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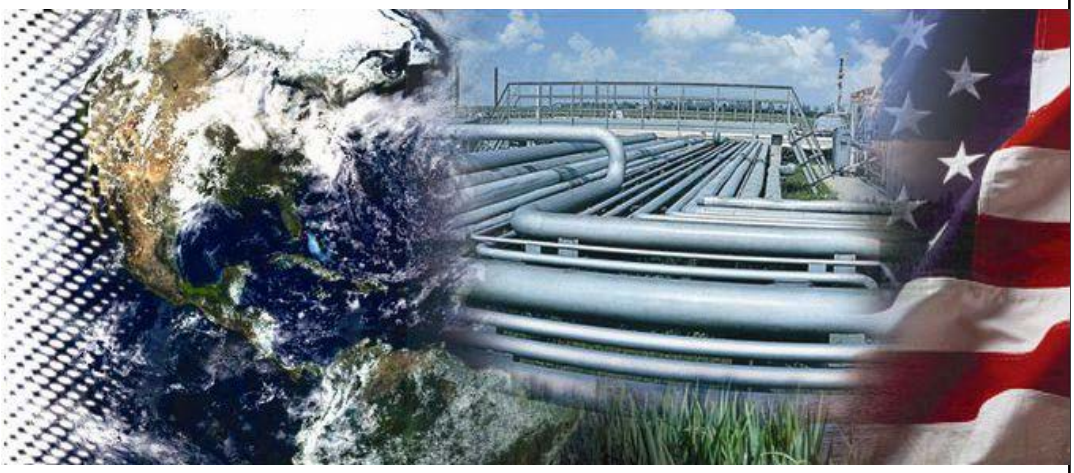

Gate-to-Grave Life Cycle Analysis Model of Saline Aquifer Sequestration of Carbon Dioxide

September 30, 2013

DOE/NETL-2013/1600

U.S. DEPARTMENT OF ENERGY

OFFICE OF FOSSIL ENERGY

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DOE Contract Number DE-FE0004001

Acknowledgments

This report was prepared by Energy Sector Planning and Analysis (ESPA) for the United States Department of Energy (DOE), National Energy Technology Laboratory (NETL). This work was completed under DOE NETL Contract Number DE-FE0004001. This work was performed under ESPA Tasks 150.04 and 150.08.

The authors wish to acknowledge the excellent guidance, contributions, and cooperation of the NETL staff, particularly:

Bruce Brown**,** NETL Subject Matter Expert

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Acronyms and Abbreviations

Btu	British thermal unit
CCS	Carbon capture and sequestration
CCUS	Carbon capture utilization and sequestration
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
GHG	Greenhouse gas
GJ	Gigajoule
GTSC	Gas turbine simple cycle
GWP	Global warming potential
H_2S	Hydrogen sulfide
Hg	Mercury
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kJ	Kilojoule
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
LC	Life cycle
LCA	Life cycle analysis
m	Meter
mg/L	Milligram per liter
MJ	Megajoule
MMBtu	Million Btu
MMcf	Million cubic feet
MPa	Megapascal
MW,MWe	Megawatt electric
N_2	Nitrogen
N_2O	Nitrous oxide
N/A	Not applicable
NO_X	Nitrogen oxides
NETL	National Energy Technology Laboratory
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
O&M	Operating and maintenance
Pb	Lead
PM	Particulate matter
psia	Pounds per square inch, absolute
psig	Pounds per square inch, gauge
RFS2	Renewable Fuel Standard, Version 2
scf	Standard cubic feet
SF_6	Sulfur hexafluoride
SO_2	Sulfur dioxide
TDS	Total dissolved solids
ton	Short ton
tonne	Metric ton
U.S.	United States
USDA	U.S. Department of Agriculture
USDW	Underground sources of drinking water
VOC	Volatile organic compound
WWTP	Wastewater treatment plant

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Executive Summary

Saline aquifers are geological formations that are saturated with brine water. In the United States (U.S.), saline aquifers have a broader geographical distribution than oil and gas reservoirs and have a large capacity potential for long-term carbon dioxide (CO_2) storage. The CO_2 storage capacity of saline aquifers in the U.S. has been estimated from 2.1 to 20 trillion metric tonnes of CO_2 (NETL, 2012a).

A gate-to-grave life cycle analysis (LCA) model was created to quantify the environmental impacts of the various processes associated with saline aquifer sequestration. The following unit processes are accounted for in this analysis:

- Site preparation
- Well construction
- CO_2 sequestration operations
- Site monitoring
- Brine management
- Well closure
- Land use

This analysis used an LCA approach for developing data and modeling saline aquifer sequestration. The energy and material flows for key processes within the gate-to-grave boundaries of the saline aquifer were calculated. These processes were then compiled in a model that scaled the flows between processes to arrive at an inventory of environmental burdens on a common basis (i.e., 1 tonne of CO_2 sequestered).

Most processes in the boundaries of this analysis produce greenhouse gas (GHG) emissions, making GHGs a good metric for understanding the dynamics of each system. However, the model developed for this analysis also includes data for other environmental metrics, including criteria air pollutants and other air emissions of concern, water withdrawal and discharge, water quality, and resource energy consumption.

The results of this analysis are on the basis of a gate-to-grave boundary. CO_2 from an unspecified source enters the boundary and is sequestered in a saline aquifer. The goal of these results is to identify the processes that are key contributors to the GHG emissions of each system and gain an understanding of how the GHG results are affected by changes to key parameters. These results do not encompass full cradle-to-grave boundaries and should be used with care.

The gate-to-grave GHG emissions for saline aquifer sequestration of CO_2 are 14.78 kg CO_2e/tonne CO_2 sequestered, with uncertainty ranging from 4.66 to 25.33 kg CO_2e (an uncertainty of approximately +/- 70 percent). The majority of LC GHG emissions are from CO_2 at 94.2 percent, with the remainder split between methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6) at 5.3 percent, 0.2 percent, and 0.3 percent, respectively. The emissions associated with the electricity for the CO_2 injection pump compose 62.6 percent of the gate-to-grave GHG emissions for saline aquifer sequestration. The next highest contributor to the gate-to-grave GHG emissions is the leakage of sequestered CO_2 from the saline aquifer formation at 33.8 percent. The third highest contributor is from brine injection process at 2.9 percent.

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1 Introduction

Saline aquifers are geological formations that are saturated with brine water. In the United States (U.S.), saline aquifers have a broader geographical distribution than oil and gas reservoirs and have a large capacity potential for long term carbon dioxide (CO_2) storage. The CO_2 storage capacity of saline aquifers in the U.S. has been estimated from 2.1 to 20 trillion metric tonnes of CO_2 (NETL, 2012a).

A gate-to-grave life cycle analysis (LCA) model was created to quantify the environmental impacts of the various processes associated with saline aquifer sequestration.

2 Technology Description

The development and use of a saline aquifer site for CO_2 sequestration includes the following processes:

- Site preparation
- Well construction
- CO_2 sequestration operations
- Site monitoring
- Brine management
- Well closure
- Land use

2.1 Site Preparation

The preparation of a saline aquifer site requires a seismic survey conducted by vibroseis trucks, or specialized explosives, which vibrate the ground and use seismic equipment to measure the geological characteristics of a site. When vibroseis trucks cannot be used, due to complications in terrain or access, specialized explosives are used. This involves the drilling of shot holes, loading the charges and detonation. These trucks consume diesel for transport and equipment operation. The survey of a typical site takes seven 12-hour days (CSLC, 2012).

2.2 Well Construction

The construction and installation of wells includes the drilling of the well bore followed by the installation of a well casing. The well casing provides strength to the well bore and prevents contamination of groundwater that surrounds the well. Eight different well types of varying depths are required for CO_2 sequestration in a saline aquifer: stratigraphic test, injection, reservoir monitoring, above-seal monitoring, groundwater monitoring, vadose zone monitoring, water production, and water disposal. The National Energy Technology Laboratory (NETL) saline aquifer storage cost model contains a representative list of possible storage formations in the U.S (NETL, 2012b). For each formation, the model provides the depth of each well type based on the special characteristics of the formation. This analysis uses the average well depths from the selected list of storage formations for the calculation of drilling and casing requirements.

Vertical drilling is used for the wells required for saline aquifer sequestration. Most drilling rigs use diesel fuel. A diesel-powered drilling rig has a power output of 600 horsepower (EPA, 1995) and a top drilling speed of 17.8 meters per hour (Reum, Dahlem, & Pollock, 2008).

Wells are lined with threaded chromium and molybdenum-alloy casings that are held in place with concrete. For the purposes of the model, each well at a saline aquifer site, with the exception of the groundwater and vadose zone monitoring wells, is assumed to have three concentric casing sections of varying diameters and depths (Meyer, n.d.). The model uses average casing diameters and casing string lengths for calculating the environmental impacts. The top string of casing, known as the conductor casing, is assumed to have a 16-inch diameter casing set in a 26-inch diameter hole to a depth of 40 feet (12.2 m). The next casing section, known as the surface casing, consists of an 8 5/8-inch diameter pipe set in a 12 1/4-inch hole extending from the surface to a depth of 2,167 feet (660.5 m). The final casing section in the series, known as the production casing, consists of a 5 1/2-inch pipe set in a 7 7/8-inch hole extending from the surface down to the depth determined from the NETL saline storage cost model for each well type.

2.3 CO_2 Sequestration Operations

The operation of CO_2 injection site uses electricity to pressurize and inject incoming CO_2 into an underground formation. The electricity requirements of a given injection site are a function of injection pressure and the number of injection wells. Further, the required injection pressure is calculated based on the representative list of possible storage formations provided in the NETL saline aquifer storage cost model (NETL, 2012b). For each formation, the model provides the pressure at the midpoint based on the corresponding geological parameters.

CO_2 arrives by pipeline as a pressurized fluid at a pressure of at least 7.38 MPa (1,070 psia), a required pressure that ensures all CO_2 is in a supercritical state at standard ambient temperatures. To achieve the correct injection pressure, a CO_2 injection pump must overcome the pressure drop that occurs in the injection well, between the surface and the aquifer (McCollum & Ogden, 2006). The boosting of supercritical CO_2 from its critical point to the required injection pressure is provided by electrically-powered injection pumps. Fugitive emissions of CO_2 escape through pump seals during the operation of CO_2 injection pumps.

In addition to the fugitive CO_2 emissions from the injection pump, this analysis also assumes leakage of CO_2 from the underground storage formation. It is assumed that a maximum of one percent of the stored CO_2 eventually migrates to the surface and is released to the atmosphere over a 100-year monitoring period. (This conservative assumption is consistent with other NETL reports on CCS and is used to bracket the current range of potential loss until measurement data from operating storage sites can validate this loss factor.) The expected parameter value for the model (0.5 percent) was selected as the midpoint between the maximum leakage rate of 1 percent and no leakage from the formation.

Brine water production from the saline aquifer is one method to control the pressure in the underground formation, but it is not always required (ANL, 2011). Extraction of water from the aquifer storage formation occurs at a safe distance from the injection wells to prevent migration of CO_2 to the surface with the produced brine.

2.4 Site Monitoring

With respect to site monitoring, this LCA model accounts for the construction of monitoring wells and seismic testing during site operations. Other types of monitoring activities are a negligible

contribution to the environmental burdens of a saline aquifer storage site. This conclusion is supported by a detailed list of capital and operating and maintenance (O&M) costs developed by NETL in support of its CO_2 transport and storage cost model (NETL, 2012b), which shows that constructing wells and conducting seismic surveys accounts for over 90 percent of lifetime capital and operating costs. This is further supported by the Environmental Protection Agency's (EPA) analysis of the costs of geologic CO_2 sequestration, which concludes that the drilling of monitoring wells accounts for the majority of site monitoring costs (EPA, 2010). Seismic monitoring during the operation phase of the aquifer is modeled in the same way as for site preparation.

2.5 Brine Management

The management of brine at a saline aquifer site consumes electricity, which is used by water treatment processes and/or injection pumps. Two water treatment technologies were used in this analysis: reverse osmosis and vapor compression distillation. The choice between these technologies depends on the concentration of total dissolved solids (TDS) in the brine. Brine water quality is highly variable among saline aquifer injection sites, with TDS levels ranging from 10,000 to over 300,000 mg/L (ANL, 2011). Reverse osmosis is effective at handling water with a TDS of less than 50,000 mg/L, while distillation is effective at higher TDS concentrations (CSM, 2009). The concentrated waste stream produced from water treatment can either be re-injected into a suitable formation or transported offsite for additional processing.

Instead of treating the produced brine water at the surface, it may be desirable to instead re-inject the stream into a suitable underground formation near the production site. This practice is common in the oil and gas industry for onshore wells (ANL, 2011). The key operating requirement for re-injection is the electricity used by injection pumps. Injection pumps are sized to overcome the head losses in a water injection well.

2.6 Well Closure

The purpose for plugging wells prior to abandonment is to ensure that the abandoned wells do not allow the injected fluids (in this case, CO_2) or natural brines to migrate up the well bore and into underground sources of drinking water (USDW) (EPA, 1994). The EPA provides guidance on plugging and abandoning wells of various types but has yet to provide specific guidance for wells that would be used for CO_2 sequestration, which are defined as Class VI wells (EPA, n.d.). This analysis uses the EPA guidance for Class II wells, defined as wells that inject fluids that are brought to the surface in connection with conventional oil or natural gas production, are used for enhanced recovery of oil or natural gas, or are used for storage of hydrocarbons (EPA, 1994). Class II guidance is a good approximation since the well depth, usage, and pressure would be similar to Class VI wells. The EPA guidance (EPA, 1994) also includes options for how to implement the bottommost plug in Class II wells, which significantly changes the amount of concrete used. Both methods, either cast iron bridge plug or the use of a cement retainer (also made out of cast iron), are accounted for in this analysis. Additionally, the shallow vadose zone and ground water monitoring wells are assumed to be plugged entirely with concrete.

2.7 Land Use

Land use effects can be roughly divided into direct and indirect. Direct land use change is determined by tracking the change from an existing land use type (native vegetation or agricultural lands) to a new land use that supports production (i.e., the production required for the supply chain of an LCA). Indirect land use effects are changes in land use that occur as a result of the direct land use effects.

For instance, if the direct effect is the conversion of agricultural land to land used for energy production, an indirect effect might be the conversion to new farmland of native vegetation, but at a remote location, in order to meet ongoing food supply/demand.

This analysis uses data that accounts for changes in greenhouse gas (GHG) emissions when alternating among forest, grassland, and agricultural land types. The data are based on research conducted by Winrock International in support of EPA's Renewable Fuels Standard, Version 2 (RFS2) final rule (Harris, Grimland, & Brown, 2009). The values for direct land use GHG emissions account for changes in above-ground biomass stocks, lost forest-carbon sequestration, and soil-carbon flux. The Winrock data account for changes in GHG emissions over an 80-year period. The time frames within this 80-year period include the impulse of emissions in Year 0, steady-state emissions during Years 1 through 19, and steady-state emissions in Years 20-80. NETL's LCA analyses of energy systems are usually on a 30-year time frame, so this analysis calculates a 30-year direct land use GHG emission factor by assembling the Winrock data over a 30-year time frame.

The Winrock data include a set of factors for non-reversion and reversion cases. This model applies the factors for non-reversion. Non-reversion means that the land does not revert back to its original use after the built facility has been completed.

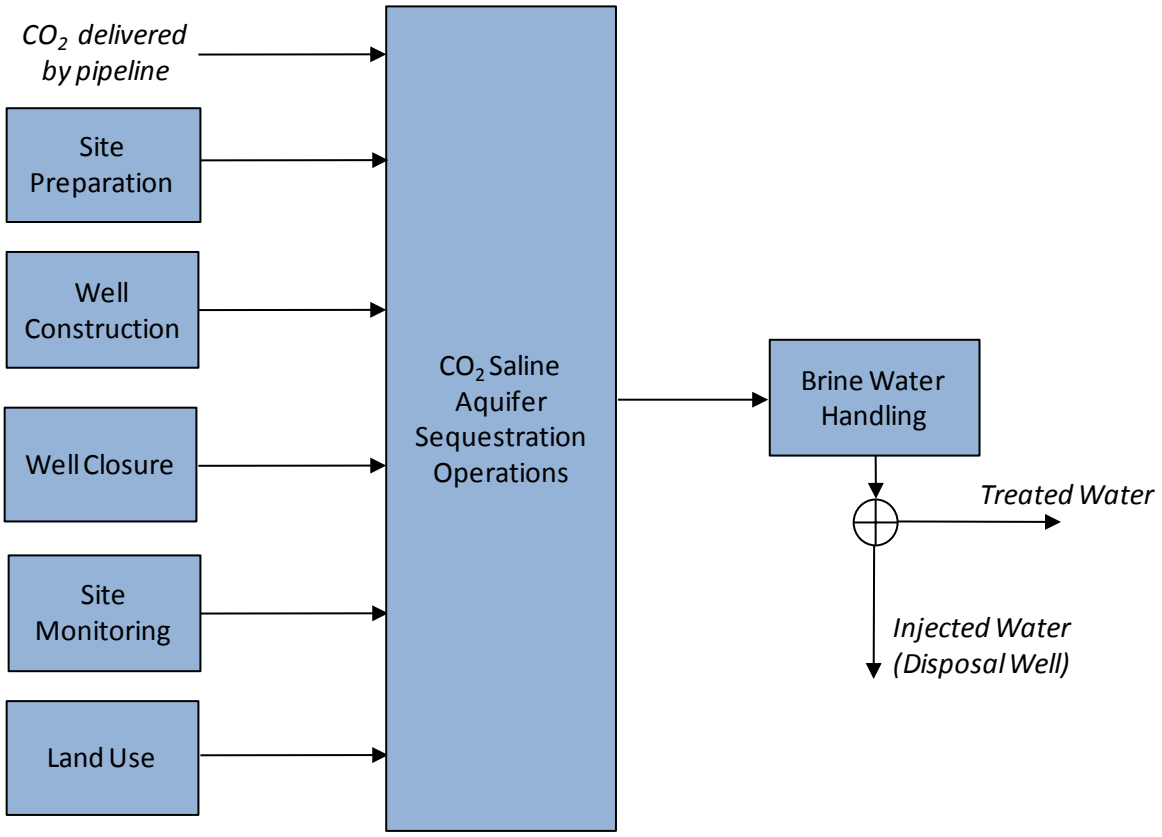
The land use modeling also includes factors for the land use profile at a state level. This model assumes that the sequestration activities are located in the Permian basin, so the land use GHG emissions are based on an equal mix of the land profiles in five states: Colorado, New Mexico, Oklahoma, Texas, and Wyoming. The land use profile accounts for the percent shares of forest, grassland, and crops and allows determination of the previous land use type (Lubowski, Vesterby, Bucholtz, Baez, & Roberts, 2006). It was assumed that it is unlikely for a saline aquifer sequestration facility to be built on agricultural land; thus, the percent share of crop land was set to zero, and the other land types (forest and grassland) were rescaled accordingly. This model references the amount of land use area for indirect land use change based on the amount of agricultural (crop) land that undergoes direct land use change. For every unit of agricultural land that undergoes direct change, the same area of indirect land change occurs elsewhere. Based on the assumption that no agricultural lands were converted, no indirect land use change occurred.

There are a total of 47 wells required for the modeled saline aquifer. Each well has an approximate footprint of 0.25 acres (NETL, 2012c). The water treatment facility was assumed to have a footprint of 6,400 m^2, and the CO_2 injection equipment was assumed to require 400 m^2. In addition, this analysis also estimated the land use for access roads to the wells. The required road area was estimated by assuming that the wells are laid out in a square grid, with equal spacing. Based on the grid formation with four road connections at each well, the total land area for access roads was determined to be 443,500 m^2. The total footprint for the saline aquifer sequestration site modeled in this analysis was 497,800 m^2.

3 Modeling Approach

The unit processes in the saline aquifer model include key preparation, construction, operation, and monitoring processes, as shown in **Figure 3-1**. **Appendix A** provides links to each of the individual unit processes included in the model, as well as a roadmap for connecting those processes.

Figure 3-1: Unit Process Flows for Saline Aquifer CO_2 Sequestration



The only input to the saline aquifer model is CO_2 delivered by a pipeline, and the only output is treated water exiting the brine water treatment process. Brine water that is injected in a disposal well does not exit the system boundaries, but brine water that has gone through treatment is a product of the saline aquifer system. The temporal period of this study is 100 years since it is an end-of-life analysis. Note that this is different from the conventional 30 year time period used is other NETL LCAs.

3.1 Data Sources

The data sources for the saline aquifer model are a mix of government reports, industry-specific literature, and previous reports completed by NETL.

- Data for site preparation are based on seismic monitoring conducted on a saline aquifer site, in California (CSLC, 2012).
- Data for well construction are based on depths contained in NETL's saline aquifer storage cost model (NETL, 2012b) applied to energy consumption data for drilling equipment

provided by an industry source (Reum, et al., 2008) and EPA emission factors for diesel combustion (EPA, 1995).

- Data for site closure are based on EPA guidance for well plugging and abandonment (EPA, 1994).
- Data for saline aquifer sequestration operations are based on compressor operating characteristics developed by the University of California at Davis (McCollum & Ogden, 2006) and brine water data compiled by Argonne National Laboratory (ANL, 2011). The required injection pressure was determined based on NETL's saline aquifer storage cost model (NETL, 2012b). It is assumed that a maximum of one percent of the stored CO_2 eventually migrates to the surface and is released to the atmosphere over a 100-year monitoring period. (This conservative assumption is consistent with other NETL reports on CCS and is used to bracket the current range of potential loss until measurement data from operating storage sites can validate this loss factor.) The expected parameter value for the model (0.5 percent) was selected as the midpoint between the maximum leakage rate of 1 percent and no leakage from the formation.
- Data for brine water management, which includes treatment and disposal options, is based on data for the volumes and quality of brine water compiled by Argonne National Laboratory (ANL, 2011). Utility requirements for the reverse osmosis and vapor compression distillation water treatment technologies are based on data from the Colorado School of Mines

3.2 Co-Product Management

None of the unit processes in the modeling network for saline aquifer CO_2 sequestration have two or more products. However, in addition to the functional unit of sequestered CO_2, treated water produced by the brine management process does leave the system boundary.

System expansion was used to manage the co-products of saline aquifer CO_2 sequestration, in which the treated water is assumed to displace treated water from another source. For example, every liter of water produced by the saline aquifer system reduces the throughput of a nearby municipal drinking water plant by one liter. As with many instances of system expansion, the assumptions about displaced products are highly uncertain.

3.3 Parameters

All unit processes used for modeling saline aquifer sequestration have adjustable parameters. Key parameters are shown in **Table 3-1**. These parameters improve the flexibility of the model and allow changes to the following properties:

- **Fuel Use Rates:** Some processes combust diesel for energy generation. The saline aquifer model has parameters that allow changes to consumption rates of these fuels. For example, the diesel-consumption rates can be varied for seismic-surveying trucks and well-drilling rigs.
- **Combustion Emission Factors:** The combustion of diesel for powering site preparation and construction equipment produces air emissions. These emissions are calculated using emission factors for diesel combustion. The total emissions from fuel combustion are the product of the fuel use rate and the combustion emission factors. While these combustion emission factors are adjustable, they do not have a high degree of variability. Unless EPA

updates the emission factors for diesel combustion, it is not necessary to adjust these parameters.

- **Non-Combustion Emission Factors:** Some processes release air emissions through leaks in equipment (fugitive emissions) or intentional venting. These emissions are described by adjustable parameters for non-combustion emission factors. For example, the operation of a CO_2 compressor releases fugitive emissions of CO_2, which escape through compressor seals and valves.
- **Electricity Consumption:** The unit processes for saline aquifer sequestration include adjustable parameters for the electricity requirements of pumps and compressors. It is not necessary to adjust these parameters, unless one wants to test the sensitivity of results to changes in electricity requirements. The electricity requirements of pumps and compressors are based on rigorous engineering calculations that accounted for the physical properties of CO_2, temperatures and pressures of inlet and outlet streams, and equipment efficiency. Brine water treatment is another saline aquifer sequestration process that requires electricity; the unit process for brine water management includes adjustable parameters for the power requirements of reverse osmosis and distillation water treatment.
- **Saline Aquifer Operations:** The operation of the saline aquifer sequestration site includes options for brine water management (reverse osmosis vs. distillation), the rate of brine water extracted per unit of CO_2 injected, the number of years that CO_2 is injected into the formation, and the leak rate of CO_2 from the formation. The parameters for saline aquifer CO_2 injection operations allow changes to these variables.

Table 3-1: Parameters for Saline Aquifer Sequestration

Parameter Name	Low	Expected	High	Units	Description
Site Preparation/Monitoring					
Seismic truck fuel efficiency	N/A	1.08E-02	N/A	km/liter	Vibroseis truck (diesel engine) seismic survey average fuel consumption
Number of trucks	N/A	4	N/A	dimensionless	Number of vibroseis trucks needed for seismic survey
Survey Area	N/A	2.89E+01	N/A	square miles	Surface area of the CO_2 plume in the formation
Well Construction/Closure					
Drill speed	1.42E+01	1.78E+01	2.13E+01	m/h	Drilling rate
Drill power	N/A	4.47E-01	N/A	MW	Power of drilling equipment in brake specific power
Diesel rate	N/A	2.21E+02	N/A	MWh	Use rate of diesel; kg of diesel combusted per MWh of brake specific drilling energy
Emission factor for NO_X	N/A	1.46E+01	N/A	kg/MWh	NOx emissions per MWh of brake specific drilling energy
Emission factor for CO	N/A	3.35E+00	N/A	kg/MWh	CO emissions per MWh of brake specific drilling energy
Emission factor for SO_2	N/A	7.38E-03	N/A	kg/MWh	SO_2 emissions per MWh of brake specific drilling energy

Parameter Name	Low	Expected	High	Units	Description
Emission factor for CO_2	N/A	7.06E+02	N/A	kg/MWh	CO_2 emissions per MWh of brake specific drilling energy
Emission factor for PM	N/A	4.26E-01	N/A	kg/MWh	PM emissions per MWh of brake specific drilling energy
Emission factor for CH_4	N/A	3.86E-02	N/A	kg/MWh	CH_4 emissions per MWh of brake specific drilling energy
Emission factor for VOC	N/A	3.90E-01	N/A	kg/MWh	VOC emissions per MWh of brake specific drilling energy
Total conductor and surface casing steel	N/A	2.48E+04	N/A	kg/well	Total weight of carbon steel well conductor and surface casing, not applicable to groundwater and vadose zone wells
Total conductor and surface casing concrete	N/A	5.13E+04	N/A	kg/well	Total weight of concrete well conductor and surface casing, not applicable to groundwater and vadose zone wells
Linear density of production casing - steel	N/A	2.08E+01	N/A	kg/m	Linear density of production casing - carbon steel
Linear density of production casing - concrete	N/A	3.06E+01	N/A	kg/m	Linear density of production casing - concrete
Above-seal monitoring well	N/A	2.36E+03	N/A	m	Well depth
Groundwater monitoring well	N/A	1.52E+02	N/A	m	Well depth
Injection well	N/A	2.52E+03	N/A	m	Well depth
In-reservoir monitoring well	N/A	2.42E+03	N/A	m	Well depth
Stratographic test well	N/A	2.62E+03	N/A	m	Well depth
Vadose zone monitoring well	N/A	1.22E+01	N/A	m	Well depth
Water disposal well	N/A	2.52E+03	N/A	m	Well depth
Water production well	N/A	2.52E+03	N/A	m	Well depth
CO_2 Injection Operations					
Brine production	1.3	1.4	1.5	kg/kg	Amount of brine produced from saline aquifer per kg of CO_2 injected
CO_2 mass flow	N/A	1.00E+04	N/A	tonne/day	Flow rate of CO_2 through compressor
Formation leakage[1]	0.0%	0.5%	1.0%	%	Percentage of sequestered CO_2 that leaks from the saline aquifer over 100 years

[1]It is assumed that a maximum of one percent of the stored CO_2 eventually migrates to the surface and is released to the atmosphere over a 100-year monitoring period. (This conservative assumption is consistent with other NETL reports on CCS and is used to bracket the current range of potential loss until measurement data from operating storage sites can validate this loss factor.) The expected parameter value for the model (0.5 percent) was selected as the midpoint between the maximum leakage rate of 1 percent and no leakage.

Parameter Name	Low	Expected	High	Units	Description
Injection pump seal leakage factor	N/A	6.36E+01	N/A	kg/MW-day	Emission factor for CO_2 released to air from injection pump
Injection pump power	2.47E-04	5.33E-04	7.70E-04	MW/tonne CO_2/day	Pumping power requirements per unit injected per day
Injection pressure	2,090	3,780	5,180	psia	Hydrostatic Pressure at Midpoint of Saline Aquifer Formation
Injection wells	N/A	2	N/A	wells	Number of injection wells for the formation
Injection years	N/A	100	N/A	years	Number of years of CO_2 injection into the saline aquifer sequestration site
Brine Handling					
Brine total dissolved solids	4.00E+04	4.00E+04	6.00E+04	mg/L	Total dissolved solids content in the brine that is produced
Distillation power	1.41E-03	1.41E-03	1.41E-03	kWh/kg	Power requirements for distillation treatment per kg of brine influent
Brine injection pump power	4.30E-04	4.30E-04	4.30E-04	kWh/kg	Power requirements for water injection pump per kg of water injected
Reverse osmosis power	7.16E-04	7.16E-04	7.16E-04	kWh/kg	Power requirements for reverse osmosis treatment per kg of brine influent
Treatment scenario	1	0	1	dimensionless	0 = reinjection; 1 = on-site treatment
Electricity Grid	**U.S. Grid Mix**	**ERCOT Mix**	**GTSC**		
Coal	45.87%	33.03%	0.00%	%	Percentage of power from coal
Geothermal	0.38%	0.00%	0.00%	%	Percentage of power from geothermal
Gas turbine simple cycle (GTSC)	0.00%	0.00%	100.00%	%	Percentage of power from natural gas simple cycle turbine
Hydro	7.30%	0.16%	0.00%	%	Percentage of power from hydropower
Natural gas	22.65%	47.90%	0.00%	%	Percentage of power from natural gas
Nuclear	20.43%	12.31%	0.00%	%	Percentage of power from nuclear
Petroleum	0.95%	1.05%	0.00%	%	Percentage of power from petroleum
Solar	0.03%	0.00%	0.00%	%	Percentage of power from solar
Wind	2.39%	5.54%	0.00%	%	Percentage of power from wind

3.4 Data Limitations

The data used in this analysis are compiled from publicly-available sources that represent the temporal, geographical, and technical properties of saline aquifer sequestration of CO_2. The life cycle model for sequestration of CO_2 in a saline formation has the following data limitations:

- This analysis assumes that a maximum of one percent of the stored CO_2 eventually migrates to the surface and is released to the atmosphere over a 100-year monitoring period. This conservative assumption is consistent with other NETL reports on CCS and is used to bracket the current range of potential loss until measurement data from operating storage sites can

validate this loss factor. The expected parameter value for the model (0.5 percent) was selected as the midpoint between the maximum leakage rate of 1 percent and no leakage from the formation.

- The electricity requirements of a given injection site are a function of injection pressure and the number of injection wells. Further, the required injection pressure was calculated based on the representative list of possible storage formations provided in the NETL saline aquifer storage cost model (NETL, 2012b). For each formation, the model provides the pressure at the midpoint based on the corresponding geological parameters. Without an operating facility, it is not possible to determine the actual injection loads that are required. Thus, estimates have been made based on the geologic information from potential sequestration sites.
- Brine water production from the saline aquifer is one method to control the pressure in the underground formation, but it is not always required (ANL, 2011). If brine is produced, it may be re-injected into a suitable underground formation for disposal, as is common in the oil and gas industries, or treated to produce potable water (ANL, 2011). The choice of treatment technology depends on the concentration of TDS in the brine. Brine water quality is highly variable among saline aquifer injection sites, with TDS levels ranging from 10,000 to over 300,000 mg/L (ANL, 2011). The brine water management scenario is ultimately dependent on the location and geology of the sequestration site.

In this model the data limitations listed above have been captured in the uncertainty bounds on the expected result. The ranges for the corresponding parameter values are indicated in **Table 3-1**.

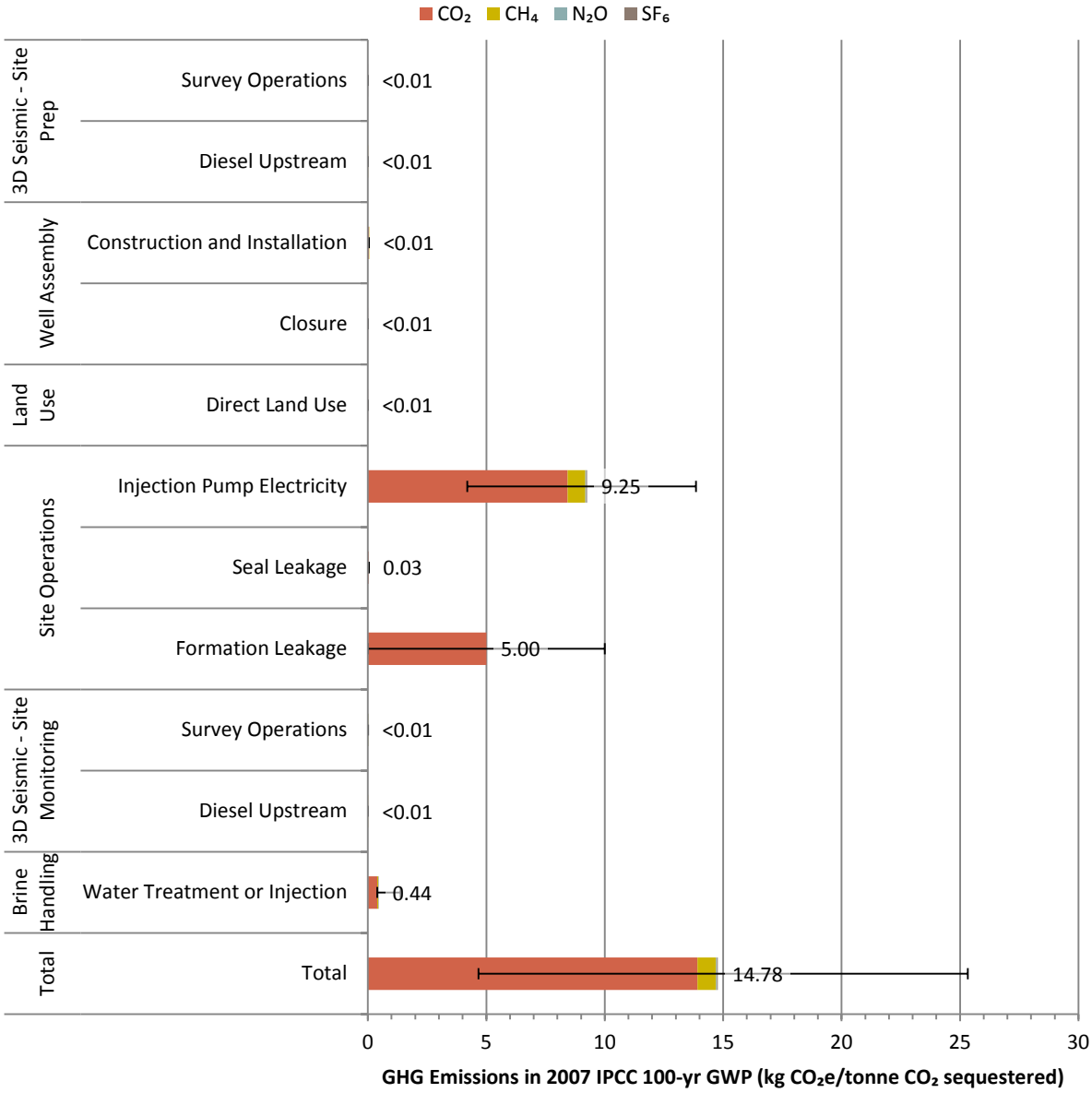
4 Gate-to-Grave Results

The following results focus on the GHG emissions from saline aquifer sequestration of CO_2. The goal of these results was to identify the processes that were key contributors to the GHG emissions of each system and gain an understanding of how the GHG results were affected by changes to key parameters. These results do not encompass full cradle-to-grave boundaries and should be used with care.

Most processes in the boundaries of this analysis produce GHG emissions, making GHGs a good metric for understanding the dynamics of the system. However, NETL also accounts for other environmental metrics, including criteria air pollutants and other air emissions of concern, water withdrawal and discharge, water quality, and resource energy consumption. The inventory results for the full list of NETL's LCA metrics are provided in **Appendix B**.

By expanding the underlying data in the LCA model, a better understanding of the key contributions to gate-to-grave sequestration emissions can be achieved. **Figure 4-1** shows the GHG contribution of specific construction and operations activities for a tonne of sequestered CO_2. Life cycle results on the basis of one tonne of CO_2 received are also available in **Appendix B**. This figure further indicates the contribution of methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6) to the total GHGs. All values are expressed in kg of CO_2 equivalents (CO_2e) per tonne of CO_2 sequestered. The CO_2e values are calculated from the GHG inventory results using 100-year global warming potentials (GWP) of 298 for N_2O, 25 for CH_4, and 22,800 for CH_4 (Forster et al., 2007).

Figure 4-1: Detailed Greenhouse Gas Emissions for Saline Aquifer Sequestration



The gate-to-grave GHG emissions for saline aquifer sequestration of CO_2 are 14.78 kg CO_2e/tonne CO_2 sequestered, with uncertainty ranging from 4.66 to 25.33 kg CO_2e (an uncertainty of approximately +/- 70 percent). The majority of LC GHG emissions are from CO_2 at 94.2 percent, with the remainder split between CH_4, N_2O, and SF_6 at 5.3 percent, 0.2 percent, and 0.3 percent, respectively.

As shown by **Figure 4-1**, emissions associated with the electricity for the CO_2 injection pump compose 62.6 percent of the gate-to-grave GHG emissions for saline aquifer sequestration. The next highest contributor to the gate-to-grave GHG emissions is the leakage of sequestered CO_2 from the saline aquifer formation at 33.8 percent. Note that the lower bound of the uncertainty bars for formation leakage is at 0, representing a scenario in which there is no leakage from the formation. The third highest contributor is the water treatment/injection process at 2.9 percent. The expected

value is based on reinjection of produced brine water into a disposal well, while the low and high are based on reverse osmosis and vapor compression distillation treatment of the brine to produce potable water. The produced water co-product is managed via displacement of conventional sources for producing potable water.

The uncertainty in the CO_2 injection pump electricity requirement bar in **Figure 4-1** is a combination of uncertainty in the power demand for the pump to achieve the required injection pressure and the makeup of the electricity grid from which the pump draws. The power demand of the pump is a function of the formation depth and geology, both of which set the required injection pressure. The uncertainty on the injection pump electricity bar also accounts for differences in the source of electricity to power the pump. For this study, ERCOT is defined as the expected electricity grid mix, the 2010 U.S. consumption mix is the low value, and 100 percent GTSC-generated electricity is the high value. The remaining processes in the model (well construction, well closure, site monitoring, site preparation, and land use) account for only 0.4 percent of the gate-to-grave GHG emissions. The majority of CH_4 emissions shown in **Figure 4-1** are from power generation.

This analysis uses a parameterized modeling approach that allows the alteration and subsequent analysis of key variables. Doing so allows the identification of variables that have the greatest effect on results. Sensitivity results are shown in **Figure 4-2** and **Figure 4-3**. In **Figure 4-2**, the percentages shown on the horizontal axes are relative to a unit change in parameter value; all parameters are changed by the same percentage, allowing comparison of the magnitude of change to the result across all parameters. Positive results indicate that an increase in the parameter leads to an increase in the result. A negative value indicates an inverse relationship; an increase in the parameter would lead to a decrease in the overall result. Based on the boundaries of this gate-to-grave system, a 100-percent increase in the CO_2 injection pump power consumptions causes a 62.8-percent increase in total GHG emissions. Similarly, a 100-percent increase in the leakage rate of CO_2 from the formation would result in a 33.8-percent increase in GHG emissions. The GHG results are also sensitive to the injection period, the brine injection pump power demand, and the amount of brine produced per unit of CO_2 sequestered. The parameters related to well construction and closure, site preparation, and site monitoring yield very little impact on the gate-to-grave GHG emissions upon a unit change.

Figure 4-2 is based on the re-injection scenario for brine disposal. For the brine treatment scenarios, the gate-to-grave GHG emissions are slightly more sensitive to the corresponding treatment electricity requirements than for the power requirements for the brine injection pump (4.9 percent for reverse osmosis and 9.1 percent for distillation). As illustrated by **Figure 4-2**, two of the four most sensitive parameters are linked to electrical power demands for a process (CO_2 and brine injection pumping). Thus, the GHG emissions associated with those activities is directly related to the composition of the electricity grid.

Figure 4-3 presents results based on the uncertainty in parameter values as provided in **Table 3-1**. In this system, the majority of uncertainty is driven by required injection pressure and formation leakage, with a smaller amount of uncertainty added based on the composition of the electricity grid and the brine production rate from the aquifer.

Figure 4-2: Sensitivity of Gate-to-Grave GHG Emissions to Parameter Changes

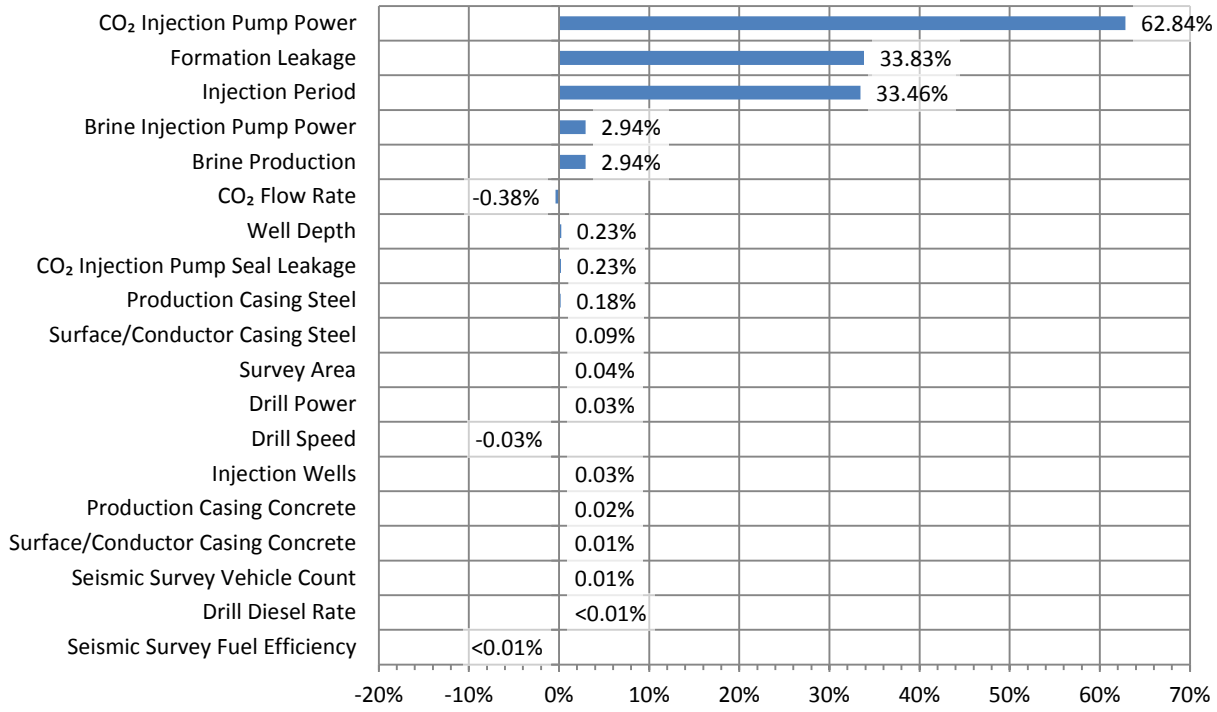
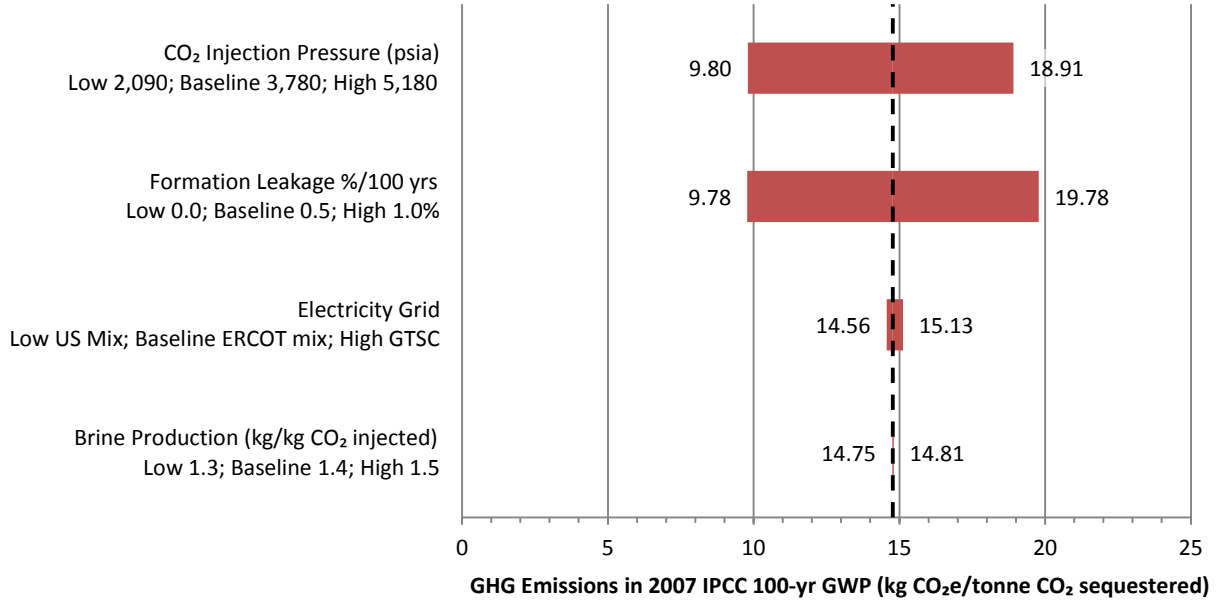


Figure 4-3: Sensitivity of Gate-to-Grave GHG Emissions to Parameter Uncertainty



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Appendix A:
Unit Process Mapping for Saline Aquifer Sequestration of Carbon Dioxide

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A.1 Model Overview

This model was created using unit processes developed by NETL and modeled in the GaBi 6.0 LCA modeling software package. All of the unit processes utilized to create this model are publicly available on the NETL website, with the exception of those noted explicitly below, which are available from PE International. The saline aquifer sequestration model can be re-created utilizing the GaBi 6.0 software or by utilizing a spreadsheet to perform the scaling calculations between the individual unit processes. The parameter values that were utilized to generate the low, expected, and high gate-to-grave values for saline aquifer sequestration are available in **Table 3-1** in the main body of the report.

A.2 Model Connectivity and Unit Process Links

The structure of LCA models in GaBi uses a tiered approach, which means that there are different groups of processes, known as plans, which are combined to create the model. To aid in the connectivity of various plans used in this model, the following naming convention will be utilized in the figure headings throughout the remainder of this section. The main plan will be referred to as the top-level plan, and all subsequent plans will be referred to as second-, third-, etc. level plans. An example of this tiered-nature of the model structure is shown in **Figure A-1**.

Figure A-1: Tiered Modeling Approach

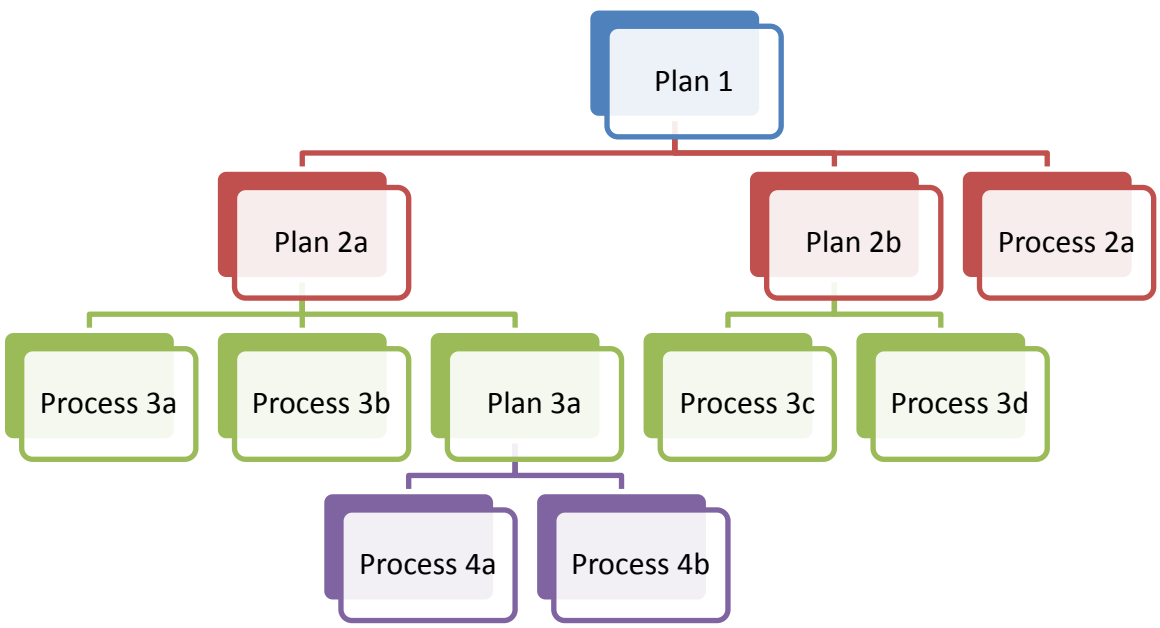

Table A-1 demonstrates the relationships between the tiers of plans used in the development of the model. The tables and figures in the remainder of the appendix illustrate the connectivity of the various processes and plans.

Table A-1: Parent/Child Plan Connections for Saline Aquifer Sequestration Model

Figure	Plan Name	Parent Plans	Child Plans
A-2	Saline Aquifer Sequestration	None	1 - Saline Aquifer Well Assembly 2 - 3D Seismic Site Prep 3 - U.S. Electricity Grid Mix 4 - 3D Seismic Site Monitoring 5 - Saline Aquifer Land Use 6 - Brine Water Management
A-3	Saline Aquifer Well Assembly	Saline Aquifer Sequestration	1 - Well Construction and Installation 2 - Well Closure
A-4	Well Construction and Installation	Saline Aquifer Well Assembly	None
A-5	Well Closure	Saline Aquifer Well Assembly	None
A-6	3D Seismic Site Prep	Saline Aquifer Sequestration	None
A-7	3D Seismic Site Monitoring	Saline Aquifer Sequestration	None
A-8	Saline Aquifer Land Use	Saline Aquifer Sequestration	None
A-9	Brine Water Management	Saline Aquifer Sequestration	None

Figure A-2: Saline Aquifer Sequestration – Top-Level Plan

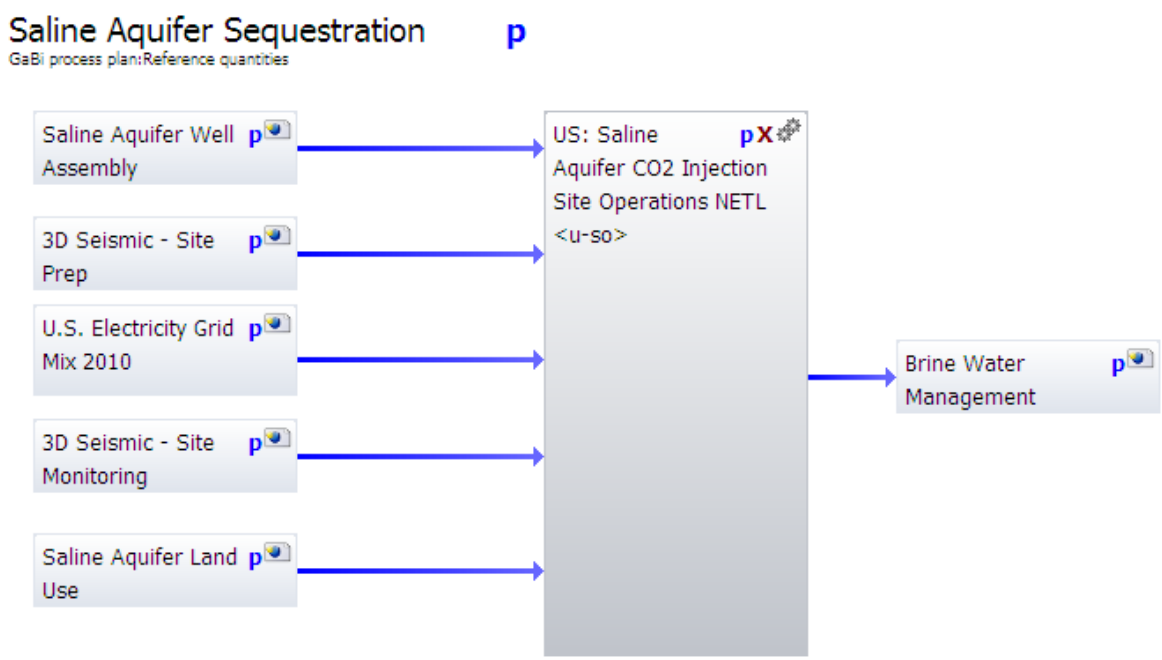

Table A-2: Unit Processes in Saline Aquifer Sequestration Plan

Unit Process	Notes	Version	Creation Date
U.S. Electricity Grid Mix 2010	This unit process includes the full life cycle results from fuel acquisition through combustion and T&D of electricity.	1	N/A
Saline Aquifer CO_2 Injection Site Operations	This unit process models the injection operations and sequestration of CO_2 in a saline aquifer formation.	1	9/2012

Figure A-3: Saline Aquifer Well Assembly – Second-Level Plan

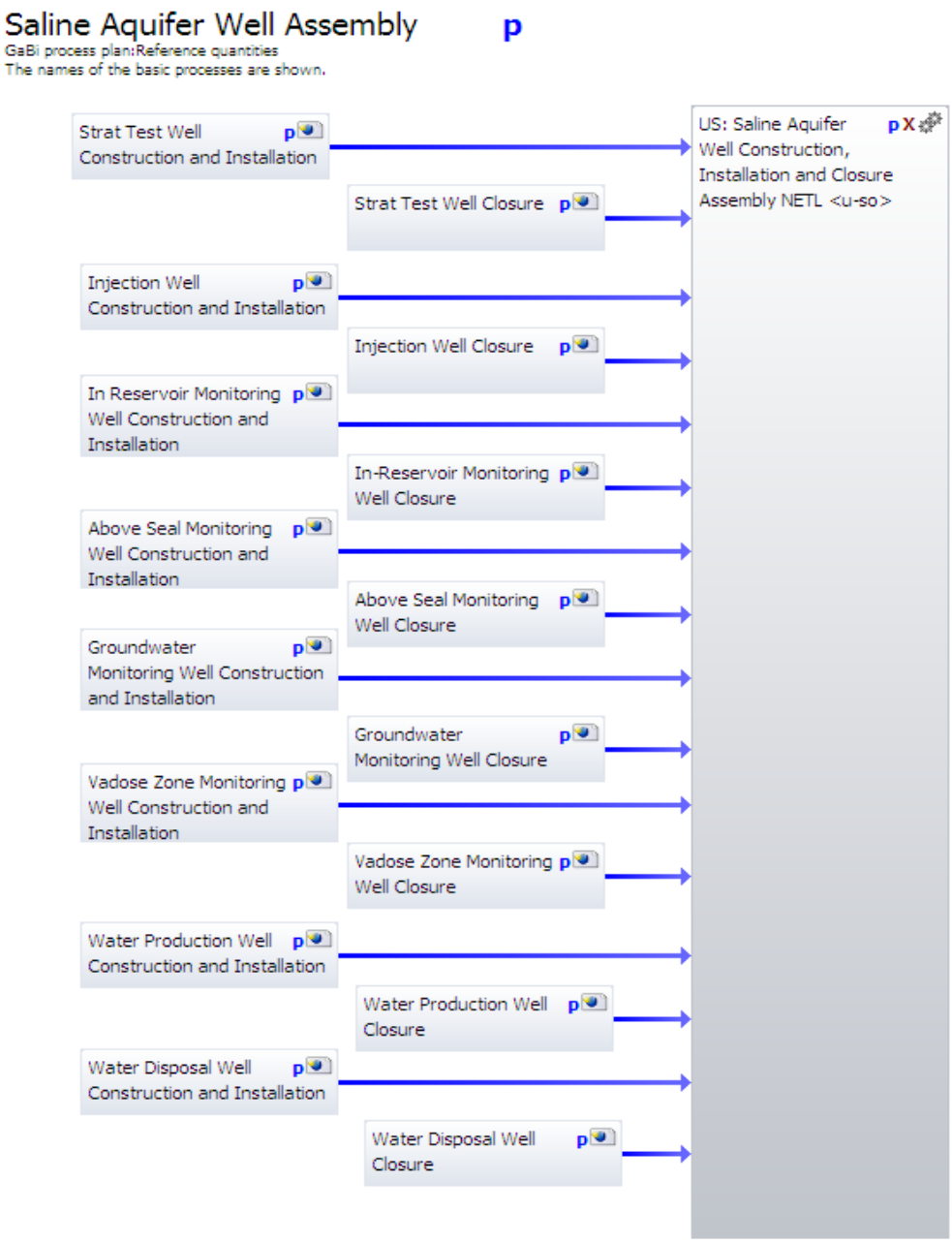

Table A-3: Unit Processes in Saline Aquifer Well Assembly Plan

Unit Process	Notes	Version	Creation Date
Saline Aquifer Well Construction, Installation, and Closure Assembly	This unit process models the assembly of the different well types required for a saline aquifer being used for CO_2 sequestration. The parameters pull the correct number of each well type required for the site.	1	8/2012

Figure A-4: Saline Aquifer Well Construction and Installation – Third-Level Plan

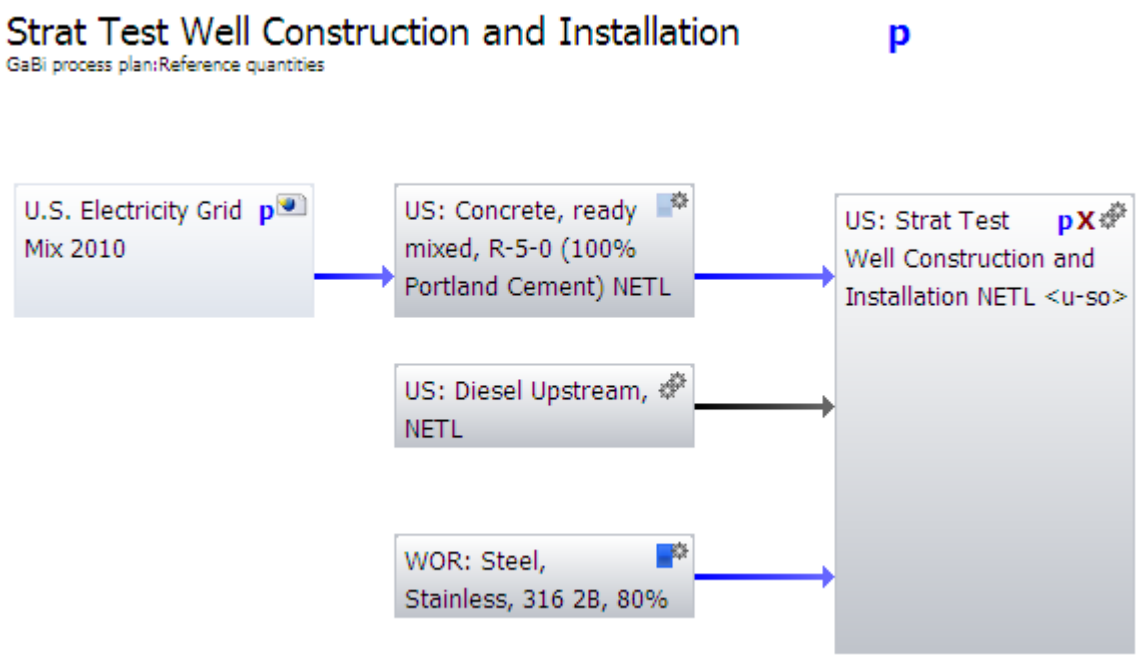

Table A-4: Unit Processes in Well Construction and Installation Plan

Unit Process	Notes	Version	Creation Date
U.S. Electricity Grid Mix 2010	This unit process includes the full life cycle results from fuel acquisition through combustion and T&D of electricity.	1	N/A
Concrete	This unit process includes the production of ready-mix concrete including direct emissions and energy input.	1	N/A
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
316 Stainless Steel	This unit process includes the production of 316 stainless steel including direct emissions and energy inputs.	1	N/A
Well Construction and Installation	This unit process pulls the appropriate amounts of construction materials and energy required for the construction and installation of a given well type for the saline aquifer site. There are eight well types used in the model as depicted in **Figure A-2**. This unit process holds the parameter values for all well types and can be duplicated to create all of the well construction and installation plans.	1	8/2012

Figure A-5: Saline Aquifer Well Closure – Third-Level Plan

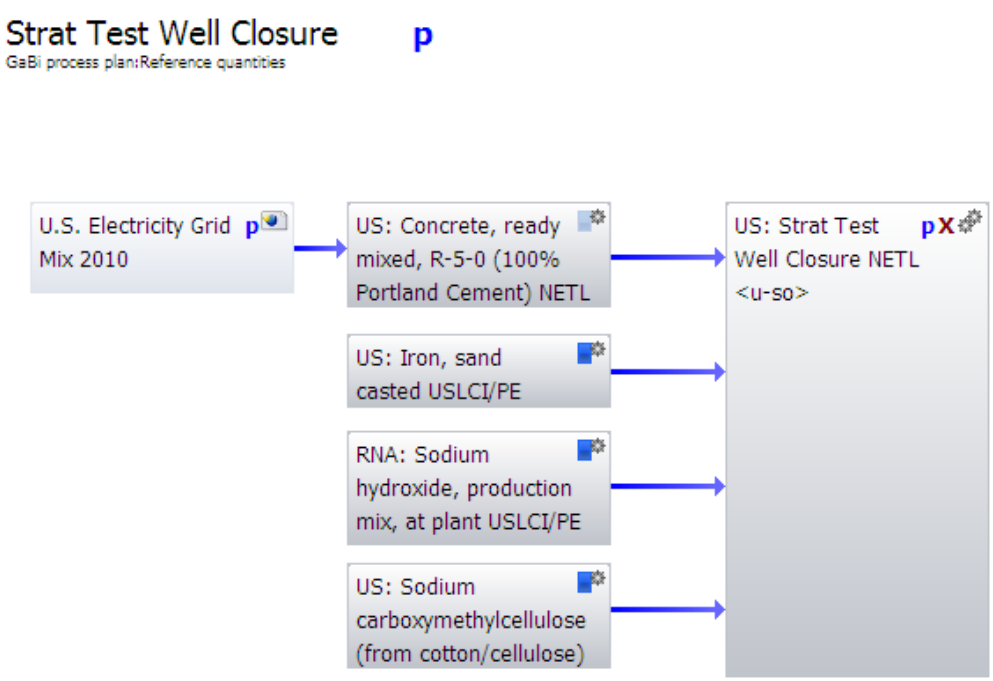

Table A-5: Unit Processes in Well Closure Plan

Unit Process	Notes	Version	Creation Date
U.S. Electricity Grid Mix 2010	This unit process includes the full life cycle results from fuel acquisition through combustion and T&D of electricity.	1	N/A
Concrete	This unit process includes the production of ready-mix concrete including direct emissions and energy input.	1	N/A
Iron, Sand Casted	Third-party data available from PE International	N/A	N/A
Sodium Hydroxide	Third-party data available from PE International	N/A	N/A
Sodium Carboxymethylcellulose	Third-party data available from PE International	N/A	N/A
Well Closure	This unit process pulls the appropriate amounts of construction materials required for the closure of a given well type for the saline aquifer site. There are eight well types used in the model as depicted in **Figure A-2**. This unit process holds the parameter values for all well types and can be duplicated to create all of the well closure plans.	1	9/2012

Figure A-6: 3D Seismic Site Prep – Second-Level Plan

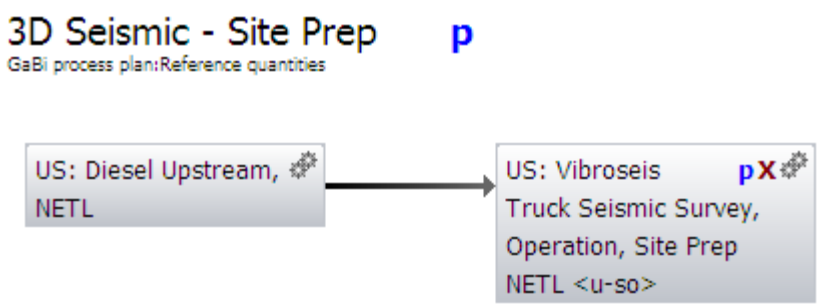

Table A-6: Unit Processes in 3D Seismic Site Prep Plan

Unit Process	Notes	Version	Creation Date
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Vibroseis Truck Operation	This unit process includes vibroseis truck operation for seismic survey, including diesel combustion.	1	10/2012

Figure A-7: 3D Seismic Site Monitoring – Second-Level Plan

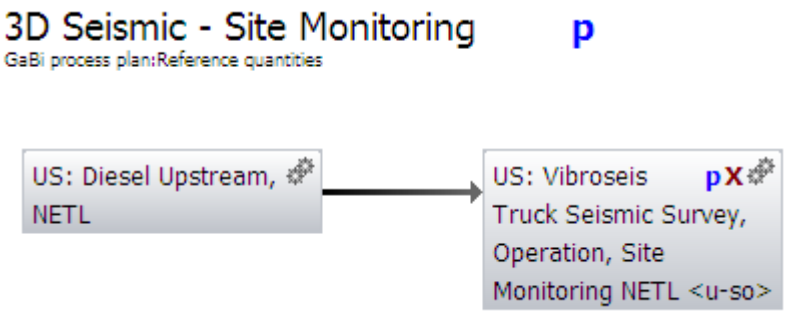

Table A-7: Unit Processes in 3D Seismic Site Monitoring Plan

Unit Process	Notes	Version	Creation Date
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Vibroseis Truck Operation	This unit process includes vibroseis truck operation for seismic survey, including diesel combustion.	1	10/2012

Figure A-8: Saline Aquifer Land Use – Second-Level Plan

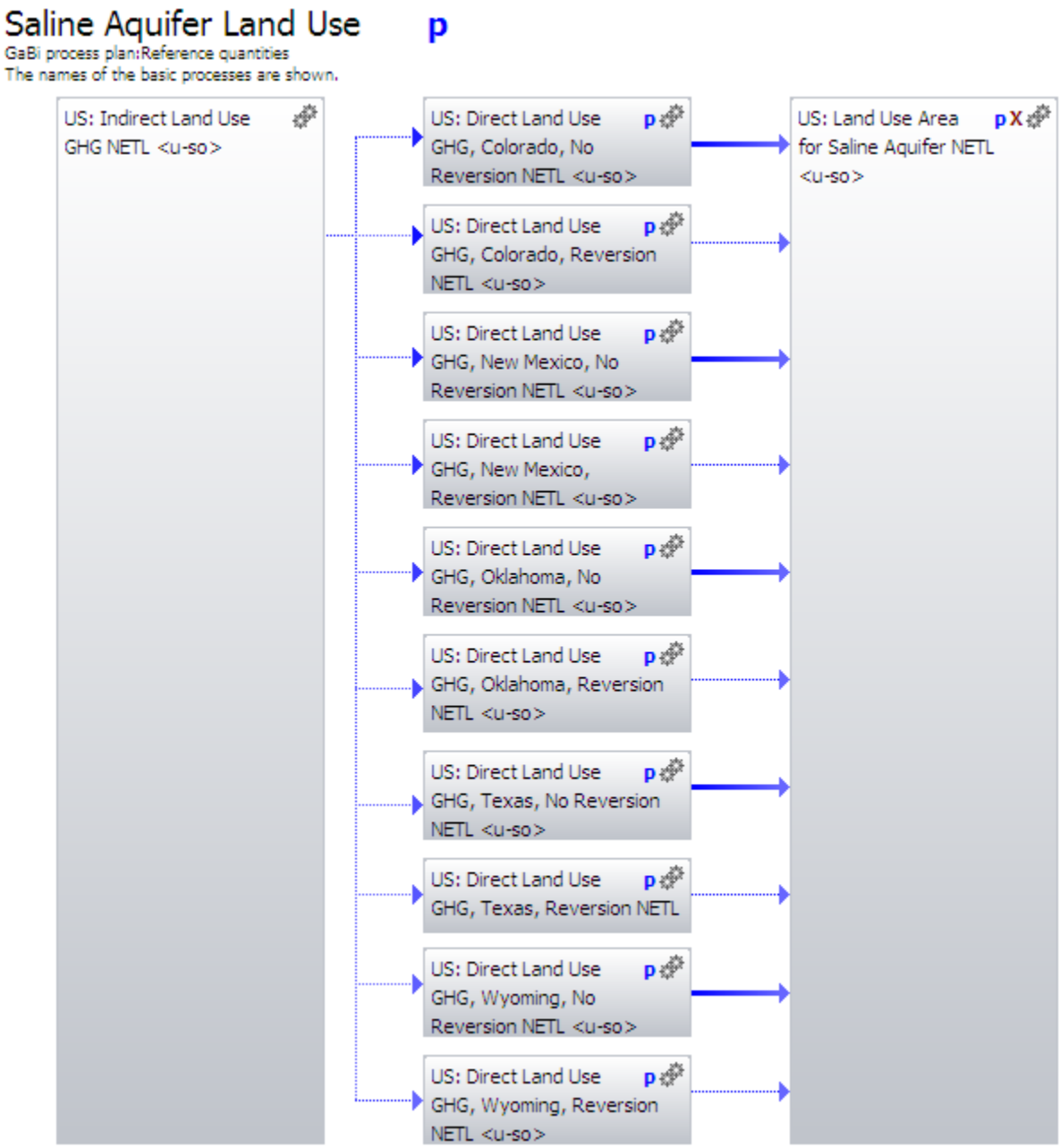

Table A-8: Unit Processes in Saline Aquifer Land Use Plan

Unit Process	Notes	Version	Creation Date
Direct Land Use GHG, Reversion	This unit process accounts for direct GHG emissions from land transformation with reversion. This model is based on a theoretical aquifer located in the Permian Basin, which encompasses five states (Colorado, New Mexico, Oklahoma, Texas, and Wyoming), as shown in **Figure A-8**. This unit process holds the parameter values for all five states and can simply be duplicated to create all of the Direct Land Use, Reversion plans.	1	12/2012
Direct Land Use GHG, No Reversion	This unit process accounts for direct GHG emissions from land transformation with no reversion. This model is based on a theoretical aquifer located in the Permian Basin, which encompasses five states as shown in **Figure A-8**. This unit process holds the parameter values for all five states (Colorado, New Mexico, Oklahoma, Texas, and Wyoming) and can simply be duplicated to create all of the Direct Land Use, No Reversion plans.	1	12/2012
Indirect Land Use GHG	This unit process accounts for indirect GHG emissions from land transformation in the U.S.	1	12/2012
Land Use Area for Saline Aquifer	This assembly unit process pulls in a fraction of the total land area from all of the states considered. In this model, an equal fraction (1/5) of the total land use change area is assumed for each state.	N/A	N/A

Figure A-9: Brine Water Management – Second-Level Plan

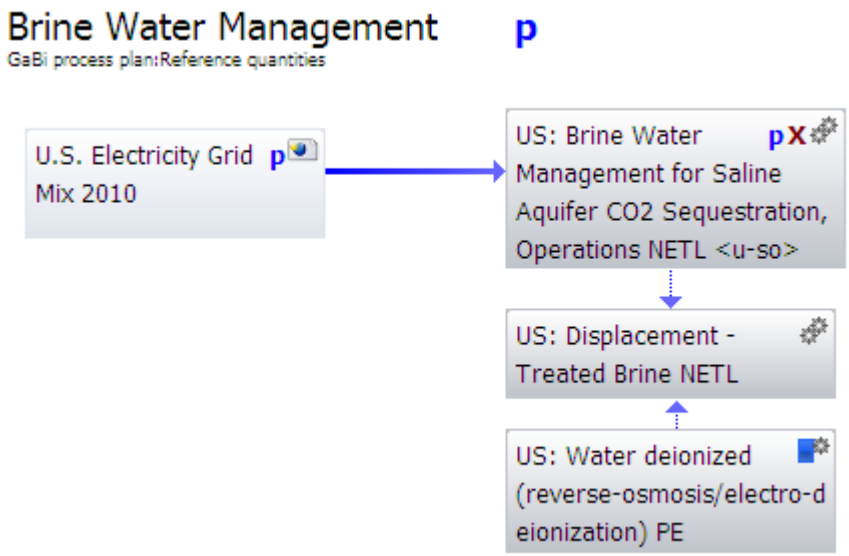

Table A-9: Unit Processes in Brine Water Management Plan

Unit Process	Notes	Version	Creation Date
U.S. Electricity Grid Mix 2010	This unit process includes the full life cycle results from fuel acquisition through combustion and T&D of electricity.	1	N/A
Brine Water Management for Saline Aquifer CO_2 Sequestration	This unit process models the treatment and/or reinjection of brine water produced as a result of CO_2 sequestration operations in saline aquifers.	1	8/2012
Displacement Treated Brine	Assembly process for displacement of treated water – inputs of treated brine and conventionally treated water to perform the displacement	N/A	N/A
Water, deionized	Third-party data available from PE International	N/A	N/A

Appendix B: Detailed Life Cycle Results for Saline Aquifer Sequestration of Carbon Dioxide

Table B-1: Detailed Gate-to-Gate LCA Results for Saline Aquifer Sequestration of Carbon Dioxide (units/tonne CO_2 sequestered) B-2
Table B-2: Detailed Gate-to-Gate LCA Results for Saline Aquifer Sequestration of Carbon Dioxide (units/tonne CO_2 received) B-3

Table B-1: Detailed Gate-to-Gate LCA Results for Saline Aquifer Sequestration of Carbon Dioxide (units/tonne CO_2 sequestered)

Category (Units)	Material or Energy Flow	3D Seismic - Site Prep		Saline Aquifer Well Assembly		Land Use	Site Operations			3D Seismic - Site Monitoring		Brine Management	Total
		Diesel Upstream	Survey Operations	Construction and Installation	Closure	Direct Land Use	Injection Pump Electricity	Pump Seal Leakage	Formation Leakage	Diesel Upstream	Survey Operations	Injection or Treatment Electricity	
GHG ($kg/tonne\ CO_2$)	CO_2	1.13E-04	7.66E-04	4.90E-02	3.79E-04	1.18E-03	8.43E+00	3.39E-02	5.00E+00	5.63E-04	3.83E-03	3.96E-01	1.39E+01
	N_2O	1.85E-09	2.58E-08	4.94E-08	1.99E-08	0	1.05E-04	0	0	9.27E-09	1.29E-07	4.92E-06	1.10E-04
	CH_4	3.78E-07	5.74E-08	1.10E-05	7.47E-07	0	3.01E-02	0	0	1.89E-06	2.87E-07	1.41E-03	3.15E-02
	SF_6	1.32E-16	0	5.12E-10	1.36E-11	0	1.84E-06	0	0	6.61E-16	0	8.65E-08	1.93E-06
	CO_2e (IPCC 2007 100-yr GWP)	1.23E-04	7.75E-04	4.93E-02	4.03E-04	1.18E-03	9.25E+00	3.39E-02	5.00E+00	6.13E-04	3.87E-03	4.35E-01	1.48E+01
Other Air ($kg/tonne\ CO_2$)	Pb	1.91E-12	0	7.97E-11	3.25E-11	0	1.89E-07	0	0	9.56E-12	0	8.90E-09	1.98E-07
	Hg	2.23E-13	0	3.73E-11	9.24E-12	0	1.14E-07	0	0	1.12E-12	0	5.34E-09	1.19E-07
	NH_3	6.53E-10	0	1.52E-08	1.89E-08	0	5.89E-06	0	0	3.26E-09	0	2.77E-07	6.20E-06
	CO	5.60E-08	1.87E-06	9.44E-05	2.86E-07	0	1.16E-03	0	0	2.80E-07	9.37E-06	5.44E-05	1.32E-03
	NOx	1.63E-07	5.47E-06	1.88E-04	7.01E-07	0	1.28E-02	0	0	8.14E-07	2.74E-05	6.03E-04	1.37E-02
	SO_2	2.31E-07	7.52E-09	1.96E-04	7.34E-07	0	1.94E-02	0	0	1.15E-06	3.76E-08	9.13E-04	2.05E-02
	VOC	5.72E-07	5.74E-08	1.56E-05	8.84E-07	0	3.33E-02	0	0	2.86E-06	2.87E-07	1.56E-03	3.49E-02
	PM	4.38E-09	0	5.83E-05	1.69E-07	0	2.77E-04	0	0	2.19E-08	0	1.30E-05	3.49E-04
Solid Waste ($kg/tonne\ CO_2$)	Heavy metals to industrial soil	8.82E-10	0	2.07E-05	5.51E-07	0	7.44E-02	0	0	4.41E-09	0	3.50E-03	7.79E-02
	Heavy metals to agricultural soil	0	0	-3.36E-10	-6.43E-10	0	1.58E-08	0	0	0	0	7.43E-10	1.56E-08
Water Use ($L/tonne\ CO_2$)	Withdrawal	5.68E-04	0	4.19E-01	1.04E-01	0	4.42E+01	0	0	2.84E-03	0	1.40E+03	1.45E+03
	Discharge	8.45E-05	0	4.29E-02	0	0	0	0	1.40E+03	4.23E-04	0	0	1.40E+03
	Consumption	4.83E-04	0	3.76E-01	1.04E-01	0	4.42E+01	0	-1.40E+03	2.42E-03	0	1.40E+03	4.68E+01
Water Quality ($kg/tonne\ CO_2$)	Aluminum	1.11E-07	0	8.14E-07	3.19E-12	0	4.30E-07	0	0	5.57E-07	0	2.02E-08	1.93E-06
	Arsenic (+V)	3.16E-09	0	1.98E-08	7.53E-11	0	8.52E-06	0	0	1.58E-08	0	4.01E-07	8.96E-06
	Copper (+II)	4.60E-09	0	2.82E-08	2.23E-10	0	1.01E-05	0	0	2.30E-08	0	4.77E-07	1.07E-05
	Iron	2.46E-07	0	1.43E-06	5.63E-08	0	1.66E-04	0	0	1.23E-06	0	7.82E-06	1.77E-04
	Lead (+II)	1.07E-08	0	6.60E-08	5.68E-10	0	1.45E-07	0	0	5.34E-08	0	6.80E-09	2.82E-07
	Manganese (+II)	1.02E-11	0	6.56E-08	1.11E-09	0	2.92E-05	0	0	5.12E-11	0	1.37E-06	3.07E-05
	Nickel (+II)	8.47E-08	0	6.87E-07	6.36E-09	0	7.89E-04	0	0	4.23E-07	0	3.71E-05	8.27E-04
	Strontium	2.32E-10	0	1.87E-09	1.04E-09	0	1.42E-07	0	0	1.16E-09	0	6.69E-09	1.53E-07
	Zinc (+II)	1.47E-07	0	8.58E-07	8.05E-10	0	1.06E-04	0	0	7.35E-07	0	4.98E-06	1.13E-04
	Ammonium/ammonia	1.26E-10	0	5.00E-07	-1.12E-08	0	1.84E-03	0	0	6.29E-10	0	8.66E-05	1.93E-03
	Hydrogen chloride	9.81E-15	0	9.91E-14	7.82E-14	0	1.35E-11	0	0	4.90E-14	0	6.35E-13	1.44E-11
	Nitrogen (as total N)	0	0	2.68E-09	1.61E-09	0	6.68E-06	0	0	0	0	3.14E-07	7.00E-06
	Phosphate	2.37E-12	0	9.04E-09	1.70E-08	0	1.29E-07	0	0	1.18E-11	0	6.06E-09	1.61E-07
	Phosphorus	1.06E-07	0	6.00E-07	4.25E-10	0	4.22E-06	0	0	5.32E-07	0	1.98E-07	5.65E-06
Resource Energy ($MJ/tonne\ CO_2$)	Crude oil	3.20E-03	0	7.71E-02	5.16E-04	0	0	2.30E+00	0	1.60E-05	0	1.08E-04	2.38E+00
	Hard coal	8.45E-05	0	1.59E-01	1.78E-03	0	0	5.02E+01	0	4.22E-07	0	2.36E-03	5.03E+01
	Lignite	8.28E-06	0	4.58E-03	7.96E-05	0	0	6.24E-03	0	4.14E-08	0	2.93E-07	1.09E-02
	Natural gas	4.94E-04	0	9.08E-02	5.42E-03	0	0	6.57E+01	0	2.47E-06	0	3.09E-03	6.58E+01
	Uranium	4.68E-05	0	2.66E-04	4.46E-04	0	0	2.89E-02	0	2.34E-07	0	1.36E-06	2.97E-02
	Renewable	5.13E-06	0	3.60E-05	6.34E-04	0	0	2.81E-02	0	2.56E-08	0	1.32E-06	2.88E-02
	Total resource energy	3.84E-03	0	3.32E-01	8.87E-03	0	0	1.18E+02	0	1.92E-05	0	5.56E-03	1.19E+02

Table B-2: Detailed Gate-to-Gate LCA Results for Saline Aquifer Sequestration of Carbon Dioxide (units/tonne CO_2 received)

Category (Units)	Material or Energy Flow	3D Seismic - Site Prep		Saline Aquifer Well Assembly		Land Use	Site Operations			3D Seismic - Site Monitoring		Brine Management	Total
		Diesel Upstream	Survey Operations	Construction and Installation	Closure	Direct Land Use	Injection Pump Electricity	Pump Seal Leakage	Formation Leakage	Diesel Upstream	Survey Operations	Injection or Treatment Electricity	
GHG ($kg/tonne\ CO_2$)	CO_2	1.12E-04	7.62E-04	4.88E-02	3.77E-04	1.17E-03	8.39E+00	3.38E-02	4.97E+00	5.60E-04	3.81E-03	3.94E-01	1.38E+01
	N_2O	1.84E-09	2.57E-08	4.92E-08	1.98E-08	0	1.04E-04	0	0	9.22E-09	1.29E-07	4.90E-06	1.09E-04
	CH_4	3.76E-07	5.71E-08	1.09E-05	7.44E-07	0	2.99E-02	0	0	1.88E-06	2.86E-07	1.41E-03	3.14E-02
	SF_6	1.32E-16	0	5.10E-10	1.36E-11	0	1.83E-06	0	0	6.58E-16	0	8.61E-08	1.92E-06
	CO_2e (IPCC 2007 100-yr GWP)	1.22E-04	7.71E-04	4.91E-02	4.01E-04	1.17E-03	9.21E+00	3.38E-02	4.97E+00	6.10E-04	3.86E-03	4.33E-01	1.47E+01
Other Air ($kg/tonne\ CO_2$)	Pb	1.90E-12	0	7.93E-11	3.24E-11	0	1.88E-07	0	0	9.51E-12	0	8.86E-09	1.97E-07
	Hg	2.22E-13	0	3.71E-11	9.19E-12	0	1.13E-07	0	0	1.11E-12	0	5.32E-09	1.18E-07
	NH_3	6.50E-10	0	1.51E-08	1.88E-08	0	5.86E-06	0	0	3.25E-09	0	2.75E-07	6.17E-06
	CO	5.57E-08	1.86E-06	9.39E-05	2.84E-07	0	1.15E-03	0	0	2.79E-07	9.32E-06	5.41E-05	1.31E-03
	NOx	1.62E-07	5.45E-06	1.87E-04	6.97E-07	0	1.28E-02	0	0	8.10E-07	2.72E-05	6.00E-04	1.36E-02
	SO_2	2.30E-07	7.48E-09	1.95E-04	7.31E-07	0	1.93E-02	0	0	1.15E-06	3.74E-08	9.08E-04	2.04E-02
	VOC	5.69E-07	5.71E-08	1.55E-05	8.79E-07	0	3.31E-02	0	0	2.85E-06	2.86E-07	1.56E-03	3.47E-02
	PM	4.36E-09	0	5.80E-05	1.68E-07	0	2.76E-04	0	0	2.18E-08	0	1.30E-05	3.47E-04
Solid Waste ($kg/tonne\ CO_2$)	Heavy metals to industrial soil	8.77E-10	0	2.06E-05	5.49E-07	0	7.40E-02	0	0	4.39E-09	0	3.48E-03	7.75E-02
	Heavy metals to agricultural soil	0	0	-3.34E-10	-6.40E-10	0	1.57E-08	0	0	0	0	7.40E-10	1.55E-08
Water Use ($L/tonne\ CO_2$)	Withdrawal	5.65E-04	0	4.17E-01	1.03E-01	0	4.40E+01	0	0	2.83E-03	0	1.40E+03	1.44E+03
	Discharge	8.41E-05	0	4.27E-02	0	0	0	0	1.39E+03	4.21E-04	0	0	1.39E+03
	Consumption	4.81E-04	0	3.74E-01	1.03E-01	0	4.40E+01	0	-1.39E+03	2.41E-03	0	1.40E+03	4.65E+01
Water Quality ($kg/tonne\ CO_2$)	Aluminum	1.11E-07	0	8.10E-07	3.17E-12	0	4.28E-07	0	0	5.55E-07	0	2.01E-08	1.92E-06
	Arsenic (+V)	3.15E-09	0	1.97E-08	7.49E-11	0	8.48E-06	0	0	1.57E-08	0	3.99E-07	8.92E-06
	Copper (+II)	4.57E-09	0	2.81E-08	2.22E-10	0	1.01E-05	0	0	2.29E-08	0	4.74E-07	1.06E-05
	Iron	2.44E-07	0	1.42E-06	5.60E-08	0	1.66E-04	0	0	1.22E-06	0	7.78E-06	1.76E-04
	Lead (+II)	1.06E-08	0	6.57E-08	5.65E-10	0	1.44E-07	0	0	5.32E-08	0	6.77E-09	2.81E-07
	Manganese (+II)	1.02E-11	0	6.52E-08	1.10E-09	0	2.91E-05	0	0	5.09E-11	0	1.37E-06	3.05E-05
	Nickel (+II)	8.43E-08	0	6.83E-07	6.33E-09	0	7.85E-04	0	0	4.21E-07	0	3.69E-05	8.23E-04
	Strontium	2.30E-10	0	1.86E-09	1.04E-09	0	1.42E-07	0	0	1.15E-09	0	6.66E-09	1.53E-07
	Zinc (+II)	1.46E-07	0	8.53E-07	8.01E-10	0	1.05E-04	0	0	7.31E-07	0	4.96E-06	1.12E-04
	Ammonium/ammonia	1.25E-10	0	4.98E-07	-1.11E-08	0	1.83E-03	0	0	6.26E-10	0	8.62E-05	1.92E-03
	Hydrogen chloride	9.76E-15	0	9.86E-14	7.78E-14	0	1.34E-11	0	0	4.88E-14	0	6.32E-13	1.43E-11
	Nitrogen (as total N)	0	0	2.66E-09	1.61E-09	0	6.65E-06	0	0	0	0	3.13E-07	6.97E-06
	Phosphate	2.36E-12	0	9.00E-09	1.69E-08	0	1.28E-07	0	0	1.18E-11	0	6.03E-09	1.60E-07
	Phosphorus	1.06E-07	0	5.97E-07	4.22E-10	0	4.20E-06	0	0	5.30E-07	0	1.97E-07	5.63E-06
Resource Energy ($MJ/tonne\ CO_2$)	Crude oil	3.18E-03	0	7.67E-02	5.13E-04	0	0	2.28E+00	0	1.59E-05	0	1.07E-04	2.37E+00
	Hard coal	8.40E-05	0	1.58E-01	1.77E-03	0	0	4.99E+01	0	4.20E-07	0	2.35E-03	5.01E+01
	Lignite	8.24E-06	0	4.56E-03	7.92E-05	0	0	6.20E-03	0	4.12E-08	0	2.92E-07	1.08E-02
	Natural gas	4.92E-04	0	9.04E-02	5.39E-03	0	0	6.54E+01	0	2.46E-06	0	3.07E-03	6.55E+01
	Uranium	4.65E-05	0	2.64E-04	4.44E-04	0	0	2.88E-02	0	2.33E-07	0	1.35E-06	2.95E-02
	Renewable	5.10E-06	0	3.58E-05	6.31E-04	0	0	2.80E-02	0	2.55E-08	0	1.32E-06	2.86E-02
	Total resource energy	3.82E-03	0	3.30E-01	8.83E-03	0	0	1.18E+02	0	1.91E-05	0	5.53E-03	1.18E+02

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