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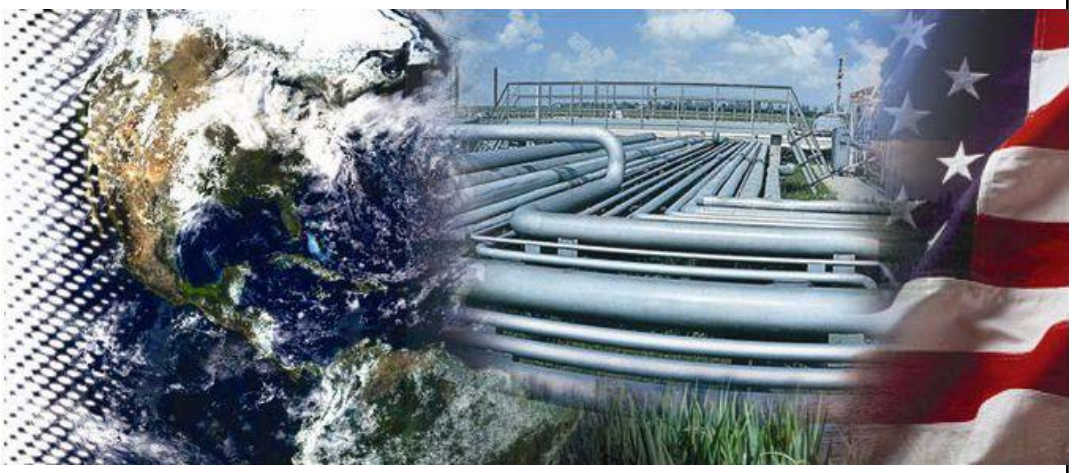

Gate-to-Gate Life Cycle Inventory and Model of CO_2-Enhanced Oil Recovery

September 30, 2013

DOE/NETL-2013/1599

U.S. DEPARTMENT OF ENERGY

OFFICE OF FOSSIL ENERGY

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Acronyms and Abbreviations

Btu	British thermal unit
CCS	Carbon capture and sequestration
CCUS	Carbon capture utilization and sequestration
C_2H_6	Ethane
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOE	Department of Energy
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
GHG	Greenhouse gas
GTSC	Gas turbine simple cycle
GWP	Global warming potential
HCPV	Hydrocarbon pore volume
H_2S	Hydrogen sulfide
Hg	Mercury
HHV	Higher heating value
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kWh	Kilowatt-hour
L	Liter
LC	Life cycle
LCA	Life cycle analysis
m	Meter
MJ	Megajoule
MMBtu	Million Btu
MPa	Megapascal
MW,MWe	Megawatt electric
N_2O	Nitrous oxide
N/A	Not applicable
NO_X	Nitrogen oxides
NGL	Natural gas liquids
NETL	National Energy Technology Laboratory
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound
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
T&D	Transmission and distribution
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
VRU	Vapor recovery unit
WAG	Water alternating gas
WWTP	Wastewater treatment plant

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Executive Summary

Enhanced Oil Recovery (EOR) is a generic term for techniques that increase the amount of crude that can be extracted from a given field. For this analysis, EOR refers to a specific technique that injects carbon dioxide (CO_2) to improve the recoverability of crude oil by reducing viscosity, swelling crude oil, and lowering interfacial tension. EOR is a multistep process with injection and production wells, separation systems, and other supporting processes.

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

- Injection and recovery
- Bulk separation and storage
    - Gas/liquid separation
    - Crude oil storage
    - Brine water storage and injection
- Gas separation
    - Ryan-Holmes
    - Refrigeration and fractionation
    - Membrane separation
- Supporting processes
    - Venting and flaring
    - Gas combustion for process heat
- Land use

The key data source of this analysis is *An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin*, published by NETL in 2010 (NETL, 2010). All variables that directly affect the performance of an EOR site are based on this data source.

This analysis used an LCA approach for developing data, and EOR and gas processing. The energy and material flows for key processes within the gate-to-gate boundaries of the EOR site 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 barrel of crude produced via EOR). 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.

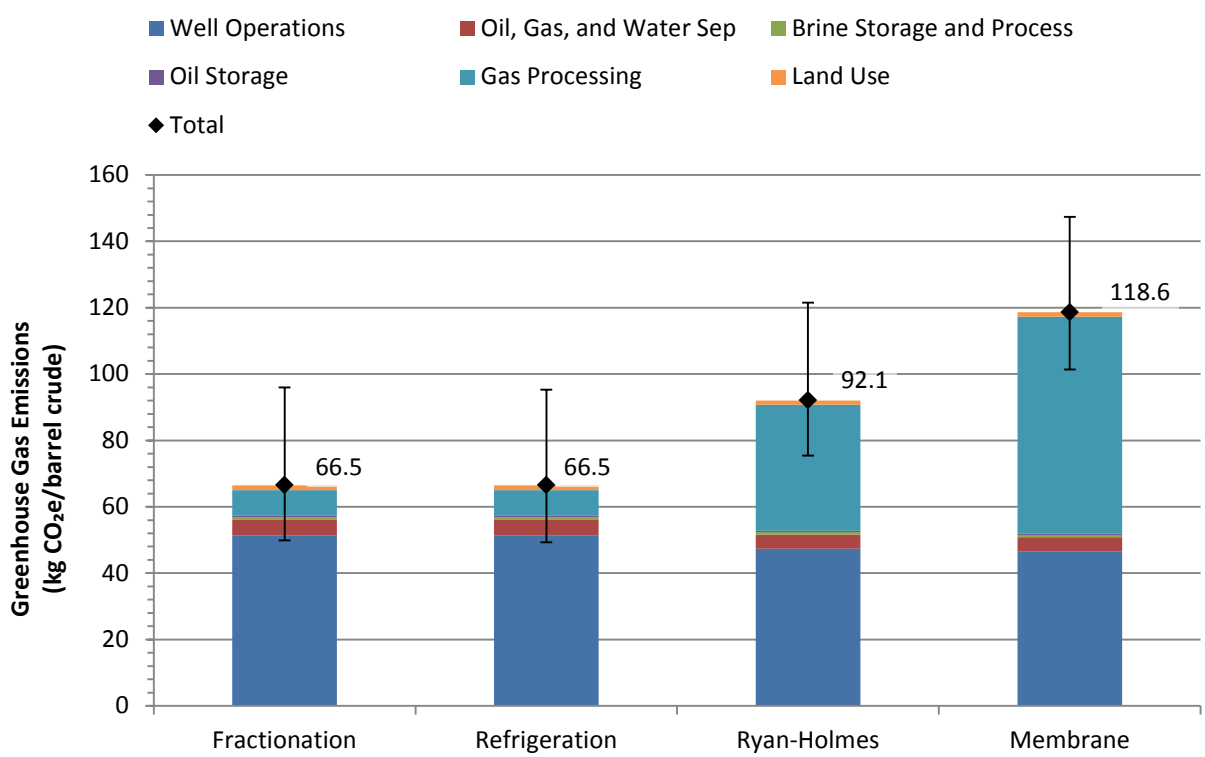
The results of this analysis are on the basis of a gate-to-gate boundary. CO_2 from an unspecified source enters the boundary, and crude oil with no specified end use exits the boundary. The goal of these results is to identify the processes that are key contributors to the GHG emissions of each system 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. Given these boundaries, the results should not be compared to cradle-to-grave results for other types of crude oil extraction.

The expected gate-to-gate GHG results for the production of one barrel of crude oil from EOR range from 66.5 to 118.6 kg carbon dioxide equivalents (CO_2e). Uncertainty in these results is driven by different EOR operating conditions, including crude oil recovery rate, injection pressure, electricity source, and formation leakage rate.

In addition to crude oil, EOR facilities also produce other types of hydrocarbon products. A co-product management scheme is necessary to determine the share of system burdens that should be assigned only to crude oil. This analysis uses mass as a basis for co-product allocation. The gate-to-gate GHG results for EOR with the four types of gas separation technologies are shown in **Figure ES-1** below. As shown, the difference between the scenarios is manifested by the difference in emissions attributed to gas processing. The fractionation and refrigeration gas processing options have similar gate-to-gate GHG emissions. The gas separation processes are identical except that the fractionation option includes two additional distillation columns to facilitate the separation of individual products out of the NGL stream. There is a small increase in the amount of natural gas required in the fractionation cases, which results in slightly higher GHG emissions; however, the difference is negligible (approximately 0.02%) based on the functional unit of 1 barrel of crude oil.

Both Ryan-Holmes and membrane gas processing are more effective at recovering NGLs than refrigeration and fractionation. The increased recovery, however, comes at the expense of additional processing energy, which is also demonstrated in the figure by the increased GHG intensity associated with gas processing for Ryan-Holmes and membrane.

Figure ES-1: Gate-to-Gate GHG Emissions Summary for EOR with Gas Processing



1 Enhanced Oil Recovery Background and Model

A description of enhanced oil recovery (EOR) technology and an approach for modeling it from a life cycle analysis (LCA) perspective are provided below.

1.1 Technology Description

Enhanced oil recovery using carbon dioxide (CO_2) injection (referred to as EOR) is one type of tertiary oil extraction technology used after primary and water-flood techniques have been exhausted (NETL, 2010). The mechanism by which CO_2 enables additional recovery of crude has to do with the miscibility with crude and the corresponding reduction of viscosity, swelling of crude, and reduction of interfacial tension (NETL, 2010). The injection of CO_2 is often alternated with the injection of brine in what is known as the water alternating gas (WAG) tertiary injection scheme (NETL, 2010). Brine injection prevents the undesired channeling of CO_2, which can result in bypassing the stored oil.

The primary function of EOR is the production of additional crude from a formation; however, EOR also sequesters CO_2 in the process. During the life of the well, CO_2 and brine are both injected and produced from the formation. The formation sequesters some fraction of the injected CO_2, but is a net producer of brine. The produced CO_2 is processed along with the other products from the well and recycled back for injection back into the well along with additional makeup CO_2 from a pipeline. In addition to CO_2 and brine, the well also produces crude oil and hydrocarbon gas (C_1-C_5). This combined production stream is processed above ground to separate gas, water, and crude. The resulting gas mixture can be processed by various methods to separate products as desired.

The key data source of this analysis is *An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin*, published by NETL in 2010 (NETL, 2010). All variables that directly affect the performance of an EOR site are based on this data source. These variables include geological characteristics, crude oil properties, and operating practices:

- Geological characteristics include the location, depth, and thickness of the resource. The EOR operating parameters in this analysis are based on EOR production in the Permian Basin of West Texas. The average depth of EOR wells in this region is 5,826 feet. The average thickness of the crude oil reservoirs are 76 feet (NETL, 2010).
- Another geological characteristic is the hydrocarbon pore volume (HCPV), which represents the volume in the reservoir initially filled with crude oil. The amount of CO_2 injected into the formation is often expressed as a fraction of HCPV[1]. Historically, total injected CO_2 has been 0.4 HCPV (i.e., the volume of injected CO_2 is 40 percent of the HCPV). Current practices inject CO_2 at a rate of 1.0 HCPV and next generation practices inject CO_2 at a rate of 1.5 HCPV. (NETL, 2010).
- Crude oil properties include crude oil gravity and gas composition. Based on a survey of wells in the basin, the crude oil produced has a mean American Petroleum Institute (API)

[1] HCPV is calculated by factoring the total volume, porosity, and water content of a reservoir.

gravity of 36 degrees (NETL, 2010) [1]. The hydrocarbon gas produced from the formation contained 72.3 percent (by weight) methane (C_1), 12.2 percent ethane (C_2), 4 percent propane (C_3), 1.3 percent butanes (C_4), and 0.5 percent pentanes (C_5), with the balance of the stream made up by hexanes-plus (C_{6+}), hydrogen sulfide, nitrogen, and helium (NETL, 2010).

- The well pattern is the spacing and arrangement of production and injection wells, and is an operating practice that affects the performance of an EOR site. This analysis uses a 5-spot well pattern that covers 40 acres (NETL, 2010). A five-spot pattern consists of four wells placed at the corners of a square and a fifth well in the middle of the square.
- The CO_2 injection pressure is another operating practice that affects the performance of an EOR site. It is important to control the injection pressure at the surface to avoid fracturing the geological formations that confine the oil bearing reservoir (NETL, 2010). Historically, the CO_2 injection pressure has been 1,400 psig. For current practices, the CO_2 injection pressure is 1,800 psig and for next generation practices the injection pressure is 2,200 psig (NETL, 2010).

The above variables for EOR operations are based on data published by NETL (NETL, 2010) and are representative of EOR facilities in the Permian Basin of West Texas. The oil recovery and CO_2 sequestration rates are based on outputs of the CO_2 Prophet model, a legacy model developed by oil field experts as part of a Department of Energy (DOE) contract in 1986. This analysis does not attempt to recreate the simulations performed by Prophet, but uses only the sequestration and production rates already calculated by Prophet. This means that variables such as formation depth, thickness, pore volume, well pattern, and injection pressure are not used in this analysis – they are embedded in the overall CO_2 sequestration and crude oil recovery rates.

In addition to injection and recovery operations, an EOR facility also has separation and supporting processes. This analysis models the following EOR activities:

- Injection and recovery
- Bulk separation and storage
    - Gas/liquid separation
    - Crude oil storage
    - Brine water storage and injection
- Gas separation
    - Ryan-Holmes
    - Refrigeration and fractionation
    - Membrane separation
- Supporting processes

[1] The API scale measures the density of crude oil relative to water, where an API gravity of 10 degrees is equal to the density of water. It is an inverse scale; the higher the API gravity, the lighter the crude oil. For comparison, the average API density of crude oil delivered to U.S. refineries in 2011 was 30.7 degrees (EIA, 2012).

  - Venting and flaring
  - Gas combustion for process heat
- Land use

1.1.1 Injection and Recovery

CO_2 is an effective fluid for EOR, because it is miscible in oil – it mixes with oil and brings it to the surface. The injection of CO_2 is often alternated with the injection of brine in what is known as a WAG tertiary injection scheme (NETL, 2010). Brine injection prevents the undesired channeling of CO_2, which can result in bypassing the stored oil.

The primary function of EOR is the production of additional crude from a formation, but EOR also sequesters CO_2 in the process. During the life of the well, CO_2 and brine are both injected and produced from the formation. The formation sequesters some fraction of the injected CO_2 but is a net producer of brine. Brine is usually sent to nearby EOR sites for further use. In addition to CO_2 and brine, the well also produces crude oil and hydrocarbon gas (C1-C5). This combined production stream is processed above ground to separate gas, water, and crude.

The injected CO_2 stream is a combination of makeup CO_2 from a pipeline and recycled CO_2 from the gas processing plant. At pipeline conditions, liquid CO_2 forms at a pressure of 7.38 MPa (1,070 psia). The pipeline pressure is maintained above this critical point to ensure that all CO_2 remains in the liquid state. CO_2 from the gas plant is assumed to be at a pressure of 0.34 MPa (50 psia). Both streams need to be compressed/pumped to the required injection pressure of 15.2 MPa (2,200 psia) at the wellhead. The calculation of the electricity requirements includes a compression load to increase the pressure of the recycle gas and a pumping load to increase the pressure of the entire CO_2 injection stream (recycle plus makeup) to the injection pressure.

Artificial fluid lifting is often required for EOR wells to yield production levels that are economical (NETL, 2010). Pumps are utilized to lift the reservoir products to the surface in cases where the produced fluid is too deep or viscous to reach the surface based on the reservoir pressure alone (NETL, 2010).

One of the critical operating parameters for EOR is the ratio of the cumulative injected CO_2 to the total HCPV in the formation. The HCPV based on best practices is 1.0 (NETL, 2010). The cost of CO_2 was the primary driver behind the lower HCPV of the historical scenario (0.4) relative to the best practice scenario.

The operating characteristics of the EOR facility of this analysis are representative of EOR facilities in the Permian Basin of West Texas.

1.1.2 Bulk Separation and Storage

The production wells at an EOR site produce a mix of crude oil, brine water, and gases. These three products must be separated to produce marketable crude, brine water that can be re-injected to the formation, and gases that can be sent to CO_2 removal and hydrocarbon processing.

1.1.2.1 Gas/Liquid Separation

The input to the separator is a single stream of wellhead product; the outputs are oil, gas (CO_2 plus hydrocarbons), and water. Gas is removed in a high-pressure vessel that causes liquids to condense into a separate stream. The gas that is separated from this process can be sent to a gas-processing

facility for further separation. Liquids are treated further in a heated vessel that separates oil and water. Volatile organic compounds (VOC) are released due to pressure changes in the system, including flashing operations and loading of streams into separation and storage vessels. VOC emissions are recovered by vapor recovery equipment (VRU) and may be flared or released to the atmosphere, depending on the use and efficiency of emission-control equipment.

The only energy input to gas/liquid separation is the natural gas consumed by a firetube heater. A firetube heater warms the oil and water mixture, causing the two liquid components to separate. It is assumed that natural gas is purchased for onsite heating, because the recovered gases from the process are high-value products that will be sent to market instead of combusted at the EOR site. The composition of the produced gas stream and market conditions could dictate alternatives.

1.1.2.2 Crude Oil Storage

Crude oil is stored in tanks at EOR sites. The flashing and working losses of crude oil storage tanks result in VOC emissions that are recovered by vapor recovery equipment and sent to venting or flaring. The loss of VOCs from a storage tank is caused by the flashing of new crude oil that enters the storage tank, the volume change caused by new crude that enters the tank (working losses), and the expansion of product in the tank due to temperature increases (standing losses) (NETL, 2010).

The composition of crude oil is a data limitation. CO_2 is entrained in the crude oil produced by EOR, but the series of liquid and gas separation processes that immediately follow crude oil extraction are designed to remove CO_2 and other gases. Further, EOR operators pay for inlet CO_2, so there is an economic case for recovering CO_2 from the crude oil product stream.

1.1.2.3 Brine Water Storage

Most of the methane from oilfield separation processes has an affinity for the crude oil and hydrocarbon gas streams, but a small fraction remains in the brine water. Brine water is stored in tanks at EOR sites. The flashing and working losses of a brine water storage tank result in methane emissions that are recovered by vapor-recovery equipment and sent to venting or flaring. All of this methane is released from the brine water during storage. A VRU is installed on the water storage tank, diverting all methane emissions to venting or flaring.

Instead of treating the excess produced brine water at the surface, it may be desirable to instead re-inject the stream into a suitable underground formation nearby 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.

1.1.3 Gas Separation

Gas separation is necessary for EOR operations, because it recovers CO_2 that can be re-injected in the EOR flood and separates hydrocarbon streams that can be sold or used as plant fuel.

1.1.3.1 Refrigeration and Fractionation

Gas separation by refrigeration chills a feed-gas stream, allowing the separation of CO_2 from ethane (C_2H_6) and higher hydrocarbons (Vargas, 2010). The hydrocarbons are then separated using a series of distillation columns that produce three saleable streams: propane, butane, and pentane plus higher hydrocarbons. The ethane is recombined with the CO_2-rich injection stream, and then sent to two compressor trains for reinjection.

This technology can be configured to bypass distillation columns, which produce a mixed stream of hydrocarbons and reduce the energy consumed by the de-ethanizer reboiler. Hydrogen sulfide (H_2S) is separated from the bottoms of the de-ethanizer using a molecular sieve.

Figure 1-1 and **Figure 1-2** show simple process overviews for the refrigeration and fractionation gas processing options modeled in this analysis.

Figure 1-1: Refrigeration Process Overview

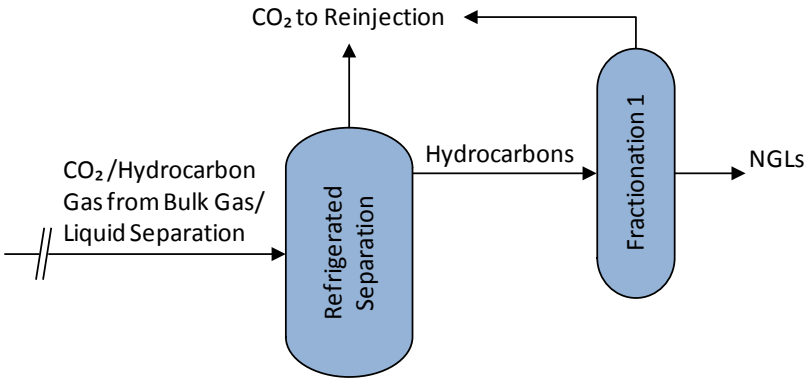
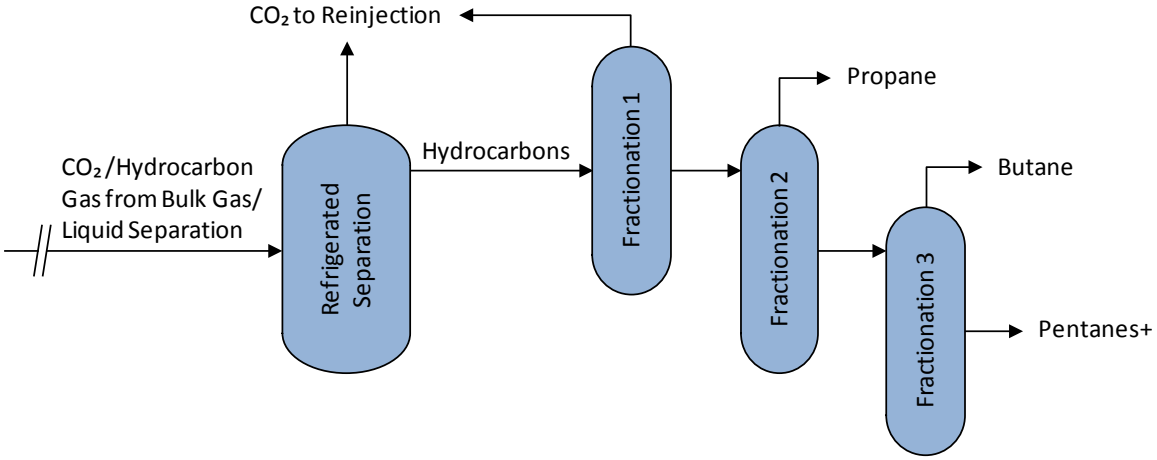


Figure 1-2: Refrigeration/Fractionation Process Overview

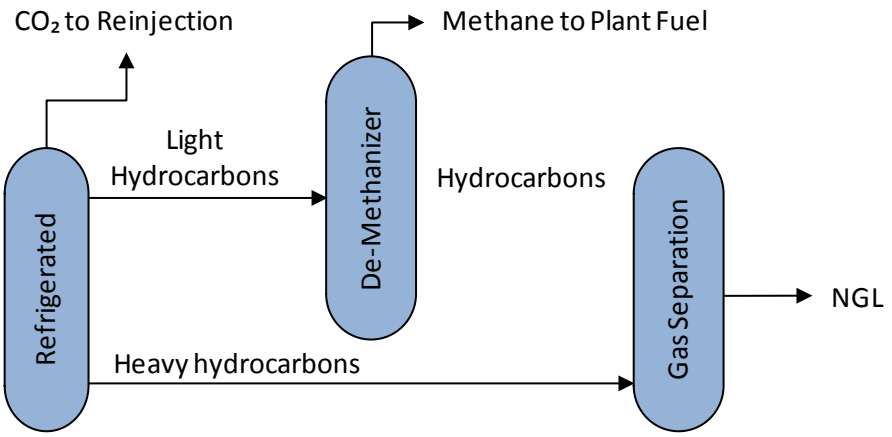


1.1.3.2 Ryan-Holmes

The Ryan-Holmes process has three steps. A refrigerated vessel separates CO_2, light hydrocarbons, and natural gas liquids (NGL). A de-methanizer recovers methane that can be used as a plant fuel. And a gas/gas separation column separates light and heavy hydrocarbons. A portion of the hydrocarbons that are recovered from the refrigerated vessel are used to break the azeotrope in the gas separation column.

An advantage of the Ryan-Holmes process is the separation of hydrocarbons into high-purity streams with higher market values than mixed streams. **Figure 1-3** shows simple process overview for the Ryan-Holmes gas-processing scheme modeled in this analysis.

Figure 1-3: Ryan-Holmes Process Overview



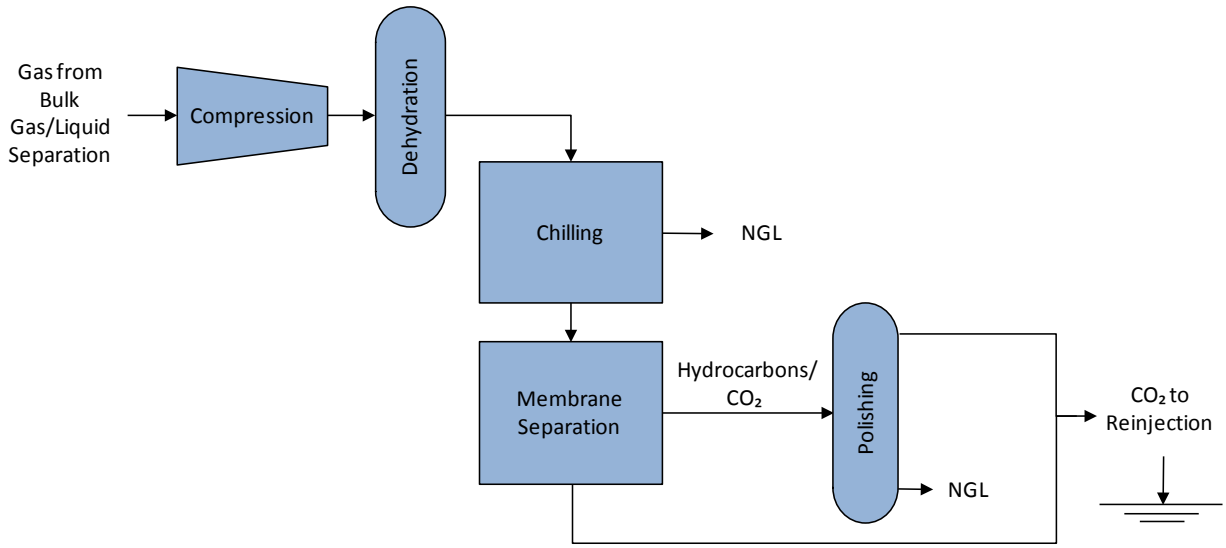
1.1.3.3 Membrane Separation

Membrane separation technology separates two types of gases based on differences between their permeation rates through a non-porous, semi-permeable membrane. Permeation is a solution-diffusion mechanism, where the solubility and diffusion properties of a gas are a function of its concentration and partial pressure. Further, diffusion is also driven by the thickness of the membrane and the concentration gradient across the membrane, as defined by Fick's Law (Wijmans & Baker, 1995). The permeability of a gas is the product of its solubility and diffusivity, and the selectivity of a membrane is the ratio of permeabilities of two gases. For example, the membranes used at EOR gas separation plants have a CO_2-to-methane selectivity of 10 to 20 (Baker & Lokhandwala, 2008)

Pretreatment is required before a gas stream is fed to a membrane-separation unit. Pretreatment includes the compression of the gas stream to 3.45 MPa (500 psi), dehydration, and chilling. Compression is necessary to drive the gas through the separation process. Dehydration removes water that could condense in the membrane separation unit and reduce selectivity. Similarly, chilling reduces hydrocarbon vapors that could condense in the membrane separation unit and reduce selectivity.

Figure 1-4 shows simple process overview for the membrane gas processing scheme modeled in this analysis.

Figure 1-4: Membrane Process Overview



1.1.4 Supporting Processes

The supporting processes at the EOR site include the venting and flaring of recovered vapor and the combustion of gas streams for the generation of process heat.

1.1.4.1 Venting and Flaring

Venting is necessary for the safe release of gas that builds up in a system. Flaring is the combustion of vented gas and converts hydrocarbons to CO_2. Flaring reduces the environmental impacts of vented gas. For example, the flaring of methane converts it to CO_2, which has a lower global warming potential (GWP) than methane.

If gas is vented without flaring, there is no chemical change between the incoming gas stream and the gas stream that is vented to air. When gas is flared, most of it is converted to CO_2. This analysis uses a 99 percent conversion efficiency of carbon to CO_2. For example, for every 1.00 kilogram of carbon that is flared, 0.99 kilogram is converted to CO_2. Based on this 99-percent conversion efficiency and the chemistry of fuel combustion, the flaring of 1.00 kg of methane results in 2.72 kg of CO_2 emissions and 0.01 kg of methane emissions. Similarly, when using pentane to represent VOCs, the flaring of 1.00 kg of VOCs results in 3.03 kg of CO_2 emissions and 0.01 kg of VOC emissions.

No data are available on the composition of VOCs from oil and gas extraction and processing operations. Pentane was chosen to represent the combustion profile for flared VOCs, but there is not much variability among the emission factors of C2 through C5 hydrocarbons. The CO_2 emissions from pentane combustion are only 4 percent higher than those for ethane combustion (3.03 vs. 2.90).

1.1.4.2 Gas Combustion for Process Heat

Natural gas is combusted to produce heat used by oil/water separation vessels and reboilers on separation columns. The air emissions from natural gas combustion are based on the Environmental Protection Agency's (EPA) emission factors for natural gas combustion.

1.1.5 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 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. The NETL 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 EOR 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 is unlikely for an EOR 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 50 wells modeled for the EOR facility based on five wells per pattern and 10 patterns per EOR facility (NETL, 2010). Each well has an approximate footprint of 0.25 acres (NETL, 2012). The gas processing facility has a footprint of 20 acres. The total footprint for the EOR site modeled in this analysis was 58,682 m^2.

1.2 Modeling Approach

Figure 1-5 shows the LCA modeling structure for EOR. **Appendix A** provides links to each of the individual unit processes included in the model, as well as a roadmap for connecting those processes. The inputs to the EOR model include CO_2 and natural gas delivered by pipelines and electricity delivered by the electricity grid. The outputs include crude oil and NGLs. Excess brine water produced is injected underground for disposal. In the Ryan-Holmes gas processing scheme, natural

gas is produced. It is assumed that this gas is used internally in the process to reduce the amount of purchased natural gas that is required.

The reference flow of the EOR model can be changed, depending on the purpose of a study. If the EOR model is used for an LCA of CO_2 sequestration, the EOR model should be scaled using a reference flow of one unit of CO_2 delivered to the EOR facility. If the EOR model is used for an LCA of energy production, the EOR model should be scaled using a reference flow of one unit of crude oil produced by the EOR facility. The results in this study are based on 1 barrel of crude produced.

1.2.1 Data Sources

The key data source of this analysis is *An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO_2-Enhanced Oil Recovery in the Permian Basin*, published by NETL in 2010 (NETL, 2010). This document includes data for the construction and operation of an EOR site, including data for Ryan-Holmes gas separation.

Another data source is NETL's unit process library. In some cases, small modifications were necessary to make existing unit processes appropriate for the EOR model. For example, a unit process for drill-rig operation was adjusted to reflect the depth and drilling time for EOR wells, the emission factors in a unit process for the venting and flaring of natural gas were changed to represent the flaring of VOC and methane at an EOR facility, and the combustion of natural gas in an auxiliary boiler was adapted to be representative of the gas combustion at the EOR facility.

Other data sources include recent literature on EOR and gas separation processes, including vendor specifications, conference proceedings, and journal articles. These data sources are cited throughout this report and appendices.

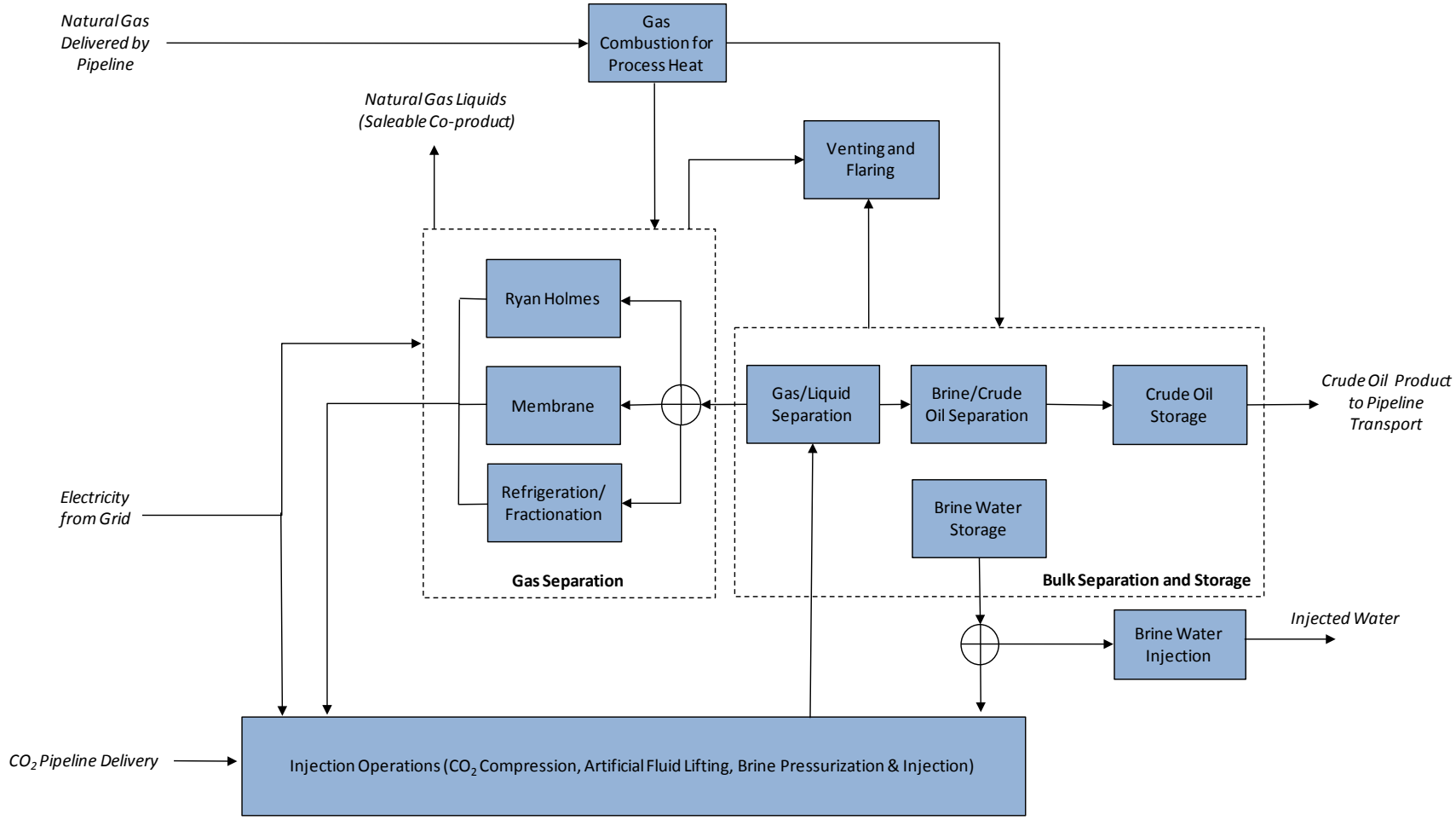
1.2.2 Co-Product Management

The EOR facility produces crude oil, NGLs, and other hydrocarbons. If desired, the model can be configured to treat excess produced brine on-site as opposed to the default of injection into a disposal well. If crude oil is the primary product (i.e., the production of crude oil is the key service provided by EOR), then the environmental burdens of the other EOR products must be accounted for using co-production allocation or system expansion.

Mass-based co-product allocation is performed because all co-products can be expressed in terms of mass. And while the crude oil and other hydrocarbons are generally valuable because of the energy they contain, not their mass, the NGLs also have high value for non-energy use in other products such as plastic. In that case, mass-based allocation is a more defensible co-product management strategy.

Energy-based co-product allocation is feasible but cannot be applied to all EOR products if treated water is produced as a product from the site. Energy can be used as a basis for co-product allocation among crude oil, NGLs, and other hydrocarbons, but cannot be used as a basis for apportioning burdens to treated water, a mass flow. Co-product allocation can be avoided by using system expansion. If crude oil is the primary product, the boundaries of the system need to be expanded until crude oil is the only product exiting the system. However, this requires assumptions about the fate of the co-products, which implies consequential impacts. Since this is an attributional LCA with the goal of understanding the environmental burdens of the EOR crude oil, mass allocation is the preferred co-product management scheme.

Figure 1-5: Unit Process Flows for EOR LCA Model



1.2.3 Parameters

All unit processes used for modeling EOR have adjustable parameters. These parameters improve the flexibility of the model and allow changes to the following properties:

- **Fuel Use Rates:** Some processes combust fuel for heat, such as the firetube heater used for oil/water separation and reboilers used by separation columns. The EOR unit processes have adjustable parameters that allow adjustments to these fuel use rates. The model tracks flows on a mass basis, so these fuel rates are expressed on the basis of kilograms of fuel combusted per kilogram of product. The heating values of the fuels were used to convert the fuel use rate parameters from an energy basis to a mass basis.
- **Non-Combustion Emission Factors:** Some processes release air emissions due to phase changes during fluid flashing or tank breathing. These emissions are described by adjustable parameters for non-combustion emission factors. For example, the crude oil storage tank has an emission factor for VOC emissions caused by fluid fluctuations, and the brine water storage tank has an emission factor for the release of methane from water.
- **Stream Composition**: The composition of the crude oil, gas, and water produced by the well is highly variable; it depends on the characteristics of the formation and changes over time. The unit process for the separation of liquid and gas products includes adjustable parameters for the shares of oil, gas, and water in the production stream. The values of these parameters affect the performance of bulk separation (separation of gas, oil, and water).
- **Electricity Consumption:** The unit processes for EOR operations and gas processing include adjustable parameters for the electricity requirements of pumps and compressors. It is not necessary to adjust these parameters, unless the user of the model wants to test the sensitivity of results to changes in electricity requirements and electricity grid composition. The model includes options to use the average United States (U.S.) mix (including imports and exports), the Electric Reliability Council of Texas (ERCOT) mix, and power sourced only from a natural gas simple cycle turbine (GTSC).
- **EOR Operations:** The operation of the EOR facility involves the mixing of makeup CO_2 from a pipeline with recycled CO_2 from gas processing, the rates of CO_2 and water injection per unit of crude produced, and the electricity requirements for injection compressors and pumps. The parameters for EOR operations allow changes to these variables.
- **Formation Leakage:** 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.

Note that adjustable parameters for combustion-related emission factors are not included in the above list. Such parameters are held by generic unit processes that feed into the EOR-specific unit processes. Further, while these combustion emission factors are adjustable, they do not have a high degree of variability. Unless EPA updates their emission factors for fuel combustion, it is not necessary to adjust these parameters.

Table 1-1 provides the parameters and corresponding values that are used to model the operation of the EOR site and gas processing facility. Some parameters are common to multiple-gas processing options, while others are specific to a technology. **Table 1-2** highlights the four major contributors (crude recovery ratio, injection pressure, grid mix, and formation leakage) to uncertainty in the model and the corresponding parameter values for the low, expected, and high cases. The goal of the low and high values is to represent a reasonable range around the average; if more data were available, the inner quartile range would be used to represent the low and high values. **Table 1-3** provides the quantity of co-products for the various scenarios in **Table 1-2**.

Table 1-1: Parameters for EOR Operations

Property (Units)	Fractionation	Refrigeration	Ryan-Holmes	Membrane
Gas Processing Utility Requirements				
Electricity (MWh/kg gas)	1.38E-05	1.38E-05	6.28E-05	2.61E-05
Natural Gas (kg natural gas/kg EOR gas)	1.91E-06	1.45E-06		6.64E-02
EOR Product Energy Content				
Crude (MJ/kg)	42.1			
Natural Gas Liquids (MJ/kg)	N/A		48.8	
Butane (MJ/kg)	50.3		N/A	
Pentane (MJ/kg)	48.6		N/A	
Propane (MJ/kg)	50.2		N/A	
EOR Well Operations				
Crude artificial lift pump electricity (kWh/kg crude produced)	1.18E-01			
Brine injection pump electricity (kWh/kg brine injected)	7.87E-04			
Crude produced over study period (barrels)	302,000			
Study period (years)	25			
Brine disposal pump electricity (kWh/kg brine)	4.30E-04			
Oil, Gas, Water Separation Ops				
VOC	1.24E-03			
Flare rate (%)	95%			
Land Use				
Transformed land area for EOR site (m^2)	58,700			
Portion of original land area that was agriculture (%)	0%			
CO_2 Compressor				
Emission factor for CO_2 released to air from injection compressor and pump [kg/(MW-day)]	63.6			

Table 1-2: Parameter Uncertainty Ranges for EOR Operations

Property (Units)	Operating Conditions		
Crude Recovery Ratio (bbl per tonne CO_2 sequestered)	**Low (4.35 bbl/tonne CO_2)**	**Expected (3 bbl/tonne CO_2)**	**High (2 bbl/tonne CO_2)**
CO_2 Production Rate (kg/kg crude product)	4.17	6.04	9.06
Hydrocarbon Gas Production Rate (kg/kg crude product)	0.143	0.21	0.310
Brine Production Rate (kg/kg crude product)	13.0	18.9	28.3
Brine Injection Rate (kg/kg crude product)	12.1	17.5	26.2
CO_2 Sequestration Rate (kg/kg crude product)	1.74	2.52	3.78
CO_2 Injection Rate (kg/kg crude product)	5.90	8.56	12.8
Makeup CO_2 Flow Rate (tonne/day)	7.70	11.2	16.7
Recycled CO_2 Flow Rate (tonne/day)	18.5	26.8	40.1
CO_2 Injection Pressure	**Low (1,400 psig)**	**Expected (1,800 psig)**	**High (2,200 psig)**
Compressor Power Factor (MW/tonne CO_2)	2.70E-03	2.70E-03	2.70E-03
Pump Power Factor (MW/tonne CO_2)	5.57E-05	1.23E-04	1.91E-04
Electricity Grid	**Low (U.S. Mix with Imported and Exported Power)**	**Expected (ERCOT Mix)**	**High (GTSC)**
Coal	45.9%	33.0%	0.0%
Geothermal	0.4%	0.0%	0.0%
GTSC (Natural Gas)	0.0%	0.0%	100.0%
Hydro	7.3%	0.2%	0.0%
Natural Gas Fleet	22.7%	47.9%	0.0%
Nuclear	20.4%	12.3%	0.0%
Petroleum	0.9%	1.1%	0.0%
Solar	0.0%	0.0%	0.0%
Wind	2.4%	5.5%	0.0%
Leakage from Sequestration	**Low**	**Expected**	**High**
Formation leakage of sequestered CO_2 (over 100 years)[1]	0.0%	0.5%	1.0%

[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.

Table 1-3: EOR Co-Product Rates by Gas Separation Technology

EOR Co-Product Rates		Fractionation	Refrigeration	Ryan-Holmes	Membrane
Natural Gas Liquids (kg/kg crude produced)	Low	N/A	4.77E-02	1.11E-01	1.24E-01
	Expected		6.92E-02	1.61E-01	1.80E-01
	High		1.04E-01	2.42E-01	2.69E-01
Butane (kg/kg crude produced)	Low	1.53E-02	N/A	N/A	N/A
	Expected	2.22E-02			
	High	3.33E-02			
Propane (kg/kg crude produced)	Low	5.60E-03	N/A	N/A	N/A
	Expected	8.20E-03			
	High	1.23E-02			
Naphtha (kg/kg crude produced)	Low	2.68E-02	N/A	N/A	N/A
	Expected	3.88E-02			
	High	5.82E-02			

1.3 Data Limitations

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

- No data are available for the long-term leakage rates of CO_2 from EOR sites. 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.
- Oil recovery and CO_2 sequestration rates are based on outputs of the CO_2 Prophet model, a legacy model developed by oil field experts as part of a Department of Energy (DOE) contract in 1986. This analysis does not attempt to recreate the simulations performed by Prophet, but uses only the sequestration and production rates already calculated by Prophet. This means that variables such as formation depth, thickness, pore volume, well pattern, and injection pressure are not used in this analysis – they are embedded in the overall CO_2 sequestration and crude oil recovery rates.
- No data are available on the composition of VOCs from oil and gas extraction and processing operations. Pentane was chosen to represent the combustion profile for flared VOCs, but there is not much variability among the emission factors of C_2 through C_5 hydrocarbons. The CO_2 emissions from pentane combustion are only 4 percent higher than those for ethane combustion (3.03 vs. 2.90).
- Data for refrigeration and fractionation technologies for gas separation are based on detailed thermodynamic modeling of a gas processing plant in Canada (Vargas, 2010). These data were used to represent EOR operations in the Permian Basin, which has different crude oil

properties than the reference facility in Canada. No data are available for refrigeration and fractionation at EOR facilities in the Permian Basin.

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 1-2**.

2 Gate-to-Gate Results for EOR

The following results focus on the GHG emissions from EOR. 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. These results are on the basis of a single barrel of crude oil produced.

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-gate EOR emissions can be achieved. This section provides detailed gate-to-gate GHG emissions figures for each of the four gas separation technologies. These figures further indicate 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 GWPs of 298 for N_2O, 25 for CH_4, and 22,800 for CH_4 (Forster et al., 2007).

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. Two sets of sensitivity results are shown for each of the four gas separation technologies. The first set of figures is based on changes to the parameter values. In these figures, 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. The second set of sensitivity figures is based on uncertainty in the model parameters. The ranges of values for these figures are based on the date provided in **Table 1-2**.

A detailed comparison of all gas technologies is presented at the end of this section.

2.1 Fractionation Gas Separation

The gate-to-gate GHG emissions for EOR with fractionation gas processing with mass allocation, as shown in **Figure 2-1**, are 66.5 kg CO_2e /barrel crude produced, with uncertainty ranging from 49.3 to 95.3 CO_2e (an uncertainty of approximately +43 percent/-26 percent). The majority of LC GHG emissions are from CO_2 at 91.7 percent, with the remainder split between CH_4, N_2O, and SF_6 at 7.7 percent, 0.3 percent, and 0.4 percent, respectively.

As shown in **Figure 2-1**, emissions associated with the electricity for the CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose the vast majority of the gate-to-gate GHG emissions for EOR with fractionation gas processing. Other significant contributors include venting

and flaring activities during oil, gas, and water separation, as well as natural gas combustion to facilitate the phase separation. The uncertainty in the total gate-to-gate GHG emissions is driven by four main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, makeup of the electricity grid used to power the operations at the EOR site, and the formation leakage. The majority of CH_4 emissions shown in **Figure 2-1** are from power generation.

Figure 2-2 shows the sensitivity of the gate-to-gate GHG emissions for EOR with fractionation gas processing relative to the key parameters in the model. The goal of the sensitivity analysis is to determine which parameters have the greatest influence on GHG results. When conducting the sensitivity analysis, an arbitrary, but uniform, increase of 100 percent is applied to each parameter while holding the other parameters at their expected values. The sensitivity analysis does not account for uncertainty (uncertainty is shown by the error bars on the detailed GHG results **Figure 2-1** and also in the **Figure 2-3** sensitivity graph).

As expected, the most sensitive parameters in the model are related crude recovery ratio and the CO_2 injection pressure, followed by the electricity demands for crude artificial lift pumping and gas processing. Based on the boundaries of this gate-to-gate system, a 100 percent increase in the crude recovery ratio causes a 67-percent decrease in total GHG emissions, and the CO_2 injection pressure causes a 57-percent increase in total GHG emissions.

The sensitivity of gate-to-gate GHG emissions to parameter uncertainty is shown in **Figure 2-3**. As shown in **Table 1-2**, the crude recovery ranges from 2 to 4.35 barrel/tonne of CO_2 sequestered. The change in crude recovery scales the other inputs and outputs to/from the EOR well accordingly, including hydrocarbon gas production, brine production, and required injection rate of CO_2. There is an inverse relationship between the crude recovery factor and the gate-to-gate GHG emissions. The required injection pressure is a function of the formation depth and geology, both of which vary from well to well. Added uncertainty in this model is due to differences in the source of electricity powering the EOR site activities (U.S. grid mix, ERCOT mix, GTSC). The fourth component of the uncertainty in gate-to-gate GHG emissions is related to the leakage of sequestered CO_2 from the formation.

Figure 2-1: Detailed GHG Emissions for EOR with Fractionation – Mass Allocation

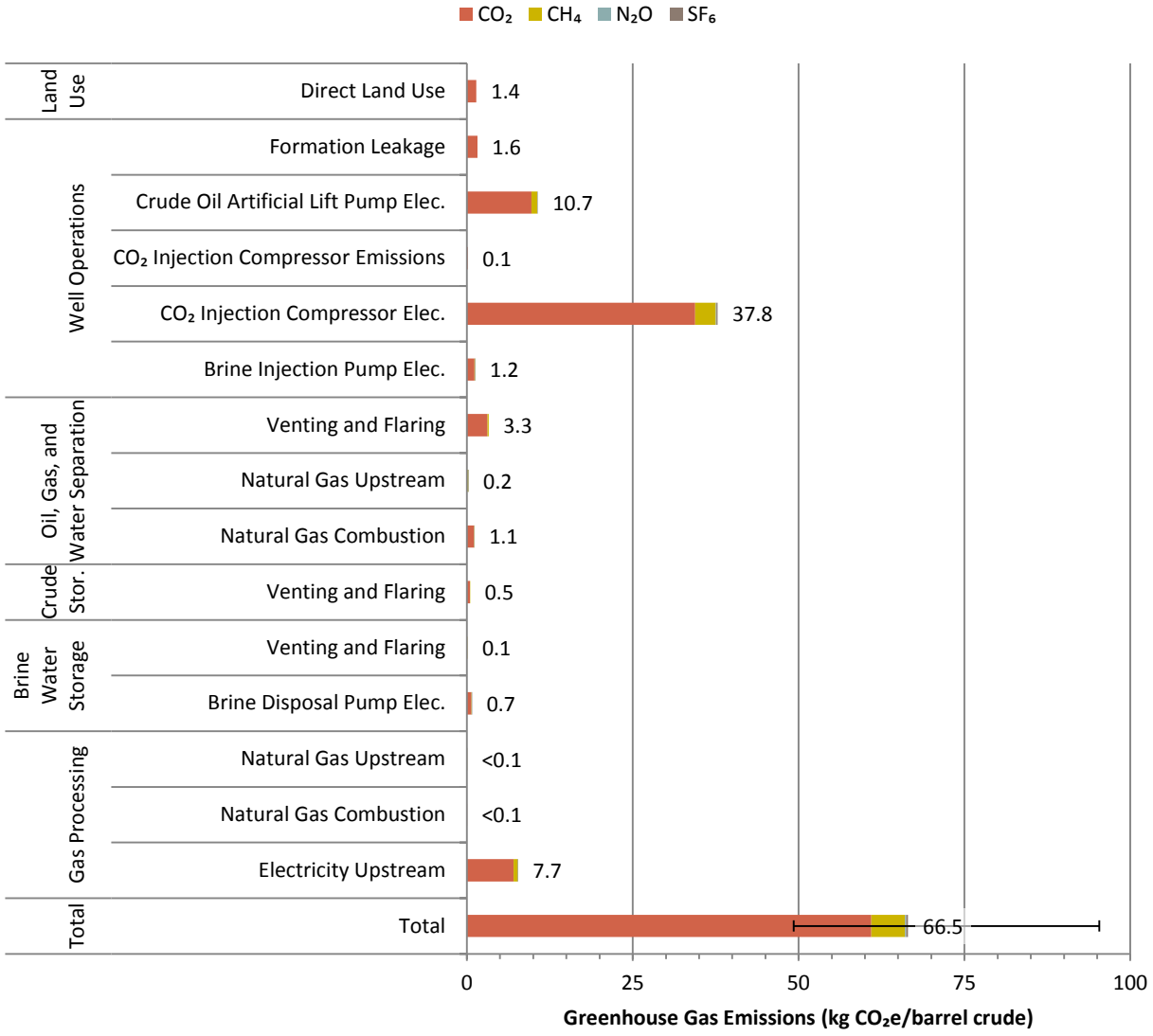


Figure 2-2: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Changes for Fractionation

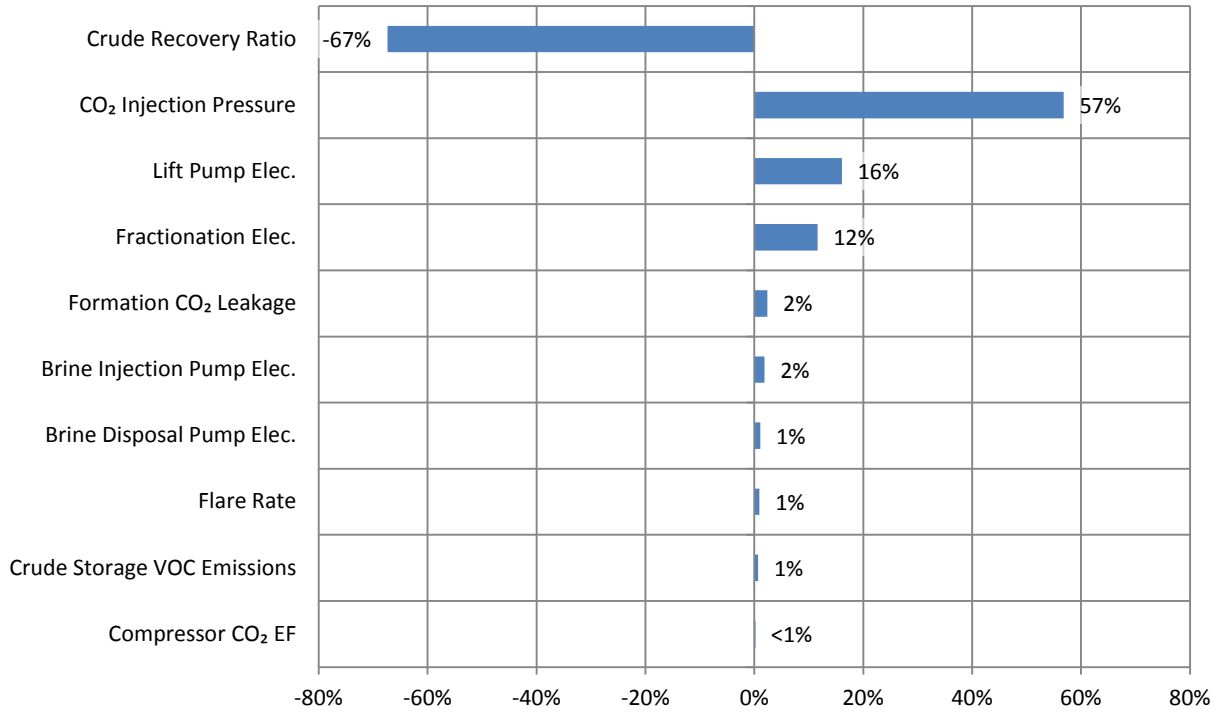
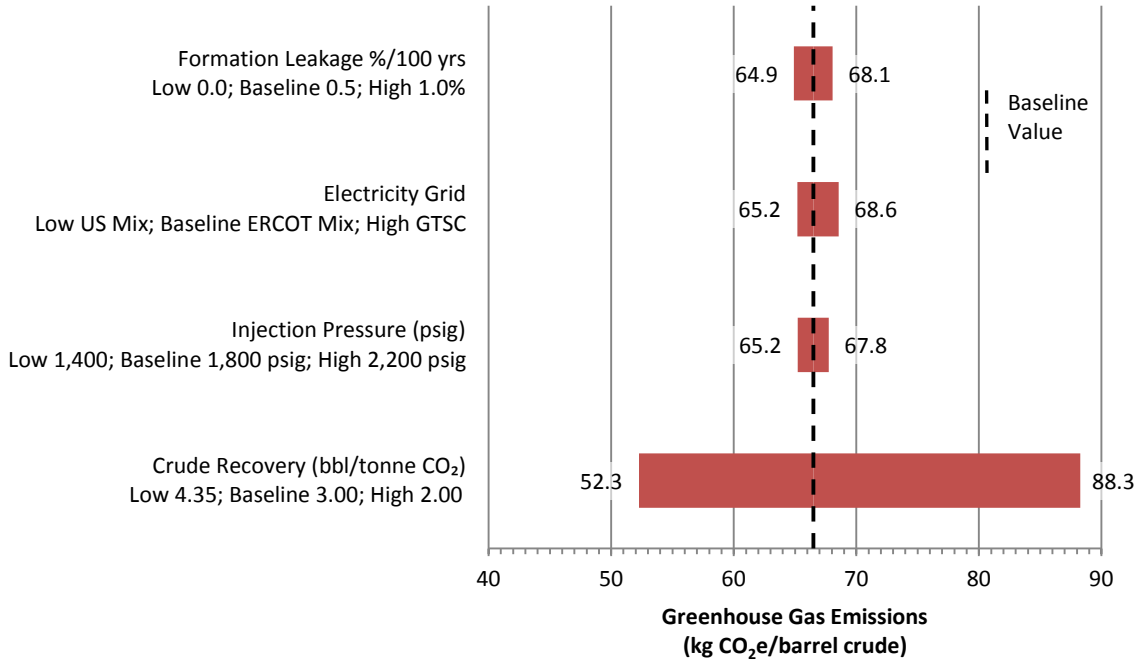


Figure 2-3: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Uncertainty for Fractionation



2.2 Refrigeration Gas Separation

The gate-to-gate GHG emissions for EOR with refrigeration gas processing with mass allocation, as shown in **Figure 2-4**, are 66.5 kg CO_2e /barrel crude produced, with uncertainty ranging from 49.3 to 95.3 kg CO_2e (an uncertainty of approximately +43 percent/-26 percent). The majority of LC GHG emissions are from CO_2 at 91.7 percent, with the remainder split between CH_4, N_2O, and SF_6 at 7.7 percent, 0.3 percent, and 0.4 percent, respectively.

As shown by **Figure 2-4**, emissions associated with the electricity for the CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose the vast majority of the gate-to-gate GHG emissions for EOR with refrigeration gas processing. The uncertainty in the total gate-to-gate GHG emissions is driven by four main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, makeup of the electricity grid used to power the operations at the EOR site, and the formation leakage. The majority of CH_4 emissions shown in **Figure 2-4** are from power generation.

Figure 2-5 shows the sensitivity of the gate-to-gate GHG emissions for EOR with refrigeration gas processing relative to the key parameters in the model. The goal of the sensitivity analysis is to determine which parameters have the greatest influence on GHG results. When conducting the sensitivity analysis, an arbitrary, but uniform, increase of 100 percent is applied to each parameter while holding the other parameters at their expected values. The sensitivity analysis does not account for uncertainty (uncertainty is shown by the error bars on the detailed GHG results in **Figure 2-4** and also in the **Figure 2-6** sensitivity graph).

As expected, the most sensitive parameters in the model are related crude recovery ratio and the CO_2 injection pressure, followed by the electricity demands for crude artificial lift pumping and gas processing. Based on the boundaries of this gate-to-gate system, a 100 percent increase in the crude recovery ratio causes 67-percent decrease in total GHG emissions, and the CO_2 injection pressure causes a 57-percent increase in total GHG emissions.

The sensitivity of gate-to-gate GHG emissions to parameter uncertainty is shown in **Figure 2-6**. As shown in **Table 1-2**, the crude recovery ranges from 2 to 4.35 barrel/tonne of CO_2 sequestered. The change in crude recovery scales the other inputs and outputs to/from the EOR well accordingly, including hydrocarbon gas production, brine production, and required injection rate of CO_2. There is an inverse relationship between the crude recovery factor and the gate-to-gate GHG emissions. The required injection pressure is a function of the formation depth and geology, both of which vary from well to well. Added uncertainty in this model is due to differences in the source of electricity powering the EOR site activities (U.S. grid mix, ERCOT mix, GTSC). The fourth component of the uncertainty in gate-to-gate GHG emissions is related to the leakage of sequestered CO_2 from the formation.

The fractionation and refrigeration gas processing options have similar gate-to-gate GHG emissions. As previously discussed, the gas separation processes are identical except that the fractionation option includes two additional distillation columns to facilitate the separation of individual products out of the NGL stream. Both processes produce the same quantity of NGLs, in the fractionation case they are just separated into different streams. The only difference in the life cycle results comes from a small increase in the amount of natural gas required in the fractionation cases, which results in slightly higher GHG emissions; however, the difference is negligible (approximately 0.02%) based on the functional unit of 1 barrel of crude oil and is not evident given the precision in the reported results.

Figure 2-4: Detailed GHG Emissions for EOR with Refrigeration – Mass Allocation

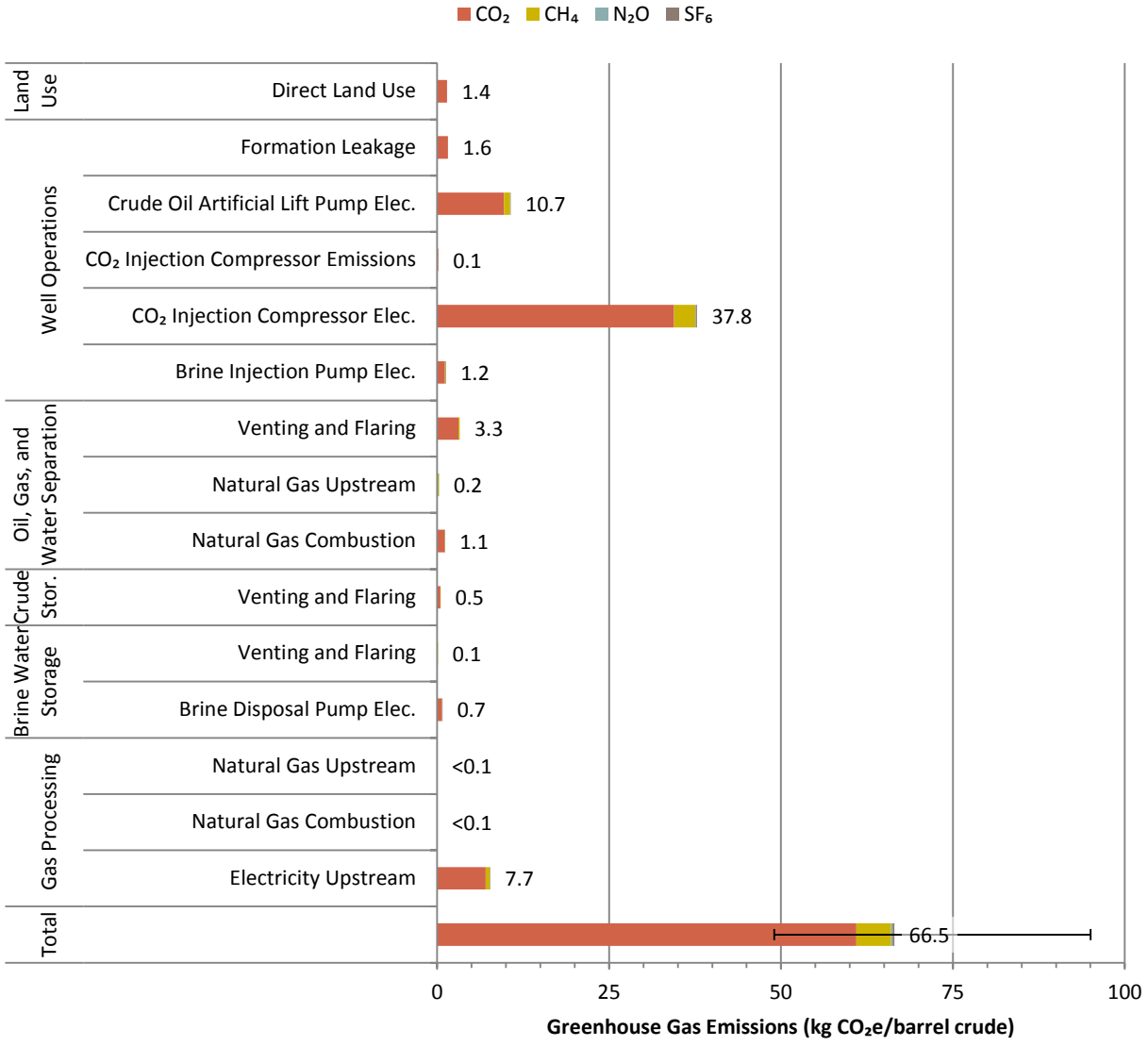


Figure 2-5: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Changes for Refrigeration

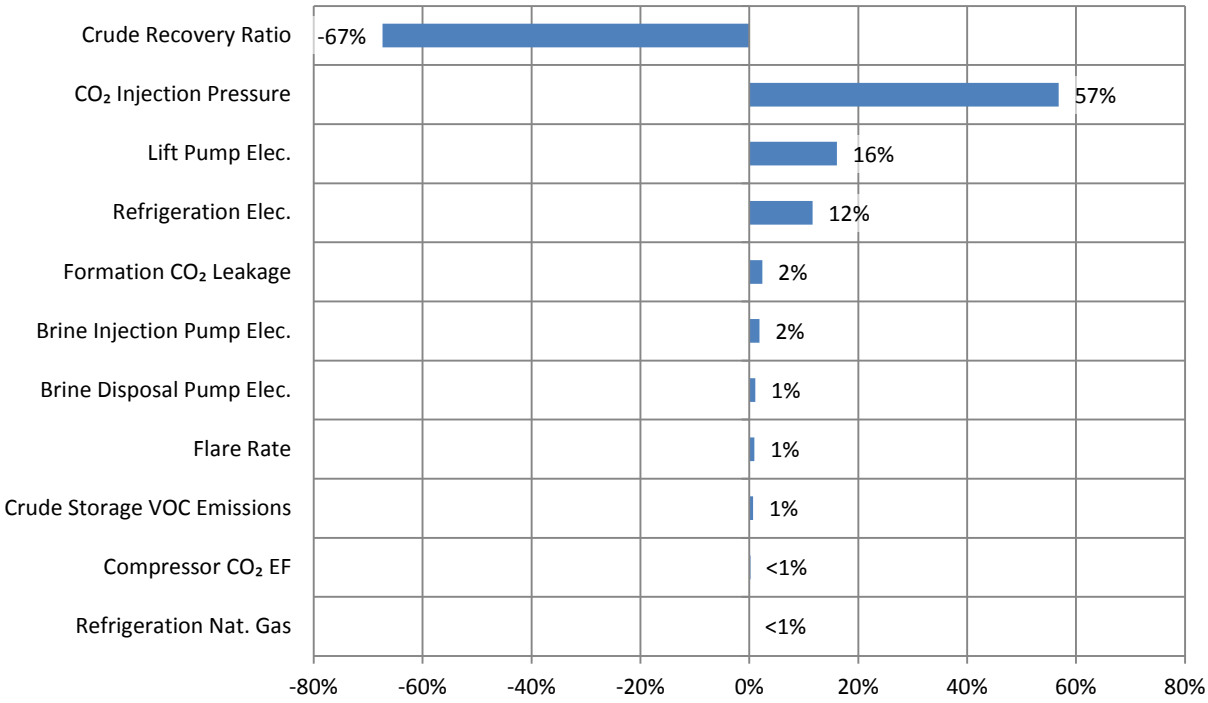
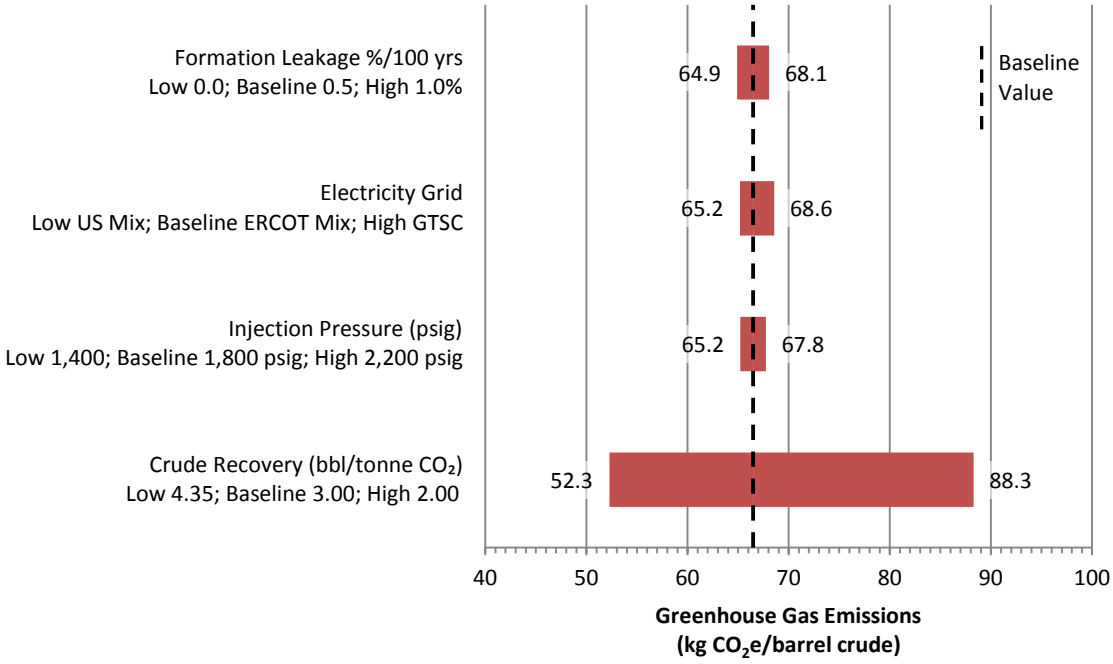


Figure 2-6: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Uncertainty for Refrigeration



2.3 Ryan-Holmes Gas Separation

The gate-to-gate GHG emissions for EOR with Ryan-Holmes gas processing with mass allocation, as shown in **Figure 2-7**, are 92.1 kg CO_2e /barrel crude produced, with uncertainty ranging from 68.3 to 129.2 kg CO_2e (an uncertainty of approximately +40 percent/-26 percent). The majority of LC GHG emissions are from CO_2 at 92.0 percent, with the remainder split between CH_4, N_2O, and SF_6 at 7.3 percent, 0.3 percent, and 0.4 percent, respectively.

As shown by **Figure 2-7**, emissions associated with the electricity for the CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose the vast majority of the gate-to-gate GHG emissions for EOR with Ryan-Holmes gas processing. Compared to fractionation and refrigeration, the electricity requirement for Ryan-Holmes gas processing is a more significant contributor to the overall gate-to-gate GHG emissions. Other significant contributors include venting and flaring activities during oil, gas, and water separation, as well as natural gas combustion to facilitate the phase separation. The majority of CH_4 emissions shown in **Figure 2-7** are from power generation.

Figure 2-8 shows the sensitivity of the gate-to-gate GHG emissions for EOR with Ryan-Holmes gas processing relative to the key parameters in the model. The goal of the sensitivity analysis is to determine which parameters have the greatest influence on GHG results. When conducting the sensitivity analysis, an arbitrary, but uniform, increase of 100 percent is applied to each parameter while holding the other parameters at their expected values. The sensitivity analysis does not account for uncertainty (uncertainty is shown by the error bars on the detailed GHG results in **Figure 2-7** and also in the **Figure 2-9** sensitivity graph).

As expected, the most sensitive parameters in the model are related crude recovery ratio and the CO_2 injection pressure. These are followed closely by Ryan-Holmes electricity usage, which is much larger contributor than in the other cases. Electricity demands for crude artificial lift pumping also remains a significant parameter. Based on the boundaries of this gate-to-gate system, a 100 percent increase in the crude recovery ratio causes a 69-percent decrease in total GHG emissions, and the CO_2 injection pressure causes a 38-percent increase in total GHG emissions.

The sensitivity of gate-to-gate GHG emissions to parameter uncertainty is shown in **Figure 2-9**. As shown in **Table 1-2**, the crude recovery ranges from 2 to 4.35 barrel/tonne of CO_2 sequestered. The change in crude recovery scales the other inputs and outputs to/from the EOR well accordingly, including hydrocarbon gas production, brine production, and required injection rate of CO_2. There is an inverse relationship between the crude recovery factor and the gate-to-gate GHG emissions. The required injection pressure is a function of the formation depth and geology, both of which vary from well to well. Added uncertainty in this model is due to differences in the source of electricity powering the EOR site activities (U.S. grid mix, ERCOT mix, GTSC). The fourth component of the uncertainty in gate-to-gate GHG emissions is related to the leakage of sequestered CO_2 from the formation.

Figure 2-7: Detailed GHG Emissions for EOR with Ryan-Holmes – Mass Allocation

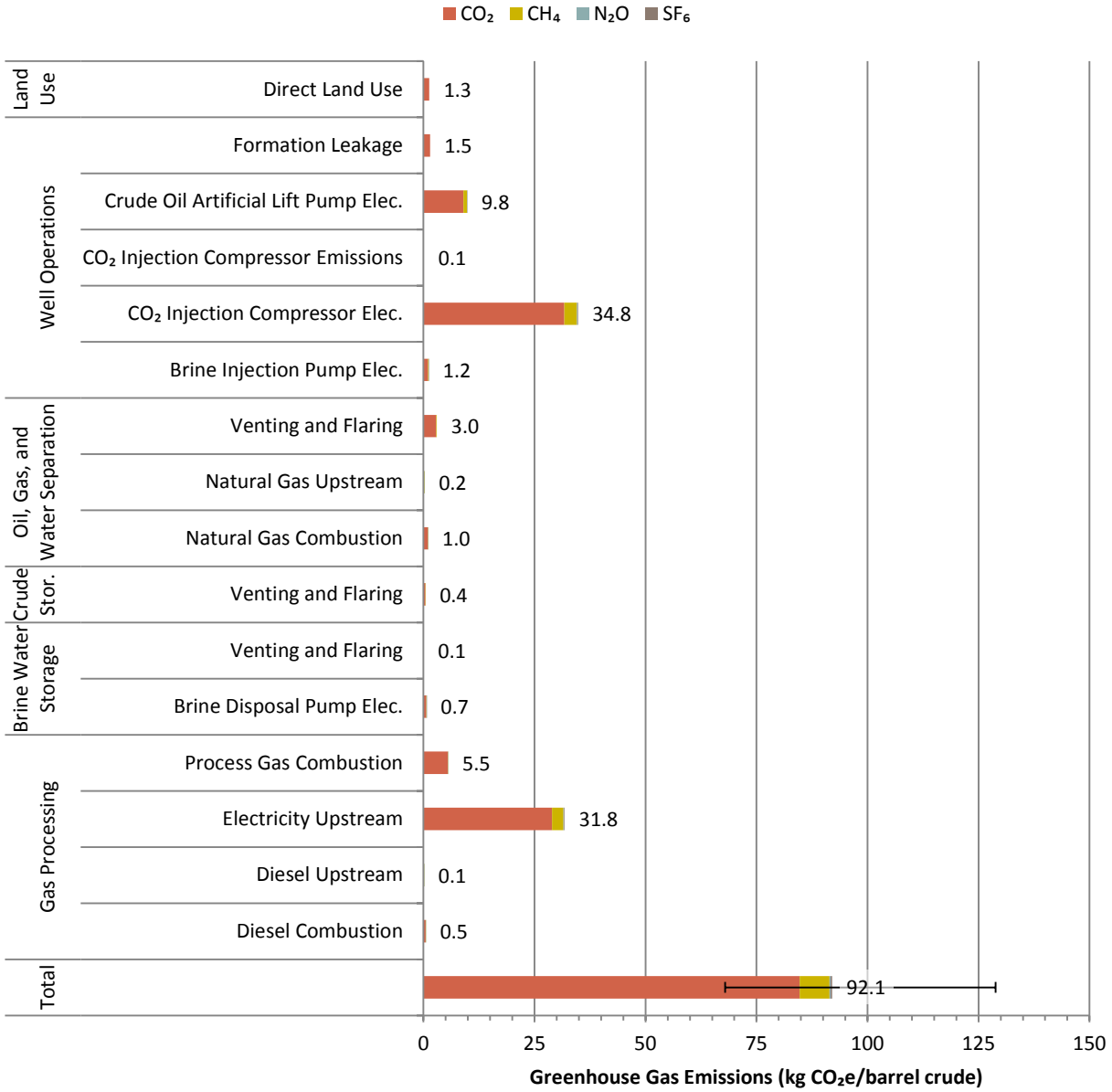


Figure 2-8: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Changes for Ryan-Holmes

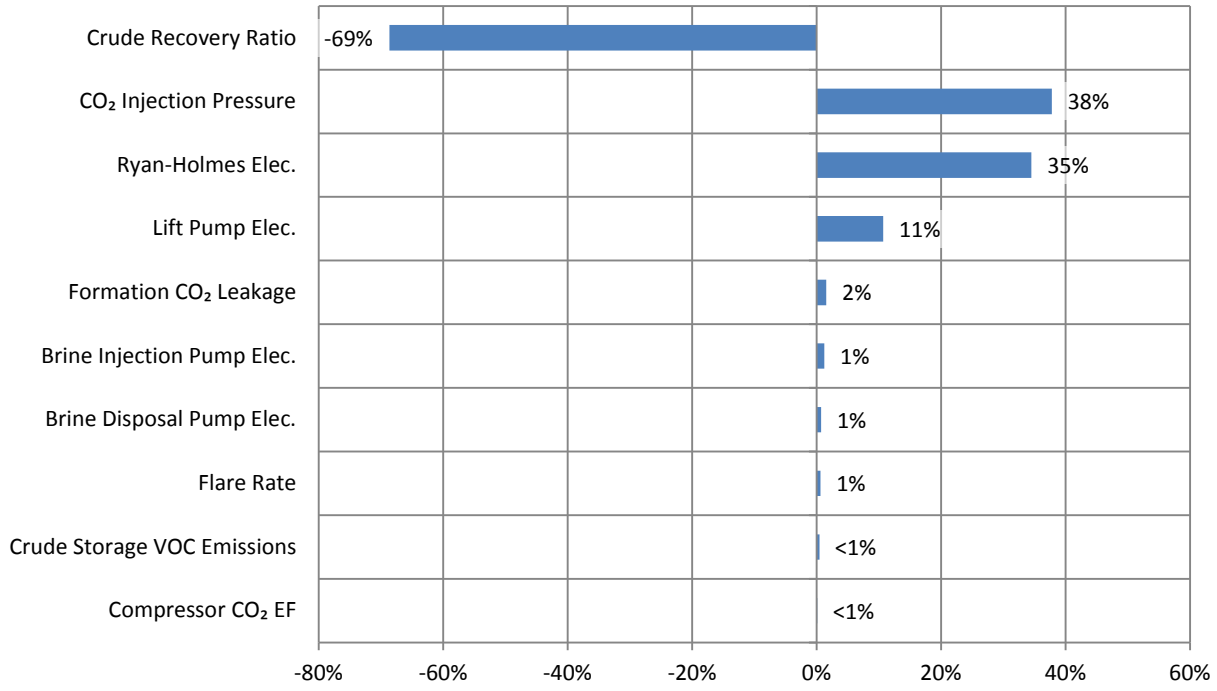
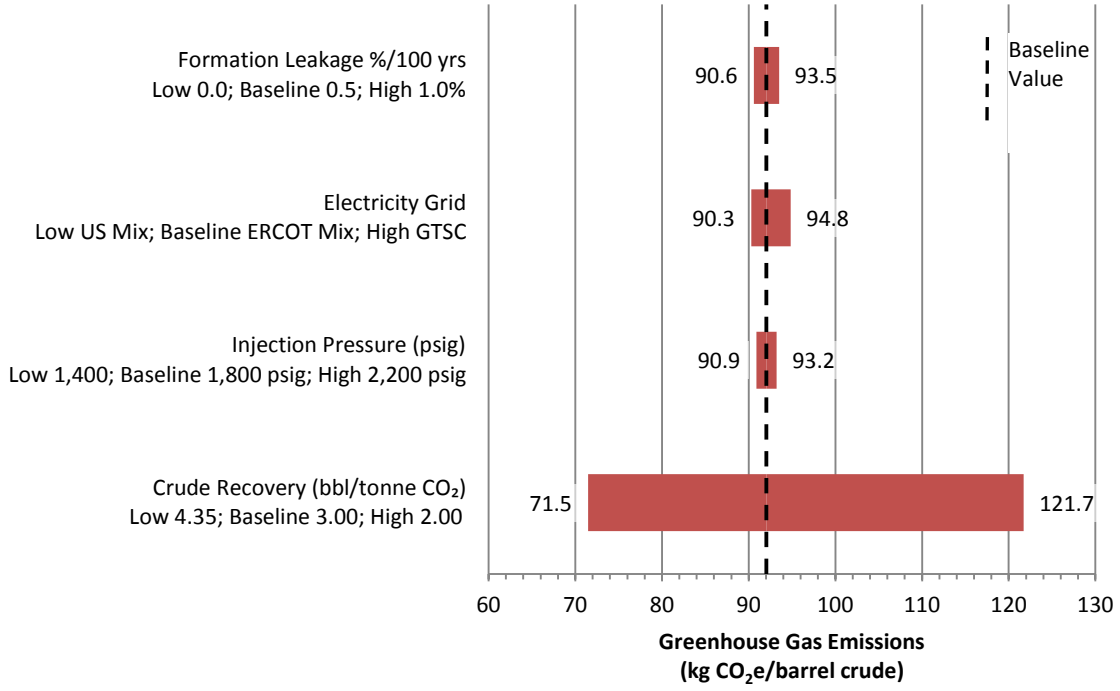


Figure 2-9: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Uncertainty for Ryan-Holmes



2.4 Membrane Gas Separation

The gate-to-gate GHG emissions for EOR with membrane gas processing with mass allocation, as shown in **Figure 2-10**, are 118.6 kg CO_2e /barrel crude produced, with uncertainty ranging from 88.1 to 164.5 kg CO_2e (an uncertainty of approximately +39 percent/-26 percent). The majority of LC GHG emissions are from CO_2 at 89.8 percent, with the remainder split between CH_4, N_2O, and SF_6 at 9.8 percent, 0.2 percent, and 0.2 percent, respectively.

As shown **Figure 2-10**, emissions associated with the electricity for the CO_2 injection compressor, crude oil artificial lift pump, and gas processing, along with natural gas combustion for gas processing compose the vast majority of the gate-to-gate GHG emissions for EOR with membrane gas processing. Other significant contributors include venting and flaring activities during oil, gas, and water separation, as well as natural gas combustion to facilitate the phase separation. Unlike the other gas processing technologies, the membrane system has a significant contribution to the gate-to-gate GHG emissions from natural gas combustion at the gas processing facility. The post-membrane amine polishing system requires natural gas to regenerate the amine solvent used to capture the CO_2 from the membrane effluent. The majority of CH_4 emissions shown **Figure 2-10** are from power generation.

Figure 2-11 shows the sensitivity of the gate-to-gate GHG emissions for EOR with membrane gas processing relative to the key parameters in the model. The goal of the sensitivity analysis is to determine which parameters have the greatest influence on GHG results. When conducting the sensitivity analysis, an arbitrary, but uniform, increase of 100 percent is applied to each parameter while holding the other parameters at their expected values. The sensitivity analysis does not account for uncertainty (uncertainty is shown by the error bars on the detailed GHG results in **Figure 2-10** and also in the **Figure 2-12** sensitivity graph).

As expected, the most sensitive parameters in the model are related crude recovery ratio and the natural gas input to make steam for the post-membrane, amine-based CO_2 capture system. The CO_2 injection pressure and the electricity demands for crude artificial lift pumping remain significant as well. Based on the boundaries of this gate-to-gate system, a 100 percent increase in the crude recovery ratio causes a 72-percent decrease in total GHG emissions, and the steam requirement for the amine-based CO_2 capture causes a 44-percent increase in total GHG emissions.

The sensitivity of gate-to-gate GHG emissions to parameter uncertainty is shown in **Figure 2-12**. As shown in **Table 1-2**, the crude recovery ranges from 2 to 4.35 barrel/tonne of CO_2 sequestered. The change in crude recovery scales the other inputs and outputs to/from the EOR well accordingly, including hydrocarbon gas production, brine production, and required injection rate of CO_2. There is an inverse relationship between the crude recovery factor and the gate-to-gate GHG emissions. The required injection pressure is a function of the formation depth and geology, both of which vary from well to well. Added uncertainty in this model is due to differences in the source of electricity to powering the EOR site activities (U.S. grid mix, ERCOT mix, GTSC). The fourth component of the uncertainty in gate-to-gate GHG emissions that is related to the leakage of sequestered CO_2 from the formation.

Figure 2-10: Detailed GHG Emissions for EOR with Membrane – Mass Allocation

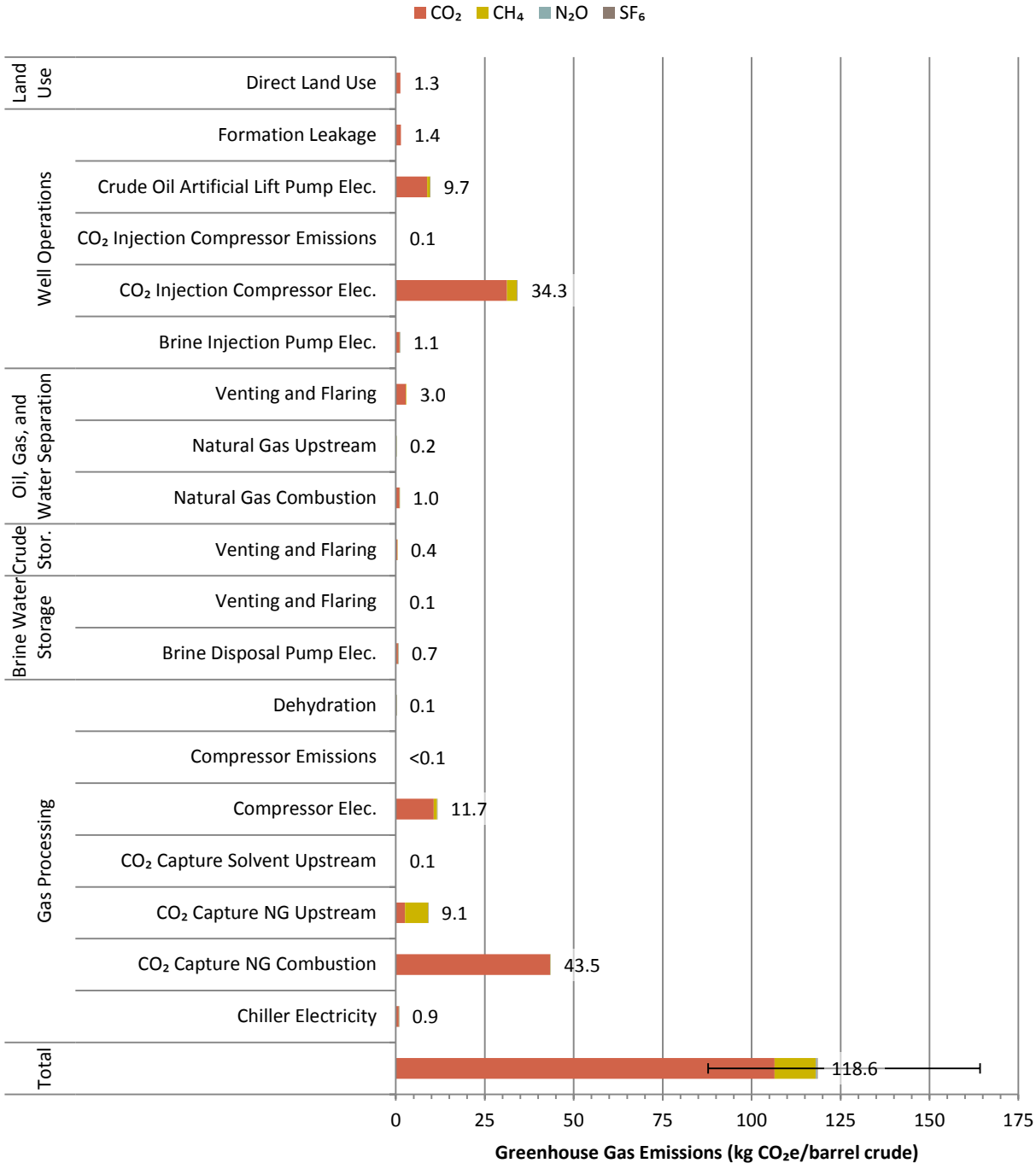


Figure 2-11: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Changes for Membrane

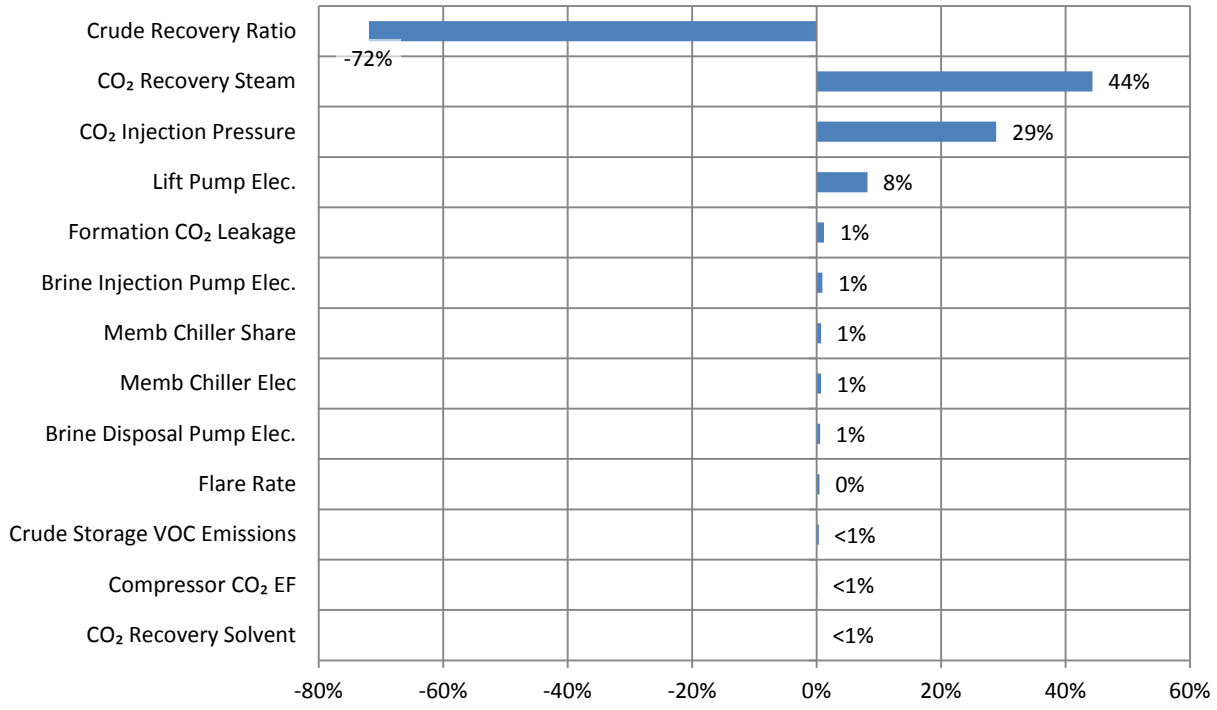
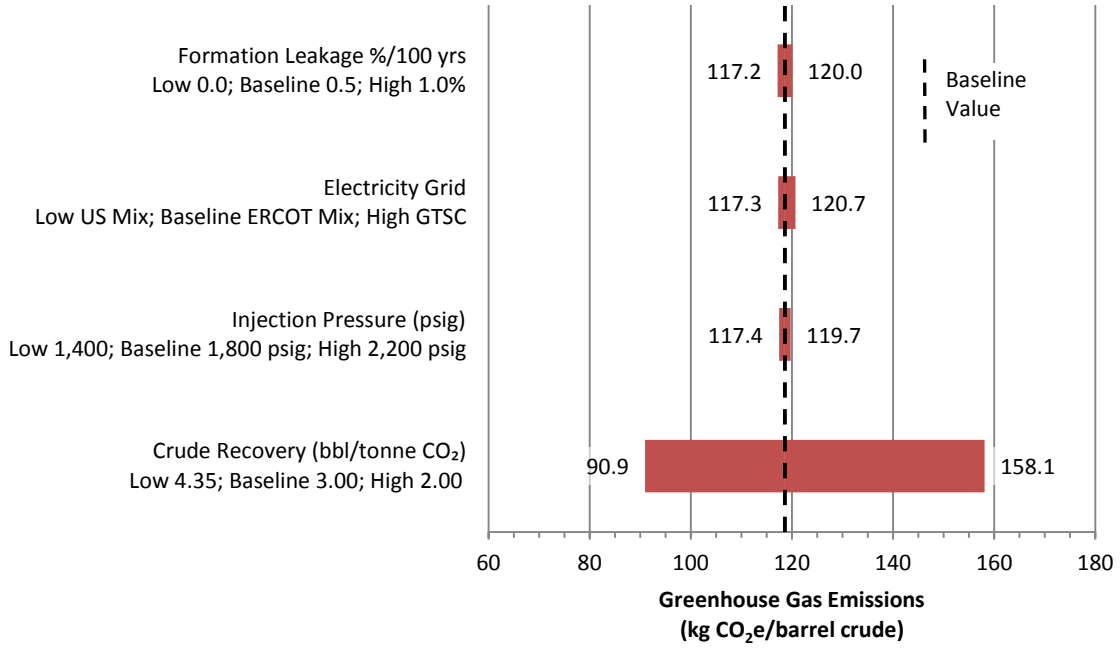


Figure 2-12: Sensitivity of Gate-to-Gate GHG Emissions to Parameter Uncertainty for Membrane

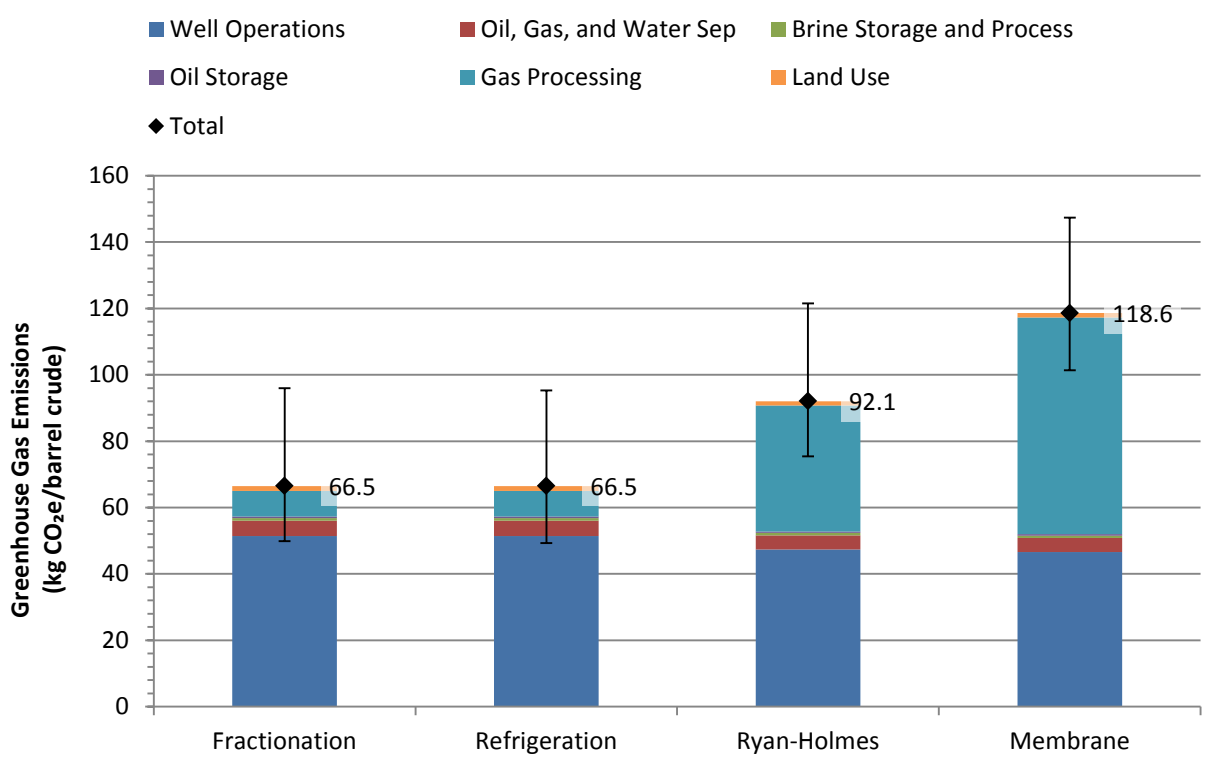


2.5 Comparative Gate-to-Gate Results

Figure 2-13 shows a comparison of the major processing components of the gate-to-gate GHG emissions for the four gas processing options for EOR. As shown, the difference between the scenarios is manifested by the difference in emissions attributed to gas processing. The fractionation and refrigeration gas processing options have similar gate-to-gate GHG emissions. As previously discussed, the gas separation processes are identical except that the fractionation option includes two additional distillation columns to facilitate the separation of individual products out of the NGL stream. Both processes produce the same quantity of NGLs, in the fractionation case they are just separated into different streams. The only difference in the life cycle results comes from a small increase in the amount of natural gas required in the fractionation cases, which results in slightly higher GHG emissions; however, the difference is negligible (approximately 0.02%) based on the functional unit of 1 barrel of crude oil and is not evident given the precision in the reported results.

Both Ryan-Holmes and membrane gas processing are more effective at recovering NGLs than refrigeration and fractionation. The increased recovery, however, comes at the expense of additional processing energy, which is also demonstrated in the figure by the increased GHG intensity associated with gas processing for Ryan-Holmes and membrane.

Figure 2-13: Gate-to-Gate GHG Emissions Summary for EOR with Gas Processing



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Appendix A:
Unit Process Mapping for Enhanced Oil Recovery

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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 enhanced oil recovery 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

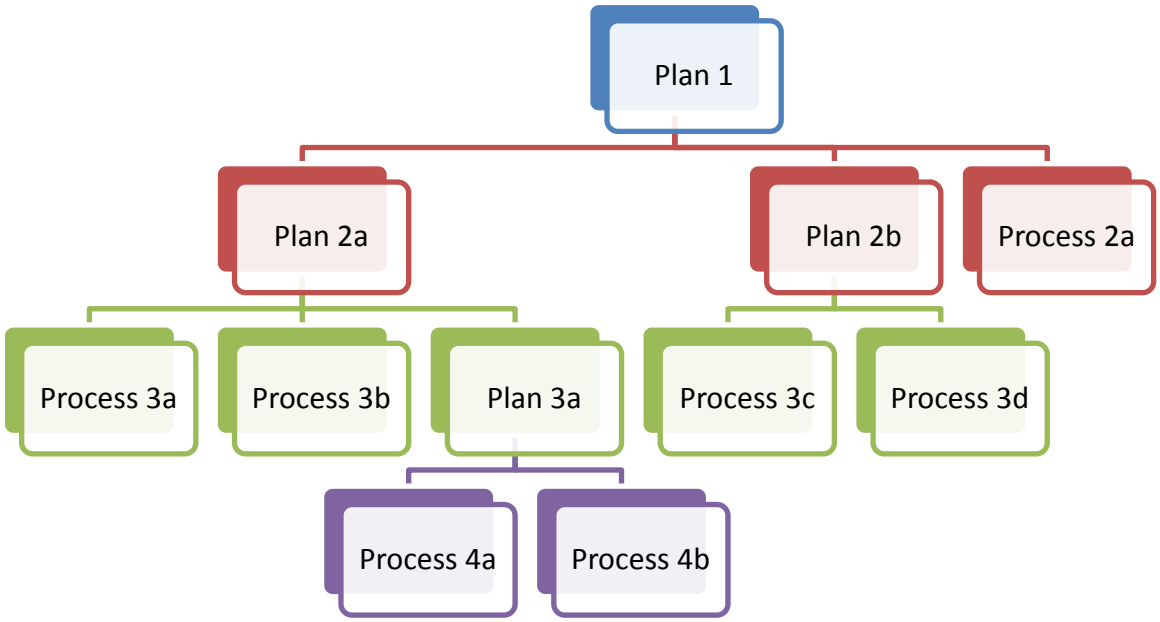

Table A-1 demonstrates the relationships between the tiers of plans used in the construction of the model. The figures in this section illustrate the connectivity of the various processes and plans.

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

Figure	Plan Name	Parent Plans	Child Plans
A-2	EOR Operations	None	1 – CO_2 for Injection – Compression/Pumping 2 – Brine Injection Pumping 3 – EOR Land Use 4 – Injection Well Construction and Installation 5 – Injection Well Closure 6 – EOR Gas Processing Facility Construction 7 – Water Disposal Well Construction and Installation 8 – Water Disposal Well Closure 9 – Crude Oil Artificial Lift Pumping 10 – Oil, Gas, and Water Separation 11 – Crude Oil Storage 12 – Brine Water Storage 13 – EOR Gas Processing – Refrigeration Only 14 – EOR Gas Process – Refrig/Fractionation 15 – EOR Gas Processing – Ryan-Holmes 16 – EOR Gas Processing - Membrane
A-3	CO_2 for Injection – Compression/Pumping	EOR Operations	None
A-4	Brine Injection Pumping	EOR Operations	None
A-5	EOR Land Use	EOR Operations	None
A-6	Injection Well Construction and Installation	EOR Operations	None
A-7	Injection Well Closure	EOR Operations	None
A-8	EOR Gas Processing Facility Construction	EOR Operations	None
A-9	Water Disposal Well Construction and Installation	EOR Operations	None
A-10	Water Disposal Well Closure	EOR Operations	None
A-11	Crude Oil Artificial Lift Pumping	EOR Operations	None
A-12	Oil, Gas, and Water Separation	EOR Operations	None
A-13	Crude Oil Storage	EOR Operations	None
A-14	Brine Water Storage	EOR Operations	1 – Brine Water Management
A-15	Brine Water Management	Brine Water Storage	None
A-16	EOR Gas Processing – Refrigeration Only	EOR Operations	None
A-17	EOR Gas Process – Refrig/Fractionation	EOR Operations	None
A-18	EOR Gas Processing – Ryan-Holmes	EOR Operations	None

Figure	Plan Name	Parent Plans	Child Plans
A-19	EOR Gas Processing - Membrane	EOR Operations	1 – Compressor Operations – Membrane Separation 2 – Dehydration Operations – Membrane Separation 3 – Chiller Operations – Membrane Separation 4 – CO_2 Capture – Post Membrane Separation
A-20	Compressor Operations – Membrane Separation	EOR Gas Processing - Membrane	None
A-21	Dehydration Operation – Membrane Separation	EOR Gas Processing - Membrane	None
A-22	Chiller Operations – Membrane Separation	EOR Gas Processing - Membrane	None
A-23	CO_2 Capture – Post Membrane Separation	EOR Gas Processing - Membrane	None

Figure A-2: Enhanced Oil Recovery Operations – Top-Level Plan

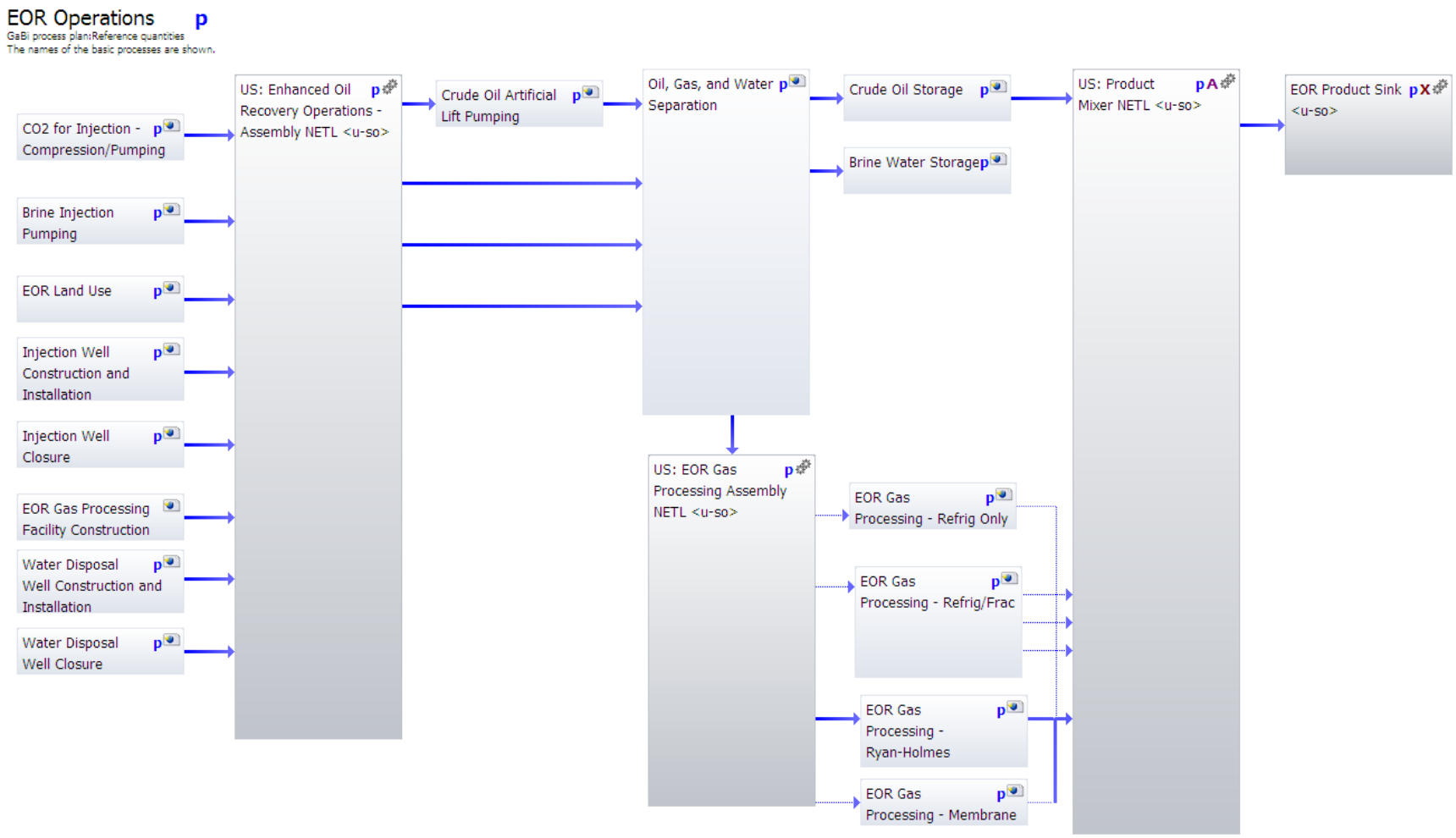

Table A-2: Unit Processes in Enhanced Oil Recovery Plan

Unit Process	Notes	Version	Creation Date
EOR Operations Assembly	This assembly scales the input flows based on the amount of EOR crude oil that is produced from the site.	1	10/2012
Gas Processing Assembly	This process was created to serve as a selector for gas processing technology.	N/A	N/A
Product Mixer	This combines the crude and NGL streams in a "virtual" sense to apply the mass allocation accounting math.	N/A	N/A
Product Sink	This process is connected to the product mixer and scales the rest of the model based on the amount of EOR crude oil desired.	N/A	N/A

Figure A-3: CO_2 for Injection – Compression/Pumping – Second-Level Plan

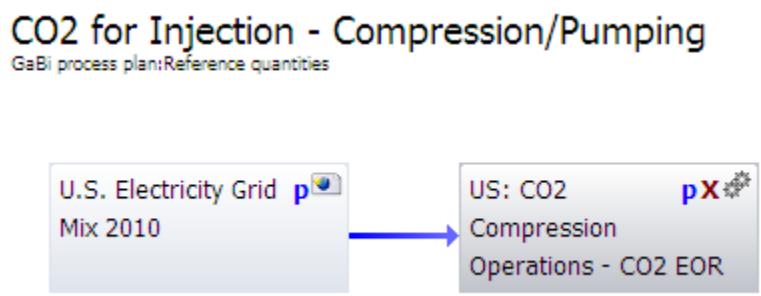

Table A-3: Unit Processes in CO_2 for Injection – Compression/Pumping Plan

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
CO_2 Compression Operations	This unit process includes the electricity requirements for the injection of CO_2 at an EOR site. It also includes fugitive leakage from compressor seals. For the purposes of this model, this process was split from the larger EOR operations process, which also included brine injection and crude lift pump activities.	1	10/2012

Figure A-4: Brine Injection Pumping – Second-Level Plan

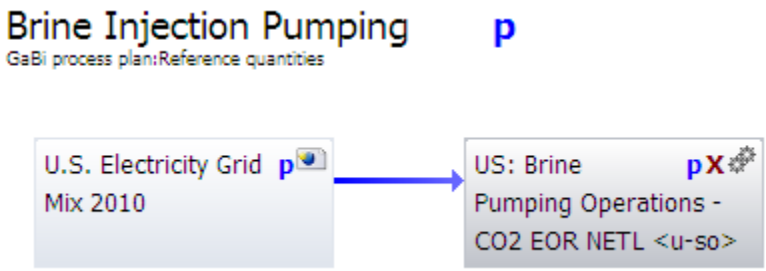

Table A-4: Unit Processes in Brine Injection Pumping Plan

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 Pumping Operations	This unit process includes the electricity requirements for the injection of brine at an EOR site. For the purposes of this model, this process was split from the larger EOR operations process, which also included CO_2 injection and crude lift pump activities.	1	10/2012

Figure A-5: EOR Land Use – Second-Level Plan

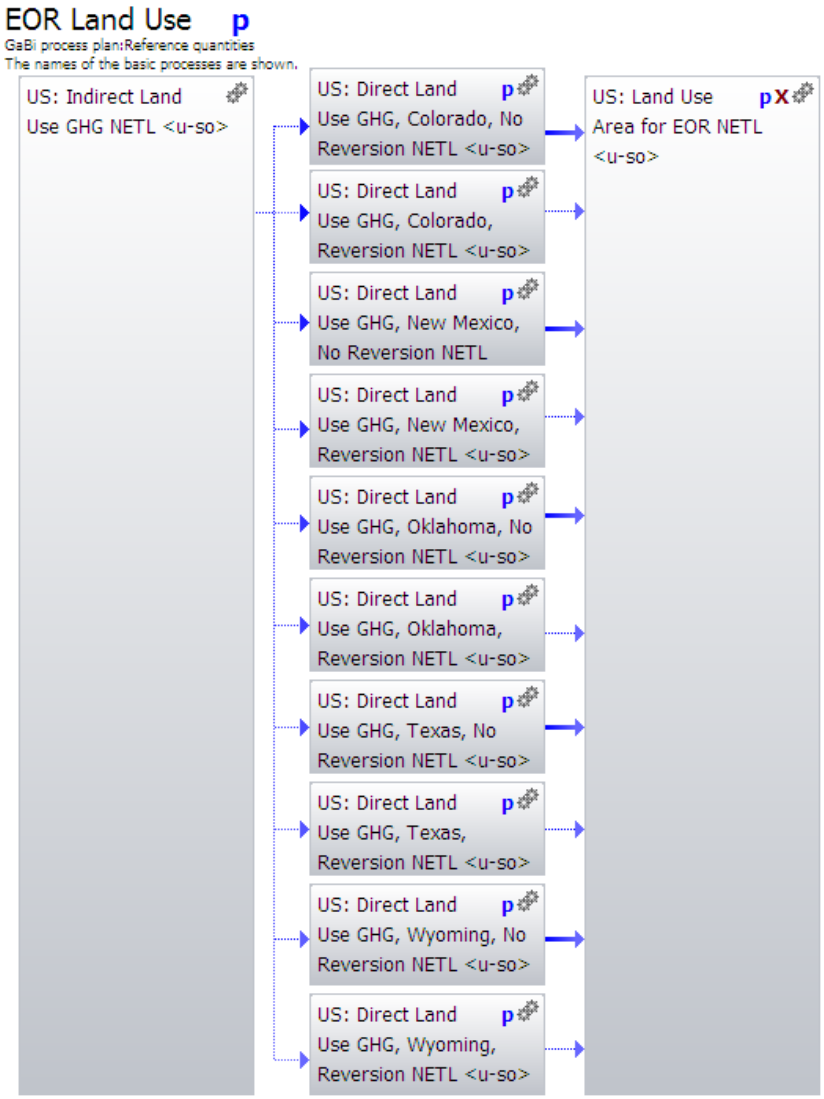

Table A-5: Unit Processes in EOR Land Use Plan

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 EOR site located in the Permian Basin, which encompasses five states as shown in **Figure A-5**. This unit process holds the parameter values for all five states in the Permian Basin and can 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 EOR site located in the Permian Basin, which encompasses five states as shown in **Figure A-5**. This unit process holds the parameter values for all five states (Colorado, New Mexico, Oklahoma, Texas, and Wyoming) and can 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 EOR	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-6: Injection Well Construction and Installation – Second-Level Plan

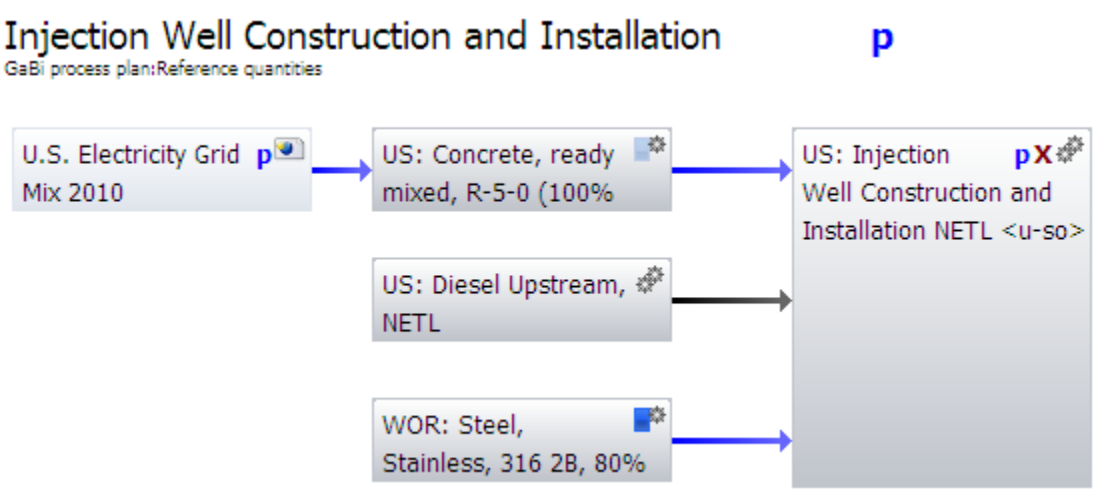

Table A-6: Unit Processes in Injection Well Construction and Installation Plan

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 an injection well at the EOR site. It is based on the same process that was used for the construction and installation of wells in a saline aquifer, with the only difference being the well depth. All inputs and outputs are scaled accordingly.	1	8/2012

Figure A-7: Injection Well Closure – Second-Level Plan

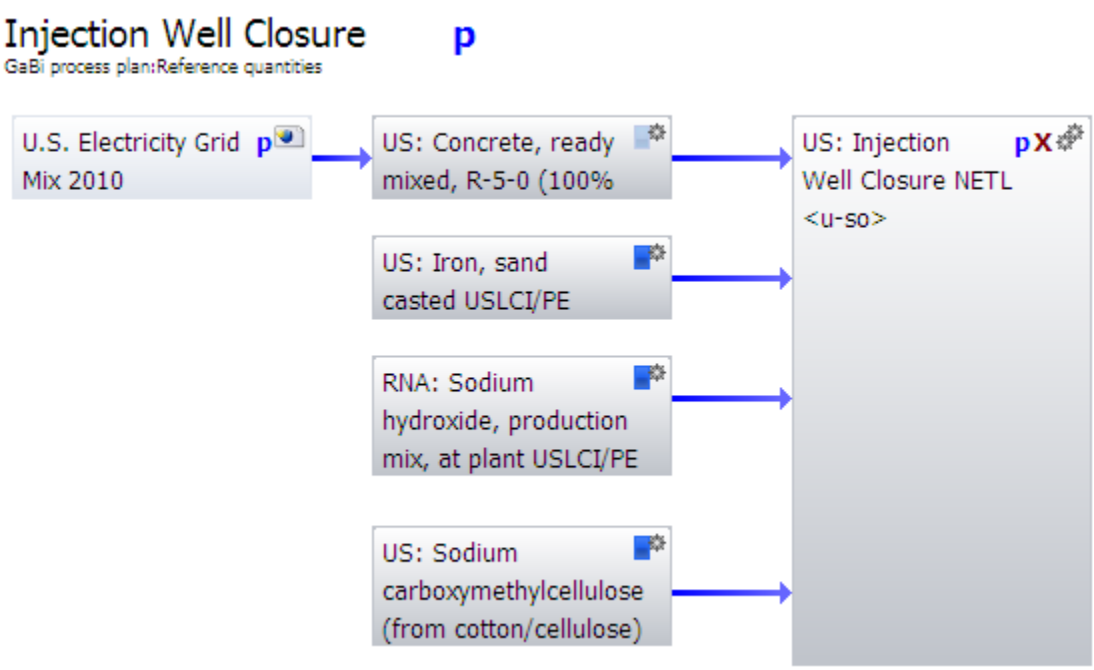

Table A-7: Unit Processes in Injection Well Closure Plan

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 an injection well at an EOR site. It is based on the same process that was used for the closure of wells in a saline aquifer, with the only difference being the well depth. All inputs and outputs are scaled accordingly.	1	9/2012

Figure A-8: EOR Gas Processing Facility Construction – Second-Level Plan

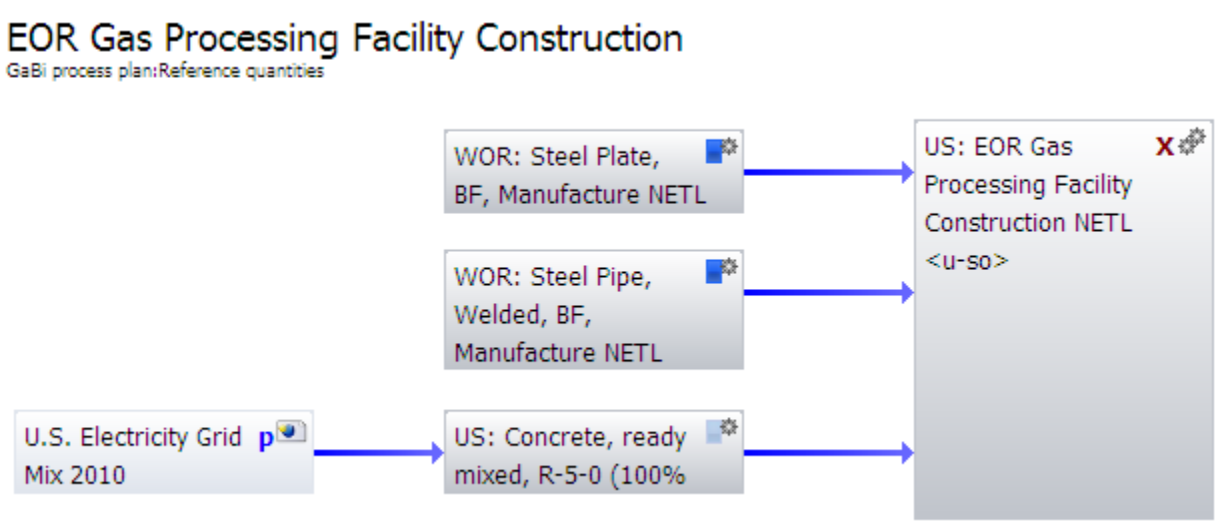

Table A-8: Unit Processes in EOR Gas Processing Facility Construction Plan

Unit Process	Notes	Version	Creation Date
Steep Plate	This unit process includes the production of steel plate including direct emissions and energy inputs.	1	N/A
Steel Pipe, Welded	This unit process includes the production of welded steel pipe including direct emissions and energy inputs.	1	N/A
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
EOR Gas Processing Facility Construction	This unit process specifies the appropriate inputs of construction materials for the EOR gas processing facility (concrete and steel). It is based on the same material requirements for a natural gas liquefaction facility.	1	N/A

Figure A-9: Water Disposal Well Construction and Installation – Second-Level Plan

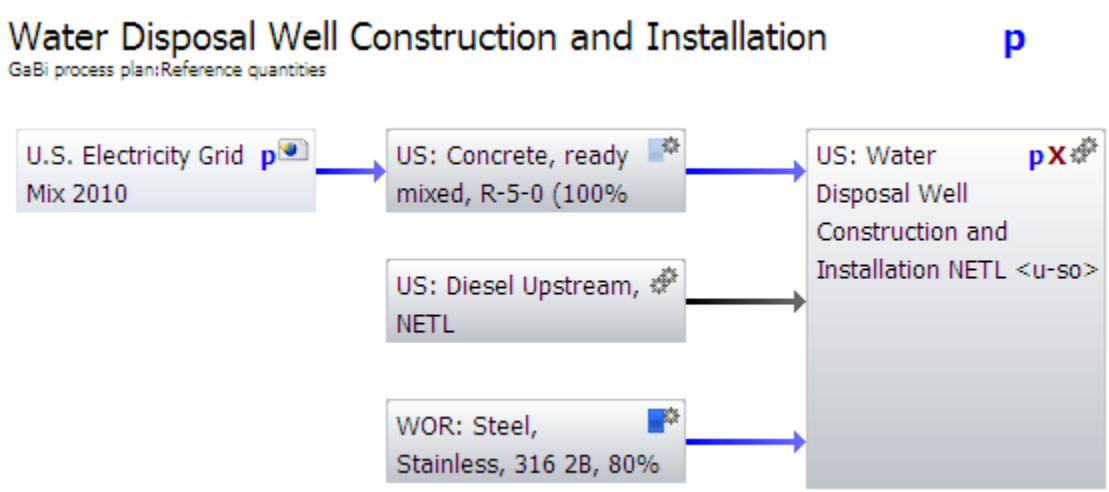

Table A-9: Unit Processes in Water Disposal Well Construction and Installation Plan

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 water disposal well at the EOR site. It is based on the same process that was used for the construction and installation of wells in a saline aquifer, with the only difference being the well depth. All inputs and outputs are scaled accordingly.	1	8/2012

Figure A-10: Water Disposal Well Closure – Second-Level Plan

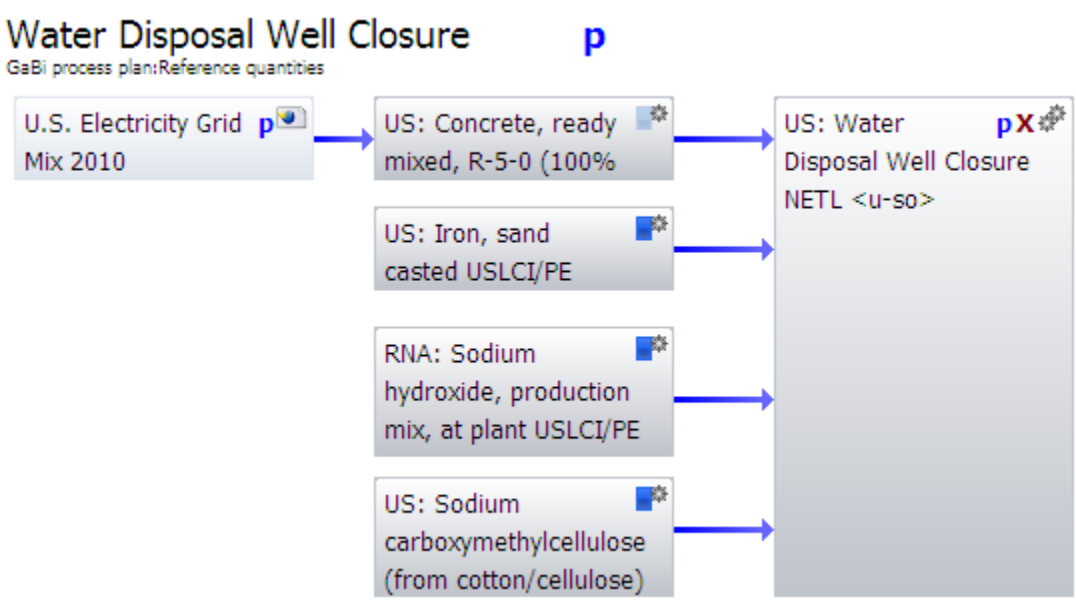

Table A-10: Unit Processes in Water Disposal Well Closure Plan

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 water injection well at an EOR site. It is based on the same process that was used for the closure of wells in a saline aquifer, with the only difference being the well depth. All inputs and outputs are scaled accordingly.	1	9/2012

Figure A-11: Crude Oil Artificial Lift Pumping – Second-Level Plan

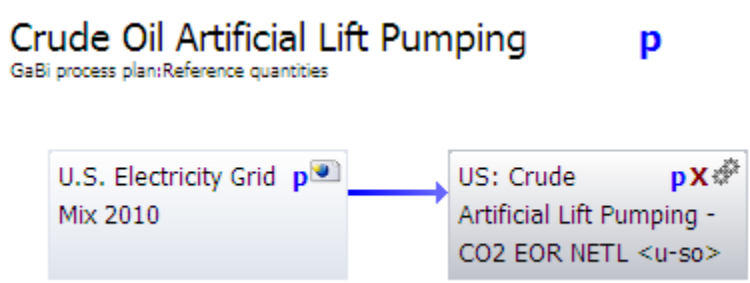

Table A-11: Unit Processes in Oil Artificial Lift Pumping Plan

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
Crude Artificial Lift Pumping	This unit process includes the electricity requirements for artificial lift pumping of crude oil at an EOR site. For the purposes of this model, this process was split from the larger EOR operations process, which also included CO_2 and brine injection activities.	1	10/2012

Figure A-12: Oil, Gas, and Water Separation – Second-Level Plan

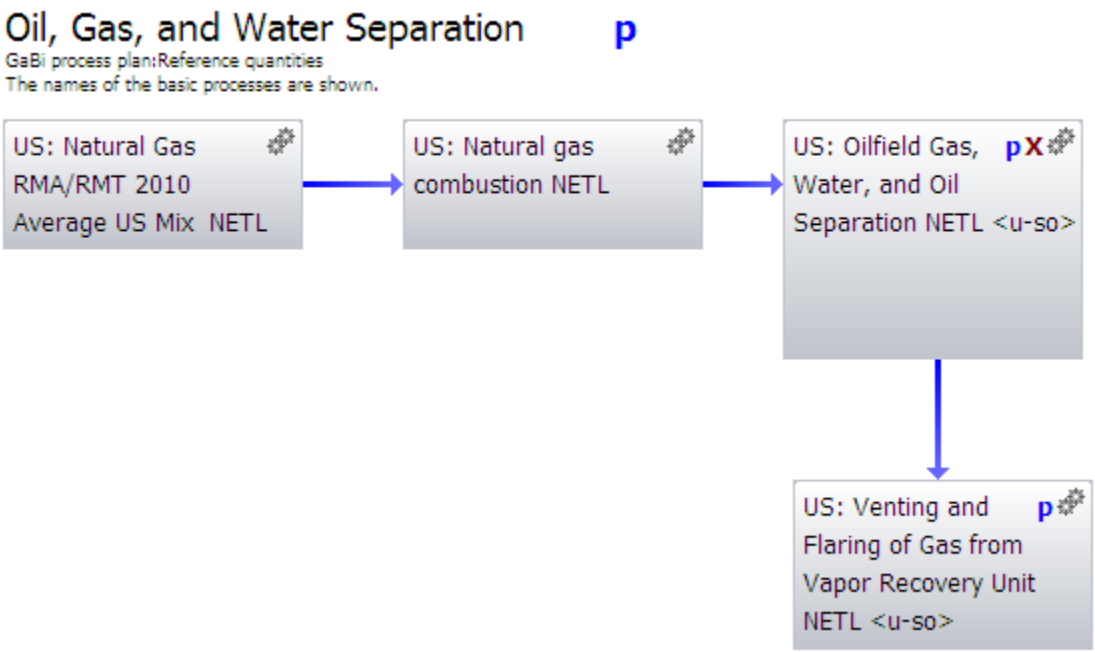

Table A-12: Unit Processes in Oil, Gas, and Water Separation Plan

Unit Process	Notes	Version	Creation Date
Natural Gas Upstream	This process includes all inputs for the raw material acquisition and raw material transportation for 1 kg of delivered natural gas proportionally from all extraction methods.	2	5/2012
Natural Gas Combustion	This unit process models air emissions and heat produced by a large-scale natural gas fired boiler, producing over 100 million Btu/hr.	1	8/2010
Oilfield Gas, Water, and Oil Separation	This unit process models the separation of wellhead product to gas, oil, and water.	1	10/2012
Venting and Flaring from VRU	This unit process quantifies the carbon dioxide and other GHG emissions associated with the flaring and venting of gas.	1	10/2012

Figure A-13: Crude Oil Storage – Second-Level Plan

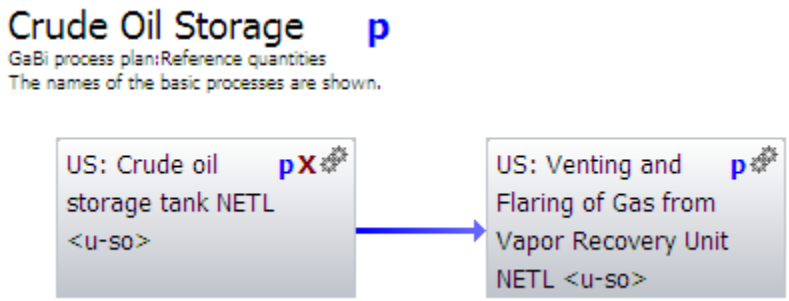

Table A-13: Unit Processes in Crude Oil Storage Plan

Unit Process	Notes	Version	Creation Date
Crude Oil Storage Tank	This unit process accounts for VOC losses from a crude oil storage tank at an EOR extraction site.	1	10/2012
Venting and Flaring from VRU	This unit process quantifies the carbon dioxide and other GHG emissions associated with the flaring and venting of gas.	1	10/2012

Figure A-14: Brine Water Storage – Second-Level Plan

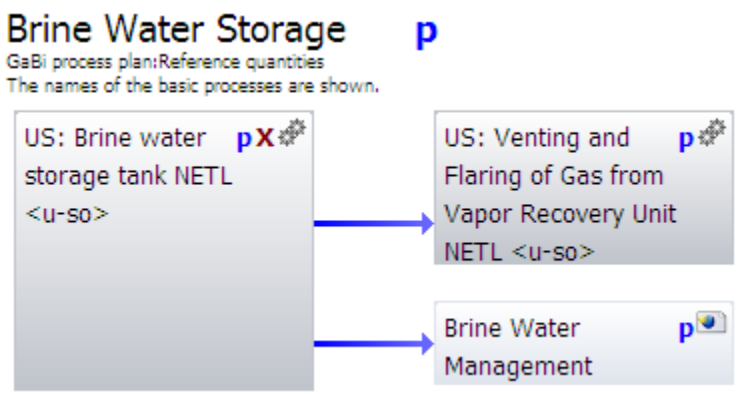

Table A-14: Unit Processes in Brine Water Storage Plan

Unit Process	Notes	Version	Creation Date
Brine Water Storage Tank	This unit process accounts for methane losses from a brine water storage tank at an EOR extraction site.	1	10/2012
Venting and Flaring from VRU	This unit process quantifies the carbon dioxide and other GHG emissions associated with the flaring and venting of gas.	1	10/2012

Figure A-15: Brine Water Management – Third-Level Plan

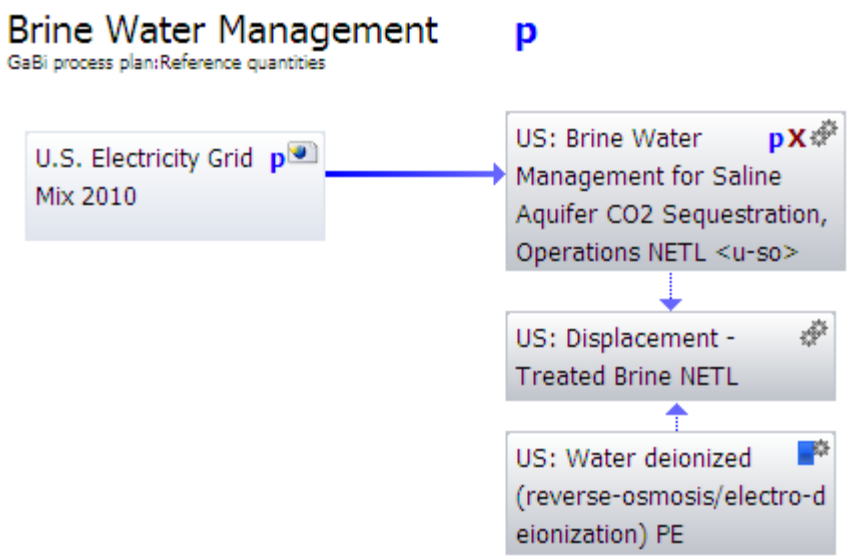

Table A-15: Unit Processes in Brine Water Management Plan

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

Figure A-16: EOR Gas Processing – Refrig Only – Second-Level Plan

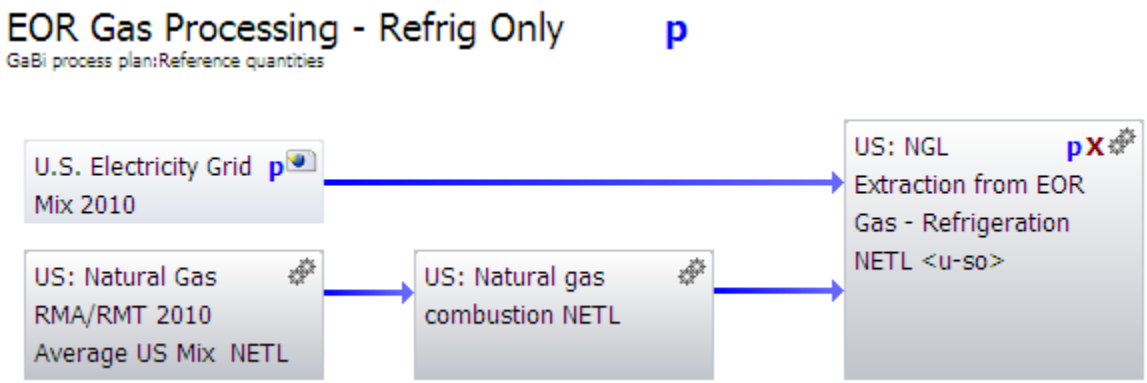

Table A-16: Unit Processes in EOR Gas Processing – Refrig Only Plan

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
Natural Gas Upstream	This process includes all inputs for the raw material acquisition and raw material transportation for 1 kg of delivered natural gas proportionally from all extraction methods.	2	5/2012
Natural Gas Combustion	This unit process models air emissions and heat produced by a large-scale natural gas fired boiler, producing over 100 million Btu/hr.	1	8/2010
NGL Extraction from EOR Gas – Refrigeration	This unit processes models the separations of natural gas liquids from EOR recycle gas by using a refrigeration process.	1	10/2012

Figure A-17: EOR Gas Processing – Refrig/Frac – Second-Level Plan

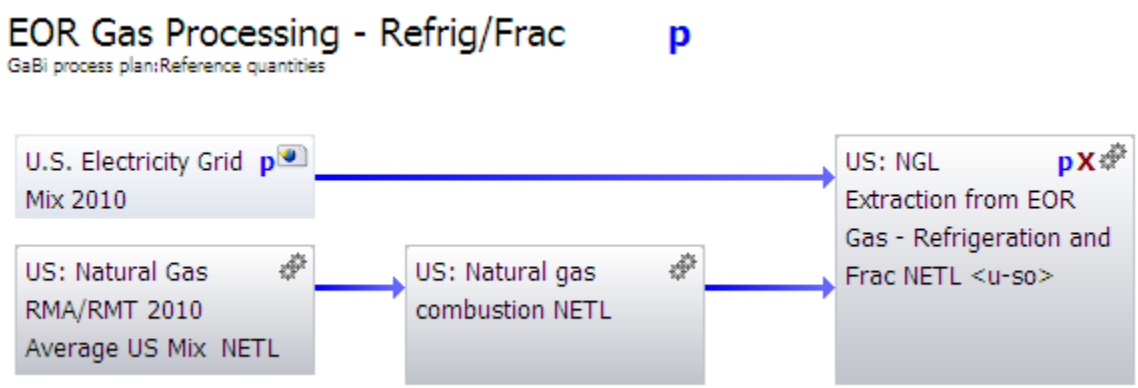

Table A-17: Unit Processes in EOR Gas Processing – Refrig/Frac Plan

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
Natural Gas Upstream	This process includes all inputs for the raw material acquisition and raw material transportation for 1 kg of delivered natural gas proportionally from all extraction methods.	2	5/2012
Natural Gas Combustion	This unit process models air emissions and heat produced by a large-scale natural gas fired boiler, producing over 100 million BTU/hr.	1	8/2010
NGL Extraction from EOR Gas – Refrigeration and Fractionation	This unit processes models the separations of natural gas liquids from EOR recycle gas by using a combination of refrigeration and fractionation processes to separate the product into three gas streams (propane, butane, and pentane).	1	10/2012

Figure A-18: EOR Gas Processing – Ryan-Holmes – Second-Level Plan

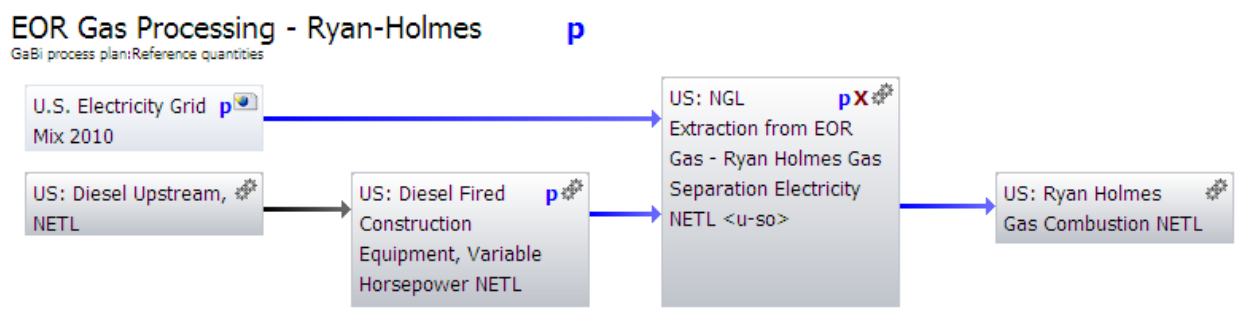

Table A-18: Unit Processes in EOR Gas Processing – Ryan-Holmes Plan

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
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Diesel Combustion	This unit process models air emissions and heat produced by a generic piece of diesel powered machinery (at least 75 HP) used during construction of buildings, roadways, infrastructure, pipelines, etc. Emission factors are for non-road equipment.	1	8/2010
NGL Extraction from EOR Gas – Ryan-Holmes Gas Separation Electricity	This unit processes models the separations of natural gas liquids from EOR recycle gas by using the Ryan-Holmes process.	1	10/2012
Ryan-Holmes Gas Combustion	This unit process models air emissions and heat produced by a large-scale natural gas fired boiler, producing over 100 million BTU/hr.	1	8/2010

Figure A-19: EOR Gas Processing – Membrane – Second-Level Plan

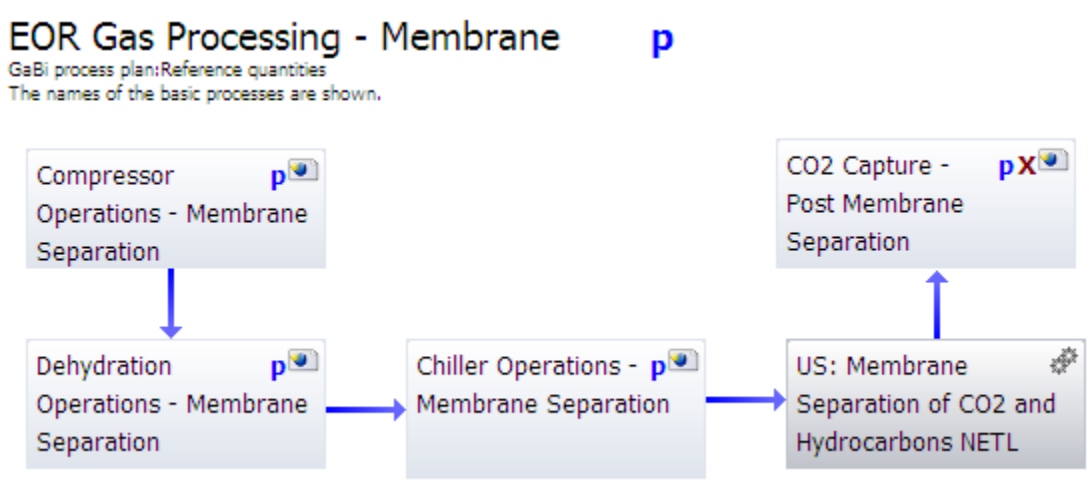

Table A-19: Unit Processes in Brine EOR Gas Processing – Membrane Plan

Unit Process	Notes	Version	Creation Date
Membrane Separation	This unit process models Separation of CO_2 and hydrocarbons using membrane technology.	1	10/2012

Figure A-20: Compressor Operations – Membrane Separation – Third-Level Plan

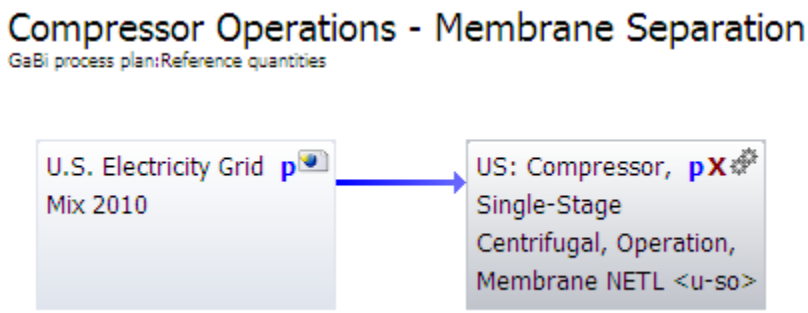

Table A-20: Unit Processes in Compressor Operations – Membrane Separation Plan

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
Compressor, Single-Stage Centrifugal, Operations	This unit process calculates the electricity required to compress a given fluid and the fugitive emissions associated with operation.	1	10/2012

Figure A-21: Dehydration Operations – Membrane Separation – Third-Level Plan

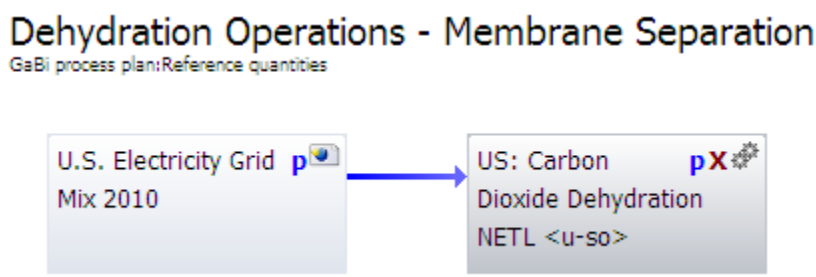

Table A-21: Unit Processes in Dehydration Operations – Membrane Separation Plan

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
Carbon Dioxide Dehydration	This unit process models the energy use for the dehydration of CO_2.	1	11/2012

Figure A-22: Chiller Operations – Membrane Separation – Third-Level Plan

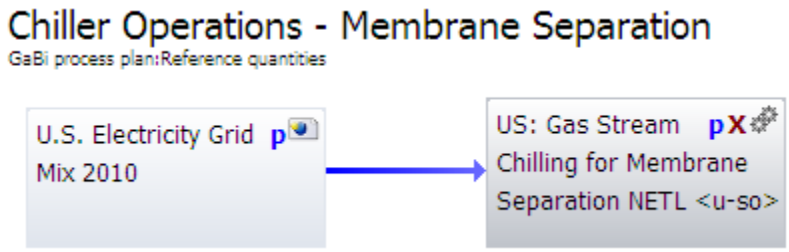

Table A-22: Unit Processes in Chiller Operations – Membrane Separation Plan

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
Gas Stream Chilling for Membrane Separation	This unit process models the energy requirements for the chilling of a carbon dioxide/hydrocarbon stream.	1	10/2012

Figure A-23: CO_2 Capture – Post Membrane Separation – Third-Level Plan

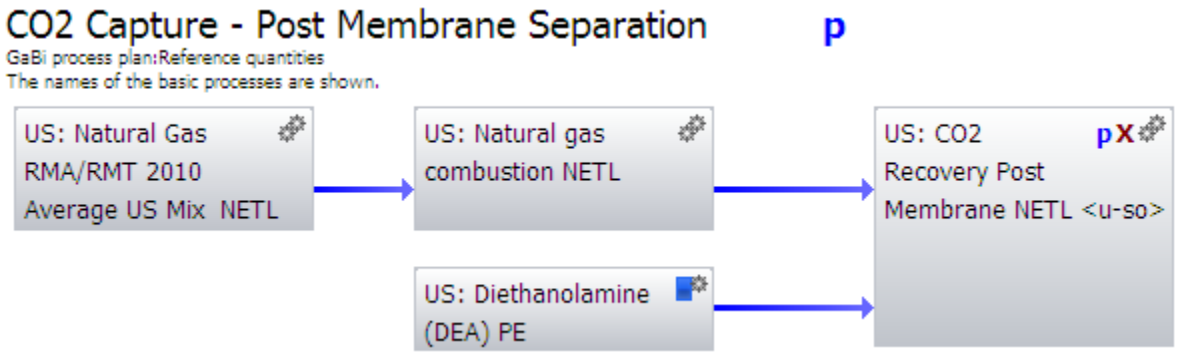

Table A-23: Unit Processes in CO_2 Capture – Post Membrane Separation Plan

Unit Process	Notes	Version	Creation Date
Natural Gas Upstream	This process includes all inputs for the raw material acquisition and raw material transportation for 1 kg of delivered natural gas proportionally from all extraction methods.	2	5/2012
Natural Gas Combustion	This unit process models air emissions and heat produced by a large-scale natural gas fired boiler, producing over 100 million BTU/hr.	1	8/2010
Diethanolamine	Third-party data available from PE International; proxy for monoethanolamine	N/A	N/A
CO_2 Recovery Post Membrane	This unit process models the operation of an amine-based CO_2 recovery system for post-membrane acid gas removal.	1	7/2012

Appendix B: Detailed Life Cycle Results for Enhanced Oil Recovery

Table B-1: Detailed Gate-to-Gate LCA Results for Fractionation – Mass Allocation (units/barrel crude produced) 2
Table B-2: Detailed Gate-to-Gate LCA Results for Refrigeration – Mass Allocation (units/barrel crude produced) 4
Table B-3: Detailed Gate-to-Gate LCA Results for Ryan-Holmes – Mass Allocation (units/barrel crude produced) 5
Table B-4: Detailed Gate-to-Gate LCA Results for Membrane Separation– Mass Allocation (units/barrel crude produced) 8

Table B-1: Detailed Gate-to-Gate LCA Results for Fractionation – Mass Allocation (units/barrel crude produced)

Category (Units)	Material or Energy Flow	Gas Processing			Brine Water Storage		Crude Oil Storage	Oil, Gas, and Water Separation		
		Electricity Upstream	Natural Gas Combustion	Natural Gas Upstream	Brine Disposal Pump Elec.	Venting and Flaring	Venting and Flaring	Natural Gas Combustion	Natural Gas Upstream	Venting and Flaring
GHG (kg/bbl)	CO_2	7.04E+00	4.24E-03	2.53E-04	6.71E-01	6.36E-02	4.43E-01	1.11E+00	6.61E-02	3.11E+00
	N_2O	8.74E-05	2.26E-08	7.19E-09	8.33E-06	0	0	5.92E-06	1.88E-06	0
	CH_4	2.51E-02	8.12E-08	2.54E-05	2.40E-03	1.33E-04	9.26E-04	2.13E-05	6.66E-03	6.50E-03
	SF_6	1.54E-06	0	2.44E-12	1.47E-07	0	0	0	6.38E-10	0
	CO_2e (IPCC 2007 100-yr GWP)	7.73E+00	4.25E-03	8.90E-04	7.37E-01	6.70E-02	4.66E-01	1.11E+00	2.33E-01	3.27E+00
Other Air (kg/bbl)	Pb	1.58E-07	0	4.47E-11	1.51E-08	0	0	0	1.17E-08	0
	Hg	9.49E-08	0	1.40E-12	9.05E-09	0	0	0	3.66E-10	0
	NH_3	4.92E-06	0	3.15E-11	4.69E-07	0	0	0	8.25E-09	0
	CO	9.66E-04	2.97E-06	5.02E-07	9.22E-05	0	0	7.77E-04	1.31E-04	0
	NOx	1.07E-02	4.94E-06	4.88E-06	1.02E-03	0	0	1.29E-03	1.28E-03	0
	SO_2	1.62E-02	2.12E-08	8.43E-08	1.55E-03	0	0	5.55E-06	2.21E-05	0
	VOC	2.62E-03	1.94E-07	3.81E-06	2.50E-04	1.01E-03	1.56E-01	5.09E-05	9.97E-04	4.91E-02
	PM	2.32E-04	0	2.00E-08	2.21E-05	0	0	0	5.22E-06	0
Solid Waste (kg/bbl)	Heavy metals to industrial soil	6.21E-02	0	7.67E-08	5.92E-03	0	0	0	2.01E-05	0
	Heavy metals to agricultural soil	6.21E-02	0	7.67E-08	9.60E-10	0	0	0	4.59E-13	0
Water Use (L/bbl)	Withdrawal	3.69E+01	0	1.56E-03	3.52E+00	0	0	0	4.08E-01	0
	Discharge	1.96E+01	0	1.77E-03	1.87E+00	0	0	0	4.64E-01	0
	Consumption	1.73E+01	0	-2.16E-04	1.65E+00	0	0	0	-5.66E-02	0
Water Quality (kg/bbl)	Aluminum	3.59E-07	0	5.21E-10	3.43E-08	0	0	0	1.36E-07	0
	Arsenic (+V)	7.12E-06	0	3.24E-11	6.89E-07	0	0	0	8.49E-09	0
	Copper (+II)	8.47E-06	0	4.24E-11	8.21E-07	0	0	0	1.11E-08	0
	Iron	1.39E-04	0	3.11E-09	1.40E-05	0	0	0	8.14E-07	0
	Lead (+II)	1.21E-07	0	5.51E-11	4.47E-08	0	0	0	1.44E-08	0
	Manganese (+II)	2.44E-05	0	2.70E-08	2.35E-06	0	0	0	7.08E-06	0
	Nickel (+II)	6.59E-04	0	1.21E-09	6.31E-05	0	0	0	3.17E-07	0
	Strontium	1.19E-07	0	1.70E-12	1.14E-08	0	0	0	4.44E-10	0
	Zinc (+II)	8.85E-05	0	9.05E-10	8.90E-06	0	0	0	2.37E-07	0
	Ammonium/ammonia	1.54E-03	0	1.89E-09	1.47E-04	0	0	0	4.96E-07	0
	Hydrogen chloride	1.13E-11	0	1.87E-16	1.08E-12	0	0	0	4.89E-14	0
	Nitrogen (as total N)	5.58E-06	0	8.76E-09	5.32E-07	0	0	0	2.29E-06	0
	Phosphate	1.08E-07	0	7.96E-14	1.02E-08	0	0	0	2.08E-11	0
	Phosphorus	3.52E-06	0	6.19E-10	6.66E-07	0	0	0	1.62E-07	0
Resource Energy (MJ/bbl)	Crude oil	1.92E+00	0	4.33E-05	1.83E-01	0	0	0	1.13E-02	0
	Hard coal	4.19E+01	0	1.92E-04	1.62E+00	0	0	0	5.11E-02	0
	Lignite	5.21E-03	0	5.89E-08	4.93E-04	0	0	0	1.54E-05	0
	Natural gas	5.49E+01	0	7.92E-02	5.23E+00	0	0	0	2.07E+01	0
	Uranium	2.41E-02	0	3.45E-07	2.38E-03	0	0	0	9.03E-05	0
	Renewable	2.35E-02	0	7.03E-06	2.23E-03	0	0	0	1.84E-03	0
	Total resource energy	9.87E+01	0	7.94E-02	7.04E+00	0	0	0	2.08E+01	0

Table B-1: Detailed Gate-to-Gate LCA Results for Fractionation – Mass Allocation (units/barrel crude produced) (continued)

Category (Units)	Material or Energy Flow	Well Operations					Land Use	Total
		Brine Injection Pump Elec.	CO_2 Injection Compressor Elec.	CO_2 Injection Compressor Emissions	Crude Oil Artificial Lift Pumping	Formation Leakage	Direct Land Use	
GHG (kg/bbl)	CO_2	1.14E+00	3.44E+01	1.39E-01	9.73E+00	1.58E+00	1.43E+00	6.10E+01
	N_2O	1.41E-05	4.27E-04	0	1.21E-04	0	0	6.66E-04
	CH_4	4.06E-03	1.23E-01	0	3.48E-02	0	0	2.04E-01
	SF_6	2.49E-07	7.52E-06	0	2.13E-06	0	0	1.16E-05
	CO_2e (IPCC 2007 100-yr GWP)	1.25E+00	3.78E+01	1.39E-01	1.07E+01	1.58E+00	1.43E+00	6.65E+01
Other Air (kg/bbl)	Pb	2.56E-08	7.73E-07	0	2.19E-07	0	0	1.20E-06
	Hg	1.53E-08	4.64E-07	0	1.31E-07	0	0	7.15E-07
	NH_3	7.96E-07	2.41E-05	0	6.81E-06	0	0	3.71E-05
	CO	1.56E-04	4.73E-03	0	1.34E-03	0	0	8.19E-03
	NOx	1.73E-03	5.24E-02	0	1.48E-02	0	0	8.33E-02
	SO_2	2.62E-03	7.93E-02	0	2.24E-02	0	0	1.22E-01
	VOC	4.23E-04	1.28E-02	0	3.62E-03	0	0	2.27E-01
	PM	3.75E-05	1.13E-03	0	3.20E-04	0	0	1.75E-03
Solid Waste (kg/bbl)	Heavy metals to industrial soil	1.00E-02	3.04E-01	0	8.59E-02	0	0	4.68E-01
	Heavy metals to agricultural soil	1.63E-09	4.92E-08	0	1.39E-08	0	0	6.21E-02
Water Use (L/bbl)	Withdrawal	5.97E+00	1.81E+02	0	5.11E+01	0	0	2.78E+02
	Discharge	3.18E+00	9.60E+01	0	2.72E+01	0	0	1.48E+02
	Consumption	2.79E+00	8.45E+01	0	2.39E+01	0	0	1.30E+02
Water Quality (kg/bbl)	Aluminum	5.81E-08	1.76E-06	0	4.97E-07	0	0	2.84E-06
	Arsenic (+V)	1.17E-06	3.53E-05	0	9.99E-06	0	0	5.43E-05
	Copper (+II)	1.39E-06	4.21E-05	0	1.19E-05	0	0	6.47E-05
	Iron	2.37E-05	7.17E-04	0	2.03E-04	0	0	1.10E-03
	Lead (+II)	7.58E-08	2.29E-06	0	6.48E-07	0	0	3.19E-06
	Manganese (+II)	3.99E-06	1.21E-04	0	3.41E-05	0	0	1.93E-04
	Nickel (+II)	1.07E-04	3.24E-03	0	9.15E-04	0	0	4.98E-03
	Strontium	1.93E-08	5.82E-07	0	1.65E-07	0	0	8.97E-07
	Zinc (+II)	1.51E-05	4.56E-04	0	1.29E-04	0	0	6.98E-04
	Ammonium/ammonia	2.49E-04	7.52E-03	0	2.13E-03	0	0	1.16E-02
	Hydrogen chloride	1.83E-12	5.52E-11	0	1.56E-11	0	0	8.51E-11
	Nitrogen (as total N)	9.03E-07	2.73E-05	0	7.72E-06	0	0	4.43E-05
	Phosphate	1.74E-08	5.25E-07	0	1.48E-07	0	0	8.09E-07
	Phosphorus	1.13E-06	3.42E-05	0	9.66E-06	0	0	4.93E-05
Resource Energy (MJ/bbl)	Crude oil	3.10E-01	9.37E+00	0	2.65E+00	0	0	1.44E+01
	Hard coal	2.74E+00	8.29E+01	0	2.34E+01	0	0	1.53E+02
	Lignite	8.36E-04	2.53E-02	0	7.15E-03	0	0	3.90E-02
	Natural gas	8.88E+00	2.68E+02	0	7.59E+01	0	0	4.34E+02
	Uranium	4.04E-03	1.22E-01	0	3.45E-02	0	0	1.87E-01
	Renewable	3.79E-03	1.15E-01	0	3.24E-02	0	0	1.78E-01
	Total resource energy	1.19E+01	3.61E+02	0	1.02E+02	0	0	6.02E+02

Table B-2: Detailed Gate-to-Gate LCA Results for Refrigeration – Mass Allocation (units/barrel crude produced)

Category (Units)	Material or Energy Flow	Gas Processing			Brine Water Storage		Crude Oil	Oil, Gas, and Water Separation		
		Electricity Upstream	Natural Gas Combustion	Natural Gas Upstream	Brine Disposal Pump Elec.	Venting and Flaring	Venting and Flaring	Natural Gas Combustion	Natural Gas Upstream	Venting and Flaring
GHG (kg/bbl)	CO_2	7.03E+00	3.22E-03	1.92E-04	6.71E-01	6.36E-02	4.43E-01	1.11E+00	6.61E-02	3.11E+00
	N_2O	8.73E-05	1.71E-08	5.46E-09	8.33E-06	0	0	5.92E-06	1.88E-06	0
	CH_4	2.51E-02	6.16E-08	1.93E-05	2.40E-03	1.33E-04	9.26E-04	2.13E-05	6.66E-03	6.50E-03
	SF_6	1.54E-06	0	1.85E-12	1.47E-07	0	0	0	6.38E-10	0
	CO_2e (IPCC 2007 100-yr GWP)	7.72E+00	3.22E-03	6.75E-04	7.37E-01	6.70E-02	4.66E-01	1.11E+00	2.33E-01	3.27E+00
Other Air (kg/bbl)	Pb	1.58E-07	0	3.39E-11	1.51E-08	0	0	0	1.17E-08	0
	Hg	9.48E-08	0	1.06E-12	9.05E-09	0	0	0	3.66E-10	0
	NH_3	4.92E-06	0	2.39E-11	4.69E-07	0	0	0	8.25E-09	0
	CO	9.65E-04	2.25E-06	3.81E-07	9.22E-05	0	0	7.77E-04	1.31E-04	0
	NOx	1.07E-02	3.75E-06	3.70E-06	1.02E-03	0	0	1.29E-03	1.28E-03	0
	SO_2	1.62E-02	1.61E-08	6.40E-08	1.55E-03	0	0	5.55E-06	2.21E-05	0
	VOC	2.62E-03	1.47E-07	2.89E-06	2.50E-04	1.01E-03	1.56E-01	5.09E-05	9.97E-04	4.91E-02
	PM	2.31E-04	0	1.51E-08	2.21E-05	0	0	0	5.22E-06	0
Solid Waste (kg/bbl)	Heavy metals to industrial soil	6.20E-02	0	5.82E-08	5.92E-03	0	0	0	2.01E-05	0
	Heavy metals to agricultural soil	1.01E-08	0	1.33E-15	9.60E-10	0	0	0	4.59E-13	0
Water Use (L/bbl)	Withdrawal	3.69E+01	0	1.18E-03	3.52E+00	0	0	0	4.08E-01	0
	Discharge	1.96E+01	0	1.35E-03	1.87E+00	0	0	0	4.64E-01	0
	Consumption	1.73E+01	0	-1.64E-04	1.65E+00	0	0	0	-5.66E-02	0
Water Quality (kg/bbl)	Aluminum	3.59E-07	0	3.95E-10	3.43E-08	0	0	0	1.36E-07	0
	Arsenic (+V)	7.21E-06	0	2.46E-11	6.89E-07	0	0	0	8.49E-09	0
	Copper (+II)	8.60E-06	0	3.22E-11	8.21E-07	0	0	0	1.11E-08	0
	Iron	1.46E-04	0	2.36E-09	1.40E-05	0	0	0	8.14E-07	0
	Lead (+II)	4.68E-07	0	4.18E-11	4.47E-08	0	0	0	1.44E-08	0
	Manganese (+II)	2.46E-05	0	2.05E-08	2.35E-06	0	0	0	7.08E-06	0
	Nickel (+II)	6.61E-04	0	9.17E-10	6.31E-05	0	0	0	3.17E-07	0
	Strontium	1.19E-07	0	1.29E-12	1.14E-08	0	0	0	4.44E-10	0
	Zinc (+II)	9.32E-05	0	6.87E-10	8.90E-06	0	0	0	2.37E-07	0
	Ammonium/ammonia	1.54E-03	0	1.44E-09	1.47E-04	0	0	0	4.96E-07	0
	Hydrogen chloride	1.13E-11	0	1.42E-16	1.08E-12	0	0	0	4.89E-14	0
	Nitrogen (as total N)	5.58E-06	0	6.64E-09	5.32E-07	0	0	0	2.29E-06	0
	Phosphate	1.07E-07	0	6.04E-14	1.02E-08	0	0	0	2.08E-11	0
	Phosphorus	6.98E-06	0	4.69E-10	6.66E-07	0	0	0	1.62E-07	0
Resource Energy (MJ/bbl)	Crude oil	1.91E+00	0	3.28E-05	1.83E-01	0	0	0	1.13E-02	0
	Hard coal	1.69E+01	0	1.48E-04	1.62E+00	0	0	0	5.11E-02	0
	Lignite	5.16E-03	0	4.47E-08	4.93E-04	0	0	0	1.54E-05	0
	Natural gas	5.48E+01	0	6.01E-02	5.23E+00	0	0	0	2.07E+01	0
	Uranium	2.49E-02	0	2.62E-07	2.38E-03	0	0	0	9.03E-05	0
	Renewable	2.34E-02	0	5.33E-06	2.23E-03	0	0	0	1.84E-03	0
	Total resource energy	7.37E+01	0	6.03E-02	7.04E+00	0	0	0	2.08E+01	0

Table B-2: Detailed Gate-to-Gate LCA Results for Refrigeration – Mass Allocation (units/barrel crude produced) (continued)

Category (Units)	Material or Energy Flow	Well Operations					Land Use	Total
		Brine Injection Pump Elec.	CO_2 Injection Compressor Elec.	CO_2 Injection Compressor Emissions	Crude Oil Artificial Lift Pumping	Formation Leakage	Direct Land Use	
GHG (kg/bbl)	CO_2	1.14E+00	3.44E+01	1.39E-01	9.73E+00	1.58E+00	1.43E+00	6.09E+01
	N_2O	1.41E-05	4.27E-04	0	1.21E-04	0	0	6.66E-04
	CH_4	4.06E-03	1.23E-01	0	3.48E-02	0	0	2.03E-01
	SF_6	2.49E-07	7.52E-06	0	2.13E-06	0	0	1.16E-05
	CO_2e (IPCC 2007 100-yr GWP)	1.25E+00	3.78E+01	1.39E-01	1.07E+01	1.58E+00	1.43E+00	6.65E+01
Other Air (kg/bbl)	Pb	2.56E-08	7.73E-07	0	2.19E-07	0	0	1.20E-06
	Hg	1.53E-08	4.64E-07	0	1.31E-07	0	0	7.15E-07
	NH_3	7.96E-07	2.41E-05	0	6.81E-06	0	0	3.71E-05
	CO	1.56E-04	4.73E-03	0	1.34E-03	0	0	8.19E-03
	NOx	1.73E-03	5.24E-02	0	1.48E-02	0	0	8.32E-02
	SO_2	2.62E-03	7.93E-02	0	2.24E-02	0	0	1.22E-01
	VOC	4.23E-04	1.28E-02	0	3.62E-03	0	0	2.27E-01
	PM	3.75E-05	1.13E-03	0	3.20E-04	0	0	1.75E-03
Solid Waste (kg/bbl)	Heavy metals to industrial soil	1.00E-02	3.04E-01	0	8.59E-02	0	0	4.68E-01
	Heavy metals to agricultural soil	1.63E-09	4.92E-08	0	1.39E-08	0	0	7.58E-08
Water Use (L/bbl)	Withdrawal	5.97E+00	1.81E+02	0	5.11E+01	0	0	2.78E+02
	Discharge	3.18E+00	9.60E+01	0	2.72E+01	0	0	1.48E+02
	Consumption	2.79E+00	8.45E+01	0	2.39E+01	0	0	1.30E+02
Water Quality (kg/bbl)	Aluminum	5.81E-08	1.76E-06	0	4.97E-07	0	0	2.84E-06
	Arsenic (+V)	1.17E-06	3.53E-05	0	9.99E-06	0	0	5.44E-05
	Copper (+II)	1.39E-06	4.21E-05	0	1.19E-05	0	0	6.49E-05
	Iron	2.37E-05	7.17E-04	0	2.03E-04	0	0	1.10E-03
	Lead (+II)	7.58E-08	2.29E-06	0	6.48E-07	0	0	3.54E-06
	Manganese (+II)	3.99E-06	1.21E-04	0	3.41E-05	0	0	1.93E-04
	Nickel (+II)	1.07E-04	3.24E-03	0	9.15E-04	0	0	4.98E-03
	Strontium	1.93E-08	5.82E-07	0	1.65E-07	0	0	8.97E-07
	Zinc (+II)	1.51E-05	4.56E-04	0	1.29E-04	0	0	7.03E-04
	Ammonium/ammonia	2.49E-04	7.52E-03	0	2.13E-03	0	0	1.16E-02
	Hydrogen chloride	1.83E-12	5.52E-11	0	1.56E-11	0	0	8.51E-11
	Nitrogen (as total N)	9.03E-07	2.73E-05	0	7.72E-06	0	0	4.43E-05
	Phosphate	1.74E-08	5.25E-07	0	1.48E-07	0	0	8.08E-07
	Phosphorus	1.13E-06	3.42E-05	0	9.66E-06	0	0	5.27E-05
Resource Energy (MJ/bbl)	Crude oil	3.10E-01	9.37E+00	0	2.65E+00	0	0	1.44E+01
	Hard coal	2.74E+00	8.29E+01	0	2.34E+01	0	0	1.28E+02
	Lignite	8.36E-04	2.53E-02	0	7.15E-03	0	0	3.89E-02
	Natural gas	8.88E+00	2.68E+02	0	7.59E+01	0	0	4.34E+02
	Uranium	4.04E-03	1.22E-01	0	3.45E-02	0	0	1.88E-01
	Renewable	3.79E-03	1.15E-01	0	3.24E-02	0	0	1.78E-01
	Total resource energy	1.19E+01	3.61E+02	0	1.02E+02	0	0	5.77E+02

Table B-3: Detailed Gate-to-Gate LCA Results for Ryan-Holmes – Mass Allocation (units/barrel crude produced)

Category (Units)	Material or Energy Flow	Gas Processing				Brine Water Storage		Crude Oil Storage	Oil, Gas, and Water Separation		
		Diesel Combustion	Diesel Upstream	Electricity Upstream	Process Gas Combustion	Brine Disposal Pump Elec.	Venting and Flaring	Venting and Flaring	Natural Gas Combustion	Natural Gas Upstream	Venting and Flaring
GHG (kg/bbl)	CO_2	4.86E-01	9.98E-02	2.90E+01	5.52E+00	6.18E-01	5.86E-02	4.08E-01	1.02E+00	6.09E-02	2.86E+00
	N_2O	1.26E-05	1.96E-06	3.60E-04	2.95E-05	7.67E-06	0	0	5.45E-06	1.73E-06	0
	CH_4	6.96E-05	6.37E-04	1.03E-01	1.06E-04	2.21E-03	1.23E-04	8.53E-04	1.96E-05	6.13E-03	5.98E-03
	SF_6	0	1.87E-13	6.32E-06	0	1.35E-07	0	0	0	5.88E-10	0
	CO_2e (IPCC 2007 100-yr GWP)	4.91E-01	1.16E-01	3.18E+01	5.54E+00	6.79E-01	6.16E-02	4.29E-01	1.02E+00	2.15E-01	3.01E+00
Other Air (kg/bbl)	Pb	0	2.25E-09	6.50E-07	0	1.39E-08	0	0	0	1.08E-08	0
	Hg	0	1.87E-10	3.90E-07	0	8.33E-09	0	0	0	3.37E-10	0
	NH_3	2.01E-05	1.27E-06	2.03E-05	0	4.32E-07	0	0	0	7.59E-09	0
	CO	2.71E-03	9.51E-05	3.98E-03	3.87E-03	8.49E-05	0	0	7.15E-04	1.21E-04	0
	NOx	2.20E-04	1.30E-04	4.41E-02	6.45E-03	9.41E-04	0	0	1.19E-03	1.18E-03	0
	SO_2	4.62E-06	2.61E-04	6.67E-02	2.76E-05	1.42E-03	0	0	5.11E-06	2.03E-05	0
	VOC	1.03E-04	2.79E-04	1.08E-02	2.53E-04	2.30E-04	9.27E-04	1.43E-01	4.68E-05	9.18E-04	4.52E-02
	PM	7.32E-06	2.29E-06	9.53E-04	0	2.03E-05	0	0	0	4.81E-06	0
Solid Waste (kg/bbl)	Heavy metals to industrial soil	0	1.60E-06	2.56E-01	0	5.45E-03	0	0	0	1.85E-05	0
	Heavy metals to agricultural soil	0	0	4.14E-08	0	8.84E-10	0	0	0	4.23E-13	0
Water Use (L/bbl)	Withdrawal	0	4.72E+00	1.52E+02	0	3.24E+00	0	0	0	3.76E-01	0
	Discharge	0	4.41E+00	8.08E+01	0	1.72E+00	0	0	0	4.28E-01	0
	Consumption	0	3.12E-01	7.11E+01	0	1.52E+00	0	0	0	-5.21E-02	0
Water Quality (kg/bbl)	Aluminum	0	0	1.48E-06	0	3.16E-08	0	0	0	1.26E-07	0
	Arsenic (+V)	0	2.07E-06	2.97E-05	0	6.34E-07	0	0	0	7.81E-09	0
	Copper (+II)	0	3.03E-06	3.54E-05	0	7.56E-07	0	0	0	1.02E-08	0
	Iron	0	1.55E-04	6.03E-04	0	1.29E-05	0	0	0	7.49E-07	0
	Lead (+II)	0	6.97E-06	1.93E-06	0	4.11E-08	0	0	0	1.33E-08	0
	Manganese (+II)	0	9.29E-09	1.01E-04	0	2.17E-06	0	0	0	6.52E-06	0
	Nickel (+II)	0	5.52E-05	2.72E-03	0	5.81E-05	0	0	0	2.92E-07	0
	Strontium	0	5.08E-08	4.90E-07	0	1.05E-08	0	0	0	4.09E-10	0
	Zinc (+II)	0	9.58E-05	3.84E-04	0	8.19E-06	0	0	0	2.18E-07	0
	Ammonium/ammonia	0	1.85E-07	6.33E-03	0	1.35E-04	0	0	0	4.57E-07	0
	Hydrogen chloride	0	1.95E-11	4.64E-11	0	9.91E-13	0	0	0	4.50E-14	0
	Nitrogen (as total N)	0	0	2.30E-05	0	4.90E-07	0	0	0	2.11E-06	0
	Phosphate	0	2.30E-09	4.42E-07	0	9.42E-09	0	0	0	1.92E-11	0
	Phosphorus	0	6.94E-05	2.87E-05	0	6.13E-07	0	0	0	1.49E-07	0
Resource Energy (MJ/bbl)	Crude oil	0	6.33E+00	7.89E+00	0	1.68E-01	0	0	0	1.04E-02	0
	Hard coal	0	9.29E-02	6.98E+01	0	1.49E+00	0	0	0	4.70E-02	0
	Lignite	0	3.40E-03	2.13E-02	0	4.54E-04	0	0	0	1.42E-05	0
	Natural gas	0	7.12E-01	2.26E+02	0	4.82E+00	0	0	0	1.91E+01	0
	Uranium	0	4.52E-02	1.03E-01	0	2.19E-03	0	0	0	8.32E-05	0
	Renewable	0	7.33E-03	9.64E-02	0	2.06E-03	0	0	0	1.69E-03	0
	Total resource energy	0	7.19E+00	3.04E+02	0	6.48E+00	0	0	0	1.91E+01	0

Table B-3: Detailed Gate-to-Gate LCA Results for Ryan-Holmes – Mass Allocation (units/barrel crude produced) (continued)

Category (Units)	Material or Energy Flow	Well Operations					Land Use	Total
		Brine Injection Pump Elec.	CO_2 Injection Compressor Elec.	CO_2 Injection Compressor Emissions	Crude Oil Artificial Lift Pumping	Formation Leakage	Direct Land Use	
GHG (kg/bbl)	CO_2	1.05E+00	3.17E+01	1.28E-01	8.96E+00	1.45E+00	1.32E+00	8.47E+01
	N_2O	1.30E-05	3.93E-04	0	1.11E-04	0	0	9.36E-04
	CH_4	3.74E-03	1.13E-01	0	3.20E-02	0	0	2.68E-01
	SF_6	2.29E-07	6.92E-06	0	1.96E-06	0	0	1.56E-05
	CO_2e (IPCC 2007 100-yr GWP)	1.15E+00	3.48E+01	1.28E-01	9.84E+00	1.45E+00	1.32E+00	9.21E+01
Other Air (kg/bbl)	Pb	2.35E-08	7.11E-07	0	2.01E-07	0	0	1.61E-06
	Hg	1.41E-08	4.27E-07	0	1.21E-07	0	0	9.62E-07
	NH_3	7.33E-07	2.22E-05	0	6.27E-06	0	0	7.13E-05
	CO	1.44E-04	4.35E-03	0	1.23E-03	0	0	1.73E-02
	NOx	1.60E-03	4.82E-02	0	1.36E-02	0	0	1.18E-01
	SO_2	2.41E-03	7.30E-02	0	2.06E-02	0	0	1.65E-01
	VOC	3.90E-04	1.18E-02	0	3.33E-03	0	0	2.18E-01
	PM	3.45E-05	1.04E-03	0	2.95E-04	0	0	2.36E-03
Solid Waste (kg/bbl)	Heavy metals to industrial soil	9.25E-03	2.80E-01	0	7.91E-02	0	0	6.29E-01
	Heavy metals to agricultural soil	1.50E-09	4.53E-08	0	1.28E-08	0	0	1.02E-07
Water Use (L/bbl)	Withdrawal	5.50E+00	1.66E+02	0	4.70E+01	0	0	3.79E+02
	Discharge	2.92E+00	8.84E+01	0	2.50E+01	0	0	2.04E+02
	Consumption	2.57E+00	7.78E+01	0	2.20E+01	0	0	1.75E+02
Water Quality (kg/bbl)	Aluminum	5.35E-08	1.62E-06	0	4.58E-07	0	0	3.77E-06
	Arsenic (+V)	1.08E-06	3.25E-05	0	9.20E-06	0	0	7.52E-05
	Copper (+II)	1.28E-06	3.88E-05	0	1.10E-05	0	0	9.03E-05
	Iron	2.18E-05	6.60E-04	0	1.87E-04	0	0	1.64E-03
	Lead (+II)	6.98E-08	2.11E-06	0	5.96E-07	0	0	1.17E-05
	Manganese (+II)	3.67E-06	1.11E-04	0	3.14E-05	0	0	2.56E-04
	Nickel (+II)	9.85E-05	2.98E-03	0	8.43E-04	0	0	6.76E-03
	Strontium	1.77E-08	5.36E-07	0	1.52E-07	0	0	1.26E-06
	Zinc (+II)	1.39E-05	4.20E-04	0	1.19E-04	0	0	1.04E-03
	Ammonium/ammonia	2.29E-04	6.93E-03	0	1.96E-03	0	0	1.56E-02
	Hydrogen chloride	1.68E-12	5.08E-11	0	1.44E-11	0	0	1.34E-10
	Nitrogen (as total N)	8.31E-07	2.51E-05	0	7.11E-06	0	0	5.86E-05
	Phosphate	1.60E-08	4.83E-07	0	1.37E-07	0	0	1.09E-06
	Phosphorus	1.04E-06	3.14E-05	0	8.89E-06	0	0	1.40E-04
Resource Energy (MJ/bbl)	Crude oil	2.85E-01	8.63E+00	0	2.44E+00	0	0	2.57E+01
	Hard coal	2.52E+00	7.63E+01	0	2.16E+01	0	0	1.72E+02
	Lignite	7.70E-04	2.33E-02	0	6.58E-03	0	0	5.58E-02
	Natural gas	8.17E+00	2.47E+02	0	6.99E+01	0	0	5.76E+02
	Uranium	3.72E-03	1.12E-01	0	3.18E-02	0	0	2.98E-01
	Renewable	3.49E-03	1.06E-01	0	2.98E-02	0	0	2.46E-01
	Total resource energy	1.10E+01	3.32E+02	0	9.40E+01	0	0	7.74E+02

Table B-4: Detailed Gate-to-Gate LCA Results for Membrane Separation– Mass Allocation (units/barrel crude produced)

Category (Units)	Material or Energy Flow	Gas Processing								Brine Water Storage	
		Chiller	Post Membrane CO_2 Capture	Post Membrane CO_2 Capture	Post Membrane CO_2 Capture	Post Membrane CO_2 Capture	Compressor	Compressor	Dehydration	Brine Disposal Pump Elec.	Venting and Flaring
		Electricity Upstream	Operations Emissions	Solvent Upstream	Natural Gas Upstream	Natural Gas Combustion	Electricity Upstream	Compressor Emissions	Electricity Upstream		
GHG (kg/bbl)	CO_2	7.80E-01	0	4.34E+01	2.59E+00	7.59E-02	1.06E+01	2.96E-02	8.98E-02	6.08E-01	5.77E-02
	N_2O	9.68E-06	0	2.31E-04	7.37E-05	3.89E-06	1.32E-04	0	1.42E-06	7.55E-06	0
	CH_4	2.78E-03	0	8.32E-04	2.60E-01	1.79E-04	3.79E-02	0	2.38E-04	2.17E-03	1.21E-04
	SF_6	1.70E-07	0	0	2.50E-08	5.98E-14	2.32E-06	0	1.97E-08	1.33E-07	0
	CO_2e (IPCC 2007 100-yr GWP)	8.56E-01	0	4.35E+01	9.12E+00	8.16E-02	1.17E+01	2.96E-02	9.66E-02	6.68E-01	6.07E-02
Other Air (kg/bbl)	Pb	1.75E-08	0	0	4.57E-07	1.14E-08	2.39E-07	0	1.50E-09	1.37E-08	0
	Hg	1.05E-08	0	0	1.43E-08	1.06E-09	1.43E-07	0	1.68E-09	8.20E-09	0
	NH_3	5.45E-07	0	0	3.22E-07	7.40E-07	7.43E-06	0	3.26E-07	4.25E-07	0
	CO	1.07E-04	0	3.04E-02	5.14E-03	3.67E-05	1.46E-03	0	1.27E-05	8.35E-05	0
	NOx	1.19E-03	0	5.06E-02	4.99E-02	1.02E-04	1.62E-02	0	1.33E-04	9.26E-04	0
	SO_2	1.80E-03	0	2.17E-04	8.63E-04	8.80E-05	2.45E-02	0	2.83E-04	1.40E-03	0
	VOC	2.90E-04	2.29E-02	1.99E-03	3.90E-02	3.12E-05	3.95E-03	0	1.64E-05	2.26E-04	9.12E-04
	PM	2.56E-05	0	0	2.04E-04	0	3.50E-04	0	3.81E-06	2.00E-05	0
Solid Waste (kg/bbl)	Heavy metals to industrial soil	6.88E-03	0	0	7.85E-04	1.98E-10	9.38E-02	0	1.32E-03	5.37E-03	0
	Heavy metals to agricultural soil	1.11E-09	0	0	1.79E-11	1.23E-08	1.52E-08	0	1.55E-10	8.70E-10	0
Water Use (L/bbl)	Withdrawal	4.09E+00	3.41E+00	0	1.60E+01	0	5.57E+01	1.35E+03	1.26E+00	3.19E+00	0
	Discharge	2.17E+00	0	0	1.82E+01	0	2.96E+01	3.59E+02	2.90E-01	1.70E+00	0
	Consumption	1.91E+00	3.41E+00	0	-2.21E+00	0	2.61E+01	9.94E+02	9.74E-01	1.49E+00	0
Water Quality (kg/bbl)	Aluminum	3.98E-08	0	0	5.33E-06	0	5.43E-07	0	2.34E-09	3.11E-08	0
	Arsenic (+V)	8.00E-07	0	0	3.32E-07	4.93E-09	1.09E-05	0	1.52E-07	6.24E-07	0
	Copper (+II)	9.54E-07	0	0	4.34E-07	5.35E-08	1.30E-05	0	1.81E-07	7.44E-07	0
	Iron	1.62E-05	0	0	3.18E-05	2.69E-06	2.21E-04	0	2.95E-06	1.27E-05	0
	Lead (+II)	5.19E-08	0	0	5.65E-07	1.44E-08	7.07E-07	0	8.06E-09	4.05E-08	0
	Manganese (+II)	2.73E-06	0	0	2.77E-04	3.00E-06	3.72E-05	0	2.24E-07	2.13E-06	0
	Nickel (+II)	7.33E-05	0	0	1.24E-05	1.74E-08	9.99E-04	0	1.40E-05	5.72E-05	0
	Strontium	1.32E-08	0	0	1.74E-08	4.76E-08	1.80E-07	0	1.97E-09	1.03E-08	0
	Zinc (+II)	1.03E-05	0	0	9.27E-06	2.37E-08	1.41E-04	0	1.94E-06	8.06E-06	0
	Ammonium/ammonia	1.70E-04	0	0	1.94E-05	1.07E-05	2.32E-03	0	3.24E-05	1.33E-04	0
	Hydrogen chloride	1.25E-12	0	0	1.91E-12	1.88E-11	1.70E-11	0	1.77E-13	9.76E-13	0
	Nitrogen (as total N)	6.18E-07	0	0	8.97E-05	2.90E-10	8.43E-06	0	3.43E-08	4.82E-07	0
	Phosphate	1.19E-08	0	0	8.15E-10	1.78E-08	1.62E-07	0	1.21E-09	9.28E-09	0
	Phosphorus	7.73E-07	0	0	6.34E-06	4.66E-07	1.05E-05	0	1.19E-07	6.04E-07	0
Resource Energy (MJ/bbl)	Crude oil	2.12E-01	0	0	4.43E-01	0	2.89E+00	0	2.42E-02	1.66E-01	0
	Hard coal	1.88E+00	0	0	2.00E+00	0	2.56E+01	0	3.00E-01	1.47E+00	0
	Lignite	5.72E-04	0	0	6.03E-04	0	7.80E-03	0	6.75E-05	4.47E-04	0
	Natural gas	6.08E+00	5.92E+02	0	8.11E+02	0	8.29E+01	0	3.49E-01	4.74E+00	0
	Uranium	2.76E-03	0	0	3.53E-03	0	3.77E-02	0	3.70E-04	2.16E-03	0
	Renewable	2.60E-03	0	0	7.20E-02	0	3.54E-02	0	2.54E-04	2.03E-03	0
	Total resource energy	8.17E+00	5.92E+02	0	8.13E+02	0	1.11E+02	0	6.75E-01	6.38E+00	0

Table B-4: Detailed Gate-to-Gate LCA Results for Membrane Separation– Mass Allocation (units/barrel crude produced) (continued)

Category (Units)	Material or Energy Flow	Crude Oil Storage	Oil, Gas, and Water Separation			Well Operations					Land Use	Total
		Venting and Flaring	Natural Gas Combustion	Natural Gas Upstream	Venting and Flaring	Brine Injection Pump Elec.	CO_2 Injection Compressor Elec.	CO_2 Injection Compressor Emissions	Crude Oil Artificial Lift Pump Elec.	Formation Leakage	Direct Land Use	
GHG (kg/bbl)	CO_2	4.01E-01	1.01E+00	5.99E-02	2.82E+00	1.03E+00	3.12E+01	1.26E-01	8.82E+00	1.43E+00	1.30E+00	1.06E+02
	N_2O	0	5.36E-06	1.71E-06	0	1.28E-05	3.87E-04	0	1.10E-04	0	0	9.76E-04
	CH_4	8.40E-04	1.93E-05	6.03E-03	5.89E-03	3.68E-03	1.11E-01	0	3.15E-02	0	0	4.64E-01
	SF_6	0	0	5.78E-10	0	2.25E-07	6.81E-06	0	1.93E-06	0	0	1.16E-05
	CO_2e (IPCC 2007 100-yr GWP)	4.22E-01	1.01E+00	2.11E-01	2.96E+00	1.13E+00	3.43E+01	1.26E-01	9.69E+00	1.43E+00	1.30E+00	1.19E+02
Other Air (kg/bbl)	Pb	0	0	1.06E-08	0	2.32E-08	7.00E-07	0	1.98E-07	0	0	1.67E-06
	Hg	0	0	3.31E-10	0	1.39E-08	4.21E-07	0	1.19E-07	0	0	7.33E-07
	NH_3	0	0	7.47E-09	0	7.22E-07	2.18E-05	0	6.17E-06	0	0	3.85E-05
	CO	0	7.04E-04	1.19E-04	0	1.42E-04	4.28E-03	0	1.21E-03	0	0	4.37E-02
	NOx	0	1.17E-03	1.16E-03	0	1.57E-03	4.75E-02	0	1.34E-02	0	0	1.84E-01
	SO_2	0	5.03E-06	2.00E-05	0	2.38E-03	7.19E-02	0	2.03E-02	0	0	1.24E-01
	VOC	1.41E-01	4.61E-05	9.04E-04	4.45E-02	3.84E-04	1.16E-02	0	3.28E-03	0	0	2.71E-01
	PM	0	0	4.73E-06	0	3.39E-05	1.03E-03	0	2.90E-04	0	0	1.96E-03
Solid Waste (kg/bbl)	Heavy metals to industrial soil	0	0	1.82E-05	0	9.11E-03	2.75E-01	0	7.79E-02	0	0	4.70E-01
	Heavy metals to agricultural soil	0	0	4.16E-13	0	1.48E-09	4.46E-08	0	1.26E-08	0	0	8.83E-08
Water Use (L/bbl)	Withdrawal	0	0	3.70E-01	0	5.41E+00	1.64E+02	0	4.63E+01	0	0	1.65E+03
	Discharge	0	0	4.21E-01	0	2.88E+00	8.70E+01	0	2.46E+01	0	0	5.26E+02
	Consumption	0	0	-5.13E-02	0	2.53E+00	7.66E+01	0	2.17E+01	0	0	1.13E+03
Water Quality (kg/bbl)	Aluminum	0	0	1.24E-07	0	5.27E-08	1.59E-06	0	4.50E-07	0	0	8.17E-06
	Arsenic (+V)	0	0	7.69E-09	0	1.06E-06	3.20E-05	0	9.05E-06	0	0	5.49E-05
	Copper (+II)	0	0	1.01E-08	0	1.26E-06	3.82E-05	0	1.08E-05	0	0	6.56E-05
	Iron	0	0	7.37E-07	0	2.15E-05	6.50E-04	0	1.84E-04	0	0	1.14E-03
	Lead (+II)	0	0	1.31E-08	0	6.87E-08	2.08E-06	0	5.87E-07	0	0	4.13E-06
	Manganese (+II)	0	0	6.41E-06	0	3.62E-06	1.09E-04	0	3.09E-05	0	0	4.72E-04
	Nickel (+II)	0	0	2.87E-07	0	9.70E-05	2.93E-03	0	8.29E-04	0	0	5.02E-03
	Strontium	0	0	4.03E-10	0	1.75E-08	5.28E-07	0	1.49E-07	0	0	9.65E-07
	Zinc (+II)	0	0	2.15E-07	0	1.37E-05	4.14E-04	0	1.17E-04	0	0	7.15E-04
	Ammonium/ammonia	0	0	4.50E-07	0	2.25E-04	6.82E-03	0	1.93E-03	0	0	1.17E-02
	Hydrogen chloride	0	0	4.43E-14	0	1.66E-12	5.00E-11	0	1.42E-11	0	0	1.06E-10
	Nitrogen (as total N)	0	0	2.08E-06	0	8.18E-07	2.47E-05	0	7.00E-06	0	0	1.34E-04
	Phosphate	0	0	1.89E-11	0	1.57E-08	4.76E-07	0	1.35E-07	0	0	8.29E-07
	Phosphorus	0	0	1.47E-07	0	1.02E-06	3.10E-05	0	8.75E-06	0	0	5.97E-05
Resource Energy (MJ/bbl)	Crude oil	0	0	1.03E-02	0	2.81E-01	8.50E+00	0	2.40E+00	0	0	1.49E+01
	Hard coal	0	0	4.63E-02	0	2.49E+00	7.51E+01	0	2.13E+01	0	0	1.30E+02
	Lignite	0	0	1.40E-05	0	7.58E-04	2.29E-02	0	6.48E-03	0	0	3.96E-02
	Natural gas	0	0	1.88E+01	0	8.05E+00	2.43E+02	0	6.88E+01	0	0	1.84E+03
	Uranium	0	0	8.19E-05	0	3.66E-03	1.11E-01	0	3.13E-02	0	0	1.92E-01
	Renewable	0	0	1.67E-03	0	3.44E-03	1.04E-01	0	2.94E-02	0	0	2.51E-01
	Total resource energy	0	0	1.88E+01	0	1.08E+01	3.27E+02	0	9.25E+01	0	0	1.98E+03

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