Greenhouse Gas Emissions Life Cycle Analysis of Carbon Capture and Storage for Industrial Sources in the Midwest-Northeast United States

J.R. Sminchak, B.L. Webster, J.B. Hawkins
Battelle, Columbus, Ohio, USA

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MRCI
Midwest Regional Carbon Initiative

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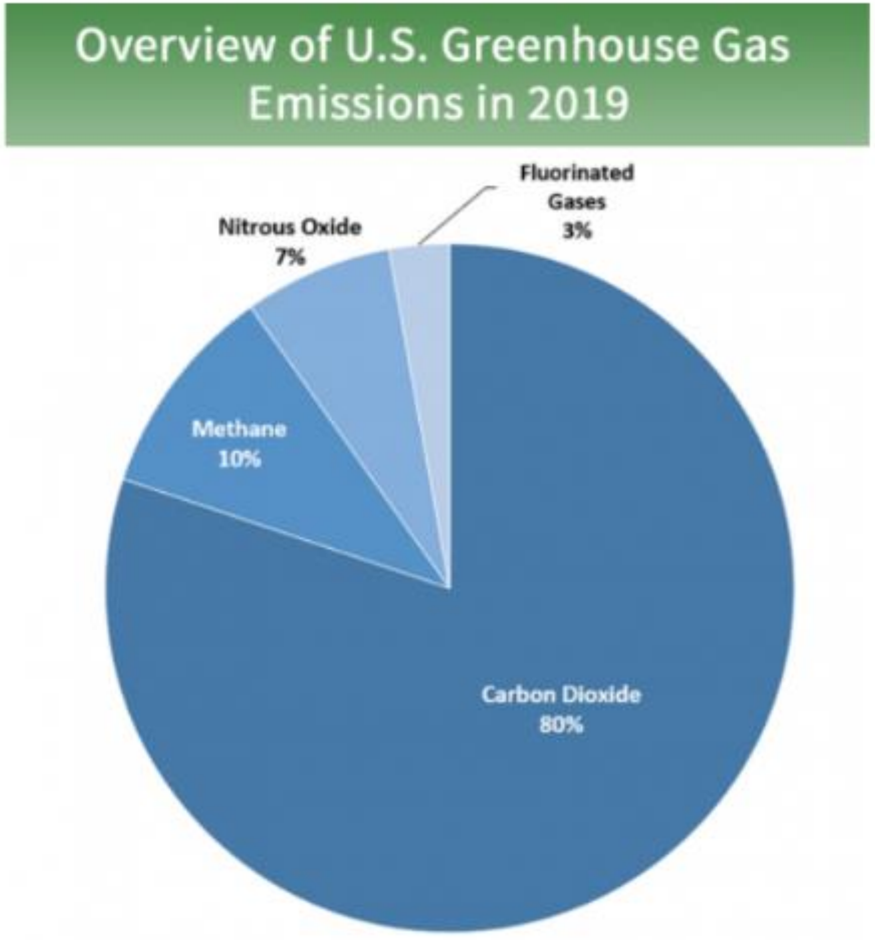
GHG Life Cycle Background

- Life cycle analysis accounts for all greenhouse gas emissions generated for a process.
- Emissions expressed as CO_2 equivalent (**kg CO_2e**).
- 1 kg methane ~ 25 kg CO_2e
- Example: Crude oil transport, refining, fuel transport, and combustion of fuel products from 1 barrel (160 L or 130 kg) of oil has ~470 kg CO_2e emission factor.
- LCA helps understand the net benefit of carbon capture and storage projects.



US 2019 Total Emissions = 6,558 Million Metric tons CO_2 e

USEPA- Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2016. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Carbon Storage GHG LCA

Life Cycle Analysis Questions:

- How much greenhouse gas emissions were emitted through Carbon Capture Utilization and Storage operations?
  - capture, compression, pipeline transport, drilling, injection, fugitive emissions, embodied emissions, land use, etc.
- How CO_2 much was left in the ground?
- What is the net carbon balance?

Example: CO_2 GHG Emissions LCA
480,000,000 kg/yr Gas Processing Source

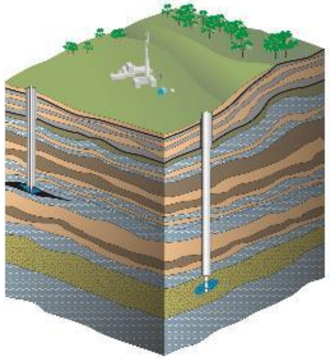
Emissions from construction, operations, materials

Capture
+42,000,000 kg CO_2e/year

Compression
+18,000,000 kg CO_2e/year

Injection
+2,000,000 kg CO_2e/year

CO_2 Storage
480,000,000 kg CO_2e/year



Net Storage = 480,000 t/yr – 62,000 t/yr **= 418,000 t/yr**
418,000/480,000 t/year = 87%

MRCI CCS Scenario GHG Life Cycle Analysis

Objectives:

1. Evaluate potential greenhouse gases generated for CCUS facilities in the Midwest-NE U.S.
2. Account for CO_2e emissions for carbon capture, transport, and storage operations in relation to volume of CO_2 stored underground.
3. Integrate MRCI specific factors on CO_2 sources, geology, and geographic location.

Endproduct: Greenhouse gas life cycle guidance for developing CCUS in the MRCI region in terms of maximizing net CO_2 storage effectiveness.

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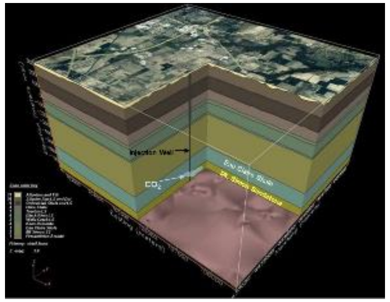

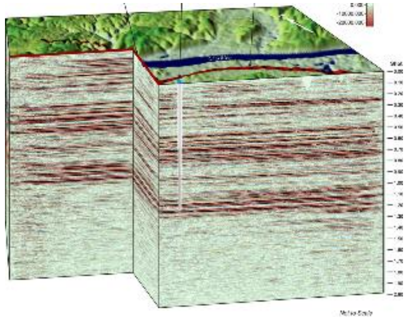

Midwest Regional Carbon Initiative (MRCI)

- This work was supported through the Midwest Regional Carbon Initiative (DE-FE0031836), a US-DOE regional initiative to accelerate CCUS deployment in the Midwestern and Northeastern US.
- Builds on more than 20 years of CCUS experience in the region.

MRCI Midwest Regional Carbon Initiative

www.midwestCCUS.org

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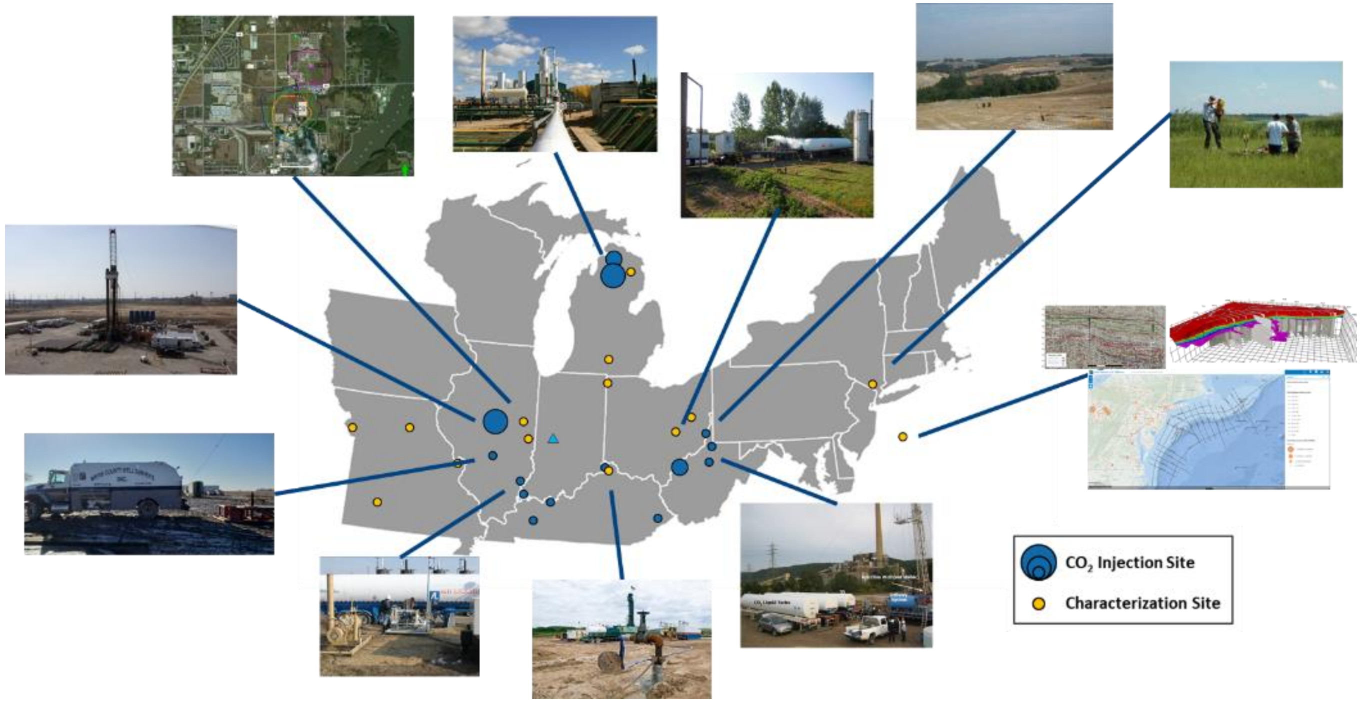

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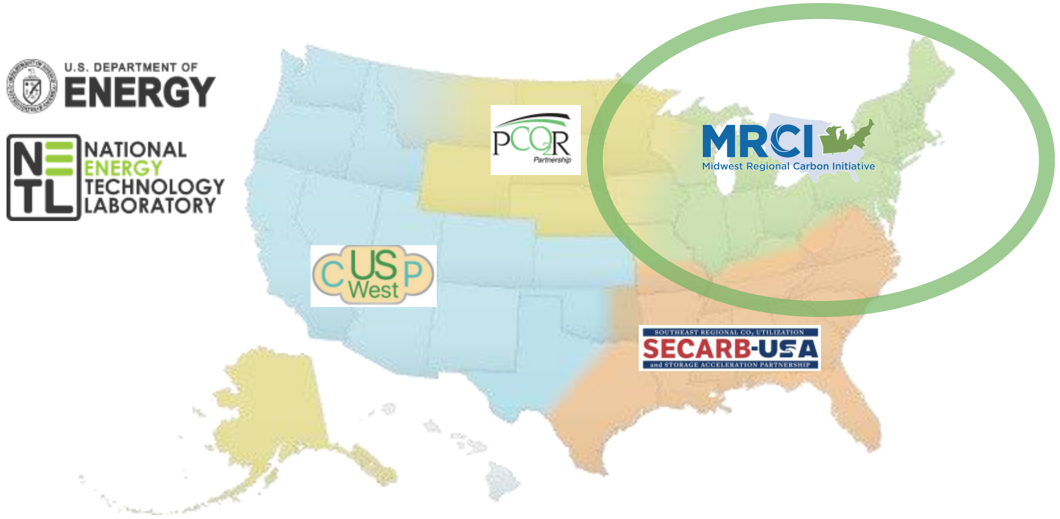
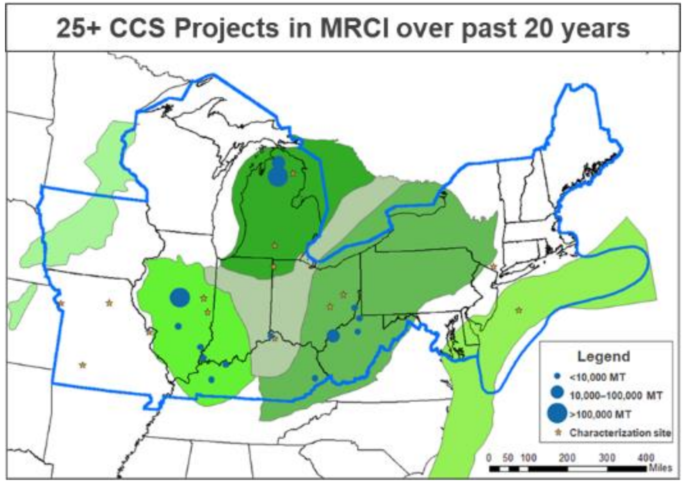
Midwest Regional Carbon Initiative

MRCI Region At a Glance:

- 20 States
- 39% of U.S. Population
- 22% of US. Continental Land Area
- 45% of U.S. GDP
- 38% of U.S. CO_2 Emissions
- 35% of CO_2 emissions in MRCI region are from Electric Power Generation.*





(*based on 2018 USEA data)

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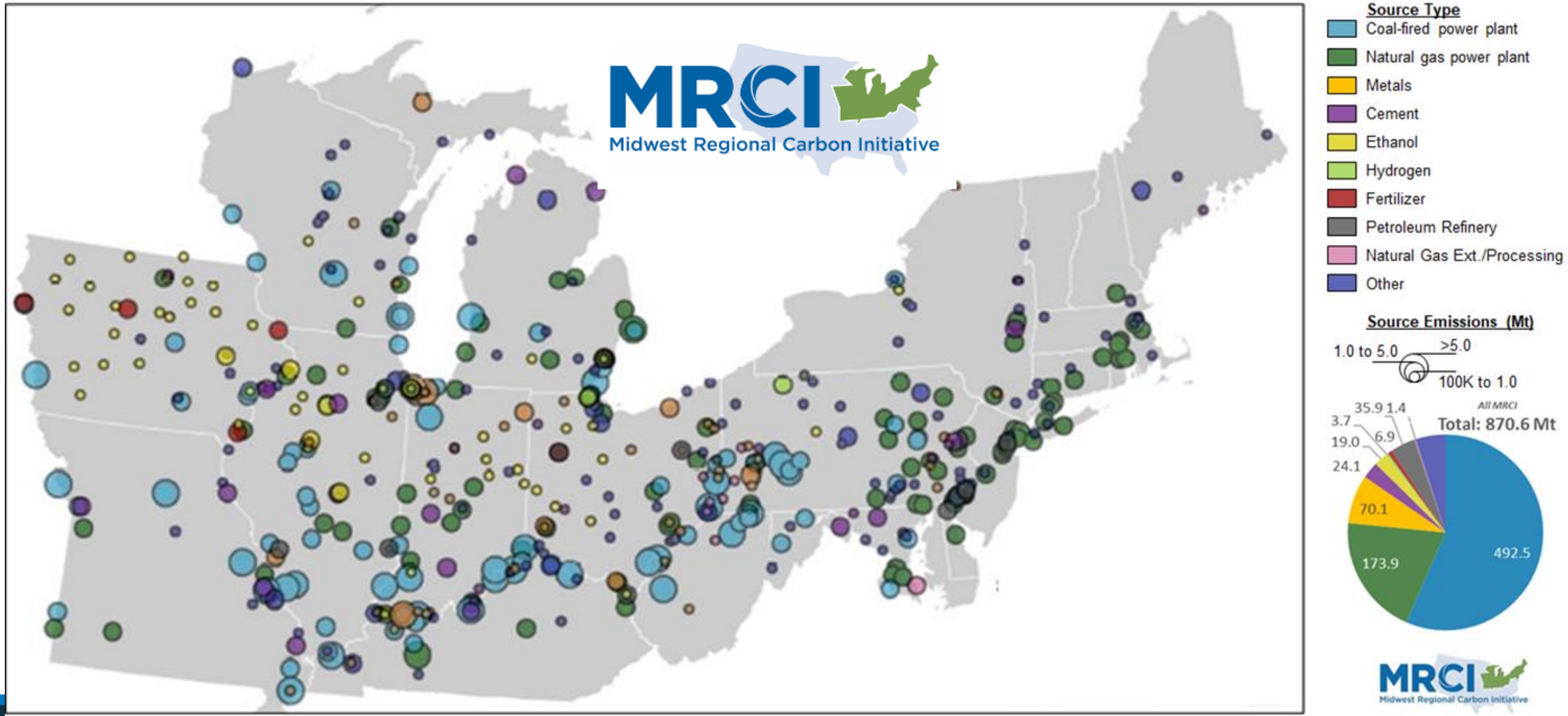
MRCI CCS Scenario GHG Life Cycle Analysis

- Greenhouse gas life cycle model applied for capture, compression, transport, and injection activities. Eight scenarios were evaluated:
  - ● Ethanol Plant (108) ● Natural Gas Power (192) ● Direct Air Capture (0) ● CO_2-EOR(1)
  - ● Hydrogen (16) ● Petroleum refinery (21) ● Cement Plant (32) ● Fertilizer/Ammonia(7)



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MRCI CCS Scenario GHG Life Cycle Analysis

- A streamlined, energy & emissions based LCA model* was applied for CCS operations that may contribute to greenhouse gas emissions.
- The model includes general process level capture parameters with more detailed parameters for CO_2 compression, transport, and injection.
- The model does not account for produced materials (like cement or fertilizer or H_2).

SEGMENT	PARAMETER DESCRIPTION	UNITS	LOW VALUE	EXPECTED	HIGH VALUE	SOURCE	NOTES	LOW-EMISSION	BASE CASE	HIGH-EMISSION
GATE-TO-GATE CO2 CAPTURE										
Capture	CO_2 Emissions	kg CO_2/yr	1,000,000,000	2,000,000,000	3,000,000,000	Source Survey		1,000,000,000	2,000,000,000	3,000,000,000
Capture	CO_2 capture efficiency	%	99%	99%	99%	Estimated		99%	99%	99%
Capture	CO_2 captured for transport to CS system	kg CO_2/yr				Derived		990,000,000	1,980,000,000	2,970,000,000
Capture	Fugitive CO_2 emissions from plant capture system	kg CO_2/yr	0.00E+00	0.00E+00	0.00E+00	Derived		0	0	0
Capture	Electricity for CO_2 captured for transport to CO_2 Storage	MWh / kg CO_2	0.00000	0.00000	0.00000		IPCC Report p. 117	0.00000	0.00000	0.00000
Capture	ife-cycle emission factor of the electricity used for captur	kg CO_2e / MWh		500		Literature	Nat gas emissions	500	500	500
Capture	CO_2 emissions from capture operations	kg CO_2/yr				Derived	Derived	0	0	0
Capture	Land area of CO2 capture facility	acre	10	20.0	30	Literature	Cooney et al. (2015)	10.0	20.0	30.0
Capture	Land area of CO2 capture facility	m^2				Derived	Derived from unit conversi	40,469	80,937	121,406
Capture	CO2 capture facility construction	kg CO_2e		755000		Literature	Taken from Cooney et al. (	755000	1510000	2265000
Capture								**755,000**	**1,510,000**	**2,265,000**
GATE-TO-GATE TRANSPORT OF CO_2 (ELECTRICITY)										
Transport	ctricity needed per tonne of CO_2 transported (100 to 1000	kWh / tonne		6.50		Literature	No pipeline pumping nee	6.50	6.50	6.50
Transport	ectricity needed per kg of CO_2 transported (100 to 1000 km	MWh / kg				Derived	Unit conversion from kWh	6.50E-06	6.50E-06	6.50E-06
Transport	Kilograms of $CO_{2\ \text{routed via pipeline}}$	kg				Derived	Derived from incremental	990,000,000	1,980,000,000	2,970,000,000
Transport	Energy needed to pipeline CO_2	MWh				Derived	Derived from the electricit	6,435	12,870	19,305
Transport	emission factor of the electricity used for pipeline transp	kg CO_2e / MWh		660		Literature	2010 U.S. mix, delivered	660	660	660
Transport	Emissions from pipeline electricity needs	kg CO_2e				Derived	Derived from the life-cycle	4,247,100	8,494,200	12,741,300
GATE-TO-GATE PIPELINE TRANSPORT OF CO_2 (FUGITIVE EMISSIONS AND SERVICES)										
Transport	Pipeline distance	km	20	40	60	Estimate	Estimate	20	40	60
Transport	itive emissions factor from pipeline transport of CO_2 (lea	kg CO_2 / km-yr	7.5	75	282	Literature	API (2009); Lamb et al. (201	7	75	282
Transport	itive emissions factor from pipeline transport of CO_2 (lea	kg CO_2 / yr				Derived	Derived from the fugitive	149	2,985	16,915
Transport	ive emissions factor from pipeline transport of CO_2 (serv	kg CO_2 / service-yr	0.36	3.6	5.5	Literature	API (2009); Lamb et al. (201	0.36	4	5
Transport	Number of pipeline services per year	services / year	10	15	20	Estimate	Estimate	10	15	20
Transport	ive emissions factor from pipeline transport of CO_2 (serv	kg CO_2 / yr				Derived	Derived from the fugitive	4	55	109
Transport	CO_2-EOR project duration	yr	1	1	1	1 year	1 year	1	1	1
Transport	Fugitive emissions from pipeline transport of CO_2	kg CO_2				Derived	Derived from the fugitive	153	3,040	17,024
GATE-TO-GATE TRANSPORT								**4,247,253**	**8,497,240**	**12,758,324**
Note: This portion of the model is taken directly from DOE NETL (2013a) and Cooney et al. (2015). The fluid balances come from the industry data set work of Azzolina et al. (2015).										
GATE-TO-GATE CARBON STORAGE: LAND USE										
Gate-to-Gate	Land area of CO2 processing facility	acre	10	20	30	Literature	Cooney et al. (2015)	10.0	20.0	30.0
Gate-to-Gate	Land area of CO2 processing facility	m^2				Derived	Derived from unit conversi	40,469	80,937	121,406
Gate-to-Gate	Well footprint	acre		2.5		Literature	Cooney et al. (2015)	2.5	2.5	2.5
Gate-to-Gate	Well footprint	m^2				Derived	Derived from unit conversi	10,117	10,117	10,117
Gate-to-Gate	Number of wells	count	2	4	6	System Data	1 Injection well	2	4	6
Gate-to-Gate	Total footprint of all wells	m^2				Derived	Derived from the well foot	20,234	40,469	60,703
Gate-to-Gate	otal land area repurposed (gas processing facility + wells	m^2				Derived	Derived from land area of	60,703	121,406	182,109
Gate-to-Gate	Emissions per sq meter of repurposed land	kg CO_2e / m^2		7.5		Literature	Derived from Cooney et al	7.5	7.5	7.5
Gate-to-Gate	CO_2 emissions	kg CO_2e				Derived	Derived from the land are	453,000	906,000	1,359,000
GATE-TO-GATE CARBON STORAGE: CONSTRUCTION (NOT CURRENTLY MODELED TAKEN DIRECTLY FROM COONEY ET AL. [2015])										
Gate-to-Gate	Injection well construction	kg CO_2e/ well		362400		System Data	Taken from Cooney et al. (	724800	1449600	2174400
Gate-to-Gate	CO2 gas processing facility construction	kg CO_2e		755000		Literature	Taken from Cooney et al. (	755000	1510000	2265000
Gate-to-Gate	CO_2 emissions	kg CO_2e				Derived	Derived from the CO_2 emis	1,479,800	2,959,600	4,439,400
GATE-TO-GATE CARBON STORAGE: WELL OPERATIONS – CO_2 COMPRESSION AND INJECTION ELECTRICTIY										
Gate-to-Gate	Total CO2 Injected	kg Co2/year				Input	Input	989,999,847	1,979,996,960	2,969,982,976
Gate-to-Gate	Compressor power factor	MW/[tonne CO_2/day]		2.70E-03		Literature	NA, Cooney et al. (2015)	2.70E-03	2.70E-03	2.70E-03
Gate-to-Gate	Compressor power	MW				Derived	NA,Derived from the comp	2,673,000	5,345,992	8,018,954
Gate-to-Gate	Natural Gas Compressor Fuel Usage	MCF/kg CO2		0.50		Derived	ed on MRCSP operational	5.00E-01	5.00E-01	5.00E-01
Gate-to-Gate	Compressor energy	MCF				System Data	ed on MRCSP operational	495,000,000	990,000,000	1,485,000,000
Gate-to-Gate	CO_2 emissions	kg CO_2e				Derived	Derived from MCF	27,052,641	54,105,282	81,157,923
Gate-to-Gate	CO_2 pump power factor	MW/[tonne injected CO_2/day]	5.57E-05	1.91E-04	1.90E-04	System Data	Cooney et al. (2015)	1.91E-04	5.57E-05	1.90E-04
Gate-to-Gate	CO_2 pump power	MW				Derived	Derived from the pump po	189090	110286	376199
Gate-to-Gate	CO_2 pump energy	MWh				Derived	Derived from the pump po	69,017,839	40,254,328	137,312,789
Gate-to-Gate	CO_2 emissions (total)	kg CO_2e				Derived	Derived from the sum of c	27,052,641	54,105,282	81,157,923
GATE-TO-GATE CARBON STORAGE: WELL OPERATIONS – CO_2 COMPRESSOR FUGITIVE EMISSIONS										
Gate-to-Gate	Compressor CO_2 emissions rate (direct to atmosphere)	kg CO_2e / MW-day		63.6		Literature	NA,Cooney et al. (2015)	63.6	63.6	63.6
Gate-to-Gate	Compressor CO_2 emissions (direct to atmosphere)	kg CO_2e				System Data	Subpart C Core forms	465,964	931,926	1,397,883
GATE-TO-GATE CARBON STORAGE: OPERATIONS – FACILITY ELECTRICITY										
Gate-to-Gate	Facility electricity rate	kWh / kg CO2 injected		4.56E-03		Literature	Based on	0.00456	0.00456	0.00456
Gate-to-Gate	Facility electricity	kWh				System Data	ed on MRCSP operational	4,514,399	9,028,786	13,543,122
Gate-to-Gate	Facility electricity	MWh				Derived	Unit conversion from kWh	4,514	9,029	13,543
Gate-to-Gate	CO_2 emissions	kg CO_2e				Derived	Derived from the MWh an	2,979,504	5,958,999	8,938,461
CARBON STORAGE EMISSIONS								**32,430,908**	**64,861,806**	**97,292,666**
CO_2 INJECTED IN RESERVOIR		kg CO_2						**989,999,847**	**1,979,996,960**	**2,969,982,976**
CO2 LEAKAGE FROM STORAGE OVER 100-YEAR TIMEFRAME		kg CO_2	0.00%	0.00%	0.00%			**0.0**	**0.0**	**0.0**
CO_2 STORED IN RESERVOIR		kg CO_2						**989,999,847**	**1,979,996,960**	**2,969,982,976**
CO_2 CAPTURE LCA EMISSIONS		kg CO2e						**755,000**	**1,510,000**	**2,265,000**
CO_2 TRANSPORT LCA EMISSIONS		kg CO_2e						**4,247,253**	**8,497,240**	**12,758,324**
CO_2 STORAGE EMISSIONS		kg CO_2e						**32,430,907.9**	**64,861,806.4**	**97,292,666.2**
GATE-TO-GATE: LCA GHG EMISSIONS		kg CO_2e						**37,433,160.8**	**74,869,046.1**	**112,315,990.4**
GATE-TO-GATE: CO_2 NET STORAGE BALANCE		kg CO_2e						**952,566,686.3**	**1,905,127,914.3**	**2,857,666,985.4**
GATE-TO-GATE: CO2 STORAGE EMISSION FACTOR PER METRIC TON CO2 Storage		kg CO_2e / metric ton CO2						**37.8**	**37.8**	**37.8**

*Sminchak et al, 2020 https://pubs.acs.org/doi/10.1021/acs.energyfuels.9b04540
Azzolina et al, 2016 https://doi.org/10.1016/j.ijggc.2016.06.008

MRCI CCS Scenario GHG Life Cycle Analysis

- Key input:
  - source size (based on existing sources in MRCI),
  - energy for capture,
  - compression requirements,
  - pipeline transport distances,
  - fugitive emissions.

Source	Count in MRCI	Source Size	Emissions (metric tons CO_2/yr)
Ethanol Plant	108	Low	22,000
		Average	215,000
		High	4,327,000
Natural Gas Power Plant	192	Low	500,000
		Average	1,500,000
		High	3,800,000
Direct Air Capture	0 (source size based on literature)	Low	50,000
		Average	200,000
		High	500,000
Hydrogen Plant	16	Low	80,000
		Average	400,000
		High	1,500,000
CO2-EOR	1	Low	NA
		Average	94,954
		High	NA
Cement Plants	32	Low	160,000
		Average	760,000
		High	3,250,000
Refineries	21	NA	NA
Ammonia/Fertilizer Plant	7	Low	500,000
		Average	1,000,000
		High	1,500,000

MRCI CCS Scenario GHG Life Cycle Analysis

- Results reflect net CO_2 stored versus emissions generated from capture, compression, transport, injection. Also, economies of scale.
- Sources that integrate capture and compression have highest net storage%.

GHG LCA Net CO_2 Storage

- **Ethanol Plant with CS (82-90%)**
- **Natural Gas Power Plant (71-76%)**
  (accounting for displaced electricity)
- **Direct Air Capture Plant (59-90%)**
  (depending on energy source for capture)
- **Hydrogen Plant (88-90%)**
- **Petroleum refinery (NA)**
- **Cement Plant (90-91%)**
  (new facility)
- **Fertilizer/Ammonia Plant (87-88%)**
- **CO2-EOR (59-66%)**
  (not including downstream combustion of fuel products)

Input Fields

SEGMENT	SUB-SEGMENT	PARAMETER DESCRIPTION	UNITS	1 Ethanol Plant with CS LOW VALUE	AVG	HIGH VALUE	2 Natural Gas Power Plant LOW VALUE	AVG	HIGH VALUE	3 Direct Air Capture LOW VALUE	AVG	HIGH VALUE
Capture	Capture plant	CO_2 Emissions Routed to Capture	kg CO_2/yr	22,000,000	215,000,000	4,327,000,000	500,000,000	1,500,000,000	3,800,000,000	50,000,000	200,000,000	500,000,000
Capture	Capture plant	CO_2 capture efficiency (CO2 Captured/CO2 emssions routed to capture)	%	99%	99%	99%	90%	90%	90%	100%	100%	100%
Capture	Capture plant	Electricity for CO_2 captured for transport to CO_2 Storage	MWh / kg CO_2	0.00010	0.00012	0.00013	0.00045	0.00050	0.00056	0.00021	0.00034	0.00047
Capture	Capture plant	Fugitive CO_2 emissions from plant capture system	kg CO_2/yr	6.60E+04	1.29E+06	4.33E+07	1.50E+06	9.00E+06	3.80E+07	1.50E+05	1.20E+06	5.00E+06
Compression	Compression	Electricity for CO2 compression	MCF/kg CO2	Included in capture			Included in capture			1.13	1.13	1.13
Transport	Pipeline transport of CO_2	Pipeline distance	km	50	100	150	50	100	200	100	150	250
Gate-to-Gate	Land use	Land area of CO2 processing facility	acre	10	20	30	10	20	30	12	20	40
Gate-to-Gate	Land use	Number of wells	count	1	2	3	3	4	6	6	10	20
Notes				Assumes neglible CO2 capture & processing			Assumes Nat. Gas Plant near sedimentary basin			Assumes more pipeline & injection wells for larger capture, no emissions for capture, emissons for compression		

PARAMETER DESCRIPTION	4 Hydrogen Plant LOW VALUE	AVG	HIGH VALUE	5 Petroleum refinery LOW VALUE	AVG	HIGH VALUE	6 Cement Plants LOW VALUE	AVG	HIGH VALUE
CO_2 Emissions Routed to Capture	80,000,000	400,000,000	1,500,000,000	1,000,000,000	3,000,000,000	5,000,000,000	160,000,000	760,000,000	3,250,000,000
CO_2 capture efficiency (CO2 Captured/CO2 emssions routed to capture)	99%	99%	99%	90%	90%	90%	90%	90%	90%
Electricity for CO_2 captured for transport to CO_2 Storage	0.00015	0.00016	0.00018	0.00030	0.00040	0.00050	0.00013	0.00014	0.00015
Fugitive CO_2 emissions from plant capture system	2.40E+05	2.40E+06	1.50E+07	0.00E+00	0.00E+00	0.00E+00	4.80E+05	4.56E+06	3.25E+07
Electricity for CO2 compression	cluded in capture			Included in capture			Included in capture		
Pipeline distance	20	40	60	20	40	60	50	100	200
Land area of CO2 processing facility	10	20	30	10	20	30	10	20	30
Number of wells	2	4	6	2	4	6	2	4	6
Notes	Assumes minimal emissions for capture b/c CO2 byproduct of H2 generation			Assumes capture similar to nat. gas			Assumes capture similar to nat. gas, longer pipeline as cement plants are not aligned with sedimentary basins		

PARAMETER DESCRIPTION	7 Ammonia/Fertilizer LOW VALUE	AVG	HIGH VALUE	CO2-EOR LOW VALUE	AVG	HIGH VALUE	CO2-EOR w/storage AVG
CO_2 Emissions Routed to Capture	500,000,000	1,000,000,000	1,500,000,000	71,272,000	133,182,000	164,590,000	94,954,545
CO_2 capture efficiency (CO2 Captured/CO2 emssions routed to capture)	99%	99%	99%				
Electricity for CO_2 captured for transport to CO_2 Storage	0.00008	0.00009	0.00010				
Fugitive CO_2 emissions from plant capture system	1.50E+06	6.00E+06	1.50E+07				
Electricity for CO2 compression	Included in capture						
Pipeline distance	10	20	30				
Land area of CO2 processing facility	10	20	30				
Number of wells	2	4	6				
Notes	Assumes minimal emissions for capture b/c CO2 byproduct of H2 generation			*based on Azzolina et al 2016 gate-to-gate LCA for CO2-EOR gate-to-gate only			*based on Sminchak 2020 LCA for CO2-EOR including upstream, gate-to-gate, downstream

Output Results

Output	Units	Ethanol LOW	AVG	HIGH	Nat. Gas LOW	AVG	HIGH	DAC LOW	AVG	HIGH
CO_2 INJECTED IN RESERVOIR	kg CO_2	21,779,623	212,842,483	4,283,687,604	449,999,623	1,349,992,483	3,419,943,508	49,999,250	199,988,752	499,929,412
CO2 LEAKAGE FROM STORAGE OVER 100-YEAR TIMEFRAME	kg CO_2	0	0	0	0	0	0	0	0	0
CO_2 STORED IN RESERVOIR	kg CO_2	21,779,623	212,842,483	4,283,687,604	449,999,623	1,349,992,483	3,419,943,508	49,999,250	199,988,752	499,929,412
CO_2 CAPTURE LCA EMISSIONS	kg CO2e	2,276,115	18,027,160	367,924,193	102,997,250	342,317,500	951,981,900	7,538,388	46,243,691	158,099,580
CO_2 TRANSPORT LCA EMISSIONS	kg CO_2e	93,813	920,644	18,419,598	1,930,877	5,799,017	14,728,292	215,250	869,248	2,215,588
CO_2 STORAGE EMISSIONS	kg CO_2e	1,570,699	3,730,549	19,393,090	3,936,820	8,563,938	17,700,727	7,157,637	19,540,321	45,604,156
GATE-TO-GATE: LCA GHG EMISSIONS	kg CO_2e	3,940,627	22,678,353	405,736,881	108,864,947	356,680,456	984,410,920	14,911,275	66,653,261	205,919,323
CO_2 NET STORAGE BALANCE	kg CO_2e	17,838,996	190,164,130	3,877,950,722	341,134,676	993,312,027	2,435,532,588	35,087,975	133,335,491	294,010,089
CO2 STORAGE EMISSION FACTOR PER METRIC TON CO2 Storage	kg CO_2e / metric ton CO2	181	107	95	242	264	288	298	333	412
Net %CO2 Storage	Net Storage/CO2 Captured	82%	89%	91%	76%	74%	71%	70%	67%	59%

Output	Hydrogen LOW	AVG	HIGH	Petroleum LOW	AVG	HIGH	Cement LOW	AVG	HIGH
CO_2 INJECTED IN RESERVOIR	79,199,847	395,996,960	1,484,982,976	899,999,847	2,699,996,960	4,499,982,976	143,999,623	683,992,483	2,924,943,508
CO2 LEAKAGE FROM STORAGE OVER 100-YEAR TIMEFRAME	0	0	0	0	0	0	0	0	0
CO_2 STORED IN RESERVOIR	79,199,847	395,996,960	1,484,982,976	899,999,847	2,699,996,960	4,499,982,976	143,999,623	683,992,483	2,924,943,508
CO_2 CAPTURE LCA EMISSIONS	6,564,320	33,784,000	135,395,250	135,755,000	541,510,000	1,127,265,000	9,827,000	49,390,000	227,490,000
CO_2 TRANSPORT LCA EMISSIONS	339,921	1,701,880	6,387,674	3,861,153	11,586,040	19,322,024	618,137	2,941,877	12,604,742
CO_2 STORAGE EMISSIONS	2,208,437	5,243,776	10,966,542	5,065,043	13,262,319	21,459,557	2,433,957	6,246,078	15,977,994
GATE-TO-GATE: LCA GHG EMISSIONS	9,112,678	40,729,656	152,749,466	144,681,196	566,358,359	1,168,046,581	12,879,094	58,577,956	256,072,736
CO_2 NET STORAGE BALANCE	70,087,169	355,267,304	1,332,233,510	755,318,652	2,133,638,602	3,331,936,395	131,120,529	625,414,527	2,668,870,772
CO2 STORAGE EMISSION FACTOR PER METRIC TON CO2 Storage	115	103	103	161	210	260	89	86	88
Net %CO2 Storage	88%	90%	90%	84%	79%	74%	91%	91%	91%

Output	Ammonia/Fertilizer LOW	AVG	HIGH	CO2-EOR LOW	AVG	HIGH	CO2-EOR w/storage AVG
CO_2 INJECTED IN RESERVOIR	494,999,922	989,998,453	1,484,991,433	71,272,000	133,182,000	164,590,000	94,954,545
CO2 LEAKAGE FROM STORAGE OVER 100-YEAR TIMEFRAME	0	0	0	0	604,000	906,000	0
CO_2 STORED IN RESERVOIR	494,999,922	989,998,453	1,484,991,433	71,272,000	133,182,000	164,590,000	94,954,545
CO_2 CAPTURE LCA EMISSIONS	21,381,650	47,347,000	77,896,050	based on gate to gate total			21,748,909
CO_2 TRANSPORT LCA EMISSIONS	2,123,628	4,248,647	6,379,217	based on gate to gate total			included in gate-to-gate
CO_2 STORAGE EMISSIONS	34,225,018	68,450,031	102,675,024	based on gate to gate total			included in gate-to-gate
GATE-TO-GATE: LCA GHG EMISSIONS	57,730,296	120,045,678	186,950,291	28,086,000	44,696,000	64,628,000	17,007,909
CO_2 NET STORAGE BALANCE	437,269,626	869,952,775	1,298,041,142	43,186,000	88,486,000	99,962,000	56,197,727
CO2 STORAGE EMISSION FACTOR PER METRIC TON CO2 Storage	117	121	126	650	505	647	303
Net %CO2 Storage	88%	88%	87%	61%	66%	61%	59%

Learning from LCA of 22 years of CO_2-EOR

- CO_2 EOR operations in N. Michigan in place since 1996, where CO_2 EOR expanded to 10 reefs over 22 years.
- 2.2 million metric tons net CO_2 in reefs thru 2018.
- 2.3 million barrels oil produced (294,326 metric tons).

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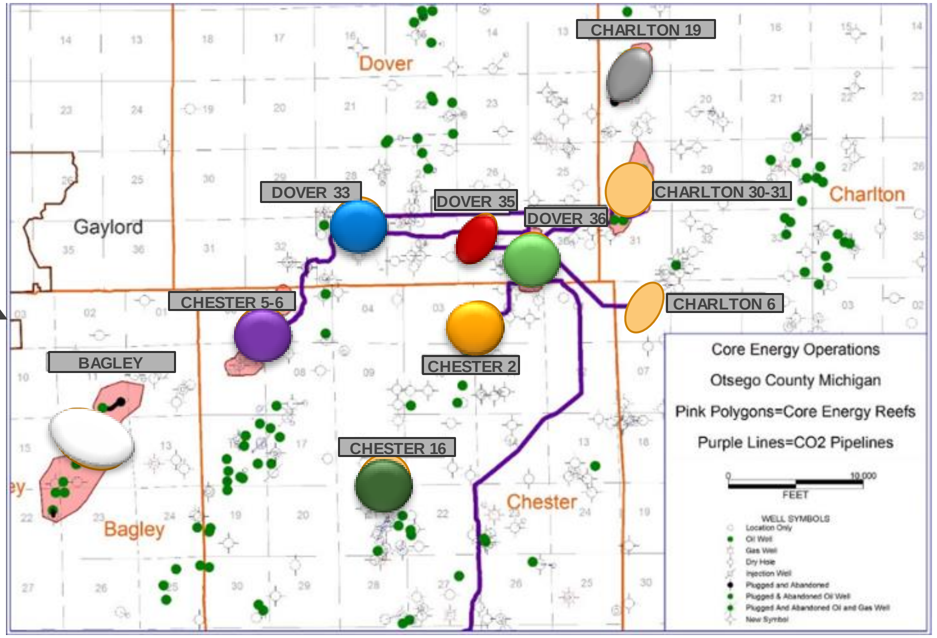
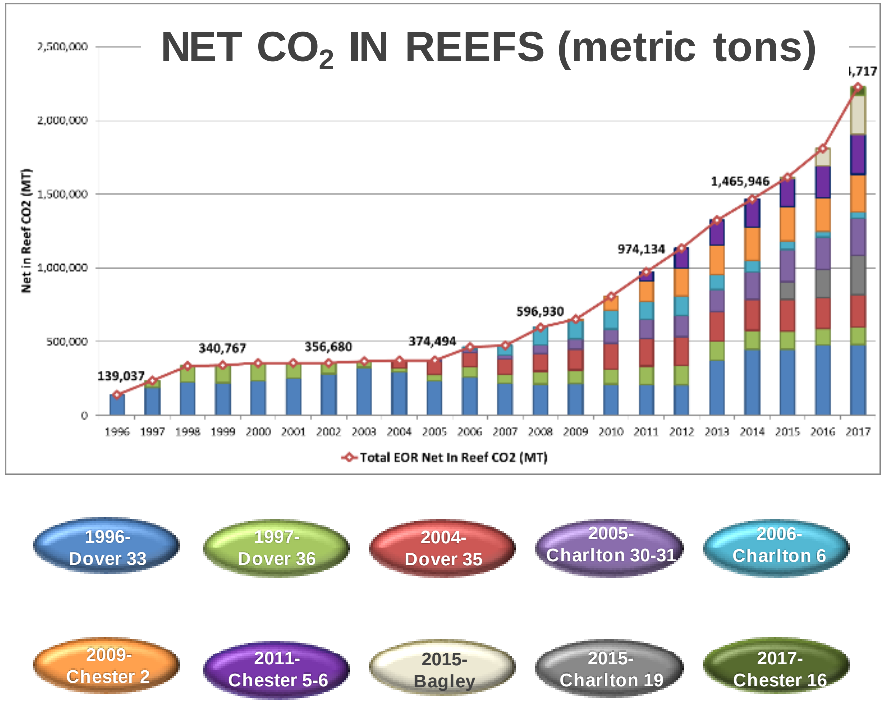
INDEX MAP OF REEFS





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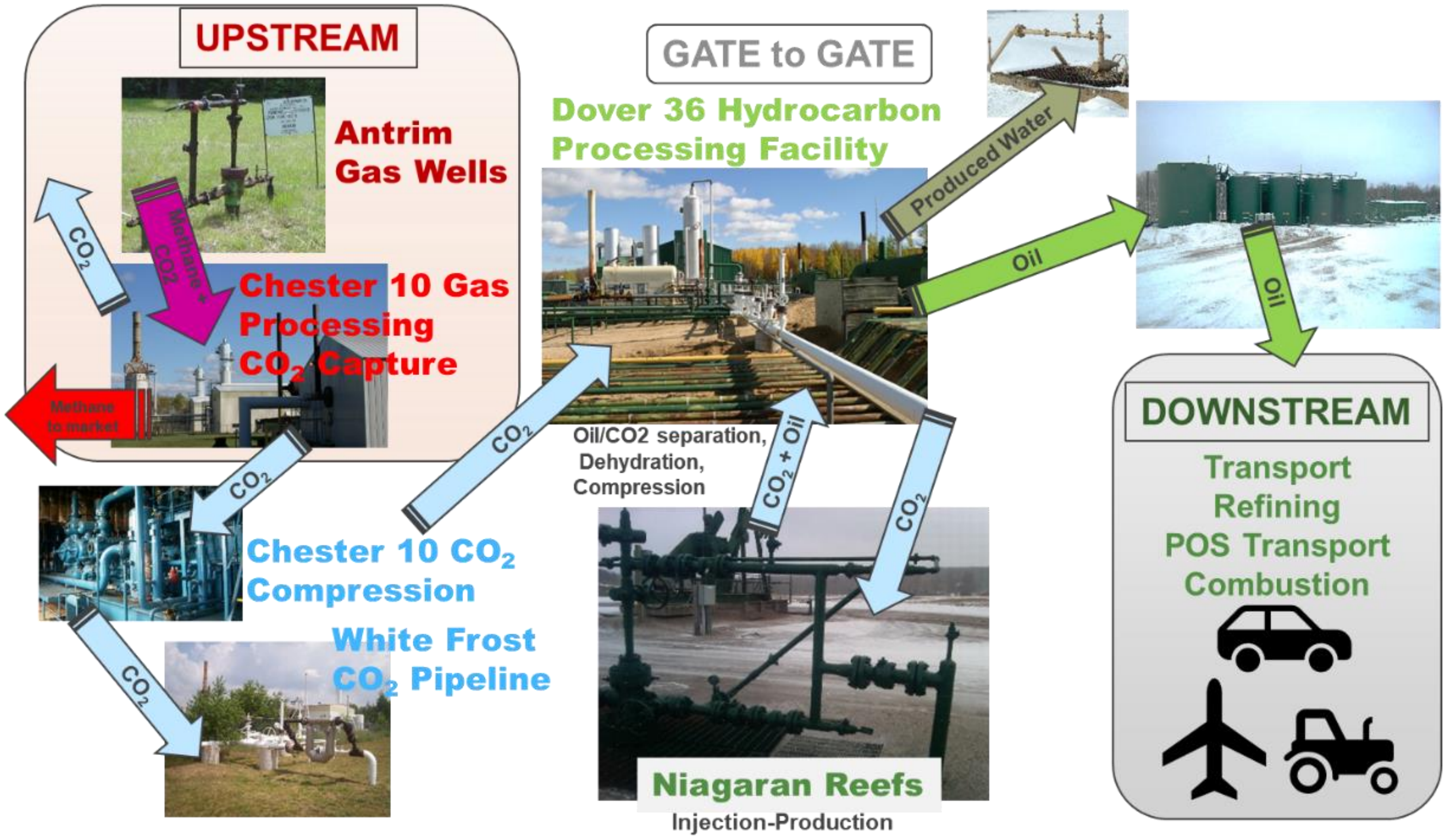
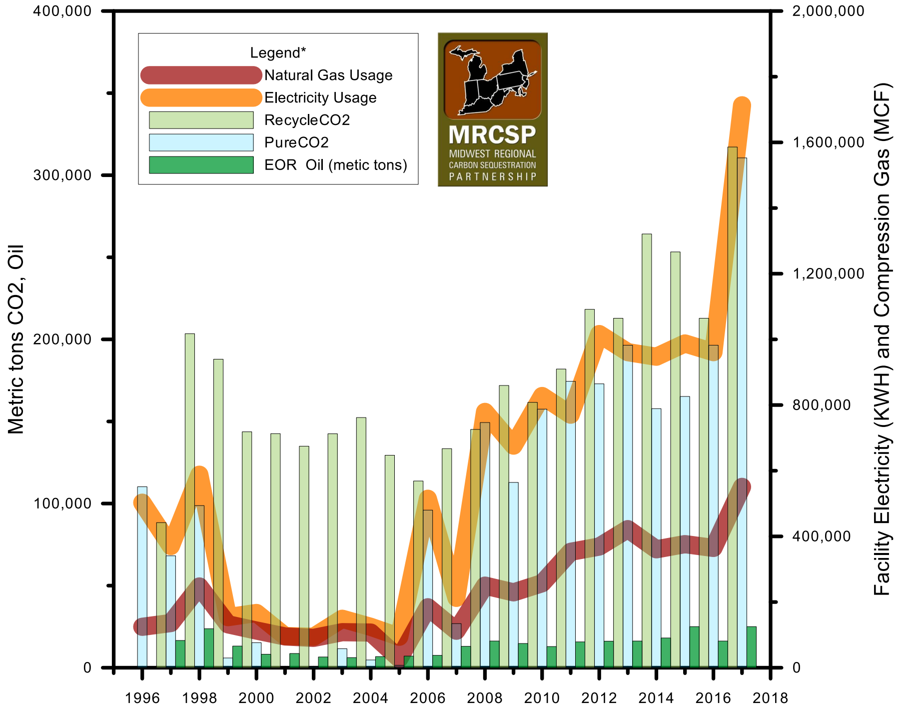
Establishing Boundary Conditions

- CO_2 EOR is part of a bigger hydrocarbon life cycle, including upstream, gate to gate, and downstream components (i.e. "Cradle to Grave.").



Gate-to-Gate Operations Data

- Direct measurements from system monitoring & operations entered into CO_2 EOR LCA model (Azzolina, 2016). Operations trends reflect CO_2-EOR cycles & additional reefs. “Cradle to Grave” results show net negative CO_2 emissions of -159,860 metric tons due to very large volume of CO_2 storage vs oil produced.



*Chester 10 Fulel estimated 1996-2009 based on pure CO2
Chester 10 electricity estimated 1996-2010 based on pure CO2
Dover 36 fuel usage estimated 1996-2004 based on CO2 Recycle
Dover 36 electricity usage estimated 1996-2010 based on CO2 Recycle
Pure CO2 estimated for 1998-2011 based on mass balance

Year	Upstream Capture Emissions* (metric tonnes)	Gate to Gate total Emssions (metric tons)	Downstream Total Emissions (Metric tons)	Total CO2 Associated Storage (metric tonnes)	Net CO2e Emissions (metric tonnes)
1996	22,872	7,166	47	139,037	-108,952
1997	14,142	10,511	60,767	97,026	-11,606
1998	38,543	19,554	86,924	98,763	46,257
1999	1,289	12,025	48,312	5,941	55,684
2000	2,061	9,786	30,084	15,259	26,673
2001	-	8,759	31,757	-12	40,529
2002	72	8,237	24,005	665	31,649
2003	1,174	9,397	22,580	11,585	21,566
2004	528	9,521	24,859	4,728	30,180
2005	175	4,697	26,011	1,500	29,383
2006	19,916	13,308	27,620	87,763	-26,918
2007	5,574	10,042	47,732	14,079	49,269
2008	30,986	18,472	59,543	120,595	-11,594
2009	23,417	17,449	54,040	56,505	38,402
2010	32,682	18,740	47,226	154,237	-55,589
2011	36,195	24,530	57,638	166,463	-48,100
2012	35,879	26,342	59,147	159,857	-38,489
2013	40,759	26,118	59,495	182,417	-56,045
2014	32,740	26,908	66,357	144,313	-18,309
2015	34,280	27,971	91,614	148,202	5,664
2016	40,759	26,118	59,495	182,417	-56,045
2017	64,433	38,495	91,614	298,010	-103,468
Total	478,476	374,147	1,076,867	2,089,350	-159,860

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Results- Total LCA results 1996-2017

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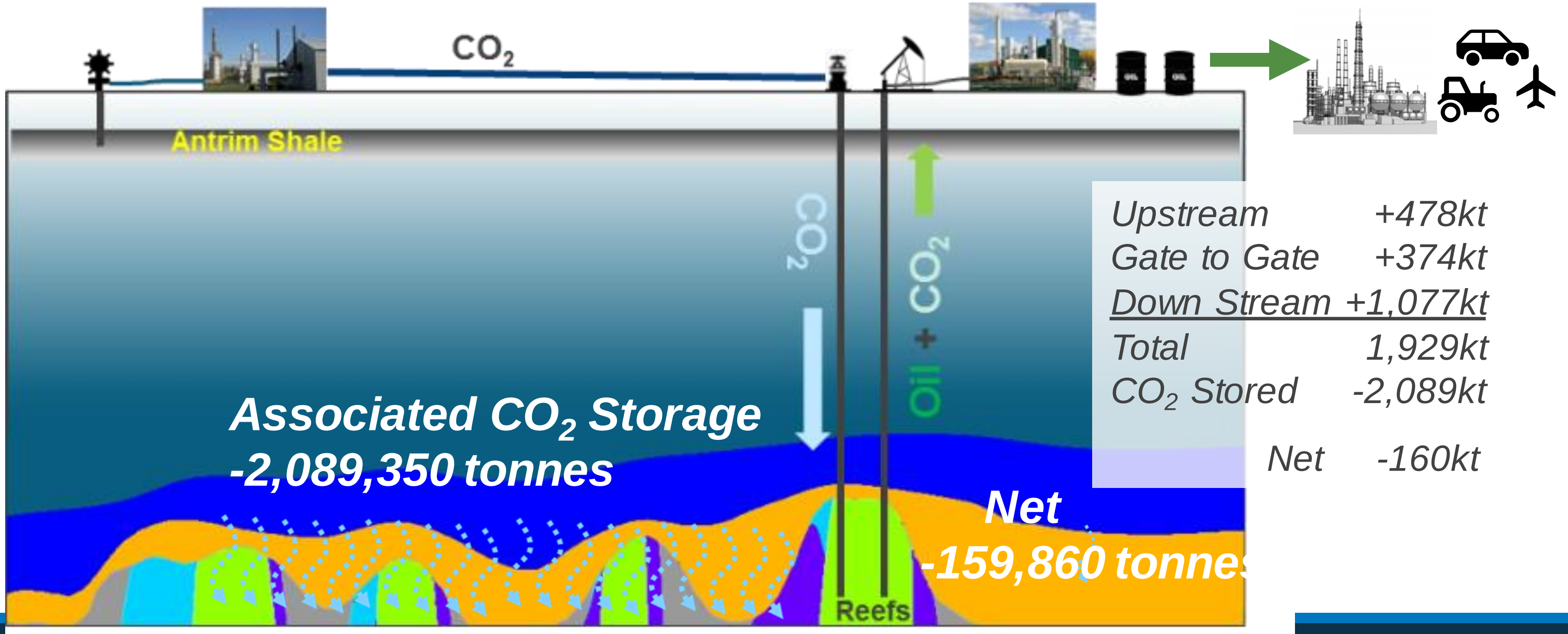
Upstream
CO_2 Capture Plant Operations
478,476 tonnes
CO_2e Generated

Gate to Gate
(compression, EOR, & gas processing)
374,147 tonnes
CO_2e Generated

Downstream
1,076,867
tonnes CO_2e
Generated



Upstream	*+478kt*
Gate to Gate	*+374kt*
Down Stream	*+1,077kt*
Total	*1,929kt*
CO_2 Stored	*-2,089kt*
Net	*-160kt*

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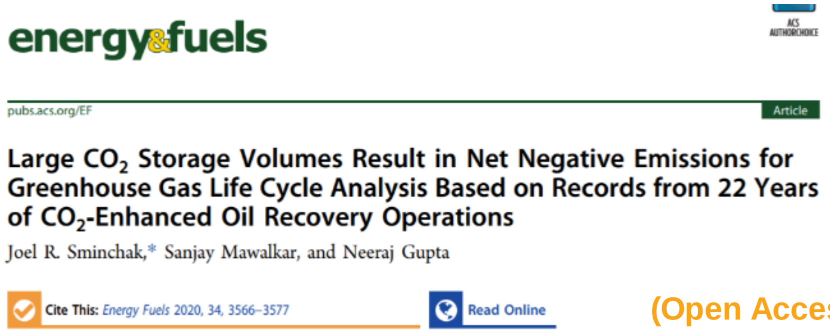
Conclusions: MRCI CCS GHG Life Cycle Analysis

- Greenhouse gas emissions life cycle analysis helps depict the ***net benefits*** of carbon capture and storage.
- Results reflect net CO_2 stored versus emissions generated from capture, compression, transport, injection. Also, economies of scale.
- There are many opportunities for CCS in the MRCI region. Sources that integrate capture and compression have highest net storage%.
- CCS LCA emissions are likely to change over time as operations are optimized to reduce emissions.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Large CO_2 Storage Volumes Result in Net Negative Emissions for Greenhouse Gas Life Cycle Analysis Based on Records from 22 Years of CO_2-Enhanced Oil Recovery Operations

Joel R. Sminchak,* Sanjay Mawalkar, and Neeraj Gupta

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Thanks!