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



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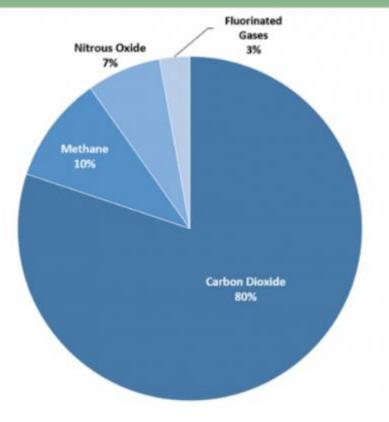
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GHG Life Cycle Background

- Life cycle analysis accounts for all greenhouse gas emissions generated for a process.
- Emissions expressed as CO₂ equivalent (kg CO₂e).
- 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 CO₂e emission factor.
- LCA helps understand the net benefit of carbon capture and storage projects.

Overview of U.S. Greenhouse Gas Emissions in 2019



US 2019 Total Emissions = 6,558 Million Metric tons CO₂ 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 CO₂ much was left in the ground?
- What is the net carbon balance?

Example: CO₂ GHG Emissions LCA 480,000,000 kg/yr Gas Processing Source

Emissions from construction, operations, materials

 Capture
 Compression
 Injection

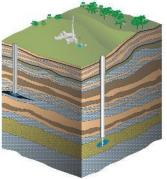
 +42,000,000 kg CO2e/year
 +18,000,000 kg CO2e/year
 +2,000,000 kg CO2e/year







CO₂ Storage 480,000,000 kg CO₂e/year



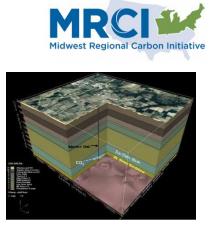
Net Storage = 480,000 t/yr - 62,000 t/yr **= 418,000 t/yr** 418,000/480,000 t/year = 87%



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 CO₂ sources, geology, and geographic location.

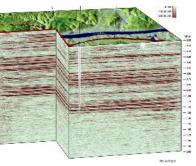
Endproduct: Greenhouse gas life cycle guidance for developing CCUS in the MRCI region in terms of maximizing net CO_2 storage effectiveness.













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.



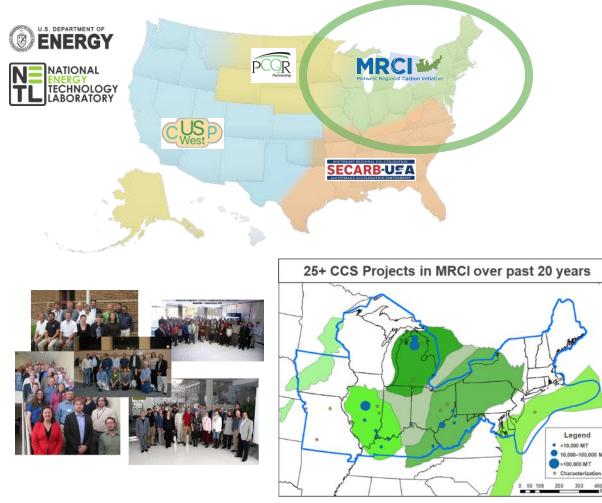


(*based on 2018 USEA data)

Midwest Regional Carbon Initiative

MRCI Region At a Glance:

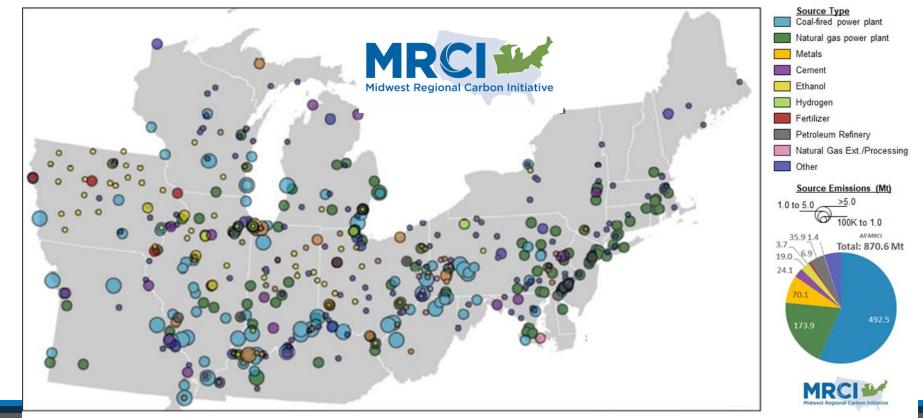
- 20 States
- 39% of U.S. Population
- 22% of US. Continental Land Area
- 45% of U.S. GDP
- 38% of U.S. CO₂ Emissions
- 35% of CO₂ emissions in MRCI region are from Electric Power Generation.*







- 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) CO₂-EOR(1)
 - Hydrogen (16) Petroleum refinery (21) Cement Plant (32) Fertilizer/Ammonia(7)





- 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 CO₂ compression, transport, and injection.
- The model does not account for produced materials (like cement or fertilizer or H₂).

*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

	PARAMETER DESCRIPTION		LOW VALUE	EXPECTED	HIGH VALUE				BASE CASE	
GATE-TO-GATE CO										
Capture	CO ₂ Emissions	kg CO2/yr	1,000,000,000	2,000,000,000	3,000,000,000	Source Survey		1,000,000,000	2,000,000,000	3,000,000,0
		xg copp	99%	99%	39%	Estimated				3,000,000,0
Capture	CO ₂ capture efficiency	s	39%	99%	99%			92%	99%	99%
Capture	CO ₂ captured for transport to CS system	kg CO ₂ /yr				Derived		990,000,000	1,980,000,000	2,970,000,0
Capture	Fugitive CO2 emissions from plant capture system	kg CO ₂ /yr	0.005+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	fe-cycle emission factor of the electricity used for captur	kg CO2e / MWh		500		Literature	Nat gas emissions	500	500	500
Capture	CO- emissions from capture operations	ke CO-/vr				Derived	Derived			
	Land area of CO2 capture facility	acre	10	20.0	30	Literature	Cooneyetal. (2015)	0	0	0
Capture			10	20.0	30			10.0	20.0	30.0
Capture	Land area of 002 capture facility	m ²				Derived	Derived from unit conversi	40,469	80,937	121,406
Capture	CO2 capture facility construction	kg CO2e		755000		Literature	Taken from Cooney et al. (755000	1510000	2265000
Capture								755,000	1,510,000	2,265,000
			-							
SATE TO GATE TO	IANSPORT OF CO ₂ (ELECTRICITY)									
Transport	tricity needed per tonne of CO, transported (100 to 1000	kWh / tonne	1	6.50	-	Literature	No pipeline pumping nee	1		
				0.30				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	6.508-08
Transport	Kilograms of CO _{2 realed via station}	kg				Derived	Derived from incremental	990,000,000	1,980,000,000	2,970,000,0
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 CO2e / MWh		660		Literature	2010 U.S. mix, delivered	660	660	660
Transport	Emissions from pipeline electricity needs	kg CD_e				Derived	Derived from the life-cycle	4.247.100	8,494,200	12.741.30
		-61-						4,247,100	8,494,200	12,741,30
	PEUNE TRANSPORT OF CO ₂ (FUGITIVE EMISSIONS AND SERVIC		-							
Transport	Pipeline distance	km	20	40	60	Estimate	Estimate	20	40	60
Transport	itive emissions factor from pipeline transport of CO ₂ (lea	kg CO2 / km-yr	7.5	75	282	Literature	API (2009); Lamb et al. (20)	7	75	282
Transport	itive emissions factor from pipeline transport of CO ₂ (lea	kg CO ₂ / yr	1			Derived	Derived from the fugitive	149	2,985	16,915
Transport	ive emissions factor from pipeline transport of CO ₂ (serv	kg CO2 / service-yr	0.36	3.6	5.5	Literature	API (2009); Lamb et al. (201	0.36	c01, s	10,915
Transport	Number of pipeline services per year		10	3.6	20	Estimate	Estimate		4	
		services / year	10	15	20			10	15	20
Transport	ive emissions factor from pipeline transport of CO_2 (serv	kg CO ₂ / yr	L			Derived	Derived from the fugitive	4	55	109
Transport	CO ₂ -EOR project duration	γr	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
			1							
SATE-TO-GATE TI	ANTONY					!	!			
ARC-TO-GATE II	DAD TOKT		1					4,247,253	8,497,240	12,758,32
Note: This portic	on of the model is taken directly from DOE NETL (2013a) an	d Cooney et al. (2015). The fluid bal	ances come from	n the industry d	ata set work o	f Azzolina et al. (2015).			
	ARBON STORAGE: LAND USE		1							
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	m²				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			
Gate-to-Gate	Number of wells	count	2	4		System Data	1 Injection well	10,117	10,117	10,117
	Number of wells									
				-	0			2	4	0
Gate-to-Gate	Total footprint of all wells	=			0	Derived	Derived from the well foor	2 20,234	4 40,469	60,703
Gate-to-Gate Gate-to-Gate	stal land area repurposed (gas processing facility + wells	° 1			0			2 20,234 60,703	4 40,469 121,406	60,703 182,109
		m ²		7.5	•	Derived	Derived from the well foor			
Gate-to-Gate	stal land area repurposed (gas processing facility + wells	m ² m ² kg CO ₂ e / m ² kg CO ₂ e			0	Derived Derived	Derived from the well foo Derived from land area of	60,703	121,406 7.5	182,109 7.5
Gate-to-Gate Gate-to-Gate	ptal land area repurposed (gas processing facility + wells Emissions per sq meter of repurposed land	m ² kg CO ₂ e / m ²	*		0	Derived Derived Literature	Derived from the well foo Derived from land area of Derived from Cooney et al	60,703	121,405	182,109 7.5
Gate-to-Gate Gate-to-Gate Gate-to-Gate	stal land area repurposed (gas processing facility + wells Emissions per sq meter of repurposed land CO ₂ emissions	m² kg CO ₂ e / m² kg CO ₂ e				Derived Derived Literature	Derived from the well foo Derived from land area of Derived from Cooney et al	60,703	121,406 7.5	182,109 7.5
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- 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)				
		Low	22,000				
Ethanol Plant	108	Average	215,000				
		High	4,327,000				
Natural Cas Dowar		Low	500,000				
Natural Gas Power Plant	192	Average	1,500,000				
Fidill		High	3,800,000				
	•	Low	50,000				
Direct Air Capture	0 (source size based	Average	200,000				
	on literature)	High	500,000				
		Low	80,000				
Hydrogen Plant	16	Average	400,000				
		High	1,500,000				
		Low	NA				
CO2-EOR	1	Average	94,954				
		High	NA				
		Low	160,000				
Cement Plants	32	Average	760,000				
		High	3,250,000				
Refineries	21	NA	NA				
Ammonia/Fertilizer		Low	500,000				
Plant	7	Average	1,000,000				
Fiain		High	1,500,000				



- Results reflect net CO₂ 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 CO₂ Storage

- Ethanol Plant with CS (82-90%)
- Direct Air Capture Plant (59-90%) (depending on energy source for capture)
- Petroleum refinery (NA)
- Fertilizer/Ammonia Plant (87-88%)

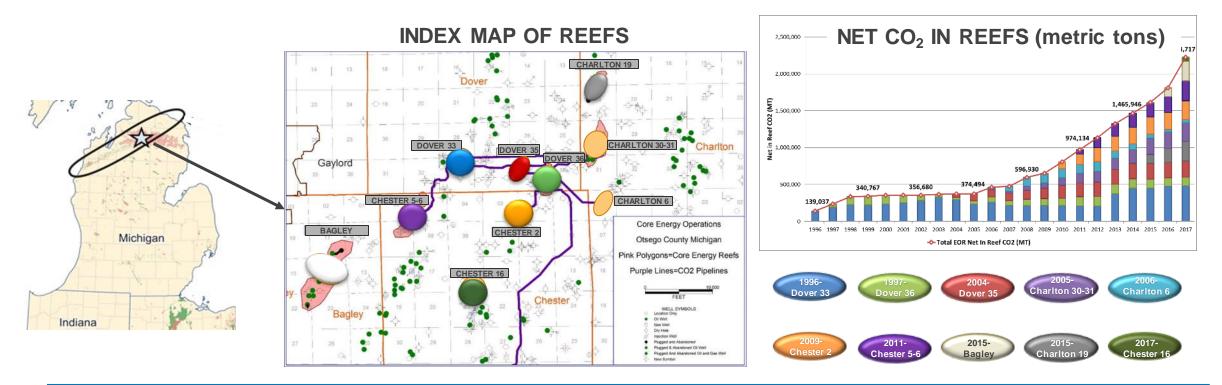
- Natural Gas Power Plant (71-76%) (accounting for displaced electricity)
- Hydrogen Plant (88-90%)
- Cement Plant (90-91%)
- CO2-EOR (59-66%) (not including downstream combustion of fuel products)

				1			2			3			4			5			6			7	•					
		Input Fields		Ethar	nol Plant wi	th CS	Natura	al Gas Powe	r Plant	Dire	ect Air Captu	ire	H	ydrogen Pla	nt	Pel	troleum refin	ery	Ċ	ement Plan	ts	Am	monia/Ferti	lizer		CO2-EOR		CO2-EOR w/storage
SEGMENT	SUB-SEGMENT	PARAMETER DESCRIPTION	UNITS	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	LOW VALUE	AVG	HIGH VALUE	AVG
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	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	500,000,000	1,000,000,000	1,500,000,000	71,272,000	133,182,000	164,590,000	94,954,545
Capture	Capture plant	CO2 capture efficiency (CO2 Captured/CO2 emssions routed to capture)	%	99%	99%	99%	90%	90%	90%	100%	100%	100%	99%	99%	99%	90%	90%	90%	90%	90%	90%	99%	99%	99%				
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	0.00015	0.00016	0.00018	0.00030	0.00040	0.00050	0.00013	0.00014	0.00015	0.00008	0.00009	0.00010				
Capture	Capture plant	Fugitive CO2 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	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	1.50E+06	6.00E+06	1.50E+07				
Compression	Compression	Electricity for CO2 compression	MCF/kg CO2	In	luded in captu	ıre	In	cluded in captu	ıre	1.13	1.13	1.13 c	luded in captur	re		Included in capture Included in capture		ıre	Ir	cluded in capt	re							
Transport B	Pipeline transport of CO ₂	Pipeline distance	km	50	100	150	50	100	200	100	150	250	20	40	60	20	40	60	50	100	200	10	20	30				
Gate-to-Gate	Land use	Land area of CO2 processing facility	acre	10	20	30	10	20	30	12	20	40	10	20	30	10	20	30	10	20	30	10	20	30				
Gate-to-Gate	Land use	Number of wells	count	1	2	3	3	4	6	6	10	20	2	4	6	2	4	6	2	4	6	2	4	6				
Notes				Assumes negl processing	ible CO2 captu	re &	Assumes Nat. (basin	Gas Plant nears		Assumes more larger capture, r emissons for co				nal emissions fo of H2 generation		Assumes captur	e similar to na		Assumes captur pipeline as cem with sedimenta	nent plants are			mal emissions f of H2 generatio			olina et al 2016 ; R gate-to-gate o		*based on Sminchak 2020 LC for CO2-EOR including upstream, gate-to-gate,
		Output Results																										
		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	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	494,999,922	989,998,453	1,484,991,433	3 71,272,000	133,182,000	164,590,000	94,954,54
	CO2 LEAKAG	GE FROM STORAGE OVER 100-YEAR TIMEFRAME	kg CO ₂	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0 0	0		0	0 0	604,000		
		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	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	494,999,922	989,998,453	1,484,991,433	3 71,272,000	133,182,000	164,590,000	94,954,54
		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	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	21,381,650	47,347,000	77,896,050	0 based on gate	to gate total		21,748,90
		CO2 TRANSPORT LCA EMISSIONS	kg CO2e	93,813	920,644	18,419,598	1,930,877	5,799,017	14,728,292	215,250	869,248	2,215,588	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	2,123,628	4,248,641	6,379,217	7 based on gate	to gate total		included in gate-to-gate
		CO ₂ STORAGE EMISSIONS	kg CO2e	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	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	34,225,018	68,450,031	102,675,024	4 based on gate	to gate total		included in gate-to-gate
		GATE-TO-GATE: LCA GHG EMISSIONS	kg CO2e	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	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	57,730,296	120,045,678	186,950,291	1 28,086,000	44,696,000	64,628,000	17,007,90
		CO2 NET STORAGE BALANCE	kg CO2e	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	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	437,269,626	869,952,775	1,298,041,142	2 43,186,000	88,486,000	99,962,000	56,197,72
	CO2 STORAGE	E EMISSION FACTOR PER METRIC TON CO2 Storage	kg CO2e / metric ton CO2	181	107	95	242	264	288	298	333	412	115	103	103	161	210	260	89	86	88	117	121	126	6 650	505	647	30
		Net %CO2 Storage	Net Storage/CO2 Captured	82%	89%	91%	76%	74%	71%	70%	67%	59%	88%	90%	90%	84%	79%	74%	91%	91%	91%	88%	88%	87%	61%	66%	61%	59



Learning from LCA of 22 years of CO₂-EOR

- CO₂ EOR operations in N. Michigan in place since 1996, where CO₂ 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).

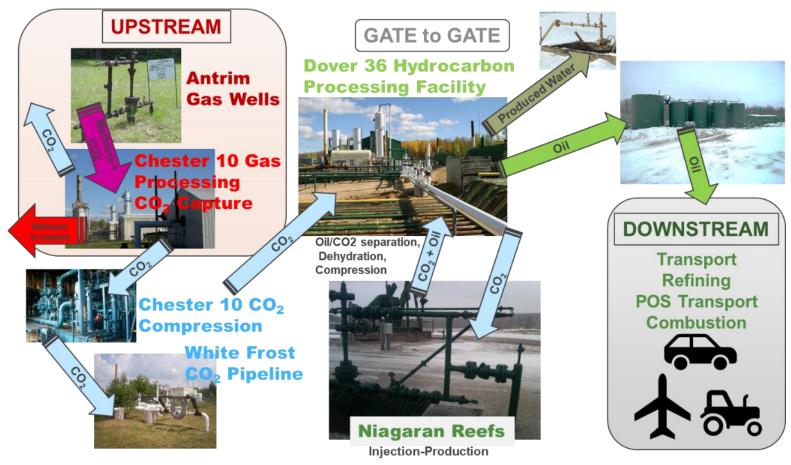






Establishing Boundary Conditions

• CO₂ EOR is part of a bigger hydrocarbon life cycle, including upstream, gate to gate, and downstream components (i.e. "Cradle to Grave.").

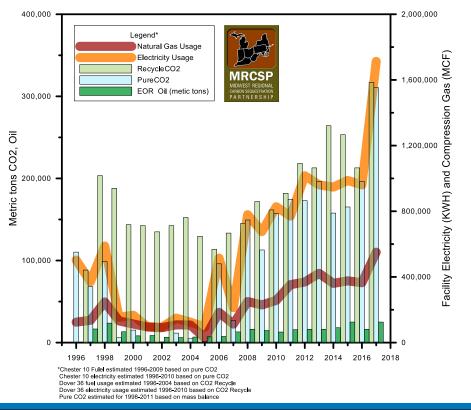






Gate-to-Gate Operations Data

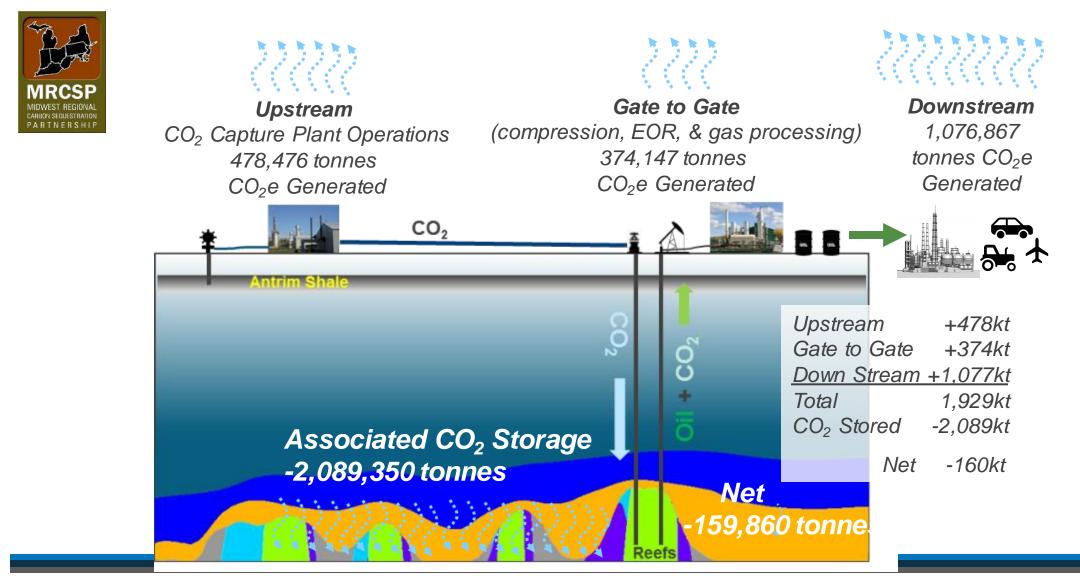
 Direct measurements from system monitoring & operations entered into CO₂ EOR LCA model (Azzolina, 2016). Operations trends reflect CO₂-EOR cycles & additional reefs. "Cradle to Grave" results show net negative CO₂ emissions of -159,860 metric tons due to very large volume of CO₂ storage vs oil produced.



	Upstream				
	Capture	Gate to Gate	Downstream	Total CO2	
	Emissions*	total	Total	Associated	Net CO2e
	(metric	Emssions	Emissions	Storage	Emissions
Year	tonnes)	(metric tons)	(Metric tons)	(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



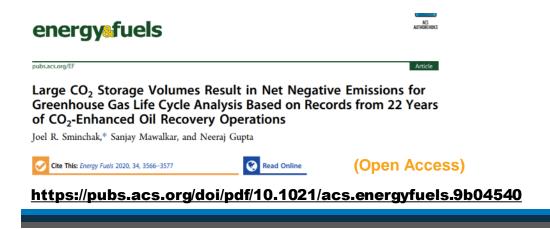
Results- Total LCA results 1996-2017





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 CO₂ 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.







Thanks!

