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Life cycle assessment of treatment and handling options for a highly saline brine extracted from a potential CO_2 storage site

Hafiz H. Salih [1], Jiaxing Li [1], Ruth Kaplan, Seyed A. Dastgheib*

Illinois State Geological Survey, University of Illinois, 615 East Peabody Drive, Champaign, IL 61820, United States

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ABSTRACT

Carbon dioxide (CO_2) injection in deep saline aquifers is a promising option for CO_2 geological sequestration. However, brine extraction may be necessary to control the anticipated increase in reservoir pressure resulting from CO_2 injection. The extracted brines usually have elevated concentrations of total dissolved solids (TDS) and other contaminants and require proper handling or treatment. Different options for the handling or treatment of a high-TDS brine extracted from a potential CO_2 sequestration site (Mt. Simon Sandstone, Illinois, USA) are evaluated here through a life cycle assessment (LCA) study. The objective of this LCA study is to evaluate the environmental impact (EI) of various treatment or disposal options, namely, deep well disposal (Case 1); near-zero liquid discharge (ZLD) treatment followed by disposal of salt and brine by-products (Case 2); and near-ZLD treatment assuming beneficial use of the treatment by-products (Case 3). Results indicate that energy use is the dominant factor determining the overall EI. Because of the high energy consumption, desalination of the pretreated brine (Cases 2 and 3) results in the highest EI. Consequently, the overall EI of desalination cases falls mainly into two EI categories: global warming potential and resources—fossil fuels. Deep well disposal has the least EI when the EI of brine injection into deep formations is not included. The overall freshwater consumption associated with different life cycle stages of the selected disposal or treatment options is 0.6–1.8 m^3 of freshwater for every 1.0 m^3 of brine input. The freshwater consumption balance is 0.6 m^3 for every 1.0 m^3 of brine input for Case 3 when desalination by-products are utilized for beneficial uses.

1. Introduction

The accumulation of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere results in global warming. However, greenhouse gas emissions can be significantly reduced by capturing CO_2 from emitting sources and storing it (Bachu and Adams, 2003). Among the various storage or sequestration options, geological sequestration by the dissolution of CO_2 into deep saline formations (Finley, 2014) is one of the most attractive long-term storage methods because of the availability of high-volume saline formations (Birkholzer and Zhou, 2009). The U.S. Department of Energy has identified deep saline reservoirs as the largest potential sinks for CO_2 storage in the United States. The CO_2 sequestration capacity of saline formations is estimated to be in the range of 2379 to 21,633 billion metric tons of CO_2 (U.S. Department of Energy, 2015); however, the ultimate CO_2 storage capacity in saline aquifers is dependent on several conditions, including pressure, temperature, and salinity of the formation water (Bachu and Adams, 2003). Large-scale industrial CO_2 sequestration in deep saline reservoirs may cause the reservoir pressure to increase; however, continuous brine extraction is a potential strategy to manage pressure buildup and increase the CO_2 storage capacity in the formation (Birkholzer and Zhou, 2009; Buscheck et al., 2011). Depending on the characteristics of the extracted brine and the availability of various brine management options, brine may be disposed of in other suitable geological formations (i.e., deep well disposal [DWD]) or considered for beneficial reuse after the required treatments.

A large-scale carbon capture and storage (CCS) demonstration project located in Decatur, Illinois, has already stored 1 million tons of CO_2 in the Mt. Simon Sandstone (Leetaru and Freiburg, 2014). The Mt. Simon Sandstone geological formation is 2600 ft thick and covered by the Eau Claire Formation (300 ft of low-permeability limestone). The Mt. Simon Sandstone, with its estimated storage capacity of 11–150 billion tons of CO_2 (Leetaru and Freiburg, 2014),

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* Corresponding author.
E-mail address: seyed@illinois.edu (S.A. Dastgheib).

[1] Both authors contributed equally to this manuscript.

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is considered one of the most suitable geological formations for carbon sequestration in the United States. Fig. 1 illustrates a scenario in which the supercritical CO_2 is injected into the Mt. Simon Sandstone at a depth of ~7000 ft and brine is extracted at a different location to regulate the formation pressure. The extracted brine is then pretreated to remove the suspended solids before either disposal by DWD into the Potosi Dolomite (depth of ~4800 ft) or further treatment by desalination processes for beneficial reuse. The Potosi Dolomite is considered an excellent reservoir for wastewater disposal in the Illinois Basin because of its depth and porosity and because it has been used for disposal of brine wastewater from the oil industry for decades (Brower et al., 1989; Leetaru et al., 2014).

Through a comparative life cycle assessment (LCA) analysis, we evaluated the environmental impact (EI) of various treatment or disposal options, including pretreatment of the extracted brine to remove suspended solids, DWD of the pretreated brine, a near-zero liquid discharge (ZLD) treatment followed by disposal of salt and concentrated brine by-products by DWD and solid waste disposal to landfill (SLD), and a near-ZLD treatment that assumes beneficial use of the treatment product (i.e., purified water) and by-products (i.e., dried salts and concentrated brine) (see Fig. 2 in the Materials and Methods Section). We focused on management options that are feasible with presently available technologies, namely, disposal or evaporation. Membrane processes such as reverse osmosis (RO) have salinity limitations that are exceeded by the Mt. Simon brine, and emerging high-total dissolved solids (TDS) desalination technologies are not yet advanced enough to accommodate the high volumes of brine that might be extracted (Kaplan et al., 2017). Selection of the best option for managing the extracted brine depends on various technical, economic, regulatory, and environmental factors. Some options might be more technoeconomically feasible but would have a greater negative impact on the environment. The main objective of this work was to evaluate and quantify the EI of each potential option for managing the extracted brine through a comparative LCA. Life cycle assessment results provide critical information for selecting the most environmentally friendly option.

Among the published studies available on the LCA of water desalination processes (e.g., Vince et al., 2008; Zhou et al., 2014), many assume or show that the EI of the desalination processes mainly depends on their energy use and that the impacts of chemical usage and infrastructure construction are less significant. For example, the EI of construction of the treatment infrastructure was estimated at 4%–10% of the total EI (Lundie et al., 2004; Zhou et al., 2014). The EI of pretreatments, including sludge disposal (i.e., sludge generated during coagulation or water softening) and management of the reject concentrated brine stream (i.e., that generated from the desalination process), is often not considered (Raluy et al., 2005a; Vince et al., 2008). Their impact might be significant, however, depending on the type of desalination process and feed water composition. The predominant impact of energy use in water desalination is evident in some LCA cases. For example, Raluy et al. (2005b) and Zhou et al. (2011a) found that ~80% of the overall EI of water desalination by RO was associated with electricity consumption (Raluy et al., 2006; Zhou et al., 2011a). However, this approach was challenged by several researchers who showed that when the pretreatment stage was considered, the construction of the infrastructure contributed 30%–50% of the total EI (Zhou et al., 2014). Furthermore, some studies indicated that chemical usage for water desalination had a significant impact on environmental acidification, global warming, eutrophication, and ozone depletion, especially when the chemical dosage was large (Tarnacki et al., 2012; Vince et al., 2008; Zhou et al., 2011a, 2014). Finally, the current literature on LCA lacks thorough investigations of the impact of desalination processes on water resources (i.e., the balance of freshwater withdrawal consumption versus the amount of freshwater produced throughout the desalination process).

In this study, we investigated the EI of high-TDS brine management options. First, the current LCA literature provides limited information on brine disposal by DWD (Coday et al., 2015). Here, we consider the EIs of pretreatment, infrastructure, and disposal in addition to energy consumption. We also consider the EI of waste management through DWD or landfill disposal. Second, although a number of desalination processes have been examined by LCA, few studies have investigated the EI of high-TDS desalination processes. The majority of publications that include an LCA of desalination are related to brackish water or seawater desalination by conventional multistage flash distillation, multiple-effect evaporation (MEE), forward osmosis, and RO (Coday et al., 2015; Fernández-Torres et al., 2012; Morton et al., 1997; Raluy et al., 2005a; Ras and Von

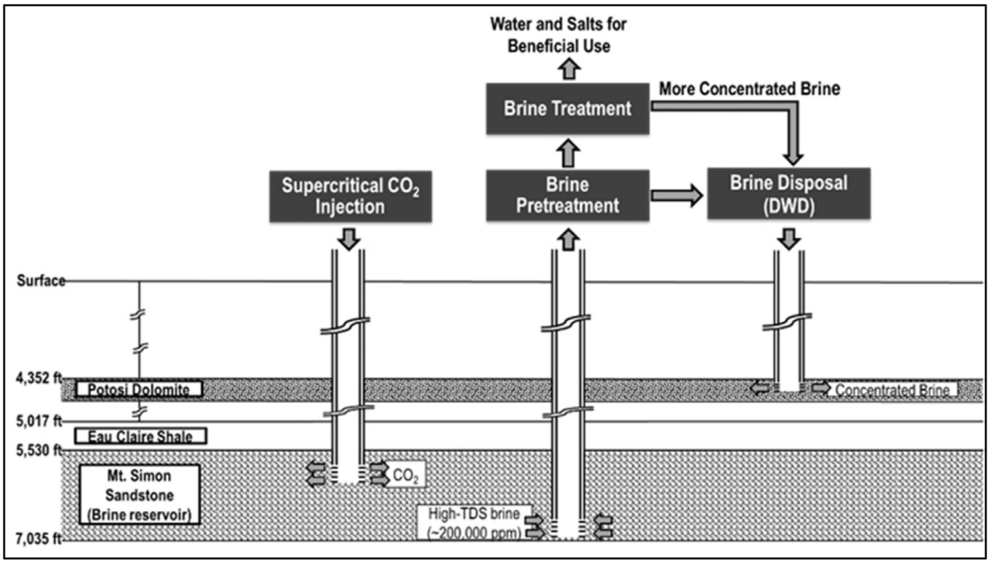

Fig. 1. Schematic diagram showing the injection of CO_2 with the extraction of brine for pressure management, and handling of the pretreated brine by deep well disposal (DWD) or a combination of brine treatment and disposal. Formation information is taken from Leetaru and Freiburg (2014) and Leetaru et al. (2014). TDS, total dissolved solids.