Cost of Capturing CO_2 from Industrial Sources

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Outline

- Objective
- Methodology
- Study Overview
- Key Takeaways
- Study Results

Objective

- **To develop baseline information on the cost of capturing CO_2 from industrial processes for use in enhanced oil recovery (EOR)**
- **To determine which industrial sources could supply CO_2 for EOR at a lower cost than fossil power plants with capture**
- **This information will feed cost-supply curves for an update to an NETL custom version of NEMS**

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Methodology

Assumption Overview

- Base Plant
- Capture Plant
- Point Sources
- CO_2 End Use
- Financing
- Uncertainties

Key Assumptions to Consider
Base Plant

- **Motivation for capture (i.e. additional revenue or to avoid a penalty) may impact the following:**
  - Extent of capture
  - CO_2 point sources to consider within plant
- **Types of industrial sources to investigate**
  - Is the industry a large emitter of CO_2?
  - Does the source provide a cost effective capture opportunity?
    - Do representative plant sizes provide necessary economies of scale?
    - Determine a cutoff point for CO_2 purity or partial pressure
  - Is the industry located near EOR or CO_2 storage sites?
- **Size of the representative plant**
  - How does assumed plant represent the industrial fleet?
    - Fleet average
    - Next build

Key Assumptions to Consider cont.
Base Plant

- **Is CO_2 being used or vented?**
  - Example: CO_2 used for urea production in an ammonia plant
- **CO_2 point source(s)**
  - CO_2 purity
  - Amount of CO_2 available to be captured
    - Multiple sources within a plant?
      - Will they be combined or utilize separate capture facilities?
      - Concentrations and partial pressures of each source?
  - End use for CO_2
    - EOR
    - Storage
  - Partial pressure of CO_2 in vent stream

Key Assumptions to Consider
Capture Plant

- **Will capture plant integrate with Base Plant?**
- **Auxiliary power purchased from grid, utilized from base plant, or produced onsite? Purchase price?**
- **Auxiliary steam source? Associated cost?**
- **Cooling water?**
- **What type of post combustion capture process?**
  - Solvent
    - MDEA, MEA, Selexol, etc.
  - Sorbent
  - Membrane
  - Additional clean-up needed?

Uncertainties to Consider

- **Finance structure**
  - Debt/Equity
  - Cost of debt and equity
  - Economic life
  - Universal or industry specific
- **Capacity Factor of capture plant**
- **Technology maturity**
- **Site specific costs**
- **Sensitivities**

Special Cases to Consider

- **Co-production?**
  - i.e. Ammionia and CO_2 used to make Urea
- **Additional clean-up needed?**
  - Cement may require SCR and FGD before CO_2 removal

Study Overview

- **Industrial processes were limited to domestic plants with flue gas streams containing higher CO_2 concentrations than that of coal-fired power plants (CFPP) (~8-14% CO_2 by volume)**
- **Representative plant sizes were selected for each industry**
  - Average, next built
- **No integration considered between the base plant and the capture plant for all cases**

Case Summary				
Process	**Data Source**	**Greenfield**	**Retrofit**	**Retrofit Factor**
Ethanol	Literature Review	X	X	1.01
Ammonia	Literature Review	X	X	1.01
Refinery Hydrogen	Literature Review	X	X	1.05
Steel/Iron	Literature Review		X	1.05
Natural Gas Processing	Literature Review	X	X	1.01
Ethylene Oxide	Literature Review	X	X	1.01
Cement	Literature Review	X	X	1.05
Coal-to-Liquids	NETL Study	X		1.01
Gas-to-Liquids	NETL Study	X		1.01

Study Overview Continued

- **Adequate plot plan space for capture and/or compression plant footprint is assumed for all cases**
- **Power purchased at $59/MWh* for CO_2 compression and other auxiliary loads**
- **Natural gas purchased at $6.13/MMBtu** for steam generation and all thermal loads**
- **Assumes NOAK cost estimate with +30%/-15% Accuracy**
- **All cases utilize post combustion capture**
- **Capture plants were modeled using the Methyldiethanolamine (MDEA) Acid Gas Removal (AGR) process**
  - MDEA was beneficial due to its sulfur tolerance
  - MDEA appropriate for low pressure requirements compared to Selexol
  - MDEA cost quotes best match for industrial sources capacities versus other amines
- **Breakeven selling price of CO_2 was the metric used to compare results across all cases**

**Purchase price for power based off the cost of electricity (COE) from a NGCC without capture from the NETL Bituminous Baseline Report*
***NETL "QGESS: Fuel Prices for Selected Feedstocks in NETL Studies" November 2012*

Process Overview

Process	Representative Plant Capacity	Process Vent Stream
Ethanol	50 MMgal/year	Distillation gas
Ammonia	907,000 tonnes/year	Stripping vent
Refinery Hydrogen	59,000 tonnes/year	PSA tail gas
Steel/Iron	2.54 Mt/year	COG PPS COG+BFS
Natural Gas Processing	500 MMscf/d	CO_2 vent
Ethylene Oxide	364,500 tonnes/year	AGR CO_2 stream
Cement	992,500 tonnes/year	Kiln Off-gas
Coal-to-Liquids	50,000 bbl/d	AGR CO_2 streams
Gas-to-Liquids	50,000 bbl/d	AGR CO_2 stream

Process Distinctions

- **High CO_2 concentration industrial sources**
  - Assumed that vent streams can meet CO_2 pipeline specs* through compression and cooling alone (e.g. ≥ 95% CO_2)
- **Low CO_2 concentration industrial sources**
  - Assumed that vent streams will need to be equipped with both CO_2 capture and compression equipment to meet CO_2 pipeline specs* (e.g. ≥ 95% CO_2)

**NETL's "Quality Guidelines for Energy System Studies: CO_2 Impurity Design Parameters" January 2012*

Financial Assumptions

Financial Parameter	High CO_2 Concentration Cases	Low CO_2 Concentration Cases
Capital Expenditure Period	1 year	3 years
Debt/Equity Ratio	50/50	50/50
Economic Life	30 years	30 years
Interest on Debt	8.0%	8.0%
Return on Equity	20%	20%
Capital Charge Factor (CCF)	15.2%	17.6%

- DCF analysis is done on a current-dollar basis, yielding a "first-year" cost of CO_2 capture.

Results

Key Takeaways

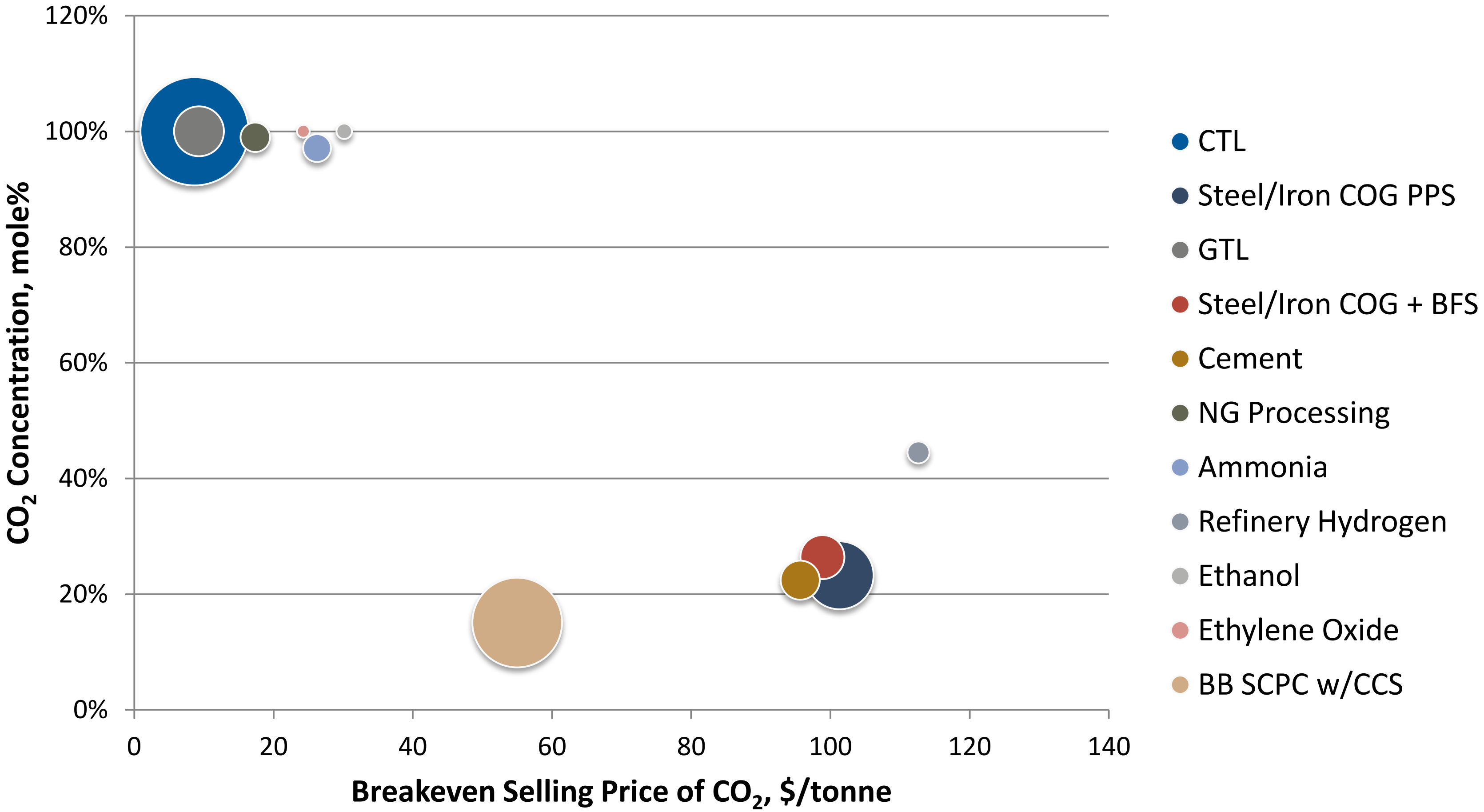
- **Many different parameters of the base plants have an effect on the breakeven selling price of CO_2. The following have the greatest effect:**
  - Concentration of CO_2 in the exhaust stream
    - Being able to meet CO_2 pipeline specifications without separation of the CO_2 greatly drives down the cost
  - Scale of the plant
    - Scale economies reduce specific capital costs

Results

	Capture Stream CO_2 Concentration (mole %)	Captured CO_2 (tonne/yr)*	Greenfield Breakeven Cost ($/tonne CO_2)	Retrofit Breakeven Cost ($/tonne CO_2)
Coal-to-Liquids	100.00	8,743,323	8.66	N/A
Gas-to-Liquids	100.00	1,858,767	9.29	N/A
Natural Gas Processing	99.00	649,198	17.38	17.56
Ethylene Oxide	100.00	121,501	24.28	24.52
Ammonia	97.10	458,400	26.26	26.52
Ethanol	100.00	143,045	30.15	30.46
Cement	22.40	1,140,697	95.66	100.44
Steel/Iron COG + BFS	23.23	2,754,966	N/A	98.84
Steel/Iron COG PPS	26.42	1,155,413	N/A	101.31
Refinery Hydrogen	44.52	273,860	112.64	118.27
BB SCPC w/CCS	15.1%	4,807,429	60	65 - 70

**100% CF assumed*
BB SCPC uses utility finance structure

Results

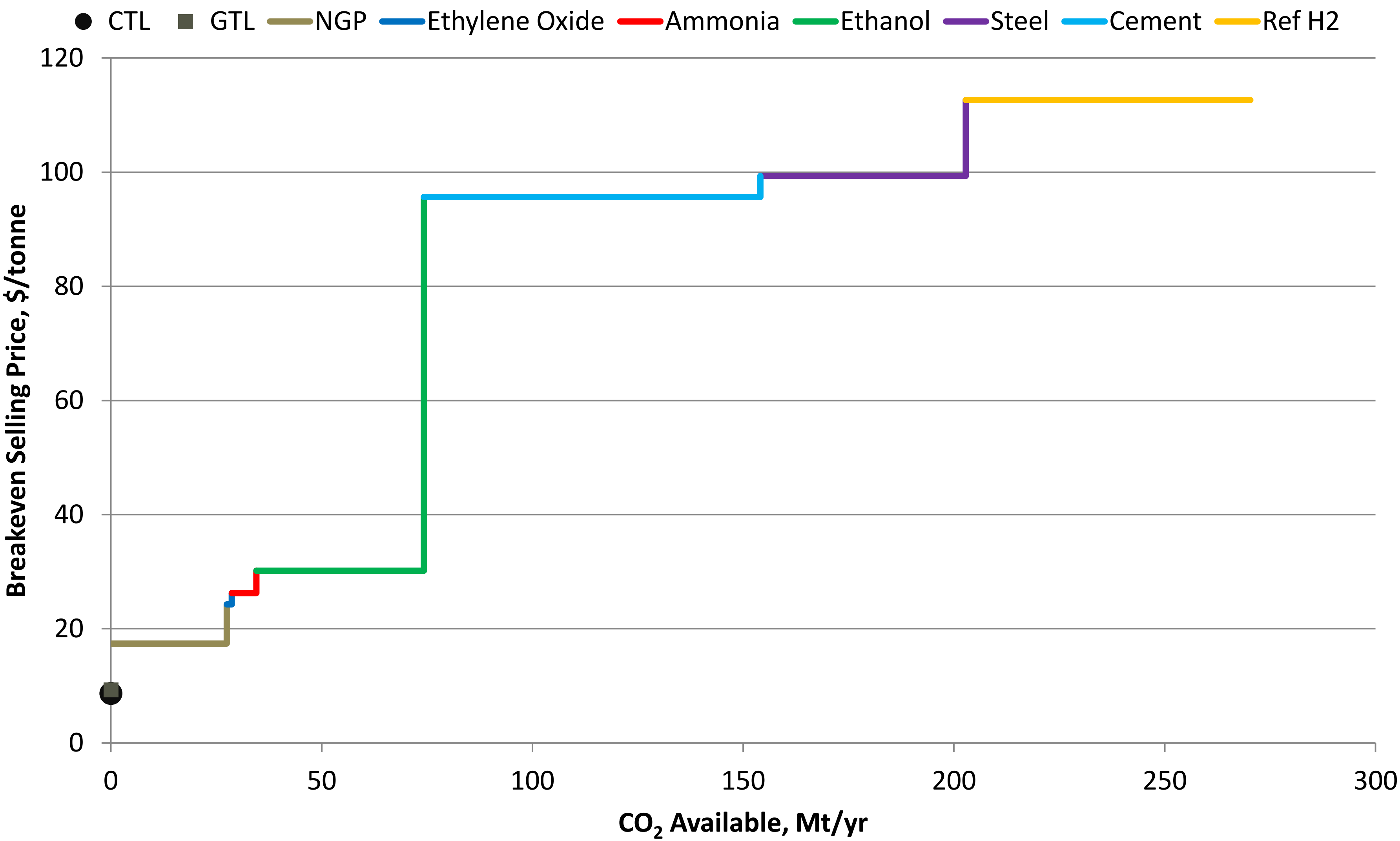


- Size of circle Illustrates relative quantity of CO_2 being captured on a plant basis

Assumed 100% Cap
BB SCPC uses utility finance structure

Incremental CO_2 Supply versus Breakeven Selling Price

Based on Greenfield Prices except for Steel Process



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Sensitivities

Sensitivities
Cement

- **Plant – 992,500 tonne/year**
- **Feed Stock – Various**
- **Point Source**
  - Kiln Off-gas
    - 22.4% CO_2
    - Partial Pressure: 3.29 psia
  - Kiln off-gas may have higher that acceptable levels of SO_x/No_x requiring addition of selective catalytic reduction (SCR) and flue gas desulfurization (FGD).
    - A sensitivity to this case was performed, and the results show that the addition of SCR and FGD has the potential to add $26.43/tonne to the retrofit costs.

Sensitivities
Cement Continued

	Cement	Purity Sensitivity
	\$/tonne CO_2	\$/tonne CO_2
Capital Charges	32.89	45.33
Fixed O&M	9.99	13.76
Variable O&M	14.99	20.64
Consumables	2.54	5.41
Purchased Power	9.45	9.90
Purchased Natural Gas	25.80	25.80
Total Breakeven Cost	95.66	120.83

Sensitivities

- **Financing assumptions**
  - A 10-yr economic life of the project increases break even CO_2 price by 16-20% compared to the assumed 30-yr economic life
- **Price of power from the grid**
  - Purchased power makes up 25% of break even cost for high CO_2 purity sources
  - Breakeven cost for low CO_2 purity sources increases more rapidly with increasing COE due to higher auxiliary loads
- **Price of natural gas for thermal loads**
  - Purchased natural gas makes up ~25% of break-even cost for low CO_2 purity sources
- **CO_2 stream purity**
  - Only assessed for cases requiring CO_2 separation (low CO_2 purity sources)
- **Plant size in terms of CO_2 emissions per year**
  - Typically varied over the range of operating US plants
- **Retrofit factor**

Questions?

High CO_2 Concentration Sources

Process	Capture Stream CO_2 Concentration (mole %)	Partial Pressure (psia)	Captured CO_2 (tonne/yr)
Coal-to-Liquids	100.0%	265	8,743,323
Gas-to-Liquids	100.0%	265	1,858,767
Ethanol	100.0%	18.40	143,045
Ethylene Oxide	100.0%	43.50	121,501
Natural Gas Processing	99.0%	23.27	649,198
Ammonia	97.1%	22.82	458,400

- Assumed that high CO_2 concentration vent streams can meet CO_2 pipeline specs* through compression and cooling alone (e.g. ≥ 95% CO_2)
- Note: 4.8 Mt CO_2/year assumed to be captured in a 550 MW SCPC with CCS

**NETL's "Quality Guidelines for Energy System Studies: CO_2 Impurity Design Parameters" January 2012*

Lower CO_2 Concentration Sources

Process	Capture Stream CO_2 Concentration (mole %)	Partial Pressure (psia)	Captured CO_2 (tonne/yr)
Refinery Hydrogen	44.5%	8.90	273,860
Steel/Iron COG + BFS	26.4%	3.88	1,155,413
Steel/Iron COG PPS	23.2%	3.41	2,754,966
Cement	22.4%	3.29	1,140,697

- Assumed that lower CO_2 concentration vent streams will need to be equipped with both CO_2 capture and compression equipment to meet CO_2 pipeline specs (e.g. ≥ 95% CO_2)
- Note: 4.8 Mt CO_2/year assumed to be captured in a 550 MW SCPC with CCS

NETL's "Quality Guidelines for Energy System Studies: CO2 Impurity Design Parameters" January 2012

Equipment Modeled

Compression

- **Quotes for two types of compressor were obtained**
  - Centrifugal compression was used for relatively high CO_2 flowrates
  - Reciprocating compression was used for low CO_2 flowrates
  - 615,900 tonnes CO_2/yr (678,900 tons CO_2/yr).

Separation

- **MDEA AGR unit with a packaged boiler to regenerate the MDEA**
  - Produces CO_2 at 19.7 psia
  - Assumes 95% capture (of CO2 in treated stream)

Capacity Factor – 85% for all cases

CO_2 Impurity Design Parameters

Component	Unit (Max unless Otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO_2 & H_2S Co-sequestration		Venting Concerns (See Section 3.0)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
CO_2	vol% (Min)	95	90-99.8	95	90-99.8	95	90-99.8	95	20 – 99.8	Yes-IDLH 40,000 ppmv
H_2O	ppm_{wt}	300	20 - 650	300	20 - 650	300	20 - 650	300	20 - 650	
N_2	vol%	4	0.01 - 7	1	0.01 - 2	4	0.01 - 7	4	0.01 – 7	
O_2	vol%	4	0.01 – 4	0.01	0.001 – 1.3	4	0.01 – 4	4	0.01 – 4	
Ar	vol%	4	0.01 – 4	1	0.01 – 1	4	0.01 – 4	4	0.01 – 4	
CH_4	vol%	4	0.01 – 4	1	0.01 – 2	4	0.01 – 4	4	0.01 – 4	Yes-Asphyxiate, Explosive
H_2	vol%	4	0.01 - 4	1	0.01 – 1	4	0.01 – 4	4	0.02 – 4	Yes-Asphyxiate, Explosive
CO	ppm_v	35	10 - 5000	35	10 - 5000	35	10 - 5000	35	10 - 5000	Yes-IDLH 1,200 ppmv
H_2S	vol%	0.01	0.002 – 1.3	0.01	0.002 – 1.3	0.01	0.002 – 1.3	75	10 - 77	Yes-IDLH 100 ppmv
SO_2	ppm_v	100	10 - 50000	100	10 - 50000	100	10 - 50000	100	10 - 50000	Yes-IDLH 100 ppmv
NO_X	ppm_v	100	20 - 2500	100	20 - 2500	100	20 - 2500	100	20 - 2500	Yes-IDLH NO-100 ppmv, NO_2 - 200 ppmv

CO_2 Impurity Design Parameters cont.

Component	Unit (Max unless Otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO_2 & H_2S Co-sequestration		Venting Concerns (See Section 3.0)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
NH_3	ppm_v	50	0 - 50	50	0 - 50	50	0 - 50	50	0 - 50	Yes-IDLH 300 ppmv
COS	ppm_v	trace	trace	5	0 - 5	trace	trace	trace	trace	Lethal @ High Concentrations (>1,000 ppmv)
C_2H_6	vol%	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	Yes-Asphyxiant, Explosive
C_3+	vol%	<1	0 - 1	<1	0 - 1	<1	0 - 1	<1	0 - 1	
Part.	ppm_v	1	0 - 1	1	0 - 1	1	0 - 1	1	0 - 1	
HCl	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 50 ppmv
HF	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 30 ppmv
HCN	ppm_v	trace	trace	trace	trace	trace	trace	trace	trace	Yes-IDLH 50 ppmv
Hg	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	Yes-IDLH 2 mg/m^3 (organo)
Glycol	ppb_v	46	0 - 174	46	0 - 174	46	0 - 174	46	0 - 174	
MEA	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	MSDS Exp. Limits 3 ppmv, 6 mg/m^3
Selexol	ppm_v	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	N.I.*	

Retrofit Assumptions

- **High Concentration Sources**
  - Retrofit factors deviate from recommendations in NETL's "Retrofit Cost Analysis for Post-combustion CO_2 Capture" due to:
    - Do not use an amine solvent-based CO_2 separation system
    - These industrial sources tend to be significantly smaller than the utility scale power plants for which these factors were developed
- **Low Concentration Sources**
  - Retrofit factors align with recommendations in NETL's "Retrofit Cost Analysis for Post-combustion CO_2 Capture" even though:
    - CO_2 separation is performed using MDEA system, rather than MEA system
    - These industrial sources tend to be significantly smaller than the utility scale power plants for which these factors were developed

Industrial Processes – High Purity Sources

Ethanol Process

- **Plant – 50 million gallon/year of Ethanol utilizing dry mill process**
- **Feedstock– Corn**
- **Point Source**
  - Fermentation off gas stream
    - 100% pure CO_2
    - Partial Pressure: 18.40 psia

Ethanol Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	12.20
Fixed O&M	4.30
Variable O&M	6.46
Consumables	0.38
Purchased Power	6.82
Purchased Natural Gas	0.00
Total Breakeven Cost	30.15

Ammonia Process

- **Plant – 907,000 tonnes/year of Ammonia**
  - 28% of total CO_2 produced is used to make Urea
  - 38% of total CO_2 produced available for EOR
- **Feed Stock – Natural Gas**
- **Point Source**
  - CO_2 Stripper Vent
    - 97.1% CO_2
    - Partial Pressure: 22.82 psia

Ammonia Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	10.44
Fixed O&M	3.69
Variable O&M	5.54
Consumables	0.20
Purchased Power	6.38
Purchased Natural Gas	0.00
Total Breakeven Cost	26.26

Ethylene Oxide

- **Plant – 364,500 tonnes/year**
  - Rectisol unit assumed to be used in the plant
- **Feed Stock – Ethylene**
- **Point Source**
  - AGR unit CO_2 stream
    - 100% CO_2
    - Partial Pressure: 43.50 psia

Ethylene Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	9.85
Fixed O&M	3.47
Variable O&M	5.20
Consumables	0.27
Purchased Power	5.49
Purchased Natural Gas	0.00
Total Breakeven Cost	24.28

Natural Gas Processing

- **Plant – 500 MMscf/day**
- **Feed Stock – Raw Natural Gas**
  - Can contain 2 to 70 % by volume CO_2
  - Assumed Michigan Basin producing formation containing 10.2 mole percent CO_2
- **Point Source**
  - CO_2 vent
    - 99% CO_2
    - Partial Pressure: 23.27 psia

Natural Gas Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	6.14
Fixed O&M	2.17
Variable O&M	3.25
Consumables	0.13
Purchased Power	5.69
Purchased Natural Gas	0.00
Total Breakeven Cost	17.38

Coal-to-Liquids

- **Plant – 50,000 bbl/day of Liquids**
- **Feed Stock – Coal**
- **Point Source**
  - AGR unit CO_2 stream
    - 100% CO_2
    - Partial Pressure: 265 psia

CTL Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	3.11
Fixed O&M	1.10
Variable O&M	1.65
Consumables	0.14
Purchased Power	2.65
Purchased Natural Gas	0.00
Total Breakeven Cost	8.66

Gas-to-Liquids

- **Plant – 50,000 bbl/day of Liquids**
- **Feed Stock – Natural Gas**
- **Point Source**
  - AGR unit CO_2 stream
    - 100% CO_2
    - Partial Pressure: 265 psia

GTL Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	3.83
Fixed O&M	1.35
Variable O&M	2.03
Consumables	0.14
Purchased Power	1.93
Purchased Natural Gas	0.00
Total Breakeven Cost	9.29

Industrial Processes – Lower Purity Sources

Refinery Hydrogen

- **Plant – 59,000 tonnes/year Hydrogen production**
- **Feed Stock – Natural gas and refinery off gas**
- **Point Source**
  - PSA tail gas
    - 44.5% CO_2
    - Partial Pressure: 8.90 psia

Refinery Hydrogen Breakeven Cost Breakout	
	\$/tonne CO_2
Capital Charges	41.37
Fixed O&M	12.57
Variable O&M	18.86
Consumables	2.71
Purchased Power	11.24
Purchased Natural Gas	25.88
Total Breakeven Cost	112.64

Steel/Iron Process

- **Plant – 2.54 million tonnes/year from BOF plant**
  - Arc Furnace produces much less CO_2 per pound of steel
- **Feed Stock – 75% raw material, 25% recycled steel**
- **Point Sources**
  - Coke oven gas (COG) power stack (PPS)
    - Blast furnace stove (BFS) PPS could have also been used
    - 23.2% CO_2
    - Partial Pressure: 3.41 psia
  - COG+ BFS combined
    - 26.4% CO_2
    - Partial Pressure: 3.88 psia

Steel/Iron Process Continued

Steel/ Iron Breakeven Cost Breakout $/tonne CO_2			
	Combined	Steel/Iron COG + BFS	Steel/Iron COG PPS
Capital Charges	33.66	34.48	33.49
Fixed O&M	10.23	10.47	10.17
Variable O&M	15.34	15.71	15.26
Consumables	2.67	2.67	2.67
Purchased Power	10.20	10.26	10.17
Purchased Natural Gas	27.27	27.72	27.08
Total Breakeven Cost	99.36	101.31	98.84

Sensitivities
Cement

- **Plant – 992,500 tonne/year**
- **Feed Stock – Various**
- **Point Source**
  - Kiln Off-gas
    - 22.4% CO_2
    - Partial Pressure: 3.29 psia
  - Kiln off-gas may have higher that acceptable levels of SO_x/No_x requiring addition of selective catalytic reduction (SCR) and flue gas desulfurization (FGD).
    - A sensitivity to this case was performed, and the results show that the addition of SCR and FGD has the potential to add $26.43/tonne to the retrofit costs.

Sensitivities
Cement Continued

	Cement	Purity Sensitivity
	\$/tonne CO_2	\$/tonne CO_2
Capital Charges	32.89	45.33
Fixed O&M	9.99	13.76
Variable O&M	14.99	20.64
Consumables	2.54	5.41
Purchased Power	9.45	9.90
Purchased Natural Gas	25.80	25.80
Total Breakeven Cost	95.66	120.83