A Parameterized Life Cycle Analysis of Crude from CO_2-Enhanced Oil Recovery

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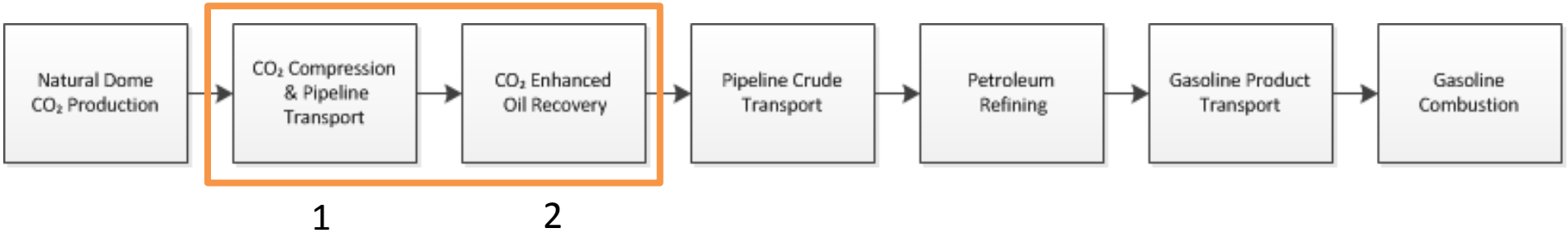
CO_2-Enhanced Oil Recovery (EOR) is a Small Part of a Much Larger Life Cycle

- **EOR: Generic term given to any tertiary means of increasing crude recovery rates (e.g. with CO_2) after primary and secondary (e.g. water flood) means are exhausted**
- **Here it means flooding a reservoir with compressed CO_2 to increase reservoir pressure, decrease crude viscosity, etc.**



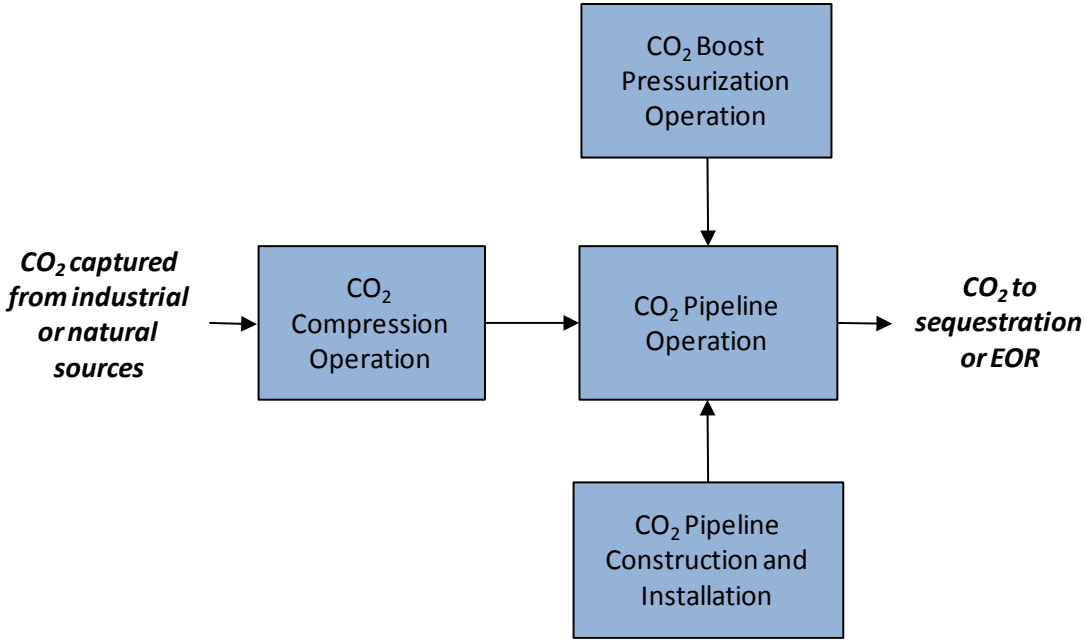
- **Undertook this bottom-up characterization to determine how the environmental footprint of EOR compared to other crude extraction methods, and assess potential for technology improvement to reduce that footprint**
  - Representative of U.S. tertiary extraction from formations similar to the Permian Basin in 2010-2011
  - Only GHGs presented here: CAPs, HAPs, Water, etc. included in inventory
  - Primary FU: 1 kg crude oil extracted; Alternate FU: 1 kg CO_2 sequestered

Detailed Gate-to-Gate Model Built for CO_2 Transport

- **Carbon steel CO_2 pipelines use electrically-powered, water-cooled, multistage compressors provide initial pipeline pressure (2,200 psi)**
  - Fugitive emissions of CO_2 escape during compressor operation
  - For long distances, boost pumps maintain pressure above critical value of 1,100 psi

Unit Processes

- **Pipeline Construction**
  - Pipeline sizing calculations are consistent with NETL's quality assurance guidelines for CO_2 transport, allowing parameterization of pipeline diameter as a function of flow rate and distance
  - API 5L pipe schedule is representative of CO_2 pipelines and allows calculation of pipeline mass per unit length
  - Inlet and outlet pressures are fixed at 2,200 and 1,200 psi
  - Temperature is fixed at 79° F
  - Adjustment factors are used to account for valve and compressor weights and pipeline tortuosity
- **Compression**
  - Compression equations are used to calculate power demand
  - CO_2 emissions escape through compressor seals
- **Pipeline Operation**
  - CO_2 emission factors are parameterized
  - Total CO_2 emissions are a function of pipeline distance
- **Boost Pressurization**
  - Necessary when pipeline length is too long to maintain pressure and flow rate
  - Based on same data used for compression at CO_2 capture site
  - Electrically powered



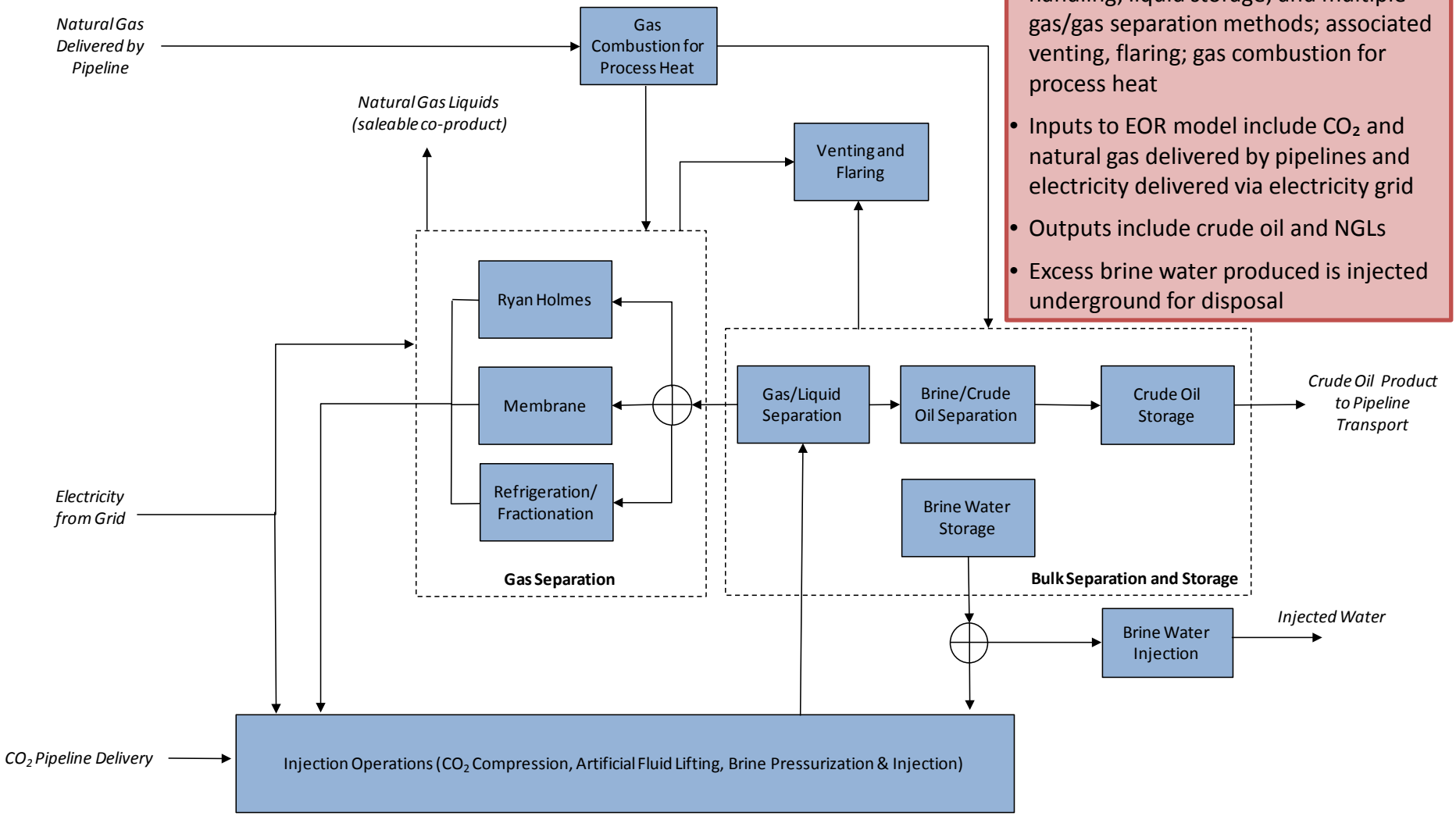
Parameterization Included in Gate-to-Gate CO_2 Transport Model

- **Low and high values for some parameters account for variability exhibited by data sources (e.g., emission factors for fugitive CO_2)**
- **Some parameters are used to control scenarios (e.g., electricity source, and study period)**
- **Some parameters are used to test result sensitivity when reliable data are not available (e.g., pipeline tortuosity, valve weight, and power scalers)**

	Low	Expected	High	Description
Compression				
Power scaler for CO_2 compressor	1	1	1	Scaler to change the electricity demand of the compressor for sens. analysis
Compressor fugitive CO_2 Emission Factor (kg/day)	19.1	63.6	318	Emission factor for CO_2 released to air from compressors
Electricity source switch	1	1	1	0 = electricity from a connected power plant; 1 = electricity from grid
Electricity grid	U.S. Mix	ERCOT	GTSC	ERCOT (Electric Reliability Council of Texas); GTSC (Gas Turbine Simple Cycle)
Pipeline Construction				
Pipeline distance (mi.)	50	250	550	CO_2 pipeline distance
Pipeline tortuosity	0.010	0.050	0.100	Pipeline tortuosity factor
Valve weight	0.050	0.050	0.050	Additional pipeline weight due to valves
Pipeline Operation				
CO_2 flow rate (tonne/day)	2,500	10,000	25,000	Flow rate of CO_2 through compressor
Emission factor for fugitive CO_2 (kg/mi.-yr.)	1,058	10,579	105,792	Fraction of CO_2 lost during pipeline operation
Study period (yrs.)	30	30	30	Study period in years
Pressure Boosting				
Power scaler for CO_2 boost pump	1	1	1	Scaler to change the electricity demand of CO_2 booster pump
Emission factor for fugitive CO_2 (kg/day)	54.0	180	900	Emission factor for CO_2 released to air from CO_2 booster pump

Gate-to-Gate Model of CO_2-EOR

- Multistep process with injection and production/recovery wells; bulk gas/liquid separation; brine water handling; liquid storage; and multiple gas/gas separation methods; associated venting, flaring; gas combustion for process heat
- Inputs to EOR model include CO_2 and natural gas delivered by pipelines and electricity delivered via electricity grid
- Outputs include crude oil and NGLs
- Excess brine water produced is injected underground for disposal



EOR Model Processes & Parameters

Injection & Recovery

- CO_2 is an effective fluid for EOR as 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
- 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 & 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

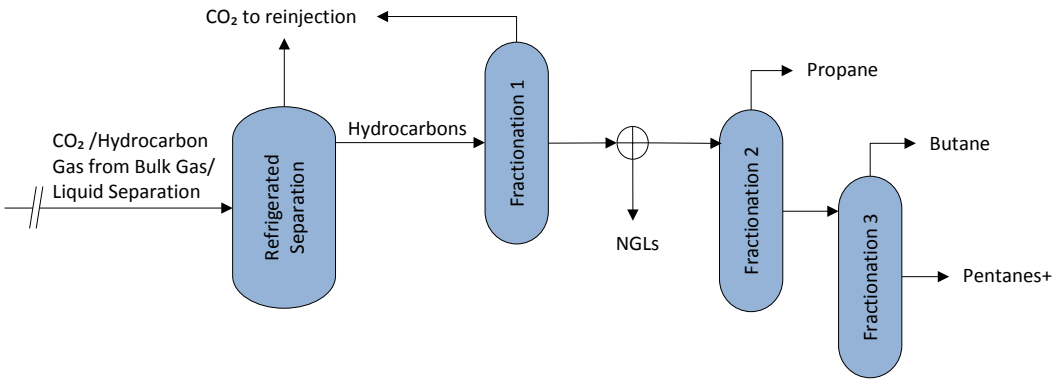
Gas Separation

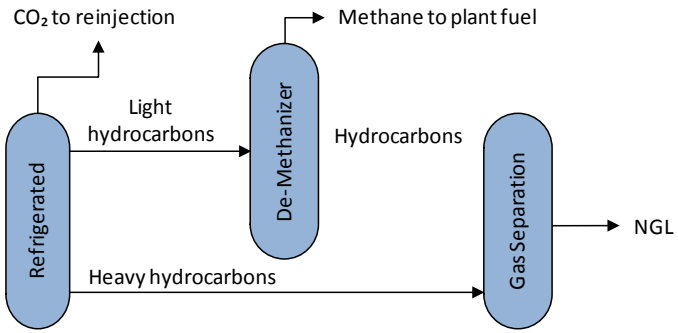
- Gas separation is necessary for EOR operations because it recovers CO_2 that can be reinjected in EOR flood and separates hydrocarbon streams that can be sold or used as plant fuel
- Four kinds of gas separation considered in this analysis: fractionation, refrigeration, Ryan-Holmes, and membrane

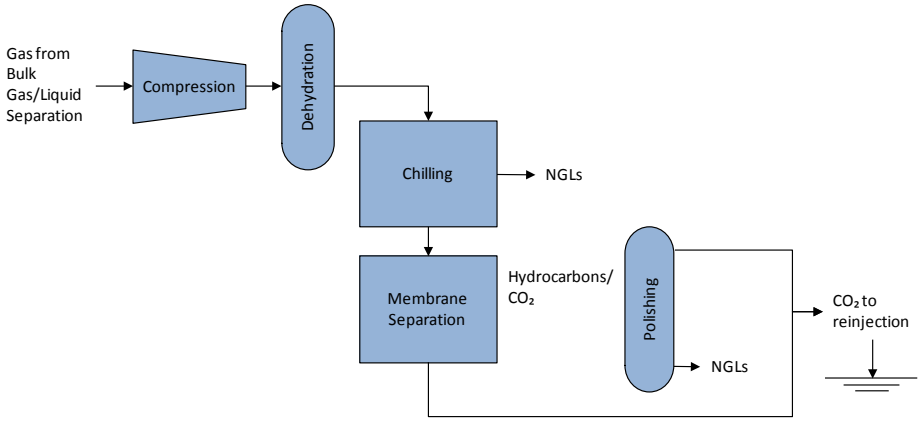
Property (Units)	**Operating Conditions**		
Crude Recovery Ratio (bbl per tonne CO_2 sequestered)	**Low (4.35 bbl/tonne CO_2)**	**Expected (3 bbl/tonne CO_2)**	**High (2 bbl/tonne CO_2)**
CO_2 Production Rate (kg/kg crude product)	4.17	6.04	9.06
Hydrocarbon Gas Production Rate (kg/kg crude product)	0.143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

Gas Separation Recovers CO_2 from Other Gases

- **Refrigeration and Fractionation**
  - Chills feed gas stream to allow separation of CO_2 from C_2H_6 and higher HCs
  - Hydrocarbons separated by a series of distillation columns: produces 3 saleable streams: propane, butane, and pentane plus higher hydrocarbons
  - Ethane recombined with CO_2-rich stream & sent to compressor for reinjection
  - Can be configured to bypass distillation columns, reducing energy consumption & producing mixed stream of NGLs
- **Ryan-Holmes**
  - Refrigerated vessel separates CO_2, light HCs, and NGLs, a de-methanizer recovers CH_4 to use as plant fuel, and a gas/gas separation column separates light & heavy HCs
  - Portion of recovered HCs from refrigerated vessel are used to break azeotrope in gas separation column
  - Ryan-Holmes can separate HCs into high purity streams with higher market values
- **Membrane**
  - Separates 2 types of gases based on differences in permeation rates through a non-porous, semi-permeable membrane (selectivity of a membrane is ratio of permeabilities of two gases)
  - Membranes used at EOR gas separation plants have a CO_2 to CH_4 selectivity of 10 to 20
  - Compression of gas stream to 500 psi, dehydration, & chilling are required before gas stream is fed to membrane separation unit







Gas Separation Process Parameterization

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) (L/EV/H)	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) (L/EV/H)	0.0153 / 0.0222 / 0.0333	N/A	N/A	N/A
Propane (kg/kg crude produced) (L/EV/H)	0.0056 / 0.0082 / 0.0123	N/A	N/A	N/A
Naphtha (kg/kg crude produced) ((L/EV/H)	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			

Crude is Primary Product: Co-Product Management Needed for Others

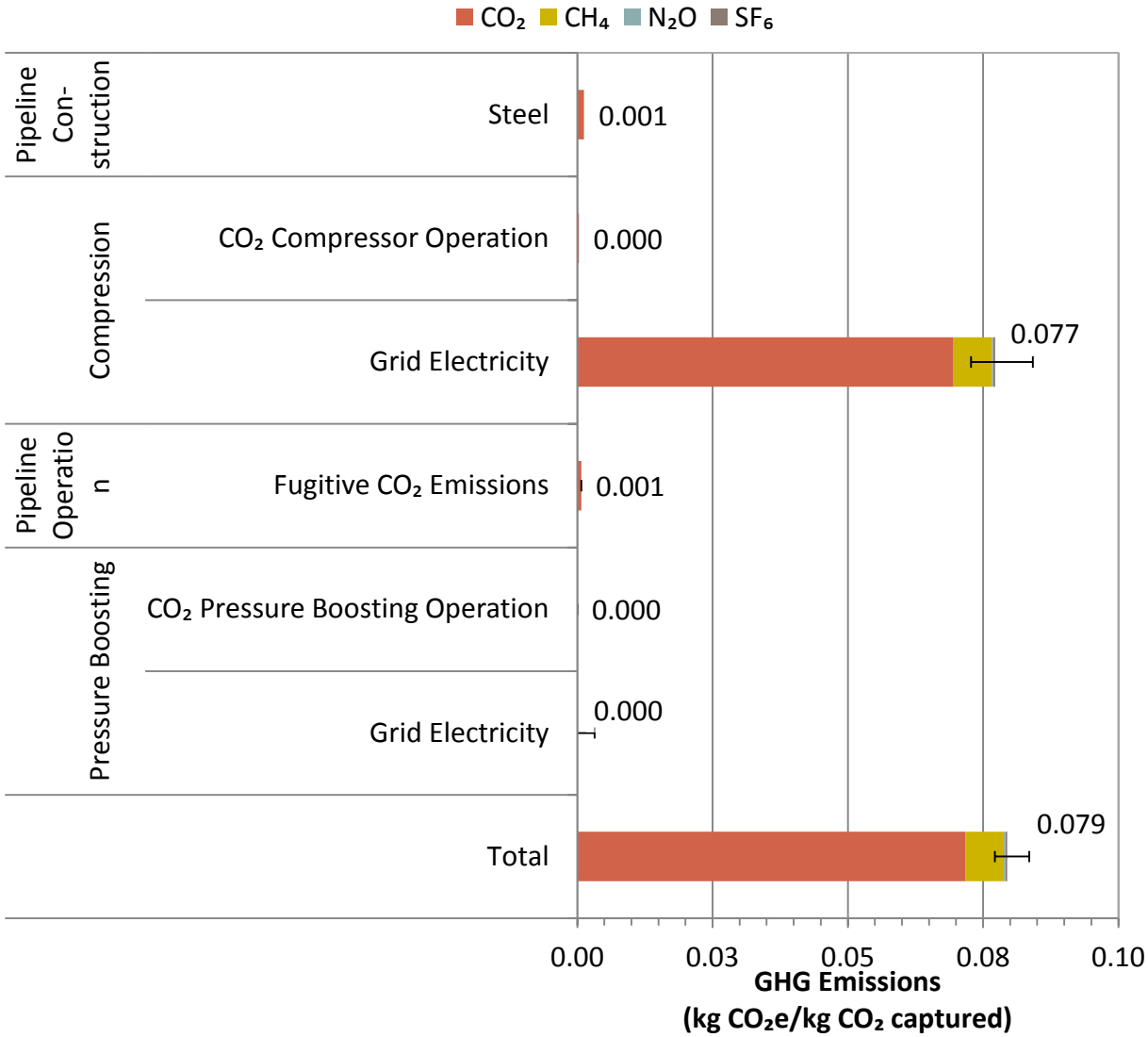
- **Evaluate Physical Allocation Methods: Energy, Volume, Mass**
  - Crude and other hydrocarbons are energy products, but NGLs have significant non-energy uses, such as in plastics
  - Volume is not conserved in the system as the products go through significant pressure and temperature changes
  - Each product *can* be expressed in terms of mass

- **System Expansion (Displacement)**
  - Boundaries of system are expanded until crude 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
  - Generally the co-products are a small portion of the product slate, so the credits received for displacement are small; answers generally similar to mass allocation

Gate-to-Gate Results for CO_2 Transport

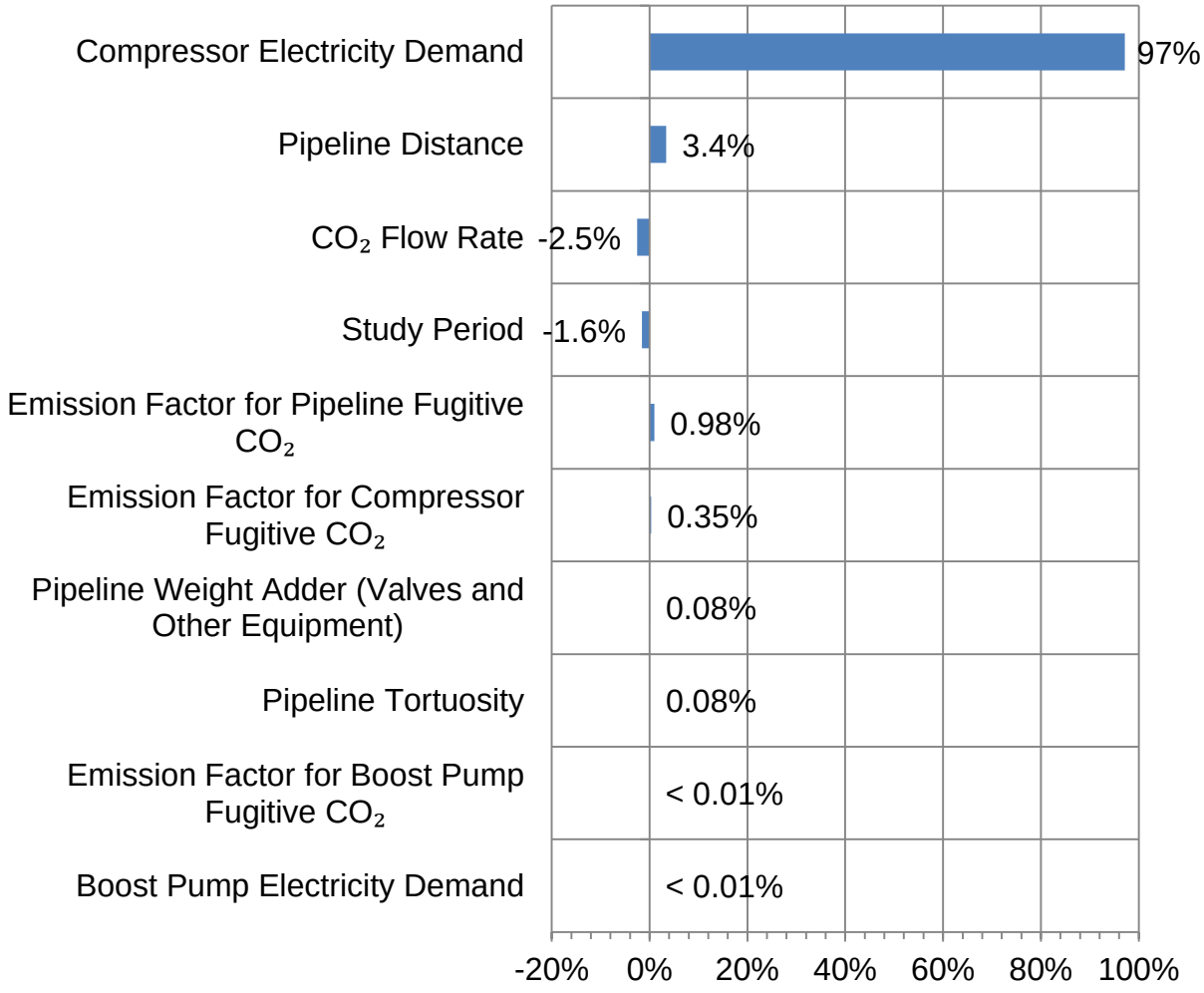
- **Electricity used for compression accounts for 97% of GHG emissions, with uncertainty driven by grid profile choice (U.S. Mix, ERCOT, or GTSC)**

- **Pressure boosting is not always necessary**
  - Not used for expected case of CO_2 flow rate of 10,000 tonnes/day & distance of 250 miles
  - Used for high case of CO_2 flow rate of 25,000 tonnes/day and distance of 550 miles

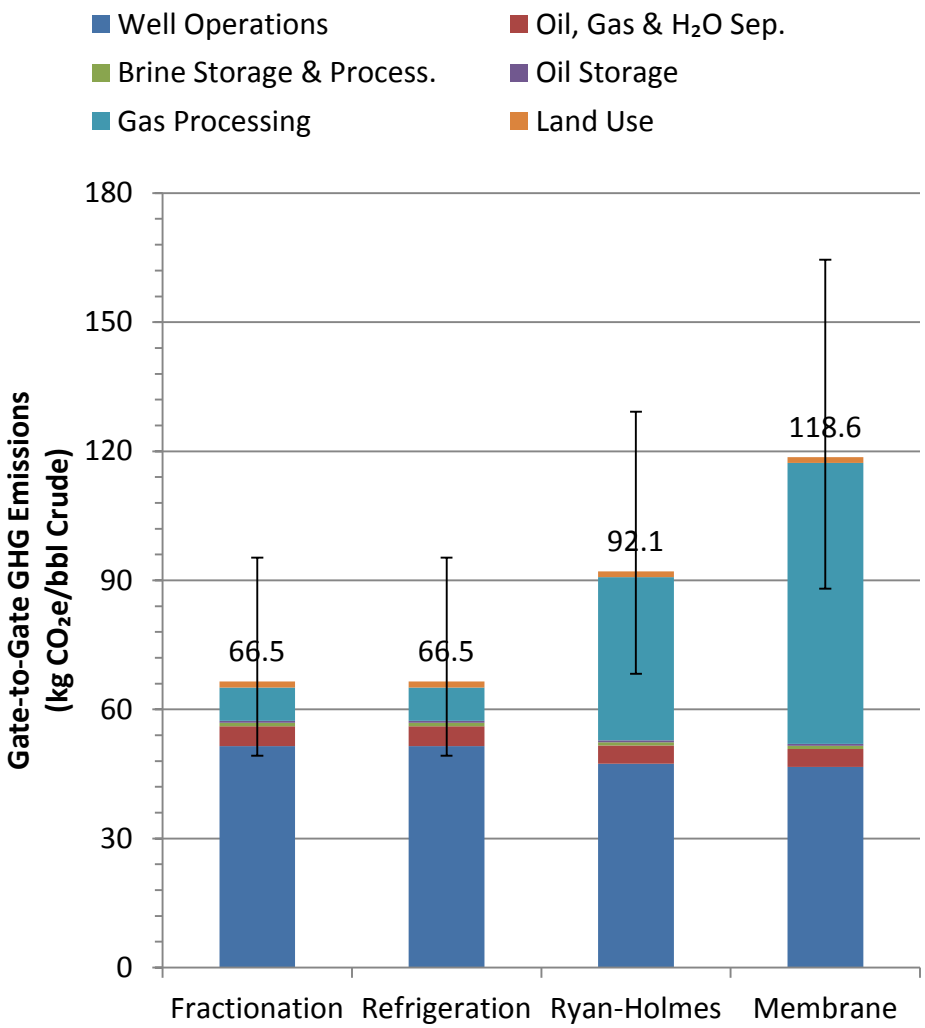


GHG Sensitivity for CO_2 Transport

- **Compression is energy intensive, so GHG results are especially sensitive to electricity demand for pipeline compressors**
- **A 100% increase in pipeline distance results in a 3.4% increase in gate-to-gate GHG emissions**
- **Inverse relationships include CO_2 flow rate and study period – as these parameters increase, the total burdens decrease per unit of CO_2 transported**

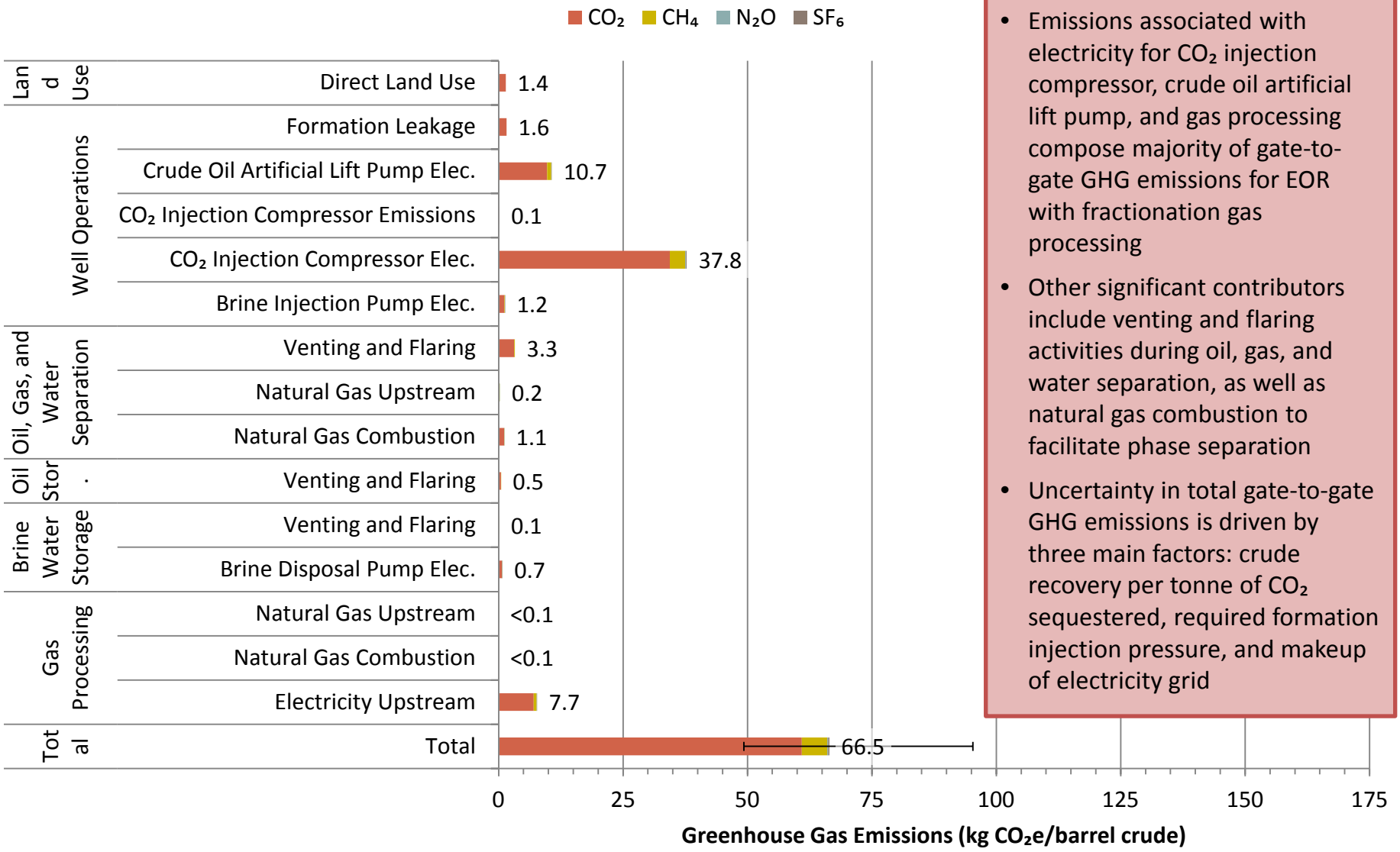


Gate-to-Gate GHG Results for Crude Extracted



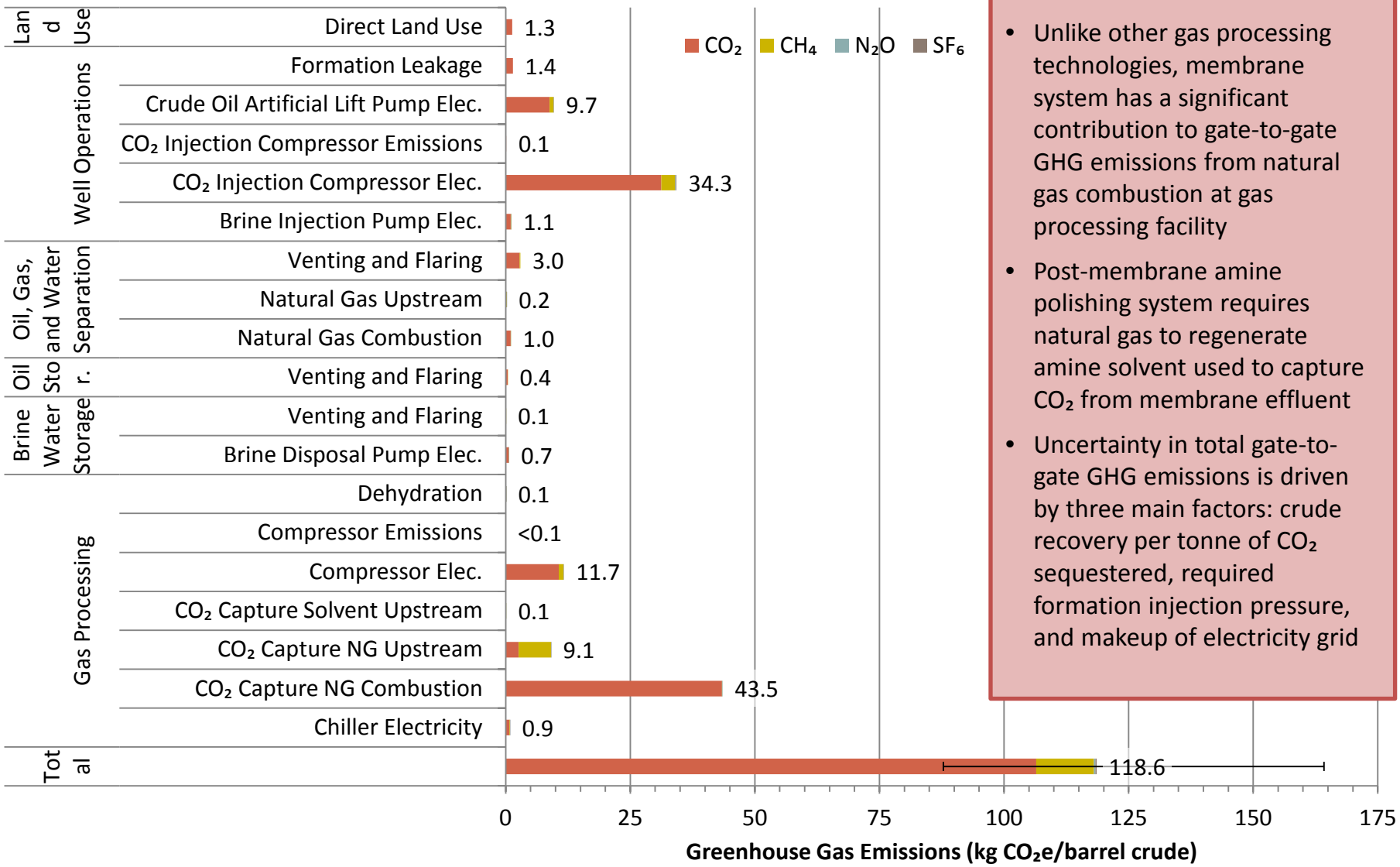
- Differences among scenarios come from differences in emissions attributed to gas processing
- Increased recovery comes at expense of additional processing energy which is demonstrated by increased GHG intensity associated with gas processing for Ryan-Holmes and membrane
- Error bars are driven primarily by crude recovery rates (low, current and advanced cases)

Gate-to-Gate Detailed Results for Crude Extracted (Fractionation Scenario)



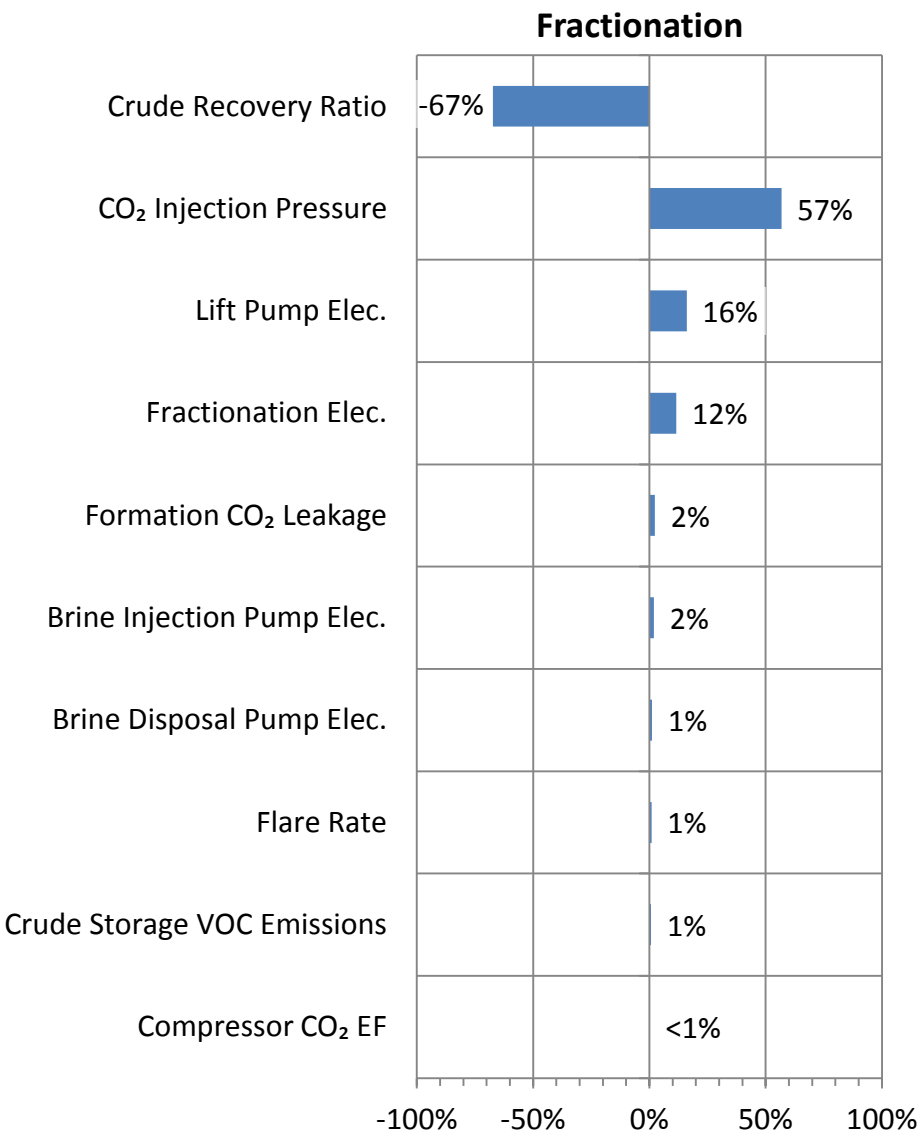
- Emissions associated with electricity for CO_2 injection compressor, crude oil artificial lift pump, and gas processing compose majority of gate-to-gate GHG emissions for EOR with fractionation gas processing
- Other significant contributors include venting and flaring activities during oil, gas, and 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

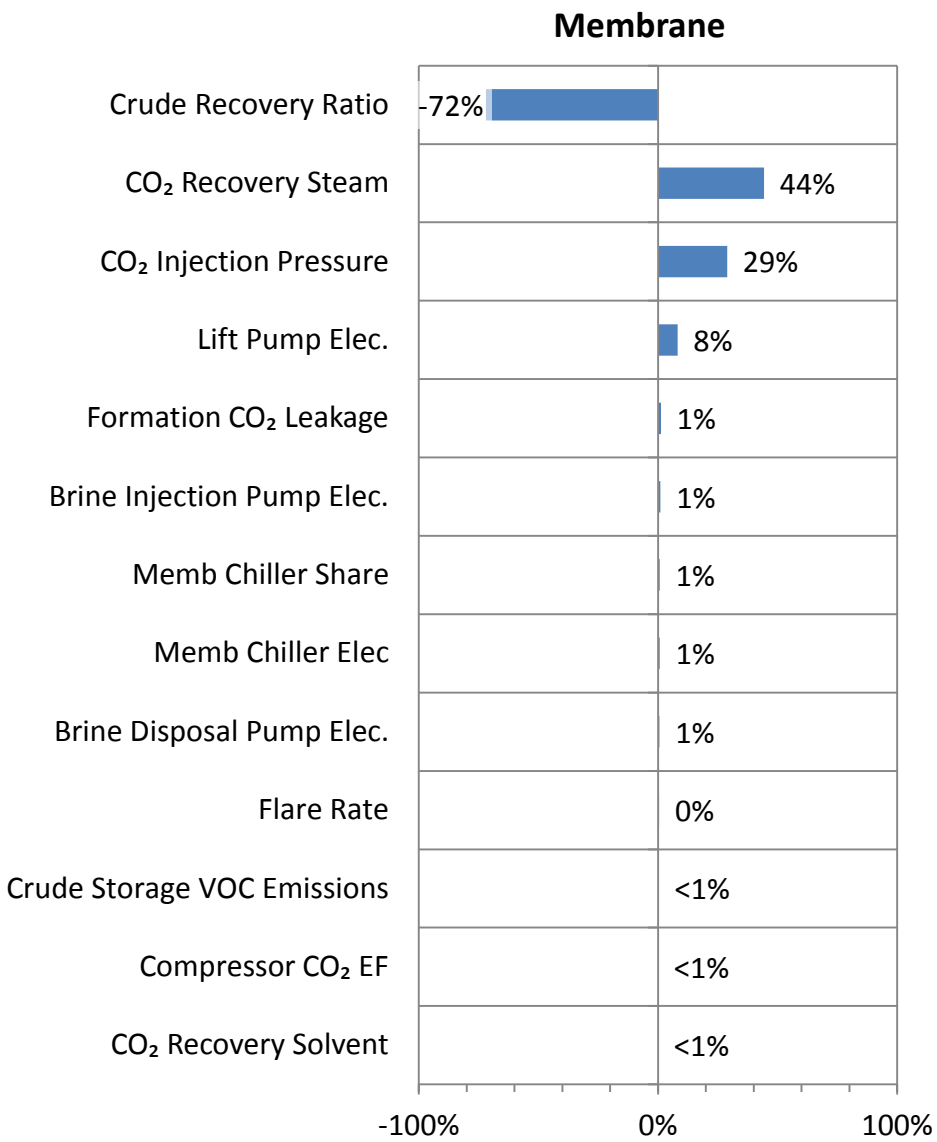
Another Gas Separation Scenario: Membrane Gate-to-Gate EOR Operations



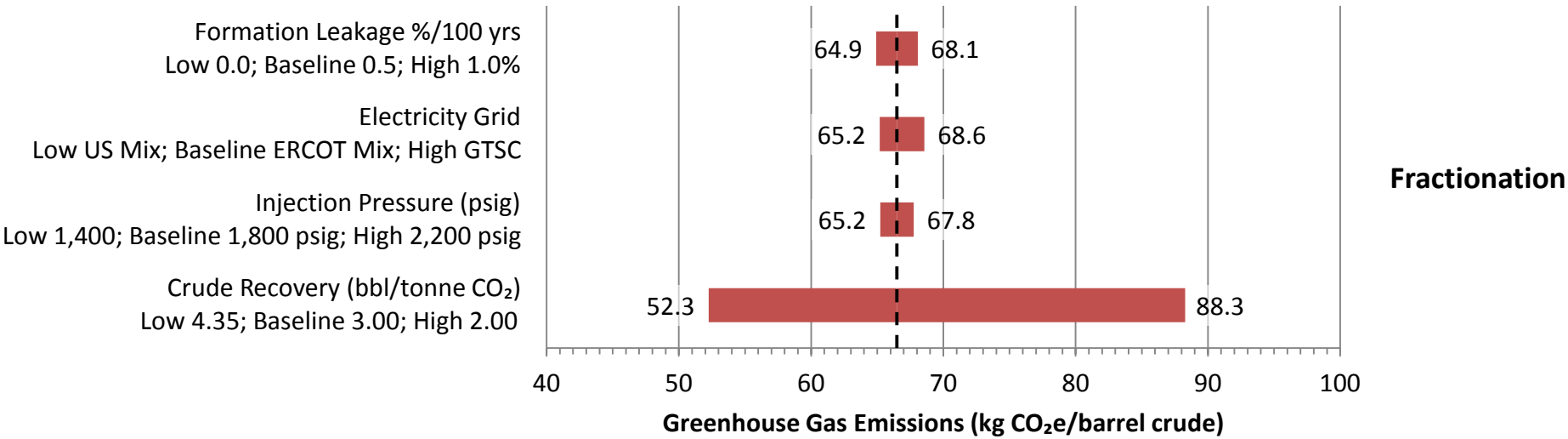
- Unlike other gas processing technologies, membrane system has a significant contribution to gate-to-gate GHG emissions from natural gas combustion at gas processing facility
- Post-membrane amine polishing system requires natural gas to regenerate amine solvent used to capture CO_2 from membrane effluent
- 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

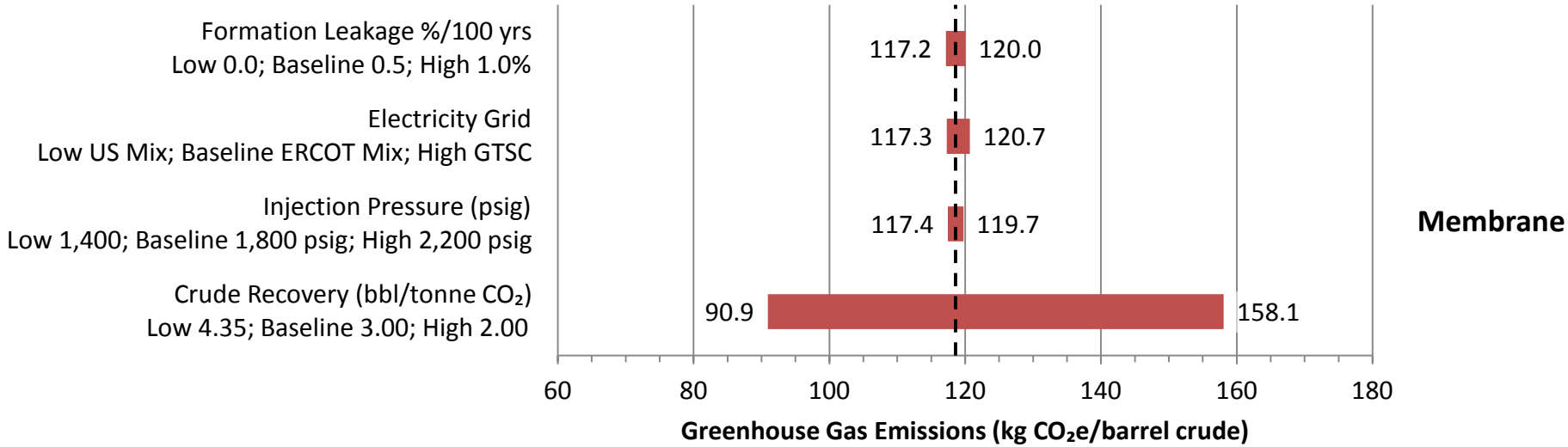
Sensitivity of Results to Gate-to-Gate Parameters



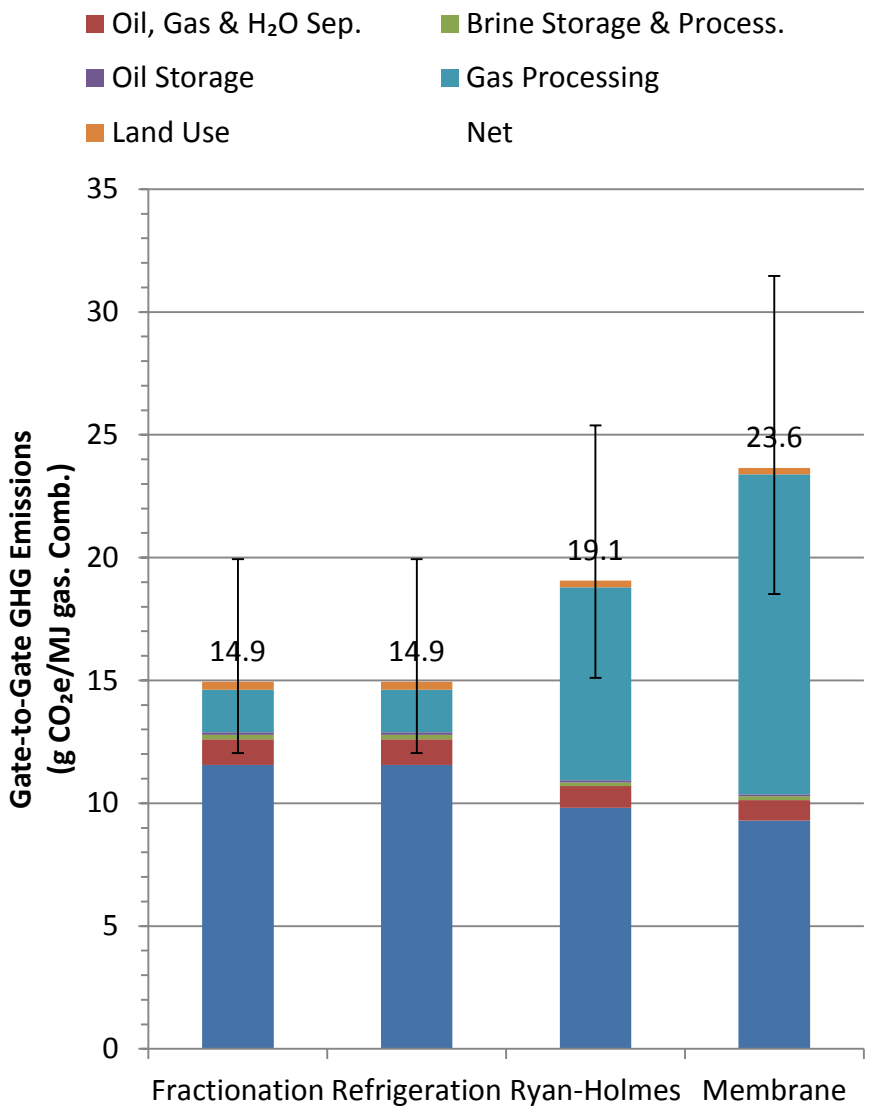


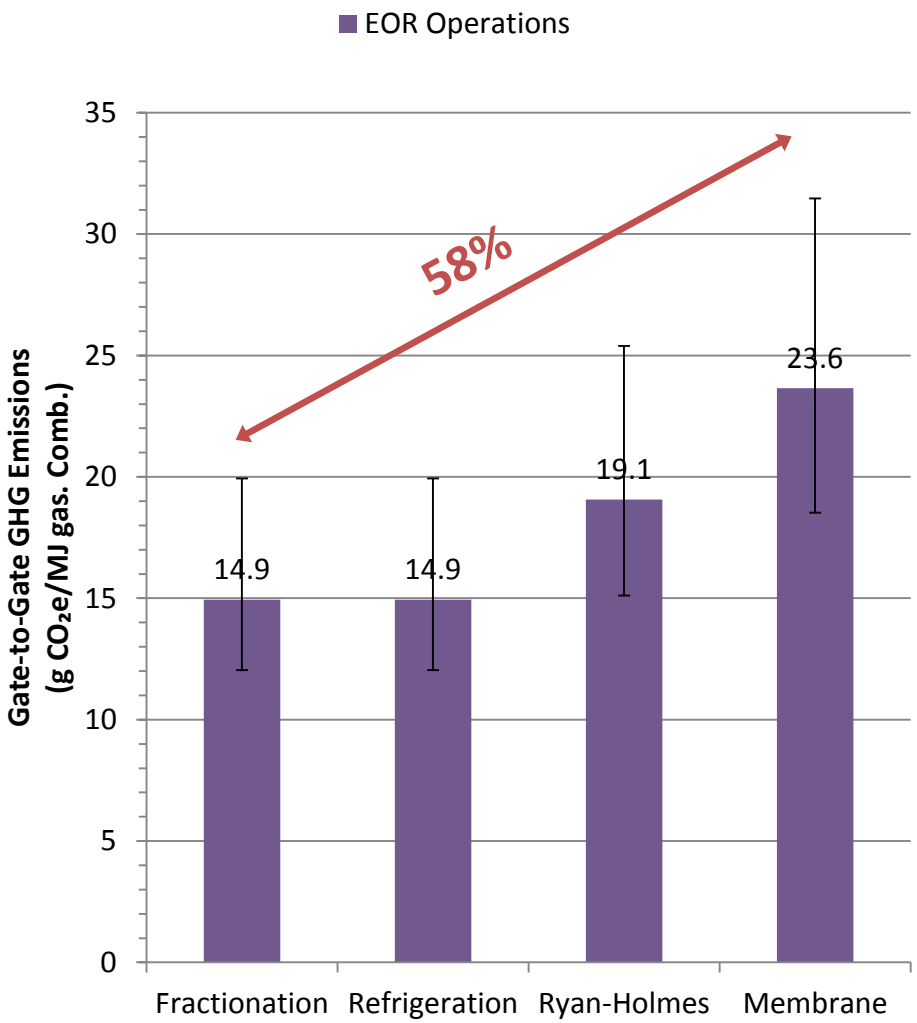
Gate-to-Gate EOR Uncertainty Relative to Baseline Case





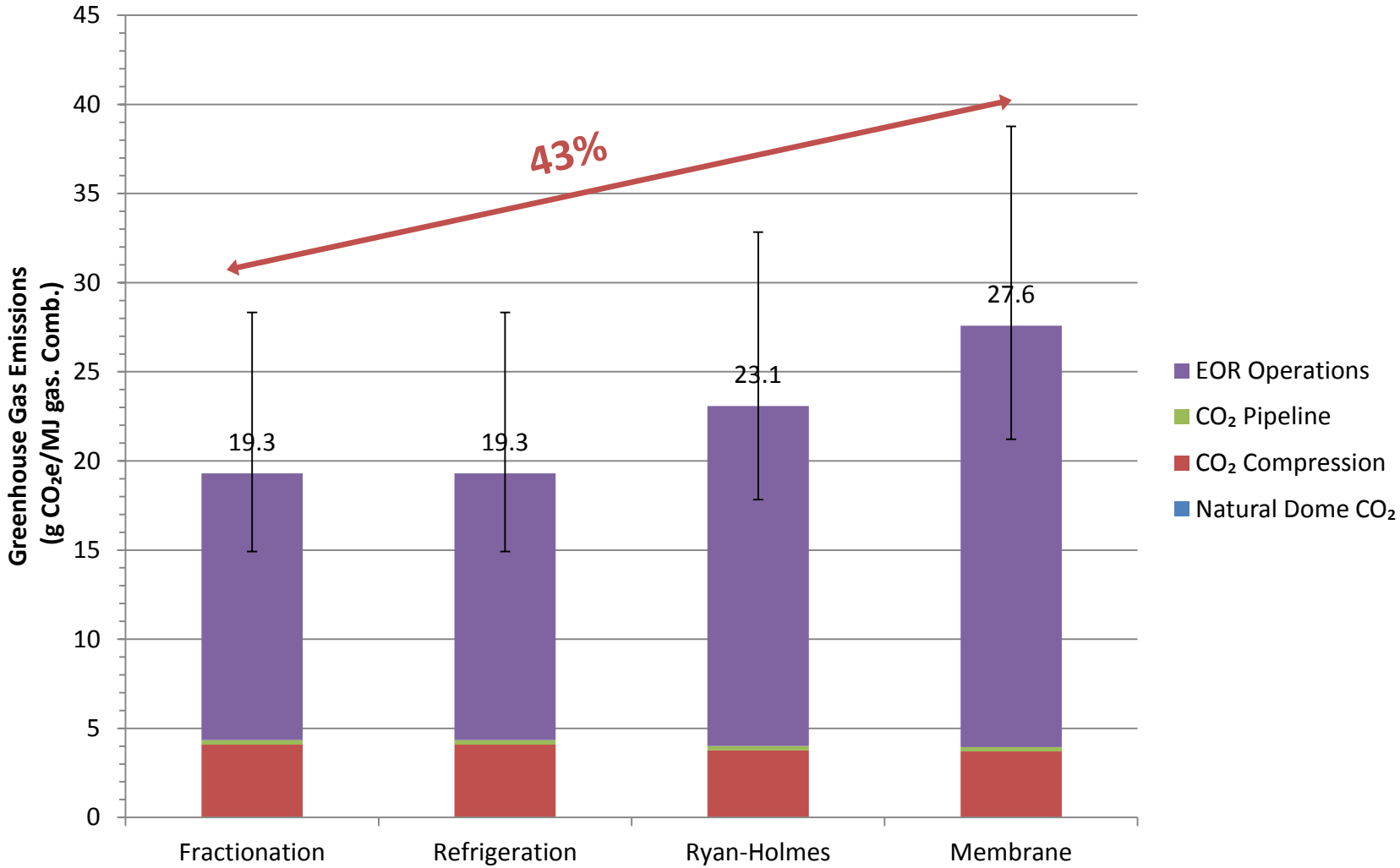
Gate-to-Gate EOR Summary Results



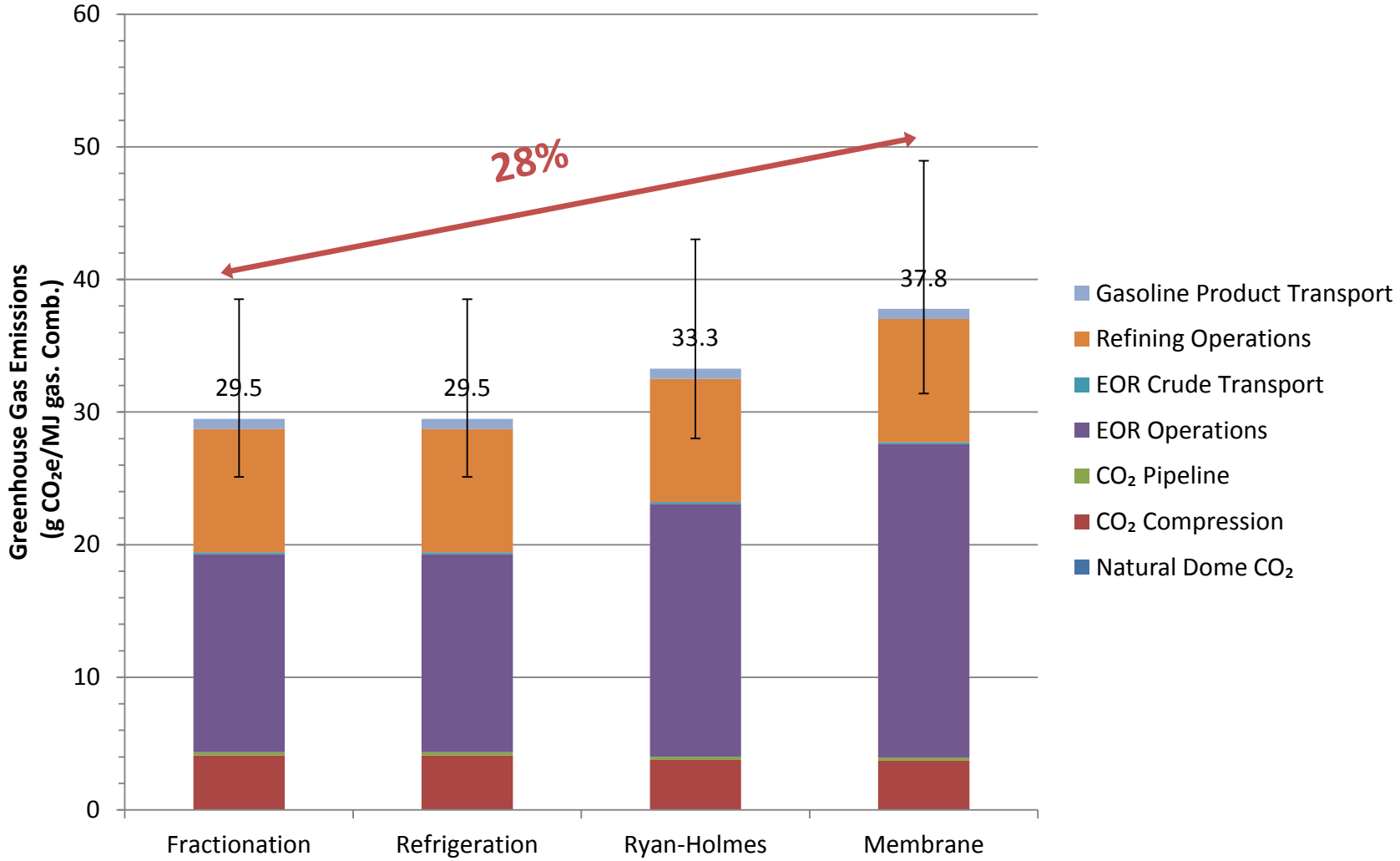


Cradle-to-Gate EOR Crude Extraction

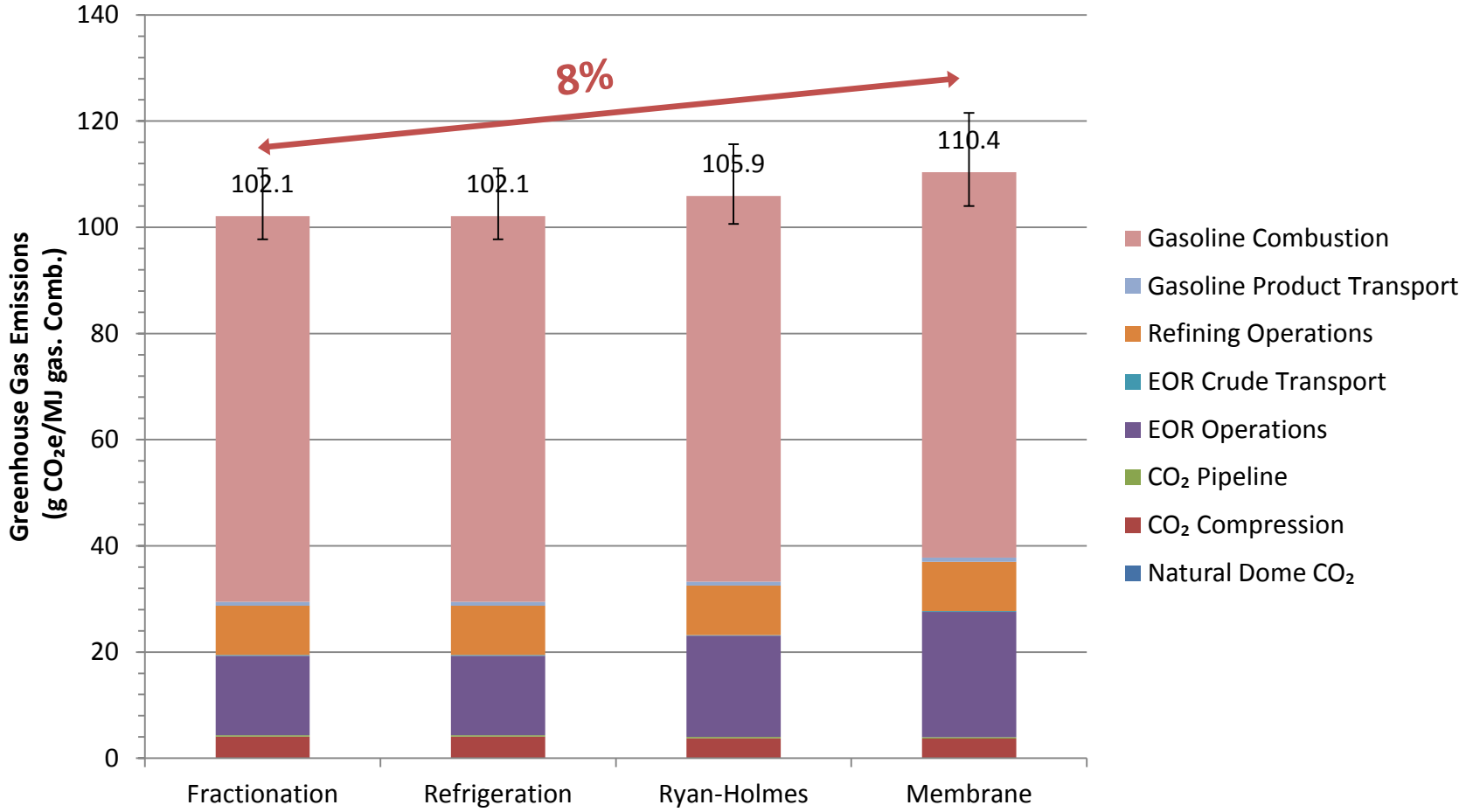
(Add Nat. Dome CO_2 & Transport)



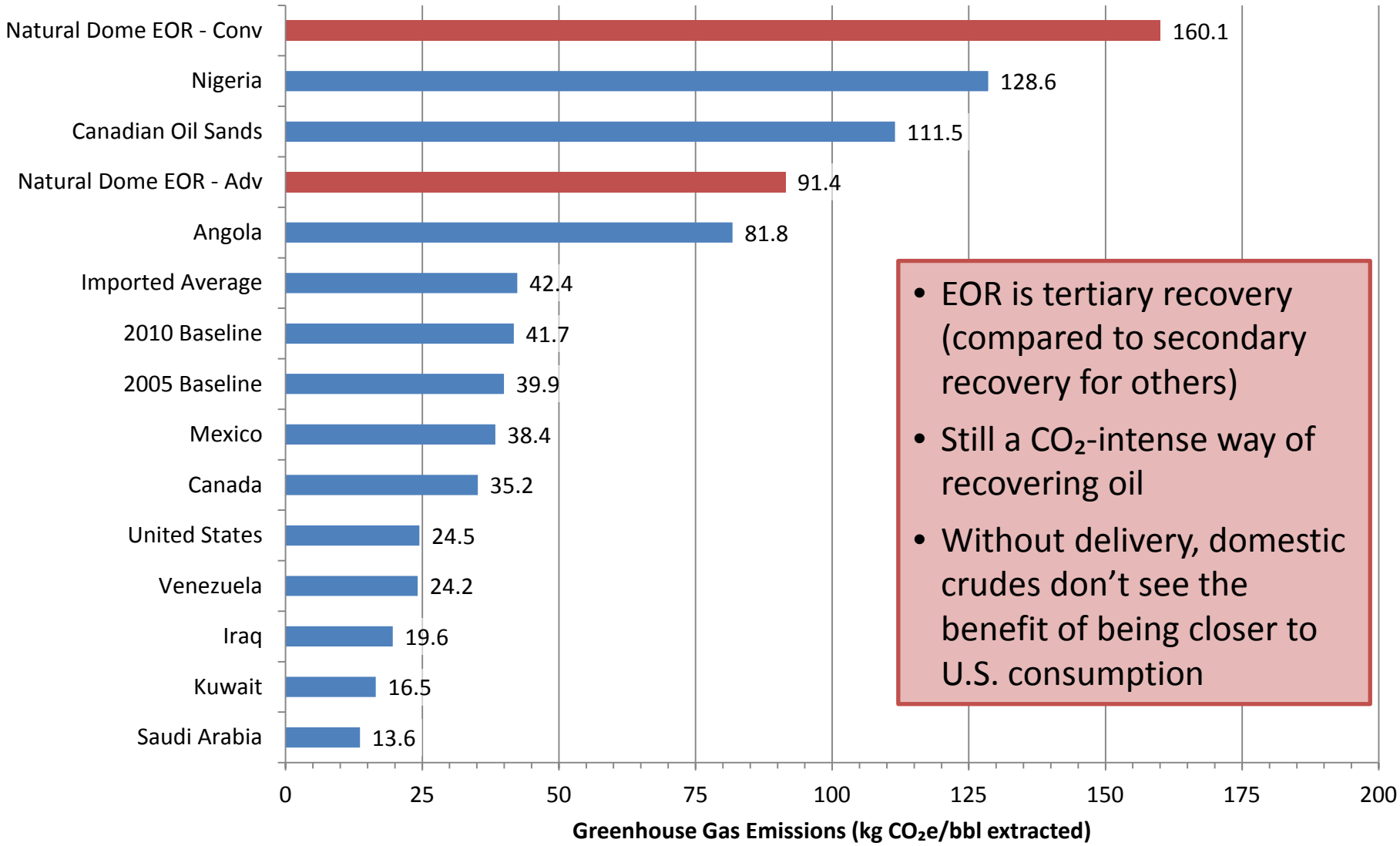
Well-to-Tank Gasoline from EOR
(Add Crude Transport, Refining, Gasoline Transport)



Well-to-Wheels Gasoline Combustion from EOR
(Add Combustion)

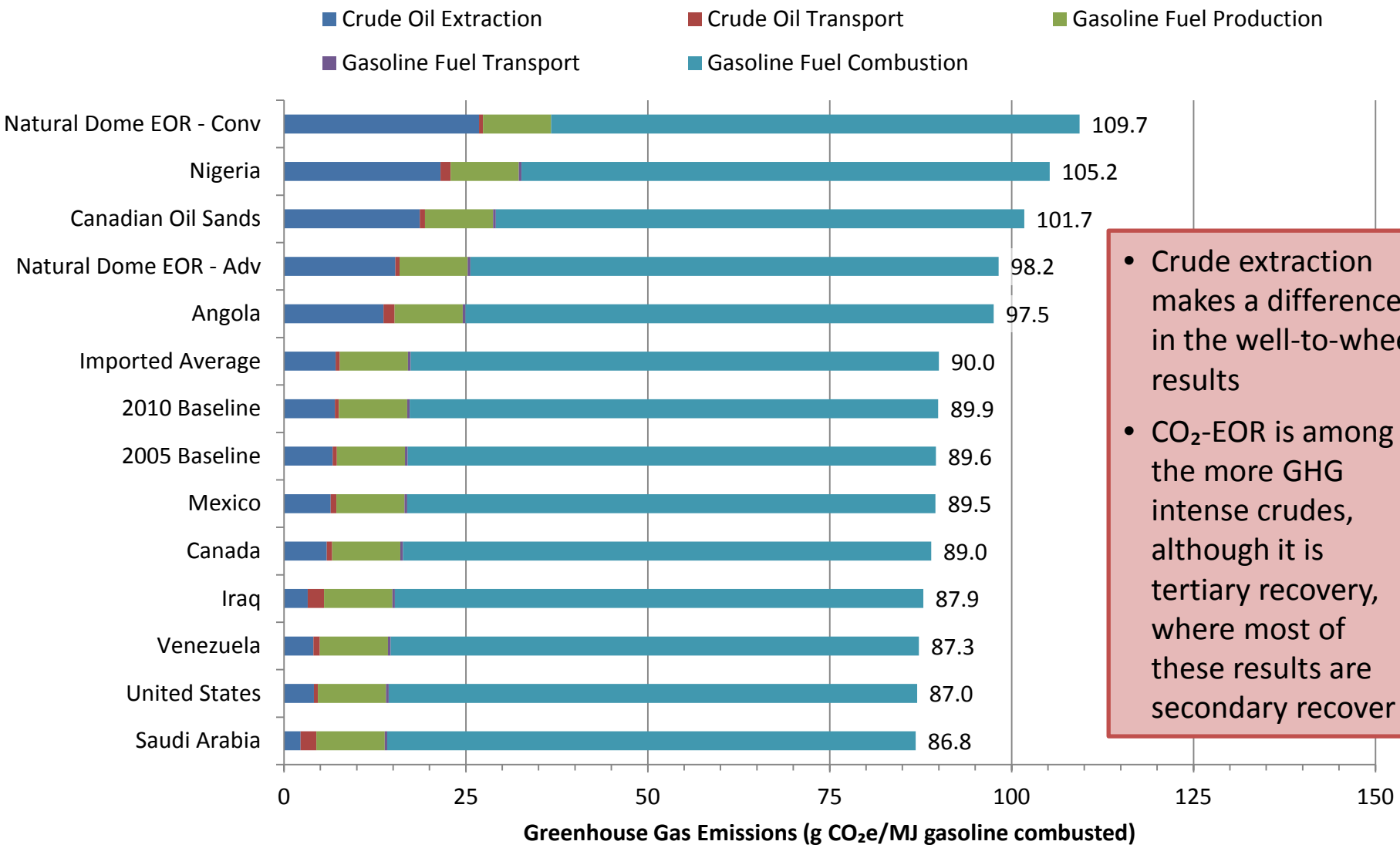


Cradle-to-Gate Crude Extraction (No Transport)



- EOR is tertiary recovery (compared to secondary recovery for others)
- Still a CO_2-intense way of recovering oil
- Without delivery, domestic crudes don't see the benefit of being closer to U.S. consumption

Well-to-Wheel Results for Gasoline by Crude Type



- Crude extraction makes a difference in the well-to-wheel results
- CO_2-EOR is among the more GHG intense crudes, although it is tertiary recovery, where most of these results are secondary recover

Recommendations and Conclusions

- Some results are only gate-to-gate, or cradle-to-gate, so they should be used with care
- EOR is tertiary recovery; comparison to crude from primary or secondary recovery is skewed
- No well goes to tertiary recovery without undergoing primary and secondary recovery, but those portions of the well's life cycle are not included here
- Relatively small amounts of CO_2 are sequestered; technology improvement decreases that amount by increasing the performance of gas separation
- A full analysis of the environmental benefit of EOR as a GHG reduction strategy requires consideration of the results in the context of anthropogenic CO_2

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