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Regional evaluation of brine management for geologic carbon sequestration

Hanna M. Breunig[a,b], Jens T. Birkholzer[c], Andrea Borgia[c], Curtis M. Oldenburg[c], Phillip N. Price[a], Thomas E. McKone[a,d,*]

[a] Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, 90R2002, Berkeley, CA 94720, USA
[b] Department of Civil and Environmental Engineering, University of California, 1 Cyclotron Road, 74R316C, Berkeley, CA 94720, USA
[c] Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, 74R316C, Berkeley, CA 94720, USA
[d] School of Public Health, University of California, Berkeley, USA

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ABSTRACT

Large scale deployment of carbon dioxide (CO_2) capture and sequestration (CCS) has the potential to significantly reduce global CO_2 emissions, but this technology faces social, economic, and environmental challenges that must be managed early on. Carbon capture technology is water-, energy-, and capital-intensive and proposed geologic carbon sequestration (GCS) storage options, if conducted in pressure-constrained formations, may generate large volumes of extracted brine that require costly disposal. In this study, we evaluate brine management in three locations of the United States (US) and assess whether recovered heat, water, and minerals can turn the brine into a resource. Climate and aquifer parameters varied between the three regions and strongly affected technical feasibility. We discovered that the levelized net present value (NPV) of extracted brine can range from −\$50 (a cost) to +\$10 (a revenue) per ton of CO_2 injected (mt-CO_2) for a CO_2 point source equivalent to emissions from a 1000 MW coal-fired power plant (CFPP), compared to CCS NPV ranging from −\$40 to −\$70 per mt-CO_2. Upper bound scenarios reflect assumed advancements in current treatment technologies and a favorable market and regulation landscape for brine products and disposal. A regionally appropriate management strategy may be able to treat the extracted brine as a source of revenue, energy, and water.

1. Introduction

Carbon dioxide (CO_2) capture and sequestration (CCS) is designed to prevent anthropogenic CO_2 from entering the atmosphere. Geologic carbon sequestration (GCS) is the injection of CO_2 into geologic formations such as sedimentary basins (Gale, 2004; Holloway, 2005). The large storage capacities of saline aquifers within sedimentary basins in the United States (US) make them a promising choice for GCS. Unfortunately, because the pore space in saline aquifers is already filled with brine, the injection of large quantities of CO_2 can lead to widespread and lasting pressure perturbation in the subsurface (Birkholzer et al., 2012; Nicot, 2008). Potential impacts related to elevated formation pressure include: (1) caprock fracturing and fault reactivation, and (2) pressure-driven leakage of CO_2 and brine (Rutqvist et al., 2008). One developing technique for mitigating pressure concerns is GCS with brine extraction, whereby CO_2 is injected into a saline formation and resident brine is brought to the surface through extraction wells to direct CO_2 plume flow and to manage formation pressure (Bergmo et al., 2011; Birkholzer et al., 2012; Buscheck et al., 2012).

While brine extraction is not required and may not be necessary for most GCS sites, it is useful to explore methods for reducing disposal costs for sites where pressure constraints require that brine be extracted. Buscheck et al. (2012) provide a qualitative overview of potentially viable options including: desalination; saline water for cooling towers; makeup water for enhanced oil recovery (EOR) systems; and geothermal energy production. Various industries provide evidence that brine-sourced heat, minerals, and water are marketable products that present an opportunity for considering the brine as a resource in certain regions of the country (Ahmed et al., 2001; Aines et al., 2011; Buscheck et al., 2011; Frick et al., 2010; Harto and Veil, 2011; Sullivan et al., 2011; Veil et al., 2004). Aside from desalination, there is currently no method for exploring the feasibility, cost, or benefit of brine management for GCS (Bourcier et al., 2011).

Our objective is to develop a spatially resolved method for quantifying the costs and environmental impacts of brine management. We assume that the GCS projects studied require extraction of brine at an extraction ratio of one (i.e., volume of CO_2 injected equals

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* Corresponding author at: Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, 9R2002, Berkeley, CA 94720, USA. Tel.: +1 510 642 8771; fax: +1 510 642 5815.
E-mail address: temckone@lbl.gov (T.E. McKone).

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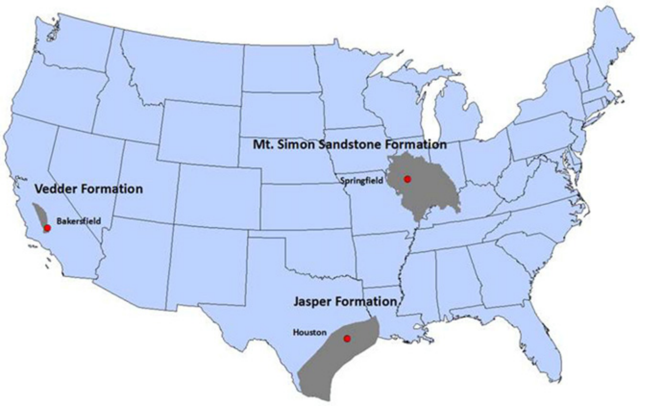

Fig. 1. Map of three saline aquifers in different regions of the US (areas in gray). Climate data used to analyze each region were taken from locations shown in red (Department of Energy, 2012; Gulf Coast Carbon Center, 2003). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

volume of brine extracted). Our cost estimates start after brine has been brought to the surface; we do not account for the infrastructure and energy cost for extracting brine. Brine management may have one disposal step, or it may involve a brine use sequence (BUS) of treatment and disposal steps. Our study is unique in that it: (1) evaluates several usages that have yet to be applied to brine management for GCS, in particular mineral harvesting, fish aquaculture, and algae biodiesel production; (2) develops a method for organizing a BUS; (3) calculates the feasibility, levelized net present value (NPV), resource production, and land footprint of BUSs in three regions of the US. Each treatment, use, and disposal option introduced in this report requires further detailed assessments, but this report is a starting point and lays the groundwork for future life cycle assessments (LCA) of brine management. LCA is an important tool for quantifying environmental impacts related to life cycle stages of a product or process and has yet to be completed for brine management (Rebitzer et al., 2004).

Disposal processes included in this report are: (1) discharge to the ocean, (2) evaporation ponds, (3) deep well injection and (4) use of brine for road de-icing. Usages included in this paper are: (1) geothermal energy, (2) desalination, (3) salt, boron, magnesium, calcium, and potassium harvesting, (4) algae pond recharge, and (5) aquaculture pond recharge. We include these options because they can be monetarily quantified using available regional data.

A BUS that creates value from the brine may help pay back part of the water-, energy-, and monetary (capital and operating) cost of brine extraction and CCS.

2. Methodology

2.1. Regional sequestration scenarios

The system boundary of our assessment begins once brine is brought to the surface and ends once components of the brine are sold or sent off site for treatment, injected underground, discharged into surface water bodies, or evaporated. We selected three saline aquifers from different regions of the US to encompass some of the variation in parameters relevant to the feasibility and economics of brine disposal: (1) the southern Mt. Simon Sandstone Formation (Mt. Simon) in the Illinois Basin, IL; (2) the Vedder Formation (Vedder) in the San Joaquin Basin, CA; and (3) the Jasper Formation (Jasper) in the eastern Texas Gulf Basin, TX (Fig. 1).

These aquifers were selected for their prominent role in GCS research, for their close proximity to CO_2 sources which makes them prospective sequestration sites, and for the large quantity of available data characterizing them (see Supporting Information (SI) Section S1).

One ton of CO_2 injected (mt-CO_2) is the functional unit of our assessment. We assumed a 1:1 volume displacement of pore water per volume of CO_2 injected and a density of supercritical CO_2 of 500 g/L. From these assumptions, we calculated that 2 m^3/mt-CO_2 of brine are extracted. Lower brine production rates will occur if formation-water extraction is conducted at extraction rates less than 1:1 or if the density of CO_2 is higher than 500 g/L.

Our scenarios evaluated one 1000 MWe coal-fired power plant (CFPP) as the CO_2 point source per brine formation, and assumed capture and storage of 90% of CO_2 emissions for 30 years. We further postulated that the energy penalty (EP) arising from the carbon capture process increased initial emissions by 24%, resulting in an annual injection of 8.9 million mt-CO_2 and a brine extraction of ~2000 m^3/h (~13 million gallons per day (GPD)) (Zenz House et al., 2009). Although our selected EP is optimistic relative to current technology, we believe that carbon capture technology will improve over time. In addition, our conservative formation-water displacement ratio favors realistic extraction scenarios. The formations chosen have the capacity to hold CO_2 from multiple CCS projects and we discuss challenges that may come with upscaling our results to multiple GCS projects later in the paper.

A cost effective BUS would maximize NPV by: (1) optimizing resource production and synergies between BUS stages, (2) reducing the total volume of brine requiring disposal, and (3) choosing BUS options that take advantage of current on and offsite infrastructure. A generic non-site-specific BUS would include: extraction of energy, extraction of freshwater from cooled brine, direct use of brine, extraction of minerals from concentrated brine, and disposal (Fig. 2). Algae production and fish production are stages that could either use the extracted brine itself, the extracted energy, or desalinated brine; these stages could act in parallel or in series with additional BUS stages. Treatment, use, and disposal stages were modeled using the equations and assumptions described in Section 2.2. Aquifer- and region-specific inputs were collected and used to generate site-specific BUS scenarios. We assumed the entire volume of extracted brine was sent through a BUS unless our assumed feasibility limits for parameters like total land footprint and maximum transportation distances would be violated. In these instances, we modeled the BUS so that a feasible fraction of brine was sent through the BUS and the remaining fraction of brine was sent through an alternative BUS.

We carried out a regionally specific literature review for each brine management option to explore the use and maturity of current practices in the US, technical limitations and results of previous environmental impact assessments (SI, Section S2). We analyzed the construction and in-use-phase costs (Tables 1 and 2). We used calendar-year 2010 mineral markets to determine sale prices and potential demands for brine resources. Data were collected to calculate ranges in NPV, land footprint, and resource production for individual management stages applied to brines from different saline aquifers (Department of Energy, 2012; Ventyx, 2012). Ranges were given for some parameters to signify heterogeneity or uncertainty in the system. Site-generic costs and values were used when site-specific data were unavailable.

2.2. Brine management options

2.2.1. Energy production

Geothermal energy production is a mature technology that has a low carbon footprint and is a growing industry in the US. If energy production was included in a BUS, we assumed it was performed at extraction and the captured energy was used onsite (Fig. 2).