup have introduced storage efficiency coefficients in calculations. The CSLF Task Force has not provided values for these coefficients, undertaking to compile a table of values for these coefficients during Phase III based on literature review. Through Monte Carlo simulations of CO_2 storage in coal beds and in deep saline aquifers for conditions characteristic to North America, the USDOE Subgroup obtained a range of values for these storage efficiency coefficients for the 15% and 85% confidence intervals, which are between 0.28 and 0.40 for coal beds, and between 1% and 4% for deep saline aquifers.

In addition, the USDOE Capacity and Fairways Subgroup proposes to use a confidence indicator from 1 (low) to 9 (high) to express the degree of confidence in the CO_2 storage capacity estimates based on the amount and quality of the data used in the estimation, and on the degree of variability in the geological storage environment. The proposed confidence indicator is presented in the following table.

Table 1:
Confidence indicator in CO_2 storage capacity estimates, proposed by the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnership Program

		CONFIDENCE INDICATOR		
Subsurface Heterogeneity	Complex subsurface, numerous structures, highly discontinuous formation properties, typical of tectonically deformed areas	**5**	**3**	**1**
	Moderately heterogeneous subsurface structure and anisotropy, possible to interpolate rock properties for up to 10 miles	**7**	**5**	**3**
	Structural complications are infrequent and range of rock properties can be projected more than 10 miles	**9**	**7**	**5**
Average Well Density		> 1 well/sq. mi.	> 1 well per 9 sq. mi.	> 1 well per 100 sq. mi.
Average Seismic Survey Spacing		> 1 line per 10 miles	> 1 line per 50 miles	> 1 line per 100 miles
		Data Density		

The close similarity between the methodologies for CO_2 storage capacity estimation at the country, regional and basin scales proposed independently by both the CSLF Task Force for Review and Development of Standard Methodology for Storage Capacity Estimation and the USDOE Capacity and Fairways Subgroup within the Geologic Working Group of the Regional Carbon Sequestration Partnerships Program indicates that these methodologies are robust and science-and-engineering based, increasing the degree of confidence in their use and in the results obtained by using them. Application of these methodologies at various appropriate scales should provide decision makers in governments and industry with information needed in assessing the potential for CO_2 geological storage and in focusing further work for site screening and selection. Further work is needed in improving the estimates of storage efficiency coefficients.

5. References

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