Carbon Capture and Reliable Storage: The Scale of the Challenge

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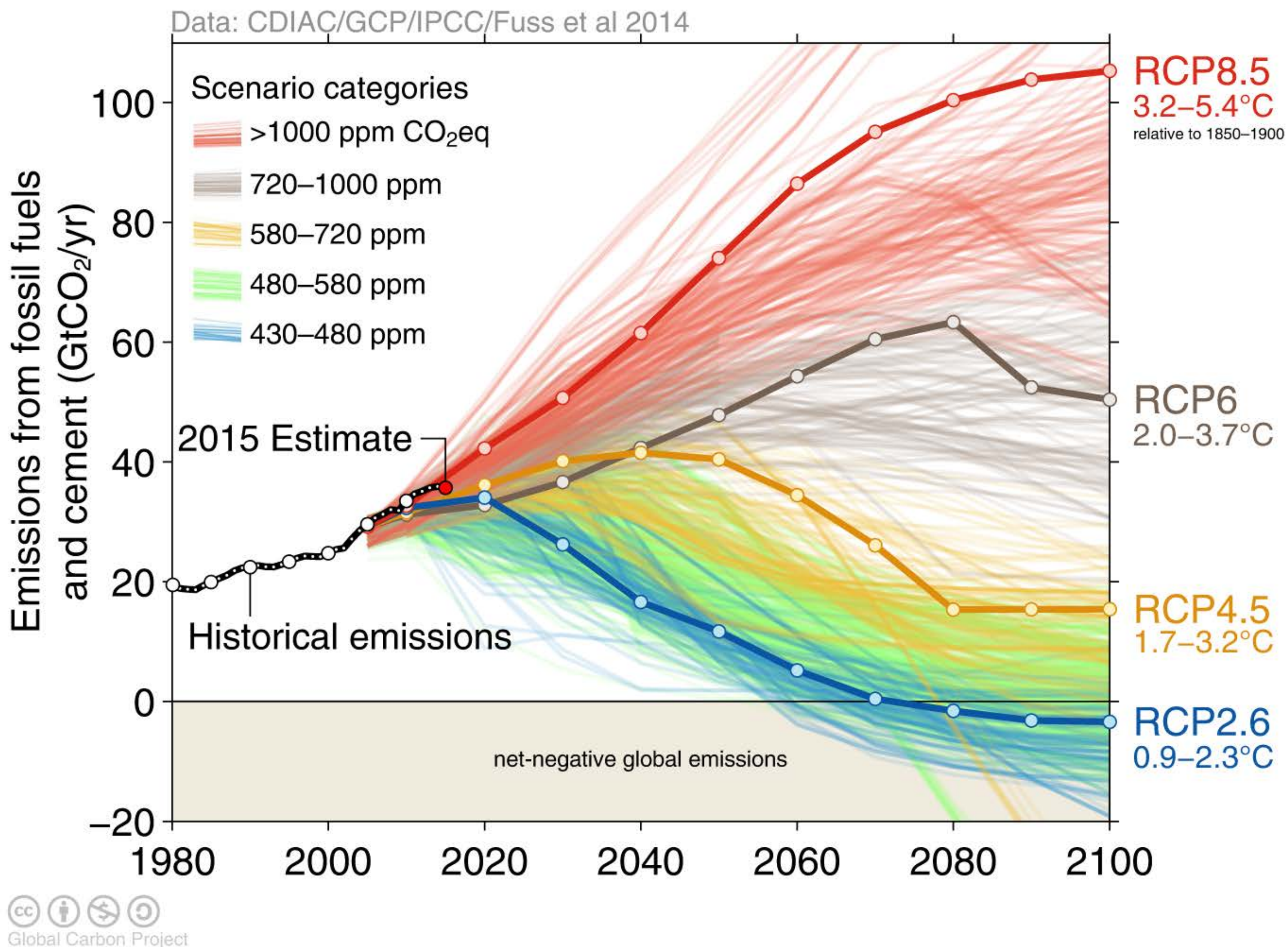
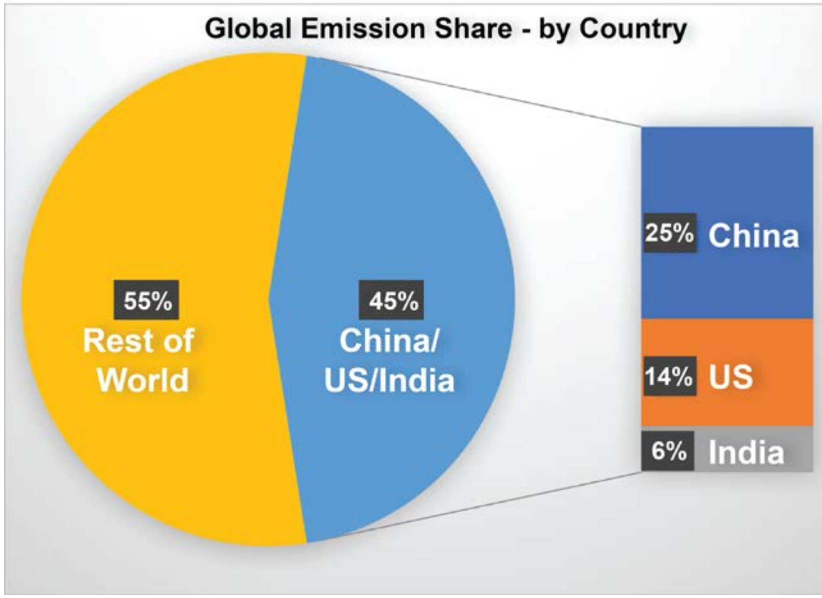
Gigatonne Impacts Are Crucial

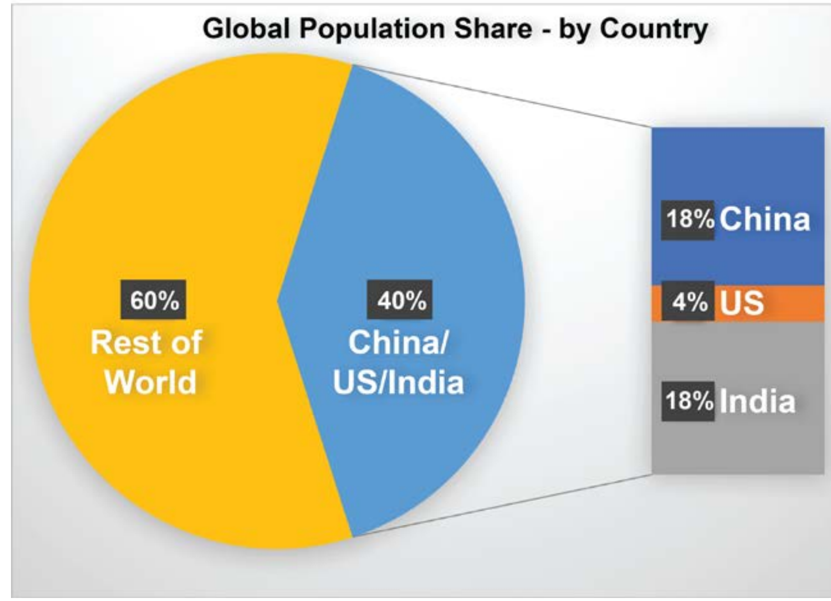


Reference: Fuss et al., Betting on Negative Emissions, Nature, 2014

Appreciating the Scale of CO_2 Emissions

Fossil Fuels Represent ~ 90% of Global Emissions
Coal (40%), Oil (30%), Natural Gas (20%)





Annual emissions (tCO_2) per capita:

- US ~ 15.6
- China ~ 6.5
- India ~ 1.5

Appreciating the Scale of CO_2 Emissions

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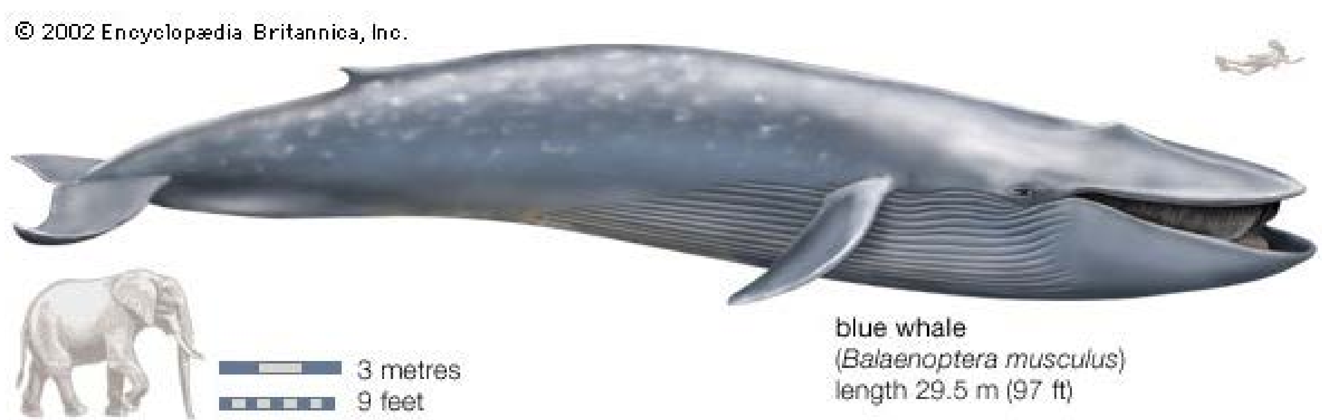
1. Consider the separation process, adsorption
2. We choose to use an ideal sorbent with today's maximum capacity
3. To capture our per capita emissions requires 150 tonnes of sorbent!



Message #1

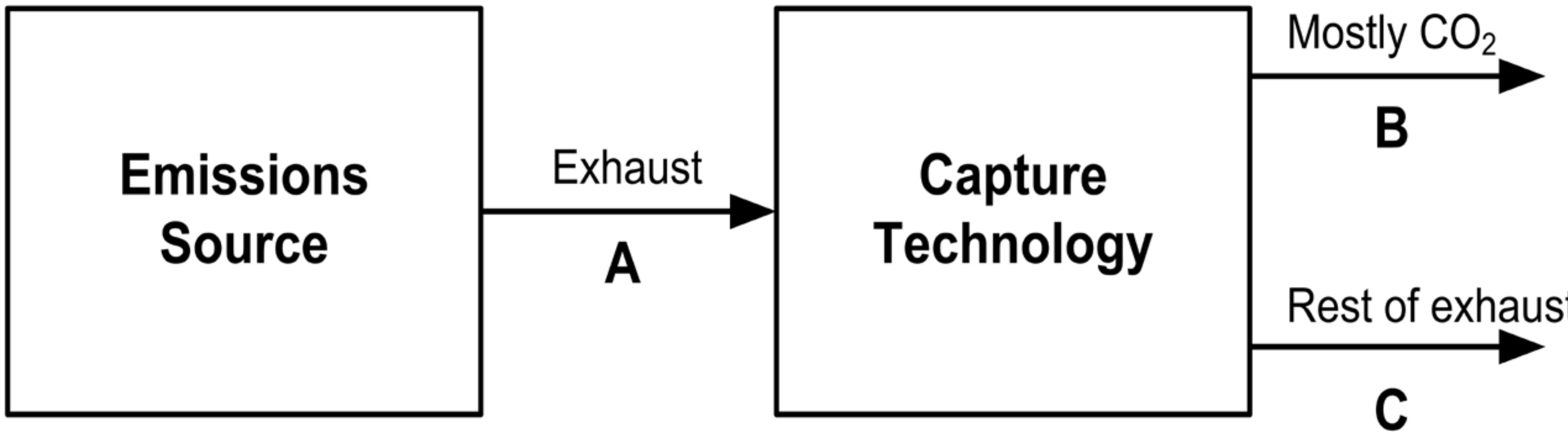
Energetics of Separation Scale with Dilution

The Majority of the CO_2 Sources are Moderate to Extremely Dilute

Category	% CO_2 (vol)	Example
High Pressure	varies	Gas Wells (e.g., Sleipner) Synthesis Gas (e.g., IGCC)
High Purity	90-100%	Ethanol Plants Ammonia
Dilute to Moderate	10-15%	Coal-Fired Power Plants → ~ 40% of emissions
Very Dilute	3-7%	Natural Gas Boilers Gas Turbines → ~ 20% of emissions
Extremely Dilute	0.04 – 1%	Ambient Air → (transport sector) ~ 25% of emissions Submarines/ Space Craft

Minimum Work for Separation

combined first and second laws



$$W_{\min} = RT\left[n_B^{CO_2}\ln(y_B^{CO_2}) + n_B^{B-CO_2}\ln(y_B^{B-CO_2})\right] + RT\left[n_C^{CO_2}\ln(y_C^{CO_2}) + n_C^{C-CO_2}\ln(y_C^{C-CO_2})\right]$$
$$-RT\left[n_A^{CO_2}\ln(y_A^{CO_2}) + n_A^{A-CO_2}\ln(y_A^{A-CO_2})\right]$$

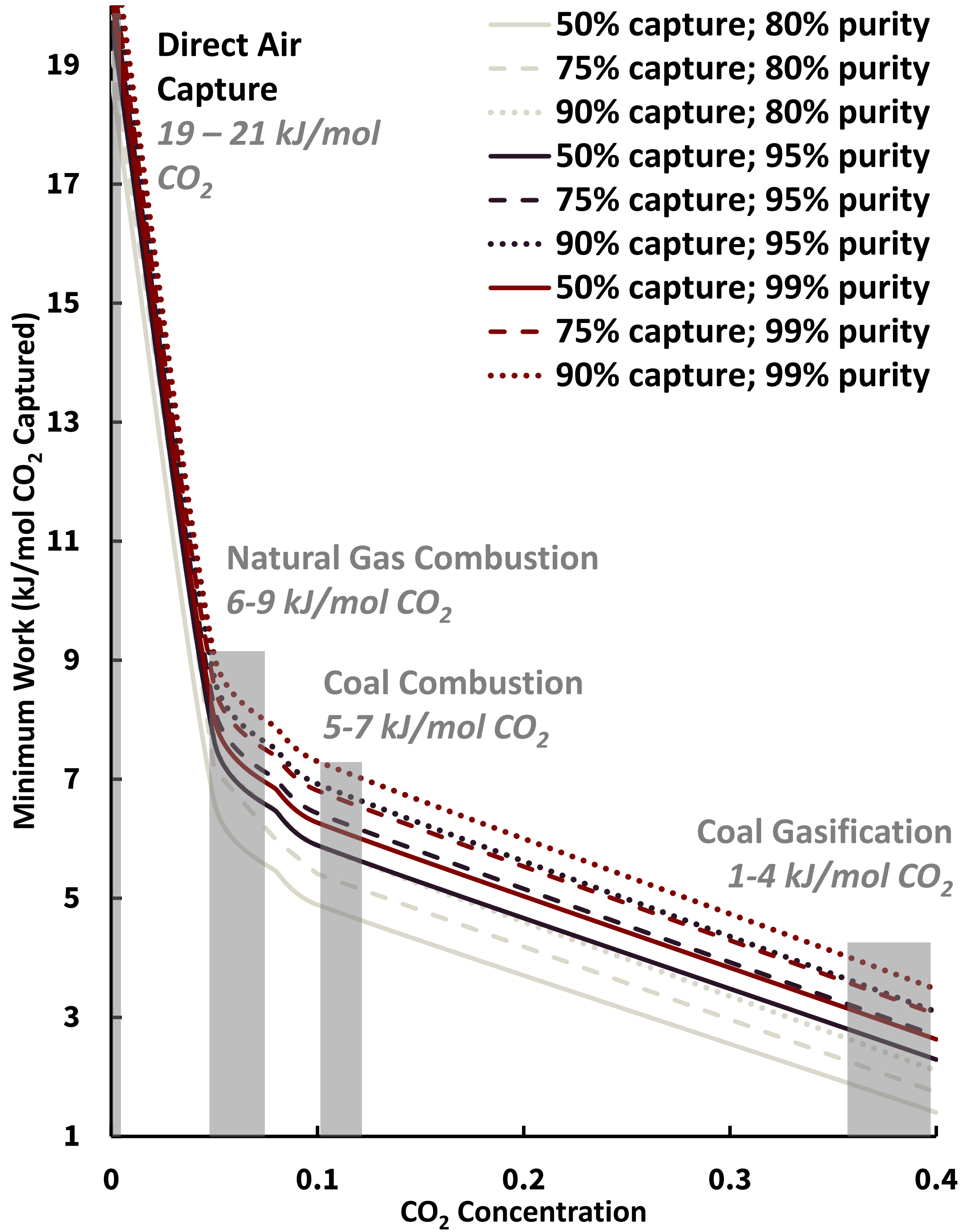
Reference: Wilcox, Carbon Capture, Springer, 2012

Capturing CO_2 From Air is Very Difficult, but technically feasible

- Energy scales with dilution!
- Density changes with purity

  $95\% CO_2 + 5\% N_2 = 681$ kg/m^3

  $80\% CO_2 + 20\% N_2 = 343$ kg/m
- ~ 0.5 kJ/mol CO_2 additional compression energy!



Reference: Wilcox, Carbon Capture, 2012

Message #2

Industrial Emissions May be Low-Hanging Fruit and Scale with Utilization

Sherwood Estimates for Separation From Industry

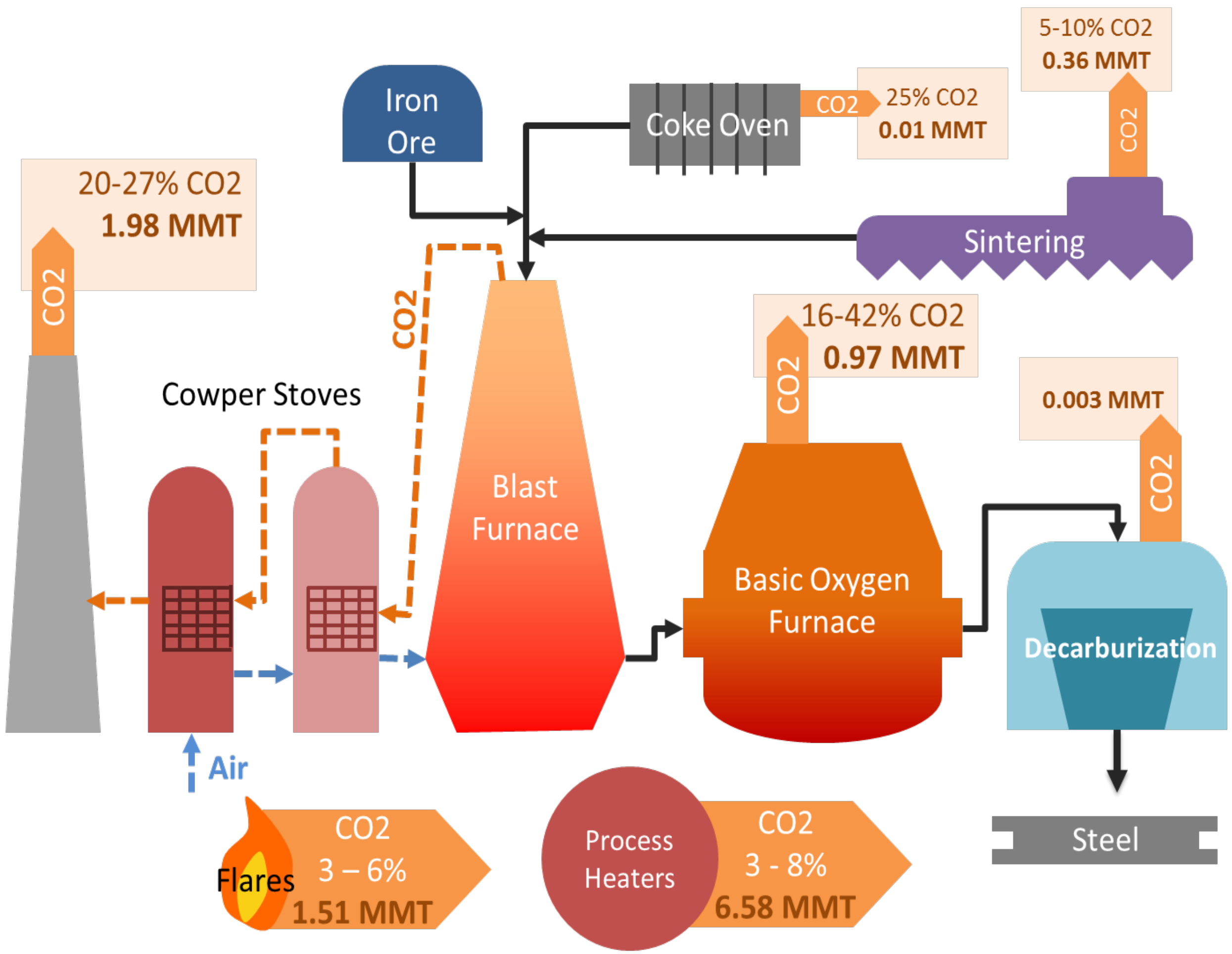
TABLE 2. Minimum work and Sherwood-derived capture cost estimations for various industries.

Source	CO_2 Content (mol %)[a]	Ref.	Min. Work (kJ/mol CO_2 Captured)[b]	Cost (US$/t CO_2 Captured)	Literature Estimates (2016 US$/t CO_2 Captured)	Ref.
Aluminum	4 – 10	6, 12, 13	8.2 – 10.8	45.8 – 65.6	68.2[c,d] – 76.3[c,e]	14
Ammonia	30 – 99.9+	15	0.0 – 5.0	0.0[f] – 29.0	21.2[c,g]	16
Carbonates	20	17	6.2	36.0		
Cement	14 – 33	18, 19	4.7 – 7.3	28.1 – 39.2	57.3[c,g], 68.4[c,g], 54.8[h] – 95.3[i],	16, 20, 21
Ethanol	99.9+	22	0.0	0.0[f]		
Ferroalloys	8 – 10	23-25	8.3 – 8.9	46.3 – 50.6		
Glass	7 – 12	23, 26	7.7 – 9.3	44.4 – 54.9		
Iron and Steel	20 – 27	18, 27	5.5 – 6.2	31.4 – 34.2	21.7[j] – 24.4[j], 32.6[k] – 44.0[k], 57.3[c,g]	16, 28, 29
Lead	15	30	7.1	40.5		
Lime	20	23	6.2	34.4		
Magnesium	15	23, 31	7.1	40.7		
Petrochemicals	30 – 99.9+	27, 32	0.0 – 5.0	0.0[f] – 28.6		
Pulp and Paper	8	33	8.9	48.0	31.1[l] – 35.0[l]	34
Refining	3 – 20	35, 36	6.2 – 11.7	33.5 – 70.4		
Silicon Carbide	8	37	8.9	51.4		
Soda Ash	36 – 40	38	4.0 – 4.4	25.6 – 26.7		
TiO_2	13	39	7.5	41.2		
Zinc	15	30, 40	7.1	40.2		
Natural Gas	3 – 5	9, 32	10.3 – 11.7	57.2 – 69.9		
Petroleum	3 – 8	9, 18	8.9 – 11.7	47.0 – 69.0		
Coal	10 – 15	32, 41, 42	7.1– 8.3	36.5 – 42.7		

[a] Range in composition due to different processes or different capture points within the same process. When not directly reported, values were estimated from a complete mass balance assuming NG fuel and 15% excess air; [b] calculated assuming 99.5% purity and 90% capture, Ref. [9]; [c] includes cost of compression; [d] calculated at 10% CO_2 purity; [e] calculated at 4% CO_2 purity; [f] for near pure streams, separation costs are considered in the compression and dehydration stage; [g] includes costs for transport and storage; [h] oxycombustion; [i] post-combustion MEA; [j] selexol capture from the blast furnace; [k] post-combustion capture from blast furnace; [l] capture using pre-combustion shift technology

Reference: Bains, Psarras, Wilcox, Progress in Energy and Combustion Science, 2017

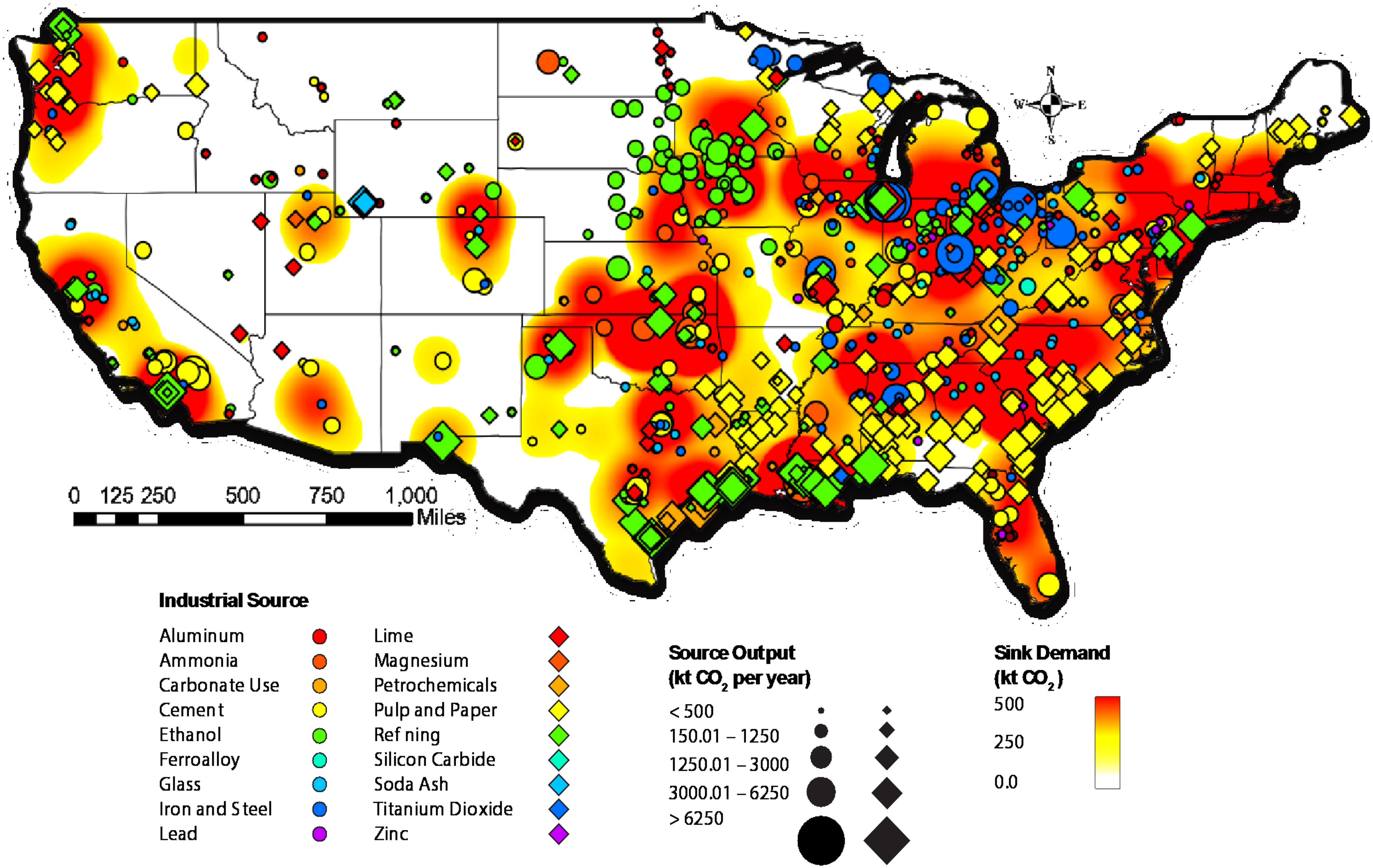
Rethinking Industry-Based Emissions



Example – US Steel Corporation plant in Gary, Indiana

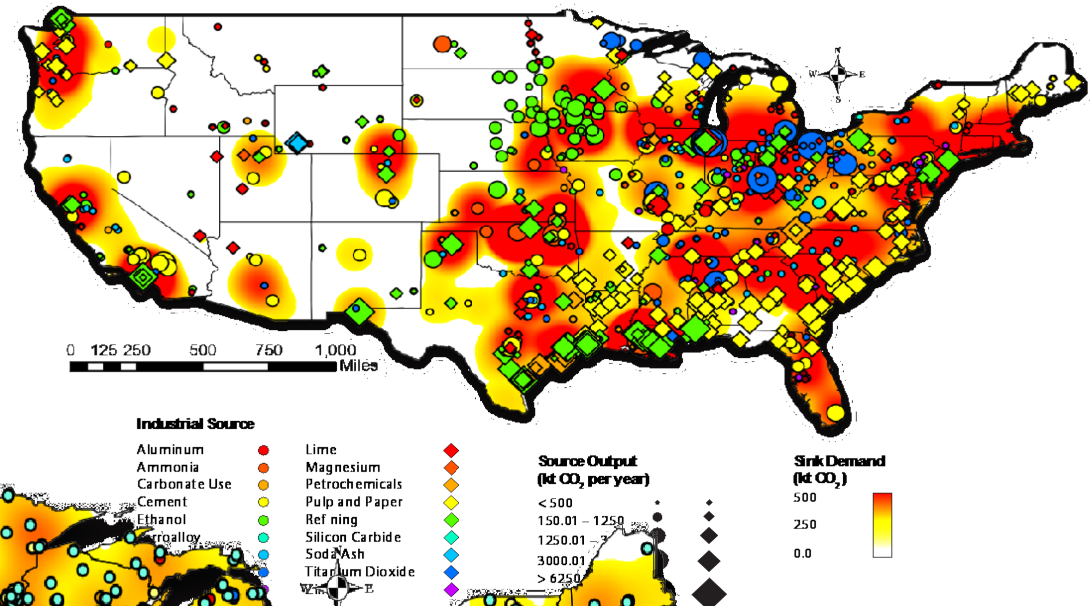
Reference: Bains, Psarras, Wilcox, Progress in Energy and Combustion Science, 2017

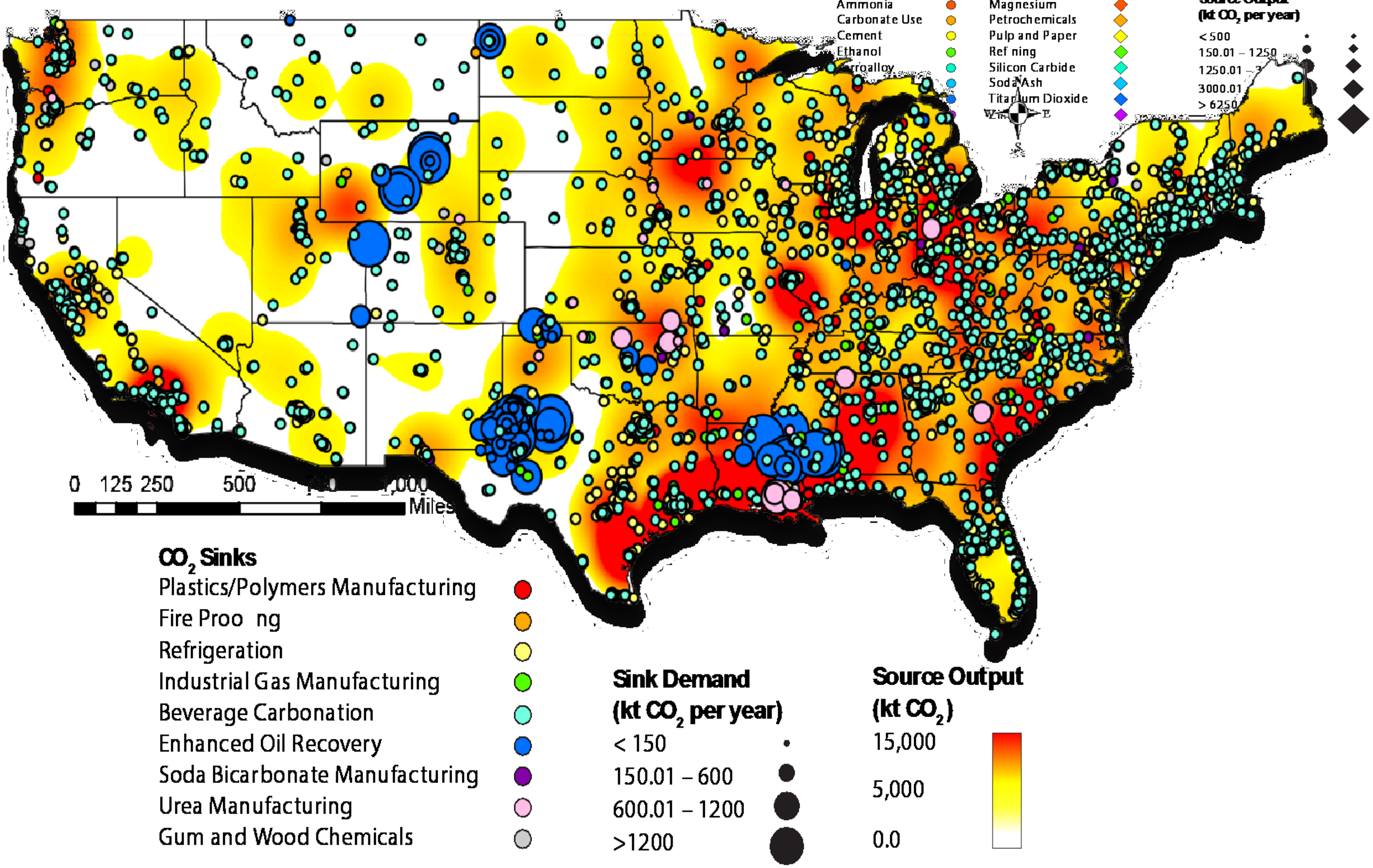
Sources vs Sinks



Reference: Psarras, Comello, Wilcox, Environmental Science and Technology, 2017

Sinks vs Sources



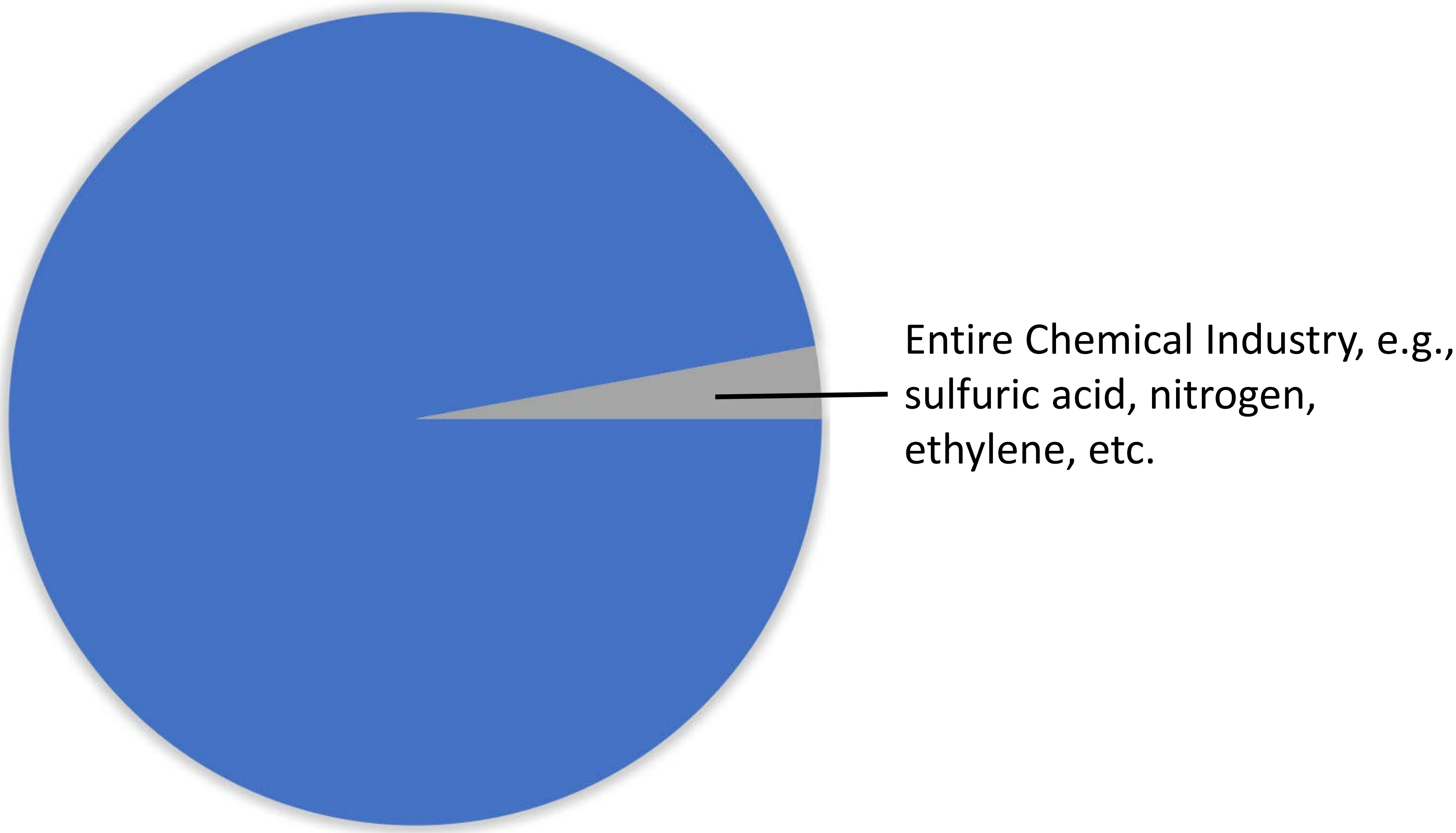


Message #3

Using CO_2 as a Chemical Feedstock May have a Minor Impact on Emissions

…but Several Opportunities Exist on a Gt-Scale

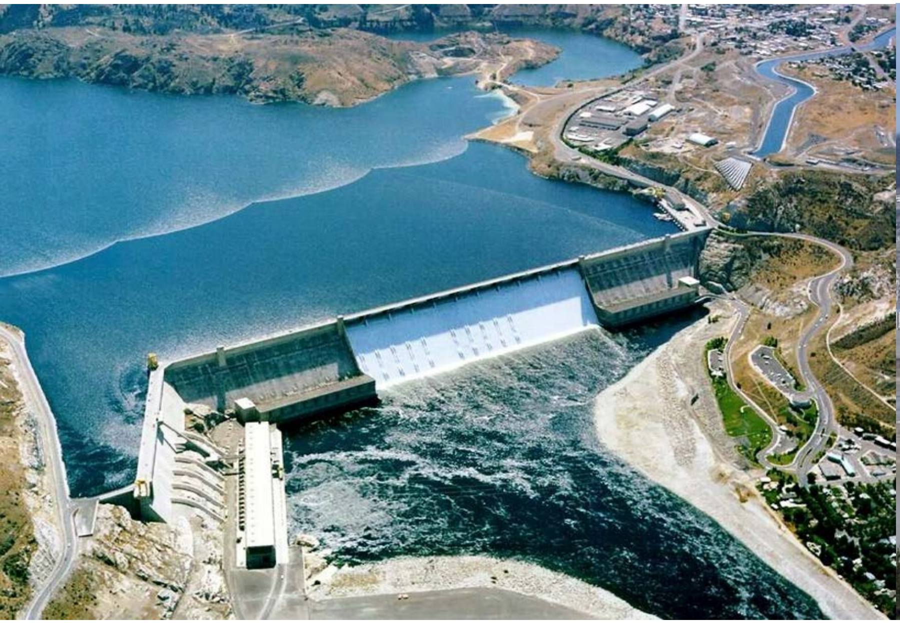
Chemical Industry Represents 3% of Emissions Globally



Products that Have an Impact on a Gt-Scale

- **Steel** market in 2018 is predicted to be ~ **1.55 Gt**
- **Construction aggregates** ~ **53 Gt in 2017**, up from 37 Gt in 2010, in terms of concrete, this represents building a sidewalk around the equator 5,000 times! or ~ 1,400 Three Gorges dams!

Grand Coulee Dam 21.3 Mt concrete



Three Gorges Dam 36.2 Mt concrete

Note: Concrete = cement + water + sand and gravel (aggregate) and cement industry ~ 4 Gt (2015) – rule of thumb is that 6-7x aggregate required; **Reference:** USGS

Message #4

First and Foremost, Mitigation Efforts Must Increase by at least 100x

CCS Demonstration Projects

There are ~ 100 projects globally that are operating, have operated, or are under construction

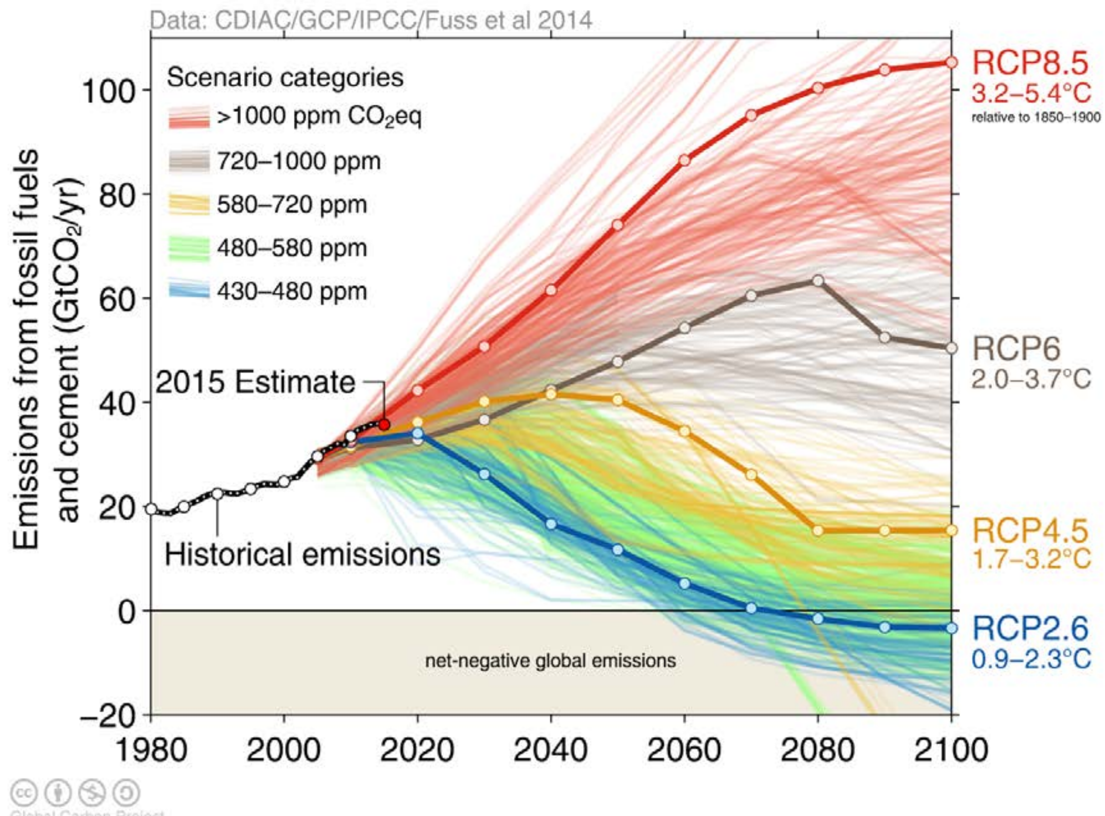
- Scale: ~1 Mt CO_2/yr (compared to ~ 35 Gt CO_2/yr emitted)
- CO_2 Sink: Geologic formations coupled with enhanced oil recovery
- EOR CO_2 storage to date – 560 Mt CO_2
- ARI Report – EOR may provide a CO_2 market of up to **7.5 GtCO_2** bet/ 2016-2030 (value of ~ $260B)

Reference: DOE-NETL Primer: CO_2 EOR, Jan 2017; IEA Technology Roadmap: CCS, 2013

Message #5

Negative Emissions will be Rquired to Prevent 2 ˚C warming by 2100

Climate Models Include NETs



Parting Message

We need everything and we need it now

e.g., fuel switching, CCS, renewables, negative emissions, etc.