IMPROVEMENTS IN THE APPLICATION OF CO_2 STORAGE EFFICIENCY VALUES FOR DEEP SALINE FORMATIONS

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 1 – Deliverable D7

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IMPROVEMENTS IN THE APPLICATION OF CO_2 STORAGE EFFICIENCY VALUES FOR DEEP SALINE FORMATIONS

EXECUTIVE SUMMARY

Throughout the Regional Carbon Sequestration Partnerships (RCSP) Phase III period, the Plains CO_2 Reduction (PCOR) Partnership has continued to refine the characterization of large-scale stationary carbon dioxide (CO_2) sources, geologic sinks, and infrastructure within the PCOR Partnership region. The objective has been to further refine the assessment of the region's CO_2 production and storage potential in an effort to optimize source–sink opportunities within the region. This continued regional characterization feeds into the CO_2 storage resource estimates for the U.S. Department of Energy (DOE) National Energy Technology Laboratory's national atlas and to provide context for extrapolating the results of the large-scale demonstrations.

Through its close involvement with DOE and the international community with respect to the development and use of storage efficiency factors, the PCOR Partnership has accrued valuable insight into the methodologies for CO_2 storage resource and capacity estimations for deep saline formations. This insight has resulted in the development of a workflow that introduces intermediate storage efficiency factors that take into account greater levels of geologic understanding to generate refined CO_2 storage resource values for saline formations. While this investigation does not focus on a site-specific characterization activity, the advancement in the understanding and application of what has become the standard DOE methodology for saline formation CO_2 storage assessment is notable.

The current DOE methodology (U.S. Department of Energy National Energy Technology Laboratory, 2006, 2008, 2010; Goodman and others, 2011) classifies a CO_2 resource as a volume of porous sedimentary rock available for CO_2 storage and accessible to injected CO_2 with current technology. This methodology is not intended for site-specific CO_2 storage capacity assessments. A key aspect of the methodology is the derivation and application of a CO_2 storage efficiency factor that gauges the fraction of the accessible pore volume that will be occupied by the injected CO_2. The efficiency factor is the product of a multiplicative function involving area, thickness, porosity, and volumetric and microscopic displacement terms. The currently published efficiency factors are applicable when a saline formation investigation has only the minimum set of geologic data or when the geologic data set is complete enough to provide net values for area, thickness, and porosity. However, in a more common scenario, the level of geologic detail lies between the two end points, an area where the current sets of storage efficiency factors do not directly apply.

Improvements in the application of the DOE saline storage methodology is founded on the premise that blindly applying the formula to the gross characteristic values of a saline formation will produce results that are frequently misinterpreted. If there is no indication of what geographic extent of the formation is deep enough to sustain supercritical CO_2 and what extent has water salinities greater than 10,000 ppm total dissolved solids, then the formation should not be considered for CO_2 resource evaluation. However, if that information (depth and salinity) is known, then a refined level of storage efficiency factors should be applied. The new intermediate storage efficiency factors result in a nearly threefold increase in storage resource at the P10 confidence level and nearly double the storage resource at the P90 level for clastic formations. The new storage efficiency factors along with a graphical representation of an assessment workflow provide needed guidance and consistency in the derivation of CO_2 storage resource values.

The accompanying report was prepared as a manuscript for submission to the *Journal of Greenhouse Gas Control Technologies*.

Improvements in the Application of CO_2 Storage Efficiency Values for Deep Saline Formations

Abstract
It is important to accurately estimate the effective volumetric (CO_2) storage resource potential of a deep saline formation. As the amount of information about a formation increases, the accuracy of the calculation of storage potential should also increase. A critical component of the CO_2 storage equation is the storage efficiency factor, and new storage efficiency values are presented to accompany an increase in knowledge. A workflow was developed to properly assess the CO_2 storage potential of a deep saline formation using the methodology proposed by the U.S. Department of Energy when used in conjunction with the new storage efficiency values.

1. Introduction

Bradshaw and others (2007) formally identified carbon capture and storage (CCS) in geologic media as an important means for reducing anthropogenic greenhouse gas emissions into the atmosphere. Several categories of geologic media for the storage of carbon dioxide (CO_2) are available, including depleted oil and gas reservoirs, deep saline (brine-saturated) formations, CO_2 flood enhanced oil recovery operations, and enhanced coalbed methane recovery. The U.S. Department of Energy (DOE) is pursuing a vigorous program for demonstration of CCS technology through its Regional Carbon Sequestration Partnership (RCSP) Program, which entered its third phase (Phase III) in October 2007. As one of the seven RCSPs, the Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is assessing the technical and economic feasibility of capturing and storing CO_2 emissions from stationary sources in the central interior of North America. A principal element of the DOE effort is core research and development which includes a significant effort to identify geologic formations that can safely and efficiently store CO_2 over long periods of time. Once identified, the task is to accurately determine the CO_2 storage resource potential of those formations.

The evaluation of potential CO_2 storage targets can differ in terms of scope, budget, and available data; however, the basic calculation of the CO_2 storage capacity is a well-defined task. A target formation's area, thickness, porosity, CO_2 density, and primary reservoir lithology are needed to evaluate the potential for CO_2 storage. Depth and salinity information are needed to determine if a formation is eligible for CO_2 storage, and distributions of porosity/permeability, if known, can refine the CO_2 storage estimate. CO_2 storage resource estimates represent the fraction of pore volume of sedimentary rocks available for CO_2 storage and accessible to injected CO_2.

As defined by DOE, saline formations comprise water-saturated porous and permeable rock capped by one or more regionally extensive low-permeability rock formations. To be assessed for CO_2 storage, the formation water should have a total dissolved solids (TDS) value greater than 10,000 ppm. Deep saline formations exist around the world in sedimentary basins and have the largest potential for storage of anthropogenic CO_2 because of their large pore volume and spatial distribution. This fact, along with the concept that large volumes of CO_2 would need to be stored in order to make a significant reduction in CO_2 emissions require accurate understanding of the CO_2 storage resource available in this geologic media.

The goal of this paper is to provide clarification on the application of the DOE National Energy Technology Laboratory (NETL) saline formation storage resource methodology and introduce new storage efficiency factors. The terms and concepts presented in this paper will provide the user with confidence in performing CO_2 storage resource assessments and help reduce under- or overestimation of the effective CO_2 storage resource potential of a target deep saline formation. For the purposes of this paper, the DOE NETL method was used (U.S. Department of Energy National Energy Technology Laboratory, 2010); however, a similar approach could be used for other volumetric approaches (e.g., Carbon Sequestration Leadership Forum, 2005).

2. Methodology

The current DOE methodology for determining the effective storage resource for a deep saline formation is a volumetric approach that calculates a mass of stored CO_2 based on formation area, thickness, porosity, and CO_2 density with the application of a storage coefficient:

$$MCO_2e = A \times h \times \varphi \times \rho_{CO2} \times E_E \qquad \text{[Eq. 1]}$$

Total area of the formation (A), gross formation thickness (h), and total porosity (φ) parameters result in the calculation of the total bulk volume of pore space. The CO_2 density (ρ) converts the reservoir volume of CO_2 to mass. An effective storage resource is a refinement of the bulk volume of pore space through the inclusion of an efficiency factor that considers technical limitations from a geologic and engineer aspect (Gorecki and others, 2009). The efficiency factor (E_E) considers a series of variables that limit the ability of injected CO_2 to occupy the entire pore space in a given formation. In an open system, it is the portion of the geologic media that is available for CO_2 storage and the fraction of that pore space where CO_2 can displace the original formation fluids (Equation 2). The suitable fraction of the formation volume that is amenable to CO_2 storage (E_{geol}) is the product of the formation's net-to-total area (E_{A_n/A_t}), the net-to-gross thickness (E_{h_n/h_g}), and the effective-to-total porosity ($E_{\varphi_{eff}/\varphi_t}$) (Equation 3).

The suitable portion of the formation (E_{geol}) is the geographic area where depths exceed 800 meters and where the salinity of the formation fluids exceed 10,000 ppm (U.S. Department of Energy, 2008). The 800-meter value represents a general depth that reflects pressure and temperature conditions that yield high-density liquid or supercritical CO_2. Site-specific depths could be deeper or shallower. The 10,000-ppm cutoff is the value defined by the U.S. Environmental Protection Agency for protected underground sources of drinking water (USDW). The second factor in the E_E, the displacement efficiency term (E_D), is divided into the volumetric displacement efficiency term (E_{vol}) and the microscopic displacement efficiency term (E_d). The volumetric displacement efficiency is the combined fraction of the pore volume that can be contacted by CO_2 from injection wells and the fraction of the net thickness that is contacted by CO_2 from injection wells and the fraction of the net thickness that is contacted by CO_2 as a result of the density difference between the injected CO_2 and the formation fluids. The microscopic displacement efficiency represents the fraction of the contacted pore space that can be filled by CO_2 and is directly related to the irreducible water saturation.

There are currently two sets of storage efficiency terms available to use, but two more sets of efficiency terms will be presented. The storage efficiency term selected depends on the type of geologic formation (clastic, dolomite, and limestone) and the amount of information known about the target reservoir.

$$E_E = E_{geol} * E_D \quad \text{[Eq. 2]}$$

$$E_{geol} = E_{A_n/A_t} * E_{h_n/h_g} * E_{\varphi_{eff}/\varphi_{tot}} \quad \text{[Eq. 3]}$$

$$E_D = E_{vol} * E_d \quad \text{[Eq. 4]}$$

2.1 General Concept

Figure 1 represents a hypothetical setting of a geologic formation situated within the confines of a structural basin. As is typical of most sedimentary basins, the formations dip toward the basin center where they are more deeply buried by overlying, younger sediments. A common, but by no means ubiquitous, aspect of sedimentary basins is that the deeper portions are more highly saline.

For this discussion, the formation represented by Region B in Figure 1 has been selected for investigation of potential CO_2 storage using the volumetric methodology described in the DOE National Carbon Sequestration Atlas (U.S. Department of Energy, 2010) and Goodman and others (2011). In this scenario, the variable A_t (total area) in the DOE methodology equation is equivalent to Region B in Figure 1. Following the definitions mentioned earlier, the area of suitable formation is defined as being deep enough for high-density CO_2 and saline enough to avoid protected USDW. The portion of the formation that is deep enough to keep CO_2 in a supercritical phase is depicted as Region C. Within that region is the extent of the formation where salinity values are greater than 10,000 ppm TDS (Region D). Therefore, the target area of the formation that is suitable for CO_2 storage is the intersection of Region C and Region D, which in this case is the same as Region D.

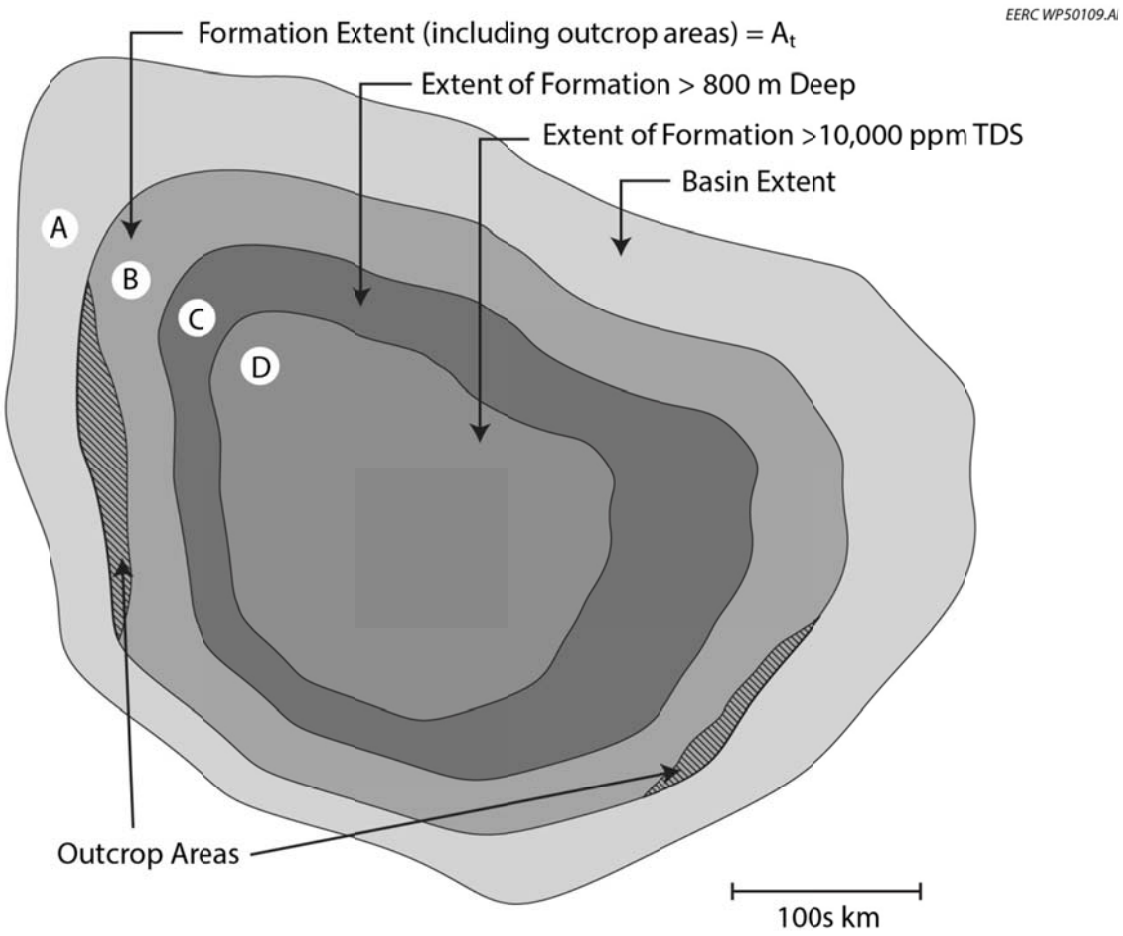

Figure 1. Hypothetical saline formation study area. Suitable formation = the intersection of Areas C and D = A_n.

With reference to the CO_2 storage efficiency formula discussed earlier (Equation 3), the area variable of the set of geologic terms, or the net-to-total area ($E_{An/At}$) ratio, is the fraction of the total basin or region area that is suitable for CO_2 storage. In this case, that ratio is Region D/Region B, and it is a straightforward task to determine net-to-total area because each of the extents has been mapped and is known. The generic DOE formula is intended to be applied when only the total formation area is known (area of Region B). The area variable of the geologic term is formulated to reduce the total area by 20% to 80% (P90 and P10, respectively) (Table 1). The caveat of this approach is that it does not specify where within the total region the area will be cut (or retained). When using a map to depict the results of a CO_2 storage resource assessment using the generic DOE formula, the calculated value would be connected to the entire formation extent (Region B) which gives a false sense of geographic precision. Any attempt to discretize the assessed value across the formation region would be invalid. Because of the inherit levels of misunderstanding that could result from geographic representation of generically derived storage resource values, it may be argued that if the suitable extent (deep enough and saline enough) of a targeted formation is not known, the calculation of a CO_2 storage resource should not be attempted.

Table 1. Parameters for saline formation efficiency

Term	Symbol	P10/P90 Values by Lithology			Description
		Clastics	Dolomite	Limestone	
Geologic Terms Used to Define the Entire Basin or Region Pore Volume					
Net-to-Total Area	$E_{An/At}$	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of total basin or region area with a suitable formation.
Net-to-Gross Thickness	$E_{hn/hg}$	0.21/0.76*	0.17/0.68*	0.13/0.62*	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection.
Effective-to-Total Porosity	$E_{\varphi e/\varphi tot}$	0.64/0.77*	0.53/0.71*	0.64/0.75*	Fraction of total porosity that is effective, i.e., interconnected.
Displacement Terms Used to Define the Pore Volume Immediately Surrounding a Single-Well CO_2 Injector					
Volumetric Displacement Efficiency	E_V	0.16/0.39*	0.26/0.43*	0.33/0.57*	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in situ water.
Microscopic Displacement Efficiency	E_d	0.35/0.76*	0.57/0.64*	0.27/0.42*	Fraction of pore space unavailable because of immobile in situ fluids.

* Values from Gorecki and others (2009).

2.2 Storage Efficiency Values

In many cases, there is enough existing information to determine the extent of a target formation that is >800 meters below ground level (structure maps, well logs, etc.) and delineate the extent of the formation that has salinity levels greater than 10,000 ppm TDS. If this suitable area of formation can be determined, it is unnecessary to determine the total formation extent and, thus, the net-to-total area ratio ($E_{An/At}$) (it effectively becomes one). Instead, a CO_2 storage efficiency factor would be applied to the suitable area. However, as noted by Ellett and others (2013), the DOE methodology does not have the flexibility to assign tighter confidence intervals for resource estimates generated from characterization efforts using richer sources of data. The exception to this is when advanced assessment efforts are used in conjunction with 3-D geocellular modeling and geostatistics. In these cases, net-to-gross thickness $E_{hn/hg}$ and effective-to-total porosity $E_{\varphi e/\varphi tot}$ are determined in addition to the understanding of net area, and the geologic efficiency values for displacement terms can be used directly (Table 2) (Goodman and others, 2011).

The DOE methodology described by Goodman and others (2011) provide a higher set of storage efficiency values for instances where all the net-to-gross parameters are known (Table 2). Conversely, if no net-to-gross parameters are known, the methodology provides a conservative set of storage efficiency values (Table 3). For instances where an intermediate level of data are available (such as knowing the net area), the storage efficiency variables associated with the two extreme cases will under- or overestimate the storage resource. As stated by Ellett and others (2013), a simple disaggregation of the individual efficiency terms is not accurate for calculating probability results (e.g., $P90 \times P90 \times P90 \neq P90$). However, Goodman and others (2011) employed the use of the log odds method (or logistical-normal distribution) to directly integrate P10 and P90 ranges of geologic and displacement parameters. Through this approach, it is a simple task to generate intermediate storage efficiency factors based on an increasing level of knowledge of the target formation (Tables 4 and 5).

As discussed above, if the target formation's net area is known, then the total formation area is essentially irrelevant. The net area, multiplied with the gross thickness and total porosity, will calculate a net pore volume. The revised storage efficiency factor (Table 4) can be applied to the net pore volume (volume that is deeper than 800 meters and TDS values greater than 10,000). The new storage efficiency factor (Goodman, 2014) revised the conservative storage efficiency factor (Table 3) and allows for the use of the net area. The new storage efficiency factor still accounts for the unknown net-to-gross thickness and the unknown effective-to-total porosity.

Table 2. Storage efficiency terms to be used if all net-to-gross terms are known (Goodman and others, 2011)

Lithology	**P10**	**P50**	**P90**
Clastics	7.4%	14%	24%
Dolomite	16%	21%	26%
Limestone	10%	15%	21%

Table 3. Conservative storage efficiency terms used in current DOE method if no net-to-gross terms are known (Goodman and others, 2011)

Lithology	**P10**	**P50**	**P90**
Clastics	0.51%	2.0%	5.4%
Dolomite	0.64%	2.2%	5.5%
Limestone	0.40%	1.5%	4.1%

Table 4. Storage efficiency terms to be used if net area is known (Goodman, 2014)

Lithology	**P10**	**P50**	**P90**
Clastics	1.62%	4.41%	9.53%
Dolomite	2.03%	4.96%	9.11%
Limestone	1.26%	3.38%	6.91%

Table 5. Storage efficiency terms to be used if net area and net thickness of target formation are known (Goodman, 2014)

Lithology	**P10**	**P50**	**P90**
Clastics	5.17%	9.88%	17.24%
Dolomite	9.32%	12.71%	16.93%
Limestone	7.18%	10.43%	14.74%

In the event the investigator knows the net area and the net thickness of the target formation, another set of storage efficiency factors is shown in Table 5 (Goodman, 2014). This set of efficiency values accounts for the unknown effective-to-total porosity. If the investigator knows all of the parameters, net area, net thickness, and effective porosity, then the previously used efficiency values can be used (Table 2).

Comparison of the values shown in Table 3 versus those in Table 4 show that just having an understanding of the area of suitable formation will result in a greater than threefold increase in storage resource value at the P10 confidence level and nearly double the storage resource value at the P90 level. If there is an understanding of the net-to-gross thickness of the formation, such as through previous work or well log interpretation, then the efficiency values shown in Table 5 can be applied and an even higher value (and confidence) of storage resource can be obtained.

2.3 Methodology Workflow

To assist in identifying which efficiency factor to use for the volumetric calculation, a workflow was created to guide users in correctly assessing the formation under investigation (Figure 2). The flow diagram accommodates the integration of formations with either open, closed, or semiclosed boundary conditions. For formations with open boundary conditions, the flow diagram presents multiple decision points based on the level of geologic detail available. The primary decision point inquires whether the net area, net thickness, or effective porosity are known. In a scenario where no net or effective values are known, the flow diagram directs the user to the most conservative efficiency values. In characterization scenarios where one or more of the key variables is known, the flow diagram splits off into one of three other sets of storage efficiency values. All of the paths through the flow diagram for open boundary formations are encountered in CO_2 storage resource calculation efforts. Those investigating potential target formations may know very little about the formation, or they may be investing a large amount of time with an abundance of information. It is common for investigators to have information on the formation's depth and salinity, which allows them to derive the net area. In this case, the more conservative storage efficiency factor should not be used because the net-to-gross factor is known, but there is not enough information known to apply the larger efficiency factors. Therefore, the new efficiency factors shown in the workflow and tables above (Figure 2, Tables 4 and 5) should be used.

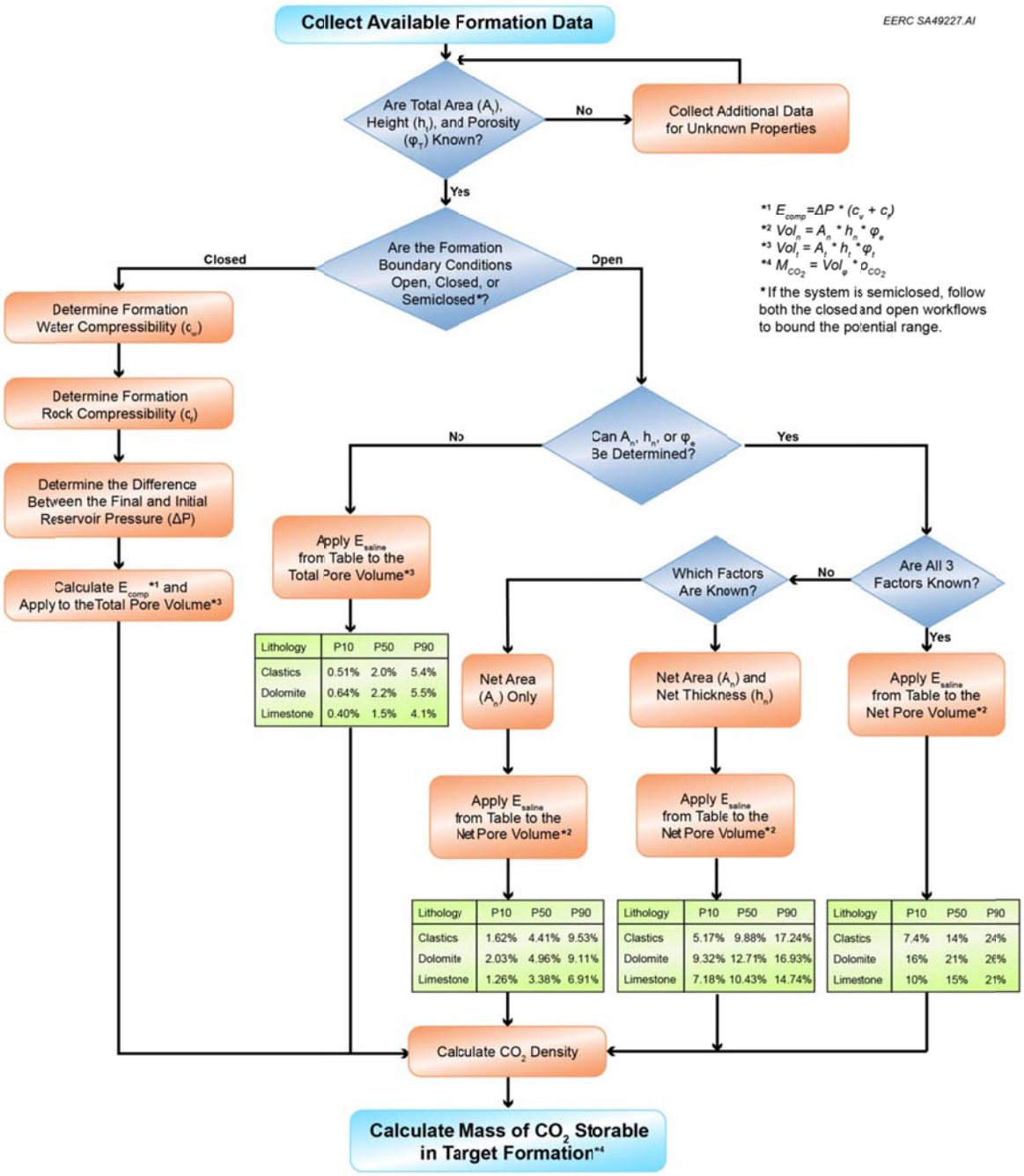

Figure 2. A workflow to estimate CO_2 storage resource in deep saline formations (Peck and others, 2014).

3. Results

The new intermediate storage efficiency factors presented in this study result in a nearly threefold increase in storage resource at the P10 confidence level and nearly double the storage resource at the P90 level. The new storage efficiency factors along with a graphical representation of an assessment workflow provide needed guidance and consistency in the derivation of CO_2 storage resource values.

4. Discussion

The current DOE methodology (U.S. Department of Energy National Energy Technology Laboratory, 2006, 2008, 2010; Goodman and others, 2011) classifies a CO_2 resource as a volume of porous sedimentary rock available for CO_2 storage and accessible to injected CO_2 with current technology. A key aspect of the methodology is the derivation and application of a CO_2 storage efficiency factor that gauges the fraction of the accessible pore volume that will be occupied by the injected CO_2. The efficiency factor is the product of a multiplicative function involving area, thickness, porosity, and, volumetric and microscopic displacement terms. The currently published efficiency factors are applicable when a saline formation investigation has only the minimum set of geologic data or when the geologic data set is complete enough to provide net values for area, thickness, and porosity. However, in a more common scenario, the level of geologic detail lies between the two end points, an area where the current sets of storage efficiency factors do not directly apply.

By being able to identify the area where the target formation meets the depth and salinity requirements (greater than 800 meters and TDS greater than 10,000 respectively), the investigator has defined the suitable area of the target formation. By comparing the suitable area to the total formation area, a net-to-gross ratio can be calculated. However, there is no need to pursue an understanding of the total formation extent; the suitable area is the total area of interest, the area where CO_2 injection could occur. The investigator can now calculate the net pore volume by multiplying the suitable area, average thickness, and average porosity and then applying revised storage efficiency values (Table 4 or Figure 2). The revised storage efficiency values provided will allow investigators to refine and improve their deep saline formation CO_2 storage calculations by eliminating the largest contributing term in the total efficiency factor uncertainty (Ellett and others, 2013), the net-to-total area. The current P10/P90 range for the net-to-total area is 0.2 to 0.8, which exceeds the range of other net-to-gross terms (U.S. Department of Energy, 2010, 2012).

If an investigator has information on the net thickness (in addition to the suitable area), then the storage efficiency factors provided in Table 5 (or Figure 2) allow for an improved CO_2 storage calculation. This set of storage efficiency factors allow for the unknown effective-to-total porosity.

Now that revised storage efficiency numbers are available, investigators will be able to reduce uncertainty and/or avoid errors. Previously, when the net area of the target formation was known, an investigator may have used either the conservative efficiency values (Table 3) or the higher values for when all net-to-gross terms are known (Table 2). The problem with using the net area with the conservative efficiency values is that these values would be reducing the net area again, effectively reducing the area twice from the total formation area. An alternative to this would be to use the total formation area, but this method would unnecessarily introduce uncertainty into the calculation with the range of net-to-total area values of 0.2 to 0.8. If the investigator already has defined the suitable area, then that area would be the more accurate value to use. With the availability of storage efficiency numbers that account for knowing the net area (Table 5), the investigator can arrive at an improved CO_2 storage value.

If the investigator applies DOE's higher-efficiency values (Table 2) when the net target area is known, the calculation would be inaccurate since the higher-efficiency values assume that the net-to-gross thickness and effective-to-total porosity are also known. The investigator cannot use the higher-efficiency values unless there is a more complete data set with all net-to-gross parameters known.

With the introduction of the new storage efficiency values from Goodman (2014), CO_2 storage calculations can be improved as described above and in the workflow diagram (Figure 2). Investigators can apply the appropriate efficiency values for the information they have available for a target formation.

5. Conclusions

Through its close involvement with DOE and the international community with respect to the development and use of storage efficiency factors, the PCOR Partnership has accrued valuable insight into the methodologies for CO_2 storage resource and capacity estimations for deep saline formations. This insight has resulted in the development of a workflow that introduces intermediate storage efficiency factors that take into account increased levels of geologic reconnaissance (e.g., the geographic distribution of salinity and depth values) to generate refined CO_2 storage resource values for saline formations. While this investigation does not focus on a site-specific characterization activity, the advancement in the understanding and application of what has become the standard DOE methodology for saline formation CO_2 storage assessment is notable.

Improvements in the application of the DOE saline storage methodology are founded on the premise that simply applying the formula to the gross characteristic values of a saline formation will produce results that are frequently misinterpreted. To avoid these misinterpretations, a formation should not be considered for CO_2 resource evaluation if there is no indication of what geographic extent is deep enough to sustain supercritical CO_2 and what portion of the reservoir extent has water salinities greater than 10,000 ppm TDS. In cases where that information (depth and salinity) is known, then a refined level of storage efficiency factors should be applied.

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References

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N.P., and Mathiassen, O.M., 2007, CO_2 storage capacity estimation—issues and development of standards: International Journal of Greenhouse Gas Control I., Elsevier, p. 62–68.

Carbon Sequestration Leadership Forum, 2005, A task force for review and development of standards with regards to storage capacity measurement—Phase I: CSLF-T-2005-9 15, 8 August 2005, 16 p., www.cslforum.org/publications/documents/PhaseIReportStorageCapacityMeasurementTaskForce.pdf (accessed July 2014).

Ellett, K., Zhang, Q., Medina, C., Rupp, J., Wang, G., and Carr, T., 2013, Uncertainty in regional-scale evaluation of CO_2 geologic storage resources–comparison of the Illinois Basin (USA) and the Ordos Basin (China): Energy Procedia, v. 37, p. 5151-5159.

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., and Guthrie, G., 2011, U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control, v. 5, no. 4, p. 952–965.

Goodman, Angela, 2014, U.S. Department of Energy National Energy Technology Laboratory. Personal communication.

Gorecki, C.D., Sorensen, J.A., Bremer, J.M., Knudsen, D.J., Smith, S.A., Steadman, E.N., and Harju, J.A., 2009, Development of storage coefficients for determining the effective CO_2 storage resource in deep saline formations: Presented at the Society of Petroleum Engineers International Conference on CO_2 Capture, Storage, and Utilization, San Diego, California, November 2–4, 2009, SPE 126444.

Peck, W.A., Glazewski, K.A., Klenner, R.C.L., Gorecki, C.D., Steadman, E.N., and Harju, J.A., 2014, A workflow to determine CO_2 storage potential in deep saline formations. Energy Procedia, in review.

U.S. Department of Energy National Energy Technology Laboratory, 2006, Carbon sequestration atlas of the United States and Canada (1st ed.).

U.S. Department of Energy National Energy Technology Laboratory, 2008, Carbon sequestration atlas of the United States and Canada (2nd ed.).

U.S. Department of Energy National Energy Technology Laboratory, 2010, Carbon sequestration atlas of the United States and Canada (3rd ed.).

U.S. Department of Energy National Energy Technology Laboratory, 2012, Carbon sequestration atlas of the United States and Canada (4th ed.).