International Journal of Greenhouse Gas Control 54 (2016) 242–249

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Prospective CO_2 saline resource estimation methodology: Refinement of existing US-DOE-NETL methods based on data availability

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ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 2 September 2016
Accepted 9 September 2016

Keywords:
CO_2 resource estimation
CO_2 sequestration
Geologic storage
Saline formations
Data availability

ABSTRACT

Carbon storage resource estimation in subsurface saline formations plays an important role in establishing the scale of carbon capture and storage activities for governmental policy and commercial project decision-making. Prospective CO_2 resource estimation of large regions or sub-regions, such as a basin, occurs at the initial screening stages of a project using only limited publicly available geophysical data, i.e. prior to project-specific site selection data generation. As the scale of investigation is narrowed and selected areas and formations are identified, prospective CO_2 resource estimation can be refined and uncertainty narrowed when site-specific geophysical data are available. Here, we refine the United States Department of Energy – National Energy Technology Laboratory (US-DOE-NETL) methodology as the scale of investigation is narrowed from very large regional assessments down to selected areas and formations that may be developed for commercial storage. In addition, we present a new notation that explicitly identifies differences between data availability and data sources used for geologic parameters and efficiency factors as the scale of investigation is narrowed. This CO_2 resource estimation method is available for screening formations in a tool called CO_2-SCREEN.

1. Introduction

Since 2007, the United States Department of Energy – National Energy Technology Laboratory (US-DOE-NETL) Carbon Storage Program and the Regional Carbon Sequestration Partnerships (RCSPs) have developed a series of Carbon Atlases approximately biannually (US-DOE-NETL, 2007, 2008, 2010, 2012, 2015). Within each Carbon Atlas, prospective CO_2 storage resources are quantified for the United States and parts of Canada and Mexico. As stated in the first Carbon Atlas (US-DOE-NETL, 2007), "The purpose of storage estimates developed using these methodologies is to provide a high-level inventory of the subsurface volume to store CO_2 in the United States and Canada. This information can be used by the general public, elected officials, and planners." Goodman et al. (2011) presented the US-DOE-NETL CO_2 storage resource estimation methodologies and methods for deep saline formations, depleted conventional oil and gas reservoirs, and unmineable coal seams, and Levine et al. (2016) presented a methodology for shale formations. Methods, their updates, and the overall methodologies are also contained in the Carbon Atlases, with revisions being adopted as improvements are made to reduce uncertainties in resource estimation. Extensive information regarding carbon storage practices can also be found in the US-DOE-NETL Carbon Storage Best Practices Manuals (US-DOE-NETL, 2013). Other groups such as the Unites States Geological Survey (USGS) and Carbon Sequestration Leadership Forum (CSLF) have also presented CO_2 storage assessment methods (Bachu, 2008; Zhou et al., 2008; Burruss et al., 2009; Brennan et al., 2010; Szulczewski et al., 2012; Blondes et al., 2013).

The US-DOE-NETL resource estimation methodology for saline formations uses a volumetric-based approach, whereby the maximum available pore volume is calculated from known or estimated geologic and reservoir parameters. This initial volume is then reduced by applying efficiency factors to represent practical and physical limitations, e.g. unfavorable geology or uncertainties in multiphase transport processes (Goodman et al., 2011). An efficiency factor is applied to gauge the fraction of the total pore volume that will be accessible to CO_2 storage.

The US-DOE-NETL methods are intended for application by interested users globally, and are therefore purposefully relatively simple. At initial stages of exploration of large regions or sub-regions, such as a sedimentary basin, prospective resource estimation relies on limited or unavailable geologic data. Therefore, assumptions must be made regarding formation and petrophysical

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http://dx.doi.org/10.1016/j.ijggc.2016.09.009
1750-5836/Published by Elsevier Ltd.

properties either from sparse geophysical data or by extrapolation from regional or national data. As the scale of investigation is narrowed down to a selected area that might be developed for commercial storage, more detailed geologic characteristics of the target storage formation may become available. These higher resolution geologic data provide the opportunity to refine prospective storage estimates and reduce associated uncertainty. A comparison study showed that uncertainties in geological properties cause greater impact on prospective storage resource estimates than the choice of estimation method (Goodman et al., 2013). Other research groups have worked to refine prospective storage estimates when detailed geologic properties are available and identified a need for procedures to reduce uncertainty in storage estimates as more geologic data are available (Frailey and Finley, 2009; Ellett et al., 2013; Liu et al., 2013; Peck et al., 2014). Currently no method or standard exists that quantifies and reduces uncertainty that comes with increased geological data as prospective storage resource is refined from large regional or sub-regional assessments to selected area or specific site assessments (Goodman et al., 2011; Blondes et al., 2013).

In this paper, we first provide an overview of the US-DOE-NETL saline resource estimation methodology for screening potential regions and sub-regions. Then, we emphasize how the availability of geologic data changes the choice of datasets used to generate petro-physical parameters and efficiency factor values. These underlying principles are then used to present refinements and improvements to the existing methodologies for prospective resource estimation. Specifically, we refine the United States Department of Energy – National Energy Technology Laboratory (US-DOE-NETL) methodology as the scale of investigation is narrowed from very large regional assessments down to selected areas and formations that may be developed for commercial storage. In addition, we present a new notation that explicitly identifies differences between data availability and data sources used for geologic parameters and efficiency factors as the scale of investigation is narrowed. Finally, this refined CO_2 resource estimation method is made publicly available in a tool named CO_2-SCREEN to calculate prospective CO_2 storage resource (Sanguinito et al., 2016).

2. Data availability and scale of investigation

Screening methods for large regions or sub-regions, such as a sedimentary basin, are designed to produce likely estimates of storage resource that are needed for broad energy-related requirements and climate stabilization (Bachu, 2015). As estimates are further refined based on improved geologic interpretation, resource assessments should progress from coarse volumetric screening approaches towards more precise numerical-based modeling to predict CO_2 storage resource. This is analogous to the methodology process used by the oil and gas industry. Gorecki et al. (2015) also advised parallels with the oil and gas industry for refining storage estimates. Initial CO_2 storage efficiency factors for regional scale assessments are designed to produce most likely estimates for the total region being assessed and are then refined as specific subsets of the total region are being assessed when more detailed information becomes available. Bachu (2015), Gorecki et al. (2015) and Thibeau et al. (2014) emphasized the fact that the oil and gas industry needed more than a hundred years to advance to secondary recovery (pressure maintenance), followed by tertiary recovery (enhanced oil recovery) and that CO_2 storage may follow a similar path, optimizing to commercial scale storage (Green and Willhite, 1998).

When estimating prospective CO_2 storage, regional geologic data, regional site data, and social data (defined below and detailed in Table 1) should be considered (US-DOE-NETL, 2013). Regional geologic data are analyzed to identify geologic formations suitable for storage at depths capable of maintaining CO_2 in a dense state with one or more impermeable confining layers to contain the CO_2 and protect Underground Sources of Drinking Water (USDW) (US-DOE-NETL, 2013). Regional site data should consider any proximity issues to the storage area in terms of protected and sensitive areas, population centers, and available resources (US-DOE-NETL, 2013). Social data considers public implications such as land ownership, pore space ownership, permitting and approval processes, and government structures (US-DOE-NETL, 2013). Specifically, demographic trends and land use should be evaluated and considered.

Data availability and specificity vary considerably from very large regional assessments down to selected areas that may be developed for commercial storage. While the framework for the volumetric equation and screening criteria are similar, the level of detail, data availability, and data sources at a selected area will be much greater than what is available for very large regions. For regional estimates, geologic data are typically limited, unavailable, or poorly distributed creating inherent uncertainty. Assumptions must be made regarding formation and petrophysical properties either from sparse, location-specific geophysical data or by geostatistical extrapolation from regional or national data. As selected areas and formations are identified, prospective resource estimates will be refined based on confirmation of existing data analysis and enhanced with additional subsurface geologic data analyzed by advanced geologic and geostatistical techniques.

3. Methodology vs. method

The distinction between a methodology and a method is important for the purposes of this paper. A methodology is a body of methods, rules, and conceptual modes of thinking that provide the theoretical basis underlying an analysis. By comparison, a method is a particular application of a methodology, with a specific and defined algorithm for computing a particular number. For example, the US-DOE-NETL resource estimation methodology for saline formations is a volumetric analysis, meaning that it is based on estimating the fraction of a given volume that can be filled with CO_2 while the method consists of a specific equation with specific geologic terms and efficiency values determined in a specific manner that are applied to estimate prospective storage (Goodman et al., 2011).

4. US-DOE-NETL methodology and method for screening potential regions and sub-regions

The US-DOE methodology and method is detailed in a previous paper and describes how to screen potential sub-regions, such as a sedimentary basin, by estimating the CO_2 prospective storage resource (Goodman et al., 2011). The method is intended to be applied to a region of interest when subsurface geologic data are sparse and limited. The total pore volume available for CO_2 storage is estimated by using average values for geologic properties such as total formation area, gross thickness, and total porosity. An efficiency factor is applied to gauge the fraction of the total pore volume that will be accessible to CO_2 storage at a regional to national scale.

For CO_2 storage, the region selected will contain saline formations which are composed of water-saturated, porous rock sealed by one or more regionally extensive low-permeability caprock formations. A saline aquifer is defined by the EPA as containing formation water with a total dissolved solids (TDS) content greater than 10,000 parts per million or ppm (EPA, 2010). The region defined for CO_2 storage may include one or multiple formations. Even with limited geologic characterization, there is a reasonable

Table 1
Guidelines for Site Screening (US-DOE-NETL, 2013).

Component	Element	Guidelines for site screening
Regional Geologic Data: Subsurface Data Analysis	Injection Formation(s)	Identify regional and sub-regional injection formation types. Utilize readily accessible data from public sources (e.g., state geological surveys, NATCARB, the Regional Sequestration Partnerships, published and open-file literature, academic sources) or acquired from private firms. Data gathered should include regional lithology maps, injection zone data (thickness, porosity, permeability), structural maps, information about structure closure and features that might compartmentalize the reservoir such as stratigraphic pinch outs, regional type logs, offset logs, petrophysical data, and regional seismicity maps
	Adequate Depth	Assessment of minimum depth of the injection zone to protect USDWs is required; in addition depths greater than 800 m generally indicate CO2 will be in a supercritical state and may be more cost-effectively stored. Shallow depths (generally <800 m) may add to the risk profile because (1) CO2 could be in gas phase and (2) the injection zone may be closer to USDW
	Confining Zone	Candidate injection zones should be overlain by a confining zone comprised of one or more thick and impermeable confining intervals of sufficient lateral extent to cover the projected aerial extent of the injected CO2. Confining zones can be identified on a regional basis from the same types of information used to identify injection formations. Wells that penetrate potential confining zones should be identified and included in the risk assessment; this information can be obtained from state oil and gas regulatory agencies. Faulting and folding information that may impact confining zone integrity should be mapped along with potential communication pathways. Confining zone integrity may be validated by presence of nearby hydrocarbon accumulations
	Prospective Storage Resources	Candidate CO2 storage formations should contain sufficient Prospective Storage Resources beneath a robust confining zone for the volume of CO2 estimated during Project Definition and the displaced fluids while maintaining acceptable pressure limits. Prospective Storage Resources (and injectivity if permeability data are available) should be estimated at the sub-regional scale utilizing existing data (e.g., NATCARB, and state geological surveys) to populate basic numerical models
Regional Site Data: Regional Proximity Analysis	Protected and Sensitive Areas	Identify environmentally sensitive areas using U.S. Environmental Protection Agency, U.S. Department of Interior, U.S. Forest Service and U.S. Bureau of Land Management GIS systems. Assess the potential for conflicts with siting of pipeline routes, field compressors and injection wells. In addition, evaluate potential for other surface sensitivities utilizing maps for other hazards (e.g., flood, landslide, and tsunami)
	Population Centers	Identify population centers using state and federal census data. Assess the potential for conflicts with siting of carbon storage projects
	Existing Resource Development	Identify existing resource development, including wells that penetrate the confining zone, using data from state and federal oil and gas, coal, mining and UIC and natural resource management offices. Assess the potential for conflicts between siting of carbon storage projects and existing or prospective mineral leases as well the availability of complementary or competing infrastructure
	Pipeline ROWs	Identify all pipelines and gathering lines/systems. Assess potential for conflicts in routing of pipelines to carbon storage projects as well as the potential for use or access to existing pipeline right-of-ways (ROWs). Identify other ROWs (e.g., power lines, RR's highways) and assess potential for synergies or conflicts in siting carbon storage projects. This data can be found through commercial and government sources
Social Data: Social Context Analysis	Demographic Trends	Describe communities above and near candidate Sub-Regions by evaluating readily available demographic data and media sources. To the extent possible, assess public perceptions of carbon storage and related issues; develop an understanding of local economic and industrial trends; and begin to identify opinion leaders
	Land Use: Industrial and Environmental History	Describe the trends in land use, industrial development and environmental impacts in communities above or near candidate Sub-Regions by evaluating sources such as online media sites, regulatory agencies, corporate websites, local environmental group websites, and other sources. Begin to assess community sensitivities to land use and the environment
Complete Site Screening	Selected Area	Develop a list of potential Selected Areas and rank based on criteria established in Project Definition

degree of confidence that the selected region will meet the following criteria: (1) pressure and temperature conditions in the saline formation are adequate to keep the CO_2 in a supercritical state, which requires hydrostatic pressures that typically occur at or below a depth of 800 m; (2) a suitable seal system, such as a caprock, is present to limit vertical flow of the CO_2 to the surface; and (3) a combination of hydrogeologic boundary and low flow conditions will isolate the CO_2 within the saline formation as a limited plume.

The volumetric approach to estimate prospective mass CO_2 storage resource (G_{CO_2}) for geologic storage in saline formations is described by Eq. (1) and Table 2:

$$G_{CO_2} = A_t h_g \phi_t \rho E_{saline} \quad (1)$$

Table 2
Definition of parameters used in Eq. (1) for estimating prospective CO_2 storage resources in saline formations for potential regions and sub-regions (Goodman et al., 2011).

Parameter	Units[a]	Description
G_{CO_2}	M	Mass estimate of saline formation CO_2 storage resource
A_t	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A_t
ϕ_t	L^3/L^3	Total porosity in volume defined by the net thickness
ρ	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over h_g and A_t
E_{saline}	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2

[a] L is length; M is mass.

In this approach, geologic data are assumed to be limited, thus the total area (A_t), gross thickness (h_g), and total porosity (ϕ_t) of the formation are multiplied to account for the total bulk volume of pore space available (Eq. (1) and Table 2). CO_2 density (ρ) is estimated at storage depth using temperature and pressure and converts the CO_2 reservoir volume to mass. At this level of screening, average, deterministic values for A_t, h_g, ϕ_t, and ρ are applied in the equation. Storage efficiency (E_{saline}) reduces the total pore volume that will be accessible to CO_2 storage at a regional to national scale. Efficiency factors were estimated by stochastic methods for the following three lithologic classes: clastics, dolomites, and limestones and range between 0.40 and 5.5% over the 10th–90th percent probability range. It is important to note that efficiency factors are not solely dependent upon lithology and that other factors such as depositional environment, formation structure, formation depth, and other parameters need to be considered when estimating storage efficiency (Blondes et al., 2013; Szulczewski and Juanes, 2009).

5. US-DOE-NETL methodology and method for screening selected areas

5.1. Methodology for estimating prospective CO_2 storage resource of selected areas

As presented here, the refined US-DOE-NETL methodology for selected areas, such as a formation, identifies pore space available for CO_2 storage based on increased data availability and advanced geologic interpretation. The volumetric approach to estimate prospective mass CO_2 storage resource (G) of the selected area, such as a formation, is described by Eqs. (2) and (3) and Table 3:

$$G = A^d h^s \phi^s \rho^s E_{saline}{}^s \tag{2}$$

and

$$E_{saline}{}^s = E_A{}^s E_h{}^s E_\phi{}^s E_V{}^s E_d{}^s \tag{3}$$

Superscripts (d) and (s) are used herein to denote whether a variable is treated deterministically (d) or stochastically (s). In this approach, geologic data are assumed to be available, allowing variables with sufficient data to be treated stochastically and be defined by the data available. Area (A^d) defines the geographical area of the formation that will be assessed for CO_2 storage, thickness (h^s) defines the thickness of the formation for CO_2 storage defined by (A^d), and porosity (ϕ^s) is the pore space in the formation defined by (A^d). CO_2 density (ρ^s) is evaluated at h^s pressure and temperature that represents storage conditions for A^d and h^s. Storage efficiency ($E_{saline}{}^s$) reflects a fraction of the total pore volume that is filled by CO_2. The net-to-total area term ($E_A{}^s$) represents the fraction of the geologic area accessible for CO_2 storage at the top of the formation, the net-to-gross thickness ($E_h{}^s$) term represents the fraction of thickness of the formation of interest that will be accessible for CO_2 storage, the effective-to-total porosity ($E_\phi{}^s$) term represents the fraction of total porosity that can effectively store CO_2, the volumetric displacement ($E_V{}^s$) term represents the combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and the fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in-situ water, and the microscopic displacement term ($E_d{}^s$) represents the fraction of pore space unavailable due to immobile in-situ fluids which is typically residual water saturation.

In this refined method for selected areas, such as a formation, A^d is treated deterministically and h^s, ϕ^s, ρ^s, and $E_{saline}{}^s$ are treated stochastically. For h^s, ϕ^s, and ρ^s the mean and standard deviation are calculated based on available geologic data and an appropriate distribution is selected that best represents the geologic interpretation (SPE/WPC, 2001). Storage efficiency ($E_{saline}{}^s$) is estimated by Monte Carlo sampling where $E_A{}^s$, $E_h{}^s$, $E_\phi{}^s$, $E_V{}^s$, and $E_d{}^s$ are based on geologic properties of the formation instead of extrapolated values from national or regional data.

For selected areas (i.e. a formation) – area, thickness, and porosity can be constrained by more detailed geologic interpretation such as identifying zones of higher porosity within the formation and the presence of low porosity zones occluded by secondary minerals or non-mobile fluid saturation. The area (A^d) of the potential storage unit is treated deterministically and should be well defined at this phase of a CO_2 storage project. Thickness (h^s) and porosity (ϕ^s) should be represented stochastically with a probability distribution (i.e. log-normal) that best represents available data and geologic interpretation. Thickness and porosity data points may not be evenly distributed across the formation and may be spatially grouped, requiring the use of geostatistics to interpolate between data points (Jensen et al., 2000; Diggle and Ribeiro, 2007; Webster and Oliver, 2007; Brennan et al., 2010). Oil and gas industry guidance on selecting distribution functions, recommends that distribution choice be based on the best fit to the geologic data (SPEE, 1988, 2001). Normal, lognormal, or other appropriate probability distributions are selected to reflect underlying uncertainty in the data. Triangular distributions are useful when data are extremely limited. A uniform distribution is applied when a probability distribution cannot be determined (SPE/WPC, 2001; Demirmen, 2007). CO_2 density in the storage formation should be based on in-situ conditions of pressure and temperature and be treated stochastically (Ellis and Singer, 2008).

5.2. Storage efficiency

A recent review article by Bachu (2015) summarizes the development of CO_2 storage efficiency estimations in deep saline formations since 2007. Storage efficiency represents the pore space

Table 3
Definition of parameters used in Eqs. (2) and (3) for estimating prospective CO_2 storage resources in saline formations for selected areas.

Parameter	Description
G	Mass estimate of saline formation CO_2 storage resource
A^d	Geographical area that defines the formation being assessed for CO_2 storage
h^s	Thickness of saline formation for which CO_2 storage is assessed as defined by A^d
ϕ^s	Porosity is the volume of void space per volume of rock
ρ^s	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over h^s and A^d
${E_{saline}}^s$	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2
Geologic terms used to define the selected area pore volume	
${E_A}^s$	Net-to-Total Area: Fraction of the geologic area accessible for CO_2 storage at the top of the formation
${E_h}^s$	Net-to-Gross Thickness: Fraction of thickness of the formation of interest that will be accessible for CO_2 storage
${E_\phi}^s$	Effective-to-Total Porosity: fraction of total porosity that can effectively store CO_2
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector	
${E_V}^s$	Volumetric Displacement Efficiency: Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and the fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in-situ water
${E_d}^s$	Microscopic Displacement Efficiency: Fraction of pore space unavailable due to immobile in-situ fluids (typically residual water saturation)

accessible to CO_2. Not all pore space will come in contact with CO_2 or be saturated by CO_2 due to geologic heterogeneity, and occupied pore volume depends on properties of the storage formation and seal, storage operations, and regulatory and legal constraints. Efficiency factors also vary temporally and spatially, and it is important to note that the scale of the assessment also affects the storage efficiency. When screening large regions or sub-regions, efficiency factors are smaller as the region of interest is not well characterized. For selected areas and specific sites, efficiency factors will approach 1 as more detailed geologic analysis and tools are available to screen portions amenable to CO_2 storage and reductions in pore volume are incorporated in storage parameters A^d, h^s, and ϕ^s rather than corresponding efficiency factors. In general, efficiency factors should be based on documented geologic interpretation as there is not a standard set of efficiency factors available. Bachu (2015) concluded that storage efficiency values have a large range, between <1 to >10%.

In US-DOE-NETL storage methods, storage efficiency is estimated after CO_2 injection is completed by a log odds approach using Monte Carlo sampling where the low and high estimated probability values are based on the P_{10} and P_{90} confidence interval (Goodman et al., 2011). Statistical inputs to predict appropriate ranges for efficiency factors are currently available from the database created by the International Energy Agency (IEA) (GHG, 2009). This database supplies ranges of variables needed to calculate storage efficiency for different lithologies and depositional environments based on numerical simulations of oil and gas reservoir field data. It is important to note that while statistical ranges for efficiency factors are available for lithology and depositional environment, other factors such as geologic structure (i.e. anticlines, synclines, and domes), formation depth, and other parameters need to be considered when estimating prospective storage resources. It is best to rely on intrinsic geologic properties when assigning statistical ranges for storage efficiency.

For selected areas, the efficiency term ${E_A}^s$ includes any processes or limiting criteria that occur on the horizontal scale, while the thickness efficiency term, ${E_h}^s$, incorporates any vertical processes. Porosity efficiency (${E_\phi}^s$) modifies porosity for the selected area. The efficiency term ${E_A}^s$ represents a reduction in the available storage area from a map view perspective of the formation after considering subsurface data analysis, regional proximity analysis, and social context analysis (see Table 1) (US-DOE-NETL, 2010). Factors to consider include: injection formation type, protected and sensitive areas, population centers, existing resource development, pipeline right-of-ways, demographic trends, and land use history (see Table 1). The efficiency term, ${E_h}^s$ represents limits placed on storage as a function of depth. Factors to consider are as follows: injection formation characteristics such as porosity and permeability heterogeneities, lithology, structure, seismicity; depth requirements for supercritical or liquid CO_2 storage; and whether an adequate confining zone is present (See Table 1). These efficiency terms, therefore, include the large scale distinctions defined in Table 1 that are not already accounted for in the geologic analysis of area (A^d), thickness (h^d), and porosity (ϕ^s) which further reduce the volume accessible for CO_2 storage.

Based on the confidence and completeness of the geologic information available for (A^d), (h^d), and (ϕ^s), efficiency terms for $\left({E_A}^s\right)$, $\left({E_h}^s\right)$, and $\left({E_\phi}^s\right)$ may not be needed. If the geologic analysis and interpretation is complete and the pore volume available to CO_2 storage has been identified, the efficiency term(s) can be eliminated by assigning the appropriate factor(s) equal to one. If the geologic data set and analysis are partially complete, a user specified efficiency range may be applied for area (${E_A}^s$), thickness (${E_h}^s$), and porosity $\left({E_\phi}^s\right)$ based on the intrinsic geologic properties available and further geologic interpretation.

The volumetric efficiency term (${E_V}^s$) captures the "sweep efficiency" defined as the fraction of a given well-scale or multi-well field-scale volume efficiency relative to the ideal efficiency of perfect displacement of the connate fluid. It includes various complex processes occurring at a variety of scales including multi-well geometry and pressure management, gravity/buoyancy effects, multiphase fluid saturation gradients as a function of radial and vertical distance, pore-scale petrophysics, and wettability-controlled pore-scale fluid occupancy and saturation. All these processes are tied to relative permeability and fluid mobility, which are often hysteretic functions of brine drainage and post-drainage re-imbibition. The displacement efficiency term, ${E_d}^s$, captures the fraction of the CO_2 contacted, water-filled pore volume that can be replaced by CO_2. Ranges for ${E_V}^s$ and ${E_d}^s$ should only be modified with detailed reservoir simulation results when well or field data are available.

5.3. Method for estimating prospective CO_2 storage resource of selected areas (CO_2-SCREEN method and tool)

CO_2-SCREEN (CO_2 Storage Prospective Resource Estimation Excel aNalysis) is an Excel based method and tool developed by the US-DOE-NETL to screen geologic formations by applying the aforementioned refined US-DOE-NETL methodology for selected areas

1

General Information	
Researcher Name	User Name
Formation Name	Example Formation
Date	1/1/2016
Run ID	123-Clastics

2

Storage Efficiency Factors

Auto-populate: Choose lithology and depositional environment

User Specified: Directly enter P_{10} and P_{90} values

Lithology and Depositional Environment	Clastics: Shallow Shelf

	Auto-populated		User Specified					
	P_{10}	P_{90}	P_{10}	P_{90}	X_{10}	X_{90}	μ_x	σ_x
Net-to-Total Area	0.20	0.80	0.75	0.75	1.10	1.10	1.10	0.00
Net-to-Gross Thickness	0.21	0.76	0	0	-1.32	1.15	-0.09	0.97
Effective-to-Total Porosity	0.62	0.78	0	0	0.49	1.27	0.88	0.30
Volumetric Displacement	0.18	0.63	0	0	-1.52	0.53	-0.49	0.80
Microscopic Displacement	0.39	0.82	0	0	-0.45	1.52	0.53	0.77

3

Physical Parameters

Mean and standard deviation values for each grid

Grid #	Area* (km^2)	Gross Thickness* (m)		Total Porosity* (%)		Pressure† (MPa)		Temperature† (°C)	
	Mean	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
1	100	50	5	10	3	25	0	100	5
2	100	50	5	10	3	25	0	100	5
3	100	75	7	6	2	25	0	100	5
4	100	75	7	6	2	25	0	100	5

Fig. 1. Inputs tab displaying data for the Example Formation example in CO_2-SCREEN.

Prospective CO_2 Storage Resource

Information

Researcher Name	Jane Doe
Formation Name	Example Formation
Date	5/27/2016
Depositional Environment	Clastics: Shallow Shelf
Number of Grids	4

CO_2 Storage Statistics

	P10	P50	P90	
Summed CO_2 Total	16.29	53.57	141.23	Mt
Average CO_2 per Grid	4.07	13.39	35.31	Mt
Summed CO_2 Total	0.016	0.054	0.141	Gt
Average CO_2 per Grid	0.004	0.013	0.035	Gt

Grid	P10	P50	P90
1	4.340	14.189	37.453
2	4.380	14.140	36.725
3	3.734	12.682	33.592
4	3.839	12.559	33.460
5	0.000	0.000	0.000
6	0.000	0.000	0.000
7	0.000	0.000	0.000
8	0.000	0.000	0.000
9	0.000	0.000	0.000
10	0.000	0.000	0.000
11	0.000	0.000	0.000
12	0.000	0.000	0.000
13	0.000	0.000	0.000
14	0.000	0.000	0.000
15	0.000	0.000	0.000
16	0.000	0.000	0.000
17	0.000	0.000	0.000
18	0.000	0.000	0.000
19	0.000	0.000	0.000
20	0.000	0.000	0.000

Fig. 2. The CO_2 storage resource results for the Example Formation scenario in CO_2-SCREEN.

(Sanguinito et al., 2016). CO_2-SCREEN is a tool designed to calculate prospective CO_2 storage resources for geologic formations from very large regional assessments down to selected areas that may be developed for commercial storage. This tool provides an interactive version of the US-DOE-NETL methodology described in this paper for refining prospective CO_2 storage resource in saline formations based on increased data availability and advanced geologic interpretation. CO_2-SCREEN is free and available for public use and can be accessed live on the NETL Energy Data eXchange (EDX) website (https://edx.netl.doe.gov/organization/co2-screen) (Sanguinito et al., 2016).

CO_2-SCREEN is comprised of two files: an Excel file used for inputs and outputs and a GoldSim Player file used to run Monte Carlo simulations. The Excel file allows a user to input subsurface geological physical parameter values, establish ranges for storage efficiency factors and set various formation-related parameters corresponding to depositional environments and intrinsic formation properties. The GoldSim Player file accesses the saved input data in the Excel file, calculates probability estimates for CO_2 storage using Monte Carlo methods, and outputs these values back into the Excel file.

The following is a brief example of how to use the CO_2-SCREEN tool but users are encouraged to see Sanguinito et al. (2016) for a comprehensive guide on using CO_2-SCREEN and its capabilities. An example input scenario for a synthetic formation named the Example Formation is shown in Fig. 1. The first step in using CO_2-SCREEN is entering general information (Fig. 1, Box 1). Next, a user has the option of choosing a lithology and depositional environment associated with their formation. Here, a clastics lithology and shallow shelf depositional environment are chosen for the Example Formation (Fig. 1, Box 2). This choice auto-populates P_{10} and P_{90} values for all five efficiency factors based on ranges calculated by the IEA (GHG, 2009). Users have the option of forgoing the auto-populated values and inputting their own P_{10} and P_{90} ranges for the storage efficiency factors. Finally, the user enters physical parameter data (Fig. 1, Box 3). The Example Formation was divided into four grids to account for geologic heterogeneity within the formation. Users have the ability to divide their formation between 1 and 300 grids based on the formation's geologic heterogeneity and user's preference. The results for the Example Formation generated from the GoldSim Player are shown in Fig. 2. Results are displayed as P_{10}, P_{50}, and P_{90} values for mass CO_2 in megatons for each grid.

6. Summary

Prospective CO_2 resource estimation of large regions or subregions, such as a basin, occurs at the initial screening stages of a project using only limited publicly available geophysical data. As the scale of investigation is narrowed and selected areas and formations are identified, prospective CO_2 resource estimation can be refined when site-specific geophysical data are available. This paper refines existing US-DOE-NETL methodologies and methods based on data availability when a greater level of geologic characterization is available. The methodology builds upon the volumetric approach previously reported at the regional scale (Goodman et al., 2011). We refined the distinctions between existing US-DOE-NETL methodologies and presented new notation that explicitly identifies differences between data availability and data sources used for geologic parameters and efficiency factors as the scale of investigation is narrowed. The refined CO_2 resource estimation method is made available in a publicly available tool named CO_2-SCREEN to calculate prospective CO_2 storage resource (Sanguinito et al., 2016).

Disclaimer

Acknowledgements

This research was supported in part by appointments to the National Energy Technology Laboratory Research Participation Program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2016.09.009.

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