Gate-to-Gate Life Cycle Analysis Model of Enhanced Oil Recovery

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Agenda

Technology Description

Unit Processes

Model Structure

Key Parameters

Co-Product Management

Gate-to-Gate Results

Sensitivities

Technology Description:
Enhanced Oil Recovery (EOR)

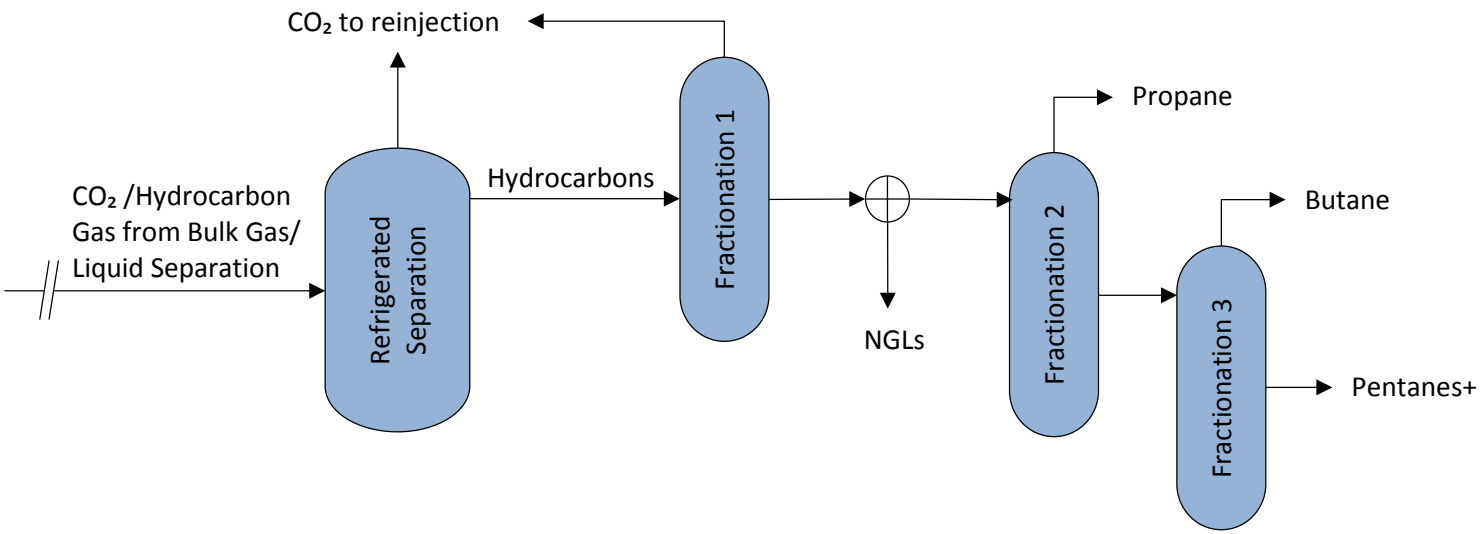
- Tertiary oil extraction
- Carbon dioxide (CO_2) extracts crude oil that cannot be extracted by secondary extraction technologies
- Multistep process with injection and production wells, gas/liquid separation, liquid storage, and gas/gas separation.
- This analysis includes following processes:
  - 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

Unit Processes

- **Injection and Recovery**
  - CO_2 is an effective fluid for EOR because it is miscible in oil
  - Injection of CO_2 is often alternated with injection of brine, known as a water alternating gas (WAG) tertiary injection scheme (NETL, 2010)
  - Brine injection prevents undesired channeling of CO_2
  - During life of well, CO_2 and brine are both injected and produced
  - Formation sequesters some fraction of injected CO_2, but is a net producer of brine
  - Brine is usually sent to nearby EOR sites for further use.
- **Bulk Separation and Storage**
  - EOR produces 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, and gases that can be sent to further processing
- **Gas Separation**
  - Gas separation is necessary for EOR operations because it recovers CO_2 that can be reinjected in EOR flood and separates hydrocarbon streams that can be sold or used as plant fuel
  - Four kinds of gas separation considered in this analysis: fractionation, refrigeration, Ryan-Holmes, and membrane

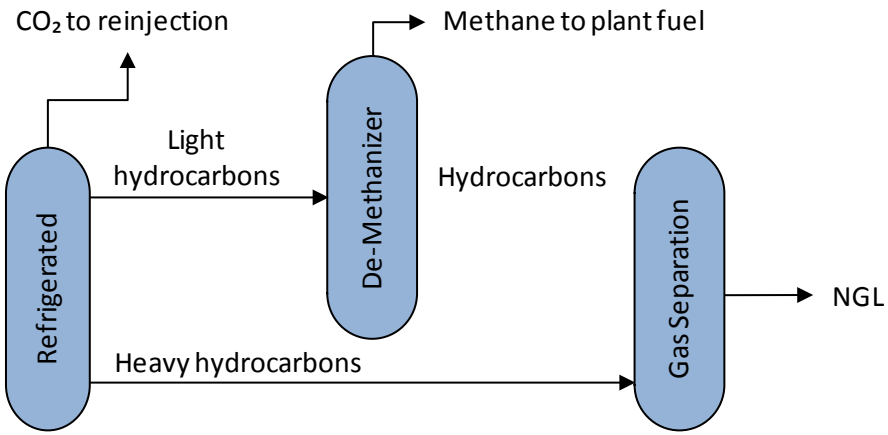
Unit Processes

- **Gas Processing – Refrigeration and Fractionation**
  - Gas separation by refrigeration chills a feed gas stream, allowing separation of CO_2 from ethane (C_2H_6) and higher hydrocarbons (Vargas, 2010)
  - Hydrocarbons are then separated using a series of distillation columns that produce three saleable streams: propane, butane, and pentane plus higher hydrocarbons
  - Ethane is recombined with CO_2-rich injection stream and sent to two compressor trains for reinjection
  - Technology can be configured to bypass distillation columns, which produces a mixed stream of hydrocarbons (NGLs) and reduces energy consumption
  - Hydrogen sulfide (H_2S) is separated from bottoms of de-ethanizer using a molecular sieve



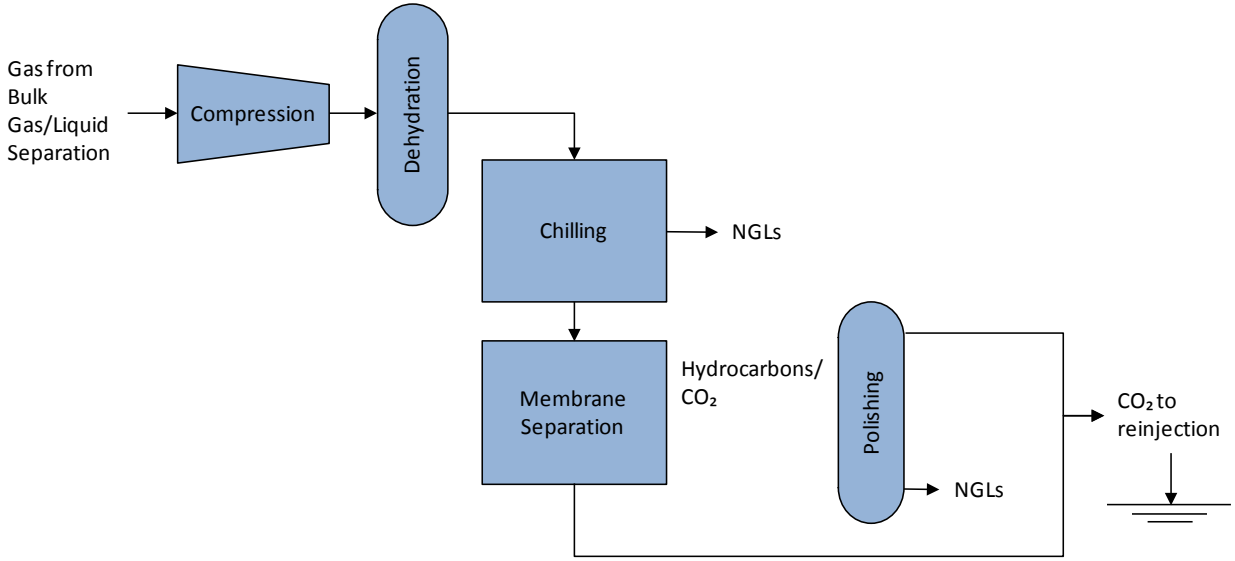
Unit Processes

- **Gas Processing – Ryan-Holmes**
  - Ryan-Holmes process has three steps:
    - Refrigerated vessel separates carbon dioxide, light hydrocarbons, and natural gas liquids (NGLs)
    - De-methanizer recovers methane that can be used as a plant fuel
    - Gas/gas separation column separates light and heavy hydrocarbons.
  - Portion of recovered hydrocarbons from refrigerated vessel are used to break azeotrope in gas separation column.
  - Advantage of Ryan-Holmes process is separation of hydrocarbons into high purity streams with higher market values than mixed streams



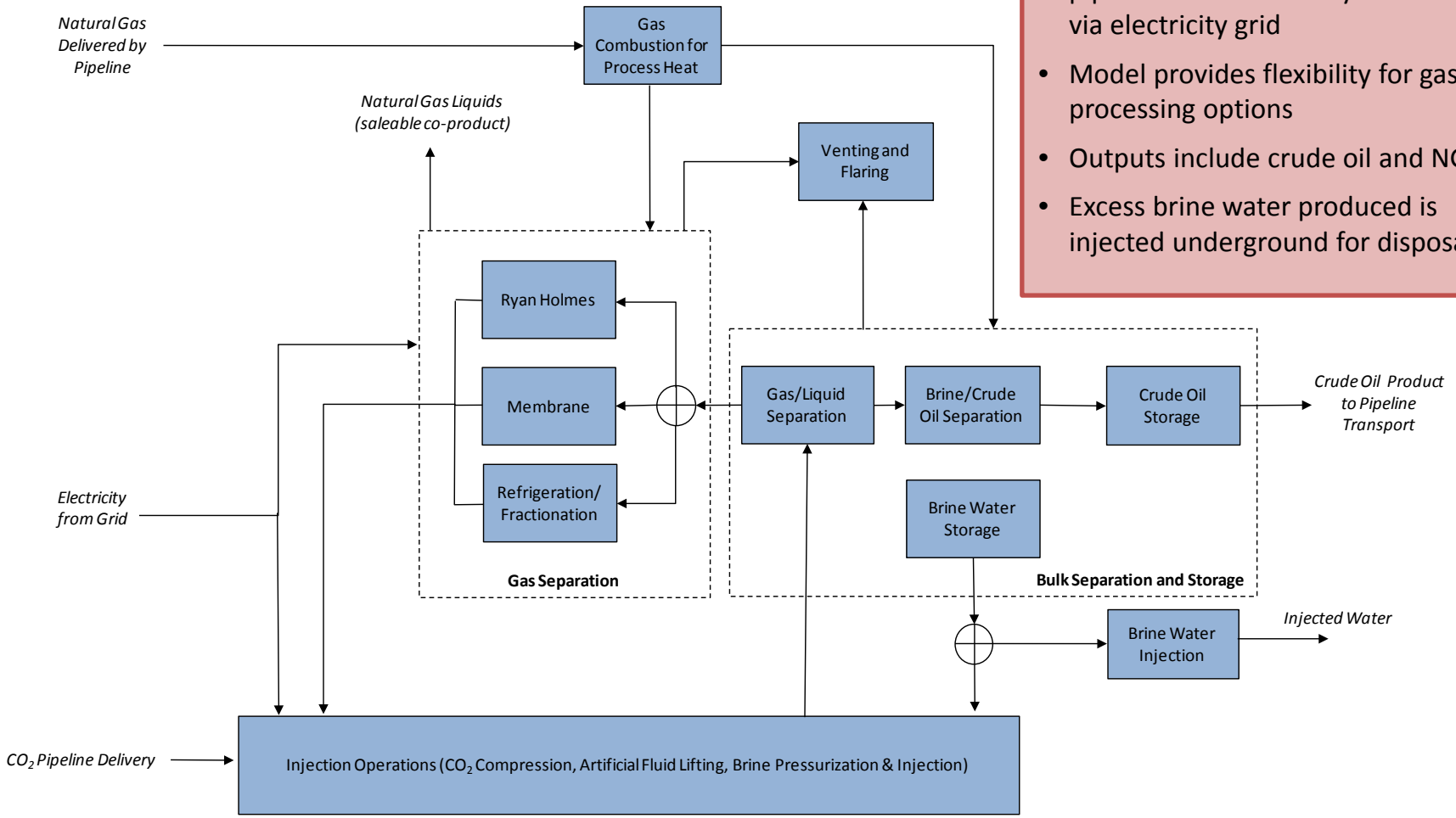
Unit Processes

- **Gas Processing – Membrane**
  - Membrane separation technology separates two types of gases based on differences between their permeation rates through a non-porous, semipermeable membrane
  - Selectivity of a membrane is ratio of permeabilities of two gases
  - 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 gas stream is fed to membrane separation unit
  - Pretreatment includes compression of gas stream to 3.45 MPa (500 psi), dehydration, and chilling



Model Structure – EOR with Gas Processing

- Inputs to EOR model include CO_2 and natural gas delivered by pipelines and electricity delivered via electricity grid
- Model provides flexibility for gas processing options
- Outputs include crude oil and NGLs
- Excess brine water produced is injected underground for disposal



Model Parameters

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	n/a	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 Co-Product Rates				
Natural Gas Liquids (kg/kg crude produced) (LOW/EXPECTED/HIGH)	N/A	0.0477 / 0.0692 / 0.1038	0.1111 / 0.1611 / 0.2417	0.1238 / 0.1795 / 0.2694
Butane (kg/kg crude produced) (LOW/EXPECTED/HIGH)	0.0153 / 0.0222 / 0.0333	N/A	N/A	N/A
Propane (kg/kg crude produced) (LOW/EXPECTED/HIGH)	0.0056 / 0.0082 / 0.0123	N/A	N/A	N/A
Naphtha (kg/kg crude produced) (LOW/EXPECTED/HIGH)	0.0268 / 0.0388 / 0.0582	N/A	N/A	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)	30			
Brine disposal pump electricity (kWh/kg brine)	4.30E-04			
Oil, Gas, Water Separation Operations				
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 [kg/(MW-day)]	63.6			

Model Parameters – Low/Expected/High

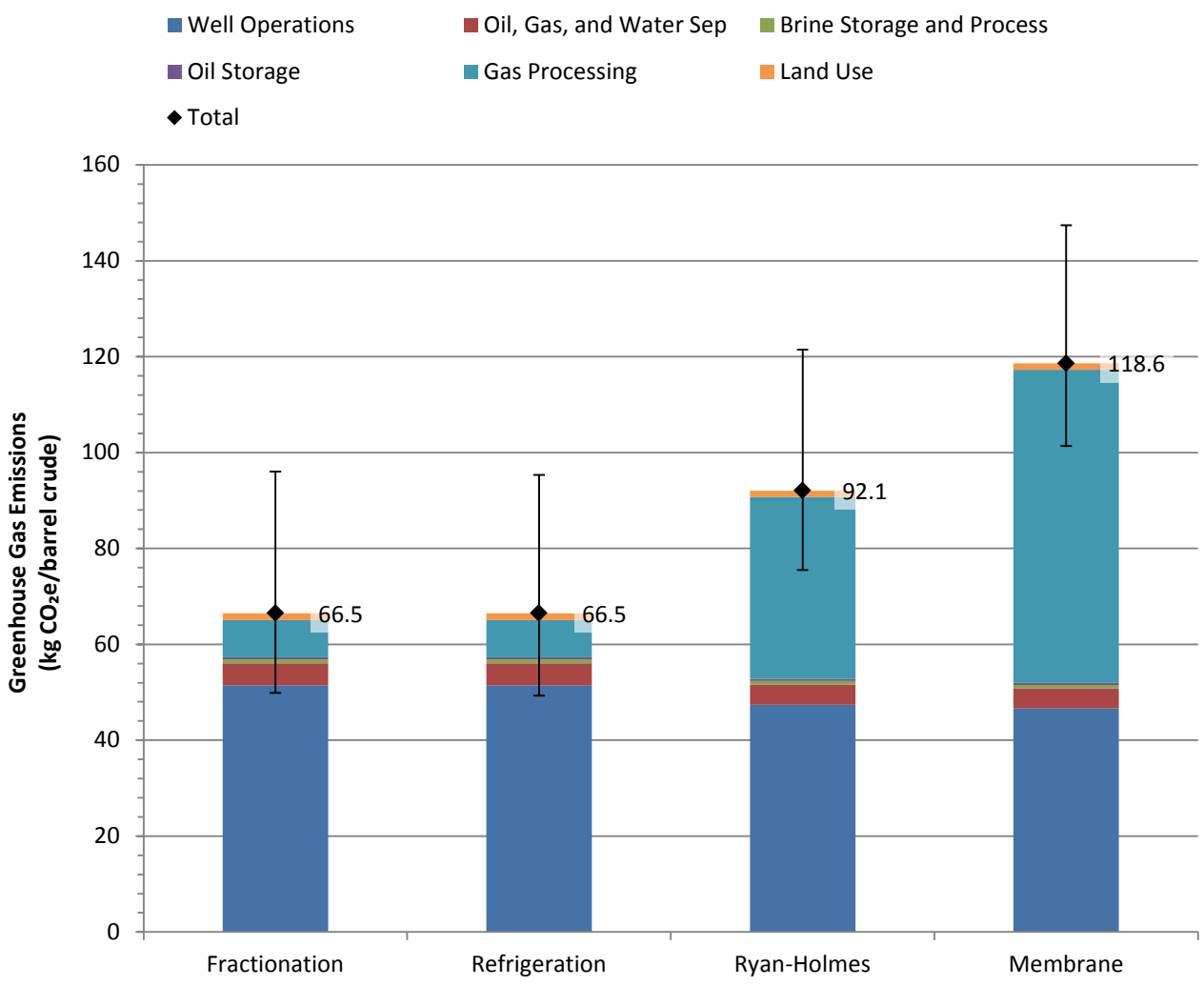
Property (Units)	Operating Conditions		
Crude Recovery Ratio (bbl per tonne CO_2 sequestered)	**Low (4.35 bbl/tonne CO_2)**	**Expected (3 bbl/tonne CO_2)**	**High (2 bbl/tonne CO_2)**
CO_2 Production Rate (kg/kg crude product)	4.17	6.04	9.06
Hydrocarbon Gas Production Rate (kg/kg crude product)	0.143	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 Injections 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 (US Mix (Import/Export))**	**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)	0.0%	0.5%	1.0%

Co-Product Management

- **Overview**
  - EOR facility produces crude oil, NGLs, and other hydrocarbons
  - If crude oil is primary product (i.e., production of crude oil is key service provided by EOR), then environmental burdens of other EOR products must be accounted for using co-product allocation (mass) or system expansion (displacement)
- **Co-Product Mass Allocation**
  - 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.
- **System Expansion (Displacement)**
  - Boundaries of system are expanded until crude oil is only product exiting system (this requires assumptions about fate of co-products)
  - For example, NGLs and other hydrocarbons displace conventional sources of liquefied petroleum gas from refineries
  - With fractionation gas processing, three individual gas streams are produced (propane, butane, and pentane) instead of a combined NGL stream

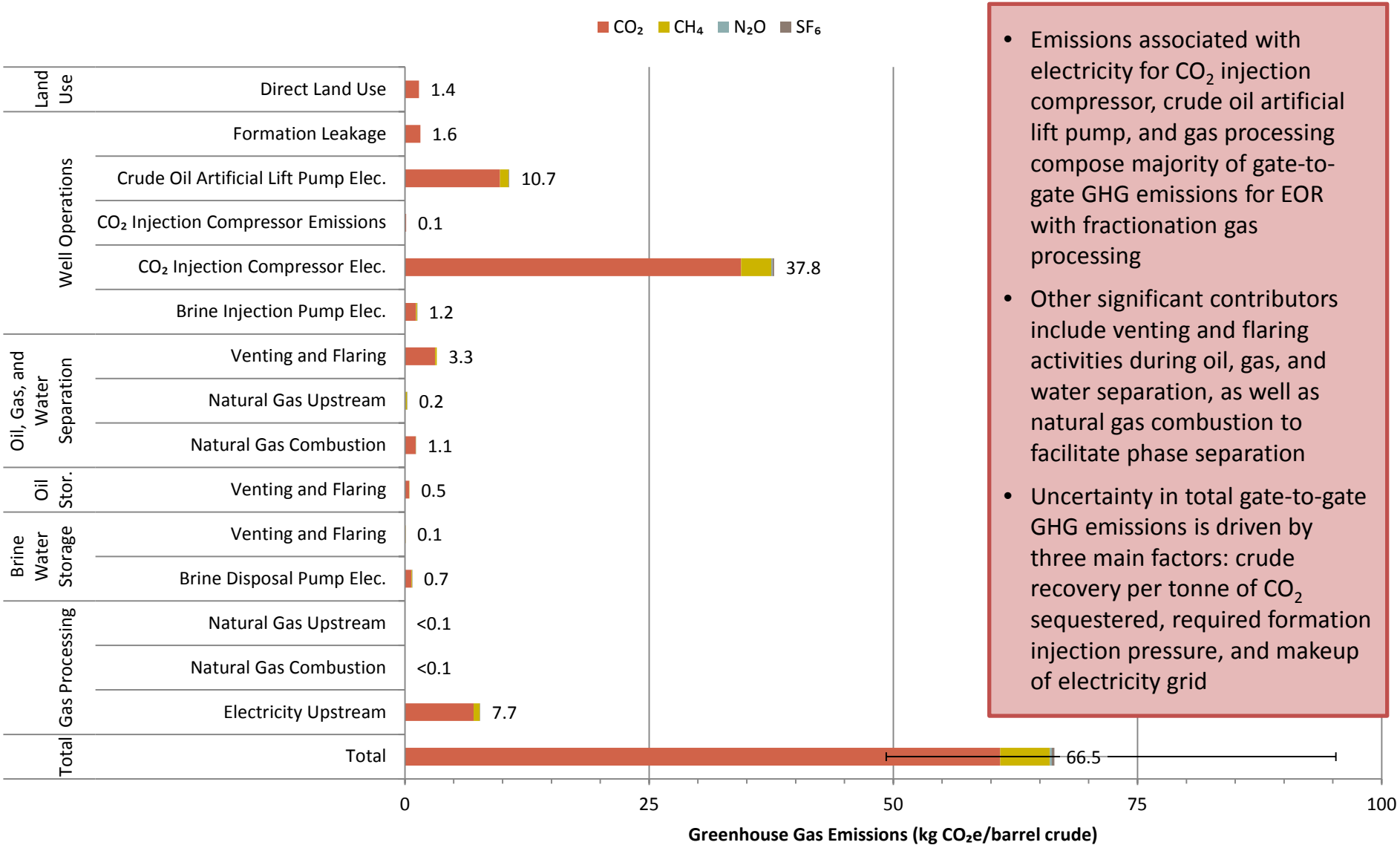
The choice between co-product allocation and displacement depends on the context of an LCA and is outside the scope of this work, which focuses only on a gate-to-gate system.

Results – Summary



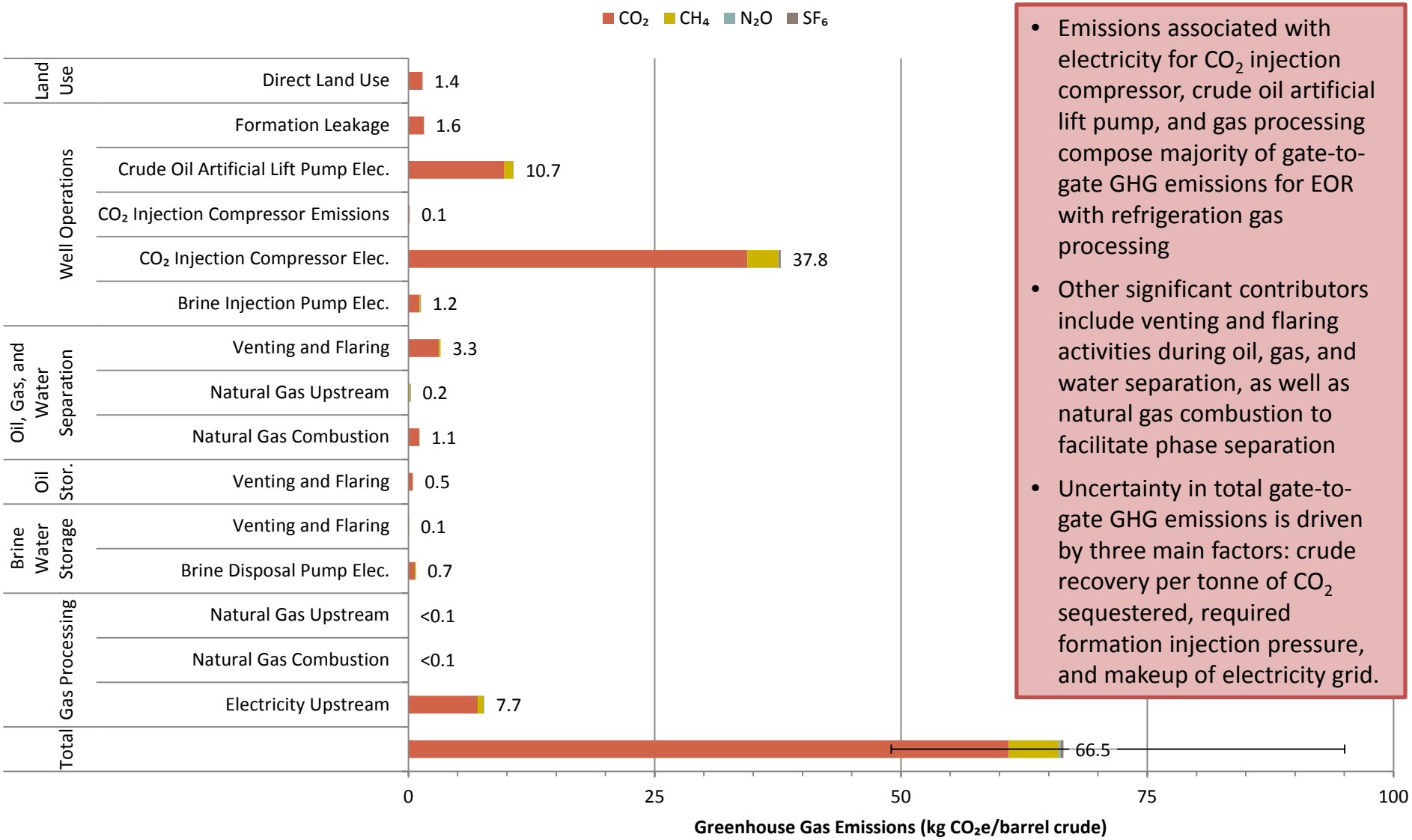
- GHG emissions for well operations, three-phase separation, brine storage and processing, crude storage, and land use are identical when using displacement to manage co-products
- Differences among scenarios is manifested by differences in emissions attributed to gas processing
- Ryan-Holmes and membrane gas processing are more effective at recovering NGLs than refrigeration and fractionation as shown by magnitude of displacement values
- Increased recovery comes at expense of additional processing energy which is demonstrated by increased GHG intensity associated with gas processing for Ryan-Holmes and membrane

Results – Fractionation – Mass Allocation



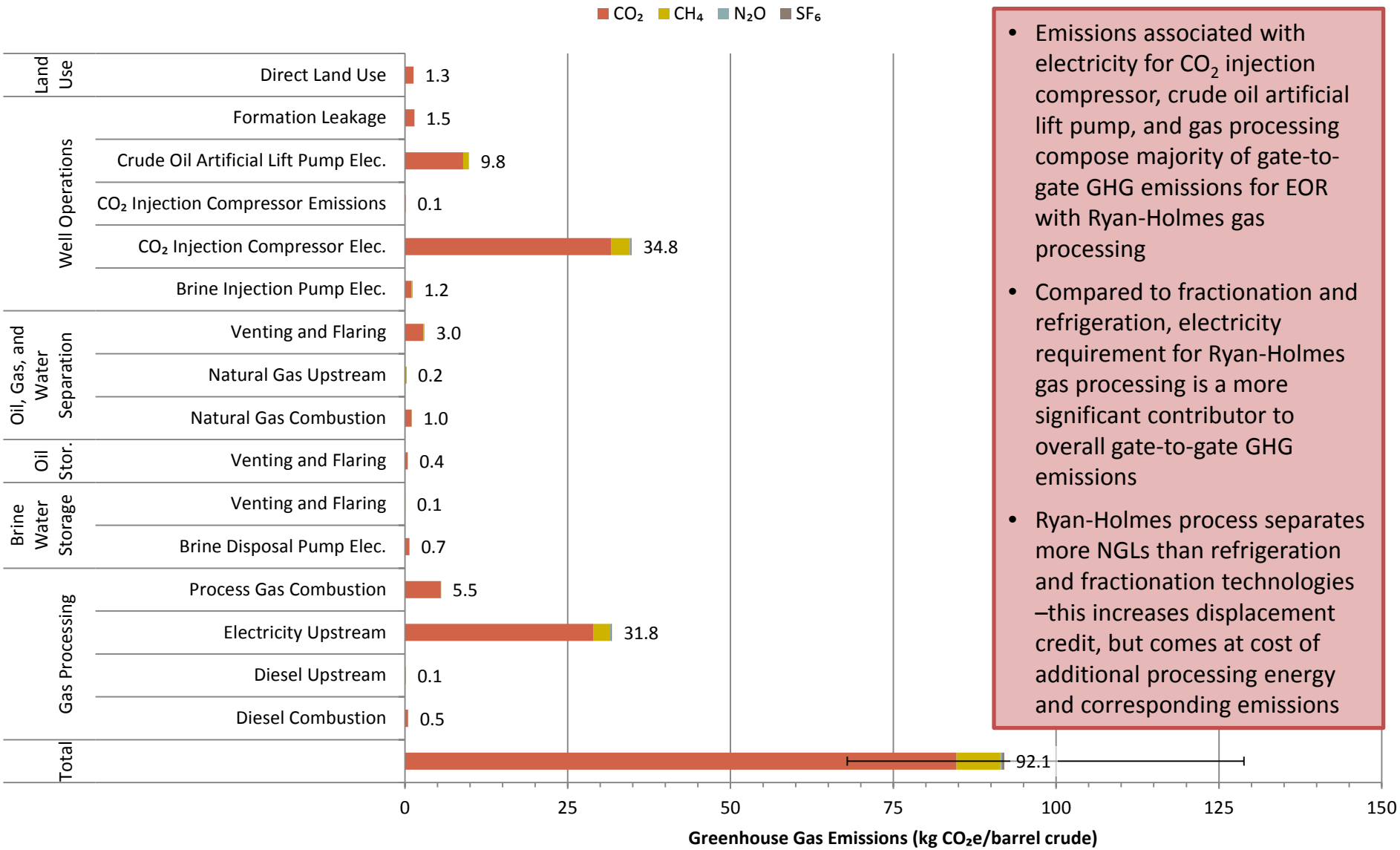
- Emissions associated with electricity for CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose majority of gate-to-gate GHG emissions for EOR with fractionation gas processing
- Other significant contributors include venting and flaring activities during oil, gas, and water separation, as well as natural gas combustion to facilitate phase separation
- Uncertainty in total gate-to-gate GHG emissions is driven by three main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, and makeup of electricity grid

Results – Refrigeration – Mass Allocation



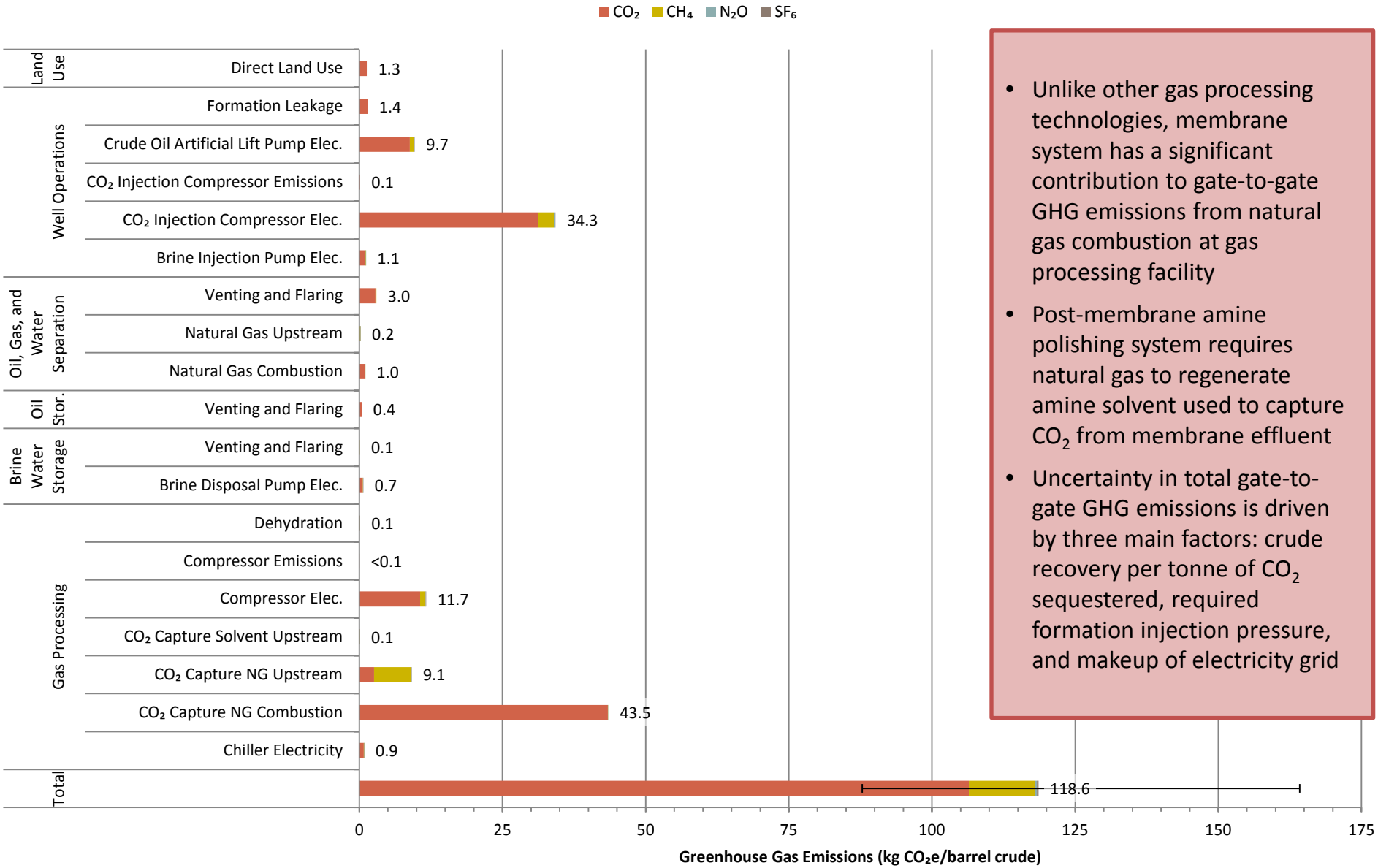
- Emissions associated with electricity for CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose majority of gate-to-gate GHG emissions for EOR with refrigeration gas processing
- Other significant contributors include venting and flaring activities during oil, gas, and water separation, as well as natural gas combustion to facilitate phase separation
- Uncertainty in total gate-to-gate GHG emissions is driven by three main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, and makeup of electricity grid.

Results – Ryan-Holmes – Mass Allocation



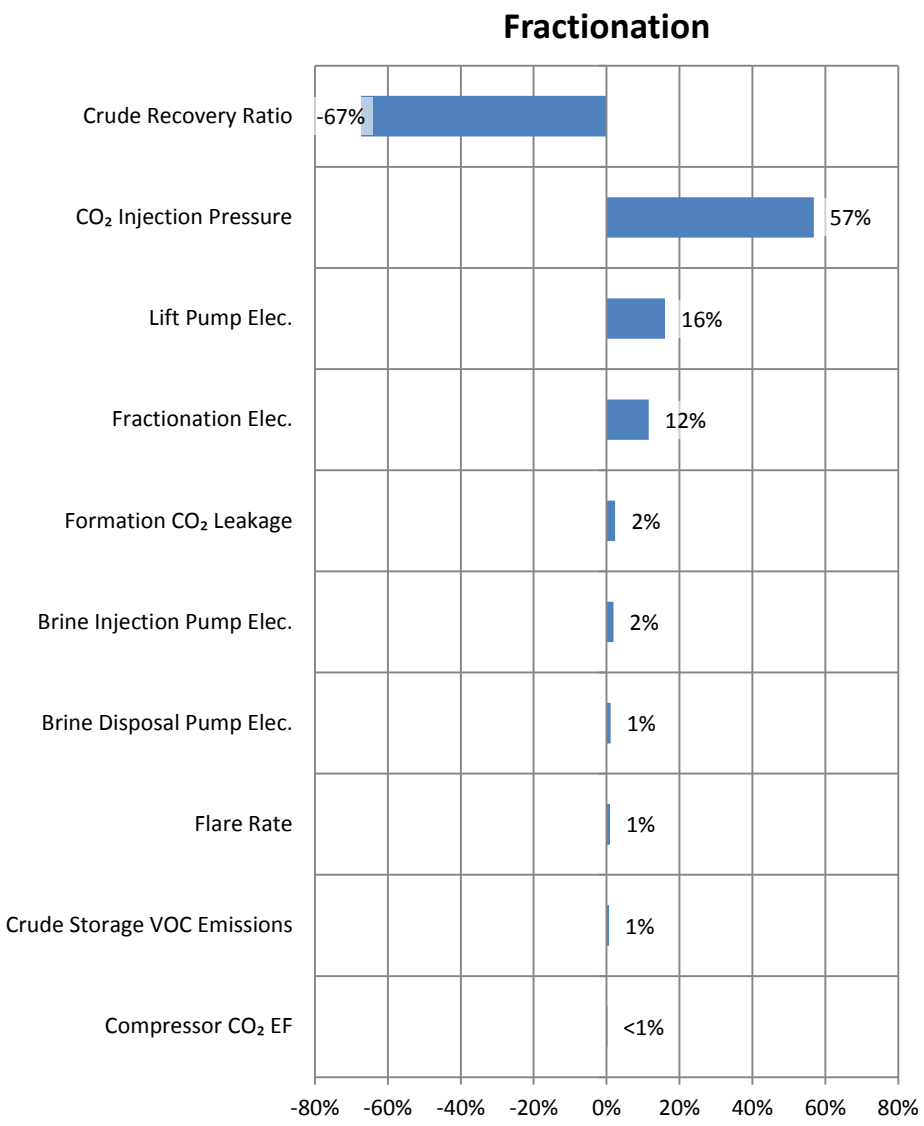
- Emissions associated with electricity for CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose majority of gate-to-gate GHG emissions for EOR with Ryan-Holmes gas processing
- Compared to fractionation and refrigeration, electricity requirement for Ryan-Holmes gas processing is a more significant contributor to overall gate-to-gate GHG emissions
- Ryan-Holmes process separates more NGLs than refrigeration and fractionation technologies –this increases displacement credit, but comes at cost of additional processing energy and corresponding emissions

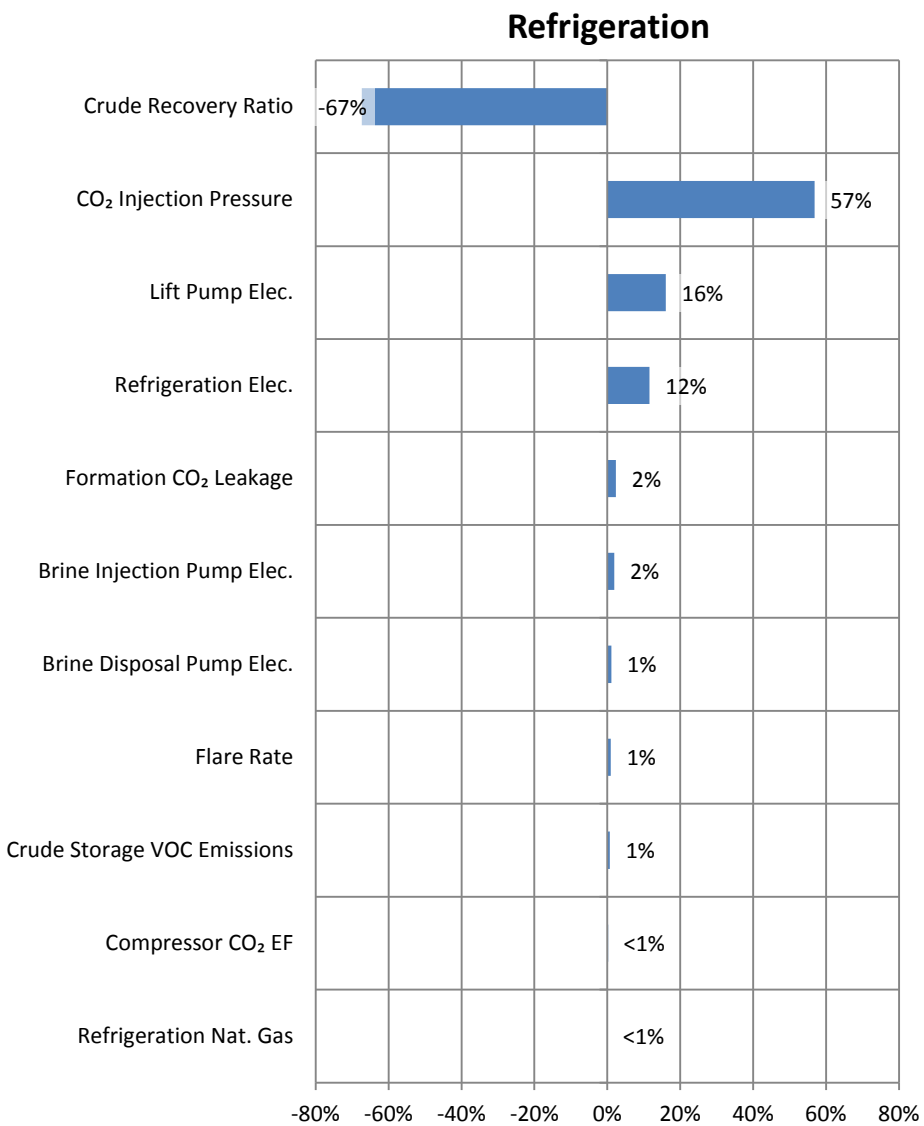
Results – Membrane – Mass Allocation



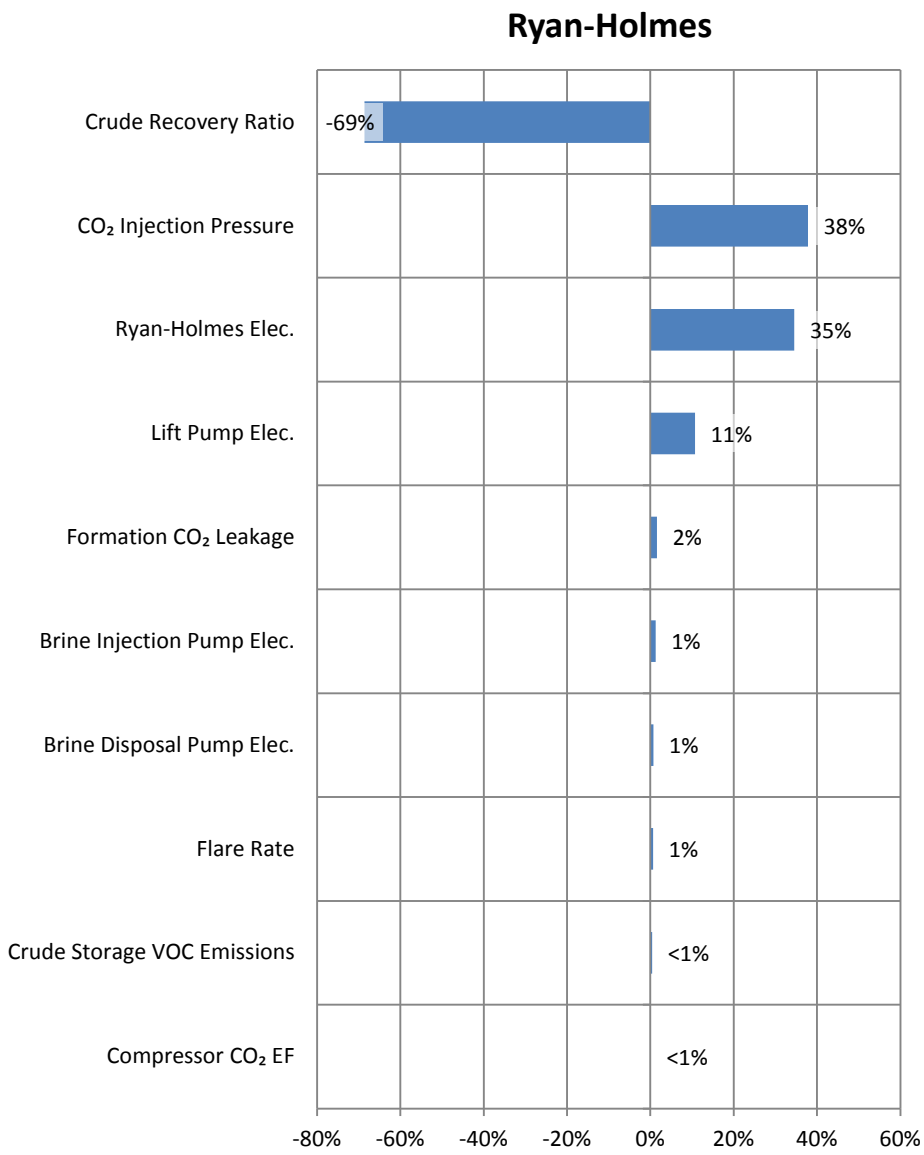
- Unlike other gas processing technologies, membrane system has a significant contribution to gate-to-gate GHG emissions from natural gas combustion at gas processing facility
- Post-membrane amine polishing system requires natural gas to regenerate amine solvent used to capture CO_2 from membrane effluent
- Uncertainty in total gate-to-gate GHG emissions is driven by three main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, and makeup of electricity grid

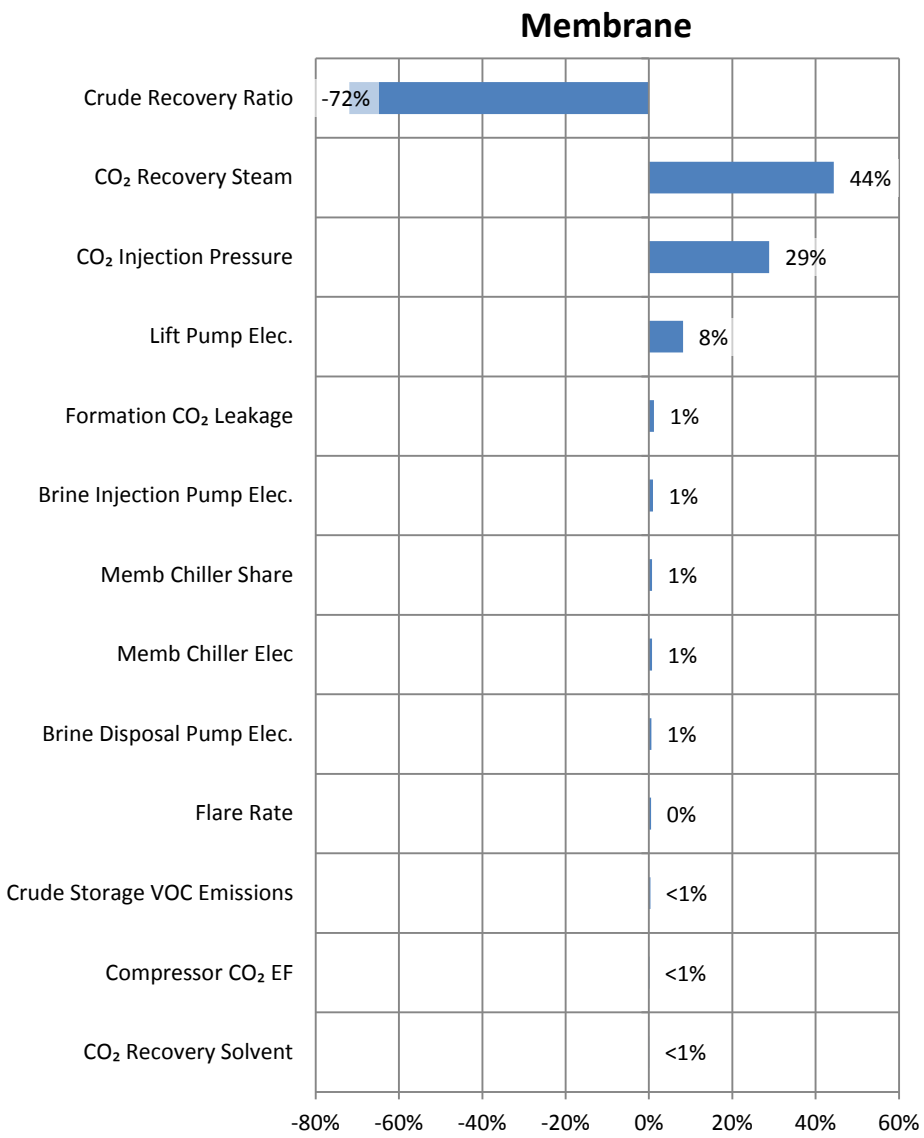
Parameter Sensitivity



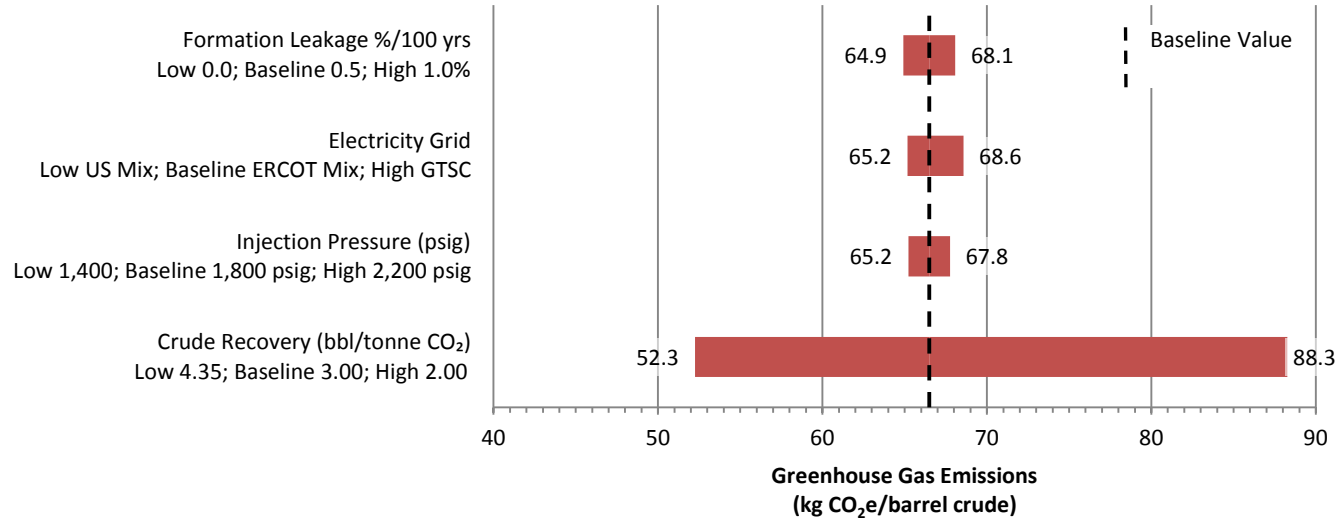


Parameter Sensitivity

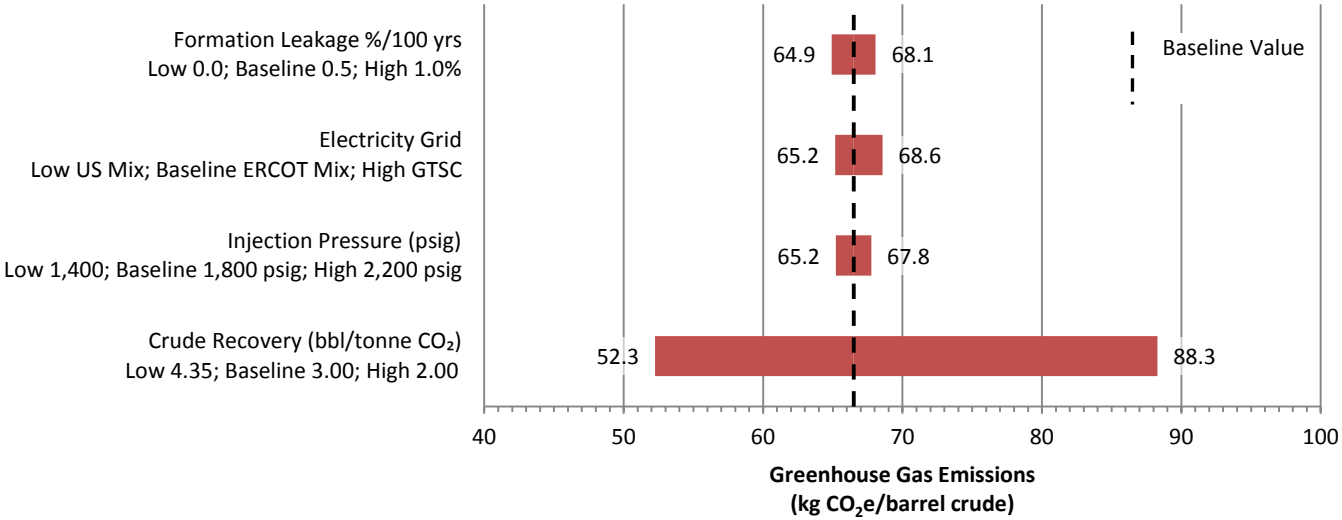




Uncertainty Sensitivity

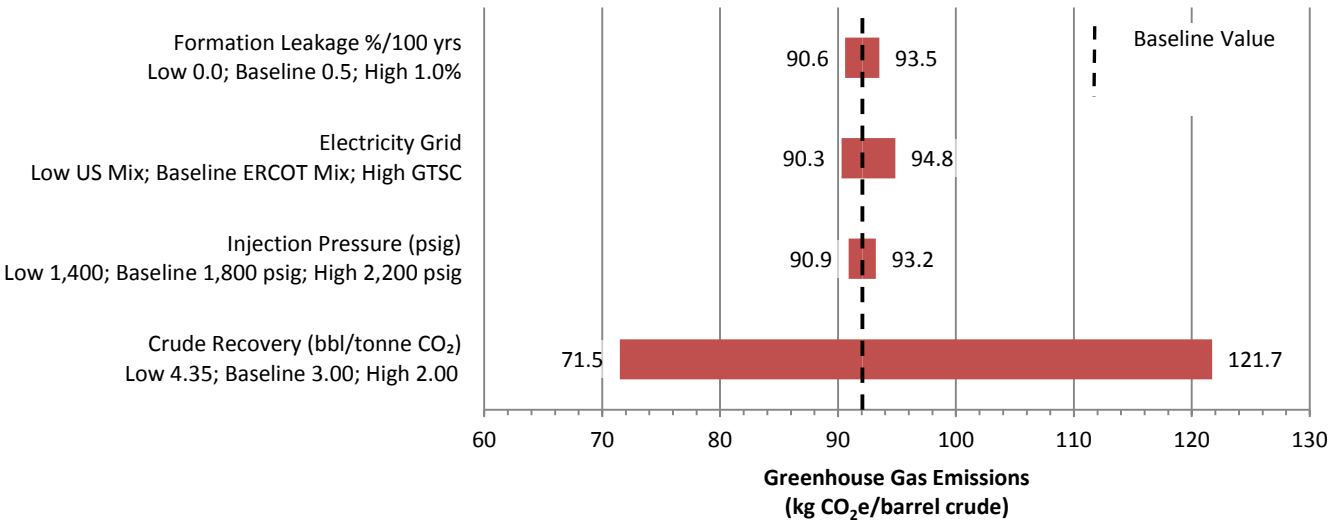


Fractionation

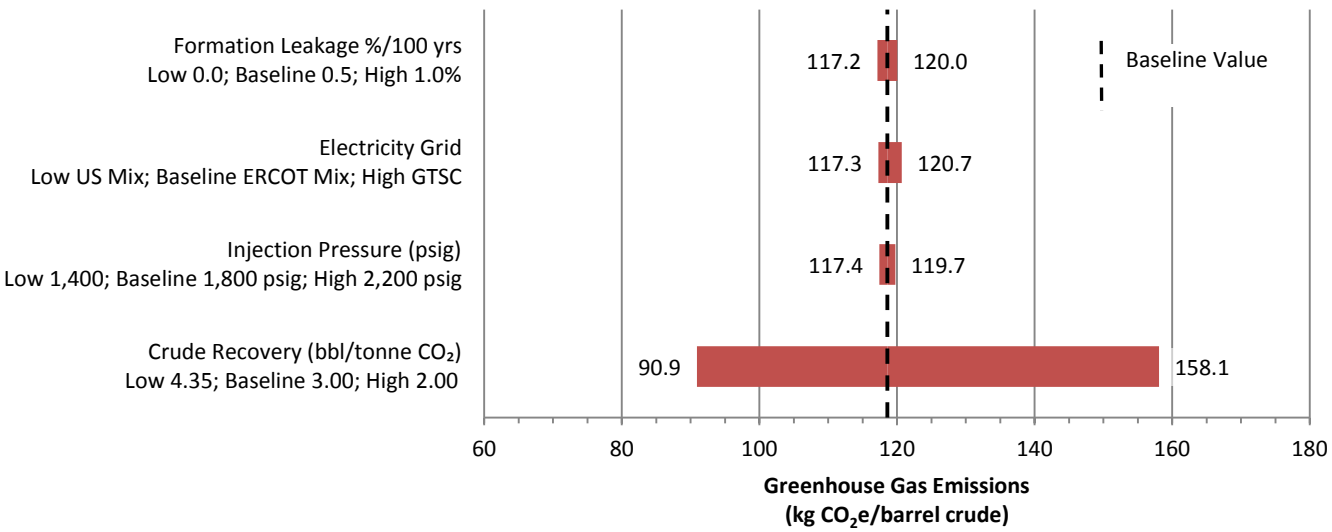


Refrigeration

Uncertainty Sensitivity



Ryan-Holmes



Membrane

Recommendations and Conclusions

- Above results are only from gate to gate, so they should be used with care
- These new unit processes will allow further LCA modeling of CCUS scenarios
- Differences among scenarios is manifested by differences in emissions attributed to gas processing
- Uncertainty in total gate-to-gate GHG emissions is driven by three main factors: crude recovery per tonne of CO_2 sequestered, required formation injection pressure, and makeup of electricity grid

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