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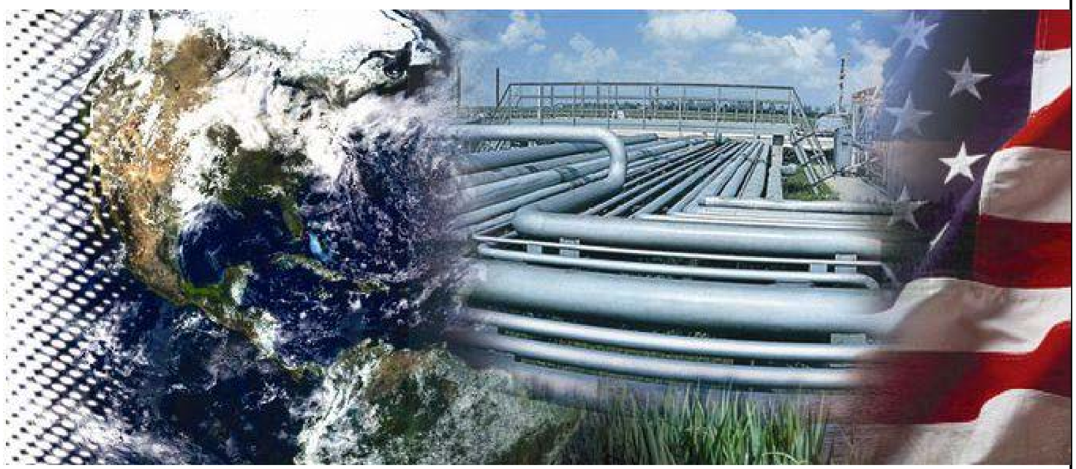

Cradle-to-Gate Life Cycle Analysis Model for Alternative Sources of Carbon Dioxide

September 30, 2013

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Tim Grant, NETL Subject Matter Expert

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Acronyms and Abbreviations

CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse gas
h	Hour
H_2	Hydrogen
H_2S	Hydrogen sulfide
kg	Kilogram
kWh	Kilowatt-hour
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
m	Meter
MSCF	Thousand standard cubic feet
MW,MWe	Megawatt electric
MWh	Megawatt-hour
N_2	Nitrogen
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
NETL	National Energy Technology Laboratory
NGL	Natural gas liquids
NH_3	Ammonia
NMVOC	Non-methane volatile organic compoound
PM	Particulate matter
SF_6	Sulfur hexafluoride
U.S.	United States
USDA	United States Department of Agriculture
VOC	Volatile organic compound

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Executive Summary

The greatest near-term opportunity for carbon dioxide (CO_2) capture from power plants is post-combustion capture (NETL, 2011). Post-combustion technologies use chemical solvents to remove CO_2 from flue gas and can be applied to new or existing coal- or natural gas-fired power plants. The flue gas from power plants has low concentrations of CO_2 at low pressures, so these CO_2 removal technologies have been designed to treat high volumes of gas (NETL, 2011).

While post-combustion capture at power plants may represent the best near-term opportunity for CO_2 capture, there are other sources of CO_2 in nature and industry. An understanding of the technologies behind these alternative sources, their key energy and material flows, and their relationships to other natural and industrial systems is useful for understanding the life cycle aspects of carbon capture, utilization, and storage. This analysis accounts for the environmental burdens of CO_2 from three alternative sources:

- **Natural CO_2 Domes:** CO_2 domes are reservoirs that contain high-purity CO_2. Existing CO_2 domes include McElmo, Sheep Mountain, Jackson, and Bravo domes in the western United States (U.S.). The recovery of CO_2 from a natural CO_2 dome requires the construction of a well with a carbon steel casing. Extracted CO_2 contains water and must be dehydrated prior to compression and pipeline transport.
- **Natural Gas Processing Plants:** Unprocessed natural gas contains acid gases (CO_2 and hydrogen sulfide [H_2S]), water, and other impurities. Natural gas processing plants remove these impurities. Natural gas processing increases the heating value and reduces the acid gas composition of natural gas.
- **Ammonia Production Plants:** CO_2 is a co-product of synthetic ammonia, which is used as fertilizer. Ammonia plants use natural gas as a fuel and feedstock (EPA, 2009). As a fuel, natural gas is used to generate steam that is used to reform methane, air, and water.

This analysis uses a life cycle analysis (LCA) approach for developing data and modeling CO_2 systems. The energy and material flows for key processes in the CO_2 supply chain 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 kilogram of CO_2 ready for compression and pipeline transport). For some technologies it was necessary to specify methods for apportioning results between co-products. For example, an ammonia plant produces ammonia and CO_2, making it necessary to decide how to calculate the burdens that are associated only with the CO_2 product stream.

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.

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1 Introduction

The greatest near-term opportunity for carbon dioxide (CO_2) capture from power plants is post-combustion capture (NETL, 2011). Post-combustion technologies use chemical solvents to remove CO_2 from flue gas and can be applied to new or existing coal- or natural gas-fired power plants. The flue gas from power plants has low concentrations of CO_2 at low pressures, so these CO_2 removal technologies have been designed to treat high volumes of gas (NETL, 2011).

While post-combustion capture at power plants may represent the best near-term opportunity for CO_2 capture, there are other sources of CO_2 in nature and industry. An understanding of the technologies behind these alternative sources, their key energy and material flows, and their relationships to other natural and industrial systems is useful for understanding the life cycle aspects of carbon capture, utilization, and storage.

The National Energy Technology Laboratory's (NETL) unit processes for alternative sources of CO_2 are discussed below. Results are shown using cradle-to-gate boundaries per unit of CO_2 produced. Full life cycle analysis (LCA) conclusions are not appropriate using these boundaries; the overall goal of this report is to document the modeling approach and data used to characterize three alternative sources of CO_2 in the United States.

2 Technology Description

This analysis accounts for the environmental burdens of CO_2 from three alternative sources:

- Natural CO_2 Domes
- Natural Gas Processing
- Ammonia Production

2.1 Natural CO_2 Domes

CO_2 domes are reservoirs that contain high purity CO_2. Existing CO_2 domes include McElmo, Sheep Mountain, Jackson, and Bravo domes in the western United States (U.S.). Based on daily production rates (DiPietro, Balash, & Wallace, 2012b) these four domes account for over 95 percent of current natural CO_2 extraction in the U.S.

The recovery of CO_2 from a natural CO_2 dome requires the construction of a well with a carbon steel casing. The interior of the carbon steel casing is lined with chrome steel to prevent acid gas corrosion, and the exterior of the carbon steel casing is surrounded by concrete (Kinder Morgan, 2002). Historically, CO_2 wells have been vertical wells, but the industry has recently applied directional drilling technologies for the construction of CO_2 wells that have lateral wellbores. Water is used during well construction as a key component of drilling fluids. This water is a mix of fresh and brackish water and is often transported by truck to the well site or is recovered from nearby well construction activity (Kinder Morgan, 2002).

Extracted CO_2 contains water and must be dehydrated prior to compression and pipeline transport. The water content in natural CO_2 is variable. At its vapor saturation point, 1 million cubic feet of CO_2 contains 50.5 pounds of water (Spycher, Pruess, & Ennis-King, 2003). The most widely used dehydration technology in the gas processing industry is the counter-current contact of gas with a glycol solvent in an absorption column that removes water from the gas stream, followed by glycol regeneration in a stripper column (EIA, 2006).

2.2 Natural Gas Processing

Unprocessed natural gas contains acid gases (CO_2 and hydrogen sulfide [H_2S]), water, and other impurities. Natural gas processing plants remove these impurities. Natural gas processing increases the heating value and reduces the acid gas composition of natural gas.

Compared to other industrial sources of CO_2, natural gas processing plants are a small share of total CO_2 production. However, significant volumes of CO_2 are produced by natural gas processing plants in the Permian Basin of western Texas and eastern New Mexico, with smaller amounts produced in western Wyoming. For carbon capture to be economically feasible at a natural gas processing plant, the gas stream must have high a concentration of CO_2 and there must be nearby opportunities for CO_2 utilization or sequestration. (EIA, 2006)

Over 30 acid gas removal technologies are used in industry (NETL, 2010). The most common technology is the absorption of acid gas by a counter-current stream of amine solvent, followed by a stripping column that separates the acid gas and regenerates the amine solvent (NETL, 2010). Most natural gas processing plants in the U.S. use amine-based separation systems to remove CO_2 and H_2S from natural gas (EIA, 2006).

The flow rate of natural gas into an acid gas removal process per unit of CO_2 captured is a function of the CO_2 recovery rate of the process and the CO_2 composition of the inlet natural gas. As the CO_2 composition of production gas increases, the amount of natural gas processed per unit of CO_2 captured decreases. Similarly, as the CO_2 recovery rate of the acid gas removal process increases, the amount of natural gas process per unit of CO_2 captured decreases.

The composition of unprocessed natural gas ("production gas") is variable. There are 5 natural gas processing facilities in the U.S. that capture CO_2. One of these facilities, the Turtle Lake processing plant in Michigan, is not near current EOR activity. The remaining 4 facilities are being used to support EOR in the Permian Basin. Data are available for the gas composition and annual production rates of three of these four facilities. These three facilities represent 93 percent of total natural gas-captured CO_2 used for EOR. The CO_2 concentrations, in terms of molar volume, for these 3 facilities are 20 percent, 65 percent, and 65 percent (DiPietro, Balash, & Wallace, 2012a). When converted to mass concentration, these three data points are 41 percent, 84 percent, and 84 percent CO_2 by mass. The mass concentration was calculated by assuming a three component mixture of CO_2, methane, and nitrogen and factoring the volumetric share of each component by its molar mass (44 for CO_2, 16 for methane, and 28 for nitrogen). It was also necessary to know the composition split between methane and nitrogen, so methane and nitrogen compositions for the LeBarge facility (21 percent and 7 percent, respectively) were used to get a 75/25 volumetric split between methane and nitrogen (MIT, 2013). The production-weighted mass composition is 78.8 percent CO_2; this is the expected parameter value for CO_2 composition. The low parameter value is 76.9 percent, which was calculated by excluding the Century gas processing facility (the facility with the highest CO_2 concentration and highest production rate) from the weighted average. Conversely, the highest parameter value is 81.1%, which was calculated by excluding the Lost Cabin gas processing facility (the facility with the lowest CO_2 concentration) from the weighted average. **Table 2-1** shows the production gas compositions for these three operating scenarios.

Table 2-1: Production Gas Composition

Component	Percent Composition by Mass for 3 Scenarios		
	Low	Expected	High
Carbon Dioxide	81.1%	78.8%	76.9%
Methane	16.4%	17.6%	18.4%
Natural Gas Liquids	0%	0%	0%
Nitrogen	2.4%	3.6%	4.7%
Total	100%	100%	100%

2.3 Ammonia Production

CO_2 is a co-product of synthetic ammonia, which is used as fertilizer. Ammonia plants use natural gas as a fuel and feedstock (EPA, 2009). As a fuel, natural gas is used to generate steam that is used to reform methane, air, and water. As a feedstock, natural gas is combusted in the presence of air and steam to form hydrogen (H_2), carbon monoxide (CO), and CO_2. Unconverted CO is then shifted to produce more H_2 and CO_2. Ammonia is then produced using the Haber process, a high-pressure, catalyzed reaction between nitrogen (N_2) and H_2 (EPA, 2009).

Urea, which is also used as fertilizer or an industrial feedstock, is produced from CO_2 and ammonia, so many ammonia production facilities also produce urea (EPA, 2009). In fact, urea production is the largest consumer of synthetic ammonia in the U.S. Fertilizer producers can send their ammonia directly to market or they can use it to produce urea. The split between ammonia sold versus ammonia used for urea is driven by market forces, and is a variable outside the scope of this analysis.

An ammonia plant has two key sources of CO_2, emissions from the reformer unit and emissions from the stripper unit that removes CO_2 from the ammonia product stream. The conditions of the reformer emission stream are not suitable for CO_2 recovery, but the acid gas stream that exits the stripper unit is 99 percent CO_2 and can be easily captured.

3 Modeling Approach Overview

The key inputs and outputs for NETL's unit processes for alternative sources of CO_2 are shown in the following figures. Detailed modeling information is provided in **Appendix A**. **Figure 3-1** represents construction and operation of a natural CO_2 dome, **Figure 3-2** shows the operation of an acid gas removal process at a natural gas processing plant, and **Figure 3-3** shows the production of ammonia. The inputs and outputs in these figures include inputs from upstream unit processes, inputs from nature, and outputs that connect to downstream unit processes. Inputs and outputs that connect to upstream or downstream unit process (i.e., "technosphere" flows) are shown in italics, while inputs from nature (i.e., "resource" flows) are not italicized. All CO_2 streams that exit these figures are at atmospheric pressure and must be compressed for pipeline transport. Compression is not included in the boundaries of this report; compression is included in NETL's unit processes for CO_2 transport, which occur downstream from CO_2 capture. The boundaries have been drawn this way to avoid double counting of compression burdens when a cradle-to-grave model of CO_2 capture and sequestration systems are assembled.

Figure 3-1: Unit Process Flows CO_2 from Natural CO_2 Domes

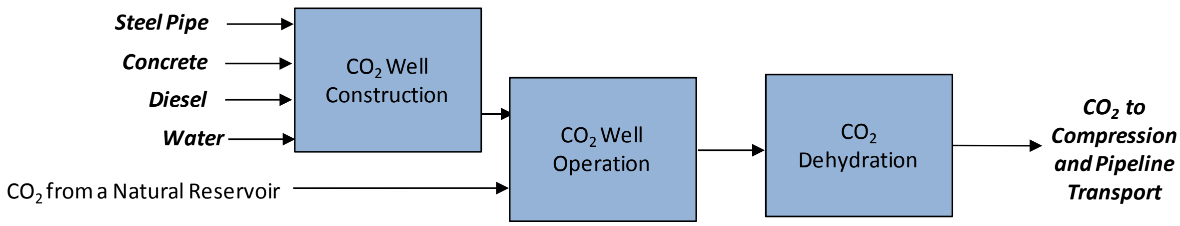


Figure 3-2: Unit Process Flows for CO_2 from Natural Gas Processing Plants

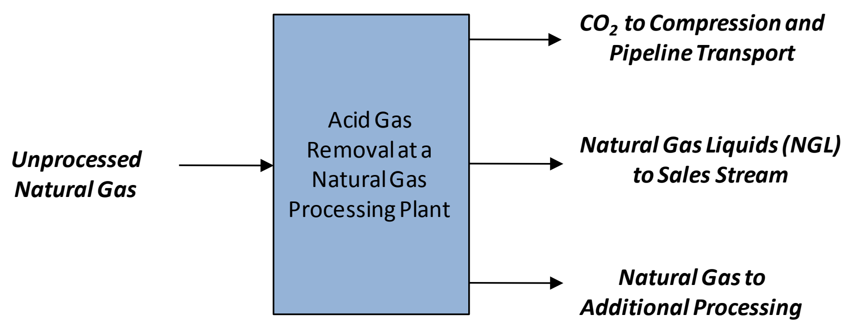
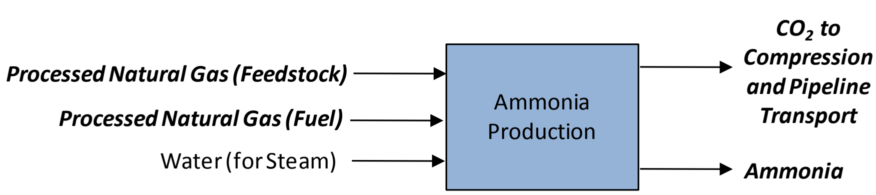


Figure 3-3: Unit Process Flows for CO_2 from Ammonia Production



3.1 Data Sources

The data sources for CO_2 sourcing options are a mix of government reports and industry-specific literature.

- Data for natural CO_2 domes are based on an environmental impact statement by Kinder Morgan for four CO_2 extraction sites, in Colorado (Kinder Morgan, 2002). This environmental impact statement was used to identify the types of processes used for natural dome CO_2 recovery and to determine the values of key parameters (such as well depth and water use rates).
- Data for natural gas processing is based on *Role of Alternative Energy Sources: Natural Gas Technology Assessment* (NETL, 2012). The unit processes in the report natural gas model have parameters that allow them to be adjusted to the gas characteristics of a particular natural gas extraction site

- Data for ammonia plant energy use and feedstock profiles are based on reports from the U.S. Department of Energy (DOE), the United States Department of Agriculture (USDA), and Lawrence Berkeley National Laboratory (DOE, 2000; LBNL, 2000; USDA, 2007). Emission factors for criteria air pollutants are from the Environmental Protection Agency (EPA) (EPA, 1993). The EPA source, AP-42, is the most recent source of emission factors for ammonia plants (EPA, 2013); ammonia production from natural gas is a mature technology, so it is not likely that the emissions from ammonia plants have changed significantly since the 1990s.Water use data is from the European fertilizer industry (EFMA, 2000); no water consumption data could be found for U.S. ammonia plants, so the European water use data is used under the assumption that ammonia technology does not change significantly across geographies.

3.2 Co-Product Management

The natural CO_2 dome produces only CO_2, but natural gas processing and ammonia production have co-products. Co-product management is necessary to calculate the energy and material flows that should be assigned to CO_2 only. This analysis uses mass-based co-product allocation to apportion burdens between CO_2 and other products. This is an attributional analysis that has the goal of assigning burdens to single products, not a consequential LCA where system expansion would be appropriate.

A natural gas processing plant produces natural gas and natural gas liquids in addition to CO_2. These three co-products can both be expressed in terms of mass, making mass-based co-product allocation feasible. An ammonia plant produces ammonia in addition to CO_2. These two co-products can be expressed in terms of mass, making mass-based co-product allocation feasible.

It is also important to note that integrated fertilizer plants produce urea in addition to ammonia. Urea production is a separate process downstream from ammonia synthesis; ammonia and urea are produced sequentially, not simultaneously. So while a fertilizer plant may produce both ammonia and urea, co-product management of ammonia and urea can be avoided by partitioning the two sequential production steps. The ammonia production data used by this analysis is representative of ammonia synthesis only, not an integrated ammonia/urea production facility.

3.3 Parameters

All unit processes used for modeling alternative sources of CO_2 have adjustable parameters. These parameters improve the flexibility of the model and allow changes to the following properties:

- **Fuel Use Rates:** Some processes combust diesel or natural gas for energy generation. For example, the drilling of a CO_2 well uses diesel, and the operation of a reboiler on an acid gas removal unit at a natural gas processing plant uses natural gas as a fuel.
- **Combustion Emission Factors:** The combustion of diesel for powering site preparation and construction equipment produces air emissions. These emissions are calculated using emission factors for diesel combustion. The total emissions from fuel combustion are the product of the fuel use rate and the combustion emission factors. While these combustion emission factors are adjustable, they do not have a high degree of variability. Unless EPA updates the emission factors for diesel combustion, it is not necessary to adjust these parameters.

- **Non-Combustion Emission Factors:** Some processes release air emissions through leaks in equipment (fugitive emissions) or intentional venting. For example, the operation of a CO_2 well has fugitive emissions of CO_2, which escape from valves and other equipment. Similarly, the regeneration of glycol solvent used for CO_2 dehydration releases CO_2 emissions.
- **Electricity Consumption:** The unit process for the dehydration of CO_2 has a parameter for electricity consumptions. This parameter represents the electricity required for the reboiler used for glycol regeneration.

The following tables (**Table 3-2**, **Table 3-3**, and **Table 3-4**) show a full listing of the adjustable parameters used by the alternative CO_2 unit processes. When applicable, these tables also show low and high values for parameters.

Table 3-2: Parameters for Natural CO_2 Extraction

Parameter Name	Low	Expected	High	Units	Description
CO_2 Well Construction					
Drill speed	1.42E+01	1.78E+01	2.13E+01	m/h	Drilling rate
Drill depth	1.00E+03	2.08E+03	2.50E+03	m	Well depth
Drill power		4.47E-01		MW	Power of drilling equipment in brake specific power
Diesel rate		2.21E+02		kg/MWh	Use rate of diesel per MWh of brake specific drilling energy
Emission factor for NOx		1.46E+01		kg/MWh	Emissions per MWh of brake specific drilling energy
Emission factor for CO		3.35E+00		kg/MWh	
Emission factor for SO_2		7.38E-03		kg/MWh	
Emission factor for CO_2		7.06E+02		kg/MWh	
Emission factor for PM		4.26E-01		kg/MWh	
Emission factor for CH_4		3.86E-02		kg/MWh	
Emission factor for VOC		3.90E-01		kg/MWh	
Total casing mass		1.03E+05		kg/well	Total mass of carbon steel well casing
Total concrete mass		1.11E+05		kg/well	Total mass of concrete well casing
Groundwater proportion		5.00E-01		dimensionless	Fraction of groundwater used during drilling
Surface water proportion		5.00E-01		dimensionless	Fraction of surface water used during drilling
Fresh water mass		6.65E+05		kg/well	Fresh water demand for drilling
Brine water mass		3.11E+05		kg/well	Brine water demand for drilling
CO_2 Well Operation					
Fugitive CO_2		4.64E-06		kg/kg	Fugitive loss of CO_2 from valves, per kg of CO_2 extracted
Well life	20	25	30	years	Production life of a CO_2 well
CO_2 production rate	5.66E+05	8.09E+05	1.05E+06	kg/well-day	Production rate of a CO_2 well
Well success rate	0.65	0.70	0.85	dimensionless	Fraction of wells drilled that have economically viable production rates, used to calculate share of well construction per unit of CO_2 produced
CO_2 Dehydration					
CO_2 loss		1.15E-04		kg/kg CO_2	CO_2 emissions released to air during glycol regeneration, in terms of CO_2 treated
Dehydration Power		1.93E-04		kWh/kg CO_2	Electricity requirements for pumping and heating glycol used for dehydration, in terms of CO_2 treated

Table 3-3: Parameters for CO_2 from Natural Gas Processing

Parameter Name	Low	Expected	High	Units	Description
Solvent makeup rate	9.98E-05	1.00E-04	1.01E-04	kg/kg CO_2 captured	Makeup rate of amine solvent for CO_2 recovery, in kg of solvent per kg of CO_2 captured
Natural gas fuel	6.33E-02	6.64E-02	6.95E-02	kg/kg CO_2 captured	Combusted natural gas input for steam generation per unit of CO_2 captured
Water input	1.48E-02	1.49E-02	1.50E-02	kg/kg CO_2 captured	Water withdrawal per unit of CO_2 captured
Surface water share	0.00E+00	5.00E-01	1.00E+00	dimensionless	Share of water withdrawn from surface water sources
CO_2 input composition	0.7690	0.7882	0.8113	dimensionless	CO_2 fraction of incoming stream
H_2S input composition	5.00E-03			dimensionless	H_2S fraction of incoming stream
NGL input composition	0			dimensionless	NGL fraction of incoming stream
CO_2 pipeline composition	4.70E-03			dimensionless	CO_2 fraction of pipeline natural gas, used to calculate amount of CO_2 removed during processing
H_2S removal rate	9.80E-01			dimensionless	Removal rate of H_2S

Table 3-4: Parameters for CO_2 from Ammonia Production

Parameter Name	Low	Expected	High	Units	Description
Natural gas input	7.78E-01	9.30E-01	1.08E+00	kg/kg CO_2 captured	Natural gas input (feedstock and fuel) per unit of CO_2 captured
Water input	1.10E+00	1.72E+00	2.35E+00	kg/kg CO_2 captured	Water input per unit of CO_2 captured
Fuel fraction	3.79E-01	4.21E-01	4.64E-01	dimensionless	Fraction of natural gas input used for fuel instead of feedstock

3.4 Data Limitations

The data used in this analysis are compiled from publicly-available sources that represent the temporal, geographical, and technical properties of three CO_2 production technologies. There are no significant data limitations for the production of CO_2 from natural domes or natural gas processing plants. The capture of CO_2 from ammonia plants has the following data limitations:

- Air emissions from ammonia production are based on 1993 EPA emission factors (EPA, 1993). As shown by EPA's WebFIRE database, the 1993 data is the most recent source of emission factors for ammonia plants (EPA, 2013). Ammonia production from natural gas is a mature technology, so it is unlikely that the emissions from ammonia plants have changed significantly since the 1990s.
- Water use for ammonia production is representative of European ammonia plants. (EFMA, 2000). No water consumption data could be found for U.S. ammonia plants, so European water data is used under the assumption that ammonia production technologies do not change significantly across geographies. It is difficult to calculate water use at ammonia plants because it is a function of reaction yields, steam cycle efficiency, and the extent of integration with urea (another fertilizer product produced by most ammonia plants).

4 Cradle-to-Gate GHG Results

The following results focus on the greenhouse gas (GHG) emissions from alternative sources of CO_2. 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.

Most processes in the boundaries of this analysis produce GHG emissions, making GHGs a good metric for understanding the dynamics of each system. However, this study 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**.

4.1 CO_2 from a Natural Dome

As shown in **Figure 4-4**, the expected cradle-to-gate GHG emissions for CO_2 from a natural dome are 0.000324 kg CO_2e/kg, with uncertainty ranging from 0.000301 to 0.000351 kg CO_2e (an uncertainty of approximately +/- 7 percent). The electricity required for CO_2 dehydration contributes the most to these GHG emissions, followed by CO_2 emissions from dehydration operations. The total uncertainty is comprised of different options for electricity sources and uncertainty in the dehydration energy consumption rate.

Figure 4-4: Cradle-to-Gate GHG Emissions for CO_2 from a Natural Dome

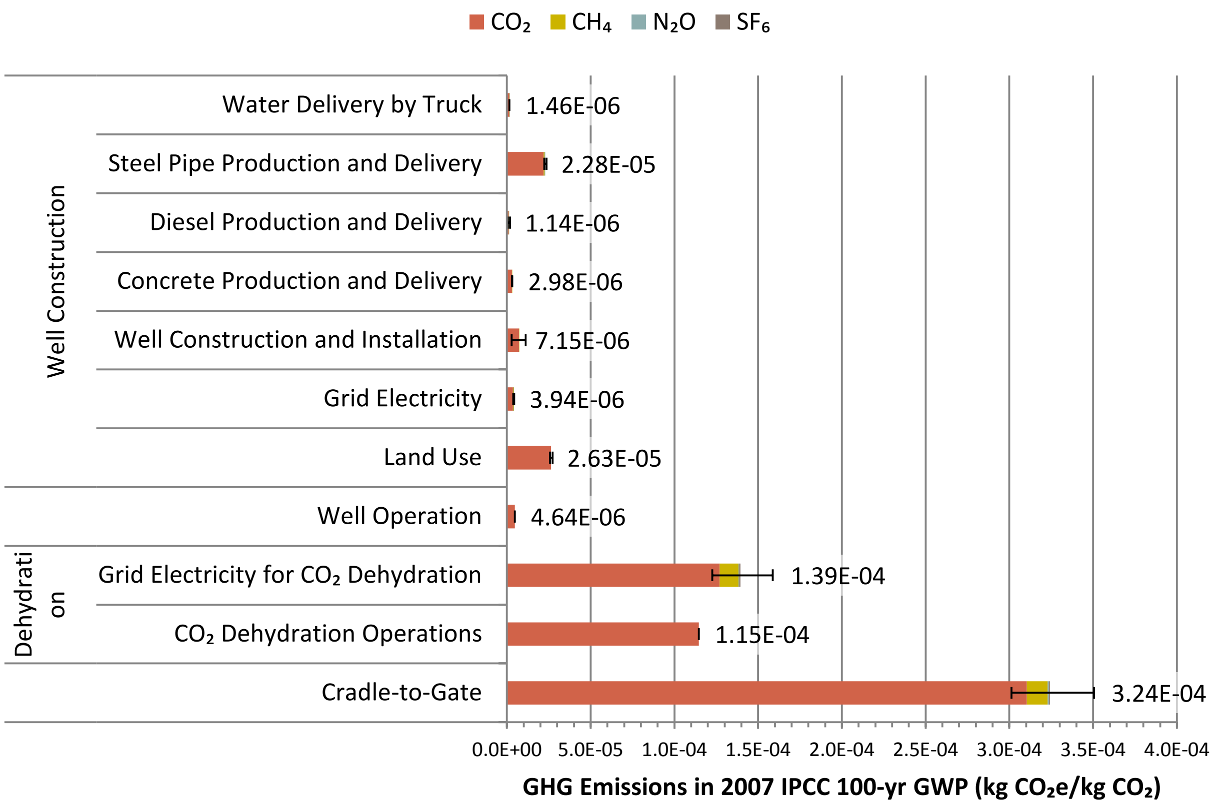


Figure 4-5 shows the sensitivity of GHG emissions from natural CO_2. Sensitivity is modeled by increasing the value of each parameter by 100 percent while holding the values for other parameters at their expected values. The GHG results are sensitive to changes in dehydrator variables, specifically the energy consumption rate and CO_2 loss rate of the dehydrator. Based on the boundaries of this cradle-to-gate system, a 100-percent increase in the dehydrator energy consumption rate causes a 43-percent increase in total GHG emissions. Similarly, a 100-percent increase in dehydrator CO_2 loss rate causes a 36-percent increase in total GHG emissions. **Figure 4-6** shows the uncertainty contributions of different parameters.

The GHG results are also sensitive to changes in well production rate, well success rate, and well life. These three parameters demonstrate an inverse relationship with total GHG emissions; as each of these parameters is increased by 100 percent, total GHG emissions decrease by 20 percent. Well production rate and well life affect the results because they affect the total amount of CO_2 produced during the life of the well; as the total amount of produced CO_2 increases, the portion of well construction and installation burdens assigned to a unit of produced CO_2 decreases. Well success rate accounts for the reliability of well exploration and development and is expressed as the fraction of wells drilled that have economically viable production rates; for example, if 30 percent of new CO_2 wells are abandoned because they are poor producers, then the CO_2 produced by the 70 percent of wells that are successful is assigned the sunk construction and installation burdens of the unsuccessful wells.

Figure 4-5: GHG Sensitivity for CO_2 Produced from a Natural Dome

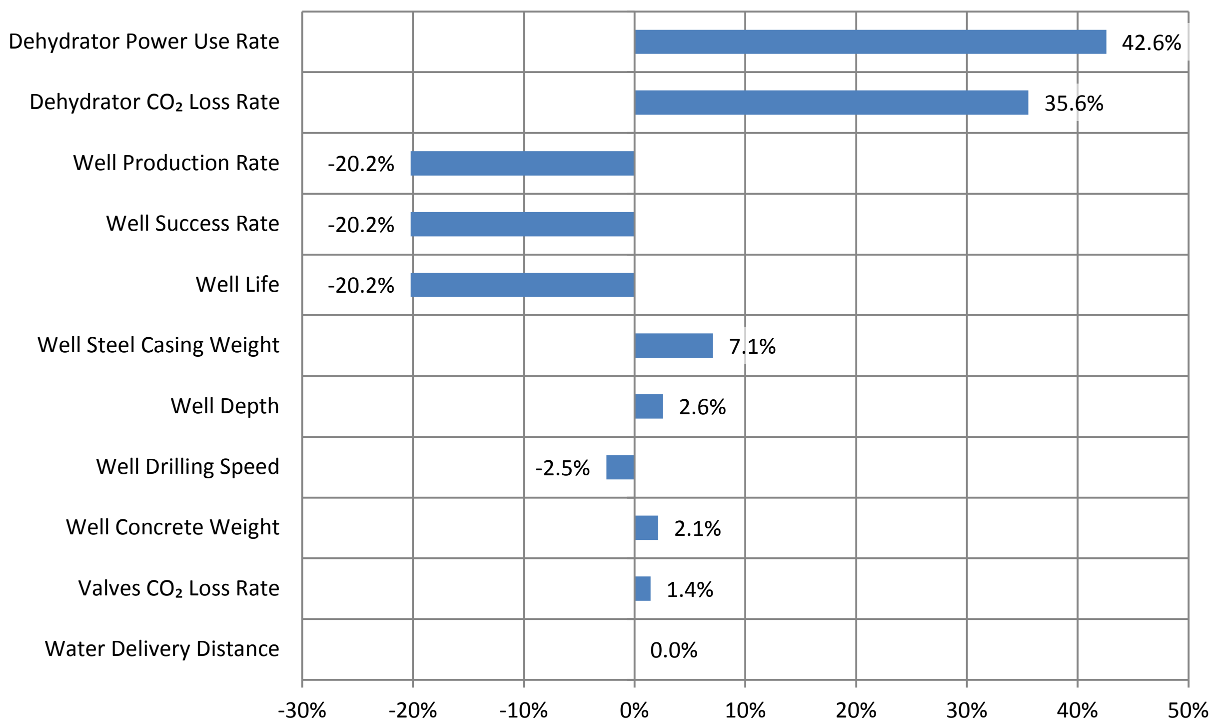
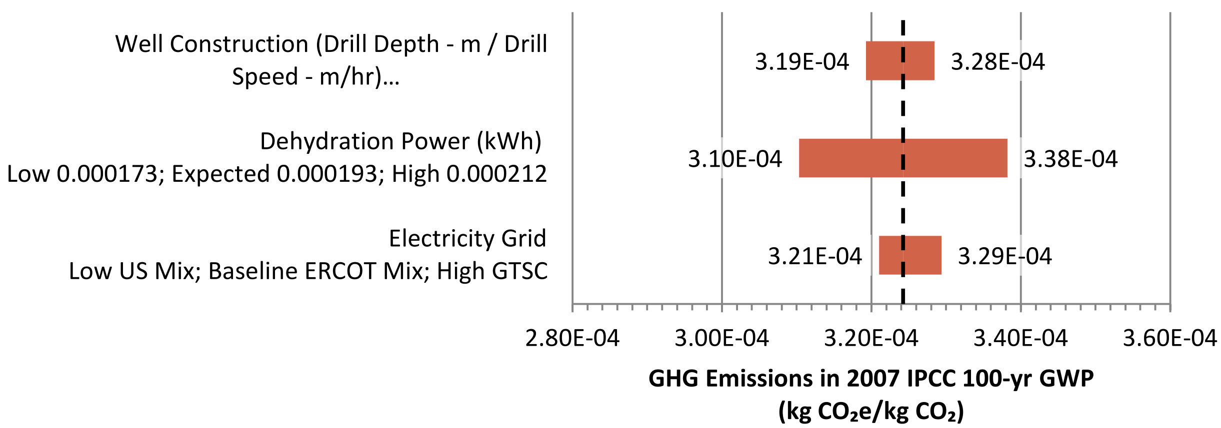


Figure 4-6: GHG Uncertainty for CO_2 Produced from a Natural Dome



4.2 CO_2 from Natural Gas Processing

The cradle-to-gate results for CO_2 from natural gas processing are based on co-product mass allocation. As shown in **Figure 4-7**, the expected cradle-to-gate GHG emissions for CO_2 from natural gas processing are 0.319 kg CO_2e/kg, with uncertainty ranging from 0.313 to 0.325 kg CO_2e. This uncertainty is driven by changes in incoming natural gas composition and its affect on mass allocation factors. As the CO_2 composition in the incoming natural gas *increases*, less natural gas is extracted per unit of CO_2 produced, but a larger share of acid gas removal burdens are allocated to the CO_2. Conversely, as the CO_2 composition in the incoming natural gas *decreases*, more natural gas is extracted per unit of CO_2 produced, but a smaller share of cradle-to-gate burdens are allocated to the CO_2. To illustrate this, **Figure 4-8** shows the change in GHG emissions as incoming natural gas CO_2 composition changes. This relationship merits further study, including a series of incremental modeling runs across a wide range of natural gas compositions.

Figure 4-7: Cradle-to-Gate GHG Emissions for CO_2 from Natural Gas Processing (Mass Co-Product Allocation)

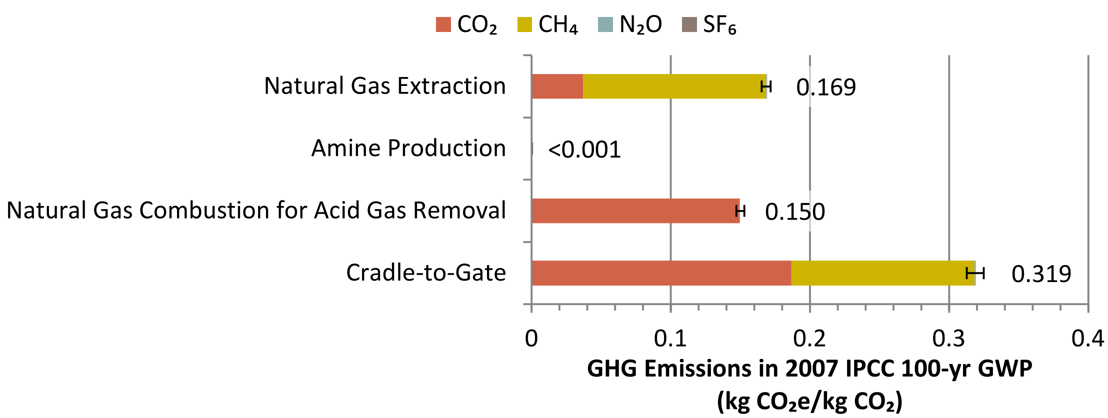


Figure 4-8: Inlet Gas CO_2 Composition versus Cradle-to-Gate GHG Emissions for CO_2 from Natural Gas Processing (Mass Co-Product Allocation)

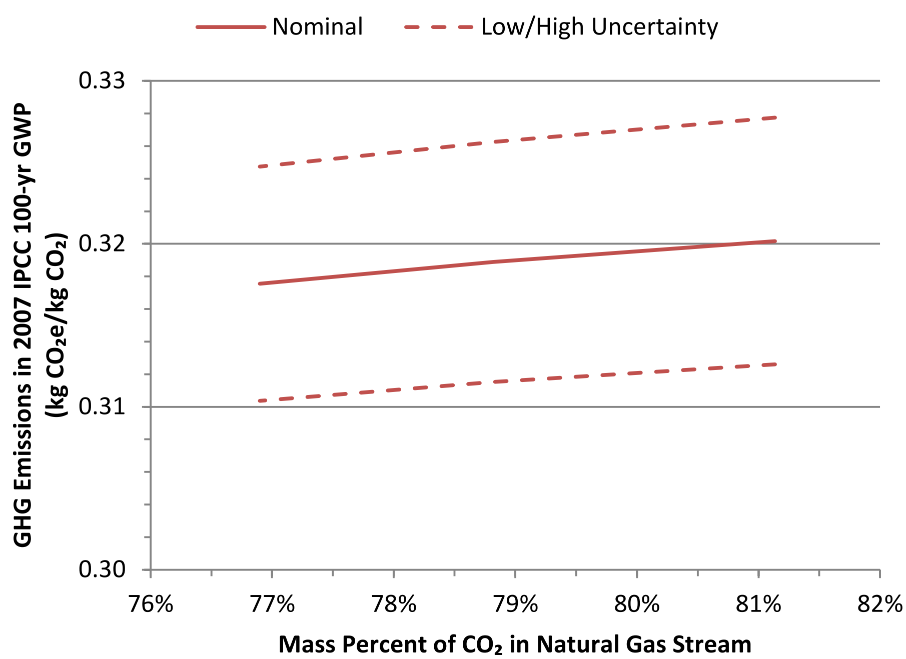


Figure 4-9 shows the sensitivity of GHG emissions for CO_2 from natural gas processing (using mass allocation). Sensitivity is modeled by increasing the value of each parameter by 100 percent while holding the values for other parameters at their expected values. The GHG results are sensitive to changes in the CO_2 composition in the incoming natural gas. Based on the boundaries of this cradle-

to-gate system, a 100-percent increase in the CO_2 composition causes a 50-percent decrease in total GHG emissions. The GHG results are also sensitive to changes in the rate of steam use for CO_2 removal; a 100-percent increase in this parameter causes a 45-percent increase in total GHG emissions. The GHG results are not sensitive to changes in requirements for amine solvent regeneration. **Figure 4-10** shows the uncertainty contributions of different parameters.

Figure 4-9: GHG Sensitivity for CO_2 Produced from Natural Gas Processing (Mass Co-Product Allocation)

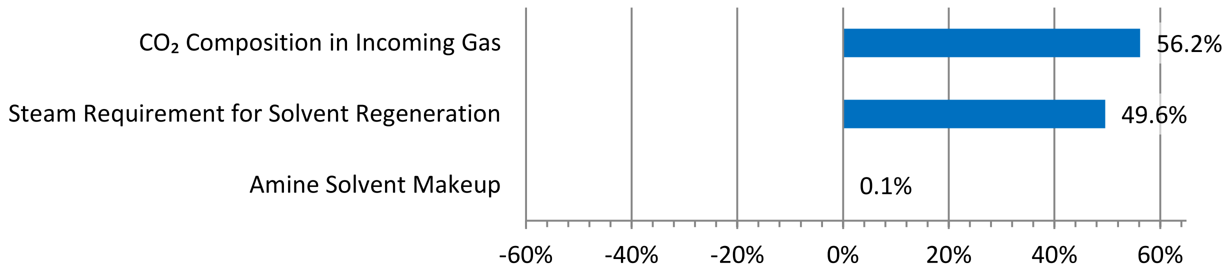
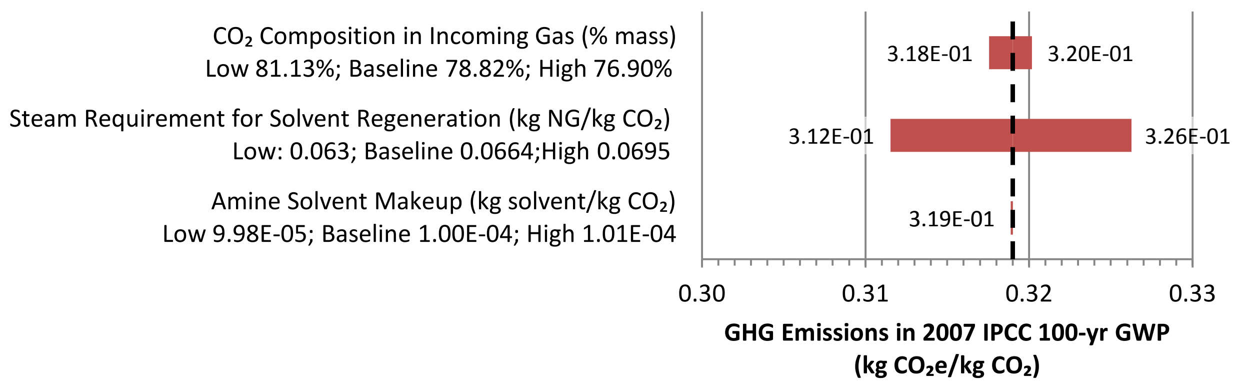


Figure 4-10: GHG Uncertainty for CO_2 Produced from Natural Gas Processing (Mass Co-Product Allocation)



The sensitivity results in **Figure 4-9** should be used with care. The percent changes shown in **Figure 4-9** use the expected value as the baseline. As discussed above (and shown in **Figure 4-7)**, there is a lot of uncertainty around the expected value, so the magnitude of the sensitivity results will change significantly as the composition of incoming natural gas changes.

4.3 CO_2 from Ammonia Production

As shown in **Figure 4-11**, the expected cradle-to-gate GHG emissions for CO_2 from ammonia production when using mass allocation are 1.41 kg CO_2e/kg, with uncertainty ranging from 1.26 to 1.56 kg CO_2e (an uncertainty of approximately +/- 11 percent). The CO_2 from ammonia production (the CO_2 from the reforming process that cannot be captured as easily as the CO_2 from the stripper unit) contributes the most to these GHG emissions, followed by CO_2 from the combustion of fuel for steam generation. The total uncertainty is comprised of the uncertainty in total fuel required for steam generation and uncertainty associated with the extraction and delivery of natural gas to the ammonia plant.

Figure 4-11: Cradle-to-Gate GHG Emissions for CO_2 from Ammonia Production (Mass Co-Product Allocation)

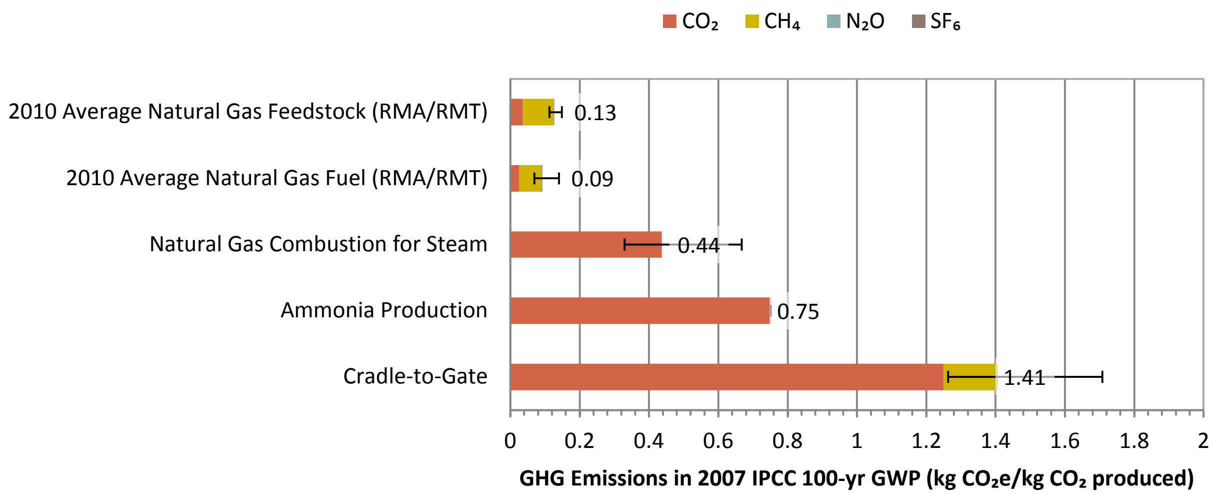


Figure 4-12 shows the sensitivity of GHG emissions for CO_2 from ammonia production when using mass allocation. Sensitivity is modeled by increasing the value of each parameter by 100 percent while holding the values for other parameters at their expected values. The GHG results are sensitive to changes in natural gas input rates. Based on the boundaries of this cradle-to-gate system, a 100-percent increase in the amount of natural gas used per unit of CO_2 captured causes a 47-percent increase in total GHG emissions. Similarly, a 100-percent increase in the fraction of natural gas input used as fuel (for steam generation) instead of for feedstock causes a 31-percent increase in total GHG emissions. **Figure 4-13** shows the uncertainty contributions of different parameters.

Figure 4-12: GHG Sensitivity for CO_2 Produced from Ammonia Production (Mass Co-Product Allocation)

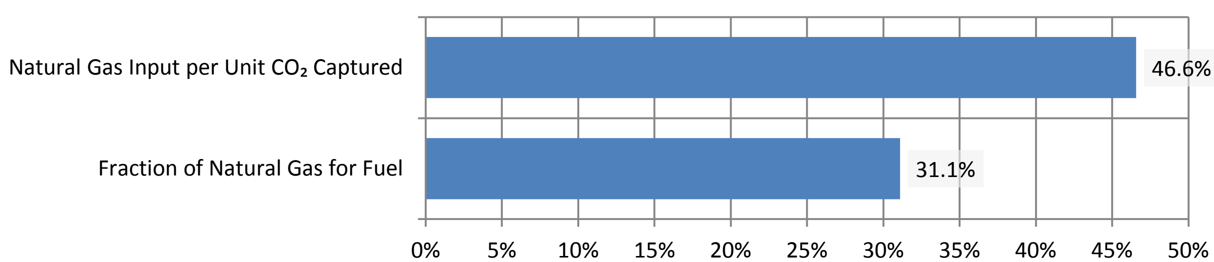
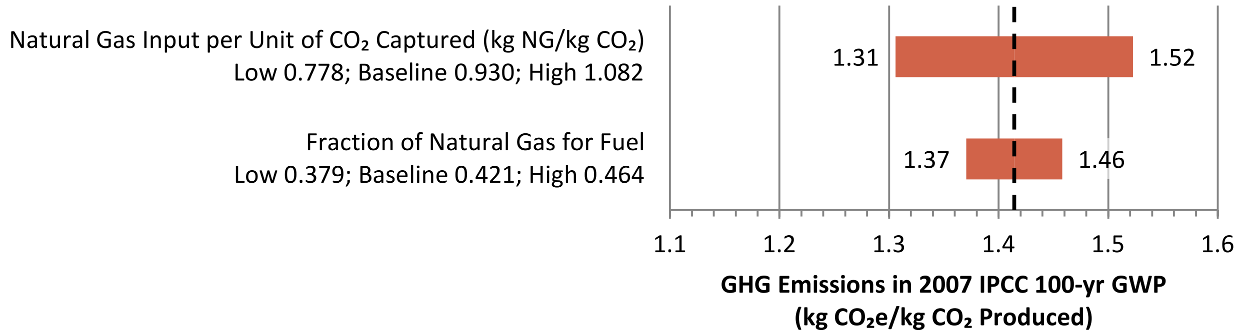


Figure 4-13: GHG Uncertainty for CO_2 Produced from Ammonia Production (Mass Co-Product Allocation)



References

DiPietro, P., Balash, P., & Wallace, M. (2012a). A Note on Source of CO2 Supply for Enhanced-Oil-Recovery Operations. *SPE Economics and Management, 4*(2).

DiPietro, P., Balash, P., & Wallace, M. (2012b). A Note on Sources of CO2 Supply for Enhanced-Oil-Recovery Operations. *SPE Economics & Management*.

DOE. (2000). *Energy and Environmental Profile of the U.S. Chemical Industry*. Washington, D.C.: U.S. Department of Energy Retrieved May 29, 2013, from http://www1.eere.energy.gov/manufacturing/resources/chemicals/pdfs/profile_full.pdf

EFMA. (2000). Best Available Techniques for Pollution and Control in the European Fertilizer Industry: Production of Ammonia. Brussels, Belgium.

EIA. (2006). *Natural Gas Processing: The Crucial Link Between Natural Gas Production and Its Transportation to Market*. Energy Information Administration, Office of Oil and Gas Retrieved November 2, 2012, from http://www.eia.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngprocess/ngprocess.pdf

EPA. (1993). *AP 42 Fifth Edition, Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*. Environmental Protection Agency Retrieved December 2, 2012 from www.epa.gov/ttnchie1/ap42/ch08/final/c08s01.pdf

EPA. (2009). *Technical Support Document for the Ammonia Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases*. Office of Air and Radiation, U.S. Environmental Protection Agency Retrieved November 2, 2012, from http://www.epa.gov/ghgreporting/documents/pdf/archived/tsd/TSD%20Ammonia%20_EPA%201-22-09.pdf

EPA. (2013). WebFIRE. Retrieved May 29, 2013, from Environmental Protection Agency http://cfpub.epa.gov/webfire/

Kinder Morgan. (2002). *Final Draft Environmental Assessment: Kinder Morgan Well Sites YE-5, HB-4, HE-5, and SC-10*.

LBNL. (2000). *Energy Use and Energy Intensity of the U.S. Chemical Industry*. Berkely, CA: Ernest Orlando Lawrence Berkeley National Laboratory Retrieved May 29, 2013, from http://www.energystar.gov/ia/business/industry/industrial_LBNL-44314.pdf

MIT. (2013). LaBarge Fact Sheet: Carbon Dioxide Capture and Storage Project Retrieved May 29, 2013, from http://sequestration.mit.edu/tools/projects/la_barge.html

NETL. (2010). *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity*. (DOE/NETL-2010/1397). Pittsburgh, Pennsylvania: National Energy Technology Laboratory Retrieved November 6, 2012, from http://www.netl.doe.gov/energy-analyses/pubs/BitBase_FinRep_Rev2.pdf

NETL. (2011). *DOE/NETL Advanced Carbon Dioxide R&D Program: Technology Update*. National Energy Technology Laboratory Retrieved November 6, 2012, from http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/CO2Handbook/CO2-Capture-Tech-Update-2011_Front-End%20Report.pdf

NETL. (2012). *Role of Alternative Energy Sources: Natural Gas Technology Assessment*. (DOE/NETL-2012/1539). Pittsburgh, PA: National Energy Technology Laboratory Retrieved November 8, 2012, from http://www.netl.doe.gov/energy-analyses/pubs/NGTechAssess.pdf

Spycher, N., Pruess, K., & Ennis-King, J. (2003). CO2-H2O mixtures in the geological sequestration of CO2: Assessment and calculation of mutual solubilities from 12 to 1000C and up to 600 bar. *Ceochimica et Cosmochimica Acta, 67(16), 3015-3031*, *67*(16), 17.

USDA. (2007). *Impact of Rising Natural Gas Prices on U.S. Ammonia Supply*. Retrieved November 21, 2012, from http://www.ers.usda.gov/media/198815/wrs0702_1_.pdf

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Appendix A: Unit Process Data for Alternative Sources for Carbon Dioxide

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A.1 Model Overview

The models were 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 these models are publicly available on the NETL website, with the exception of those noted explicitly below, which are available from PE International. The alternative CO_2 sources models can be re-created by 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 grave-to-gate values for Natural Dome are available in **Table 3-2**, Natural Gas Processing in **Table 3-3**, and Ammonia Production in **Table 3-4**, all in the main body of the report. Other parameters to generate Natural Gas Processing results can be found in *Role of Alternative Energy Sources: Natural Gas Technology Assessment (NETL, 2012)*.

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

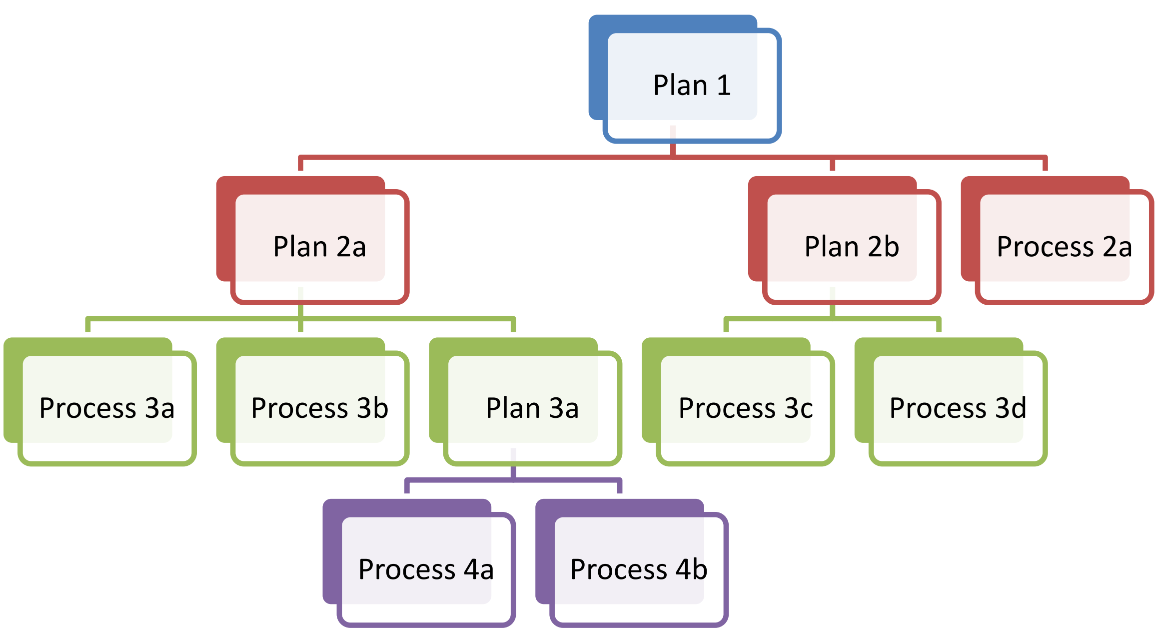

Table A-1 demonstrates the relationships between the tiers of plans used in the construction of the models. The figures and tables in this section illustrate the connectivity of the various processes and plans.

Table A-1: Parent/Child Plan Connections for CO_2 from Natural Dome, Natural Gas Processing, and Ammonia Production

Figure	Plan Name	Parent Plans	Child Plans
Natural Dome			
A-2	Natural CO_2 Dome	None	1 - CO_2 Dome Well Construction 2 - U.S. Electricity Grid Mix 2010
A-3	CO_2 Dome Well Construction	Natural CO_2 Dome	1 - CO_2 Natural Dome Land Use
A-4	CO_2 Natural Dome Land Use	CO_2 Dome Well Construction	None
Natural Gas Processing			
A-5	Natural Gas RMA/RMT - CO_2 from NG Processing	None	1 - Conventional Onshore Extraction 2 - Domestic Pipeline Transport
A-6	Conventional Onshore Extraction	Natural Gas RMA/RMT - CO_2 from NG Processing	1 - Natural Gas Extraction Processes 2 - Natural Gas Processing
A-7	Natural Gas Extraction Processes	Conventional Onshore Extraction	None
A-8	Natural Gas Processing	Conventional Onshore Extraction	None
A-9	Domestic Pipeline Transport	Natural Gas RMA/RMT - CO_2 from NG Processing	1 - Gas Pipeline Operation 2 - Onshore Pipeline Deinstallation 3 - Onshore Pipeline Const. & Installation
A-10	Gas Pipeline Operation	Domestic Pipeline Transport	None
A-11	Onshore Pipeline Deinstallation	Domestic Pipeline Transport	None
A-12	Onshore Pipeline Construction & Installation	Domestic Pipeline Transport	None
Ammonia Production			
A-13	Ammonia Production w/ CO_2 Capture	None	None

Figure A-2: Natural CO_2 Dome - Top-Level Plan

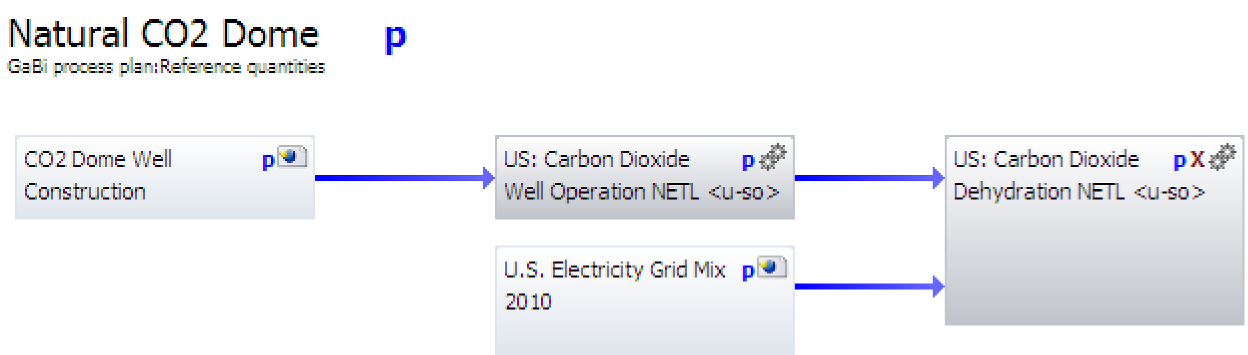

Table A-2: Unit Processes in Natural CO_2 Dome Plan

Unit Process	Notes	Version	Creation Date
Carbon Dioxide Well Operation	This unit process models the operating life and performance parameters for CO_2 well operation and pulls the well construction data.	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
Carbon Dioxide Dehydration	This unit process models the energy use for the dehydration of carbon dioxide extracted from a salt dome well	1	11/2012

Figure A-3:CO_2 Dome Well Construction - Second-Level Plan

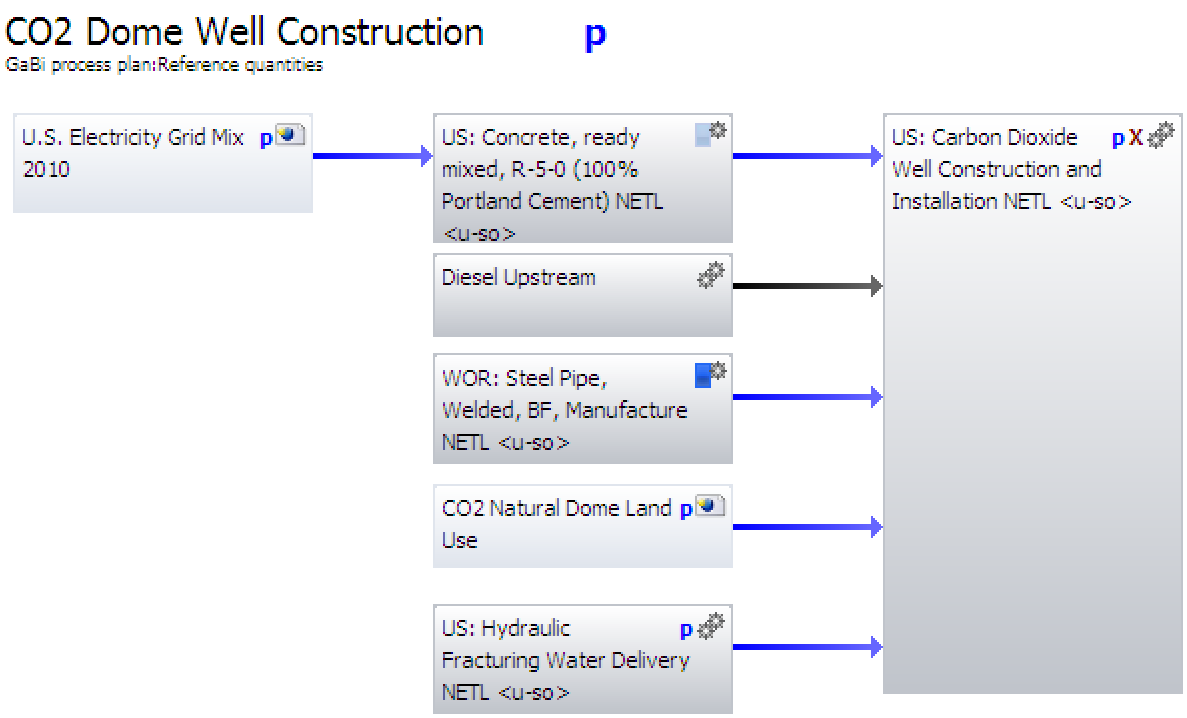

Table A-3: Unit Processes in CO_2 Dome Well Construction Plan

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
Steel Pipe	This unit process has third-party data available from PE International.	N/A	N/A
Hydraulic Fracturing Water Delivery	This unit process includes the withdrawal and delivery of water to a natural gas well.	1	10/2011
Carbon Dioxide Well Construction and Installation	Materials of construction and installation fuels and emissions for a carbon dioxide well.	1	11/2012

Figure A-4: CO_2 Natural Dome Land Use - Third-Level Plan

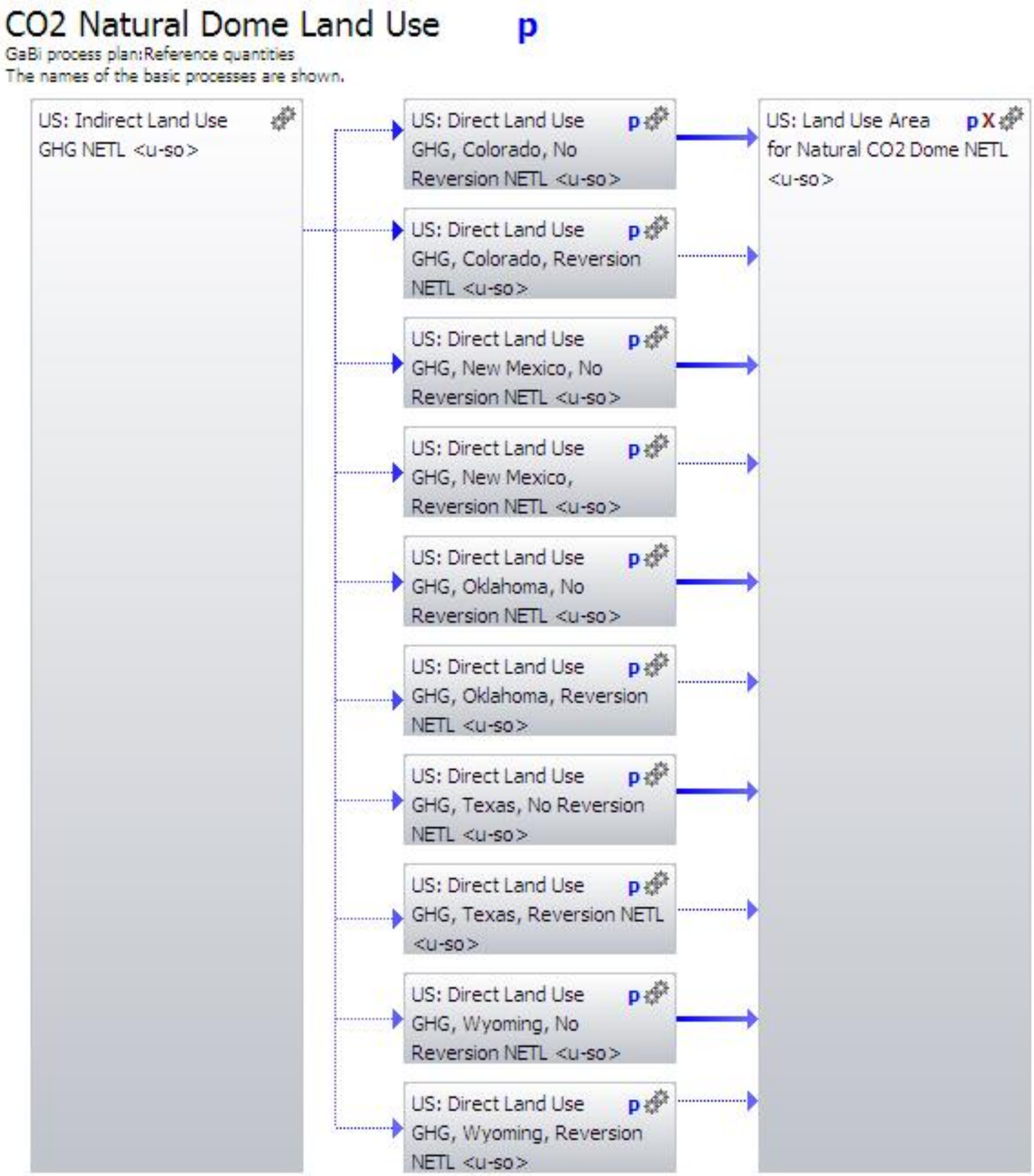

Table A-4: Unit Processes in CO_2 Natural Dome Land Use Plan

Unit Process	Notes	Version	Creation Date
Direct Land Use GHG, Reversion	This unit process accounts for direct GHG emissions from land transformation with reversion. This model is based on a theoretical aquifer located in the Permian Basin, which encompasses five states in the Permian Basin (Colorado, New Mexico, Oklahoma, Texas, and Wyoming) as shown in **Figure A-4**. This unit process holds the parameter values for all five states 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 aquifer located in the Permian Basin, which encompasses five states as shown in **Figure A-4**. This unit process holds the parameter values for all five states (Colorado, New Mexico, Oklahoma, Texas, and Wyoming) and can simply be duplicated to create all of the Direct Land Use, No Reversion plans.	1	12/2012
Indirect Land Use GHG	This unit process accounts for indirect GHG emissions from land transformation in the U.S.	1	12/2012
Land Use Area for Natural CO_2 Dome	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 without reversion is assumed for each state.	N/A	N/A

Figure A-5: Natural Gas RMA/RMT - CO_2 from NG Processing – Top-Level Plan

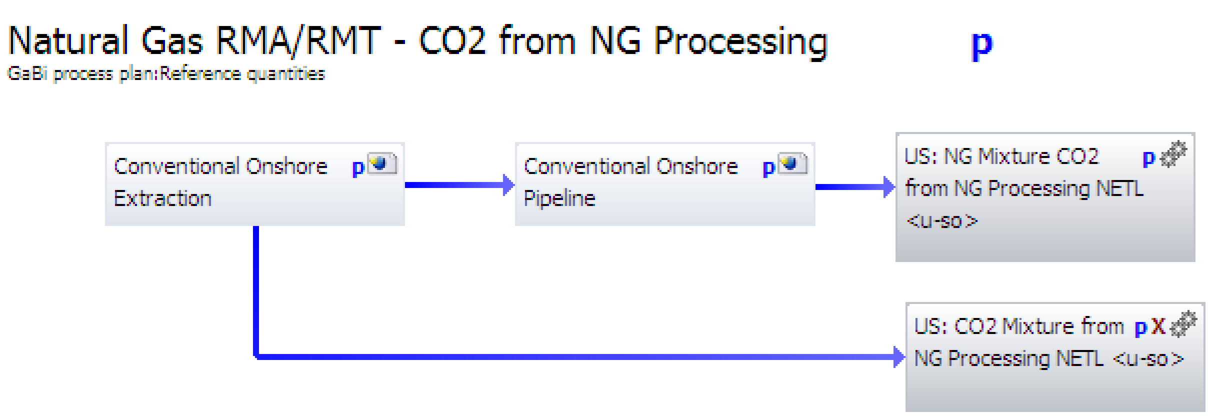

Table A-5: Unit Processes in Natural Gas RMA/RMT - CO_2 from NG Processing Plan

Unit Process	Notes	Version	Creation Date
NG Mixture CO_2 from NG Processing	This unit process converts the flow name of natural gas for tracking purposes.	N/A	N/A
CO_2 Mixture from NG Processing	This unit process converts the flow name of the carbon dioxide for tracking purposes.	N/A	N/A

Figure A-6: Conventional Onshore Extraction - Second-Level Plan

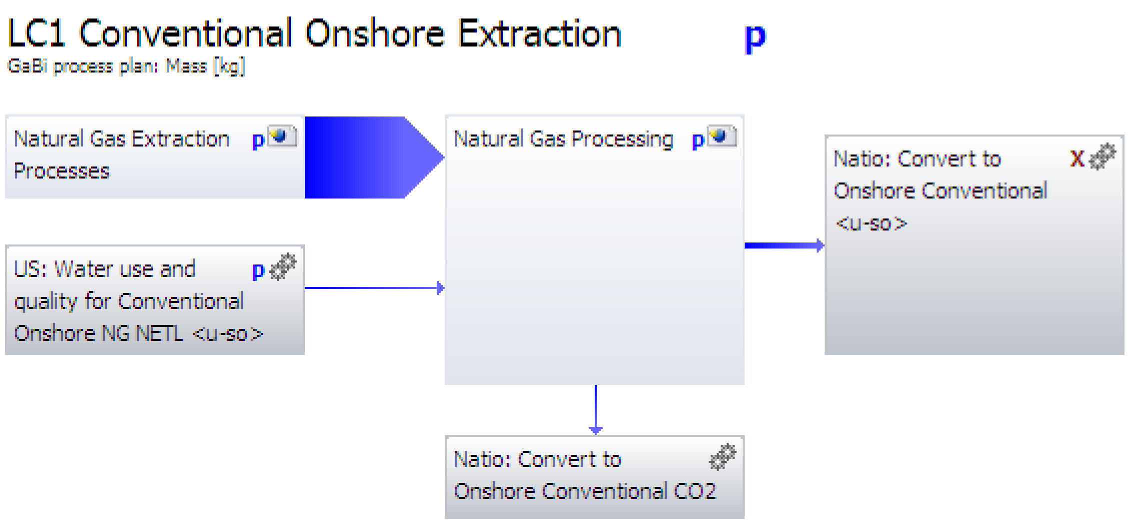

Table A-6: Unit Processes in Conventional Onshore Extraction Plan

Unit Process	Notes	Version	Creation Date
Convert to Onshore Conventional	This unit process converts the flow name of natural gas for tracking purposes.	N/A	N/A
Convert to Onshore Conventional CO_2	This unit process converts the flow name of the carbon dioxide for tracking purposes.	N/A	N/A
Water Use and Quality for Conventional Onshore NG	This unit process provides the withdrawal and discharge amounts, along with the emissions to water associated with conventional onshore natural gas extraction.	1	4/2011

Figure A-7: Natural Gas Extraction Processes - Third-Level Plan

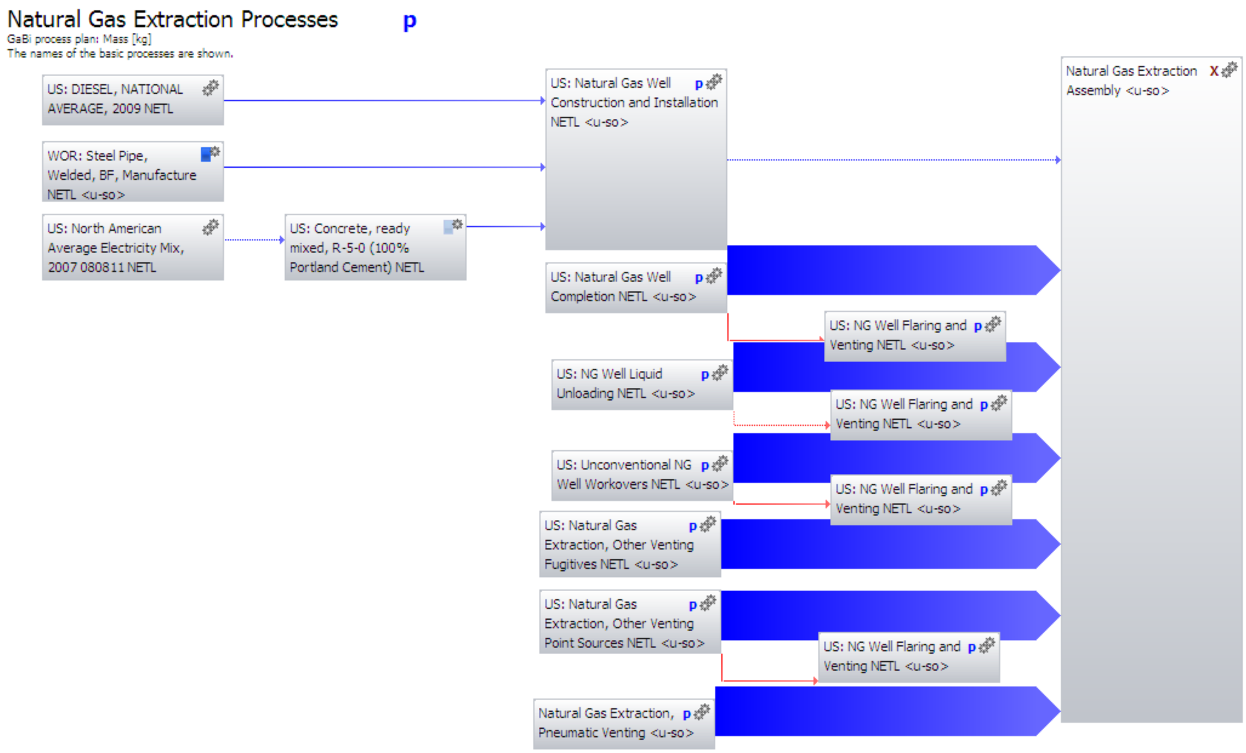

Table A-7: Unit Processes in Natural Gas Extraction Processes Plan

Unit Process	Notes	Version	Creation Date
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Steel Pipe	This unit process has third-party data available from PE International.	N/A	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
Natural Gas Well Construction and Installation	This unit process quantifies the materials, fuels, and emissions that are needed for/would result from construction and installation of a generic natural gas well.	1	2/2013

Unit Process	Notes	Version	Creation Date
Natural Gas Well Completion	This unit process quantifies the materials, fuels, and emissions that are needed for/would result from construction and installation of a generic natural gas well. Includes natural gas venting during well completion.	1	4/2011
Natural Gas Well Liquid Unloading	This unit process quantifies the mass of vented natural gas that is anticipated to occur during liquid unloading at a natural gas well.	1	4/2011
Unconventional Natural Gas Well Workovers	This unit process quantifies the mass of vented gas that is anticipated to result from natural gas well workovers, associated with the production of natural gas from conventional and unconventional wells.	1	4/2011
Natural Gas Extraction, Other Venting Fugitives	This unit process quantifies the mass of gas emitted as a result of fugitive venting from unidentified natural gas extraction activities.	1	5/2011
Natural Gas Extraction, Other Venting Point Sources	This unit process quantifies the mass of methane emitted as a result of other venting from point sources from unidentified natural gas extraction processes.	1	5/2011
Natural Gas Extraction, Pneumatic Venting	This unit process quantifies the mass of gas emitted as a result of (fugitive) venting from pneumatic devices and valves used during natural gas extraction.	1	3/2011
Venting and Flaring	This unit process quantifies the carbon dioxide and select criteria air pollutant emissions associated with the flaring and venting of natural gas at the extraction site or processing plant.	1	4/2011
Natural Gas Extraction Assembly	This assembly unit process pulls in the appropriate amount of upstream processes based on the required output of natural gas.	N/A	N/A

Figure A-8: Natural Gas Processing - Third-Level Plan

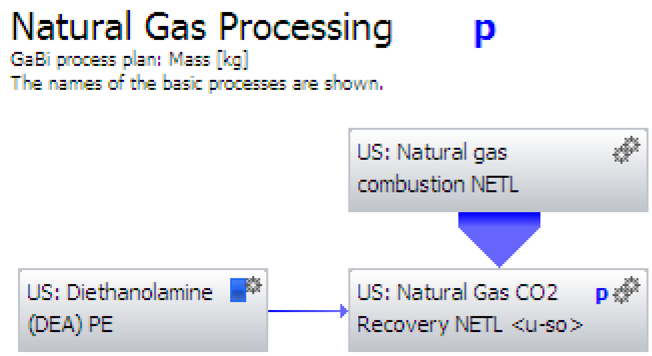

Table A-8: Unit Processes in Natural Gas Processing Plan

Unit Process	Notes	Version	Creation Date
Diethanolamine	Third-party data available from PE International, used as a proxy for monoethanolamine	N/A	N/A
Natural Gas Combustion	Air emissions from the combustion of natural gas in an auxiliary boiler	1	8/2010
Natural Gas CO_2 Recovery	Operation of an amine-based CO_2 recovery system for production natural gas	1	7/2012

Figure A-9: Domestic Pipeline Transport - Second-Level Plan

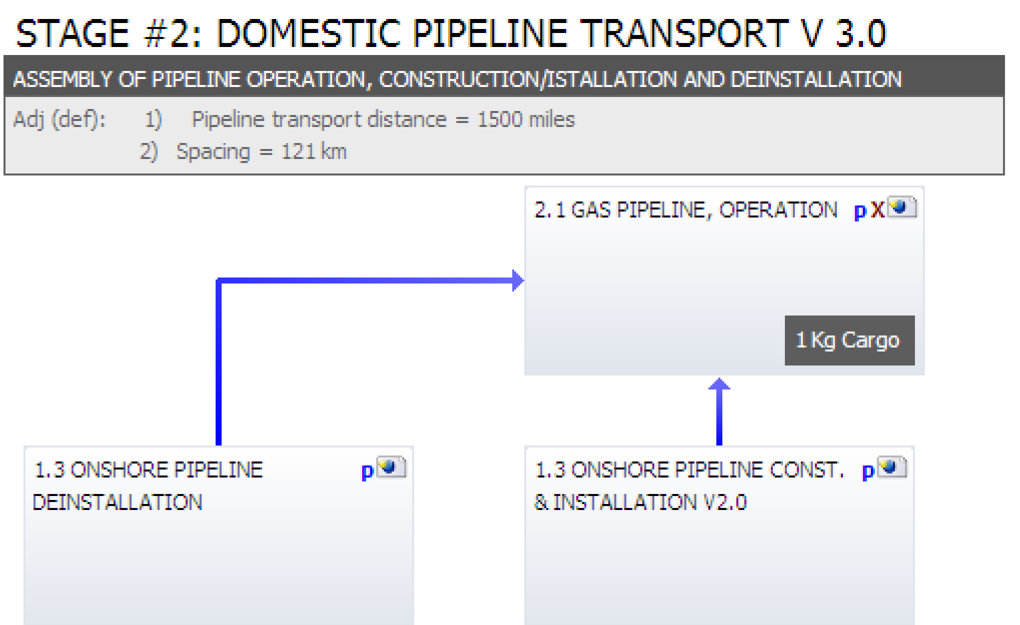

Table A-9: Unit Processes in Natural Gas Extraction Processes Plan

Unit Process	Notes	Version	Creation Date
None	This plan does not have any dependent unit processes.	N/A	N/A

Figure A-10: Gas Pipeline Operation - Third-Level Plan

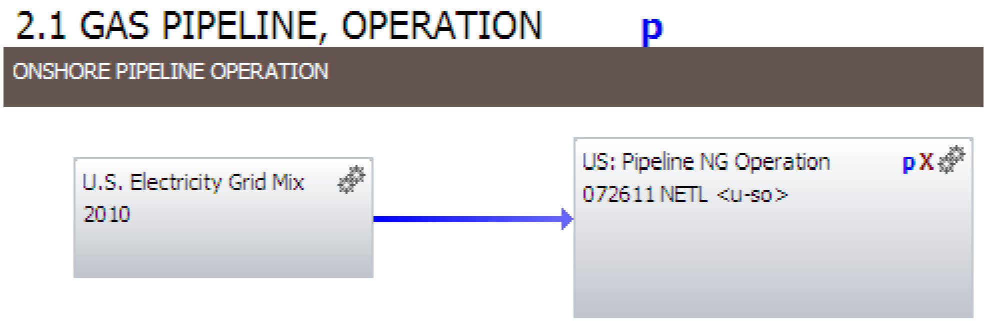

Table A-10: Unit Processes in Natural Gas Extraction Processes Plan

Unit Process	Notes	Version	Creation Date
U.S. Electricity Grid Mix 2010	U.S. Electricity Consumption Mix for 2010 – includes full life cycle results from fuel acquisition through combustion and T&D of electricity	1	N/A
Pipeline NG Operation	The energy consumption and air emissions for the pipeline transmission of natural gas	1	2/2010

Figure A-11: Onshore Pipeline Deinstallation - Third-Level Plan

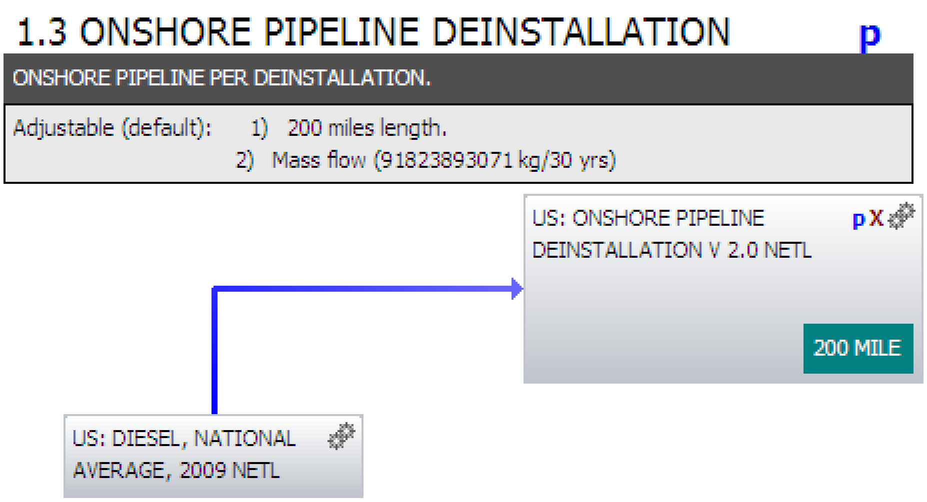

Table A-11: Unit Processes in Onshore Pipeline Deinstallation Plan

Unit Process	Notes	Version	Creation Date
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Onshore Pipeline Deinstallation	This unit process accounts for the emissions from underground pipeline laying and construction: heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust. One unit process provides installation and deinstallation inventories.	1	2/2010

Figure A-12: Onshore Pipeline Construction & Installation - Third-Level Plan

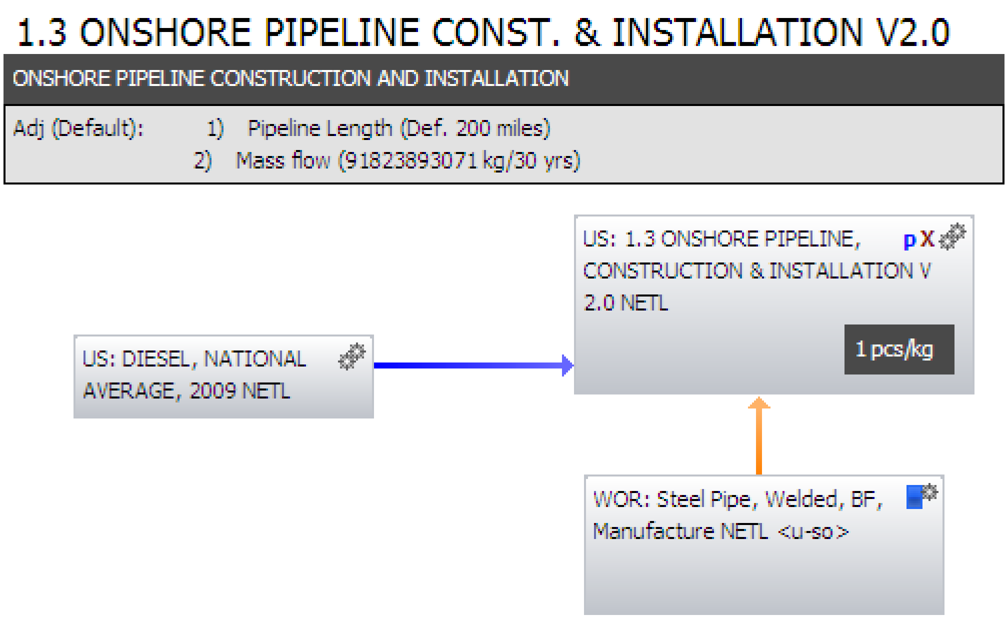

Table A-12: Unit Processes in Pipeline Construction and Installation Plan

Unit Process	Notes	Version	Creation Date
Diesel Upstream	This unit process includes the production of diesel including crude extraction, transport, and refining.	2	5/2012
Onshore Pipeline Installation	This unit process accounts for the emissions from underground pipeline laying and construction: heavy construction equipment exhaust emissions, emissions from transport of pipes and associated materials (200 miles round-trip), and fugitive dust - one unit process provides installation and deinstallation inventories.	1	2/2010

Steel Pipe	Third-party data available from PE International		

Figure A-13: Ammonia Production w/ CO_2 Capture - Top-Level Plan

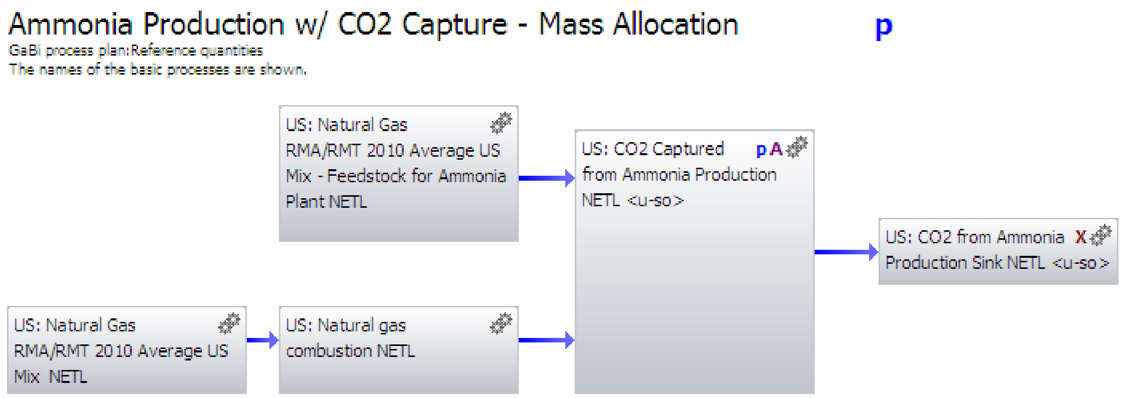

Table A-13: Unit Processes in CO_2 Natural Dome Land Use Plan

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 Upstream - Feedstock for Ammonia Plant	This process is the same as the "Natural Gas RMA/RMT 2010 Average US Mix" except that the name has been changed to indicate that this is ammonia plant feedstock natural gas, not fuel gas. The ammonia plant UP has two natural gas inputs - one for fuel, and the other as feedstock. This unique process name is required because GaBi will not allow the same process to be used twice in a plan as inputs to a single process. It will also not allow the user to see the difference between contributions of natural gas for fuel and feedstock when the balance is performed.	2	5/2012
Natural Gas Combustion	Air emissions from the combustion of natural gas in an auxiliary boiler	1	8/2010
CO_2 Captured from Ammonia Production	Fuel, feedstock, and emissions associated with 1 kg of CO_2 captured from an ammonia plant	1	12/2012
CO_2 from Ammonia Production Sink	This unit process converts the flow name of the carbon dioxide for tracking purposes.	N/A	N/A

A.3 References

NETL. (2012). *Role of Alternative Energy Source: Natural Gas Technology Assessment* (NETL/DOE-2012/1539). Pittsburgh, PA: National Energy Technology Laboratory. Retrieved May 23, 2013, from http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=435

Appendix B: Detailed Life Cycle Results for Alternative Sources of Carbon Dioxide

List of Tables

Figure B-1: Detailed Cradle-to-Gate LCA Results for CO_2 from a Natural Dome (units/kg of CO_2 produced)

Category (Units)	Material or Energy Flow	CO_2 Well Construction							Well Operation	Dehydration Operations		Total
		Land Use	Elec. Grid	Well Installation	Concrete	Diesel	Water	Steel		Elec. Grid	Dehydration	
GHG (kg/kg)	CO_2	2.63E-05	3.59E-06	7.14E-06	2.98E-06	1.05E-06	1.45E-06	2.19E-05	4.64E-06	1.27E-04	1.15E-04	3.10E-04
	N_2O	0	4.46E-11	0	0	1.73E-11	3.72E-11	1.22E-09	0	1.58E-09	0	2.89E-09
	CH_4	0	1.28E-08	3.90E-10	1.36E-10	3.53E-09	2.89E-11	2.31E-08	0	4.53E-07	0	4.93E-07
	SF_6	0	7.84E-13	0	0	1.23E-18	0	0	0	2.77E-11	0	2.85E-11
	CO_2e (IPCC 2007 100-yr GWP)	2.63E-05	3.94E-06	7.15E-06	2.98E-06	1.14E-06	1.46E-06	2.28E-05	4.64E-06	1.39E-04	1.15E-04	3.24E-04
Other Air (kg/kg)	Pb	0	8.07E-14	0	0	1.79E-14	0	6.66E-11	0	2.85E-12	0	6.95E-11
	Hg	0	4.84E-14	0	0	2.08E-15	0	1.76E-12	0	1.71E-12	0	3.52E-12
	NH_3	0	2.51E-12	0	0	6.09E-12	0	0	0	8.86E-11	0	9.72E-11
	CO	0	4.93E-10	3.38E-08	3.84E-09	5.23E-10	6.13E-10	1.62E-07	0	1.74E-08	0	2.18E-07
	NOx	0	5.52E-09	1.48E-07	9.09E-09	1.60E-09	1.82E-09	3.57E-08	0	1.95E-07	0	3.96E-07
	SO_2	0	8.27E-09	0	6.92E-09	2.16E-09	1.83E-10	6.21E-08	0	2.92E-07	0	3.72E-07
	VOC	0	1.42E-08	4.34E-09	4.71E-10	5.34E-09	1.82E-10	2.61E-08	0	5.01E-07	0	5.52E-07
	PM	0	1.61E-10	4.31E-09	9.31E-08	5.90E-11	7.23E-11	2.57E-08	0	5.68E-09	0	1.29E-07
Water Use (L/kg)	Withdrawal	0	1.88E-05	1.89E-04	1.28E-06	5.30E-06	0	2.45E-04	0	6.66E-04	0	1.13E-03
	Discharge	0	0	0	0	7.89E-07	0	0	0	0	0	7.89E-07
	Consumption	0	1.88E-05	1.89E-04	1.28E-06	4.51E-06	0	2.45E-04	0	6.66E-04	0	1.12E-03
Water Quality (kg/kg)	Aluminum	0	2.25E-12	0	0	1.04E-09	0	0	0	7.97E-11	0	1.12E-09
	Arsenic (+V)	0	3.63E-12	0	0	2.95E-11	0	0	0	1.28E-10	0	1.61E-10
	Copper (+II)	0	4.32E-12	0	0	4.29E-11	0	0	0	1.53E-10	0	2.00E-10
	Iron	0	7.09E-11	0	0	2.29E-09	0	1.21E-09	0	2.51E-09	0	6.08E-09
	Lead (+II)	0	6.17E-14	0	0	9.98E-11	0	7.67E-12	0	2.18E-12	0	1.10E-10
	Manganese (+II)	0	1.24E-11	0	0	9.56E-14	0	0	0	4.40E-10	0	4.52E-10
	Nickel (+II)	0	3.36E-10	0	0	7.91E-10	0	2.24E-12	0	1.19E-08	0	1.30E-08
	Strontium	0	6.06E-14	0	0	2.16E-12	0	0	0	2.14E-12	0	4.37E-12
	Zinc (+II)	0	4.52E-11	0	0	1.37E-09	0	2.42E-12	0	1.60E-09	0	3.02E-09
	Ammonium/ammonia	0	1.02E-09	0	0	1.13E-08	0	1.70E-10	0	3.60E-08	0	4.85E-08
	Hydrogen chloride	0	5.76E-18	0	0	9.16E-17	0	0	0	2.03E-16	0	3.01E-16
	Nitrogen (as total N)	0	2.85E-12	0	0	4.49E-18	0	0	0	1.01E-10	0	1.03E-10
	Phosphate	0	5.49E-14	0	0	2.21E-14	0	0	0	1.94E-12	0	2.02E-12
	Phosphorus	0	1.80E-12	0	0	9.94E-10	0	1.26E-12	0	6.35E-11	0	1.06E-09
Resource Energy (MJ/kg)	Crude oil	0	9.78E-07	0	0	2.99E-05	0	3.70E-05	0	3.46E-05	0	1.02E-04
	Hard coal	0	2.14E-05	0	0	7.88E-07	0	1.53E-04	0	7.55E-04	0	9.31E-04
	Lignite	0	2.66E-09	0	0	7.73E-08	0	0	0	9.39E-08	0	1.74E-07
	Natural gas	0	2.80E-05	0	0	4.61E-06	0	6.33E-05	0	9.89E-04	0	1.09E-03
	Uranium	0	1.23E-08	0	0	4.37E-07	0	0	0	4.35E-07	0	8.84E-07
	Renewable	0	1.20E-08	0	0	4.79E-08	0	0	0	4.23E-07	0	4.83E-07
	Total resource energy	0	5.04E-05	0	0	3.58E-05	0	2.54E-04	0	1.78E-03	0	2.12E-03

Figure B-2: Detailed Cradle-to-Gate LCA Results for CO_2 from Natural Gas Processing – Mass Allocation (units/kg of CO_2 produced)

Category (Units)	Material or Energy Flow	Conventional Onshore Natural Gas Extraction	Natural Gas Processing			Total
			Amine Production	CO_2 Recovery from an Acid Gas	Natural Gas Combustion for Acid Gas Removal	
GHG ($kg/kg\ CO_2$)	CO_2	3.71E-02	2.42E-04	0	1.49E-01	1.87E-01
	N_2O	1.51E-06	1.29E-08	0	7.97E-07	2.32E-06
	CH_4	5.25E-03	5.48E-07	0	2.86E-06	5.26E-03
	SF_6	2.00E-10	6.78E-17	0	0	2.00E-10
	CO_2e (IPCC 2007 100-yr GWP)	1.69E-01	2.60E-04	0	1.50E-01	3.19E-01
Other Air ($kg/kg\ CO_2$)	Pb	1.84E-08	4.00E-11	0	0	1.85E-08
	Hg	5.05E-10	1.52E-12	0	0	5.07E-10
	NH_3	3.05E-09	2.40E-09	0	0	5.46E-09
	CO	5.90E-05	1.23E-07	0	1.05E-04	1.64E-04
	NO_X	7.09E-05	3.16E-07	0	1.74E-04	2.46E-04
	SO_2	2.38E-05	2.29E-07	0	7.47E-07	2.47E-05
	VOC	6.93E-04	9.94E-08	7.89E-05	6.85E-06	7.79E-04
	PM	1.11E-05	-1.01E-14	0	9.46E-06	2.05E-05
Water Use ($L/kg\ CO_2$)	Withdrawal	1.03E-01	4.89E-02	1.17E-02	0	1.64E-01
	Discharge	3.11E-02	4.71E-02	0	0	7.82E-02
	Consumption	7.23E-02	1.75E-03	1.17E-02	0	8.58E-02
Water Quality ($kg/kg\ CO_2$)	Aluminum	4.00E-07	2.41E-10	0	0	4.00E-07
	Arsenic (+V)	1.28E-08	2.34E-11	0	0	1.28E-08
	Copper (+II)	1.83E-08	2.11E-10	0	0	1.85E-08
	Iron	1.24E-06	3.52E-08	0	0	1.28E-06
	Lead (+II)	4.04E-08	5.39E-11	0	0	4.05E-08
	Manganese (+II)	2.23E-09	7.47E-10	0	0	2.98E-09
	Nickel (+II)	3.70E-07	6.72E-11	0	0	3.71E-07
	Strontium	4.47E-09	1.41E-10	0	0	4.61E-09
	Zinc (+II)	5.44E-07	8.36E-11	0	0	5.45E-07
	Ammonium/ammonia	4.52E-06	4.72E-08	0	0	4.57E-06
	Hydrogen chloride	4.65E-14	6.66E-14	0	0	1.13E-13
	Nitrogen (as total N)	6.15E-10	7.65E-13	0	0	6.15E-10
	Phosphate	1.39E-11	6.37E-11	0	0	7.76E-11
	Phosphorus	3.82E-07	1.61E-09	0	0	3.83E-07
Resource Energy ($MJ/kg\ CO_2$)	Crude oil	2.20E-02	9.49E-04	0	0	2.29E-02
	Hard coal	5.02E-02	3.50E-04	0	0	5.06E-02
	Lignite	3.11E-05	4.62E-05	0	0	7.74E-05
	Natural gas	1.16E+00	4.04E-03	6.09E+01	0	6.20E+01
	Uranium	1.77E-04	1.58E-04	0	0	3.35E-04
	Renewable	5.93E-04	7.03E-05	0	0	6.63E-04
	Total resource energy	1.24E+00	5.62E-03	6.09E+01	0	6.21E+01

Figure B-3: Detailed Cradle-to-Gate LCA Results for CO_2 from Ammonia Production – Mass Allocation (units/kg of CO_2 produced)

Category (Units)	Material or Energy Flow	Natural Gas Feedstock	Natural Gas Fuel	Ammonia Plant		Total
				Ammonia Production	Natural Gas Combustion for Steam	
GHG (kg/kg)	CO_2	3.62E-02	2.64E-02	7.52E-01	4.36E-01	1.25E+00
	N_2O	1.01E-06	7.34E-07	0	2.33E-06	4.07E-06
	CH_4	3.75E-03	2.73E-03	0	8.36E-06	6.49E-03
	SF_6	3.44E-10	2.50E-10	0	0	5.94E-10
	CO_2e (IPCC 2007 100-yr GWP)	1.30E-01	9.49E-02	7.52E-01	4.37E-01	1.41E+00
Other Air (kg/kg)	Pb	6.27E-09	4.56E-09	0	0	1.08E-08
	Hg	1.96E-10	1.43E-10	0	0	3.39E-10
	NH_3	4.44E-09	3.24E-09	1.28E-03	0	1.28E-03
	CO	7.08E-05	5.15E-05	4.82E-03	3.05E-04	5.25E-03
	NOx	6.89E-04	5.02E-04	0	5.09E-04	1.70E-03
	SO_2	1.18E-05	8.63E-06	1.76E-05	2.18E-06	4.02E-05
	VOC	4.28E-03	3.12E-03	2.88E-03	2.84E-05	1.03E-02
	PM	8.01E-06	5.83E-06	0	2.76E-05	4.15E-05
Water Use (L/kg)	Withdrawal	2.16E-01	1.58E-01	6.71E-01	0	1.05E+00
	Discharge	2.46E-01	1.79E-01	0	0	4.25E-01
	Consumption	-2.97E-02	-2.16E-02	6.71E-01	0	6.20E-01
Water Quality (kg/kg)	Aluminum	7.33E-08	5.34E-08	0	0	1.27E-07
	Arsenic (+V)	4.54E-09	3.31E-09	0	0	7.85E-09
	Copper (+II)	5.95E-09	4.33E-09	0	0	1.03E-08
	Iron	4.34E-07	3.16E-07	0	0	7.50E-07
	Lead (+II)	7.68E-09	5.59E-09	0	0	1.33E-08
	Manganese (+II)	3.75E-06	2.73E-06	0	0	6.48E-06
	Nickel (+II)	1.70E-07	1.24E-07	0	0	2.94E-07
	Strontium	2.37E-10	1.73E-10	0	0	4.10E-10
	Zinc (+II)	1.26E-07	9.21E-08	0	0	2.18E-07
	Ammonium/ammonia	1.20E-06	8.71E-07	0	0	2.07E-06
	Hydrogen chloride	2.63E-14	1.91E-14	0	0	4.54E-14
	Nitrogen (as total N)	1.23E-06	8.96E-07	0	0	2.13E-06
	Phosphate	1.12E-11	8.17E-12	0	0	1.94E-11
	Phosphorus	8.62E-08	6.27E-08	0	0	1.49E-07
Resource Energy (MJ/kg)	Crude oil	6.06E-03	4.41E-03	0	0	1.05E-02
	Hard coal	2.70E-02	1.97E-02	0	0	4.66E-02
	Lignite	8.21E-06	5.98E-06	0	0	1.42E-05
	Natural gas	1.11E+01	8.01E+00	5.96E+00	0	2.51E+01
	Uranium	4.80E-05	3.49E-05	0	0	8.29E-05
	Renewable	9.92E-04	7.22E-04	0	0	1.71E-03
	Total resource energy	1.12E+01	8.03E+00	5.96E+00	0	2.52E+01