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A method and cost model for treatment of water extracted during geologic CO_2 storage

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ABSTRACT

Extraction of water as a part of CO_2 storage may be desirable for risk management and process optimization. Treatment and repurposing of this water creates a useful resource and reduces the volumes that must otherwise be disposed. To better understand the tradeoff of costs versus processes and risks, we use a systems approach to evaluate treatment costs that are reasonable for the chemical and physical qualities (salinity, temperature, pH and turbidity) of water that could be extracted from target geologic formations. We evaluate primary and secondary pretreatments, membrane desalination processes (reverse osmosis and nanofiltration), thermal processes (multiple effect distillation and multi-stage flash distillation), and several concentrate (brine) disposal methods. The results indicate that for waters extracted from storage sites, salinities and temperatures may often be higher than for municipal treatment scenarios. Thus, thermal treatment methods are more cost-feasible than membrane methods in many cases, although pressure recovery methods for reverse osmosis can mitigate this. Treatment costs including concentrate disposal fall within a range of US\$0.50–2.50/ton CO_2 injected, although some costs can be much higher (up to US\$30/ton CO_2 under certain concentrate disposal cost ranges). A sensitivity analysis shows that temperature is the most important in determining costs followed by selection of concentrate disposal method.

1. Introduction

Extraction of water as a part of a CO_2 storage program may be desirable for risk management and process optimization. Water may be extracted to manage movement of the CO_2 plume, reduce induced seismicity risk, and increase valuable CO_2 storage volume. Treatment creates a useful clean water stream and reduces the total volume of extracted water that would need to be stored, moved, and disposed, up to 80% lower than the original extracted stream volume. This is significant because extracted water is subject to regulation because of its high salinity. Large volumes of water are projected to be moved during a typical large-scale CO_2 storage operation. For example, it is projected that over a 50 year cycle of CO_2 injection from a single 2.1 GW power plant into a single reservoir unit, approximately 1 km^3 of water could be extracted, if the pressure in the reservoir is to be maintained below caprock fracture pressure (Deng et al., 2012; Stauffer et al., 2009, 2011). This volume is, on average, similar to a small stream (302 L/min or 435,000 L/day) and is a potential long-term, drought-proof source of water. For the purposes of this paper, “extracted water” is defined as any water that is taken out of a rock formation during CO_2 storage; “produced water” is water specifically associated with oil and gas production and also is considered extracted water when oil and gas formations are used for CO_2 storage.

Costs to capture CO_2 from power generation facilities are estimated to vary between US\$15 and US\$75/ton CO_2, while costs for geologic storage may vary from US\$0.5 to US\$8/ton CO_2 (Benson et al., 2005). These ranges do not incorporate the costs of water extraction, treatment, or disposal. The cost of water treatment as a portion of capture and storage is critical for decision policies regarding total system costs, net benefits of treatment and use, types of uses that could be considered feasible, and the relative value of risk mitigation during storage (Keating et al., 2010; Viswanathan et al., 2008). Most water treatment cost data available in the literature is for desalination of brackish water (inland or coastal bays) or seawater, which has a maximum salinity of about 35,000–40,000 mg/L total dissolved solids (TDS) (El-Manharawy and Azza, 2003). Water extracted during CO_2 storage operations will be saline (at least 10,000 mg/L TDS or higher) and may have

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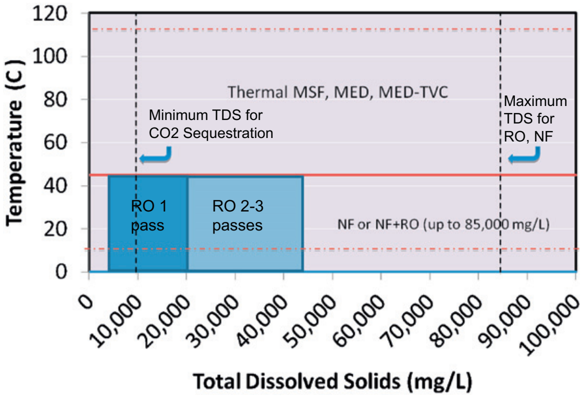

Fig. 1. Ranges of temperature and salinity for treatment options. NF + RO at high TDS ranges is highly dependent upon water chemistry. Maximum viable temperature for membrane processes is set at 45 °C. Dashed lines enclose the region of expected temperatures and TDS for CO_2 sequestration sites.

After Sullivan et al. (2012).

characteristics either of deep brine aquifer waters (e.g., greater hardness or silica contents) or of oil and gas produced waters (e.g., increased organic content) (Buscheck et al., 2011; Harto and Veil, 2011). These waters will require pre-treatment and desalination along with disposal of residual brine or brine solids, to optimize use. Therefore, actual costs to treat extracted waters may exceed costs to treat municipal, brackish, or seawaters. Fig. 1 shows scenarios for treatment that are likely to be feasible under different temperature and salinity scenarios (adapted from Sullivan et al. (2012)).

Newmark et al. (2010) discuss the potential for water use in energy resource development and carbon storage. Substantial quantities of water are needed for capture processes at power plants and subsequent increases in power plant cooling water from the “parasitic” load increase or capture penalty (Kobos, 2009). Up to 50% more water of high quality is likely to be needed for these processes (Newmark et al., 2010). In exchange, waste heat from power plants, extracted water, or CO_2 compression may contribute to thermal desalination processes, while captured pressure from CO_2 compression or water extraction (Wolery et al., 2009) may be used to reduce costs of pressurized membrane desalination (reverse osmosis, RO; or nanofiltration, NF). The treated, extracted water could be used as a stable supplement to offset increased water use in capture processes, consumptive use in cooling towers from nearby power plants, and as a long-term water source in arid regions for agricultural or other industrial uses. In some states, treated water may be assigned a water right when put to beneficial use, with an attached market value. It may be possible to supplement local stream flows with treated water to offset the costs of purchased water rights for power generation and storage processes. Kobos (2009) evaluated the specific use of extracted water in power generation systems. Work by Chapman Wilbert et al. (1998) and Watson et al. (2003) provides detailed information about membrane desalination processes and pretreatment options. These methods are widely applicable with the exception of waters exceeding maximum membrane temperature and salinity tolerances (approximately 45 °C and 45,000 mg/L TDS). Voutchkov (2011) discusses limitations of desalination, including the brine concentration factor for membrane processes, and the relative value of treated water to a region. Costs and energy use of thermal methods are discussed by multiple authors (Hamed, 2004; Wangnick, 2004; Hamed et al., 2005; Pankratz, 2005; Acharya et al., 2011).

The costs and sources of energy used to treat water have an impact on feasibility of treatment of extracted water. Electricity costs comprise the highest percentage of RO costs (44%) (Cooley et al., 2006). Recovery of costs from RO include pressure recovery devices such as Pelton-wheel devices, which utilize existing membrane treatment system pressure and transfer this energy to reduce pump pressurization costs in the system (Stover, 2006). For thermal treatment, electrical energy is a much lower cost factor; pumping is the largest user of electrical power in thermal treatment systems. Thermal energy is the largest energy component overall for thermal treatment; waste heat (e.g., from thermoelectric power plants) is the typical source of most of the treatment energy in these plants. Produced water is sometimes thermally treated using electric power in mobile crystallizer units (Acharya et al., 2011; Puder and Veil, 2006). In the case of extracted water, it is possible that much of the thermal energy could come from the reservoir itself (geothermal sources) if industrial sources such as a power plant were not available.

Desalination is typically a multi-step process, and includes extraction, pre-treatment, treatment (desalination) to a desired salinity, and post-treatment to adjust water composition for the chosen purpose. Our analysis is limited to costs of pre-treatment and treatment, although our model is being developed as a component of the CO_2-PENS system model (Stauffer et al., 2009; Keating et al., 2010; Viswanathan et al., 2008) that accounts for costs for extraction. Pretreatments are usually classified as conventional or non-conventional methods. Conventional methods include pH adjustments by the addition of acids or bases, to prevent precipitation of insoluble mineral salts (hardness and silica) during the desalination process, and the addition of coagulant steps (lime or chemical precipitation) or scale-inhibition chemicals. Coarse filtration steps (sand filters, cartridge filters) and microfiltration may accompany both conventional and non-conventional pretreatments (National Research Council, 2008; DiNatale, 2010; Pearce, 2010). Non-conventional pretreatments utilize microfiltration, ultrafiltration, and nanofiltration in advance of membrane desalination, often in lieu of some chemical additions. These steps remove inorganic and biological colloids, and divalent ions such as Ca^{2+} and Mg^{2+}, which contribute to membrane fouling. Nanofiltration as a pretreatment also has been used in advance of thermal methods to prevent fouling (Pankratz, 2005; El-Nashar and Qamhiyeh, 1993; Andrianne and Alardin, 2003). In the case of oil and gas produced waters, additional organic removal steps in advance of any nanofiltration or acid additions may be necessary. Oil–water separation, filtration with nutshells, carbon, or other organophilic materials, and more recently, the use of advanced oxidation methods may be considered for these applications (Kwon et al., 2011). We do not consider organic removal methods in this paper.

Four desalination methods are considered: two membrane processes, RO and NF, and two thermal processes, namely, multistage flash distillation (MSF) and multiple-effect distillation (MED) (Pankratz, 2005). RO and NF require high pressure to force contaminated water through membranes that are designed to hold back dissolved constituents and allow water to pass through. Recoveries for seawater and more saline waters can be as low as 30–40% treated water by volume (single pass) or 55–65% (double or triple pass systems). Membranes are subject to variability in transmissivity because of temperature, pH, fouling, and other properties of the contaminated water. Typical final water (permeate) quality is quite high for RO, usually less than 500 mg/L TDS. Permeate quality for NF is more variable, as it depends upon the original salt type and content. Divalent ions are preferentially filtered, while monovalent ions pass through to create a concentration less than 100% of the original solution. For seawater, the theoretical minimum energy to separate salt from water (seawater) is 0.7 kWh m^{-3}, and for RO, the electrical energy consumption is reported to be between 2.25 and 2.75 kWh m^{-3} (Tonner, 2008). NF energy consumption is normally lower because of higher design membrane transmissivity.