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Publication Date
2013-09-13

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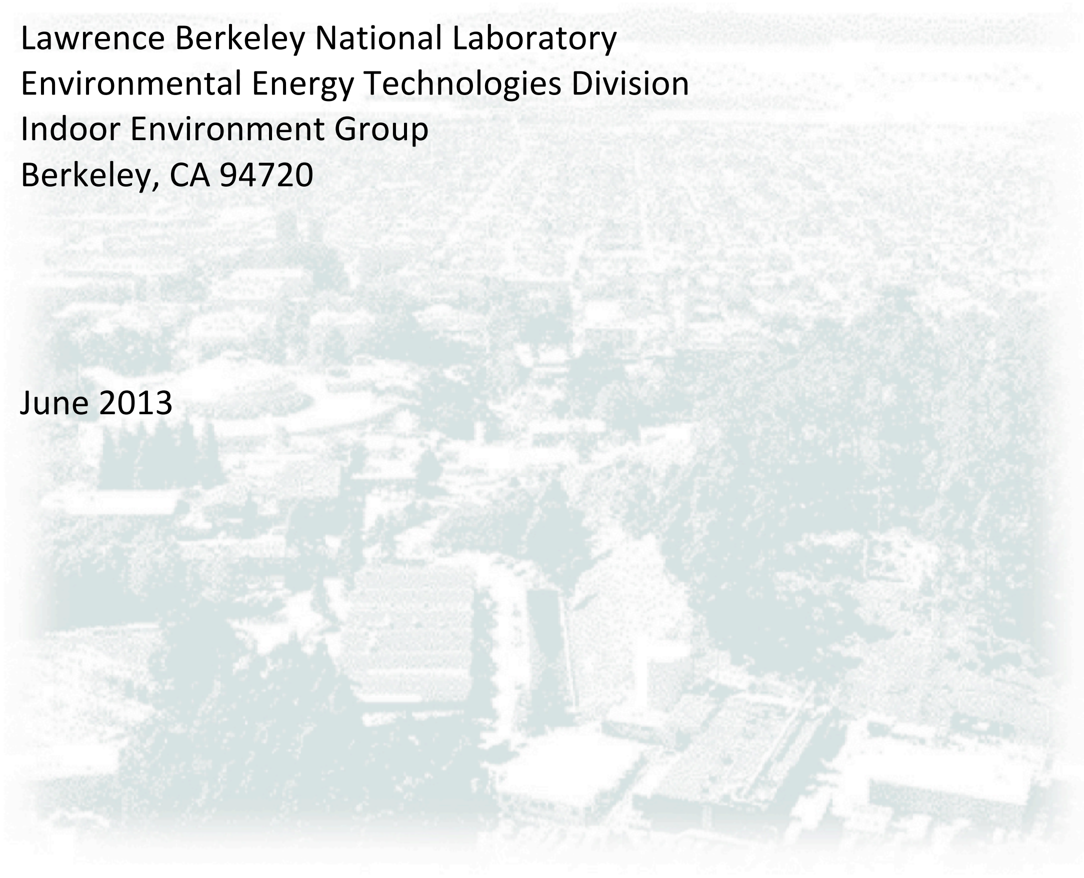
June 2013



Assessment of Brine Management for Geologic Carbon Sequestration

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June 16, 2013

ABSTRACT

Geologic carbon sequestration (GCS) is the injection of carbon dioxide (CO_2), typically captured from stationary emission sources, into deep geologic formations to prevent its entry into the atmosphere. Active pilot facilities run by regional United States (US) carbon sequestration partnerships inject on the order of one million metric tonnes (mt) CO_2 annually while the US electric power sector emits over 2000 million mt-CO_2 annually. GCS is likely to play an increasing role in US carbon mitigation initiatives, but scaling up GCS poses several challenges. Injecting CO_2 into sedimentary basins raises fluid pressure in the pore space, which is typically already occupied by naturally occurring, or native, brine. The resulting elevated pore pressures increase the likelihood of induced seismicity, of brine or CO_2 escaping into potable groundwater resources, and of CO_2 escaping into the atmosphere. Brine extraction is one method for pressure management, in which brine in the injection formation is brought to the surface through extraction wells. Removal of the brine makes room for the CO_2 and decreases pressurization. Although the technology required for brine extraction is mature, this form of pressure management will only be applicable if there are cost-effective and sustainable methods of disposing of the extracted brine.

Brine extraction, treatment, and disposal may increase the already substantial capital, energy, and water demands of Carbon dioxide Capture and Sequestration (CCS). But, regionally specific brine management strategies may be able to treat the extracted water as a source of revenue, energy, and water to subsidize CCS costs, while minimizing environmental impacts. By this approach, value from the extracted water would be recovered before disposing of any resulting byproducts. Until a price is placed on carbon, we expect that utilities and other CO_2 sources will be reluctant to invest in capital intensive, high risk GCS projects; early technical, economic, and environmental assessments of brine management are extremely valuable for determining the potential role of GCS in the US.

We performed a first order feasibility and economic assessment, at three different locations in the US, of twelve GCS extracted-water management options, including: geothermal energy extraction, desalination, salt and mineral harvesting, rare-earth element harvesting, aquaculture, algae biodiesel production, road de-icing, enhanced geothermal system (EGS) recharge, underground reinjection, landfill disposal, ocean disposal, and evaporation pond disposal. Three saline aquifers from different regions of the US were selected as hypothetical GCS project sites to encompass variation in parameters that are relevant to the feasibility and economics of brine disposal. The three aquifers are the southern Mt. Simon Sandstone Formation in the Illinois Basin, IL; the Vedder Formation in the southern San Joaquin Basin, CA; and the Jasper Interval in the

eastern Texas Gulf Basin, TX. These aquifers are candidates for GCS due to their physical characteristics and their close proximity to large CO_2 emission sources. Feasibility and impacts were calculated using one mt-CO_2 injected as the functional unit of brine management. Scenarios were performed for typical 1000MW coal-fired power plants (CFPP) that incurred an assumed 24 percent carbon capture energy penalty (EP), injected 90 percent of CO_2 emissions (~9 million mt-CO_2 injected annually), and treated extracted water onsite. Net present value (NPV), land requirements, laws and regulations, and technological limits were determined for each stage of disposal, and used to estimate feasibility. The boundary of the assessment began once extracted water was brought to the surface, and ended once the water evaporated, was injected underground, or was discharged into surface water bodies. Results of the assessment were generated, stored, and analyzed using Microsoft Excel spreadsheets and ESRI Geographical Information System (GIS) maps.

Conclusions about the relative benefits and impacts of alternative brine-management strategies were highly sensitive to local climate and weather, and aquifer water chemistry. The NPV of certain scenarios ranged from -\$50/mt-CO_2 (a cost) to +\$10/mt-CO_2 (revenue). The land footprint of the scenarios in this study ranged from <1 km^2 to 100 km^2.

Brine extraction as a pressure management tool for GCS has potential for improving the economics and for minimizing the environmental impacts of CCS. In order to maximize this potential, careful analysis of each saline aquifer and region must be conducted to determine a regionally appropriate brine use sequence (BUS) at the time of site selection. Models that use GIS will be essential tools in determining such sequences for individual CFPP. Future studies that perform risk and life cycle assessments (LCA) of BUS scenarios, incorporate additional impact metrics into the BUS model, and enhance the temporal sensitivity of the model would improve the robustness of this regional assessment method.

ACKNOWLEDGEMENTS

This research was supported by Laboratory Directed Research and Development (LDRD) funding at the Lawrence Berkeley National Laboratory, which is operated for US Department of Energy under Contract Grant No. DE-AC02-05CH11231. We acknowledge the comments and help of the members of the Carbon Cycle 2.0 initiative and we thank Agnes Lobscheid for her careful review.

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ACRONYMS & ABBREVIATIONS

American Petroleum Institute	API
Bureau of Economic Geology	BEG
Billion Gallons per Year	BGY
Brine Use Sequence	BUS
Carbon dioxide Capture and Storage	CCS
Carbon Dioxide	CO_2
Coal-Fired Power Plant	CFPP
Combined Heat and Power	CHP
Cumulative Energy Demand	CED
Disinfection By-Products	DBP
Enhanced Geothermal System	EGS
Energy Penalty	EP
Geologic Carbon Sequestration	GCS
Geographic Information System	GIS
Gigatonnes Carbon (metric)	GtC
Global Warming Potential	GWP
Integrated Gasification Combined Cycle	IGCC
Known Geothermal Energy Resources	KNER
Metric tonnes	mt
Midwest Geologic Sequestration Consortium	MGSC
Million Gallons per Day	MGD
Muriate of Potash	MOP
National Carbon Sequestration Database and Geographic Information System	NATCARB
Nano-Filtration	NF
Order of Magnitude	OM
Pulverized Coal	PC
Rare Earth Elements	REE
Renewable Fuel Standard	RFS
Relative Humidity	RH
Reverse Osmosis	RO
SERC Reliability Corporation	SERC
Surface Area	SA
Southeast Regional Carbon Sequestration Partnership	SECARB
Sulfate of Potash	SOP
Texas Reliability Entity	TRE
Triacylglycerides	TAG
Total Dissolved Solids	TDS
US Geological Survey	USGS
West Coast Regional Carbon Sequestration Partnership	WESTCARB
Water Recycling Facilities	WRF
Waste Water Treatment Facilities	WWTF
Western Electricity Coordinating Council	WECC
Zone of Initial Dilution	ZID

1. Assessment Goals and Approach

Carbon dioxide (CO_2) capture and storage (CCS) can mitigate CO_2 emissions from stationary point sources in the United States (US). Geologic carbon sequestration (GCS) refers to the storage part of CCS, specifically the injection and trapping of CO_2 in deep geologic formations to prevent its entry into the atmosphere where it would cause climate change. The primary locations for GCS are saline aquifers in large sedimentary basins, depleted oil and gas reservoirs, unmineable coal seams, basalt formations, and organic-rich shale basins. The CO_2 storage capacity of saline aquifers in the US alone is estimated to be between 2 and 20 trillion metric tonnes (mt) (Department of Energy 2010). Despite the large storage capacity of US geologic carbon sinks, injecting the gigatonnes of CO_2 required to meet even a fraction of proposed CO_2 emission reductions presents significant logistic and economic challenges.

Injecting CO_2 into sedimentary basins raises fluid pressure in the pore space, which is typically already occupied by naturally occurring, or native, brine. This pressure rise spreads over large areas in permeable formations and can cause rock fracturing, induce seismic activity, and drive lateral and vertical migration of native brine or CO_2 (Vilarrasa et al. 2010). Brine extraction (or production) is one method for pressure management. This is achieved by removing resident saline water, often highly saline brine[1], from the pore space to the ground surface via wells to accommodate injected CO_2. Brine extraction is currently being viewed as an added cost to CCS and prior research has focused on its potential for CO_2 plume management and as a source of cooling tower water (Court et al. 2011). To date, brine treatment research has focused on the costs and technological limits of membranes for desalinating the water and for using it in power plant cooling towers (Aines et al. 2011; Buscheck et al. 2011). These studies focus on cost-benefit analysis, but have not fully addressed environmental impacts or regional variability in the feasibility of disposal of related waste streams. Brine extraction may become a necessary component of GCS in cases where geological hazards of pressure rise are unacceptable and where it is desired to increase CO_2 storage capacity. Nevertheless, if the goal of GCS is to avoid CO_2 emissions, a regionally sensitive life cycle assessment (LCA) of brine management must be conducted to determine the true mitigation potential of GCS.

The primary objective of our study was to develop a method for quantifying the costs and environmental impacts of brine management in different regions of the United States (Breunig et al.

[1] We use the term *brine* when referring to any resident saline water found in GCS targeted sedimentary basins.

2013). In doing so, we developed and analyzed brine use sequences (BUS) in three different regions of the US to identify regional challenges and opportunities for brine extraction for pressure management. Identifying feasible BUS required the development of a decision framework. In the first stages of our assessment, we assumed all options were feasible in each of the three regions. We modeled the resource consumption and production, land use, costs, and disposal requirements for the twelve brine management options using region-specific data, and paired our findings with regional regulatory standards. Options were removed from the decision process if they did not comply with technical limits or had unrealistic resource and land requirements. We included management stages starting after the brine was brought to the surface through wells, in the system boundary. Environmental and cost management stages following brine disposal through evaporation, underground injection, or surface discharge, were excluded from the study. This method allowed us to generate a summary of the potential benefits, net present value (NPV), and environmental risks of brine disposal. The inventory data, methods, and results included in this report will expedite the next critical step in brine sequestration and management research: an LCA of brine management strategies.

A background on beneficial-use-technologies and brine treatment options is provided in Section 2 of this report. In Section 4, we address NPV, legal/regulatory issues, and land footprint for the various stages of brine management. Net present values of these impacts are integrated into the BUS framework and used to assess the feasibility of brine management scenarios in different regions of the US in Section 5. A preliminary environmental analysis and regional feasibility and cost assessment can be found in Breunig et al. 2013 and its supplementary materials.

1.1 Assessment of brine use sequences for GCS in three regions of the US

Our decision framework evaluated brine as a potential resource of minerals, salts, thermal energy, and water before treating it and its byproducts as waste. Geothermal energy extraction, reverse osmosis (RO) treatment for non-potable uses, salt harvesting, and saline algae pond recharge are examples of processes that could be used, alone or in combination, to convert brine to a resource. Eventually the unused components of the brine do become waste, and they are subject to disposal via reinjection, direct surface water discharge, disposal to wastewater treatment facilities, and discharge into evaporation ponds.

Brine disposal options are extremely site-specific for several reasons, including the following. First, the water chemistry varies between and within formations (Eccles et al. 2009).

Second, the volume of water extracted will vary depending on the quantity of CO_2 available for CCS and on the number of active GCS projects using the aquifer. Third, geographical variability of saline surface water bodies (e.g., proximity to the Pacific or Atlantic Oceans, or the Gulf of Mexico), large wastewater treatment facilities, topography, markets, climate, and unused, cheap land will affect the feasibility of disposal options.

Our scenarios were modeled for three aquifers in different regions of the US to evaluate how spatial variation affects feasibility and economics of brine disposal. The three aquifers are: the Mt. Simon Sandstone Formation (Mt. Simon) in the Illinois Basin, IL; the Vedder Formation (Vedder) in the southern San Joaquin Basin, CA; and the Jasper Formation (Jasper) in the eastern Texas Gulf Basin, TX (Figure 1). These aquifers were selected for their prominent role in CCS and GCS research and pilot projects, for their close proximity to CO_2 sources, and for the large quantity of available data characterizing them. Our selection of case study regions was not meant to imply that brine production would be necessary (or desired) for a GCS operation in these aquifers. Such a determination would require detailed and site-specific modeling predictions of pressure buildup in response to a specific CO_2 injection plan.

Using a combination of Microsoft Excel spreadsheets and ArcGIS geographic information system (GIS) maps, we conducted regionally specific feasibility and economic assessments of brine management for GCS. Due to the dynamic nature of emerging technologies and the variable reliability of current data sets, this assessment was not meant to support policy recommendations or to be used as a tool for making predictions. The specific aims of this project were to identify key problems that must be confronted to dispose of brine, to enumerate the possible solutions to these problems, and to provide baseline estimates of the human, economic, and environmental impacts.

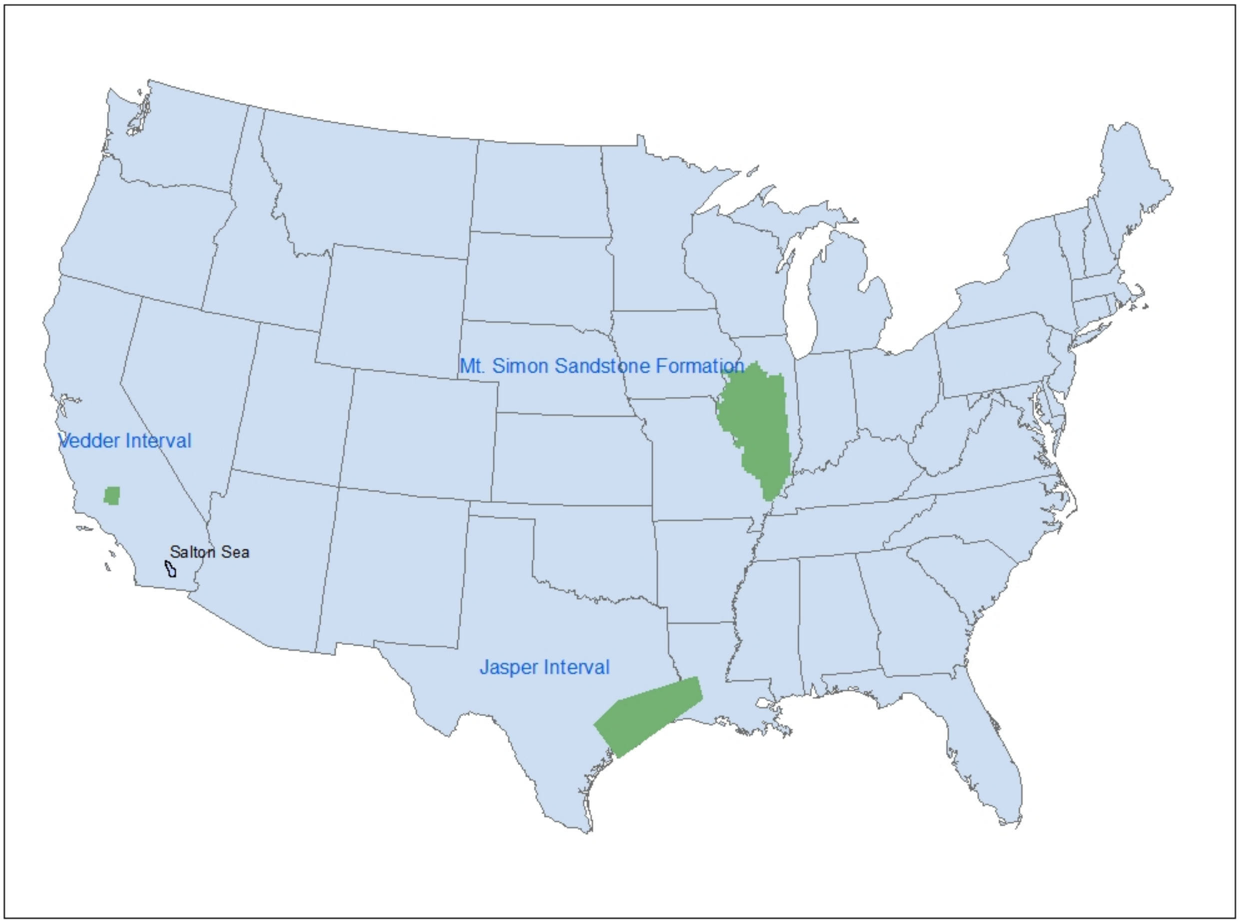

Figure 1. Map of three US saline aquifers (green areas) used in this study. Aquifer GIS data, including surface area shape estimates, were adapted from different NATCARB partnerships, the BEG, and the USGS.

2. BACKGROUND

2.1 Life Cycle Assessment

Life cycle assessment (LCA) quantifies the environmental impacts that result from the each life cycle stage of a process or product. As defined by ISO Standard 14040, an LCA includes four stages of analysis: (1) establish the goals and scope of the study (this includes defining system boundaries); (2) construct a life cycle inventory (gather data on materials and energy flows and processes); (3) conduct a life cycle impact assessment (use characterization factors to compare the impacts of different product components); and (4) perform life cycle management (integrate all this information into a form that supports decision-making) (Udo de Haes et al. 2004). LCA requires that we address impacts both upstream and downstream in the life-stages of resources, technologies, and wastes for a management option. The flows of resources and pollutants provide a framework for assessing human-health, environment, and resource impacts.

The purpose of an LCA applied to brine management is to quantify and compare environmental flows of resources and pollutants (to and from the environment) associated with a range of brine-management options. A comprehensive LCA for some brine management options, like algae pond recharge, must address cumulative impacts to human health and the environment from all stages, impacts from alternative materials, and impacts from obtaining feedstocks and raw materials. This study was intended to characterize and determine technologically feasible, legal, and economic brine management options and sequences in specific regions of the US, laying the groundwork for valuable, regionally appropriate comprehensive LCA.

2.2 Brine Disposal Options

Our overall approach was to identify and compare brine management options that deal with brine as a waste, a resource, or some combination of the two. We began by summarizing the performance of each option, and then compiled performance measures for NPV and feasibility. Particular attention was paid to waste disposal laws, maturity of the practice, characterization of current practice, physical and chemical limitations, and conclusions of previous environmental impact assessments. Three disposal processes are included in this report in detail: (1) surface discharge to saline water bodies such as the ocean, with and without dilution using wastewater treatment facility effluent; (2) evaporation ponds disposal; and (3) reinjection into disposal wells, similar to Class II disposal wells. Landfill disposal, the fourth disposal option is modeled as a part of evaporation pond disposal, and is discussed briefly in this report and in more detail in Breunig et al.

2013. These options could be chosen for brine management with or without using the brine for resources prior to final disposal.

2.2.1 Discharge to Surface Water Bodies

The disposal of saline water is a major economic and environmental issue (Kim 2011). Unlike municipal wastewater, saline water includes dissolved inorganic compounds in their simplest forms, and desalinization with RO alone is not typically economic above ~50,000 mg/L total dissolved solids (TDS) (Bourcier et al. 2011). The common policy has been to treat these effluents as a waste management problem, and over 70 percent of US desalinization plants have opted to discharge their high salinity waste to surface water bodies and sewers (Khan, Murchland et al. 2009). Ocean discharge is the most common disposal method, especially for saline effluent sources located near coastlines. For inland sources there are the following options: discharge to surface water bodies, wastewater treatment facilities (sewer systems), deep well injection into sedimentary basins and disused mines, land application, waste minimization, irrigation, aquaculture, salt production, and evaporation ponds. The feasibility of alternative disposal options is influenced by the composition, flow volume, and geographical source of the brine. Additional factors affecting feasibility include available sinks, local and regional regulations, public acceptance, proximity to sensitive ecosystems, capital and operational costs, and the potential for sink expansion (Ahmed et al. 2000). Discharge to surface water bodies is likely to be a viable disposal option for GCS sites located along US coastlines; treatment for heavy metals and dilution may be required depending on brine composition and state regulations.

2.2.2 Evaporation Ponds

Evaporation ponds are an attractive choice because they are inexpensive, and simple to construct and maintain. In addition to their low capital cost, evaporation ponds have the potential to be combined with salt recovery, mineral harvesting, solar ponds for electricity generation, and saline aquaculture including: fish, brine shrimp, and algae growth for biofuels or for beta carotene production (Ahmed et al. 2003; Van Der Bruggen et al. 2003). In these cases, the saline effluent is converted from a waste to a resource. In addition to land costs, basin liners such as polyvinyl chloride (PVC) and clay will constitute a large portion of the costs. Site selection will be influenced by freshwater resource proximity due to the high likelihood of leakage from evaporation ponds.

Regular monitoring of local groundwater will be important for monitoring and minimizing the environmental impact of evaporation ponds. The cost of salt solids disposal to landfills or surface water bodies will depend on the level of salt and bittern recovery, on the composition of extracted brines, and on the transportation distance (Chelme-Ayala et al. 2009).

Evaporation ponds are best suited for arid and semi-arid climates that have high evaporation rates, low annual precipitation, and low land costs (Ravizky and Nadav 2007). The required surface area (SA) is inversely proportional to local evaporation rates. The evaporation rate E [m/day] is given by

$$E = c * (e_s - e_a) \qquad \textit{Equation 1}$$

where e_s [bar] is the saturated vapor pressure at the temperature of the water surface, e_a [bar] is the air vapor pressure at the temperature near the air/water interface, and c [m/day-bar] is an evaporation rate constant. Although evaporation rates are a function of water surface temperature, air temperature, relative humidity (RH), wind, and salinity, standard simplified equations do not reflect how evaporation rates vary temporally and spatially due to variability in water composition and climate. These parameters affect the vapor pressure difference that ultimately is what influences evaporation rates (Kokya and Kokya 2008).

Therefore, instead of using equations, evaporation ponds are typically designed using empirically determined local monthly pan evaporation rates, multiplied by a factor to scale the pan rate to pond rate and to scale for salinity. A pan factor of 0.69 and a salt coefficient of 0.7 are commonly used in the literature (Moore and Runkles 1968; Ahmed et al. 2000; Weghorst 2004). The pan factor corrects for the fact that evaporation in large water bodies is slower than evaporation in shallow testing pans. The salt coefficient corrects for the fact that evaporation of salty water is slower than evaporation of freshwater.

In general evaporation ponds are sized to ensure the volume of water evaporated, minus the volume of precipitation caught by the pond, is larger than the volume of saline effluent flowing into the basin each year. In addition to calculating the evaporation rate for each month, the average monthly precipitation must be taken into account. The larger the surface area, the more precipitation will be captured by the evaporation pond. A large pond may capture enough rain water to negatively affect local water tables and local ecosystems. This result, as well as the potential impact of large quantities of water vapor blowing off the ponds, may lead locally to unforeseen complications or benefits. An impermeable membrane can prevent rain from seeping into the bottom and sides of the pond so that recharge from rain through the ground will not be a concern for water storage capacity.

So far, the effect of pond depth on evaporation rates is unknown. A review by Ahmed et al (2000) suggested depths between 25 and 45 cm will maximize evaporation. Most studies suggest values around 30 cm to prevent drying and cracking of the pond liner. Depth is typically designed based on required surge, salt, and water storage capacities. A 20 cm freeboard is added in case of rain and wave action. Evaporation ponds that also function for algae growth are usually 30 cm or less in depth to allow for photosynthesis throughout the water column.

Evaporation ponds are a promising disposal option for arid GCS sites, especially if the site is inland and located near cheap, available land. This option will become limited over time as additional GCS sites develop nearby and require land for evaporation pond disposal.

2.2.3 Brine Reinjection

Six classes of wells are defined in the US EPA's regulation for underground injection of various liquid wastes in the US.[2] Class II wells involve the injection of brines from oil and gas industries for storage, disposal, or Enhanced Oil Recovery (EOR). Over 7.6 billion liters of brine are injected annually into 151,000 active wells in US (US EPA 2011). Class II wells are present in CA, TX, and IL. 41 percent of permitted wells in Texas are considered Class II wells. Wells in California are regulated by the Department of Conservation, while wells in Illinois are regulated by the EPA State Department of Natural Resources. In order to use a Class II well, Sections 1422-1425 of the Safe Drinking Water Act (SDWA) must be met in addition to obtaining a permit. This involves regular demonstration that local drinking water sources are not being contaminated (Illinois State DNR 2012). We modeled the same permitting process as Class II wells. The feasibility of reinjection will decrease if new wells or new permitting processes must be developed for GCS waste brine. Well disposal is available for all three GCS sites included in this study, but they may become limited over time as injection sites reach their storage capacities.

[2] Further details on the major characteristics of EPA disposal well classes can be found at: http://water.epa.gov/type/groundwater/uic/wells.cfm

2.3 Options for Managing Brine as a Resource

For the purposes of our assessment, we assumed brine leaves the system boundary when it enters evaporation ponds, is discharged to water bodies, or is reinjected into the ground. There are several treatment processes that could be applied to the brine prior to final disposal. Based on a literature review, we generated and evaluated the technical, spatial, and economic metrics of these treatment processes and brine applications.

Seven options are considered in detail in this report: (1) geothermal energy capture from brine, (2) recharge of geothermal reservoirs for EGS, (3) RO treatment of brine, (4) salt and mineral harvesting from evaporation ponds, (5) rare earth element harvesting from brine, (6) road de-icing using brine, (7) brine use for saline algae ponds for biofuels, and (8) aquaculture. In the sub-sections below, we provided information on the engineering parameters, the extent of current infrastructure, the state of resource markets, limitations, and regional characteristics of each of these disposal options.

2.3.1 Geothermal Energy and EGS

Geothermal energy is heat originating from the earth's interior. Geothermal reservoirs are areas relatively near the earth's surface where this heat has concentrated, resulting in temperatures that can range from 45°C to over 300°C.[3] Water- or vapor-dominated geothermal systems are the most commonly used geothermal reservoirs because the heat in the resident water or steam can be extracted and used for generating electricity. Lower-temperature systems typically use heat exchangers or the extracted water itself for space heating, greenhouse heating, aquaculture pond heating, agriculture drying, industrial uses, bathhouses, or for snow melting (Lund 2010). Wet steam fields are the most commonly used reservoirs for electricity generation. They are characterized by fluid temperatures exceeding 100°C and by high chemical content. Hot water fields are reservoirs with temperatures below 100°C. These reservoirs are usually used if they are less than 2 km deep and have TDS below 60 g/kg (60,000 ppm) (Barbier 2002). Temperatures as low as 45°C can be used for space heating: in a typical application, geothermal heating can work even with fluids can used with fluids as little as 15°C above the desired indoor temperature. Binary cycle plants use heat exchangers that transfer heat from reservoir water to a

[3] Often listed as a renewable energy, geothermal energy is only renewable if the reservoir's water is recharged to compensate for the water extracted by wells and if the heat mined from the rocks can be restored on the same time scale as it is extracted.

low boiling point fluid like isobutane. Reservoir water is then reinjected underground. The efficiency of this system is low, around 5 percent, but the system is cost effective and it can utilize low-temperature geothermal resources as long as the water is above 85°C (Frick, Kaltschmitt et al. 2010).

A power plant using a water/isobutane binary cycle requires up to 400 kg/kWh of water if the reservoir temperatures are 90-150°C. For a 100°C source, this is equivalent to 115 L/s (≈1840 gallons per minute) of water for 1 MWe. Another study estimated that for a 120°C source, 63 L/s (1000 gallons per minute) of water would be needed to generate 1 MWe (Callison 2010).

A majority of the water demand from geothermal energy systems comes from the need to maintain geothermal reservoir productivity; water is injected into the formation to maintain pressures. An EGS injects water into geological formations that are hot and have artificially-enhanced permeability. Water or vapor is then extracted through a well system and used for geothermal energy. The map in Figure 2 shows the potential areas where EGS may be possible in the US. Recharge of hydrothermal systems provides replacement fluid to compensate for losses due to steam and water extraction and helps maintain reservoir pressure. EGS recharge as an option for brine management is limited to a few regions of the country with EGS infrastructure and will not be an option for most GCS sites.

Harvesting geothermal energy is a promising option for brine management because even the low temperature brines that cannot be used to generate electricity can provide some thermal energy savings for the GCS site. In addition, the injection of CO_2, instead of water, creates the pressure required to maintain reservoir pressures and minimizes the cost and water demand of geothermal energy.

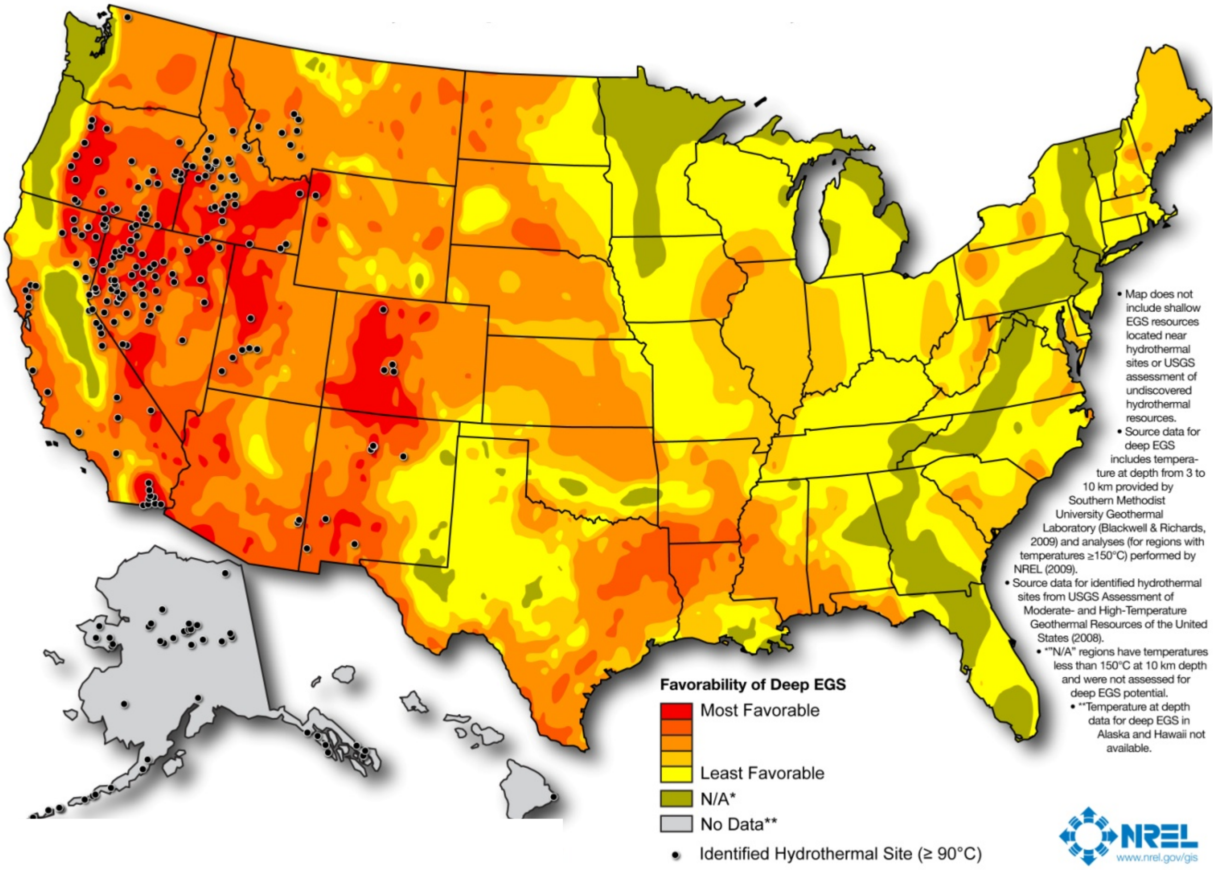

Figure 2. Map of geothermal resources of the US: Locations of identified hydrothermal sites and favorability of deep EGS (Roberts 2009).

2.3.2 Reverse Osmosis Treatment

Desalination is the process of generating freshwater from saltwater sources. RO is a mature technology that is economic for desalinization of saline groundwater where TDS is low and where freshwater demand is high (Aines et al. 2011; Bourcier et al. 2011). Using RO to treat water with TDS greater than 50 g/L is rarely practiced by desalination plants for technical and economic reasons. We performed a careful literature review of brackish water, seawater, industrial waste, and brine desalination and determined that plants performing desalination and those performing GCS brine management face different technical and economic challenges and opportunities. These differences allowed us to set the technical limit at 85 g/L instead of 50 g/L. The research found in Bourcier, et al. (2011) confirmed our assumption that RO membranes can treat brines up to 85 g/L at lower recovery fractions, high brine extraction volumes, and with anti-scale pretreatment.

Permeate generated from the process can be used for non-potable water uses or, with further treatment, for drinking water. The portion of water demand in cooling towers attributed to adding carbon capture technology could be met through desalination of extracted water (Newark et al. 2010). Other industrial or agricultural processes that require freshwater vary by region and offer potential markets for desalinated water. In addition, future changes in regional water supply due to global warming, population growth, or changes in agriculture will affect water demand (Carney 2010). For example, the southwest is a region with high probability of future water shortages.

The application of RO in the US is currently limited and concentrated in a few coastal regions mostly in Florida and California. This is due in part to the challenges of waste stream disposal (Ahmed et al. 2003). Direct surface water discharge is the most common disposal method. While twice as concentrated as the source water, the brine waste stream has the same constituents and the salts are not anthropogenic in origin. This is advantageous because the environmental impact of a discharge site is minimal if the water is returned within 10-30 km of the source and is diluted thorough turbulence or co-disposal (Del Bene et al. 1994; Chelme-Ayala et al. 2009; Voutchkov 2011). Desalination is a promising option for the management of lower salinity brines if there is a demand for the desalinated water, a disposal option for the highly concentrated brine, and if there is available, cheap electricity.

2.3.3 Salt and Mineral Harvesting

In the US, non-metallic mineral mining is an annual $4.9 billion industry that supplies many industrial, agricultural and transportation sectors (Bueno 2011). Nonmetallic mineral mining includes the mining of ore and rocks, deep well solution mining, open pit mining, solar evaporation ponds, and chemical extraction. Boron compounds (borate and boric acid), potash (potassium salts), phosphate, soda ash (sodium carbonate and sodium sulfate), and rock salt bring in the majority of mineral mining revenue in the US (Bueno 2011). Table 1 summarizes the average sale prices for several minerals and salt in 2010. Key external drivers include consumer spending on manufactured goods, food, and housing; trends in agriculture industries that affect fertilizer demand; the occurrence of natural disasters like ice storms; and legislative regulations on mining (Ripley 2011).

Table 1. Salt and mineral market summary for 2010. Sale price given in $/mt for each compound.

[$/mt]	
Boric Acid	360
Salt in Brine	8
Potash	600
Magnesium	3200
Crude Gypsum	6.9
Calcined Gypsum	20
Salt Used on Roads 2009	35

The two largest known deposits of boric acid (B_2O_3) are found in Southern California and in Turkey. Two companies in Southern California lead the world in boron compound and mineral production. Production data are treated as proprietary and not currently available for the US. Excluding the US, the world produced 3.5 million mt of boron-containing ore in 2010, with Turkey producing 1.2 million mt (Angulo 2011). Over 78 percent of produced boron is used in fiberglass and ceramics manufacturing. The remainder is used in products such as soaps, detergents, bleaches, and fire retardants. Open pit methods are used to extract boric acid and sodium borate from ores such as kernite and tincal. Extraction solution mining techniques are also practiced, and borate compounds are harvested from extracted brines.

Potash, which is the name for various potassium-containing salts, is a valuable source of soluble potassium for plants and animals. Annual world production capacity is expected to increase from 43 to 55 billion mt by 2014. In 2010, 60 percent of production was potassium chloride or Muriate of Potash (MOP), primarily used to make fertilizers and for food processing (Jasinski 2011).

Companies in Utah and Michigan harvest MOP from sylvinite through deep well solution mining and solar evaporation. NaCl is an important byproduct of this process. Potassium sulfate or Sulfate of Potash (Sing, et al.) is used as a fertilizer and is harvested from surface and subsurface brines by evaporation (Sing et al. 2011). Solar evaporation ponds are run near the Great Salt Lake in Utah for SOP production.

In 2010, over 54 percent of magnesium came from California, Delaware, and Florida companies using seawater and Utah and Michigan companies using brines from wells. Magnesium hydroxide is the primary product from seawater processing (Kramer 2011).

The US is the world's second largest salt producer after China. The demand for salt steadily increased over the last few decades, and a 0.4 percent annual growth in salt production is estimated for the next five year (Bueno 2011). Salt and mineral harvesting may be a profitable option for brine management if there is a market for the products, and if there is cheap, available electricity for the salt electrolysis stage. This option may become limited over time as additional GCS sites generate salts and minerals and saturate markets. Silica, soda ash, lithium, potassium chloride, and chloride gas are marketable by-products of salt and mineral harvesting processes that could improve the NPV of brine management (Armaroli et al. 2011). Their production will be assessed in a future study.

2.3.4 Recovery of Rare Earth Elements

Rare Earth Elements (REE) are usually found in the minerals bastnaesite and monazite, both of which can contain a varying mixture of lanthanum, cerium, yttrium, and other elements. The REE are extracted through a complex and expensive process that involves pulverizing the minerals and using an acid or organic solvent to separate the REE. Ion exchange and other technologies are being rapidly developed in many countries to try to catch up to China's progress in monopolizing the REE world market. The concentration of rare metals in GCS saline formations is expected to be one to several orders of magnitude (OM) lower than 100 μg/L (Kharaka and Hanor 2003). If this is true, then the average mass of REE produced annually from the extracted water of one 1000 MW coal fired power plant will be one to several OM less than 2 mt. Current US demand for REE is roughly 15,000-18,000 mt/yr and rising steadily as wind turbine, smartphone, and electronics production increases. There was no US production in 2010, but the Mountain Pass mine in CA is expected to reopen (Molycorp, 2011). In 2008 prices were around \$0.36/mt for terbium, \$0.11/mt for dysprosium, \$0.48/mt for europium, \$0.79/mt for thulium, \$0.006/mt lanthanum, and \$0.005/mt for cerium. Cost and environmental impacts of harvesting REE were not calculated in this report because reliable scientific sources discussing the cost of REE harvesting from brines were not acquired.

2.3.5 Materials for De-Icing and Anti-Icing Roads

De-icing refers to breaking bonds between road and ice after they have formed. This usually involves applying dry or pre-wetted salt to roads after a layer of snow and ice has formed. Dry salt is dissolved in water to 23 percent weight and applied to roads for de-icing at volumes between 151-190 L per lane-mile (Mitchell et al. 2004).[4] Calcium chloride ($CaCl_2$) is very effective as a de-icing chemical due to its hygroscopic nature, but it is more expensive than NaCl and leaves undesirable residues on roads.

Anti-icing refers to slowing or preventing the formation of ice-road bonds. This involves applying chemicals or brine onto dry roads prior to precipitation or freezing. Several European countries and American states have transitioned to anti-icing techniques because they use less salt than de-icing techniques and because they minimize sand application.

Sanding is often used to increase vehicle traction when icy conditions develop. Sand can carry pollutants, cause negative respiratory and pulmonary health affects in humans, kill sensitive aquatic organisms, clog sewers, and increase local water turbidity. Decreasing the sand used in winter maintenance is likely to save money and protect local ecosystems.

Some transportation authorities have attempted to manufacture brine for anti-icing. A 23 percent wt salt brine costs ~$0.03/L to produce in Europe. Most states do not have an established infrastructure to generate and store brine for road maintenance, and extracted brine from GCS could be a readily available source.

The quality of brine used for de-icing is regulated in several states. For example, North Dakota allows oilfield extracted water to be used for de-icing as long as it: (1) does not have hazardous concentrations of H_2S, (2) has a combined Ca and Mg concentration above 10 g/L, and (3) has a chlorine concentration above 75 g/L (ND Department of Health 2009).

A large seasonal market for brine becomes available if the brine could replace pre-wetted rock salt or anti-icing chemicals for winter maintenance of roads. The average volume of brine applied is 1.3 L/m^2 each winter month in North Dakota, for example, and the national use of highway salts fluctuates between 15 and 25 million tons per year over the past decade (Figure 3). Snow and ice occurs on 70 percent of major roads in the US and roughly $1.5 billion is spent plowing, salting and sanding roads each winter (Mitchell et al. 2004; Ripley 2011). The rising rock

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[4] When salt dissolves it releases heat, and this heat breaks bonds between road and ice. Another benefit of applying prewetted salt to roads is that wet salt will stick to snow, ice, and roads instead of bouncing off. The effectiveness of salt depends on temperature. For example, it takes 2.3 kg of salt to melt 21 kg of ice at temperatures around -7°C, but it takes 4 kg at temperatures around -12°C. Sand is also applied to roads when temperatures drop below -12°C 37. (a) Donahey, T. J.; Burkheimer, D. In *Prewetting with Salt Brine*, Semisequicentennial Transportation Conference, Ames, Iowa State University: Ames, 1996; (b) Cloutier, J.; Newbury, G. *Salt Brine, Salt Brine Blends and Application Technologies During the 2008-2009 Winter Maintenance Season*; State of Vermont Agency of Transportation; Federal Highway Admistration: Montpelier, 2009..

salt prices and additional governmental budget constraints will increase pressure to find a cheaper source of salt for highway deicing (Salt Institute 2011). GCS extracted brines may provide an alternative.

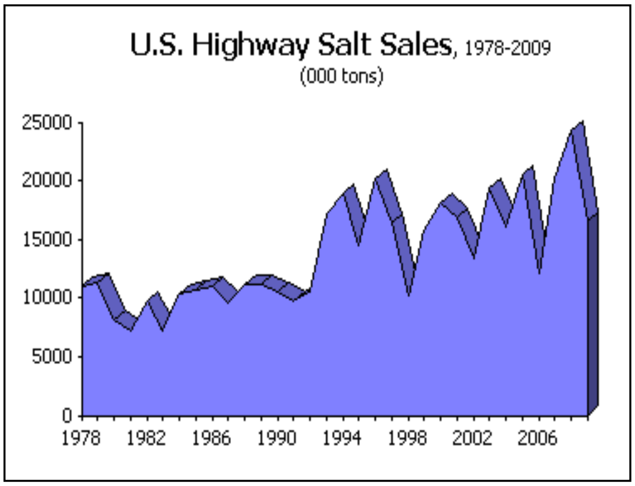

Figure 3. Graph of US highway salt sales (dry salt). Units in thousand tons (Salt Institute 2011).

2.3.6 Algae Production for Biodiesel

In 2007, the US Renewable Fuel Standard (RFS) expanded the target for biofuels production in 2022 to 136 billion liters per year (36 billion gallons per year (BGY)). 15 billion liters per year (4 BGY) were allocated to "advanced biofuels", meaning third-generation biofuels from sources like lipid-rich algae (Pate et al. 2011). Renewed interest in algae biodiesel has led to an increase in research focused on lowering barriers to scaling up algae biodiesel production in the US. Algae species and strains are selected that have high growth rates, lipid content, and productivities. Algae are grown in open ponds or in photobioreactors (Singh and Olsen 2011). They use photosynthesis to capture carbon from atmospheric or injected CO_2 and store it in carbohydrates and lipids like triacylglycerides (TAG). Lipids are extracted and the rest of the biomass is usually processed to recycle phosphorus and nitrogen, and to produce animal feed, methane, ethanol, butanol, H_2, long chain polyunsaturated fatty acids, carotenoids, and alkanes. TAG is processed and converted into biodiesel using transesterfication (Gong and Jiang 2011).

Although algae research started in the 1970s, the technology is still immature. Productivity levels that make algae biodiesel competitive against plant biodiesels or fossil fuels have only been achieved at the laboratory scale (Campbell et al. 2011). Algae are living organisms, and the production of biodiesel is dependent on maintaining optimal conditions to promote high growth rates. The species of algae chosen will determine the allowable range in salinity, pH, temperature, and nutrient load. This limits the application of algae ponds to specific climates and provides minimal flexibility in pond design.

Nevertheless, there are many advantages to producing biodiesel from algae. Unlike first generation biofuels, growing algae does not compete with food crops for arable land and for freshwater. Species like *Dunaliella salina* can grow in treated wastewater and in nutrient-supplemented saline waters. Extracted saline water from GCS pressure management could supply algae ponds. Also, most algae chosen for biodiesel production can survive highly concentrated injections of CO_2. This is important because CO_2 captured from a power plant's flue gas can act as a carbon source for the algae. Reducing the quantity of CO_2 injected into saline aquifers for GCS will minimize the volume of extracted water required for pressure management in those aquifers.

Saline pond water gives halophilic algae a natural advantage over microbes that will inevitably contaminate the open ponds (Gong and Jiang 2011). *Dunaliella salina* grows well in open ponds with or without mixing. A disadvantage of using saline water for algae production is the necessity of an impermeable liner to prevent salts from seeping into underground freshwater. This could double the capital cost because most facilities either line their ponds with a thin layer of clay or nothing at all. Several LCAs were conducted in 2010 and 2011 to evaluate the land, water, and nutrient costs of algae production (Sander and Murthy 2010; Campbell et al. 2011; Singh and Olsen 2011). Land and nutrient requirements were predicted to act as major bottlenecks in large scale algae production unless improved nutrients recycle and higher algae productivities are achieved.

The use of extracted brine from GCS for algae ponds could lower the cost and environmental impact of both algae biodiesel and GCS and make both technologies more profitable.

3. METHODS

We relied on the BUS framework to conduct an assessment of brine management, using three aquifers as case studies. At each aquifer site, we quantified the CO_2 storage capacity, identified CO_2 sources that could use these locations, and compiled information about the brine composition at each candidate site. In the following subsections, we describe the methods and impact metrics used to carry out the assessment.

3.1 Development of a Brine Use Sequence (BUS)

Without a rigorous LCA that lays out the potential multiple benefits, costs, and impacts, the extraction of brine could increase penalties and create a waste stream that has a large negative environmental impact. The BUS is a temporal and spatial framework for maximizing beneficial uses of the extracted brine and can be used to conduct comprehensive LCAs (Figure 4). We used the BUS method to conduct a first order economic and feasibility assessment in this report.

There are a large number of well-known uses for extracted brine. The options range from heating or cooling in electricity generation to aquaculture pond recharge. The most promising options were introduced in Section 2 of this report.

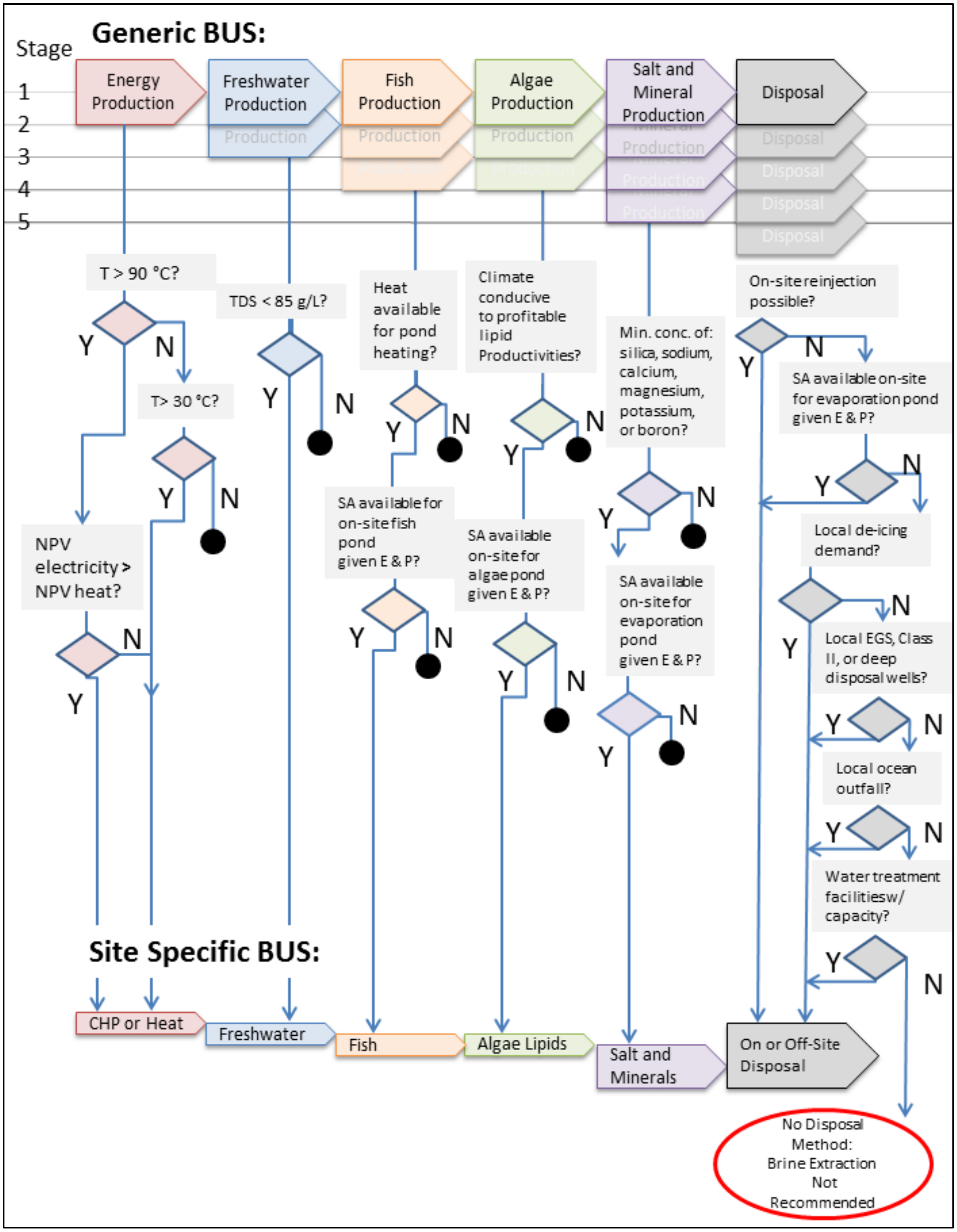

Figure 4. Diagram of BUS method for sequencing on- and off-site brine management stages included in study. Brine temperature (T), brine TDS, treatment net present value (NPV), and surface area (SA) requirements calculated from evaporation (E) or precipitation (P) data are some inputs. Combined heat and power (CHP) is the generation of electricity as well as heat. A black dot indicates the brine management option cannot be included in the site specific BUS. See text for explanation (Breunig et al. 2013).

In assessing beneficial uses of brine, we discovered the clear advantages of setting the different uses in a sequence so that the output (waste stream) of one use can become the input (feedstock) of the next use. Problems that may occur in one of the uses within the sequence can affect both upstream and downstream BUS stages. In this report, we attempt a first-order study of brine-use-coupling within the BUS. We selected a few promising options for treatment and disposal and performed background analysis, and economic and land use assessments using regionally appropriate data. We constructed simple, first-order metrics to determine if brine use options are feasible. For example, Figure 4 shows that brine with TDS > 85 g/L cannot be treated with current RO membrane technology and thus would not be desalinized (black dot indicates this option cannot be included in the BUS).

To devise the potential sequence of different uses detailed in Figure 4, we must consider a number of first-order approximation rules. These rules allow the generation of a logical and unique sequence of uses that optimizes brine management on economic and logistical grounds.

They are:

A. A brine use may be chosen only once; after it has been assigned to a specific position in the BUS, it cannot be reassigned to another.

B. When possible, the waste stream of one use should serve as the input for the following uses. For instance:

   1) Cooling water for coal-, oil- or gas-fired power plant towers, heat-harvesting, if applicable, should come before, or be contemporaneous with other uses.

   2) Evaporation pond disposal should come after salt-harvesting and water recycling.

C. Some brine usages exclude others in the BUS.

D. Some brine uses can occur only at the end of the BUS. For instance:

   1) Brine for deicing or dust control.

   2) Final disposal methods should be at the very end of the sequence.

E. Even though the ideal BUS was designed to incorporate all possible uses, some brine uses could be very site-specific or, on the contrary, impossible to apply to any site. Therefore, at any specific site, the BUS could become substantially reduced relative to the general framework presented here.

F. In future studies, the power plant generating CO_2 should be included in the assessment of the sequence; in fact, there are an appreciable number of uses that can benefit from the plant waste stream and, vice versa, the production and waste streams from some uses could be fed back into the power plant. Therefore, all of the uses could be further characterized by their distance relative to a certain power plant, and assigned to the near-, mid- or far-field. These categories can be thought of as: within the power plant, on power plant property, or off power plant property and potentially outside of the saline aquifer region respectively.

G. In future studies, the brine extraction well location(s) should also be included in the BUS. This allows for feed-back relationships that derive from alternative forms of CO_2 sequestration and usages relative to the amount that is actually injected, in addition to the necessary use of the electric energy of the power plant. For instance:

   1) Part of the CO_2 emissions could be used for enhanced algae growth for biodiesel production.

   2) Part of the CO_2 emissions could be combined with extracted brine and power plant fly ash to sequester carbon into limestone.

   Both of these uses decrease the amount of CO_2 injected and ultimately the amount of brine extracted.

Based on the above rules we devised the overall BUS illustrated in Figure 4. In tracking the sequences in this figure, one sees how the various waste-streams become employed in subsequent uses.

Near-field uses of the brine can be developed in direct association with or in the immediate vicinity of a power plant. Two primary near-field uses are:

1) Hot brine extracted from wells could be used to generate electricity or thermal energy

2) Desalinated brine could be used to meet freshwater demands at the power plant or in sequential BUS stages

Two additional near-field uses, not included in this study, are:

1) If the extracted brine is sufficiently cool, it can be recycled directly into the cooling towers of the power plant. A reverse osmosis step may be required. The waste-stream from the cooling tower, heated and enriched in salts (and of course any hotter extracted brine), can be harvested as geothermal energy and used in low-enthalpy applications, such as buildings or green-house heating.

2) Brine could be combined with the CO_2 and fly-ash from the power plant to sequester CO_2 into valuable calcium carbonate.

Mid-field brine uses that can accept the brine, or the waste brine from the near-field activities, as an input include the following:

1) Aquaculture, which includes brine-shrimp (for feeding fish larvae) and sea fish
2) Algae ponds for biodiesel production
3) Salt and mineral harvesting
4) Onsite evaporation ponds

Mid-field uses that can accept the desalinated brine from the near-field activities as an input include:

1) Aquaculture, which includes freshwater fish like tilapia
2) Salt and mineral harvesting freshwater demand
3) Local non-potable water demand

Far-field uses that can accept the brine or the concentrated brine from desalination include:

1) The use of brine for de-icing and dust control

Far-field disposal options include:

1) Discharge into off-site surface water bodies
2) Disposal through sewers and water treatment facilities
3) Disposal through reinjection
4) Disposal through evaporation ponds or disposal pits

Our BUS model, while still evolving, provides a useful framework with the potential for improving the impact assessment of brine management. Future studies are needed to improve the robustness of the BUS framework, making it spatially and temporally sensitive to markets, geographic characteristics, and developing technology.

3.2 Candidate Saline Aquifers

3.2.1 Selection of Saline Aquifers

Because many saline aquifers have not been fully evaluated, largely due to their lack of geo-resources like natural gas or oil, there are only a few, relatively incomplete datasets that include aquifer characteristics such as water chemistry, temperature, permeability, and pressure. The US National Carbon Sequestration and Geographic Information System (NATCARB) and the Texas Bureau of Economic Geology (BEG) GIS online databases were queried to identify saline aquifers that have been targeted for GCS (Gulf Coast Carbon Center 2003). Figure 5 provides a map identifying regions in the US with higher salinity aquifers that have been targeted for GCS. Data required to characterize the aquifers that could not be obtained from online GCS databases were obtained by importing the USGS produced-water database into GIS maps, by literature review, and through web searches for well data (Fisher 1990; USGS 2002; California Department of Conservation 2010). Data from the USGS produced water database were queried by selecting wells that produce water within the depth range of the relevant local aquifer. We used ArcGIS spatial analysis tools such as Interpolation to find average water chemistry and temperatures in regions of saline aquifers with limited well data. Mapped data are projected using the USA Contiguous Albers Equal Area Conic and North American 1983 datum.

Based on the data available, we selected three candidate saline aquifers to illustrate our brine management analysis, explore different physical and chemical characteristics of GCS target sites, and document nearby well activity and history, number of local CO_2 emission sources, and geographical location. The three aquifers are: the Jasper Formation (Jasper), TX; the Vedder Formation (Vedder), CA; and the Mt. Simon Sandstone Formation (Mt. Simon), IL.

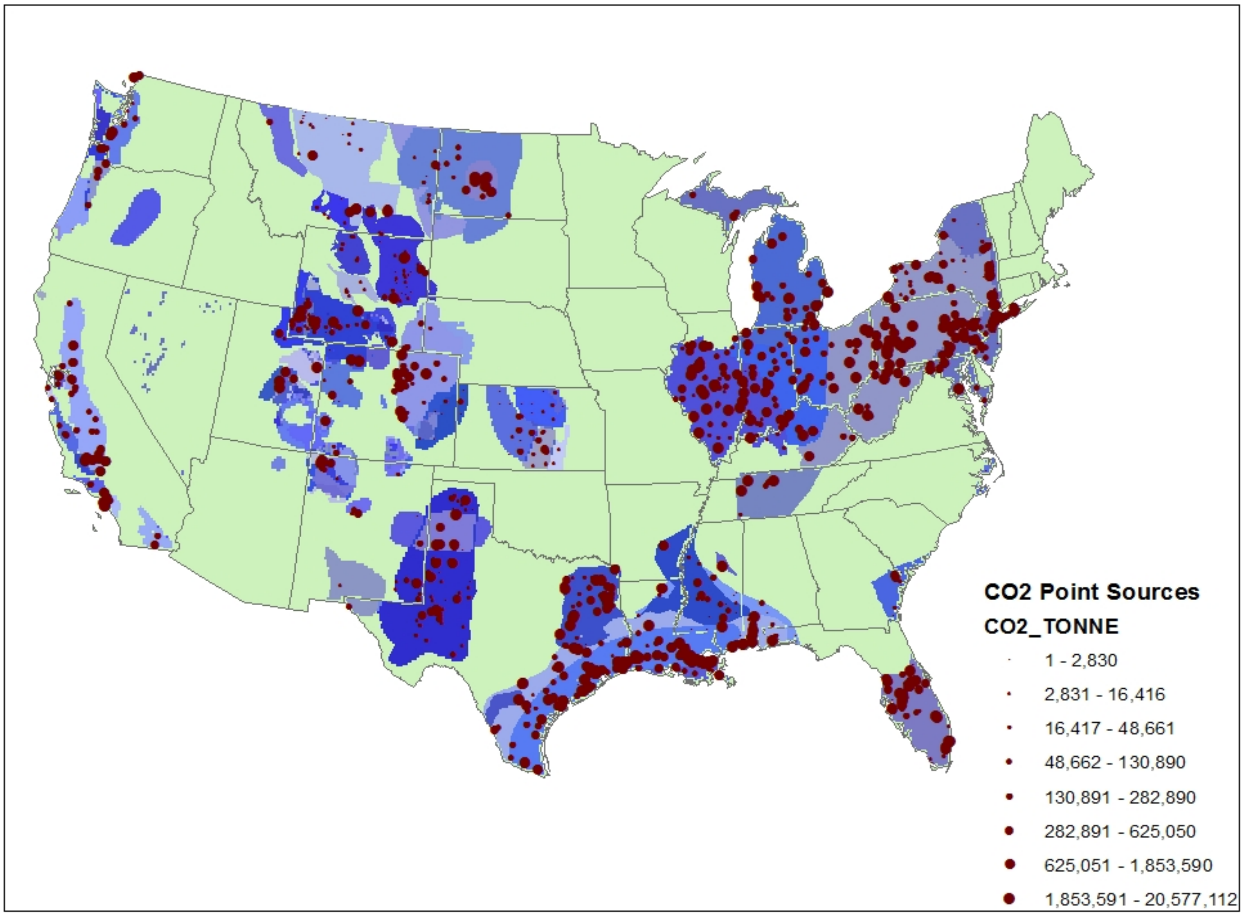

Figure 5. Map showing proximity of saline aquifers to major CO_2 sources. CO_2 sources (red dots) are above major deep saline aquifers (blue). Darker blue indicates higher salinity in the aquifer. Map created using data from the NATCARB database (Department of Energy 2010).

3.3.2 CO_2 Sources near Saline Aquifers

The average 1000 MW CFPP emits ~ 8 million mt-CO_2 annually. In our scenarios, we used a typical 1000 MW CFPP with a 24 percent EP, injecting 90 percent of its total CO_2 emissions as the basis for assessing the need for sequestration capacity. There are 170 CO_2 sources located within 150 km of the Jasper. The smallest CO_2 point source emits 40,000 mt-CO_2 annually while the largest emits 20,600,000 mt-CO_2 or more annually (Ventyx 2012). 240 CO_2 sources are located within 150 km of the southern Mt. Simon. Point source emissions range from 40,000 to 20,000,000 mt-CO_2 or more annually (Ventyx 2012). Although there are no CO_2 sources that emit 8 million mt-CO_2 within 150 km of the Vedder, there are 90 CO_2 sources that have individual annual emissions ranging between 40,000 to 2,000,000 mt-CO_2 (Ventyx 2012).

3.3.3 CO_2 Storage Capacity

The CO_2 storage capacity varies significantly among our three candidate sites. The Mt. Simon is an expansive saline aquifer that has the potential to store large quantities of CO_2. The Midwest Geologic Sequestration Consortium (MGSC) estimates the Mt. Simon can store between 10-150 billion mt-CO_2. Several saline aquifers in the southern San Joaquin Basin meet criteria for GCS. Of these, the Vedder was targeted for the planned Kimberlina GCS pilot project (which was later abandoned). The West Coast Regional Carbon Sequestration Partnership (WESTCARB) and the National Energy Technology Lab (NETL) estimated that the San Joaquin Basin can store between 2-35 billion mt-CO_2 (Srivastava 2009). The Jasper is a potential saline aquifer available for GCS in eastern Texas. It is composed of the Miocene Lagarto and Oakville Formations. The Southeast Regional Carbon Sequestration Partnership (SECARB) estimates that this interval has the potential to store 400-5,500 billion mt-CO_2. The Jasper overlies a second saline aquifer called the Frio Formation. Both have the capacity to store large quantities of CO_2.

All three saline aquifers appear capable of storing 25 years of CO_2 from one or more of the major local point sources without exceeding lower storage capacity estimates. Unfortunately, these lower storage capacity estimates, calculated based on pore space and other physical properties, do not necessarily incorporate pressure and risk mitigation adjustments which tend to diminish capacity. The Jasper and the Mt. Simon have high porosity and permeability, making it less likely that pressure management will become a necessity for CCS in these regions. Still, effective local pressure management will help with plume management, will minimize local leakage concerns, and may decrease the cost of property rights acquisition if the utility is charged for plume spread (Gresham et al. 2010).

3.3.4. Brine Water Chemistry

The USGS Produced Water Database provides information on water extracted from wells throughout the US as does the Bureau of Economic Geology, at the University of Texas at Austin. Various characteristics of brine from the three aquifers were collected, including concentrations of compounds like magnesium, potassium, calcium, sodium, chloride, and total dissolved solids (TDS). Figure 6 provides the concentration (mg/L) of these compounds at each of the three candidate aquifers. We collected relevant brine composition information from these databases by selecting wells in the depth range of the saline aquifers targeted for carbon sequestration (800-3000 meters). For quality assurance, well API numbers, depths, ownership, latitude, and longitudes were checked against a second database whenever possible (California Department of Conservation 2010). Additional water chemistry was collected from well data in the literature (Fisher 1990; Gulf Coast Carbon Center 2003). Concentrations can vary over 6 orders of magnitude within and between the three aquifers. The top depth varies in all three formations, and concentrations vary in shallower and deeper regions of the aquifers. The Mt. Simon Sandstone Formation has concentrations ranging over 6 orders of magnitude, with near freshwater concentrations in the shallower regions in northern Illinois. Water characterization presents a major source of uncertainty in the feasibility of disposal options due to the variability in data quality and completeness. In the case of these three aquifers, the average pH and aquifer water chemistry obtained from the water datasets agree with composition and salinity predictions in the literature (Zhou et al. 2008; Department of Energy 2010; Zhou et al. 2010).

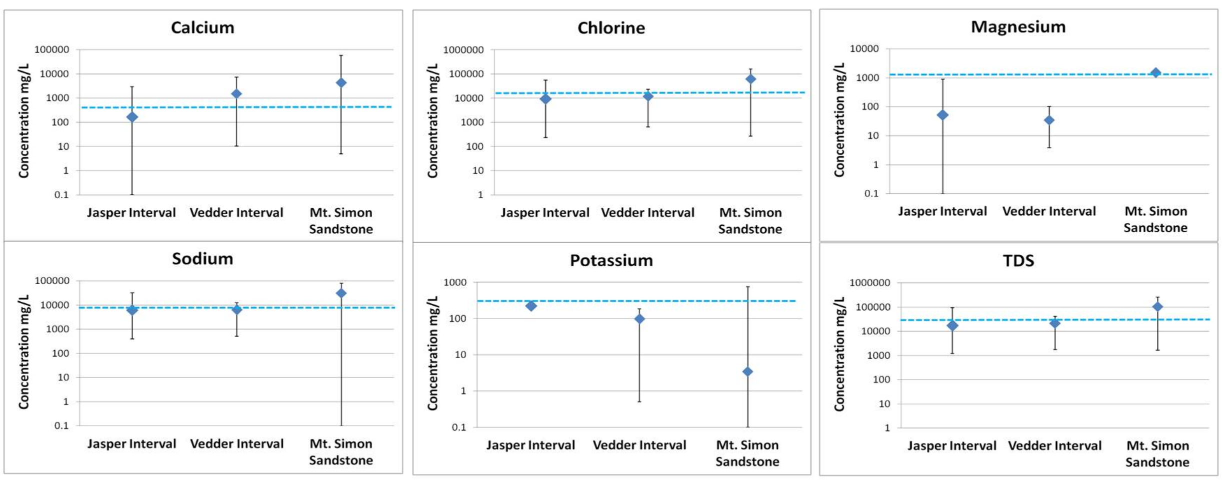

Figure 6. Scatter plot of aquifer water chemistry (blue diamond) compared to natural seawater (blue dashed line). Concentrations are in mg/L, and bars indicate the range from minimum to maximum in each aquifer.

3.3.4 Valuation Metrics for Assessment

Brine management options were investigated for each of the three saline aquifers. Feasibility of each option was determined based on a literature review, analysis of aquifer water chemistry, aquifer water temperature, local geography, local hydrology, and established regional brine management infrastructure. NPV, water demand, and land requirements were metrics used to value the relative impacts and benefits in order to characterize feasibility for brine management at different sites. After analyzing each disposal or resource option, we created a spreadsheet to optimize the BUS based on overall cost.

The overall cost of CCS is affected by economies of scale, and it is likely that large CO_2 sources such as CFPP and cement plants will be the first to carry out CCS. CO_2 sources that emit less than 40,000 tons CO_2 annually are unlikely to adopt CCS (Forbes et al. 2008; Liu and Liang 2011). It is possible for a power plant to capture 90 percent of CO_2 emissions using current technology (Gerdes 2011). Unfortunately, the addition of carbon capture technology comes with an energy penalty (EP)[5] of 24-40 percent (Zenz House et al. 2009; Liu and Liang 2011). Our brine-use scenarios assume that power plants inject 90 percent of CO_2 emissions for 25 years, and that EP increases initial emissions by 24 percent. While an EP of 40 percent is easily achievable with current technology, we are optimistic that carbon capture technology is improving, and that an EP as low as 24 percent is obtainable. We assumed 25 years as a typical assessment timescale for carbon sequestration projects and pipeline transportation infrastructure. The equivalent mass of CO_2 annually injected (mt-CO_2/yr) was used as the functional unit in this LCA. This CO_2 emission unit can easily be converted to energy (kWh) and then dollar values.

We developed Microsoft Excel spreadsheets to manage input, including CO_2 injection rates, total CO_2 storage, and total water extracted annually and over 25 years. These volumes were used to quantify the potential geothermal heat, mass of salts and minerals, volume of water reclaimed using RO, mass of tilapia and volume of algae biodiesel that could be harvested. The land footprint of geothermal energy systems, evaporation ponds, algae ponds and the volume of low-salinity water required for dilution were also calculated using these spreadsheets. Sensitivity analyses were performed for the NPV [$/mt-$CO_2$] of geothermal heat, desalination water, algae bio-diesel, as well as for the land footprint required by evaporation disposal ponds for each of the three GCS sites (Section 6).

It is important to note that CO_2 density increases with pressure and thus with depth underground. The temperature and pressure at which CO_2 reaches its critical point, beyond which it has the density of a liquid but the viscosity of a gas, are reached at around 800 m depth depending on local hydrostatic pressure and geothermal gradient. Supercritical CO_2 has a density of 500 mt/L (500 kg/m^3) or greater (Figure 7). Therefore, the volume of water (V_{Water}) extracted for every mt-CO_2 injected was determined by:

$$V_{Water} = M_{CO2}/\rho_{CO2} \qquad \textit{Equation 2}$$

[5] Carbon capture technology requires energy, and an energy penalty (EP) accounts for this increase in power plant energy demand.

where M_{CO2} is the mass of CO_2 injected into the aquifer, and ρ_{CO2} is the density for supercritical CO_2. We assumed a 1 to 1 volume displacement of pore water per volume of CO_2 injected, and that V_{Water} has a value of 2000 L/mt-CO_2 injected (528.3 gallons/mt-CO_2). However, in reality, it is unlikely that formation water displacement will be as high as 1 to 1, or that the density of CO_2 will be as low as 500 mt/L, so we may have overestimated the volume of extracted brine.

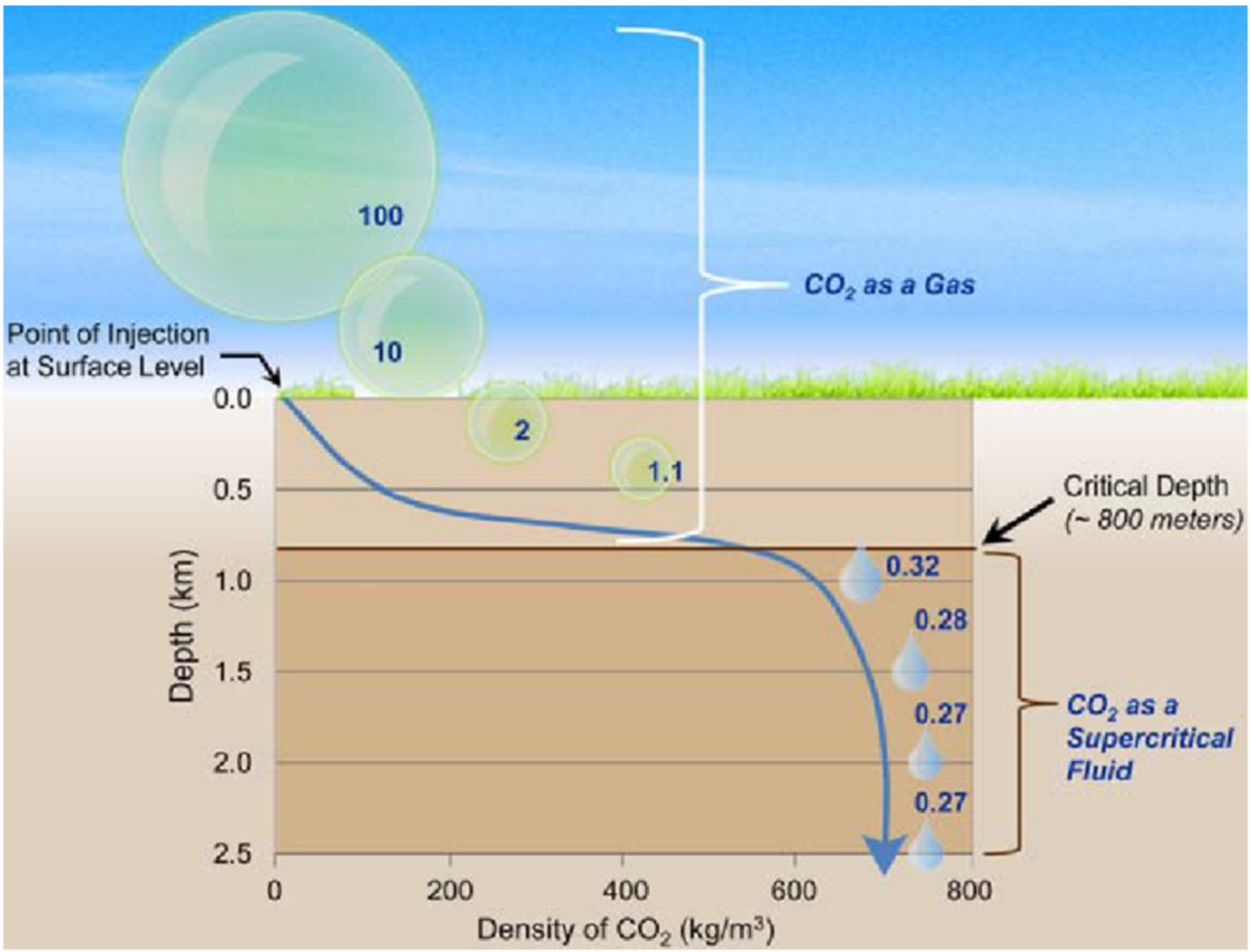

Figure 7. Diagram showing the change in CO_2 density and phase with depth (Department of Energy 2010).

4. COMPARATIVE ASSESSMENT OF BRINE MANAGEMENT OPTIONS

Based on the three candidate saline formations and the methods/assumptions described above, we compared the land footprint and NPV of brine management options at the Jasper, Mt. Simon, and Vedder aquifer sites. Additional LCA metrics, such as fresh water use, ecological impacts, cumulative energy demand (CED), and air emissions will be covered in a future study. To carry out the assessment, we collected regional climate, infrastructure, saline aquifer, and market data and organized it in GIS maps and spreadsheets. We used GIS spatial analysis tools to determine the distance between power plants, saline aquifers, wastewater treatment facilities, and the ocean. These values allowed us to determine distances between brine sources and sinks, and determine exposure regions that can be associated with sensitive ecosystems. We analyzed the construction and in-use-phase costs of geothermal energy capture, reverse osmosis treatment, salt and mineral harvesting, brine algae ponds, and evaporation ponds. We evaluated 2010 salt and mineral markets to determine sale prices and potential demands for brine and specfic compounds and elements in the brine. We estimated the feasibility and potential commercial value of RO treatment for the three aquifer brines. Some values, such as shallow reinjection values at the three aquifer sites were estimated from previous studies (Klett 2003; Gerdes 2011). In the following sections, we provide details on the methods to assess in-use phase costs, and land footprint associated with each BUS option.

Table 2 provides a summary of high and low NPV calculated for each treatment or disposal option performed at each of the three GCS locations. Costs or revenues calculated in Section 4 and 5 were amortized over a 30-year study period, assuming an 8 percent interest rate. Data were scaled to a functional unit of one metric tonne of CO_2 injected into an aquifer. Although we have not yet carried out a formal uncertainty analysis, we limit the presentation of calculated results to one and no more than two significant numbers in order avoid the implication of high certainty. Evaluating the joint probability of linked management options is important but we did not find sufficient data to actually construct reliable probability distributions. We developed a portfolio of bounding scenarios, in addition to the max and min NPV scenarios using the commercial values found in Table 2. We selected this range of scenarios as those that we believe are most feasible and likely to be implemented in the near future. This approach reveals that, although the range of NPV reaches \$10/mt-CO_2, a majority of the possible scenarios will not achieve this level of return. The primary sources of uncertainty in the costs were the uncertainties in the brine characteristics and in the economic value of the produced resources such as geothermal energy, water for aquaculture, and so on.

Table 2. Summary of the low and high NPV for optional BUS stages in three different aquifers. NA: Not Available.

	Vedder		Jasper		Mt. Simon	
$/mt-$CO_2$-injected	LOW	HIGH	LOW	HIGH	LOW	HIGH
Brine as a Resource						
Section 5.1 Geothermal Energy and Aquaculture						
Indirect Water Heating (to keep pool at 35C)						
Geothermal Heat Only	NA	0.82	0.20	0.48	0.18	0.89
CHP Binary Cycle	0.04	0.14	NA	NA	0.04	0.10
Fish Sales	0.03	0.14	0.01	0.14	0.02	0.14
Section 5.2 Land NPV for Geothermal Energy Systems						
CHP Binary Cycle	0.00	-0.60	NA	NA	0.00	-0.40
Section 5.3 Non-potable Water NPV						
Reverse Osmosis Treatment						
Water Sold at Desalination Price ($0.42/m3)	0.13	0.25	-0.05	0.25	NA	-0.05
Water Sold at Reclaimed Water Price ($0.58/m3)	-0.08	0.12	-0.08	0.12	NA	-0.08
Water Sold at Drought/Arid Region Price ($1.45/m3]	0.83	1.12	0.12	1.12	NA	0.12
Section 5.4 Salt and Minerals NPV						
Land Cost for Evaporation Pond						
with Reverse Osmosis prior	-0.30	-0.03	-4.30	-0.20	NA	NA
without Reverse Osmosis prior	-0.70	-0.07	-4.70	-0.50	-2.70	-0.30
Salt Production from Evaporation Ponds						
with Reverse Osmosis prior	-1.00	NA	-1.80	NA	NA	NA
without Reverse Osmosis prior	-4.00	NA	-4.00	NA	-3.84	NA
Salt Sales						
Boron	0.01	0.42	0.25	0.28	0.00	2.33
Potash	0.00	0.22	0.22	0.49	0.44	0.86
Gypsum	0.00	0.01	0.01	0.12	0.24	0.50
Magnesium	0.03	0.28	0.24	2.90	8.25	10.98
Salt	0.02	0.43	0.26	1.43	0.99	1.80
Road Salt					4.37	7.88
Section 5.6 Algae Biodiesel						
Net Value Including Land Cost	0.05	0.30	0.01	0.14	0.01	0.06
Section 5.7 EGS Recharge NPV						
Geothermal Reinjection Well	-0.03	-0.01	-0.01	0.00	-0.03	-0.01
Cost Including Avoided Groundwater Cost	0.23	0.26	0.25	0.26	0.23	0.26
Brine as a Waste						
Section 5.9 Cost Disposal NPV						
Surface Discharge	NA	NA	-0.09	-0.01	NA	NA
Offsite Commercial Treatment	-13.00	-2.00	-13.00	-2.00	-52.83	-12.58
Evaporation Pond	-1.01	-0.13	-1.01	-0.13	-1.01	-0.13
Landfill/Burial	-13.00	NA	-13.00	0.00	-13.00	0.00
Disposal Wells	-33.00	-0.60	-33.33	-0.63	-33.33	-0.63
Shallow Reinjection	-16.73	-1.26	-16.73	-1.26	-16.73	-1.26
Transportation of Brine						
Transportation Brine through Pipeline (NPV per mile	-0.02	-0.01	-0.02	-0.01	-0.02	-0.01
Transportation of Brine through Truck	-0.14	-0.03	-0.14	-0.03	-0.14	-0.03
Carbon dioxide Capture and Sequestration NPV						
PC	-65.90		-65.90		-65.90	
IGCC	-42.70		-42.70		-42.70	

4.1 Geothermal Energy

4.1.1 Heat Capacity

Calculating available geothermal heat for non-direct water heating requires knowledge of the formation water acting as the geothermal reservoir. The heat available to do work in the brine that goes through the heat system was calculated using:

$$\Delta\dot{Q} = \dot{m}_{brine} * c_p * \Delta T \qquad \textit{Equation 3}$$

where $\Delta\dot{Q}$ is heat flow [kJ/h], $\dot{m}_{brine}$ is the mass flow of brine [kg/h], c_p is the specific heat capacity of the brine (4.18 [kJ kg^{-1} K^{-1}]), and ΔT is the difference in temperatures between the brine entering and exiting the system [K]. It was assumed that the return temperature is 30°C (303.14 K) for pond heating systems and 40°C (313 K) for district heating systems.

The mass of brine was calculated using:

$$\dot{m}_{brine} = \rho * \dot{V}_{brine} \qquad \textit{Equation 4}$$

where ρ is the density of brine (1.03 [kg/L] for the Vedder and Jasper; 1.04 [kg/L] for the Mt. Simon), and $\dot{V}_{brine}$ is the volumetric flow rate of brine extracted hourly [L/h] and calculated using:

$$\dot{V}_{brine} = \frac{\rho_{criticalCO2} * M_{CO2} * EP * e}{365d * 24h} \qquad \textit{Equation 5}$$

where $\rho_{criticalCO2}$ is the density of supercritical CO_2 [L/mt-CO_2], M_{CO2} is the annual amount of CO_2 emitted from a power plant (8 million mt-CO_2 for a 1000MW CFPP), EP is the energy penalty resulting from the additional carbon capture system (1.24 assuming a 24 percent EP), and e is the efficiency of the carbon capture system (0.9).

4.1.2 Geothermal Capacity:

Temperature in the Mt. Simon Sandstone Formation ranges from 50-150°C and temperature in the Vedder Interval ranges from 30-150°C. Temperature in the Jasper Interval ranges from 30-80°C, with temperature decrease with distance from the gulf coast (Gulf Coast Carbon Center 2003). It was assumed that heat production has an efficiency $e_{thermal}$ of 40 percent and that annual thermal load hours $t_{thermal}$ are 7000 h/yr (Frick et al. 2010). This means the facility is operating 7000 hours of the year at full installed thermal capacity. These variables were used in the following equation to calculate installed thermal capacity $C_{thermal}$ of the system [$MW_{thermal}$]:

$$C_{thermal} = e_{thermal} * \frac{\Delta\dot{Q}}{t_{thermal}*60m*60s*(\frac{1000KW}{1\,MW})} \qquad \textit{Equation 6}$$

4.1.3 Power Capacity:

In a combined heat and power (CHP) binary cycle, the brine is used to produce electricity and then heat. Water exits the binary cycle at a temperature of 77°C and enters the heat system at a temperature of 70°C. The power capacity was calculated using:

$$C_{elect} = \ e_{elect} * \frac{\Delta\dot{Q}}{t_{elect}*60m*60s*(\frac{1000KW}{1\,MW})} \qquad \textit{Equation 7}$$

where C_{elect} is the power capacity of the binary cycle [MW_{elect}], e_{elect} is the efficiency of the binary cycle's conversion of heat energy to electrical energy (10 percent), and t_{elect} is the number of load hours [h/yr]. Load hours were assumed to be 6529 h/yr for the binary cycle and 1800h/yr for the on-site heating system. Geothermal capacity of the CHP binary cycle was calculated using the methods described in Section 4.1.1, and assuming the influent temperature is 70°C.

4.1.4 Net Power:

Auxiliary power loads P_{aux} were included in binary cycle calculations to incorporate the energy demand of pumping and cooling in the system. Waste heat was calculated as:

$$\Delta\dot{Q}_{waste} = \dot{m}_{brine} * c * \Delta T \qquad \textit{Equation 8}$$

where $\Delta\dot{Q}_{waste}$ has units of [kJ/h], ΔT is the difference between the temperature of the brine exiting the binary cycle and the temperature of the brine entering the heat system (ΔT = 7°C); and c is the specific heat capacity of the brine as before.

We assumed that 20 kWh of auxiliary power $Paux_{recooling}$ per $MW_{thermal}$ capacity would be required for cooling. This was calculated using:

$$Paux_{recooling} = \frac{\Delta\dot{Q}_{waste}}{60m*60s*(\frac{1000KW}{1\,MW})} * \frac{20\,KW}{1\,MW_{thermal\,waste}} \qquad \textit{Equation 9}$$

It was assumed that 10 percent of power capacity was used to meet feed pump energy requirements. Net power was calculated using:

$$P_{net\_elect} = (C_{elect} - C_{elect} * 0.1 - Paux_{recooling}) * t_{elect} \qquad \textit{Equation 10}$$

where the unit of P_{net} is MWh_{elect}.

Table 3 provides a summary of the NPV that could be obtained from two different applications of geothermal heat using either a heat system or a CHP binary cycle. The two applications are pond water heating for algae lipid harvesting for biodiesel and pond water heating for tilapia aquaculture. Although GCS-sourced heat could be used for district heating, we found little to no infrastructure in the three regions under study; we assumed selling heat for district heating was technically feasibility but had low feasibility as a source of revenue for GCS projects. As discussed in Section 2.3.1 of this report, binary cycles used for CHP generate both electricity and heat onsite and will be profitable if the reservoir temperature is much greater than 85°C. Maximum reservoir temperatures were used to assess the potential energy production from a CHP binary cycle system for the three aquifers. With 80°C being the hottest temperature in the Jasper, the extracted brine will not be hot enough to generate electricity. As seen in Table 3, calculations for a binary cycle were not performed for the Jasper. However, the minimum and maximum reservoir temperatures were hot enough for a district heating system and these values were used to calculate the low and high heat production from the Jasper. The low reservoir temperature and a cutoff temperature of 90°C were used to calculate the low and high geothermal heat production from the Vedder and Mt. Simon assuming a CHP binary cycle was not chosen in a BUS. Generated thermal [$MJ_{thermal}$/mt-CO_2] and electrical power [kWh/mt-CO_2], and the NPV of energy production [$/mt-$CO_2$] are summarized in Table 3. CO_2 and air pollutants, both emitted and avoided, will be calculated using specific electricity grid emission factors in a future study.

Table 3. Summary of economic analysis for geothermal heating of water using extracted brine heat energy. NPV is highlighted in bold and is in US dollars 2011 [55].

Reservoir		Jasper		Vedder		Mt Simon	
Reservoir Temperature	°C						
Geothermal Heat Only (low, high)		50	80	30	150	50	150
CHP (low, high)		NA	NA	90	150	90	150
In-Direct Heating of Pond Water On-Site							
Geothermal Heat Only (low, high)	MJ/mt-CO_2	55	165	0	330	55	330
Net Present Value	$/mt-$CO_2$	**2.3**	**5.4**	**0.0**	**9.2**	**2.0**	**10.0**
CHP Binary Cycle							
Net Power	kWh_el/mt-CO_2	NA	NA	1.8	11.1	1.8	11.1
Thermal Heat	MJ/mt-CO_2	NA	NA	28.3	28.3	28.3	28.3
Net Present Value	$/mt-$CO_2$	NA	NA	**0.5**	**1.6**	**0.4**	**1.1**
Land Footprint (low, high)	[km²]	NA	NA	0.3	10.4	0.3	7.3
Cost Electricity [¢/kWh]		9.4		13.0		9.1	
Cost Natural Gas [¢/kWh]		3.2		3.0		2.9	

4.1.5 Use of Geothermal Heat for Non-Direct Pool Heating

The net value of using geothermal energy from the extracted water was calculated from:

$$\frac{\$}{mt-CO_2} = Value - Cost \qquad \text{Equation 11}$$

The value was calculated as

$$Value = \ \$_{elec} * P_{net\_elect} + \$_{thermal} * \frac{1.11 * C_{thermal} * t_{thermal} * (\frac{1000kJ}{MJ})}{mt-CO_2} \qquad \text{Equation 12}$$

where $\$_{elec}$ ($\frac{\$}{kWh}$) is the 2011 regional electricity price[6], P_{net_elect}, $C_{thermal}$, and $t_{thermal}$ are defined above. It was assumed that an electrical pond heating system has an efficiency of 90 percent, therefore requiring 10 percent more energy than what is put into the pond through geothermal heating. *Cost* is the associated capital and maintenance costs, calculated as:

$Cost = \frac{\$}{Q_{thermal}} * \frac{kJ}{mtCO_2}$, where $Q_{thermal}$ is the energy produced from the geothermal process in kJ.

The capital investment and operations cost of using geothermal energy was calculated from:

[6] The daily average retail price of electricity was 13, 9.3, and 9.1 ¢/kWh for the Vedder (WECC), Jasper (TRE), and Mt. Simon (SERC) formation (NERC region) respectively (U.S. Energy Information Administration 2012).

$$Cost = \$_{geo\ process} * e_{thermal} * \Delta\dot{Q}_{thermal} \qquad \textit{Equation 13}$$

where $\$_{geo\ process}$ is in units of [$/kW-yr], and provided in Table 4, and $e_{thermal}$ and $\Delta\dot{Q}_{thermal}$ are defined above.

Table 4. Construction and maintenance cost of geothermal heating. Based on calculation for a shallow well (300m) with a 30 yr life, 8% interest and O&M calculated as 10% of capital cost (Lund 2010).

	$/kW yr
Resident Space Heating	78.2
District Heating	63.5
Greenhouse Heating	24.4
Aquaculture Pond Heating	19.6
Geothermal HP	83.1

4.1.6 Geothermal Heating of Ponds with Production of Tilapia

Current practice shows that the energy required to produce fish like tilapia in aquaculture ponds *E_tilapia* is 0.24 $TJ_{thermal}$/mt-tilapia-yrs (Boyd and Lund 2003). This heat requirement can be partly met by solar energy hitting the aquaculture pond in warmer seasons. At the same time, tilapia farming practices in the US have shown that production volume increases when ponds are supplied a continuous heat source, like geothermal heat, since tilapia growth diminishes when pond water drops below 30°C. Tilapia production would have to be a seasonal application of brine in Illinois, unless the tilapia ponds were indoors. The mass of tilapia that could be raised and harvested annually, assuming brine was used to heat the fish ponds, was calculated using:

$$M_{tilapia} = \frac{e_{thermal} * \Delta\dot{Q}_{thermal}}{E_{tilapia} * \frac{1e6\ MJ}{1\ TJ}} \qquad \textit{Equation 14}$$

where $e_{thermal}$, and $\Delta\dot{Q}_{thermal}$, and $E_{tilapia}$ are defined above.

The temperature of an outdoor pond will be affected by variables like: radiation, precipitation, pond water recharge, waste removal, water circulation mechanisms, and wind. Since tilapia grow well in waters much hotter than 30˚C, it was assumed that a constant geothermal heat flow would be sent to the pond, regardless of the season. This calculation is simplistic, but it provides an estimate of the scale of fish production possible using brine geothermal energy. Potential net returns were adapted from budget estimates provided by Langston University Aquaculture and the Southern Regional Aquaculture Center (Gebhart and Williams 2000). A NPV of

+$300/mt-fish if fish were sold wholesale within 50 miles of the GCS project site using short-haul freight trucks with carrying capacities of 5.4 tonnes. Diesel prices were assumed to be $4.3, $4.0, and $3.9 per gallon for CA, IL, and TX respectively (US EIA 2012); this variation did not significantly change the NPV of fish aquaculture per mt-CO_2.

4.1.7 Land Footprint and Land Cost of Geothermal Energy Systems

The land footprint or land surface area (SA) [km^2] of a CHP binary system (SA_{CHP}) was calculated using:

$$SA_{CHP} = (P_{net_{elect}} * L) * \frac{1\,TWh\ elect}{1e6\ MWhelect} \qquad \textit{Equation 15}$$

assuming land intensity (L) ranges between 18-74 km^2/TWh electricity [60]. We assumed that the land footprint of the pond heating system (heat exchanger and pipes) would be included in the SA of the pond system, and was not calculated.

Results are summarized in Table 3. The low and high values reflect the range in SA that results from using the minimum and maximum average land footprint estimated by Evans et al. 2009.

Geothermal energy systems require <1 km^2 for the Jasper, and less than 1 to 10 km^2 for the Vedder and Mt. Simon. A small percent of a geothermal energy system's land footprint is allocated to well pads or to equipment for electricity production (DiPippo 1991). The rest represents the extraction and reinjection well system area. However, if extracted brine is not injected, then the land footprints summarized in Table 3 may overestimate the required SA for GCS energy capture stages.

4.2 Non-potable Water

4.2.1 Reverse Osmosis Treatment

The feasibility of treating extracted waters with RO was estimated by comparing average TDS concentrations in a saline formation with TDS vs. RO treatment cost diagrams (Bourcier et al. 2011). This reference shows that RO can treat the average water from the Jasper and Vedder with freshwater recoveries of 10 and 50 percent, respectively. Current desalination technologies are limited by how much pressure spacers and membranes can support. The high salinity of the Mt. Simon brine makes even nano-filtration (NF)-RO extremely expensive. The higher the salinity, the less economic RO becomes as a treatment method Therefore, we concluded that RO cannot be part of a BUS for the higher TDS in the Mt. Simon.

The volume [L/mt-CO_2] of permeate (desalinated water) $V_{permeate}$ that could be sold as reclaimed water, desalination water, cooling tower water, or irrigation water was calculated using:

$$V_{permeate} = \%Recovery * V_{water} \qquad \textit{Equation 16}$$

where $\%Recovery$ is the maximum fraction of water entering the RO system that can be recovered for low salinity, non-potable uses, and V_{water} is the total volume of brine [m^3/mt-CO_2].

The cost to produce a cubic meter of permeate using RO is dependent on water salinity, pretreatment decisions, and volumetric flow rates; these variables determine recovery fraction and production volume. Using this method, the levelized costs, over 25 years, is \$0.32/m^3 permeate for 50 percent recovery, equal to 6.5 million gallons per day (MGD), and \$0.81/m^3 permeate for 10 percent recovery, equal to 1.3 MGD (Bourcier et al. 2011). The cost of RO per metric tonne of CO_2 injected was found using:

$$Cost_{RO\_treatment} = \$_{permeate} * V_{permeate} \qquad \textit{Equation 17}$$

where $\$_{permeate}$ is the cost per L of permeate and $v_{permeate}$ is defined above. The commercial value of RO freshwater is dependent on sale prices of water for various non-potable uses and was calculated using:

$$Value_{RO\_freshwater} = \$_{freshwater} * V_{permeate} \qquad \textit{Equation 18}$$

where $\$_{freshwater}$ is the value per L of freshwater which varies regionally due to variability in water demand and supply across the country (Maulbetsch and DiFilippo 2006). In addition, levelized cost curves developed by Bourcier et al (2011) include permeate production rate and freshwater recovery fractions. The permeate production rate, often given in MGD, varies linearly with the extracted brine production rate. Osmotic pressure can be determined for a RO membrane given a TDS concentration and a desired freshwater recovery fraction. Pressure thresholds of current membrane technologies can be compared to these osmotic pressure functions to determine technological limits to RO treatment as a function of TDS concentration. The maximum possible recovery fraction can be estimated for TDS concentrations ranging from 0 to 100g/L. A sensitivity analysis was performed to determine the effect of $\$_{freshwater}$ variability on the cost of desalinization treatment in Breunig et al. 2013.

It is likely that the cost for RO will fall in the higher range because it is unlikely that pressure from the well will be available for RO. This is especially true if the water is pumped through geothermal heat exchangers prior to RO treatment.

4.3 Salt and Minerals

4.3.1 Evaporation Ponds

The NPV of evaporation ponds used for brine management depends strongly on the regional climate in the vicinity of the candidate formations. Evaporation and precipitation data needed for calculating evaporation pond land requirements were compiled and analyzed for areas near the three formations. For the Vedder, we use monthly and annual average evaporation data for Southern California taken from a 50-year joint research project on the Salton Sea, funded by the U.S. Department of the Interior, Bureau of Reclamation, and the Salton Sea Authority (Weghorst 2004). The data were adjusted by subtracting monthly precipitation from monthly evaporation, and by include a pan factor of 0.69. A pan factor was used to adjust for the fact that large ponds have lower evaporation rates than rates measured in small test pans. In effect, the salinity factor was already incorporated into the data because the Salton Sea has total dissolved solids (TDS) similar to the Vedder Interval's water. For the Mount Simon, we use monthly and annual average evaporation data for Springfield Illinois taken from a 10-year database maintained by the Illinois State Water Survey, Prairie Research institute (Illinois State Water Survey 2011). Monthly average precipitation rates for Windsor, Illinois were subtracted from these average evaporation rates. For the Jasper, we use monthly and annual average evaporation and precipitation data for Houston, Texas were taken from a 67-year database (Texas Water Development Board 2010).

With an annual flow of 18 million L and an annual cost of $34 million, it would cost a power plant -$3.84/mt-$CO_2$.

The volume of water was multiplied by a RO recovery factor if the water was treated prior to being sent to evaporation ponds (*Equation 20*). SA_{evapo} was calculated using:

$$SA_{evapo} = \frac{V_{in}}{(E-P)} \qquad \textit{Equation 19}$$

where $V_{in} = \frac{(1-\%\text{Recovery})*(M_{CO2})}{\rho_{CO2}}$, E is annual evaporation (m/yr) and P is annual precipitation (m/yr).

The depth of water flowing into the pond each month was calculated by assuming a constant flow rate of extracted water. The monthly depth of extracted water entering the pond was compared to the varying depth of water evaporated each month. In summer months, the depth of the pond water drops slightly (5-10 cm) because there is a net flux of water leaving (evaporating) from the pond.

Figure 8 shows an example of the effect precipitation has on the SA requirements for evaporation ponds at three power plants near the Jasper in Texas. The evaporation pond SA requirements of a typical 1000MW CFPP were compared to those for Fayette Power Project and WA Parish, two of the largest CO_2 point sources above the aquifer. High humidity and high annual precipitation in eastern Texas make net evaporation very low. While this climate is not conducive to evaporation pond maintenance, it is ideal for algae pond development because the precipitation provides a natural source of freshwater to recharge the ponds.

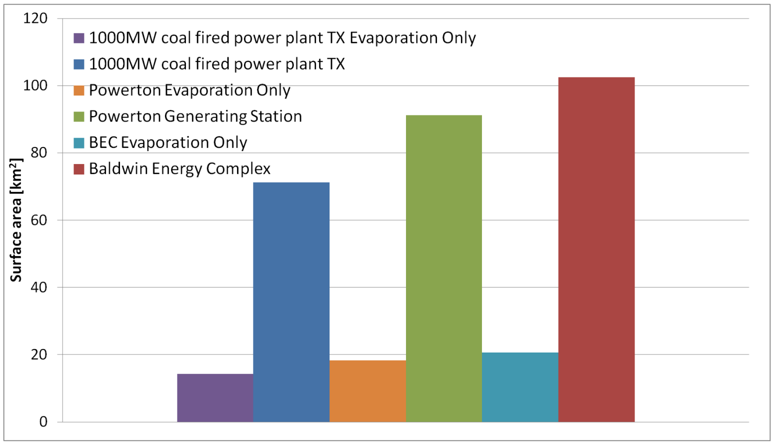

Figure 8. Histogram of evaporation pond surface areas for three power plants in Texas. The effect of local precipitation on evaporation pond SA requirements assuming no RO treatment.

Total SA will be the summation of multiple ponds, and not representative of one large evaporation pond. We multiplied SA by 1.2 to account for roads, maintenance equipment and buildings when calculating land costs. For simplicity, we assumed that evaporation ponds will be filled to H = 30 cm to prevent drying of the pond's liner in the initial years of use. Annual volume-balance calculations reflect the assumption that the evaporation basin lining is impermeable to water. Manmade barriers are installed and maintained for two primary reasons: to prevent brine leakage out of the pond and into local freshwater sources; to prevent seepage from rainfall into the pond through the sides and bottom of the pond.

Annual volume entering the pond $V_{in\_}a$ and annual volume exiting the pond V_{out_a} were calculated using:

$$V_{in\_a} = V_{in} + P * SA_{evapo} \qquad \textit{Equation 20}$$

where *Vin, P,* and SA_{evapo} are defined above (*Equation 20*).

$$V_{out\_a} = E * SA_{evapo} \qquad \textit{Equation 21}$$

where E and SA_{evapo} are defined above *(Equation 20),* assuming: $V_{in\_a} - V_{out\_a} = 0$

4.3.2 Salts and Mineral Harvesting

Salts and minerals can be harvested from GCS extracted brines through evaporation ponds, chemical processing, and electrolysis. Based on production rates and brine compositions found in literature, we estimated that the efficiency of harvesting elements like Na, K, and Ca from brine is around 70%, the efficiency of harvesting Mg is around 80% (Kim 2011; Fritzmann et al. 2007). The efficiencies of harvesting Na, K, and Ca are likely to be higher if RO is performed prior to a mineral harvesting stage (Fu and Wang 2011). Boron can be recovered at very high rates if GCS sourced brine is treated using ultrafiltration or RO. The commercial value of salts and minerals per mt-CO_2 injected was calculated using current market prices and saline aquifer mineral concentrations, as

$$Commercial\ Value = \sum_{\mathrm{i}} \left(\frac{\$}{\text{tonne compound i}} * \mathrm{C_i}\right) * \mathrm{e}_i * \frac{\mathrm{V_{in}}}{mt{-}CO_2} \qquad \textit{Equation 22}$$

where C_i is the concentration of compound i in the brine [mt/m^3], e_i is the assumed extraction efficiency of compound i, and $\mathrm{V_{in}}$ is defined above (*Equation 20*).

Cost, in terms of capital costs and operation costs per mt-CO_2 injected, for maintaining the salt harvesting evaporation ponds was calculated as:

$$Cost = \$_{\text{vol water}} * \frac{\mathrm{V_{in}}}{mt{-}CO2} \qquad \textit{Equation 23}$$

where $\$_{\text{vol water}}$ is the volume of water ($/L), and $\mathrm{V_{in}}$ is defined above (Equation 20). We assumed brine composition would not change due to CO_2 injection because extraction wells are placed a distance from where the CO_2 plume front is predicted to be in 25 years. We also assumed that the average price of arid, semi-arid, and desert land is between $200-2000/acre, which is consistent with the 2011 price of nonagricultural land. We calculated the price of land per mt-CO_2 injected by determining the SA required to evaporate extracted brine over a one-year period. We estimated the cost of this harvesting stage using the methods of previous studies. Cost ranged between $2-4/mt-$CO_2$-injected if no RO was performed prior to mineral harvesting (Kim 2011). The total cost was the sum of the production costs, the capital and operation cost of the evaporation ponds, and the land cost. The maximum production of boron, sodium, potassium, magnesium, and calcium was calculated using: the maximum concentration measured in the brine, recovery efficiencies found in the literature, and the extraction of brine determine for our case study CFPP. The annual mass that could be harvested from the brine from one CFPP was compared to the mass of domestic production in 2010 (Table 5). Mineral harvesting produced less than 5 percent of US domestic production in 2010 for all scenarios, excluding magnesium production in the Mt. Simon, which reached 13 percent.

Table 5. Regionally variable assumptions and inputs for mineral and salt production.

	Vedder		Jasper		Mt. Simon			
	% US domestic production 2010						US domestic production 2010 [mt/yr]	GCCC, (2003);
Annual Average Evaporation-Precip [m]	1.6		0.2		0.2			USGS (2002)
Days of Operation for Ponds	365		365		183			
Concentration Boron* (low, high) [mg/L]	(3, 91)		(53, 60)		(0, 500)			
Concentration Sodium (low, high) [mg/L]	(500, 10400)	*1*	(6250, 35200)	*4*	(24569, 44295)	*4.5*	17,100,000	
Concentration Potassium (low, high) [mg/L]	(0.5, 100)	*0.4*	(100, 225)	*1*	(200, 393)	*1.4*	900,000	
Concentration Magnesium (low, high) [mg/L]	(4, 44)	*0.3*	(37, 453)	*3*	(1287, 1713)	*12.6*	243,000	
Concentration Calcium (low, high) [mg/L]	(10, 147)	*0.1*	(169, 2150)	*1*	(4292, 9023)	*3.8*	18,000,000	Mitchell et al, (2004);
Value Brine for Road De-icing [$/mt]	0		0		35		15,000,000	Ripley, (2011)

Salt, or sodium chloride (NaCl), is the most widely used de-icing and anti-icing chemical for roads. Figure 9 shows the breakdown of salt sources and applications. Almost 40 percent of salt produced in the US was sold for highway deicing in 2009 (Kostick 2011). For regions where climate does not allow year-long evaporation, the final net cost of harvesting salts from an evaporation basin included the cost of land, the capital cost of building the evaporation ponds, and the cost of salt harvesting during warmer, drier months. If it was possible to sell the brine for anti-icing roads, then that value was added to the calculated value of brine management.

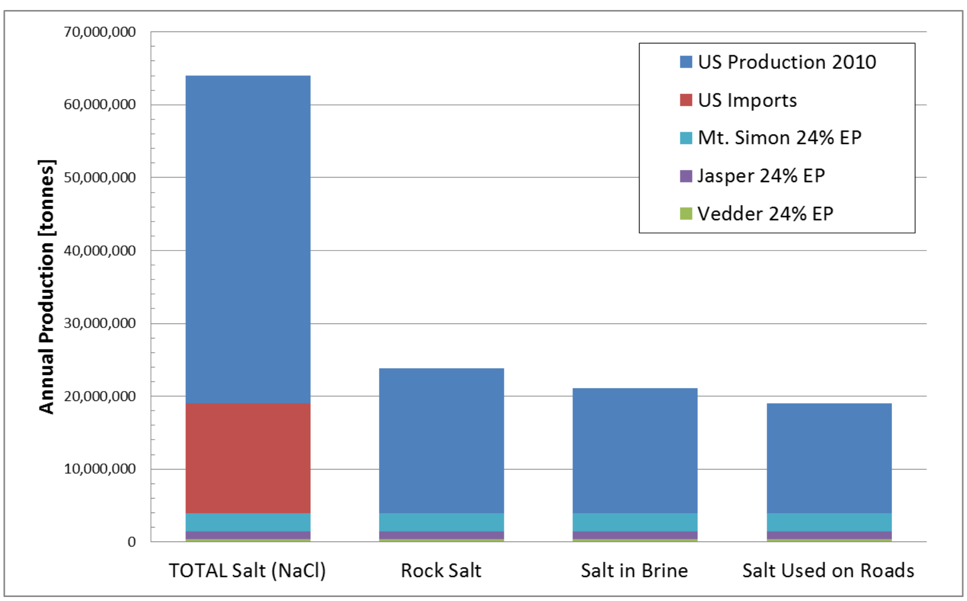

Figure 9. Histogram of potential annual salt production from brine. Masses of salt obtained from three different extracted waters are compared to US production and US imports in 2010. Production of salt from rock mining, brine mining, and total mass of salt used on roads are compared to annual aquifer production using an assumed recovery efficiency of 70%.

4.4 Algae Biodiesel

Similar to evaporation ponds, open algae ponds are inexpensive to construct and relatively easy to operate. There are several different types of open ponds, but the racetrack model is the most common. In this pond, paddles circulate water to avoid biomass settling, to increase gas diffusion, and to promote photosynthesis by increasing the time algae spend near the surface. Pond water is maintained at a depth between 0.2 and 0.3 m (Campbell et al. 2011). This is the same depth range that is optimal for evaporation ponds. If algae ponds are designed to meet a biodiesel production volume (gal/yr), then the SA was calculated based on required algae productivity and growth rates. Climate and lipid characterization of the algae species chosen will be inherent in these values.

If algae ponds are designed for GCS brine management, then the SA can be calculated based on required water storage capacity, evaporation, precipitation, pond recharge requirements, harvesting frequency and water recycle rates. The volume of biodiesel produced can be estimated and given a dollar value if algae productivity is estimated, and if a pond's SA is known. Lipid production values from Pate et al. (2011) were compared with lipid production levels estimated by Borowitzka and Moheimani 2010 in order to determine algae productivity and interpolate required pond area in different regions of the US (Table 6). While algae require less land than first- and second-generation biofuel crops, scaling production to meet a significant volume of biodiesel demand will require large SA for ponds, infrastructure, and processing facilities (Clarens et al. 2010). LCAs have calculated anywhere between 20-50 percent of the land requirement is allocated to supporting infrastructure and processing facilities; we assumed 30 percent.

Algae will reach their highest production rates in climates with high solar incidence, high temperatures, and low precipitation (Borowitzka and Moheimani 2010). Hot arid climates have the largest evaporation rates and thus the largest water requirements to sustain a set depth in the algae ponds. If saline water is used, the algae ponds will become saltier over time and algae growth will be hindered once salinity exceeds an optimal range. Salts will have to be extracted, diluted, or sent to evaporation ponds. Nutrient inputs, include urea, nitrogen and phosphorus fertilizer, iron sulphate and excess CO_2, and algae pond construction materials were estimated from a LCA of an Australian algae pond (Campbell et al. 2011).

The largest limitation to scaling up algae growth is the high nitrogen and phosphorus requirements. Facilities that use wastewater have a convenient source of these nutrients, but facilities that use saline groundwater will have to add them. Finding a potential wastewater source that could feed into ponds supplied by extracted water is a possibility. It is likely that the challenge to provide algae with the type and quantity of nutrients they require using wastewater treatment facility water, without diluting saline waters below an optimal TDS range, will be more costly than supplementing ponds with nutrients. The addition of anaerobic digesters for methane production has the added advantage that nutrients like phosphorus, potassium, and nitrogen can be captured and recycled from the digester waste. A detailed input/output data set will be generated in a future study to determine the environmental impacts of using brine to recharge algae ponds for biodiesel and biogas (methane) production via anaerobic digesters (Collet et al. 2011).

Table 6 summarizes the potential algae production and pond sizes for a single 1000 MW CFPP injecting CO_2 into salt formations of the three study regions of the US. Productivity, lipid content, and the SA of a single algae pond were adapted from previous regional studies assuming the California site is like the Southwest, Texas is in the Nineteen-Lower Tier Region (NLTR), and Illinois is in the Midwest (Pate et al. 2011). The number of algae ponds (N_{ponds}) required was calculated using the following equation:

$$N_{ponds} = \frac{V_{extracted}}{SA_{pond} * H} \qquad \textit{Equation 24}$$

where $V_{extracted}$ is the volume of water extracted annually, H is the height of the algae ponds (assumed to be 30 cm), and SA_{pond} is provided in Table 6. The land footprint was found by multiplying the SA of one pond by the number of ponds required for a given brine extraction rate and evaporation rate. We multiplied this by a factor of 1.3 to account for the land required for initial treatment and processing of the algae, maintenance equipment, and roads.

Table 6. Metrics for algae ponds in different regions of the US, with different estimated productivity levels. Algae harvesting efficiencies, maintenance, and land requirement assumptions were taken from (Pate et al. 2011; Borowitzka et al. 2010; Collet et al. 2011).

Algae Pond Design						
Region	Texas low	Texas high	Midwest low	Midwest high	Southwest low	Southwest high
Aquifer	Jasper	Jasper	Mt. Simon	Mt. Simon	Vedder	Vedder
Algae Productivity [g m^{-2} d^{-1}]	20	20	30	30	30	30
Algae Lipid Content [% dry wt]	30	40	30	40	40	40
Days of Operation	365		183		365	
Pond SA [km^2]	8	80	6	80	5	80
Depth [m]	0.3	0.3	0.3	0.3	0.3	0.3
Biomass Production [kg-drywt/mt-CO2]	7	70	4	50	6	100
Lipid Production [L-TAG/mt-CO2	2	22	1	16	2	33
Total Land Requirement [km^2]	10	104	8	104	7	104
NP Construction and Land Value $/mt-$CO_2$	$ (0.1)	$ (7.5)	$ (0.0)	$ (10.2)	$ (0.0)	$ (25.0)
NP Value Lipid-TAG $/mt-$CO_2$	$1	$12	$1	$9	$1	$18
NPV/mt-CO_2	**$1.1**	**$4.8**	**$0.7**	**-$1.4**	**$1.2**	**-$6.9**

The volume of water lost to evaporation was calculated by multiplying the SA of a pond, by the annual evaporation rate in the region over the period of activity. We assumed that ponds with a brine recycling and pond purging system did not need freshwater to replenish the pond or to control salinity (low scenarios); fresh brine is routinely introduced into the ponds. 80 acre ponds, designed to hold brine throughout the active period, are diluted with low salinity water (high scenarios). The cost of this water is included in the NPV calculation for algae ponds, assuming water is purchased at a price of $1.45/m^3$. The volume of biodiesel and biomass produced per mt-CO_2 injected and the total maximum land footprint were calculated for each region (Table 6). Operation costs were assumed to be $20,000 per hectare and were added to the annual land cost. Algae ponds were not cost effective at the large pond size in the Mt. Simon and Vedder until the price of water dropped to -$1.08/m^3$ and -$0.96/m^3$ respectively.

While some algae thrive in saline conditions, production drops dramatically outside an optimal salinity range. Both Illinois and Texas have heavy annual precipitation that will provide freshwater for algae pond recharge. On the other hand, significant land-coverage (with liners) may cause a negative impact on local water tables. For example, large volumes of redirected rain water could affect ground water table recharge.

4.5 EGS Recharge

`There are multiple geothermal reservoirs and systems established in southern California (Figure 10) while there is less geothermal system infrastructure established in Illinois and in Texas. We determined that the feasibility of using brine from the Mt. Simon is very low. The eastern coast of Texas is considered a favorable area for EGS but may not be cost effective (Figure 2). It is likely that the lack of local geothermal reservoirs or EGS projects in Illinois and Texas will push the cost of EGS into a higher price range than that in Figure 2; the cost to transport saline water to the geothermal reservoirs is a large expense by itself, and it must be included in the NPV. Current geothermal projects, located within 50 miles of a GCS project site, may be potential options for brine management, whether through recharging reservoirs, or through water or space heating.

Source: California Energy Commission

Figure 10. Known Geothermal Resource Areas in California (CAC 2005).

Currently, there is little data available on the economics of EGS. We estimate EGS costs by assuming extracted water can be sold at groundwater price and by estimating the cost of a geothermal reinjection well (Table 2). The cost of a geothermal reinjection well (GRWS) was determined using [\$/mt-CO_2]:

$$GRW = \frac{\$_{GRW} * \frac{1000\ kW}{1\ MW} * C_{thermal}}{M_{CO2}} \qquad \textit{Equation 25}$$

where $\$_{GRW}$ is a value in the specific cost range of \$10-20/kW (DiPippo 1991), $C_{thermal}$ [$kW_{thermal}$] is calculated using *Equation 6* and M_{CO2} is the mass of CO_2 injected at the GCS site [mt-CO_2].

4.6 Disposal

In the following sub-sections we evaluate the brine disposal options and technologies, including direct and co-disposal to surface saline water bodies, evaporation pits, disposal wells and shallow reinjection. We also provide cost estimates associated with transporting brine, and for construction and operation of pipelines.

4.6.1 Direct and Co-Disposal to Surface Saline Water Bodies

To evaluate the feasibility of discharges to surface waters, we calculated dilution and mixing requirements needed to comply with the current practice of diluting discharged water until the TDS concentration is within ±1000 mg/L of seawater. As seen in Figure 6, the average concentrations of TDS in Vedder water are lower than seawater. The only exception is calcium. Calcium is not a primary concern in terms of marine toxicology because calcium naturally fluctuates in seawater (Selim 1970). If there is a concern about the hardness of this water, water softening techniques could be applied. Dilution will be cheaper if there is a nearby abundant source of freshwater that can dilute the formation water to seawater calcium concentration, which would require a dilution factor of eight. Average concentrations of TDS in the Jasper and the Mt. Simon are higher than seawater. Calcium, sodium, chloride and magnesium scale with TDS concentrations in these formations, and diluting to acceptable TDS concentrations will get concentrations in the range of seawater. These dilution requirements are illustrated in Figure 11.

Dilution factors were calculated to determine the volume of low salinity water required to dilute maximum formation water TDS concentrations to an ocean salinity of 34,700 mg/L. We estimated that dilution factors of 0.85, 0.37, and 0.13, are needed for the average Vedder, Jasper, and Mt. Simon brines, respectively (Khan et al. 2009; Del Bene et al. 1994). Using maximum concentrations provided a conservative measure of dilution because TDS varies dramatically throughout formations. All three dilution factors require large volumes of fresh or waste water for mixing with extracted formation waters. Our determination of dilution-water needs is shown in Figure 11. Clearly, direct disposal to surface water bodies has a large water footprint.

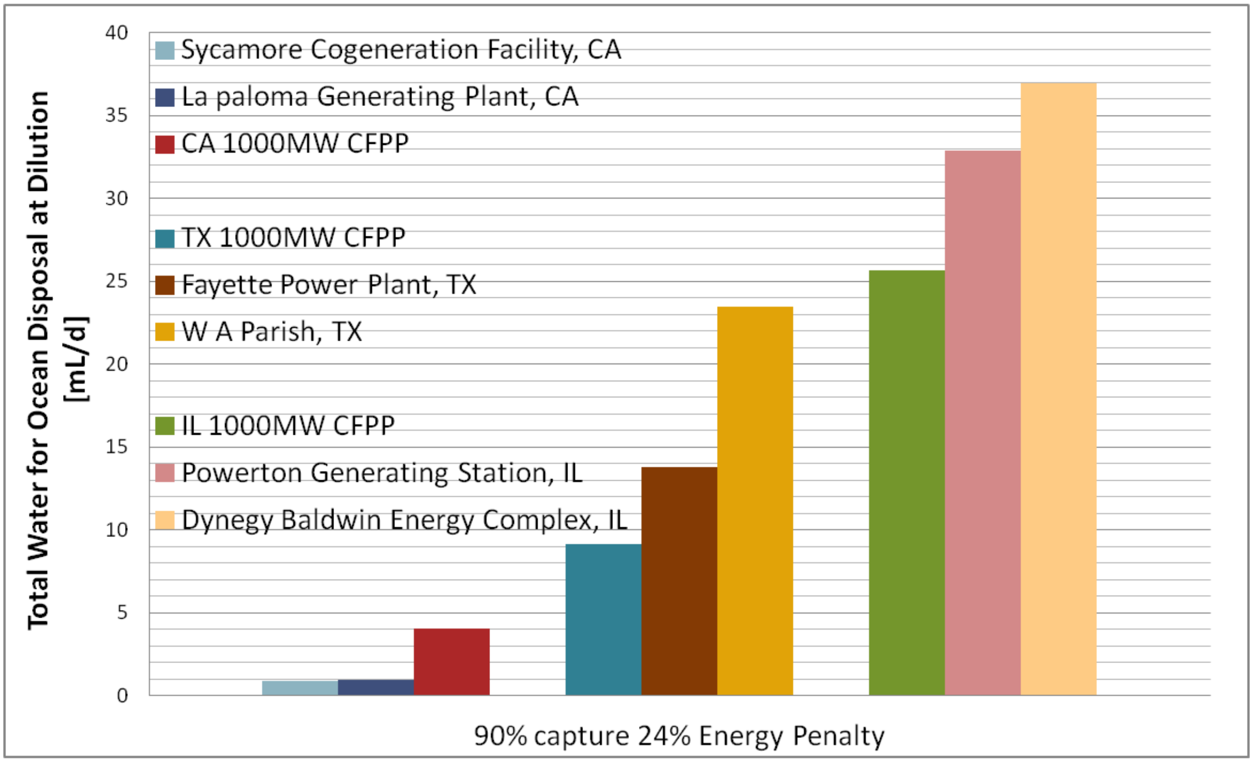

Figure 11. Histogram of water required to dilute extracted water to ocean salinity. Values are given for the two largest CO_2 point sources above or within 150 km of each formation, and for a typical 1000 MW CFPP. Units are million liters per day [mL/d].

Disposal costs for surface discharge were calculated to be between \$0.1-1/mt-CO_2-injected as summarized in Table 2 (\$0.002-0.02/L). This was adapted from produced water disposal cost estimates generated in Jackson and Myers 2003 (Veil et al. 2004). Site selection for a saline-water outfall will affect the cost and environmental impact of direct discharge into surface saltwater bodies. Aside from transportation costs, outfalls for desalination plant effluents must be constructed and must meet local regulations. Regulatory dilution requirements are influenced by local turbulence, salinity, boating activity, and the proximity of sensitive ecosystems. Regions with a natural zone of initial dilution (ZID) will require less freshwater/wastewater for diluting extracted water TDS (Voutchkov 2011).

An alternative approach to discharge into surface saltwater bodies is to use the effluent of WWTF or water recycling facilities (WRF) for co-disposal at an established outfall. In order to evaluate this option, we plotted local WWTF and WRF in ArcGIS to evaluate regional treatment capacities and compare available effluent volumes with the dilution requirements for each saline aquifer (Ventyx 2012).

In addition to proximity, size, and excess flow rate capacities, we selected WWTF based on the size of the pipeline transportation network, the established ocean outfall systems, and disinfection methods. Disinfection byproducts (DBP) can form when salt water mixes with residual compounds of disinfection. A key example is the formation of bromate when hard water mixes with water that has been treated with ozone. But chlorination remains the most common disinfection method in the US, and chlorination residuals are not reactive with salts in the formation waters.

As seen in Figure 11, the volume of freshwater required to dilute Mt. Simon Sandstone brine to seawater salinity is enormous (> 30 mt/d). A power plant injecting 90% of its annual emissions, with a 24% energy penalty, requires 22 million liters per day (mL/d) of freshwater to dilute the 3.4 mL/d of extracted water (resulting in a total of ~25 mL/d). The Mt. Simon is landlocked, has high salinities, and is far from a saline body of water, we assumed that surface discharge was not feasible.

Building pipelines and pumping water is capital and energy intensive, and the volume of water released into surface saltwater bodies is likely to have an environmental impact on local ecosystems and natural hydraulic systems. While local WWTF are large, and discharge enough wastewater to dilute extracted waters to seawater salinity levels, it would not be practical to dilute 3.4 mL/d to 22 mL/d prior to pipeline transmission. Clearly, direct disposal into surface saltwater bodies is not a practical solution for extracted brine from the Mt. Simon Sandstone Formation.

Ocean disposal for the Vedder brine was not feasible due to the large, steep, distances new pipelines would have to travel. The feasibility of discharging brine from the Jasper is expected to improve if local sources of low salinity water can be found for co-disposal. New mixing technologies are emerging to improve outfall dispersion and to avoid density gradients that may impair local benthic populations (Voutchkov 2011; Del Bene 1994). These technologies reduce or remove the need to dilute the extracted water to seawater TDS concentrations by providing a mechanical form of dilution.

4.6.2 Evaporation Pits, Disposal Wells, Shallow Reinjection

The cost of well disposal reinjection ranges from inexpensive, ~\$-0.6/mt-CO_2-injected, to very expensive, \$-33/mt-CO_2-injected. The lower range represents the cost of water disposal in regions that have established reinjection systems and that are not under significant legal or environmental constraints. Such low costs may occur in Texas, where a brine management or extracted water infrastructure is well organized. The upper cost range represents the cost of drilling, maintaining, and operating new disposal wells, in addition to obtaining the rights for the well. This upper cost reflects the cost in areas of Illinois where there is little brine management or extracted water management infrastructure or where nearby fresh water resources need to be carefully monitored for later contamination.

The costs associated with evaporation pond disposal, disposal wells, offsite commercial treatment and disposal, and landfill disposal were adapted from regional industrial waste and produced water disposal cost estimates (Table 2) (Veil et al. 2004; Puder et al. 2006; Clark et al. 2009; Harto and Veil 2011). Costs, initially in $/bbl were converted to $/mt-$CO_2$-injected assuming a 1 to 1 ratio of extracted brine to injected CO_2 and assuming CO_2 has an in depth density of 500 mt/L. As a first approximation, costs were multiplied by a disposal fraction based on the volume reduction achieved during a BUS. For example, RO treatment can substantially reduce the volume of brine requiring disposal, thus lowering the cost of disposal per mt-CO_2-injected.

Each region varied in terms of climate, local geographies, land use, and hydrology. The size of evaporation ponds required for extracted water from GCS depended on the evaporation rates and precipitation rates. The southern San Joaquin Valley is characterized by a hot and arid climate. This results in the relatively small evaporation pond land requirement for the Vedder's extracted water. Both eastern Texas and southern Illinois have large annual precipitation. In addition, Illinois has cold winters that limit the use of evaporation ponds to warmer seasons. We assumed that the extracted water in Illinois would be send to an onsite evaporation pond for only half of the year, and an alternative disposal option would be used in the winter.

Several brine management options reduce the volume of brine requiring disposal. Desalination is one option that can significantly reduce the surface area of evaporation ponds Section 6. Evaporation pond surface area was reduced with proper pond purging or frequent salt harvesting, (Breunig et al. 2013).

4.6.3 Brine and of CO_2 Pipeline Transportation

Constructing, operating and maintaining pipelines for brine disposal will incur major expenses both economically and environmentally. It will be advantageous to either use available pipelines or to construct pipelines that are short and avoid steep topography. While the Jasper is on a coastline, it will still require expensive and potentially contentious pipelines to actually transport the extracted water to the ocean. Future studies will include cost and impact calculations of brine transportation that use regionally specific pumping, maintenance, and construction costs and parameters The construction and operation of pipelines for brine disposal is costly. We determined the net present value (NPV) of pipeline transportation using data from the construction and operation of a 100 km pipeline for water and biomass transportation (Deutz 2012) . Our calculation assumed a 10% discount rate, 30 year lifespan, $2,000,000 operation and maintenance cost, and $60,000,000 capital cost. This resulted in a NPV of -$7/mt-$CO_2$ (-$0.1/mt-$CO_2$-mile). Another source calculated that brine pipeline operation cost $0.08-0.1/mt-$CO_2$-mile [75c]. We assumed pipeline NPV could range from -$0.1 to -$0.2/mt-CO_2-mile.

Methods for reducing costs include paying to use local pipelines or constructing pipelines that are less than 50 miles, do not cross state borders, and avoid steep (Puder et al. 2006).

5. RESULTS OF LAND AND ECONOMIC ASSESSMENT

An estimate of the NPV of a BUS can be obtained by using commercial values in Table 2. To use Table 2, a column is selected that correlates to the aquifer and cost range (low or high) of interest. Rows correlate to treatment and disposal options. Values from the same column can be used in NPV calculations of extracting brine from a given aquifer. The NPV of a BUS can be compared to the cost of CCS for a pulverized coal (PC) CFPP or an integrated gasification combined cycle (IGCC) CFPP, listed in the last two rows of Table 2 (Gerdes 2011). All values have a functional unit of one mt-CO_2-injected.

Based on the inputs and methods summarized in Sections 3 and 4 we have developed scenarios for brine management that maximize the overall brine management revenue to CCS and those that we determined to be most feasible in the next 30 years. In some cases the income from the BUS is negative—adding more cost to CCS. In other cases there can be significant income to offset CCS cost. In the following sections, we provide an overview of these scenarios for each of our candidate sites. As discussed in this report, there are additional metrics that can be used to determine the "optimal" BUS. For example, a sequence that has a high commercial value from algae pond biodiesel production may have an unacceptably large land footprint. Future studies will determine water footprint and other LCA metrics for each potential BUS stage or disposal option and integrate them into the BUS model to provide a means of comparing environmental impacts with commercial value.

In addition to NPV, we used our assumed feasibility estimates as guidelines for the development of brine management sequences (Table 7). A 0.5 in Table 7 implies a BUS options was economically feasible, but had little to no presence in the region (extracted brine for road deicing) or a BUS option required substantial maintenance to ensure production (fish and algae aquaculture systems). We determined that the feasibility of an option decreases if a GCS project must initiate the permitting process for new land uses or disposal options. We found that 15 km^2 and 0.1 km^2 were feasible sizes for evaporation ponds and aquaculture ponds respectively. The pond limits used in feasibility calculations were included in the Comments section of Table 7. For example, aquaculture ponds fed with desalinated brine were feasible for the Jasper and Vedder if they were on the order of 0.1 km^2 in size. These ponds would not hold all of the desalinated brine produced from a 1000MW CFPP GCS project extracting a 1:1 ratio of brine to injected CO_2.

Table 7. Feasibility estimates for one 1000MW CFPP located over three different saline aquifers. Feasibility ranges from 0 to 1, where 0 implies a BUS option is not feasible and a 1 implies a BUS option is feasible.

BUS Options:	**Mt. Simon**	**Jasper**	**Vedder**	**Comments**
CHP	1	0	1	
Heat Recovery Only	1	1	1	
Desalination	0	1	1	
Aquaculture w/ Brine	0	0	0	
Aquaculture w/ Desalinated Water	0	0.5	0.5	Pond Limit 0.1 km^2
Aquaculture w/ Energy	0.5	0.5	0.5	Pond Limit 0.1 km^2
Algae Ponds Biodiesel w/ Energy	0.5	0	0.5	
Algae ponds Biodiesel	0.5	0.5	0.5	
Salt & Mineral Recovery	0.5	0.5	0	No Pond Limit
Salt & Mineral Recovery Concentrate	0	0.5	0.5	No Pond Limit
De-Icing Brine	0.5	0	0	
De-Icing Desalinated Water	0	0	0	
De-Icing Salt	0.5	0	0	
Wastewater Treatment Company/Facility	0.5	0.5	0.5	
Landfill	0.5	0.5	1	
Landfill Concentrate	0	0.5	1	
Reinjection Disposal	0.5	1	1	
EGS Disposal	0	0.5	1	
Ocean Discharge	0	1	0	
Evaporation Ponds Offsite	0.5	0.5	0.5	No Pond Limit
Evaporation Ponds Disposal All Brine	0	0	1	Pond Limit 15 km^2
Evaporation Ponds Disposal All Concentrate	0	0	1	Pond Limit 15 km^2
Evaporation Ponds Offsite	0	0	0.5	Pond Limit 15 km^2

5.1 Jasper Interval, TX

Management of the extracted water by harvesting geothermal heat only prior to transporting the brine 25 miles to a discharge point in the Gulf of Mexico, has a levelized NPV between -\$0.3 and +\$0.3/mt-CO_2. If the water is treated using RO so that desalinated water is sold at desalinated price, and concentrate is sent to evaporation ponds for magnesium and salt harvesting prior to surface disposal, the brine management has a commercial value between -\$4.5 to +\$5.2/mt-CO_2. Additional revenue of +\$0.2 to +\$0.5 /mt-CO_2 could be acquired if geothermal heat could be capture for onsite district heating prior to this sequence. At -\$16.7/mt-CO_2, shallow reinjection of brine near freshwater resources is the most expensive disposal option. The most profitable and feasible BUS has a NPV ranging from +\$1.3 to +\$6.4/mt-CO_2 and involves: harvesting geothermal energy for onsite heating; treating the brine with RO, using the RO freshwater on-site, harvesting minerals and salts, and disposing of waste onsite in evaporation ponds. Sending the heat, desalinated water, and concentrated brine to a small algae pond system, rather than to a mineral harvesting stage, generates a NPV of \$1/mt-CO_2; this BUS is less feasible since a competitive algae biodiesel market is not established in that region.

In the case of eastern Texas, the average algae ponds will capture more CO_2, and will require a smaller land footprint (10 km^2) than the average evaporation ponds for salt harvesting with reverse osmosis treatment, (100 km^2).

5.2 Vedder Interval, CA

Using geothermal energy for district heating onsite prior to evaporation pond disposal has a commercial income between -\$0.7 and +\$0.7/mt-CO_2. This will require a land footprint <10 km^2. If the brine is desalinated and all salts and minerals are harvested from the concentrate while the reclaimed water was used for cooling towers at the CFPP prior to evaporation pond disposal, brine management would cost between +\$1.0 and +\$1.5/mt-CO_2. At -\$33/mt-CO_2, shallow injection of brine near freshwater resources is the most expensive disposal option. The most profitable scenario, at +\$2.1/mt-CO_2, involves harvesting geothermal heat for algae ponds, producing algae biodiesel, performing RO to produce drought price water, and disposal of concentrate via onsite evaporation ponds.

Algae ponds will require the same scale land footprint (5 km^2) as evaporation ponds for salt harvesting with reverse osmosis treatment, (5 km^2) or without reverse osmosis treatment (10 km^2). Geothermal systems require <10 km^2 of land. Approximately 2% of this SA is used by buildings and equipment. The land footprint and cost of land for brine management may be affected by the addition of geothermal energy systems.

5.3 Mt. Simon Sandstone Formation, IL

Geothermal heating and feeding of desalinated brine to algae ponds prior to transporting the brine 25 miles to deep disposal well sites during the summer would have a NPV ranging from -\$2.5 to +\$0.6/mt-CO_2. This BUS would not generate a profit if the GCS project could not find a demand for the geothermal heat. Sending the extracted water to evaporation ponds for all salt and mineral harvesting prior to sending the brine 25 miles to reinjection sites would have a NPV between -\$2.5 and +\$12.2/mt-CO_2. The variation in the prices for disposal wells and the range in achievable mineral production lead to these large price ranges. Use of extracted water for geothermal onsite heat and then road anti-icing solution could be valued as high as \$6.3/mt-CO_2, assuming 50% of the brine could be used for road deicing within a 100 mile radius and that the remaining 50% is transported 25 miles to a deep well disposal site. Seasons with low road anti-icing demand could lead to significant losses if a GCS project has not invest in a backup winter BUS. At a NPV of -\$53.3 to -\$12.8/mt-CO_2, sending the brine for commercial treatment and subsequent surface disposal in Illinois can double the cost of CCS. We assumed this option would not be feasible, but we included it to show how costly brine disposal can be. The greatest profit, at +\$17.7/mt-CO_2 is obtained in the summer by harvesting geothermal heat for a secondary salt and mineral harvesting stage prior to onsite evaporation pond disposal. Evaporation ponds will require a large footprint due to high precipitation rates (30 km^2), and because RO treatment is not possible for the Mt. Simon Sandstone Formation extracted water due to its high TDS. A low volume of water will be required for dilution of algae ponds due to the high precipitation experienced during the warmer half of the year. Geothermal power production buildings and equipment require <7 km^2 of land.

6. SENSITIVITY ANALYSIS

Based on the assumptions, inputs, and methods described above, we estimate and compare the land footprint and NPV of brine management options among the Vedder, Mt. Simon, and Jasper candidate saline formations. The land footprint of evaporation ponds alone can range from 10 km^2 to 100 km^2. The NPV of brine resource recovery sequences can range from -\$50/mt-CO_2, (a cost) to +\$10/mt-CO_2 (revenue). Relative benefits/impacts are highly sensitive to local climate and weather, and aquifer water chemistry.

6.1 Algae Productivity and Land Footprint

Algae biomass productivity [g/m^2-day] is sensitive to available nutrients, physical circulation, and to annual solar energy. Algae lipid content [%] varies with species and is sensitive to growth conditions. Previous studies have calculated algae lipid productivity by predicting achievable algae biomass productivities for different species (different lipid contents) for a given regional climate. Lipid contents of 30-40% have been achieved at lab scale and it is predicted that an average lipid content of 30% is achievable in arid climates (southern California), or during the warmer months of temperate climates (Illinois). Developments in genetic engineering and selection may improve efforts to predict obtainable large scale algae lipid productivities. NPV was calculated for algae pond systems designed to hold annual brine and low salinity dilution water, and to generate large quantities of biodiesel; these ponds had a SA of 80 km^2. Lipid content and freshwater price were varied over a range of algae productivities (Figure 12.A). At fixed algae productivity, the feasibility of large scale ponds is most sensitive to the price of water. We determined that these large scale ponds were not feasible and water recycling could be included in operations to limit freshwater demand (Figure 12.B). Smaller ponds reduced the production of bio-oils, but generated a positive NPV. Algae ponds maintained in hot, arid climates with high solar incidence, like southern California, can achieve higher annual lipid productivity levels, but they will also have large evaporation rates and thus large water requirements.

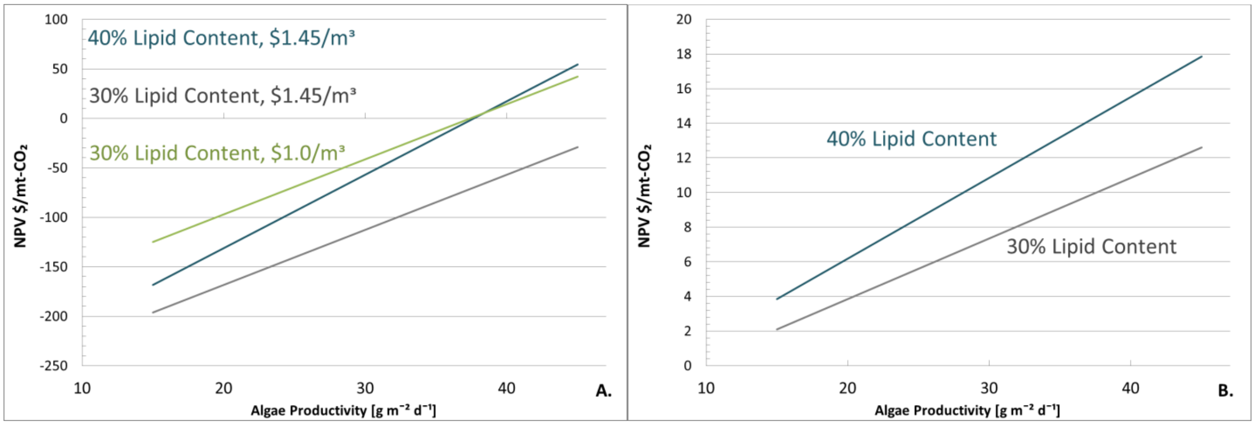

Figure 12. Sensitivity analysis showing the behavior of algae lipid NPV for to variations in regionally achievable algae productivity, lipid content, and freshwater prices. Scenarios are modeled for arid regions, like those found around the Vedder, where water footprint is greatest due to high evaporation rates. Graph A: 80 km^2 algae pond system with freshwater recharge and no water recycling (left graph) and Graph B: 5 km^2 algae pond system with water recycling.

Regions that have high humidity and high annual precipitation, like eastern Texas, will have low net evaporation and large evaporation pond land footprints (Figure 13). Although this climate is not conducive to disposal or salt harvesting evaporation ponds, it is ideal for aquaculture pond development because the precipitation provides a natural source of freshwater to dilute and recharge the ponds. Hot, arid regions, like southern California, have the smallest land footprint. Naturally, a greater RO recovery factor results in a smaller surface area since desalinated water will not be sent to evaporation ponds. The land requirements shown in Figure 13 are much larger than the feasibility limit for evaporation ponds, set at 15 km^2; clearly there is a need for brine volume reduction through brine management prior to evaporation pond disposal.

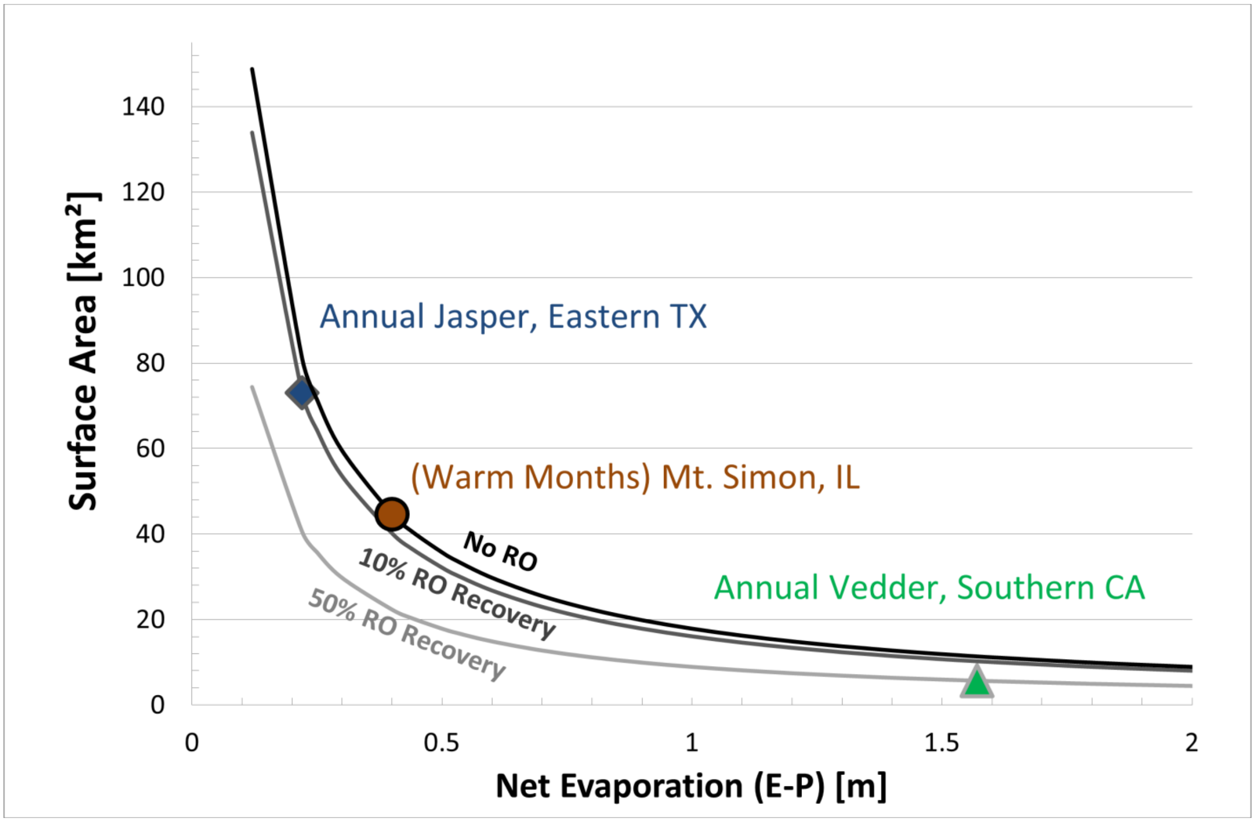

Figure 13. Sensitivity analysis showing the behavior of evaporation pond land surface area to varying climate and desalination recovery factor. Average annual evaporation (E) and precipitation (P) rates are used to estimate land surface areas for the regions of three saline aquifers: Mt. Simon (brown circle), Vedder (green triangle), and Jasper (blue diamond) (Breunig et al. 2013).

7. DISCUSSION

Carbon dioxide capture and sequestration (CCS) has the potential to play a large role in US carbon mitigation initiatives. Early economic and environmental assessments can help streamline deployment of CCS and other emerging energy technologies by predicting avoidable economic barriers and environmental impacts. Integrated assessments, such as the assessment conducted in this report, may prevent the need for costly future technology retrofitting stages and they may provide insight on unique regional opportunities or constraints that face a new technology.

Geologic carbon sequestration (GCS) is currently performed by the oil and gas industry for enhanced oil recovery (EOR), whereby CO_2 is injected into mature oil and gas reservoirs to improve hydrocarbon production. Not every US CO_2 source is located near an oil or gas reservoirs that would enable them to perform EOR. In addition, some EOR opportunities will be depleted over the next 50 years and new EOR projects may not be pursued in the long term if alternative sources of energy take precedence. CO_2 sources could use nearby saline aquifers for carbon sequestration; many of these formations have large CO_2 storage potentials. Formation-water extraction is not a requirement for GCS in saline aquifers, but it can increase CO_2 storage potential and decrease the risk of induced seismicity. CCS is capital-, energy-, and water intensive. In order to transform extracted brine in the GCS process from a costly disposal issue to a potential resource, this study considers brine management as a sequence of options that are characterized by geographic, technological, and economic factors. Some options lower the volume of water that is required for disposal while others provide a positive monetary return to CO_2 sources in certain regions of the US.

In this report, we summarize the background, assumptions, inputs and methods of an innovative approach for looking at the economic and environmental impacts of brine management for GCS. Unlike previous studies, this assessment evaluates a number of treatment and disposal options, beyond RO and reinjection, using regionally specific data. Large variations in land requirements and cost revealed the sensitivity of these metrics to saline aquifer characteristics and geographic location. We determined that brine management is very expensive in the Midwest, Gulf Coast, and Southwest if the volume of brine requiring final disposal cannot be reduced. This is especially true if final disposal sites are over 25 miles away from the GCS project. Feasibility for a brine use sequence (BUS) decreased if stages in the BUS required infrastructure that: was not already in place (such as infrastructure for algae biodiesel markets), required new permits or policies (such as long distance pipeline transportation or the development of a new class of disposal wells). Multiple BUS scenarios could provide revenue to GCS projects in each of the three regions if: the brine had low salinity and regional water demand was high, mineral and salt concentrations in the brine were high and land costs were low, and the brine was extracted at temperatures above 100 °C and onsite demand for heat was substantial. While no disposal or resource option is optimal for the nation, unique sequences of resource and disposal options can be determined for each formation or region of the US using the method developed in this study.

8. FUTURE WORK

Future work will include an analysis environmental impacts and economic risk associated with brine management scenarios. Effects of extracted water on local ecosystems, effects of large quantities of water vapor from evaporation ponds on downwind ecosystems, and the effect of changes in land use will be explored. Metrics that will be incorporated in future studies include global warming potential, acidification potential, eutrophication potential, the use of risk assessment to address human-health and eco-toxicity, cumulative energy demand, and ecological impacts including air emissions of criteria and hazardous air pollutants such as particulate matter (PM), Hg, NO_x, SO_2, and SO_2. Where sufficient information is available, these metrics will be evaluated for the construction and use phases of technologies and infrastructure, and the end of life phase.

In addition, temporal projections will be enhanced to account for changes in markets, technologies, and climate. These additional areas of study will be added into an adaptive modeling framework, intended to identify optimal management scenarios in a streamlined, efficient manner.

The concept of waste-to-resource is likely to be extended to the carbon dioxide itself in CCS future CCS research. A team of scientists at the Lawrence Berkeley National Laboratory, including several of the authors on this report, are already starting to explore local, regional, and national uses for carbon dioxide.

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