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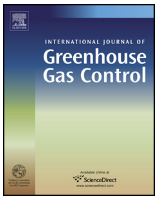

A comparison of volumetric and dynamic CO_2 storage resource and efficiency in deep saline formations

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ABSTRACT

A reliable carbon dioxide (CO_2) storage resource estimation method is crucial if carbon capture and storage in deep saline formations (DSFs) is to gain widespread deployment for reducing anthropogenic CO_2 emissions to the atmosphere. Most of the published methodologies are based on a volumetric calculation and do not consider the effect of site-specific dynamic factors (e.g., injection rate, pressure interference). Several studies suggest these dynamic components may play the dominant role in storing CO_2 in DSFs. In this study, CO_2 storage resource estimates and efficiencies for two deep saline systems were calculated using volumetric and dynamic methodologies.

Comparison of the results indicates that dynamic CO_2 storage efficiency is time-dependent. For short injection lengths (~50 years), an open system has an efficiency similar to a closed system, and volumetric storage resource estimates are too high. For long injection time frames (~2000 years), the dynamic storage resource of open systems approaches the volumetric potential. These results suggest that volumetric assessments are reliable provided it is understood that it may take hundreds of wells and/or injection for hundreds of years to reach a formation's effective CO_2 storage resource potential. Additionally, operational factors such as water extraction can increase CO_2 storage resource and efficiency.

1. Introduction

As interest in reducing anthropogenic carbon dioxide (CO_2) emissions continues to grow, one of the primary methods under consideration is CO_2 storage in deep saline formations (DSFs). In order to make a significant reduction in annual emissions, the amount of CO_2 that would need to be stored is on the order of hundreds of millions of tons of CO_2 a year. To date, it is unknown if DSFs contain enough storage potential to meet this large target. To increase stakeholder confidence, several methods have been developed to estimate the CO_2 storage capacity, or CO_2 storage resource potential, of DSFs, including methods developed by the U.S. Department of Energy (USDOE) (2007, 2008, 2010; Litynski et al., 2010), the Carbon Sequestration Leadership Forum (CSLF) (2005, 2007, 2008; Bachu et al., 2007; Bradshaw et al., 2007), the IEA Greenhouse Gas R&D Programme (IEAGHG) (2009; Gorecki et al., 2009), the U.S. Geological Survey (USGS) (Brennan et al., 2010; Blondes et al., 2013), CO_2 GeoCapacity (Vangkilde-Pedersen et al., 2009), Zhou et al. (2008), and Szulczewski et al. (2012). These methods are based on volumetric approaches that do not account for site-specific dynamic factors (e.g., rate, pattern, and timing of injection and pressure interference between injection locations) and their effect on CO_2 storage resource. These methods are useful for generic, high-level comparisons between formations or basins, but are limited in that they are not supported by full-formation injection simulations and industry case studies. As a result, they may misrepresent the actual effective storage resource potential in DSFs.

Because of concerns about the validity of current CO_2 storage resource estimation methodologies, an effort was undertaken to compare volumetric storage resource estimates with estimates made using numerical simulation, i.e., dynamic storage resource (Thibeau and Mucha, 2011; Zhou and Birkholzer, 2011; Ehlig-Economides and Economides, 2010). The Energy & Environmental Research Center (EERC), working with IEAGHG and USDOE, used both approaches to estimate the effective CO_2 storage resource and efficiency of two deep saline systems, namely, the Minnelusa Formation in the Powder River Basin, United States, and the Qingshankou and Yaojia Formations (which act as a single-flow unit) in the Songliao Basin, China (IEAGHG, 2014). The resulting storage

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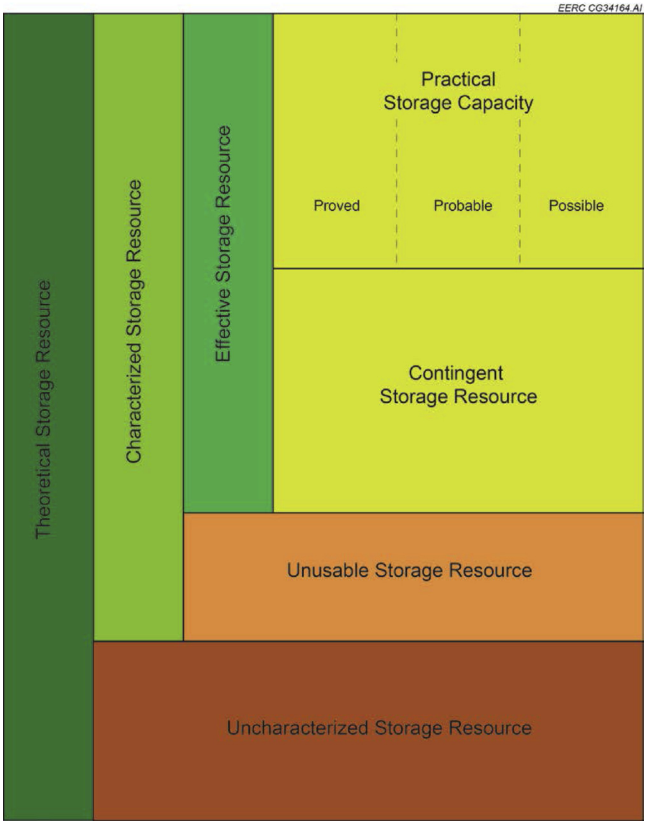

Fig. 1. Storage resource/capacity classification system (IEA Greenhouse Gas R&D Programme, 2009).

resource estimates were compared for the two case studies, and conclusions were drawn based on the results of this comparison.

2. Materials and methods

2.1. Existing storage resource methodologies

The first effort in this work focused on identifying the existing published methodologies for estimating the volumetric "static" CO_2 storage resource of DSFs. In order to evaluate the methods using the same framework, the effective storage resource level of the classification system developed by IEAGHG (2009) was used (Fig. 1).

This resource level was considered to be the best basis for comparison, as it takes into account both the geologic and technical constraints affecting the CO_2 storage potential of a given saline formation. Using the effective storage resource level, several methodologies were examined, including those developed by CSLF (2005, 2007), USDOE (2008, 2010), USGS (Brennan et al., 2010), Szulczewski et al. (2012), and Zhou et al. (2008). It was decided that the methodology presented in the Carbon Sequestration Atlas of the United States and Canada (3rd edition) (USDOE, 2010) would adequately represent all of the methodologies since it is equivalent to the CSLF method and results in estimates on the same order of magnitude as the other methodologies (IEAGHG, 2009; USDOE, 2012). Additionally, since the closed-system compressibility method described by Zhou et al. (2008) consistently resulted in some of the lowest storage resource estimates among the above-mentioned methods, it was decided that the closed-system approach and resulting coefficients would be used for comparison purposes.

2.2. Modeling

Geologic modeling was used as the basis for comparing the volumetric and dynamic CO_2 storage resource estimates since it provides a way to directly compare results. Modeling was conducted using Schlumberger's Petrel. A static 3-D geologic modeling workflow was carried out by building a structural framework; performing petrophysical interpretation; performing data analysis; conducting a geostatistical interpolation of reservoir properties into a 3-D model; performing uncertainty analysis to create high-, mid-, and low-pore volume cases; upscaling for dynamic simulation; and calculating the volumetric CO_2 storage resource potential. More detail on the modeling can be found in the IEAGHG report (2014).

The facies attribute was the most uncertain reservoir property in both models, with its uncertainty having a large effect on the connected volumes and overall pore volume. By randomly varying the "good" reservoir facies, different probabilistic models were produced creating high-, mid-, and low-pore volume cases to evaluate the effect on storage coefficients. The high case (a 90th percentile [P_{90}]) contains more of the primary storage facies and more pore volume, while the low case (a 10th percentile [P_{10}]) has less primary storage facies and less total pore volume. The midcase is represented by a 50th percentile (P_{50}) and is similar to the base case realization. In order to compare the volumetric and dynamic approaches, CO_2 storage simulations needed to be conducted to estimate the dynamic storage potential. The static models were prepared for numerical simulation using upscaling methods. This process minimizes simulation run time while retaining the geologic heterogeneity of the system. Once upscaled, the effective volumetric storage resource was calculated for each model.

2.3. Volumetric storage resource calculation

The basis for all DSF volumetric CO_2 storage resource estimation methodologies is essentially the pore volume of the storage target multiplied by some "efficiency" term (E), multiplied by the average CO_2 density at reservoir conditions at the end of injection (ρ_{CO_2}). This results in a CO_2 storage resource potential defined as the mass of CO_2 that could be stored in the target formation (M_{CO_2}) (Eq. (1)). The pore volume is typically defined as the total area (A_t), multiplied by the gross thickness (h_g), multiplied by the total porosity (φ_t), but pore volume was more accurately described by CSLF (2007) by integrating porosity in three dimensions (Eq. (2)), as porosity is a heterogeneous property that typically varies quite widely throughout any formation.

$$M_{CO_2} = A_t * h_g * \varphi_t * E * \rho_{CO_2} \tag{1}$$

$$M_{CO_2} = E * \rho_{CO_2} * \iiint \varphi_t \mathrm{d}x\mathrm{d}y\mathrm{d}z \tag{2}$$

The efficiency term (E) represents the percentage of the formation's pore volume that can be occupied by CO_2 and is represented differently between open and closed systems. In open systems, the efficiency term represents the fraction of the geology that is amenable to storage and the portion of that pore space that CO_2 can occupy by displacing the original formation fluids during the course of injection (E_E) (Eq. (3)). The amenable geology is defined as the fraction of the total formation volume that has suitable geology for CO_2 storage (E_{geol}) and is a multiplicative combination of the net-to-total area (E_{A_n/A_t}), the net-to-gross thickness (E_{h_n/h_t}), and the effective-to-total porosity ($E_{\varphi_{\mathrm{eff}}/\varphi_t}$) (Eq. (4)). E_{geol} is generally defined as the area where there is sufficient formation at a depth where CO_2 will remain in the supercritical state, typically greater than 800 m and, in some jurisdictions, where the salinity of the formation fluids is above the total dissolved solids (TDS) cutoff for