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

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Agenda

Technology Descriptions

Unit Processes

Key Parameters

Co-product Management

Cradle-to-Gate Results

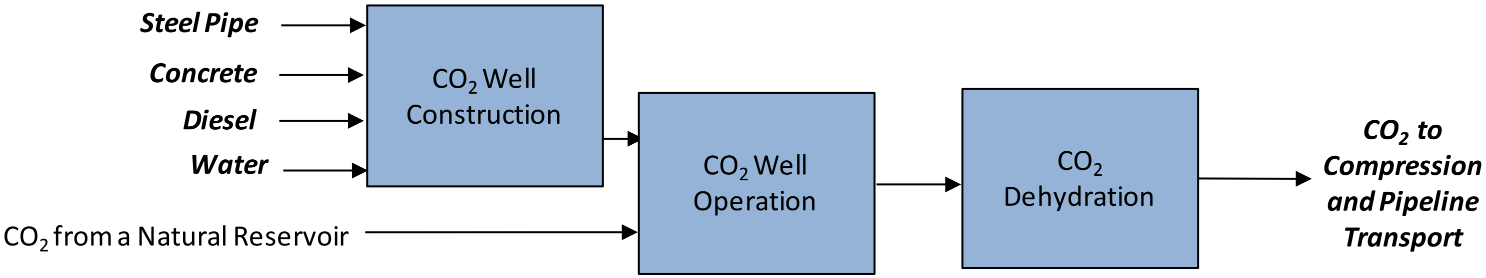
Sensitivities

Technology Descriptions

- **CO_2 from Natural Dome**
  - CO_2 domes are reservoirs that contain high purity CO_2
  - Existing CO_2 domes include McElmo, Sheep Mountain, Jackson, and Bravo domes in Western U.S.
  - Recovery of CO_2 from natural dome requires construction of a well with a carbon steel casing
  - Natural CO_2 contains water and must be dehydrated prior to compression and pipeline transport
- **CO_2 from Natural Gas Processing**
  - Unprocessed natural gas contains acid gas, including variable concentrations of CO_2
  - Natural gas processing increases the heating value and reduces the acid gas composition of natural gas
  - Most natural gas processing plants vent natural gas, but at some scales it may be feasible to capture CO_2
- **CO_2 from Ammonia Production**
  - CO_2 is a co-product of synthetic ammonia
  - Ammonia plants use natural gas as a fuel and feedstock
  - An ammonia plant has two key sources of CO_2, emissions from *reforming* and emissions from *stripping*. CO_2 from reforming cannot be easily captured, but acid gas from stripping is 99 percent CO_2 and can be easily captured.

Unit Processes for CO_2 from Natural Dome

- **CO_2 well construction adapted from existing unit process for natural gas well construction**
  - Based on environmental impact statement for Kinder Morgan CO_2 extraction sites in Western U.S.
  - Key parameters include well depth, well life, and well production rate
  - Inputs include construction materials (steel and concrete), diesel used by drilling rig, and water used for drilling mud
- **CO_2 well operation accounts for fugitive CO_2 emissions**
  - Valve leakage and other fugitive CO_2 emissions are accounted for by single emission factor, adapted from NETL's existing unit processes for natural gas extraction
  - Existing natural gas emission factor was adapted according to molecular weights of methane vs. CO_2
- **CO_2 dehydration adapted from existing unit process for natural gas**
  - Reboiler heat and pump power provided by grid electricity instead of natural gas



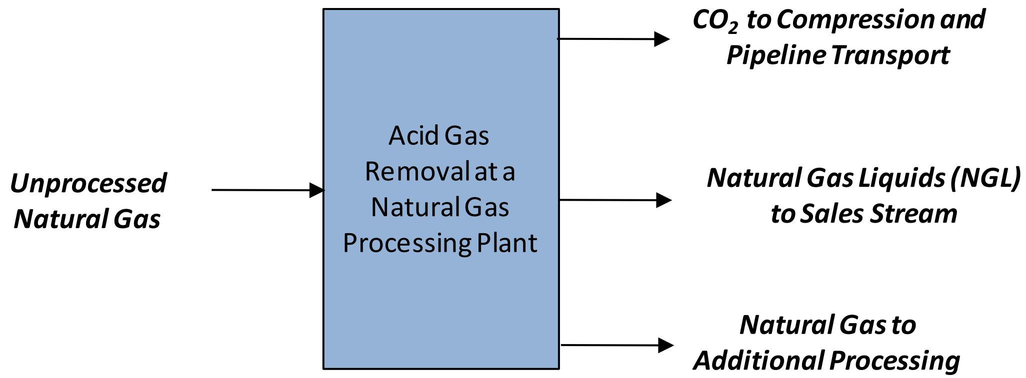
Key Parameters for CO_2 from Natural Domes

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; kg of diesel combusted per MWh of brake drilling energy
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, used to calculate share of well construction per unit of CO_2 dehydrated
CO_2 production rate	5.66E+05	8.09E+05	1.05E+06	kg/well-day	Production rate of a CO_2 well, used to calculate share of well construction per unit of CO_2 dehydrated
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 dehydrated
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

- Well construction and operation parameters based on discussions with representatives of Kinder Morgan and comparisons between natural gas and CO_2 well practices
- Dehydration parameters based on comparisons between natural gas and natural CO_2 compositions

Unit Process for CO_2 from Natural Gas Processing

- **Adapted from existing acid gas removal process (from NETL's natural gas model)**
  - Unlike existing natural gas model, CO_2 is captured instead of vented
  - Processed natural gas is sent to additional processing steps that are not necessary for CO_2
- **Parameters are used to account for variable CO_2 concentrations**
  - Production gas contains 1.5 to 70 percent (by mass) CO_2
  - Reference flow of unit process is 1 kg of captured CO_2, so energy and material flows scale according to incoming CO_2 concentration



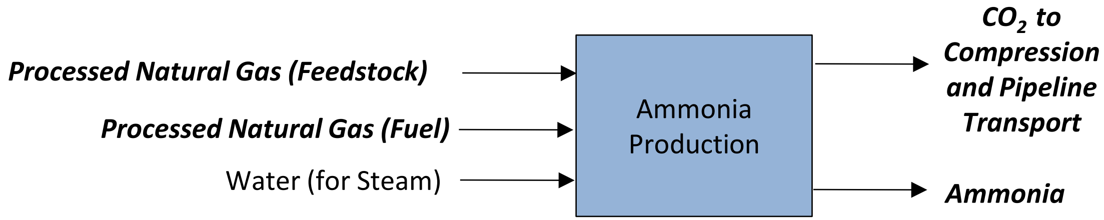
Key Parameters for CO_2 from Natural Gas Processing

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	0.8113	0.7882	0.7690	dimensionless	CO_2 fraction of incoming stream
H_2S input composition		5.00E-03		dimensionless	H_2S fraction of incoming stream
NGL input composition		1.50E-01		dimensionless	Natural gas liquids (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

- Solvent makeup and natural gas fuel rates based on variability shown by data sources (FLUOR, 2003; NETL, 2010; NETL, 2011)
- CO_2 composition in incoming gas (i.e., “production gas”) based on characteristics of natural gas wells that capture CO_2 for use in EOR in the Permian Basin
- CO_2 removal rate is a dependent variable, calculated based production gas composition (variable) and pipeline gas composition (0.47% mass CO_2) (NETL, 2012)

Unit Process for CO_2 from Ammonia Production

- New unit process, not based on existing NETL unit processes
- Natural gas is feedstock and fuel (coal is a negligible share of ammonia feedstock in the U.S.)
- Ammonia production is a two-step process
  - Step 1: Steam reforming of natural gas to produce carbon monoxide (CO) and hydrogen (H_2)
  - Step 2: Catalyzed conversion of hydrogen and nitrogen to ammonia
- Instead of being used for urea production, CO_2 is sent to carbon capture, utilization and storage (CCUS)
- Key data sources
  - Energy and feedstock profiles by government-sponsored research (Energetics, 2000; USDA, 2007; Worrell et al., 2000)
  - EPA emission factors for ammonia plants (EPA, 2009)
  - Water use data from European fertilizer industry (EFMA, 2000)



Key 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	1.10	1.72	2.35	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

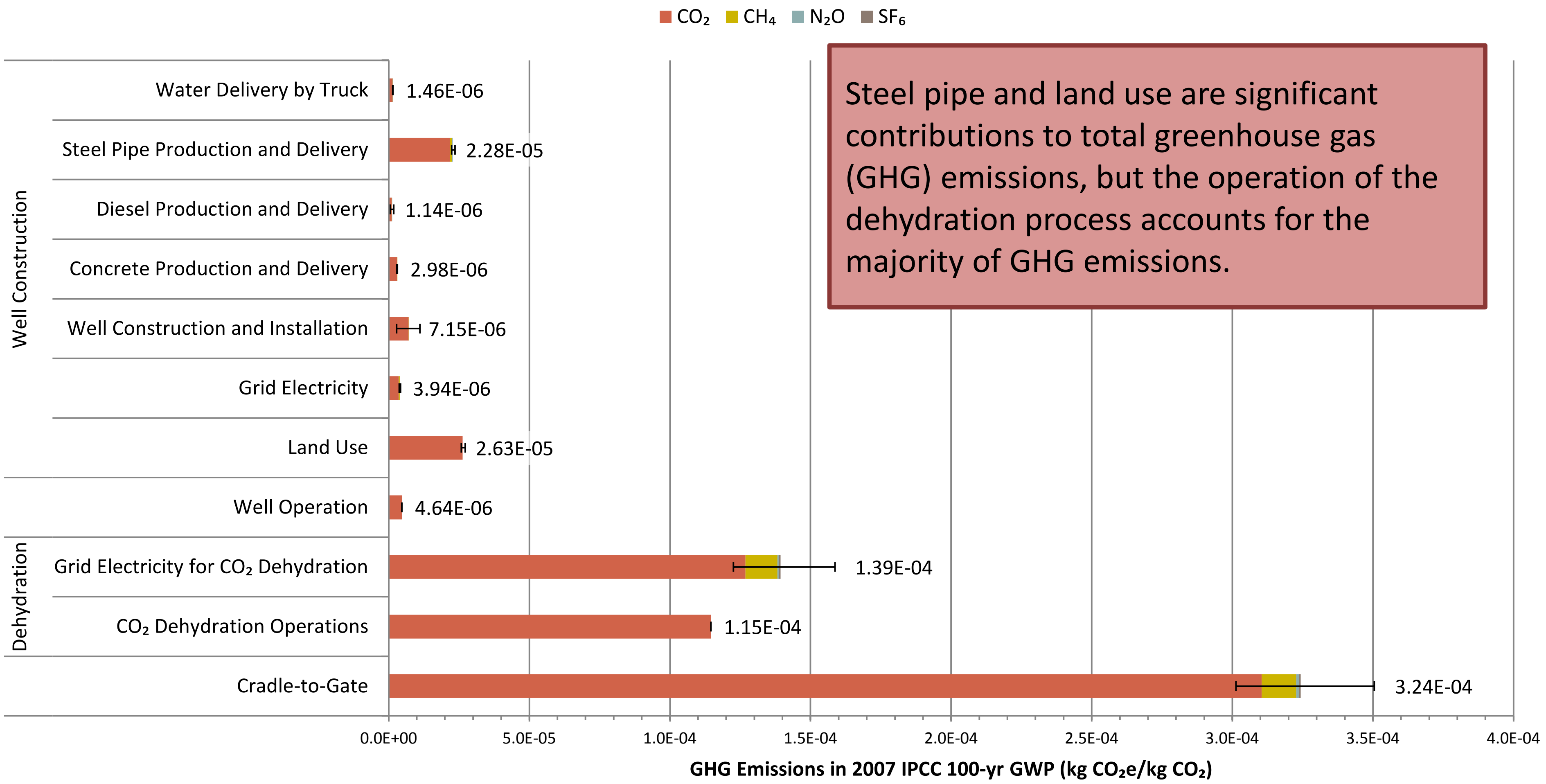
- Total natural gas input is variable
  - Reformer efficiency affects amount of natural gas required for synthesis gas production
  - Intermediate reactions that shift CO to CO_2 also affect amount of natural gas feedstock
  - Extent of heat exchange between ammonia and urea production affects amount of natural gas required for fuel
- Water input is also variable
  - Majority of water input is consumed for steam generation
  - Steam requirements depend on reformer efficiency
- CO_2 production rate is also variable, but is accounted for in the natural gas and water input parameters
- Data limitations prevent parameterization of flows within ammonia plant

Co-Product Management

- Natural CO_2 dome produces only CO_2 (no co-products)
- Natural gas processing produces CO_2, natural gas, and NGL
  - CO_2 cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced CO_2 and natural gas
  - System expansion is also feasible, but requires consequential assumptions
- Ammonia plant produces CO_2 and ammonia
  - CO_2 cannot be expressed in terms of energy, so energy-based co-product allocation is *not* feasible
  - Mass-based co-product allocation is feasible and is based on masses of produced CO_2 and ammonia
  - System expansion is also feasible, but requires consequential assumptions

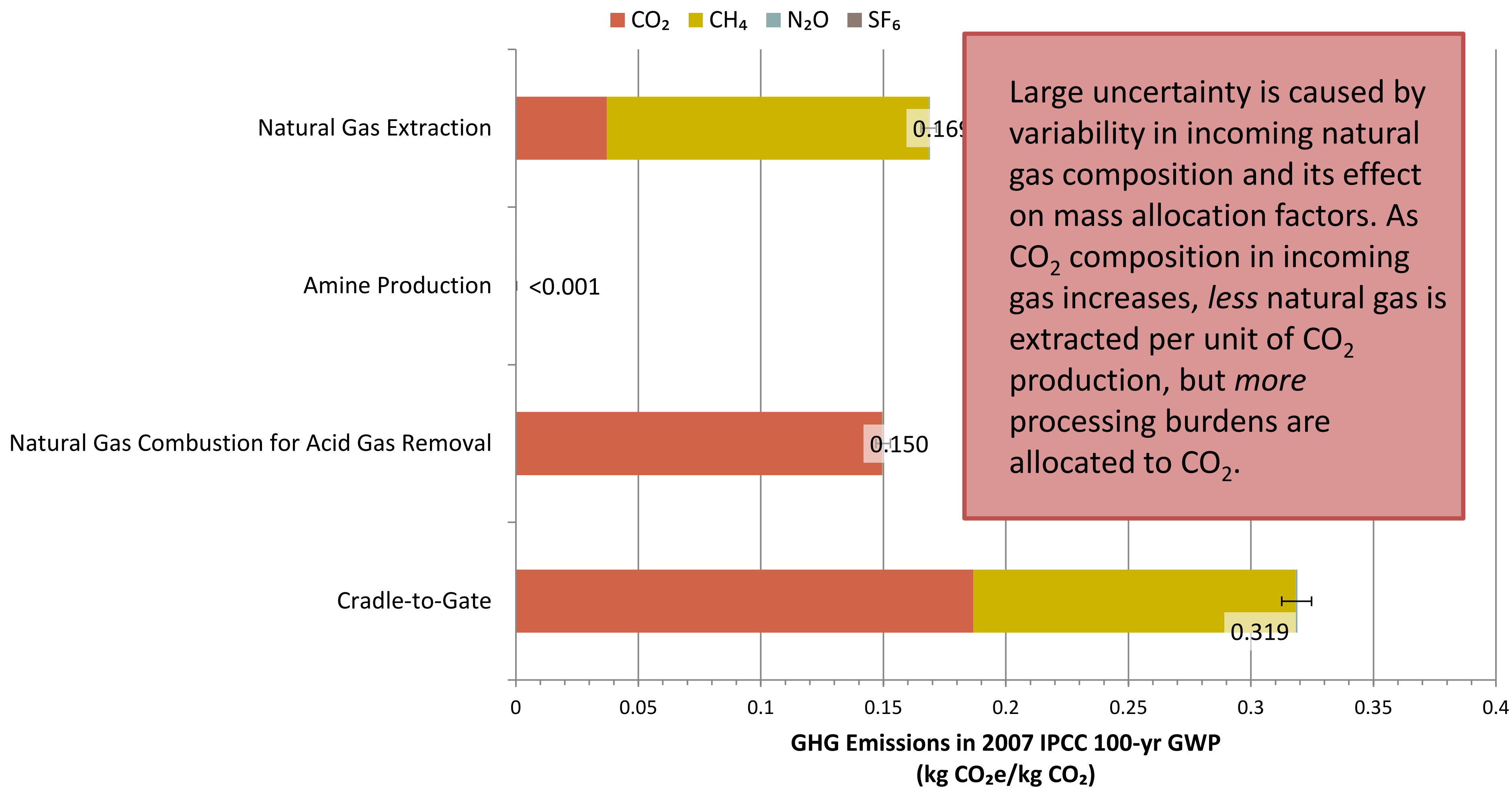
These data will be used for attributional LCAs, making mass based allocation the appropriate co-product management method.

Cradle-to-Gate Results for CO_2 from Natural Dome



Steel pipe and land use are significant contributions to total greenhouse gas (GHG) emissions, but the operation of the dehydration process accounts for the majority of GHG emissions.

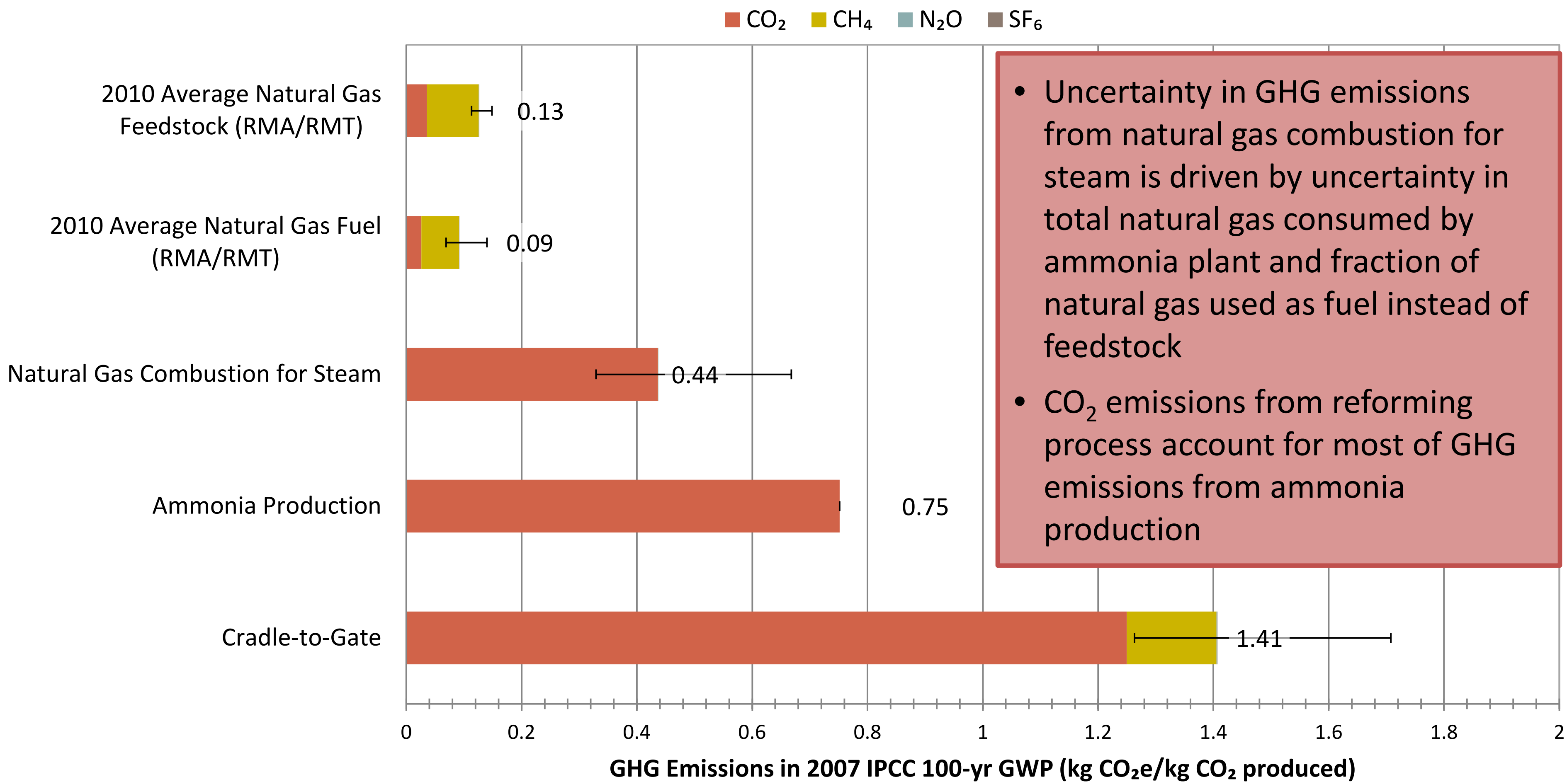
Cradle-to-Gate Results for CO_2 from Natural Gas Processing (Mass Allocation)



Large uncertainty is caused by variability in incoming natural gas composition and its effect on mass allocation factors. As CO_2 composition in incoming gas increases, *less* natural gas is extracted per unit of CO_2 production, but *more* processing burdens are allocated to CO_2.

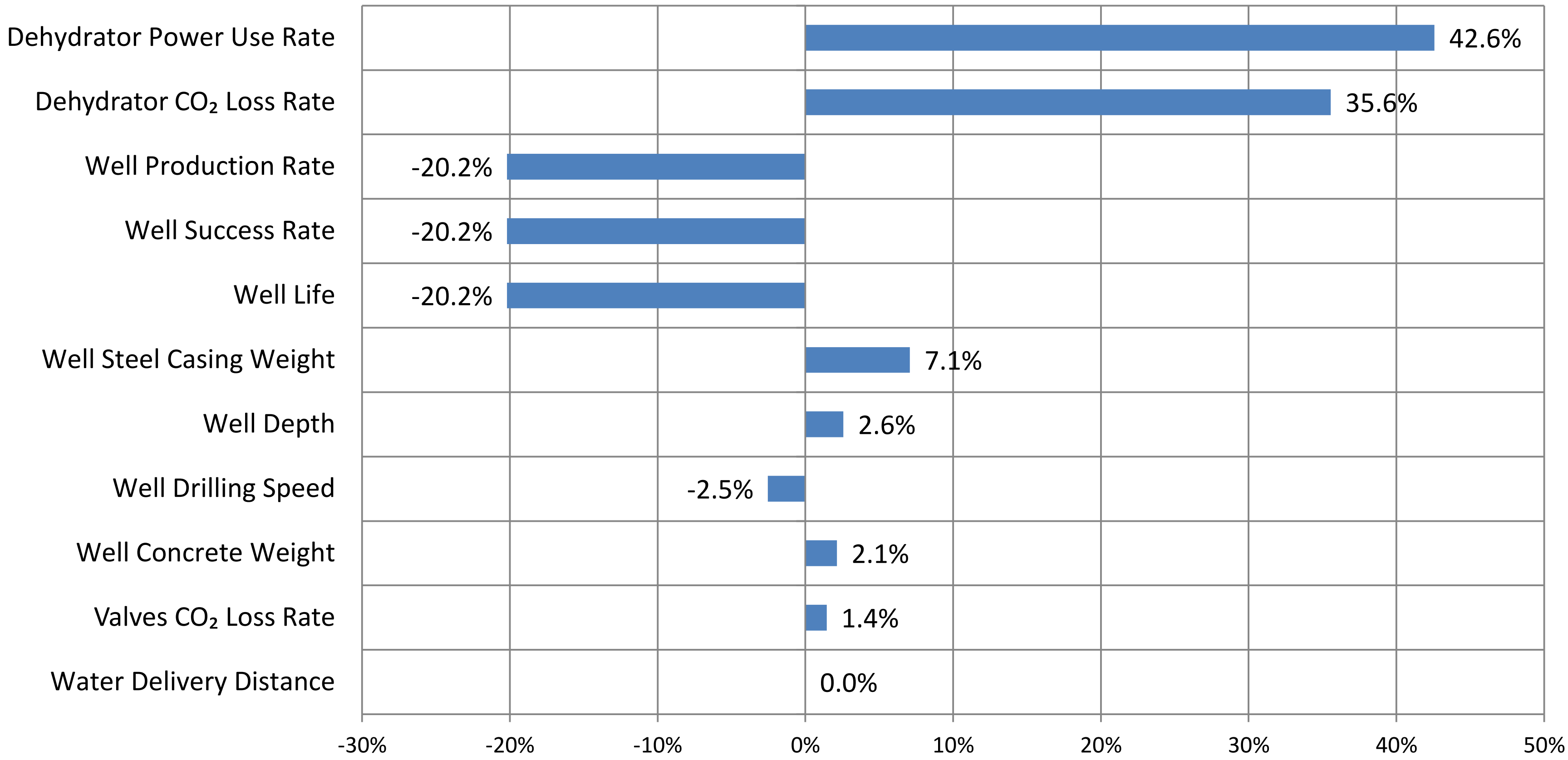
NETL

Cradle-to-Gate Results for CO_2 from Ammonia Production (Mass Allocation)



- Uncertainty in GHG emissions from natural gas combustion for steam is driven by uncertainty in total natural gas consumed by ammonia plant and fraction of natural gas used as fuel instead of feedstock
- CO_2 emissions from reforming process account for most of GHG emissions from ammonia production

GHG Sensitivity for CO_2 from a Natural Dome



- GHG results are sensitive to changes in dehydrator variables (power use and CO_2 loss rate)
- GHG results show an inverse relationship to well production rate, well success rate, and well life – these parameters affect denominator used for apportioning construction and land use burdens

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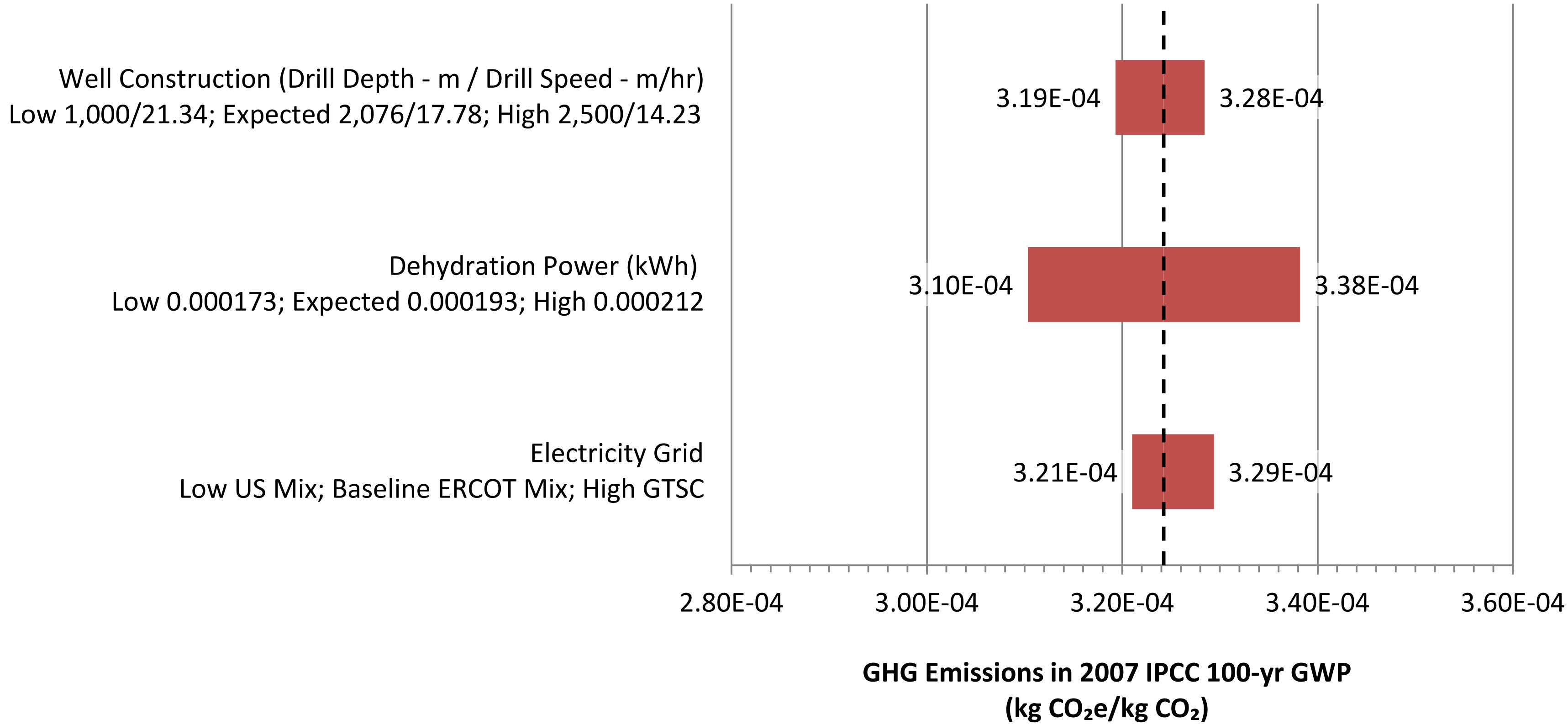
GHG Uncertainty for CO_2 from a Natural Dome



Greatest uncertainty in GHG results is caused by uncertainty in CO_2 processing (dehydration)

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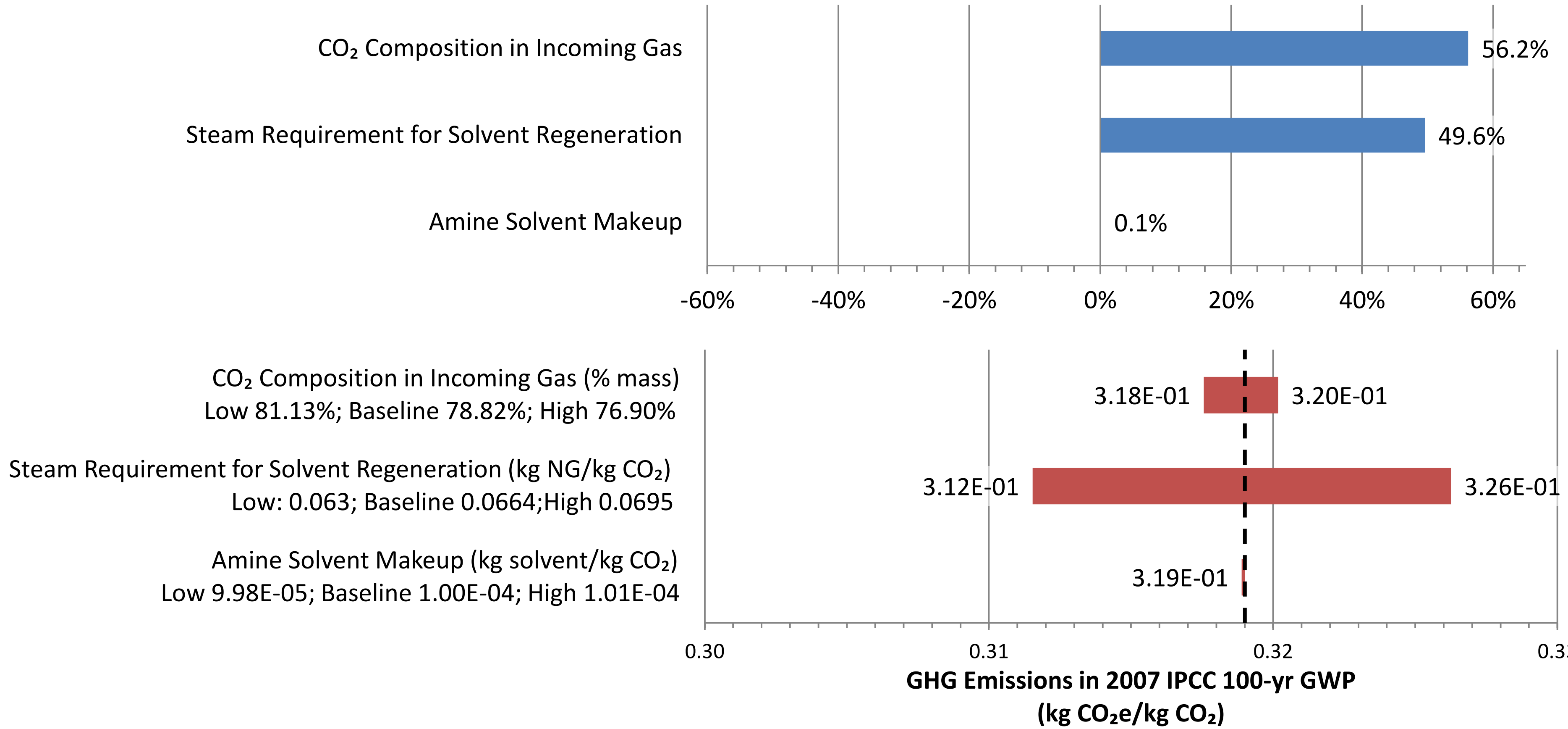
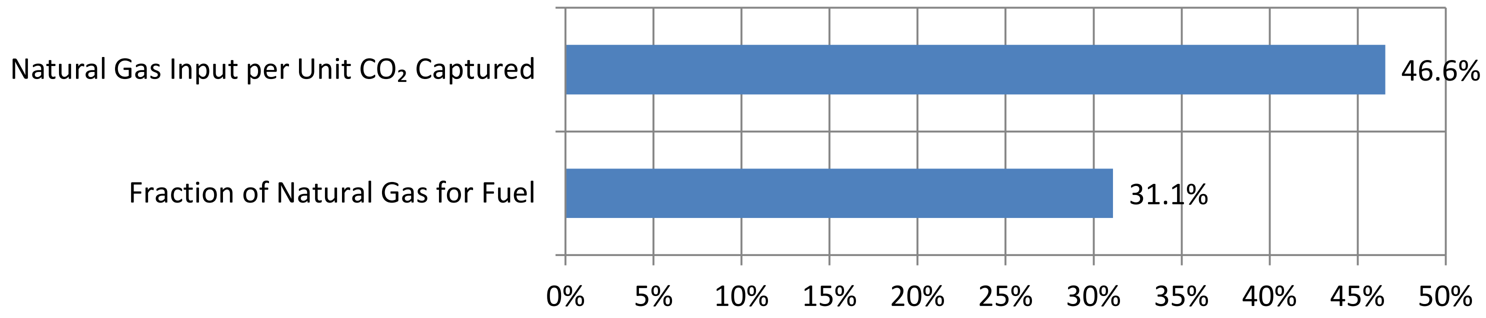
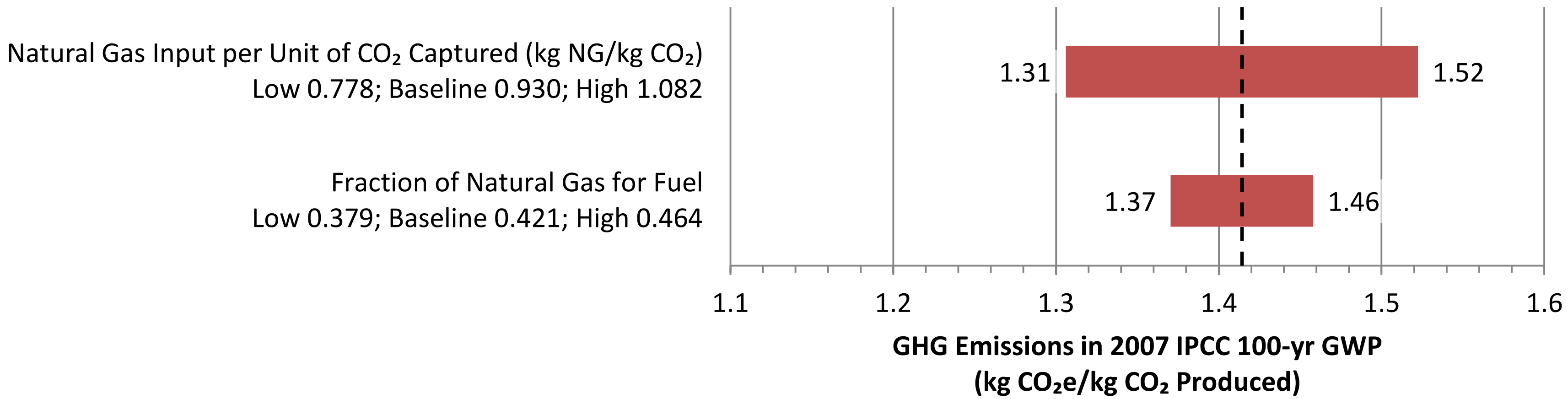
GHG Sensitivity and Uncertainty for CO_2 from Natural Gas Processing



GHG emissions sensitive to changes in CO_2 composition of incoming gas and steam rates for gas processing

GHG Sensitivity and Uncertainty for CO_2 from Ammonia Production





- Due to the high GHG footprint of natural gas extraction , GHG emission sensitivity *and* uncertainty driven by natural gas input rate
- Data limitations prevent parameterization of other ammonia plant operating characteristics

Recommendations and Conclusions

- Above results are only from cradle to gate, so they should be used with care
- These new unit processes will allow further LCA modeling of CCUS scenarios

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