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Regional evaluation of brine management for geologic carbon sequestration

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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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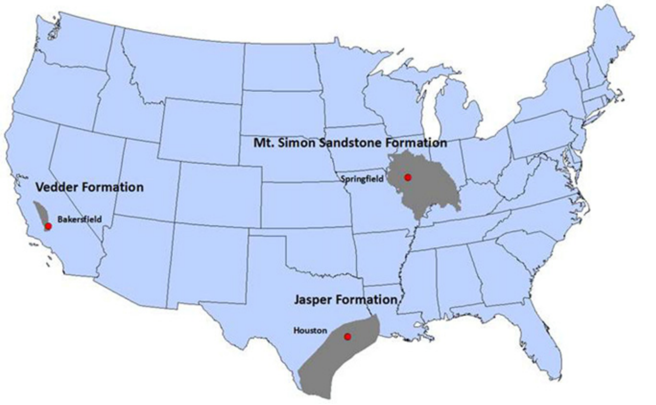

Fig. 1. Map of three saline aquifers in different regions of the US (areas in gray). Climate data used to analyze each region were taken from locations shown in red (Department of Energy, 2012; Gulf Coast Carbon Center, 2003). (For interpretation of the references to color in this figure legend, the 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 $\sim$2000 m^3/h ($\sim$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).

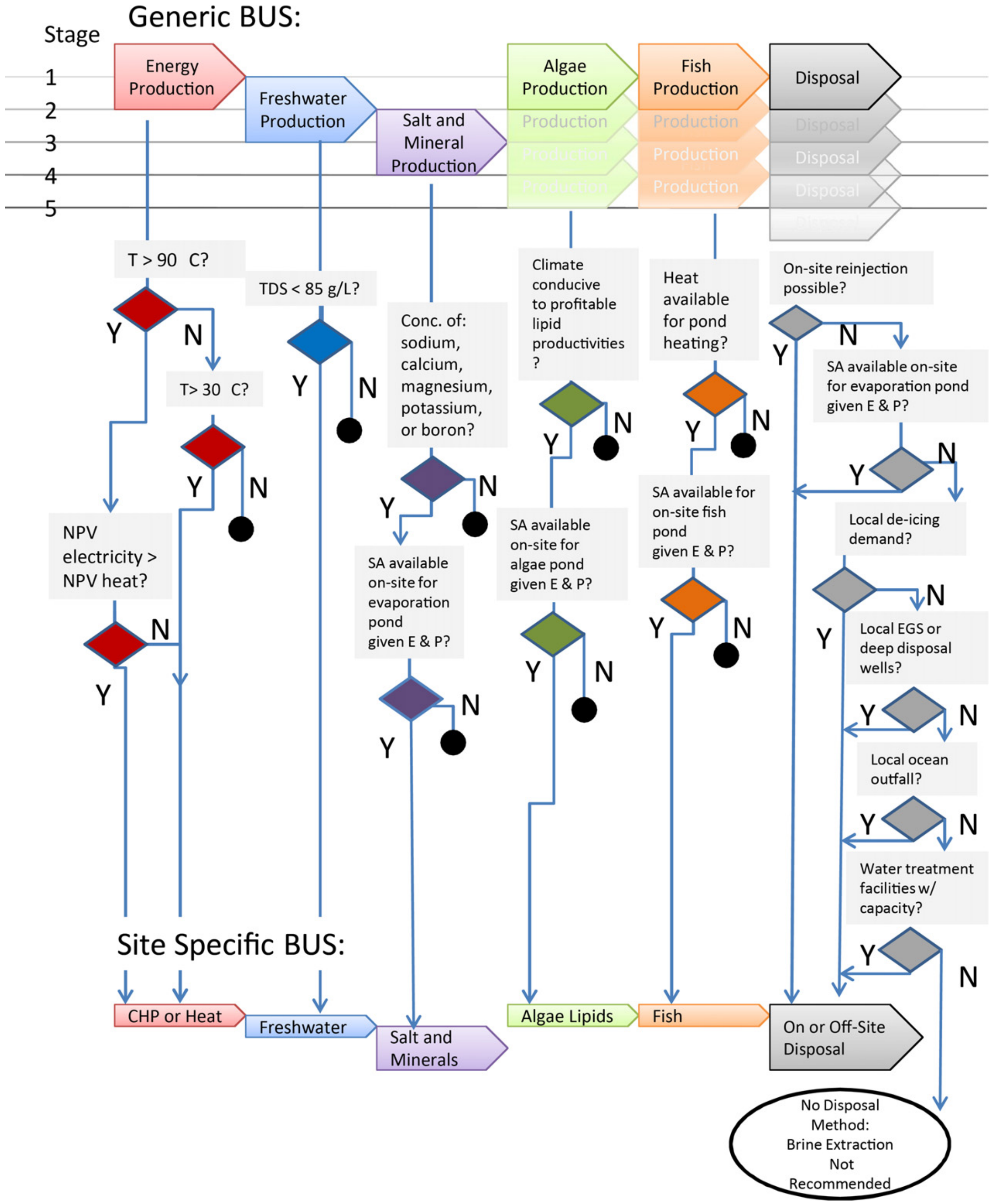

Fig. 2. System diagram. This diagram shows on- and off-site resource harvesting, treatment and disposal stages included in the study. Inputs include parameters like brine temperature (*T*), brine TDS, treatment net present value (NPV) and surface area (SA) requirements calculated from evaporation (E) or precipitation (P) data. Combined heat and power (CHP) is the generation of electricity as well as heat.

The feasibility of this BUS option is dependent on there being a demand for heat onsite. The NPV of combined heat and power (CHP) generation using a binary cycle and heat exchangers was calculated and compared to the NPV of heat generation for brines with average temperature above 90 Celsius (°C) (Table 2) (Lund, 2010). Heat and power savings reflect assumed annual load hours and auxiliary electricity requirements for pumping and re-cooling (Table 2) (Frick et al., 2010). NPV was calculated using:

$$\mathrm{NPV}/(\mathrm{mt\text{-}CO_2}) = (\text{Capital Cost}) + (\text{Heat Savings}) + (\text{Power Savings}) + (\text{O\&M Cost}) + (\text{Land Cost}) \quad (1)$$

where potential thermal [$\mathrm{MJ_{th}/mt\text{-}CO_2}$] and electrical energy [$\mathrm{kWh/mt\text{-}CO_2}$] production ranges were used to determine

Table 1
Regionally variable inputs and assumptions. Percent of 2010 US domestic mineral production that could be met by the maximum production from one brine management project are listed in italics (%). NA stands for not applicable.

Region	Southwest		South		Midwest		
Formation	Vedder		Jasper		Mt. Simon		
Energy production inputs and assumptions							Frick et al. (2010)
North American electric reliability corporation grid region	WECC		TRE		SERC		
Cost electricity [¢/kWh]	13.0		9.3		9.1		
Cost natural gas [¢/kWh]	3.0		3.2		2.9		
Heat recovery only							
Assumed temperature (low, high) [°C]	(50, 90)		(50, 80)		(50, 90)		
Heat and power generation (binary cycle)							
Assumed T low [°C]	(90, 150)		NA		(90, 150)		
Freshwater production inputs and assumptions							Bourcier et al. (2011)
Assumed percent recovery [%]	50		10		NA		
Assumed cost reverse osmosis [\$/m^3 permeate]	0.32		0.81		NA		
Mineral production inputs and assumptions	*% US domestic production 2010*						GCCC (2003) and USGS (2002)
Annual average evaporation-precip [m]	1.6		0.2		0.2		
Days of operation for ponds	365		365		183		
Concentration boron[a] (low, high) [mg/L]	(3, 91)		(53, 60)		(0, 500)		
Concentration sodium (low, high) [mg/L]	(500, 10,400)	*1*	(6250, 35,200)	*3.6*	(24,569, 44,295)	*4.5*	
Concentration potassium (low, high) [mg/L]	(0.5, 100)	*0.4*	(100, 225)	*0.8*	(200, 393)	*1.4*	
Concentration magnesium (low, high) [mg/L]	(4, 44)	*0.3*	(37, 453)	*3.3*	(1287, 1713)	*12.6*	
Concentration calcium (low, high) [mg/L]	(10, 147)	*0.1*	(169, 2150)	*0.9*	(4292, 9023)	*3.8*	Mitchell et al. (2004) and Ripley (2011)
Value brine for road de-icing [\$/mt]	0		0		35		
Algae production inputs and assumptions							Borowitzka and Moheimani (2010) and Pate et al. (2011)
Assumed algae productivity (warm days) [g/(m^2 d)]	30		20		30		
Assumed algae lipid content (low, high) [% dry wt]	40		(30, 40)		(30, 40)		
Days of operation for ponds	365		365		183		
Disposal inputs and assumptions [\$/mt-CO$_2$-injected]							Khan et al. (2009)
Dilution factors for ocean discharge (low, high) [%]	NA		(0, 0.37)		NA		Clark and Veil (2009)
Surface discharge cost (low, high)	(−0.1, −1.0)		NA		NA		Veil et al. (2004), Puder and Veil (2006), Clark and Veil (2009) and Harto and Veil (2011)
Evaporation pond for disposal cost (low, high)	(−0.1, −1.0)		(−0.1, −1.0)		(−0.1, −1.0)		
Disposal wells (low, high)	(−0.6, −33)		(−0.6, −33)		(−0.6, −33)		
Offsite commercial treatment (low, high)	(−2, −13)		(−2, −13)		(−13, −53)		
Landfill	(−13)						
Transportation of brine through pipeline	(−0.1, −0.2)		(−0.1, −0.2)		(−0.1, −0.2)		

[a] Did not find sufficient US production data for boric acid.

high and low revenue [\$/mt-CO$_2$] assuming current regional energy prices. Costs were adapted from (Lund, 2010), assuming a 30-year life time and 8% interest rate; operations and maintenance (O&M) were assumed to be 10% of capital costs. Land costs used in this study are listed in Table 1.

Synergies between geothermal energy production, GCS, and other BUS options could improve joint feasibility:

Table 2
Inputs and assumptions that are not regionally specific.

Energy production inputs and assumptions		Source
Heat recovery only		Frick et al. (2010)
T_ambient [°C]	20	Lund (2010)
Desired T_Pond [°C]	35	
Assumed heating system efficiency [%]	40	
Assumed thermal load hours [h/yr]	7000	
Construction & maintenance [$/kW yr]	19.6	
Heat and power generation		
Assumed binary cycle efficiency [%]	10	
Assumed binary cycle load hours [h/yr]	6529	
Binary cycle T_exit [°C]	77	
Heat recovery T_ enter [°C]	70	
Assumed auxiliary power for recooling [kWh/MWth]	20	
Assumed percent of power capacity used for pumps [%]	10	
Construction & maintenance [$/kW yr]	63.4	
Freshwater production inputs and assumptions		Maulbetsch and DiFilippo (2006)
Value desalinated water [$/m^3]	0.42	
Value reclaimed water [$/m^3]	0.58	
Value water in arid regions [$/m^3]	1.45	
Mineral production inputs and assumptions		
Assumed evaporation pan factor	0.69	Ahmed et al. (2003)
Assumed height pond [m]	0.03	
Cost salt production [$/L]	1.92	Jeppesen et al. (2009)
Value boric acid [$/mt]	360	USGS (2011)
Value salt in brine [$/mt]	8	Bueno (2011)
Value potash [$/mt]	600	USGS (2011)
Value magnesium [$/mt]	3200	USGS (2011)
Value crude gypsum [$/mt]	6.5	USGS (2011)
Algae production inputs and assumptions		Borowitzka and Moheimani (2010) and Pate et al. (2011)
Value algae lipids [$/L]	0.69	
Assumed height pond [m]	0.3	
Fish production inputs and assumptions		Boyd and Lund (2003)
Assumed energy for tilapia [TJ/(yr mt-fish)]	0.24	
Assumed height pond [m]	0.7	
Sale price tilapia [$/mt-tilapia]	2200	
Construction & maintenance [$/kW yr]	19.6	Lund (2010)
Land footprint inputs and assumptions		
Geothermal land footprint (low, high) [km^2/TWh]	(18, 74)	Evans et al. (2009)
Road and buildings (R&B) SA for algae ponds [%SA]	30	
R&B SA for evaporation disposal ponds [%SA]	20	
Price arid, semi-arid, desert land (low, high) [$/acre]	(200, 2000)	

- Sequestered CO_2 would maintain formation pressures and thus brine production rates. This would greatly reduce the energy demand and water withdrawal typical of enhanced geothermal systems (EGS) which recharge geothermal reservoirs by injecting water.
- Energy production could provide a low carbon source of electricity or heat to the CO_2 source or to subsequent BUS stages.
- Energy capture removes the necessity for a cooling stage prior to desalination.

2.2.2. *Freshwater water production*

Numerous technologies are available for treating high salinity water. Membrane treatment is one mature technology used by water utilities and other industries throughout the US. RO desalination is typically used to treat seawater (around 35 g/L), but we assumed RO was feasible for saline groundwater with TDS less than 90 g/L at low recovery rates and in water scarce regions (Aines et al., 2011; Bourcier et al., 2011). This assumption may be optimistic given current RO membrane technology, but we assumed the technology will improve over time. Additional filtration or chemical pre-treatment stages can improve the performance of current RO membranes by removing silica and minerals that cause scale.

Desalination treatment would come after heat capture if the two stages were included in a BUS (Fig. 2). NPV was calculated using:

$$\text{NPV}/(\text{mt-CO}_2) = (\text{Capital Cost}) + (\text{Water Savings}) + (\text{O\&M Cost}) \quad (2)$$

where water savings occur either on-site, or through the sale of water off-site (Maulbetsch and DiFilippo, 2006). Capital, operation, and maintenance costs were adapted from (Bourcier et al., 2011) given our assumed freshwater production rate (dependent on volume of extracted water) and our assumed maximum freshwater recovery fraction (function of TDS concentration). Synergies between freshwater production, GCS, and other BUS options could improve joint feasibility:

- GCS with brine extraction could reduce competition between future CCS projects and future brackish water desalination projects (Udo de Haes et al., 2004).
- Desalination could provide a source of freshwater for cooling towers or to subsequent BUS stages.
- Desalination would generate a concentrated stream of brine. This would reduce the land footprint of evaporation ponds for mineral harvesting or for disposal.
- The volume of brine requiring disposal would be reduced.

2.2.3. *Mineral production*

We assumed harvesting of salt NaCl, magnesium Mg, boron for boric acid B_2CO_3, potassium for potash K_2O, and calcium for gypsum $Ca(SO_4)\cdot 2(H_2O)$ would incorporate evaporation ponds and a salt electrolysis treatment similar to the process used to treat concentrated water from the Great Salt Lake in Utah (Ahmed et al., 2003; Thayer and Neelameggham, 2001; Tripp, 2009). These compounds were selected due to maturity in harvesting technology, and higher current market values (Bueno, 2011; USGS, 2011). Mineral harvesting could occur directly after extraction, or it could occur after geothermal energy and freshwater are harvested from the brine (Fig. 2). The mass mineral production was estimated from brine concentration ranges (Gulf Coast Carbon Center, 2003; Kharaka and Hanor, 2003; USGS, 2002). NPV was calculated using:

$$\begin{aligned} \text{NPV}/(\text{mt-CO}_2) &= (\text{Capital Cost}) + (\text{Mineral Revenue}) \\ &\quad + (\text{O\&M Electrolysis Stage Cost}) + (\text{Land Cost}) \qquad (3) \end{aligned}$$

where the revenue is a function of the brine composition and current compound market value. Cost for evaporation ponds is composed of land and construction costs, and is directly proportional to pond SA (Table 2; SI, Section 3) (Jeppesen et al., 2009).

While it is possible to capture rare earth elements (REE) from extracted brine, little to no data were available on the presence of recoverable REE in our three saline aquifers.

Synergies between mineral production, GCS, and other BUS options could improve joint feasibility:

- Potassium could be used as fertilizers for algae ponds or for local agriculture.

- Salt could be used for road de-icing if brine cannot be applied to roads.
- Evaporation and mineral production would substantially reduce the volume of brine requiring disposal.

2.2.4. Algae biodiesel production

Algae biodiesel is an emerging technology, and renewed interest in algae biodiesel has led to an increase in research of species that can grow in nutrient-supplemented saline waters (Borowitzka and Moheimani, 2010; Pate et al., 2011; Singh et al., 2011). Brine could supply algae ponds directly after extraction, or after geothermal energy and/or freshwater are harvested (Fig. 2). Algae reach their highest production rates in climates with high solar incidence and high temperatures. Pond purging is necessary to maintain optimal salinity concentrations; a BUS with algae production must include a stage that manages pond wastewater (SI, Section S3).

Productivity and lipid content achievable during the months of operation at the three sites were adapted from previous regional studies (Borowitzka and Moheimani, 2010; Pate et al., 2011). Regional algae productivity [L lipid/(ha-yr)] values were compared to those estimated by (Borowitzka and Moheimani, 2010) (Table 2). Algae reach their highest production rates in climates with high solar incidence and high temperatures. NPV was calculated using:

$$\text{NPV}/(\text{mt-CO}_2) = (\text{Capital Cost}) + (\text{Lipids Revenue}) + (\text{Operation Cost}) + (\text{Land Cost}) \quad (4)$$

where revenue from lipid production was estimated using the current sale price of lipids. The value of selling byproduct algal biomass was not included in this calculation due to our assumption that biomass sales would yield little revenue.

Synergies between algae production, GCS, and other BUS options could improve joint feasibility:

- Bio-diesel and/or biogas from the anaerobic digestion of bio-solids could be used at the CO_2 point source or in other BUS stages.
- Captured CO_2 could supply the algae ponds with a pure source of carbon and reduce the volume of CO_2 injected into the aquifer (and thus the volume of extracted brine).
- Seasonal evaporation could reduce the volume of brine requiring final disposal.

2.2.5. Fish production

Brine could recharge fish ponds directly after extraction if the water composition is acceptable for aquaculture. Since most brines are not suitable and require costly pre-treatment, geothermal energy and/or desalinated brine could be used to support fish ponds instead (Kharaka and Hanor, 2003; Zheng et al., 2009). Current practice shows that 0.24 TJ_{th}/yr is required for producing one ton of fish, like tilapia, in aquaculture ponds and that tilapia growth diminishes when pond water drops below 30 °C (Boyd and Lund, 2003). This heating requirement can be partly met by insulation of the aquaculture pond in warmer seasons. The additional mass of fish that could be raised and harvested using geothermal heat captured from the brine was calculated using:

$$M_{fish} = \frac{(e_{th} \times \Delta Q_{\text{th}})}{(0.24 \times 1e6\,\text{MJ/TJ})} \quad (5)$$

where ΔQ_{th} is heat flow [kJ/h], and it was assumed that heat production has an efficiency (e_{th}) of 40%. NPV was calculated using:

$$\text{NPV}/(\text{mt-CO}_2) = (\text{Capital Cost}) + (\text{Fish Revenue}) + (\text{Pond Operation Cost}) + (\text{Land Cost}) \quad (6)$$

where the SA of the ponds depended on fish production (SI, Section S3) and where the cost was adapted from a previous study that assumed a 30-year life time and an interest rate of 8% (Boyd and Lund, 2003; Lund, 2010). Production would have to be seasonal in Illinois unless the ponds were indoors. A disposal stage that manages organic wastes and concentrated salts must follow in a BUS that includes fish production. The value of tilapia was included in this study as a reference; it does not imply that the CFPP will reap the value of the tilapia without paying for fish cultivation.

Synergies between algae production, GCS, and other BUS options could improve joint feasibility:

- Anaerobic digestion of bio-solids could provide a small source of energy.
- Seasonal evaporation could reduce the volume of brine requiring final disposal.

2.2.6. Disposal

A BUS can include multiple stages of treatment prior to disposal, or it could include only disposal stages (Fig. 2). In effect, brine management inevitably becomes waste management despite the potential for resource harvesting.

Saline water bodies and treatment facility within 50 miles were considered potential disposal sites. Only the Jasper is within 50 miles of a saline water body, the Gulf of Mexico. Site selection for brine discharge into the ocean must meet local regulations and this may require a local source of low salinity water for dilution (Khan et al., 2009; Voutchkov, 2011). The sale of brine for road de-icing was a possible application in Illinois; this option was treated as both a use and a disposal stage for winter months (Table 2) (Mitchell et al., 2004; ND Department of Health, 2009; Ripley, 2011). Evaporation ponds and deep well injection were feasible options at all three sites, although ponds were seasonal in Illinois. Off-site disposal of brine by truck cost \$0.3–1.6/mt-CO_2-mile; disposal using newly constructed pipelines had a NPV of −\$0.1 to 0.2/mt-CO_2-mile. The NPV and feasibility of pipeline disposal is discussed in SI, Section 4.

Cost ranges for brine disposal were adapted from regional produced water management assessments and were used to calculate NPV assuming a 30-year life time and 8% interest rate (Table 2) (Clark and Veil, 2009; Puder and Veil, 2006). These values were multiplied by the fraction of brine remaining for disposal at the end of a BUS. When converted to our functional unit, costs incurred by the oil and gas industry equaled \$0.1–100/mt-CO_2 assuming the entire volume of water was sent for disposal (Veil et al., 2004).

We predict that finding cost effective disposal options that have large capacities and low environmental footprints will continue to be a significant challenge of brine management. Disposal options may change over time if brine sink capacities are reached by CCS projects in a region.

3. Results

3.1. NPV

Potential NPV was maximized using our BUS method after we generated a list of viable treatment and disposal options for each site; these results represent the High Scenarios shown in Fig. 3. Alternative scenarios were explored for each location (Fig. 3). Results were levelized over a 30-year period and are given per ton CO_2 injected.

For brine from the Vedder, (1) capturing geothermal heat, (2) sending brine to supply algae ponds, and (3) disposing of brine in evaporation ponds resulted in the largest NPV, ranging from +\$1 to +\$2. This range reflects variations in potential heat capture, in the price of land and disposal, and in potential algae productivity. A BUS with a higher probability of being implemented in the near future

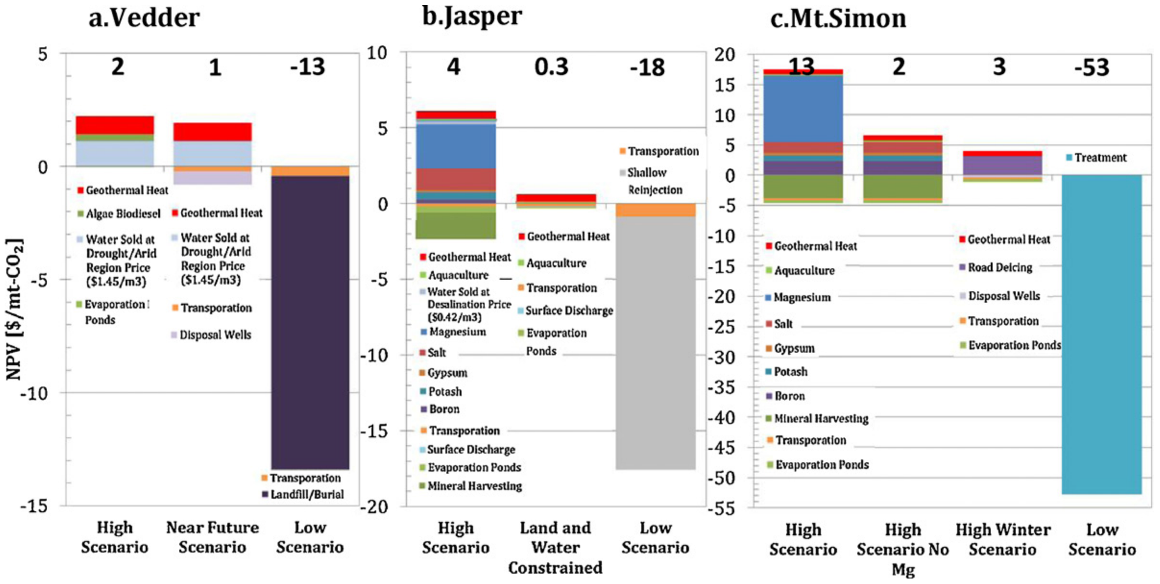

Fig. 3. Net present value (NPV) for alternative BUS scenarios in three saline aquifers. Each scenario's BUS stages are listed in the column. Cumulative NPV is listed in bold at the top of each scenario's column.

and which includes: (1) capturing geothermal heat, (2) desalinating brine and selling the freshwater, and (3) paying to have the concentrated brine transported 50 miles to disposal wells, would result in a NPV of −$33 to +$1. This large range is due to the varying cost of deep well disposal. The Vedder has TDS below 40,000 mg/L and could become a valuable source of water for agriculture in the San Joaquin Valley (Udo de Haes et al., 2004). Direst disposal of brine into evaporation ponds and landfills within 25 miles represents a Low Scenario and could reach −$13.

The largest potential NPV or High Scenario, ranging from −$10 to +$4, for Jasper brine management resulted from: (1) capturing geothermal heat for fish ponds, (2) desalinating brine and selling the freshwater, (3) harvesting salt, boron, potash, gypsum, magnesium, and (4) paying to have the brine transported 25 miles to a disposal site and diluted in the Gulf of Mexico. NPV was affected by variations in potential heat and mineral capture, in the price of land, and in waste discharge costs which include permit, transportation, and dilution. Available land near Houston, TX is limited and water is not scarce (Ventyx, 2012); a more feasible BUS would exclude desalination and mineral harvesting steps (requiring over 80 km^2 of land) and would result in a NPV of −$0.3 to $0.3. Shallow reinjection of brine 50 miles from the CFPP near freshwater resources could reach −$18.

The largest potential NPV, ranging from $1 to +$13, for Mt. Simon brine management in warm months results from (1) capturing geothermal heat for fish ponds, (2) harvesting salt, boron, potash, gypsum, magnesium, and (3) discharging wastes into evaporation ponds 25 miles away via trucks. This range would drop to −$7 to +$2 if magnesium is not harvested and sold. In the winter, use of extracted water for geothermal heat onsite and then as a road anti-icing solution could reach $3/mt-CO$_2$, assuming 50% of the brine could be used for road de-icing within a 100 mile radius and that the remaining 50% is transported 25 miles to a deep well disposal site (the cost of land for evaporation ponds would still be incurred during winter months). Seasons with low road anti-icing demand could lead to significant losses for a GCS project that did not invest in a backup winter BUS (−$35). At the upper range of disposal costs, sending the brine for commercial treatment and subsequent surface disposal in Illinois could double the cost of CCS (−$53). We assumed this option would not be feasible in the near future, but we included it to show how costly brine disposal can be.

Net present value of brine management ranged 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 one 1000 MW CFPP.

3.2. Resource production

Maximum production of magnesium, potash, gypsum, or salt using brine from one CCS project in any of the three formations resulted in annual quantities less than 5% of US domestic production (Table 1). Exceptions include magnesium from the Mt. Simon, where high concentrations resulted in maximum productions equivalent to 13% of 2010 US production. Total US imports for 2007 reached nearly 400,000 mt-tilapia, while ~9000 mt-tilapia were produced domestically in the US (Harvey, 2012). Desalination of extracted brine at maximum TDS could produce 25 million liters per day of freshwater from the Vedder and 5 million liters per day from the Jasper. Ponds supplied with the average geothermal heat captured from the Mt. Simon, Jasper, or Vedder could produce 8, 6, or 14 mt-tilapia respectively; pond systems supplied with desalinated brine from the Vedder or Jasper could produce 3000 or 4000 mt-tilapia respectively, but we assumed these ponds were not feasible due to land, energy, and freshwater requirements (SI, Section S3). Annual US rock salt sales have fluctuated around 18 million tons the last 5 years. Salt produced from Mt. Simon sourced brine during four winter months in Illinois could supply 5% of US winter demand for road de-icing rock salt. These values are for one CCS project. In order for CCS to make a measurable impact in climate mitigation, many CCS projects will be needed, and market thresholds and excessive land use may hinder the application of some BUS options in certain regions of the country.

3.3. Environmental impacts

Peer reviewed environmental impact assessments were found for many BUS options, including: geothermal systems, desalination systems, algae biodiesel production, magnesium harvesting, fish aquaculture, and ocean discharge of brine (SI, Section S2). Opportunities for mitigating local, regional, and global environmental impacts associated with each brine management option, and with the CO$_2$ source itself, may be recognized through careful allocation of energy, water, and material supply and demand

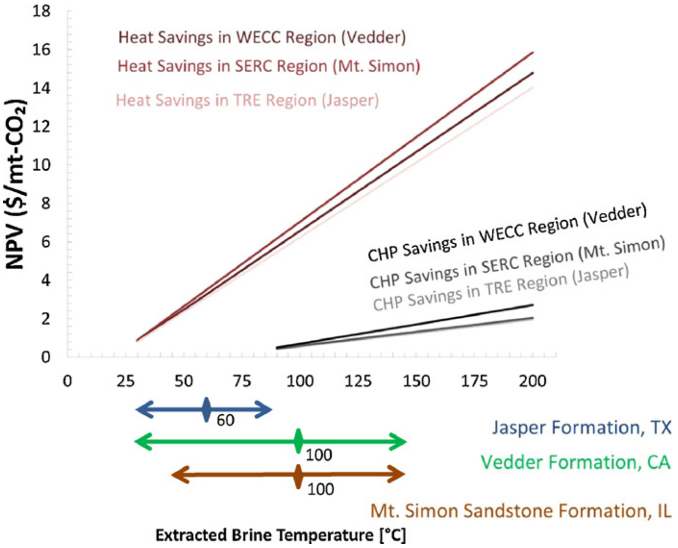

Fig. 4. Parameter variation analysis for energy production. Geothermal energy can be used for (1) heating aquaculture ponds if brine *T* is above 30 °C, and (2) combined heat and power (CHP) if brine *T* is above 90 °C. Temperature ranges for saline aquifers are shown as solid arrows below graph. Representative aquifer temperatures are marked as diamonds on the solid arrows.

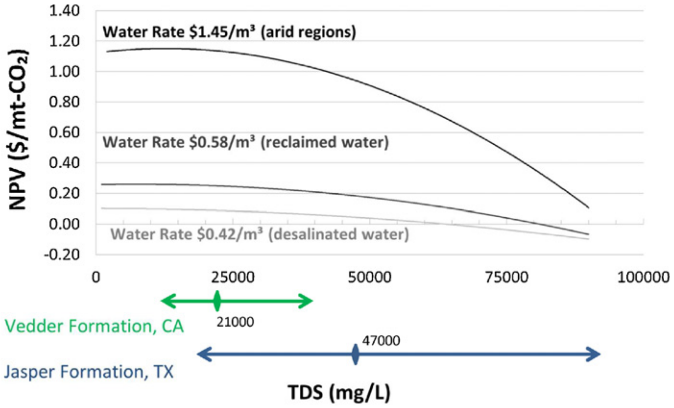

Fig. 5. Parameter variation analysis for freshwater production. The NPV of desalinated water was plotted as a function of TDS in extracted brine and regional water rates. The current RO membrane technological limit was used as an upper bound (~90,000 mg/L). TDS ranges for saline aquifers are shown as solid arrows below graph. Representative aquifer TDS concentrations are marked as diamonds on the solid arrows. The TDS concentrations found in the southern Mt. Simon Sandstone Formation are much higher than the technological limit and were not included.

across a BUS. Using Vedder brine as an example, a geothermal system needing ~0.1 m^3/mt-CO$_2$ of low salinity water could supply an average of 1 kWh/mt-CO$_2$ of electricity to a desalination system requiring ~4 kWh/mt-CO$_2$ of electricity and producing fresh water at an average of 1 m^3/mt-CO$_2$. Impacts attributed to the construction of buildings and roads could be allocated between the two systems, reducing their individual contributions. The potential for these synergies at different GCS sites will be evaluated in a future study.

Evaporation system land footprint ranged from 5 km^2 in southern California to 90 km^2 in eastern Texas. Total land footprint increased when geothermal systems (<1 km^2), algae (<10 km^2), or fish ponds (<0.1 km^2) were included (SI, Section S3). Additional land for brine storage tanks may be required in scenarios where the load hours of BUS steps differ significantly. Substantial land alterations may lead to indirect land use changes and negatively impact local ecosystems.

3.4. *Sensitivity analysis*

A sensitivity analysis was performed for energy and freshwater production to gain insight on how the NPV of these brine treatment options vary between and within saline aquifers (Figs. 4 and 5). We determined that the NPV of energy production is sensitive to brine temperature, regional electricity costs, and energy capture efficiencies (Fig. 4). Electricity generation is more expensive than heat generation at temperatures found in the three saline formations due to lower conversion efficiencies and higher auxiliary energy demands (Evans et al., 2009). Regardless, CCS projects may choose to generate electricity, or capture energy after some cooling of the brine if they cannot find adequate demand for heat.

The NPV of freshwater production is also sensitive to technology efficiencies, as well as TDS concentration and regional water rates. As seen in Fig. 5, revenue can be obtained from desalinating brine from both the Jasper and Vedder formations if the water is sold at a high rate.

Temporally dynamic variables, like changing market prices and market responses to new domestic sources of products like magnesium, are a major source of uncertainty. The effects of fluctuations in resource market prices on BUS utility were not quantified, as this was beyond the scope of our current study. In addition, implementation of emerging technologies like algae biodiesel depends on political, social, and economic forces that are difficult to predict and that add uncertainty to any future-looking study.

We explored brine management in the context of pressure management for GCS projects. As such, we chose an injection:extraction ratio of 1:1 to avoid reservoir pressure build-up. The extraction ratio required to control pressure rise may be less than a 1:1 ratio due to site specific geologic conditions that are outside the scope of this study. Certain aspects of our economic assessment would scale linearly with brine extraction volume due to the sequential nature of our method. For example, desalination reduces the volume of brine entering later BUS stages like evaporation ponds (SI, Fig. S1). We predict that other aspects of our economic assessment will show non-linear behavior at low brine volumes, capital costs for geothermal facilities for example. Exploring these non-linearities will be an important topic for a future study.

Inconsistencies and limitations of available regional data are another source of uncertainty (SI, Section S5). For example, well data without sufficient depth information in the Mt. Simon were excluded from the study. These values gave higher TDS concentrations and thus higher potential mineral recovery ($18 vs. $13/mt-CO$_2$-eq) for the Mt. Simon High Scenario.

3.5. *Perspective on brine extraction for GCS and produced water from oil and gas*

A natural question is: if brine can be economically valuable under certain circumstances, then why has it not been used as such by the oil and gas industry? Unlike select GCS sites, where brine is extracted to reduce formation pressure, large quantities of brine (produced water) are unavoidably co-produced by the oil and gas industry as fields mature (Clark and Veil, 2009). After oil and gas are separated out of the water (Ahmadun et al., 2009) the most common method of disposal for onshore sites is re-injection back into the reservoir; most offshore sites discharge the water into the ocean. Likely answers to the question posed include: (1) there is no need to keep the brine out of the oil and gas reservoir, making reinjection an obvious option (Stewart, 2006); (2) there is a desire to maintain reservoir pressure to enhance oil and gas recovery which makes reinjection useful; (3) lack of familiarity with water, mineral, and aquaculture markets and technologies (Stewart, 2006);

(4) removal of soluble organics, gases, carcinogenic production contaminants, and unpredictable production rates greatly increase the cost and difficulty of brine management options (Ahmadun et al., 2009; Mondal and Wickramasinghe, 2008; Veil et al., 2004); and (5) their interest in taking on the responsibility of produced water management may fluctuate with the price of fossil fuels (Puder and Veil, 2006). That being said, economic and environmental reuse of produced water through wetlands, irrigation, desalination, as water for cooling towers, for dust and fire control, and for enhanced oil and gas recovery is an active area of study (Finnveden et al., 2009; Mondal and Wickramasinghe, 2008; Stewart, 2006; Veil et al., 2004; Zamagni et al., 2012). For example, Devon Energy Corporation has treated produced water from the Barnett Shale in Texas to freshwater quality for reuse in hydrofracking wells since 2005 (Earles and Halog, 2011). The volume treated in the Barnett Shale project is smaller than the total volume of brine modeled in this study (~10%), but Devon Energy Corporation has other projects exploring treatment, transportation, disposal, and storage of volumes of produced water on the same order of magnitude as our study. In 2010, a project in Oman started using reed beds to treat the equivalent volume of produced water modeled in our report; local applications for the treated water are being explored (Rebitzer et al., 2004).

In GCS sites with pressure constraints, reinjection of the brine back into the same reservoir is not practical, hence the need to consider brine management. Despite the large role that GCS could play in US carbon emissions mitigation, the cost of GCS and brine management is likely to inhibit national adoption unless methods are found to lower costs or until carbon policy incentivizes CCS adoption by large CO_2 stationary sources (Fischbeck et al., 2012).

4. Discussion and conclusions

Multiple BUSs provided positive NPV for each site. These scenarios were sensitive to market prices for energy and water, fluctuations in brine temperature and chemistry, and relied on the assumption that related technologies would mature by the time of implementation. As a result, BUSs that provided revenue under optimal conditions did not show robustness under less optimal market and technological conditions. In addition, it is possible that the BUS maximizing NPV for one CCS project may not be feasible for multiple CCS projects in the same region due to limitations in land availability, brine disposal capacities, climate, and potential market thresholds. Brine management at each site had the potential to reach very negative NPV when the strictest regional disposal regulations were included (Fig. 3). Reducing the volume of waste brine improved the feasibility of disposal options in all regions evaluated.

There is a risk that certain local, regional, and global environmental impacts will be introduced by brine management options. Although we used our method to generate BUS scenarios that maximize NPV in this study, our method can also be used in a LCA to generate BUS scenarios that minimize environmental impacts.

The method developed in this study captures a high level of spatial heterogeneity in climate, market, and aquifer data. As a result, we were able to characterize prospective regional constraints and opportunities for cost effective local environmental management of large brine waste streams associated with large-scale GCS projects. Assessment of brine management should be integrated into a GCS project as early as site selection to avoid or manage challenges that may act as barriers to CCS deployment. We predict that rising water scarcity and progressive regulatory changes regarding GCS brine transportation and disposal will be key driving-forces for increasing the feasibility of brine management.

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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.2013.01.003.

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