370 CenSARA - CO_2 Sequestration

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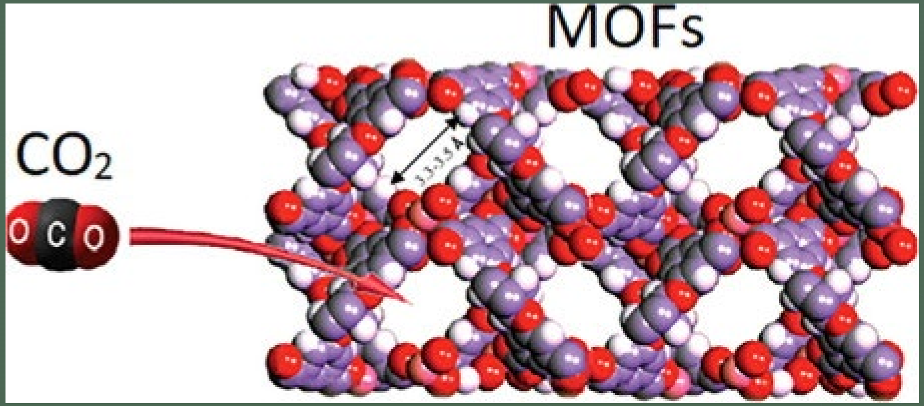
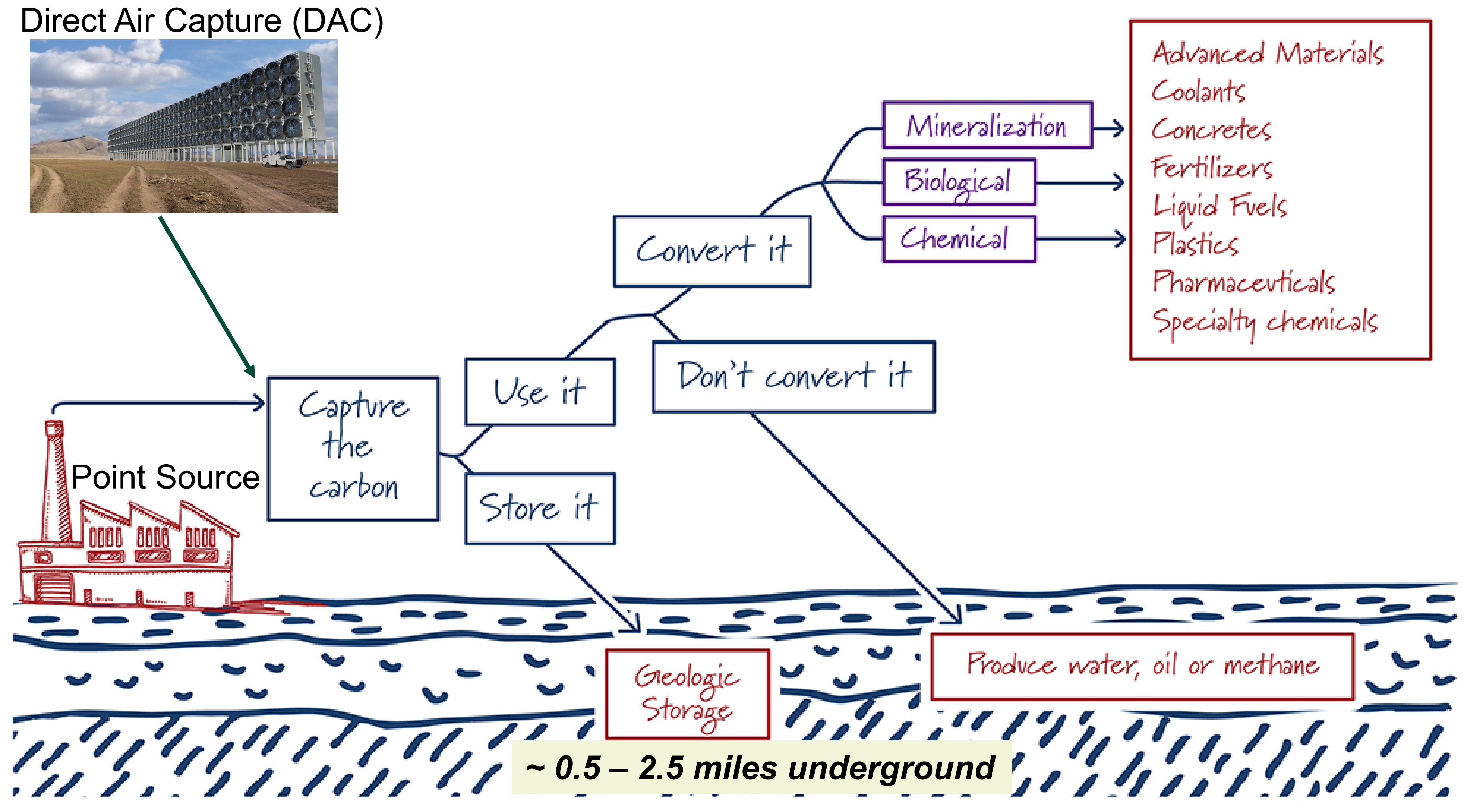
About Me?

- Environmental Engineering Assistant Professor, California Polytechnic State University
- Teach Air and Water Quality Engineering classes since 2016
- Research: Environmental Nanotechnology – including applications in CO_2 capture



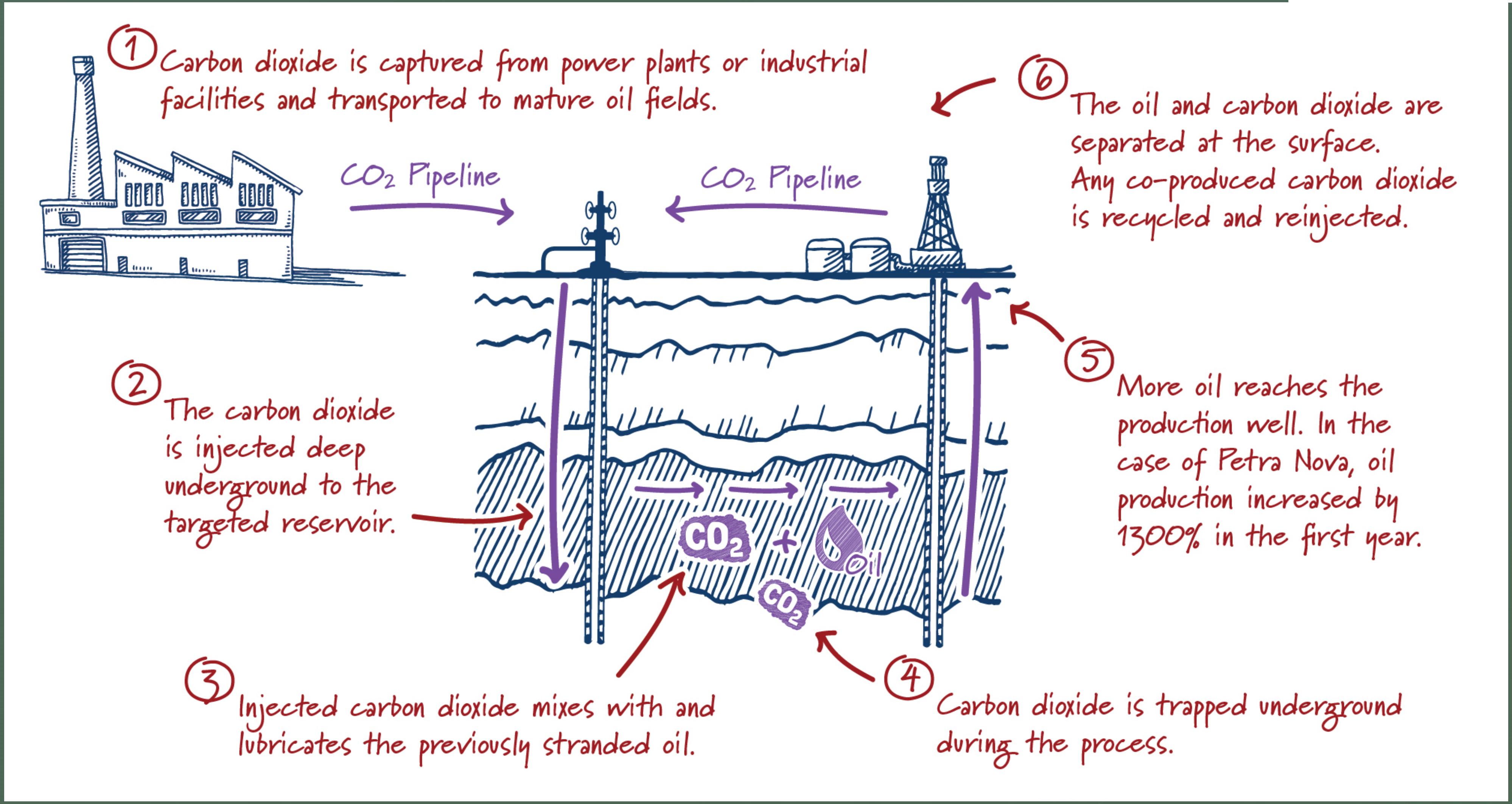
https://www.sciencedirect.com/science/article/pii/S004896971935082X

370 CenSARA: A Journey through the Life Cycle of Carbon Capture and Sequestration



https://clearpath.org/tech-101/carbon-capture-101/

Enhanced Oil/Gas Recovery - has been in use since the 1970s



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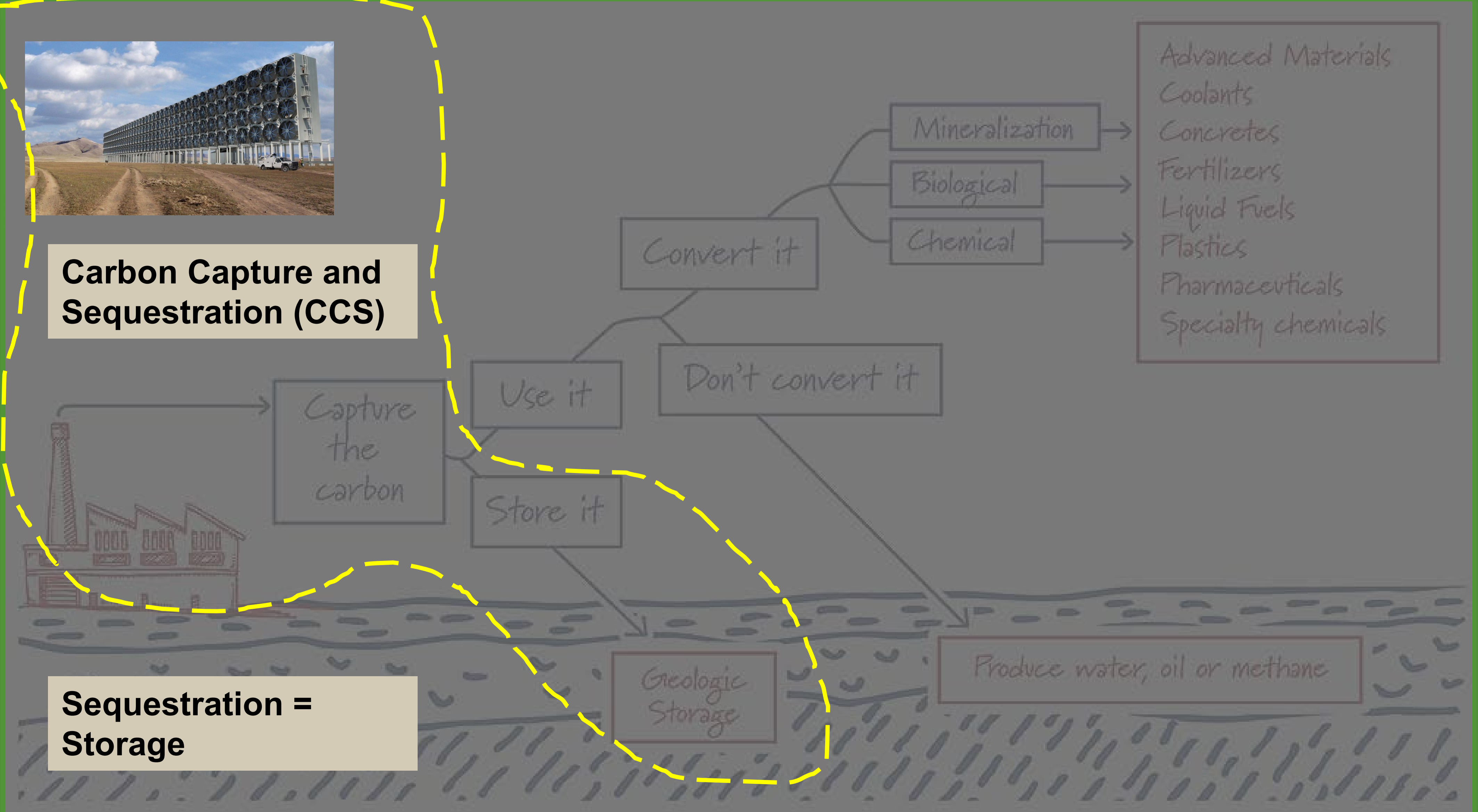

Carbon Capture and Sequestration (CCS)

Sequestration = Storage

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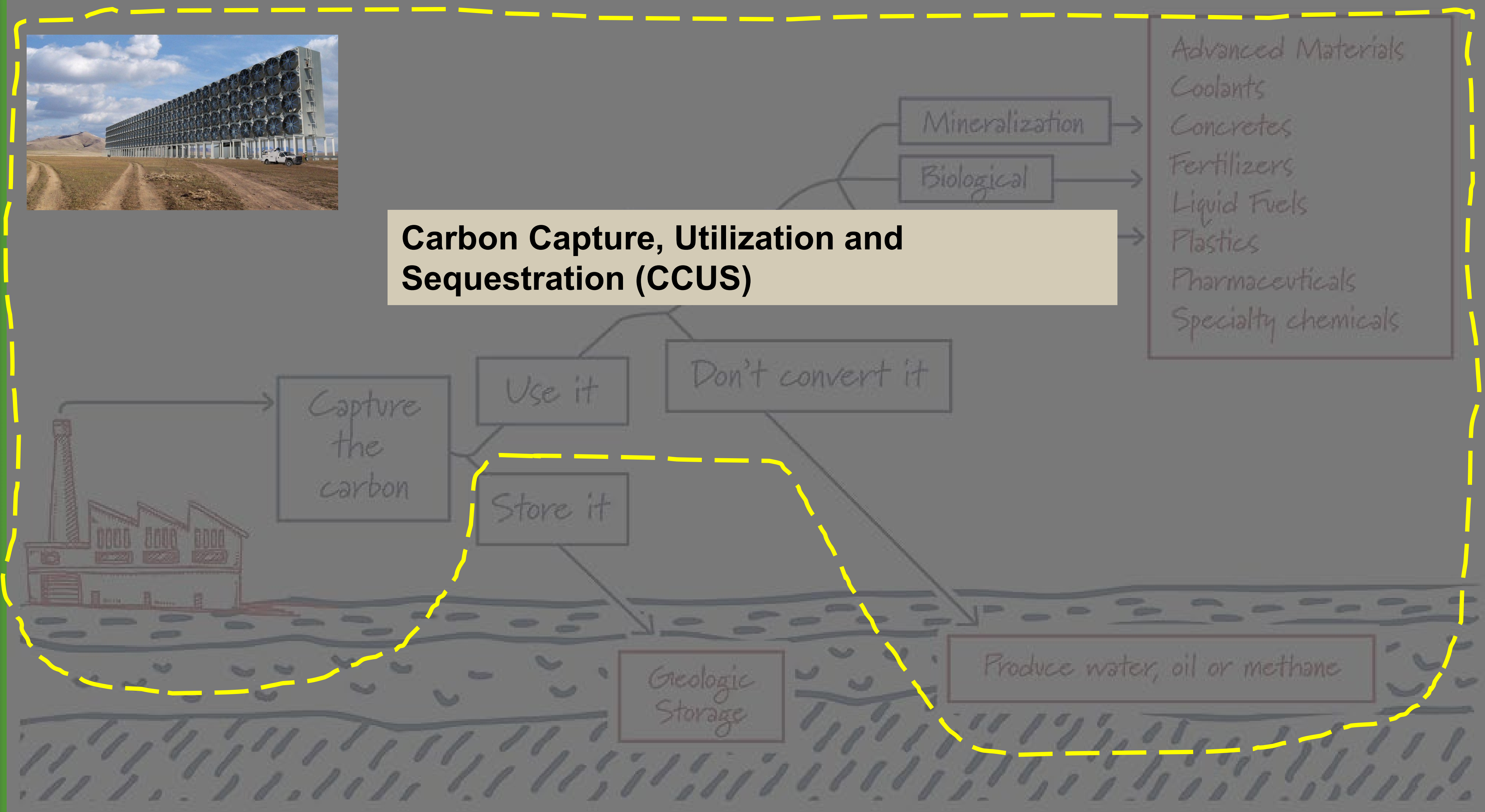

Carbon Capture, Utilization and Sequestration (CCUS)

https://clearpath.org/tech-101/carbon-capture-101/

- All Components of CCUS are commercial today!

  - *Not a pie in the sky (not a technology of the future)*

Course Topics (a lot of questions to answer!)

- Begin with a big picture → Need and Status of CCUS & briefly discuss the entire cycle
- Discuss the system stage by stage:
  - Capture
  - Transport
  - **<u>Sequestration</u> & Monitoring**
  - Utilization
- Environmental and Regulatory Side of the Story:
  - Impacts and Risk?
  - Permitting & Regulatory Framework for CCS
- Other:
  - Cost and Readiness Level of CCS Technologies
  - Helpful Resources

Day 1	
9:00	Welcome, Registration, and Introductions
9:15	Pre-Test & Review
9:45	**Overview**
10:30	Break
10:45	**Overview (Contd.)**
12:00	Lunch Hour
1:00	**Technologies and Equipment for Carbon Transport and Sequestrati**
3:00	Break
3:15 **(Contd.)**	**Technologies and Equipment for Carbon Transport and Sequestrati**
5:00	Adjourn for the Day
Day 2	
9:00	**CO_2 Utilization and Its Market**
10:30	Break
10:45	**CO_2 Utilization and Its Market (Contd.)**
12:00	Lunch Hour
1:00	**Environmental Impact Assessment of Carbon Sequestration Project**
3:00	Break
3:15	**Regulatory and Legal Issues of Carbon Sequestration Projects**
4:15	Post-Test & Course Evaluation
5:00	Adjourn

Before we get started – Participants Introduction

Big Picture CCUS

- CO_2 emissions (we are in trouble)
- Options to achieve net zero emissions by 2050?
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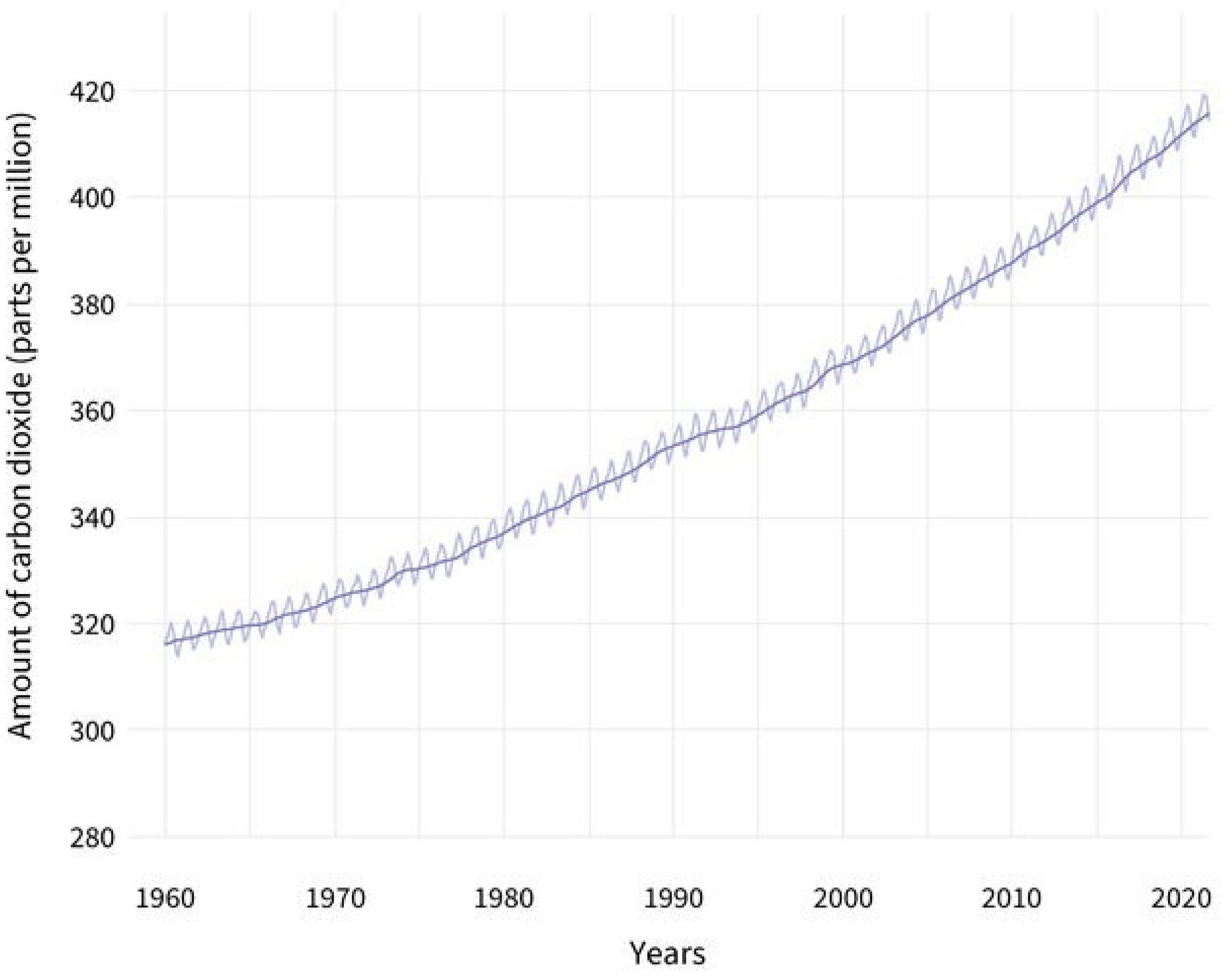
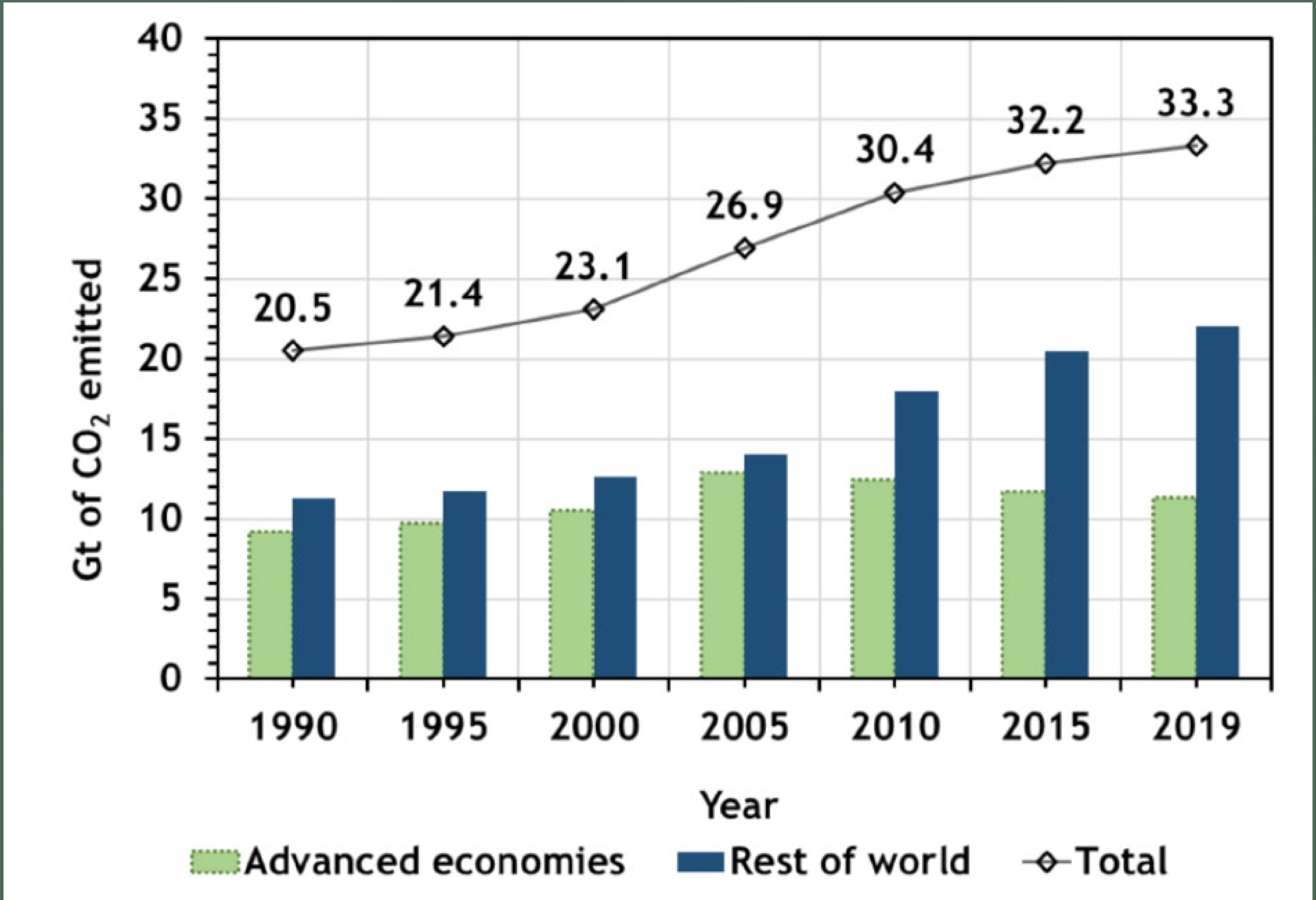
- Concluding Remarks

ATMOSPHERIC CARBON DIOXIDE (1960-2021)



https://www.climate.gov/



Regufe, M. J. et al., *Energies*, 2021 *14*(9), 2406

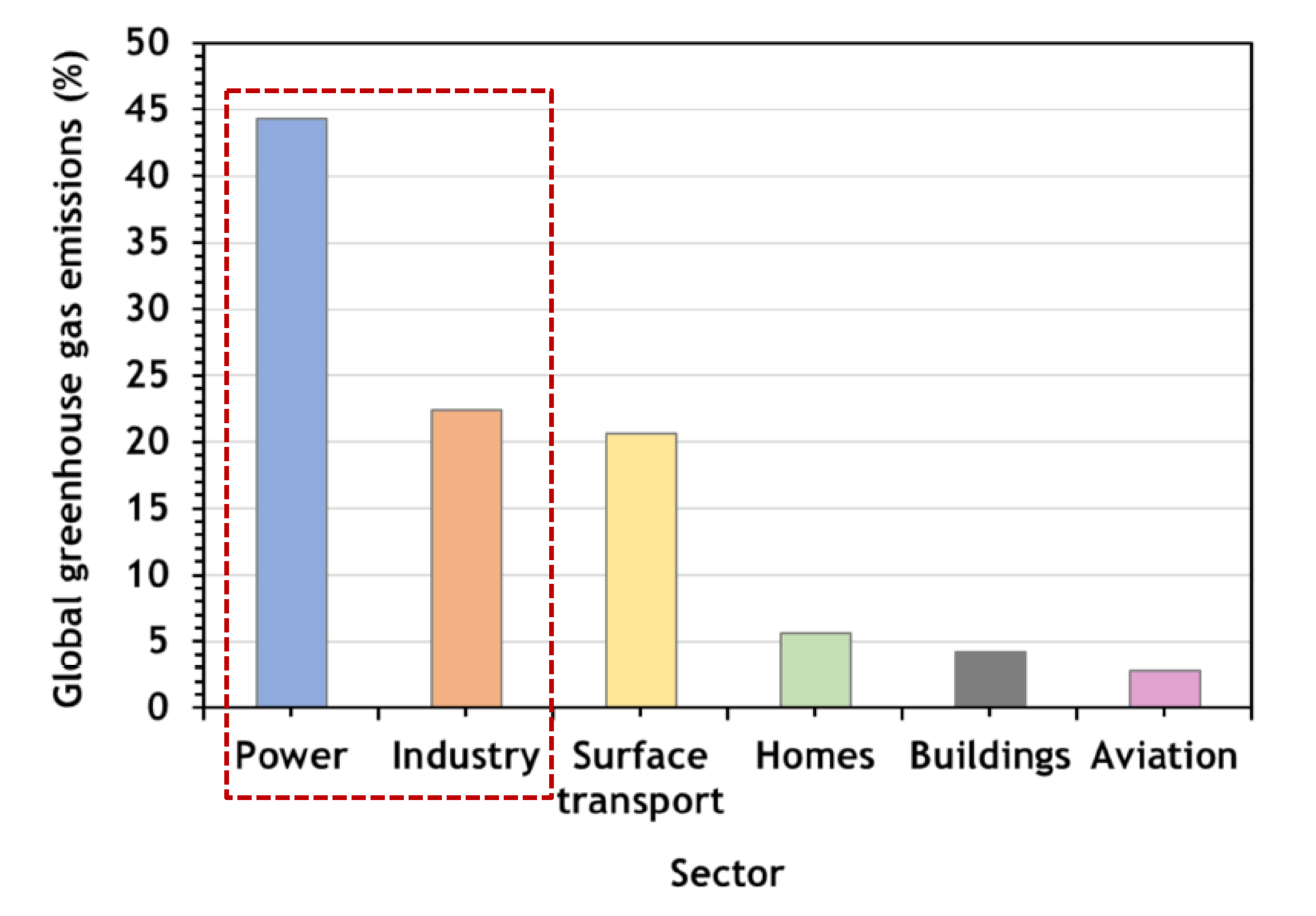
Let’s put this number in perspective

33 Gt = equivalent to ~ 34,000 fully loaded aircraft carriers

How about all GHGs?

- ~ 59 Gt $CO2_e$ /year

Big contributors?



Regufe, M. J. et al., *Energies*, 2021 *14*(9), 2406

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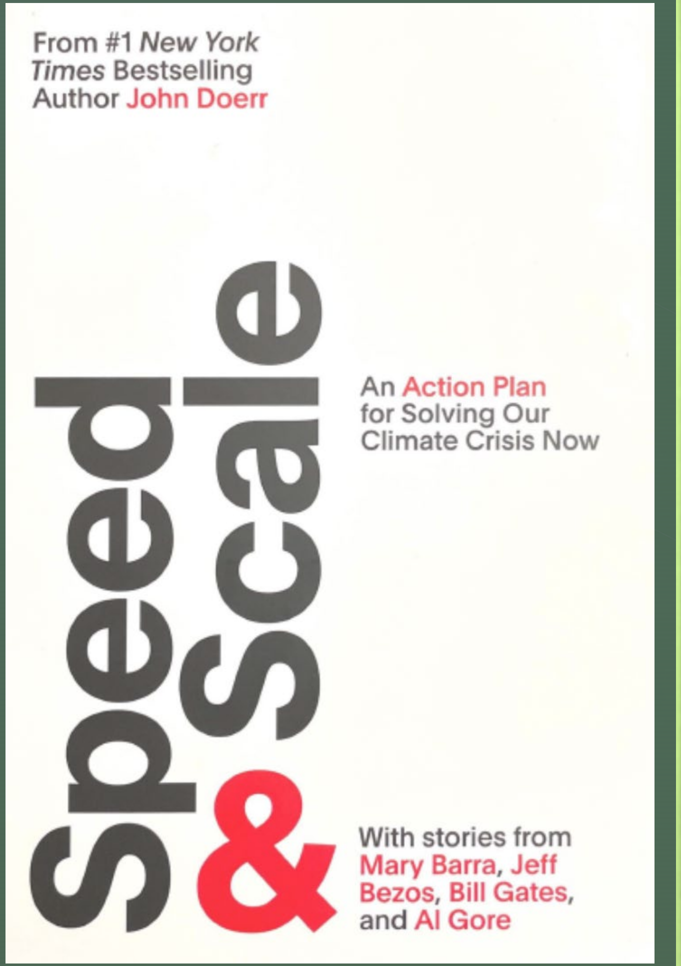
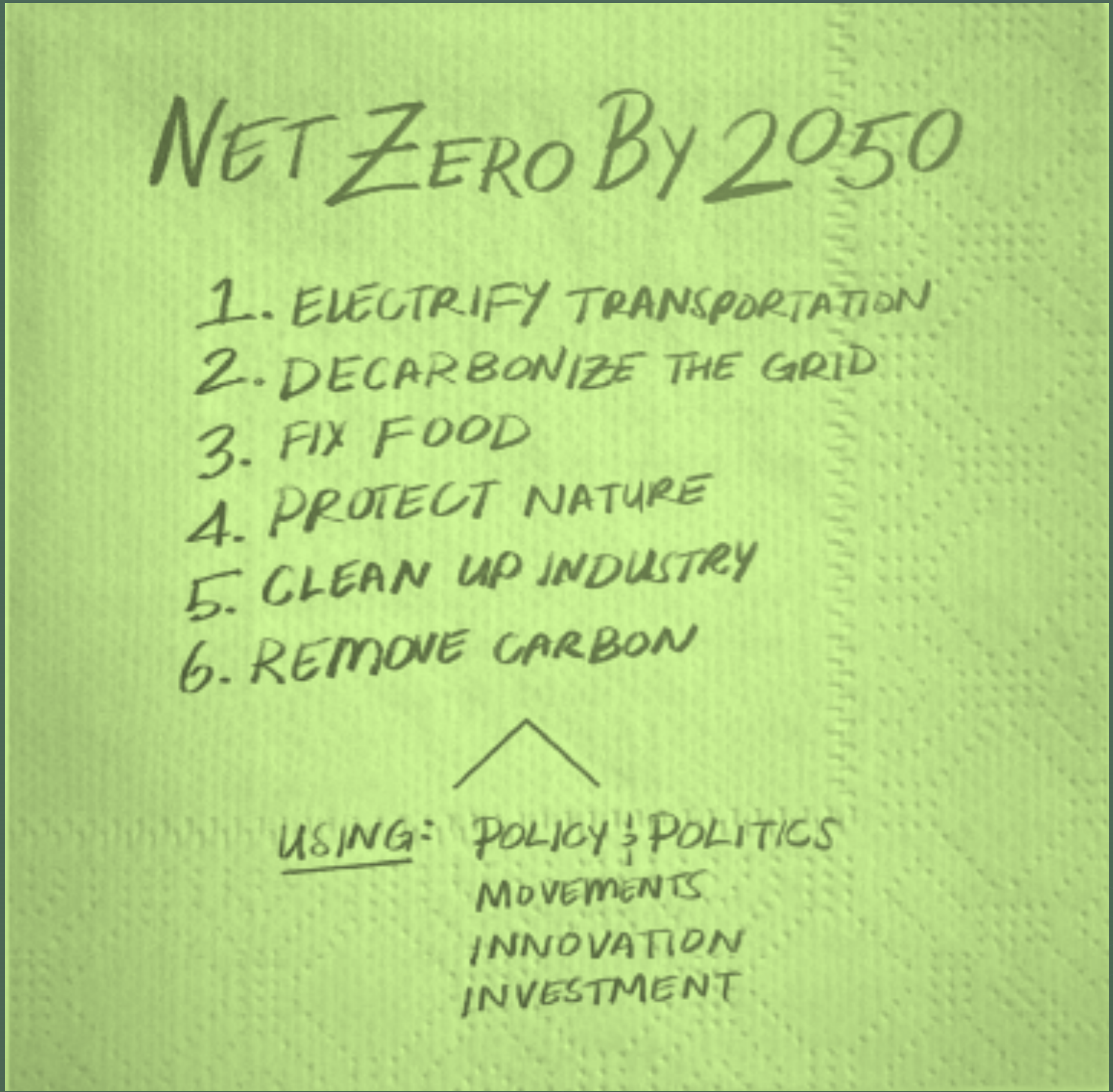
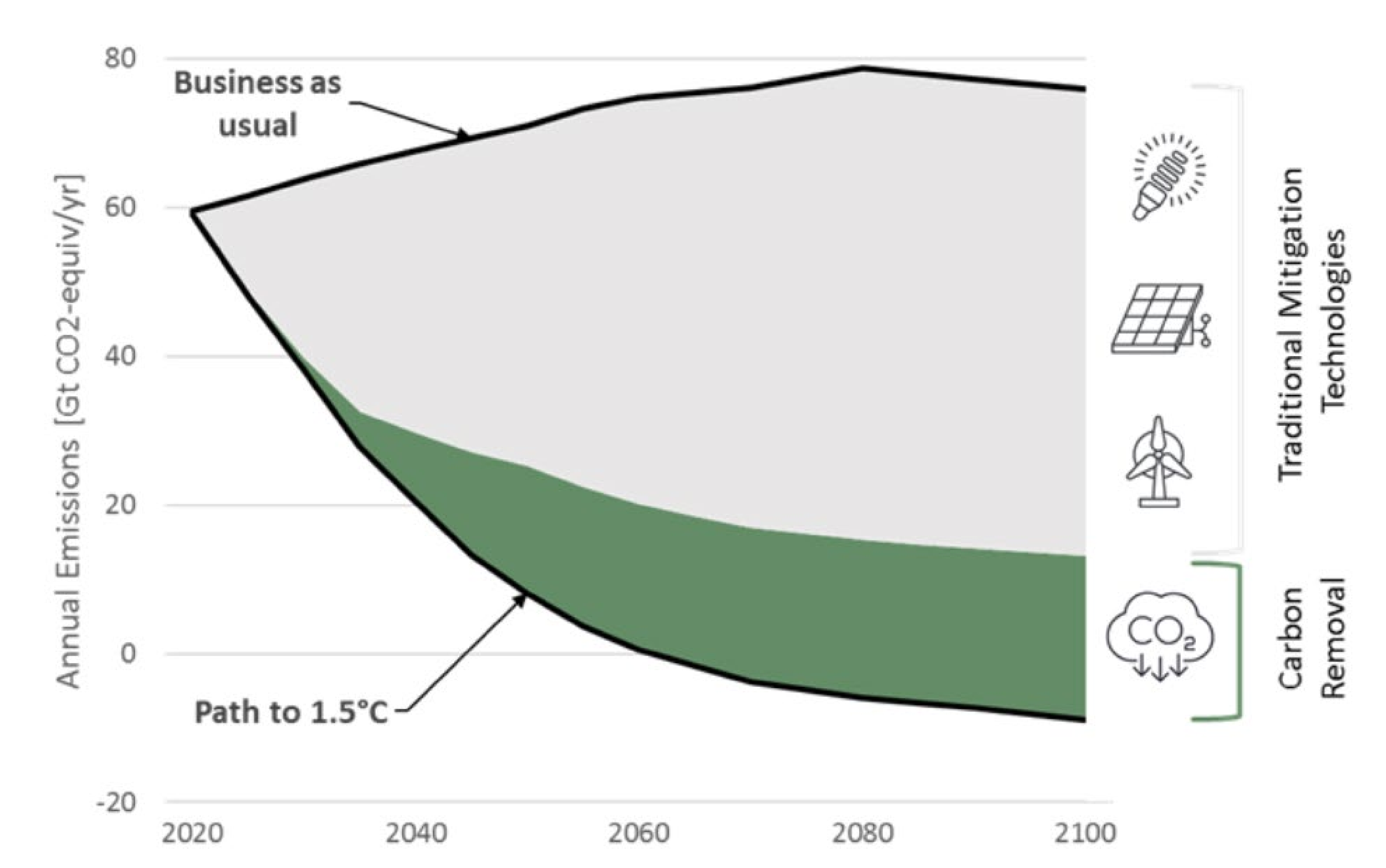
Just get rid of fossil fuels??

- Experts (e.g., IPCC & IEA) say NOT enough →
  - We have to use a portfolio of options (no silver bullet)
  - & CCS is a key component

Most net zero portfolios call for CCUS….







Predictions for **Carbon removal needed = 10 - 20% of the current global emissions**
(estimates by IEA, IPCC, McKinsey, Network for Greening the Financial System (NGFS))

https://energypost.eu/comparing-four-carbon-removal-scenarios-ipcc-iea-mckinsey-ngfs-and-policy-implications/

A closer look….

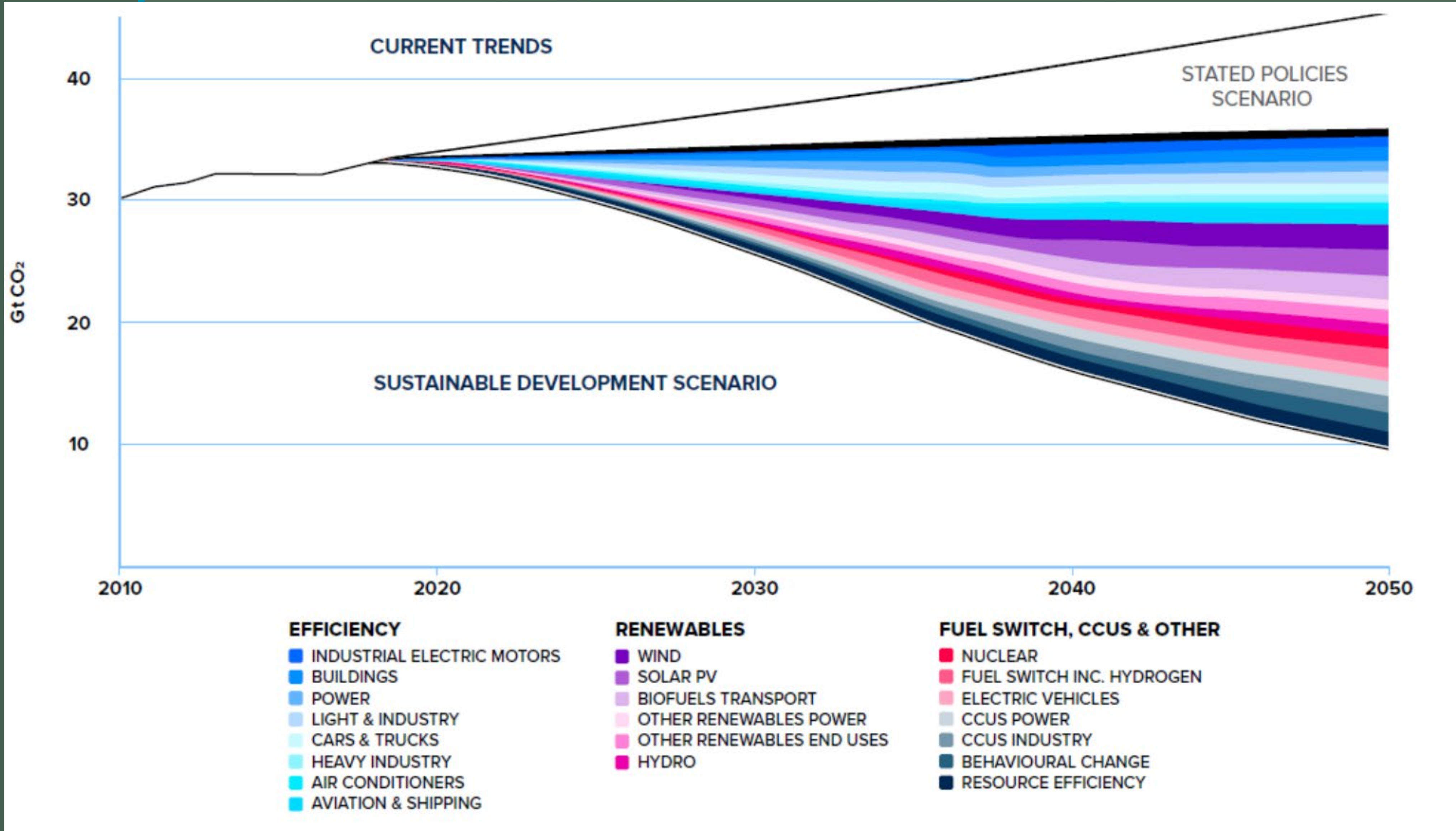


FIGURE 21 THE IEA'S SUSTAINABLE DEVELOPMENT SCENARIO

In this IEA's pathway → 15% of the reductions would be met by CCS

Global Status of CCS 2021, Global CCS Institute

We have to pursue CCS….

- Near-term solution to bridge the gap until renewables can dominate the energy sector

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Currently:

The world sequester ~ 40 Mt CO_2/year

- 1 million ton CO_2/year = removing ~ 218,000 gas-fueled passenger cars from the road
- ~ 40 million tons/year (what we currently sequester = removing ~ 8.7 million gas-fueled passenger cars from the road

Current CCS	Required CCS by 2030	Required CCS by 2060
• ~ 40 Mt/year	• 200 –1000 Mt/year (0.2-1 Gt/year)	• 5000 – 10,000 Mt/year (5 – 10 Gt/year)

2018 IPCC Estimate to achieve 1.5 °C climate outcome

It is a long way to go………..

- Huge scale → need to capture and store millions of tons of CO_2 per year over several decades
- In the past, lack of policy support and economic drivers impacted progress and project cancellations
- But the situation is different now (as we will see shortly)

5 -10 Gt CCS / year by 2050 → Is this financially doable?

- Capital investment needed = $655 - $1280 billion dollars
- 1 trillion dollar is big money → but that is needed over ~ 30 years (maybe not that bad then)
- Think about this, in 2018, the investments in jut the energy sectors were ~ $1.85 trillion

Global Status of CCS 2021, Global CCS Institute

If money is not a major barrier → time is

- These large infrastructure projects take about 7-10 year from concept → feasibility → design → construction → start operation
- (permitting itself may take 1 – 2 years)

Global Status of CCS 2021, Global CCS Institute

Big Picture CCUS

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A bit old data but gets the point across

Table 1
Global industrial activities and total emissions yearly (Plaza et al., 2012).

Production method	Sources	Total emissions ($MtCO_2/yr$)
Fossil products		
Power	4942	10,539
Cement production	1175	932
Refinery	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	7887	13,466

Let us highlight a few good candidates for CCS

Power plants

- Responsible for ~ 1/3 of the global CO_2 emissions
  - 500 MW coal-fired power plant produces ~10,000 tons of CO_2/day
- CO_2 Capture efficiency = 85 – 95%
- Cons: Would require 10 - 40% more energy for CCS (capture, compression, and storage)
- Net result → 80 - 90% reduction in CO_2 emissions

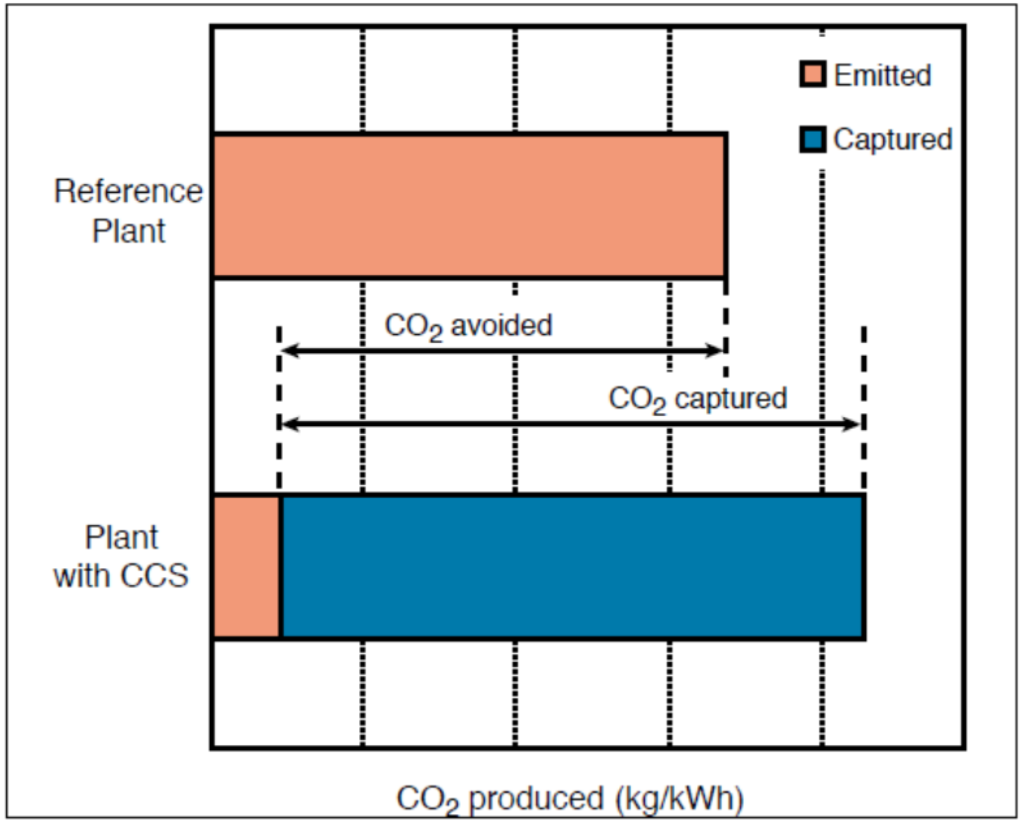
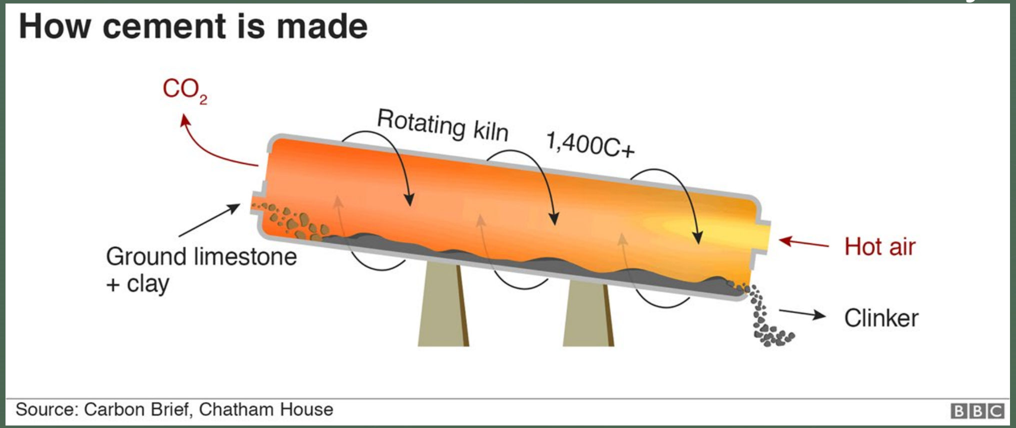


Figure SPM.2. CO_2 capture and storage from power plants. The increased CO_2 production resulting from the loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage and any leakage from transport result in a larger amount of "CO_2 produced per unit of product" (lower bar) relative to the reference plant (upper bar) without capture (Figure 8.2).

IPCC Special Report on Carbon Capture and Storage, 2005

Cement & Iron and Steel Industries

- Power plants → we will have other options to decarbonize (e.g., renewable energy)
- But for cement and steel:
  - CO_2 does not come from combustion of fossil fuel → it is a byproduct of the manufacturing reactions and processes
    - $CaCO_3$ splits to CaO and CO_2 (cement production)
    - 0.78 ton CO_2 emits/ton CaO produced (CaO is the primary constituent of cement)
- Big industries, 4.1 and 2.6 billion tons of CO_2 emission per year, respectively
- Thus, CCS is the way to go to decarbonize the cement and iron and steel industry

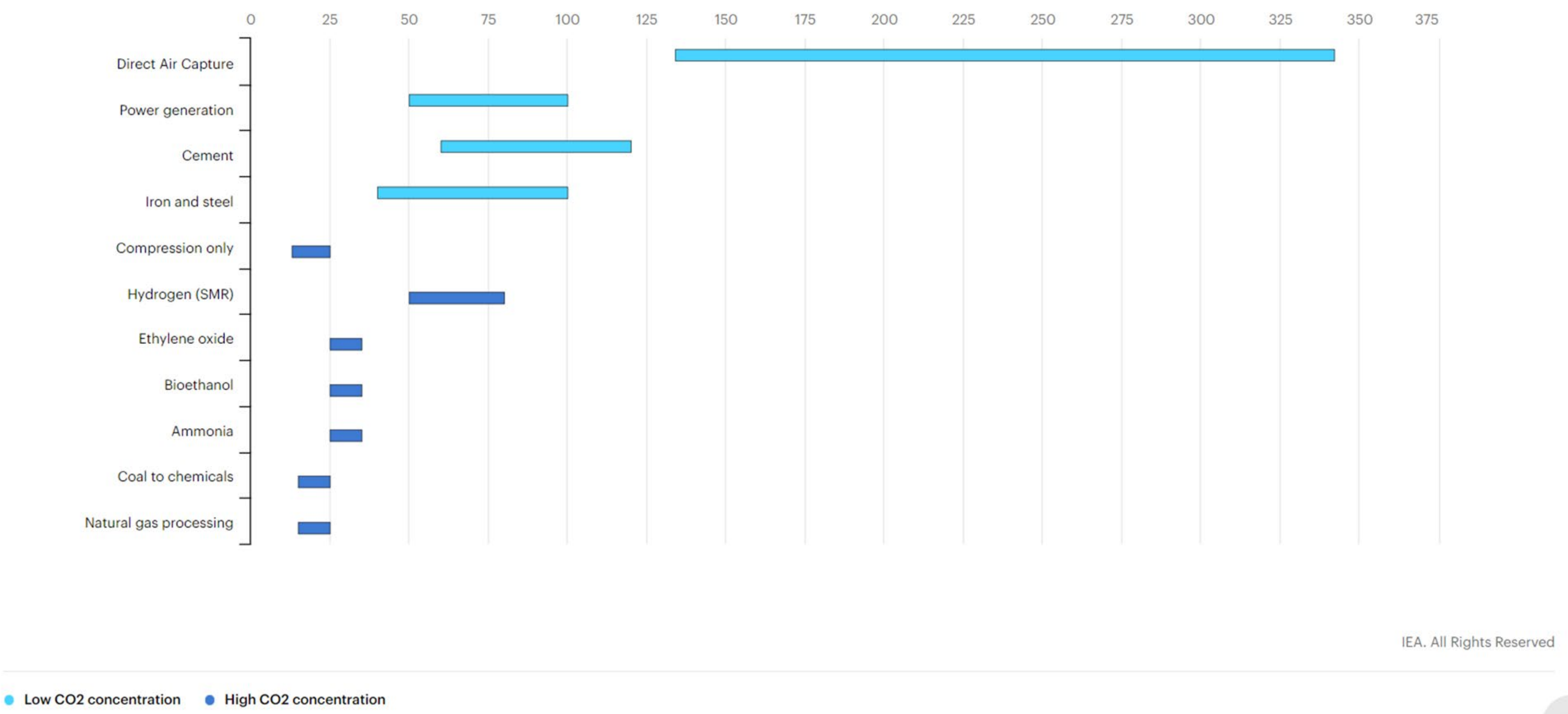


Global Status of CCS 2021, Global CCS Institute

The selection of a source for CCS is not only about the amount of CO_2 produced

- The concentration of the CO_2 in the gas stream matters alot! (the higher the CO_2 concentration, the lower the cost of CCS)
- Why? That is what thermodynamics say ☺ → we need more energy to capture dilute CO_2
- We should try to look for the low hanging fruits (gas streams with high CO_2)

- x-axis is cost of CCS (\$/ton CO_2 removed)



https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Why is that trend → it is about concentration of CO_2

Table 2.1 Properties of candidate gas streams that can be inputted to a capture process (Sources: Campbell et al., 2000; Gielen and Moriguchi, 2003; Foster Wheeler, 1998; IEA GHG, 1999; IEA GHG, 2002a).

Source	CO_2 concentration % vol (dry)	Pressure of gas stream MPa[a]	CO_2 partial pressure MPa
CO_2 from fuel combustion			
• Power station flue gas:			
Natural gas fired boilers	7 - 10	0.1	0.007 - 0.010
Gas turbines	3 - 4	0.1	0.003 - 0.004
Oil fired boilers	11 - 13	0.1	0.011 - 0.013
Coal fired boilers	12 - 14	0.1	0.012 - 0.014
IGCC[b]: after combustion	12 - 14	0.1	0.012 - 0.014
• Oil refinery and petrochemical plant fired heaters	8	0.1	0.008
CO_2 from chemical transformations + fuel combustion			
• Blast furnace gas:			
Before combustion[c]	20	0.2 - 0.3	0.040 - 0.060
After combustion	27	0.1	0.027
• Cement kiln off-gas	14 - 33	0.1	0.014 - 0.033
CO_2 from chemical transformations before combustion			
• IGCC: synthesis gas after gasification	8 - 20	2 - 7	0.16 - 1.4

[a] 0.1 MPa = 1 bar.
[b] IGCC: Integrated gasification combined cycle.
[c] Blast furnace gas also contains significant amounts of carbon monoxide that could be converted to CO_2 using the so-called shift reaction.

IPCC Special Report on Carbon Capture and Storage, 2005

Bioethanol

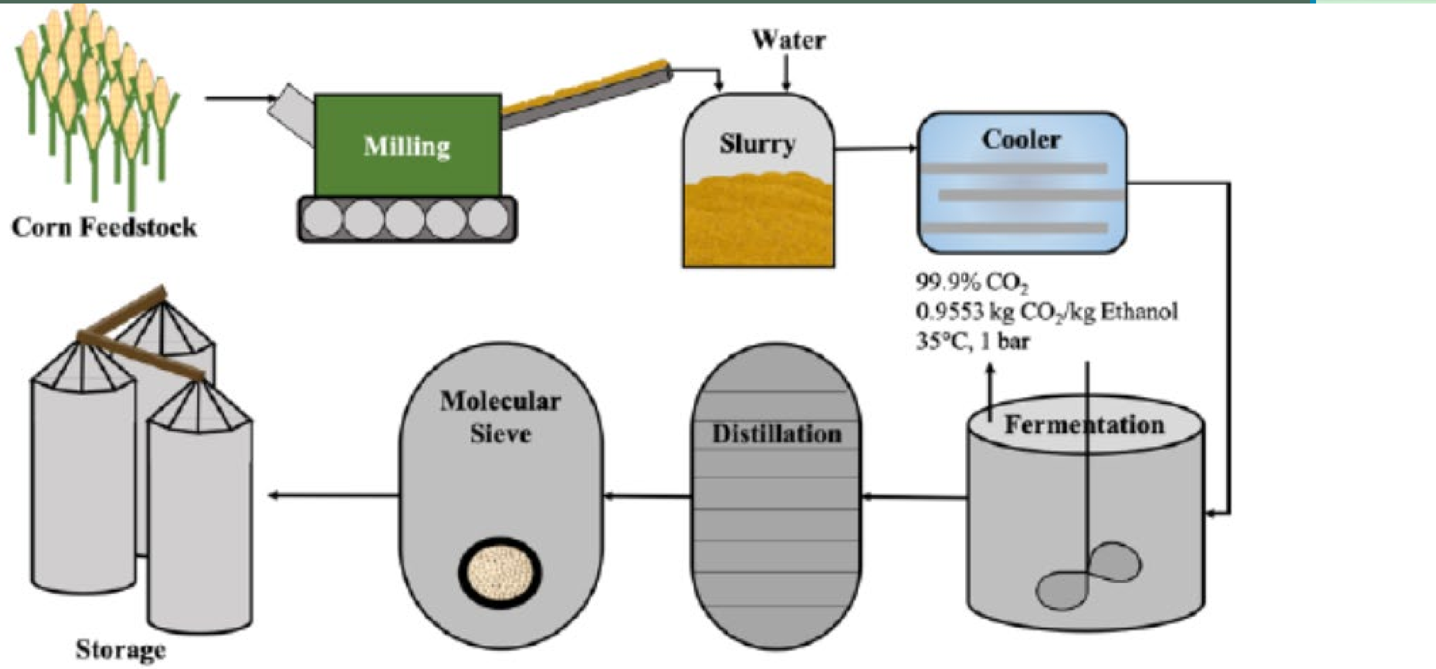


Figure S2. Process flow diagram of bioethanol production from corn via fermentation. The primary stream contains high-purity CO_2 (99+%) existing the fermenter.[32]

- Bioethanol → liquid fuel produced from fermentation of feedstock (e.g., corn)
- > 99% CO_2 (almost pure) →28 of the 202 ethanol facilities in US sell it for commercial use
- That is a perfect source for CCS project (should be called CS in this case → no capture, transport and injection cost only)
- They call such sources "Low-cost capture possibilities"

Pilorge, H. et al., Environmental Science and Technology, 2020 *54*(12), 7524-7532

- BECCS = Biomass energy with CCS
- Mtpa = million metric ton per year)

Table 3. Brief description of BECCS facilities operating today and planned projects (Notes: Mtpa—million tonnes per annum; tpa—tonnes per annum; tpd—tonnes per day).

Operating Today—Five Facilities in USA
Illinois CCS (USA)—**1 Mtpa**
Ethanol is produced from corn at its Decatur plant, producing CO_2 as part of the fermentation process
Kansas Arkalon (USA)—**200,000 tpa**
CO_2 is compressed and piped from an ethanol plant in Kansas to Booker and Farnsworth Oil Units in Texas for EOR
Bonanza CCS (USA)—**100,000 tpa**
CO_2 is compressed and piped from an ethanol plant in Kansas to nearby Stewart Oil field for EOR
Husky Energy CO_2 Injection (Canada)—**250 tpd**
CO_2 is compressed and trucked from an ethanol plant (Saskatchewan) to nearby Lashburn and Tangleflags oil fields for EOR
Farnsworth (USA)—**600,000 tonnes**
CO_2 is compressed from an ethanol plant (Kansas) and fertiliser plant (Texas) and piped to Farnsworth oil field for EOR

A lot of momentum for bioethanol CCS projects right now, we will see that shortly

Regufe, M. J. et al., *Energies*, 2021 *14*(9), 2406

Other "low-cost capture" possibilities

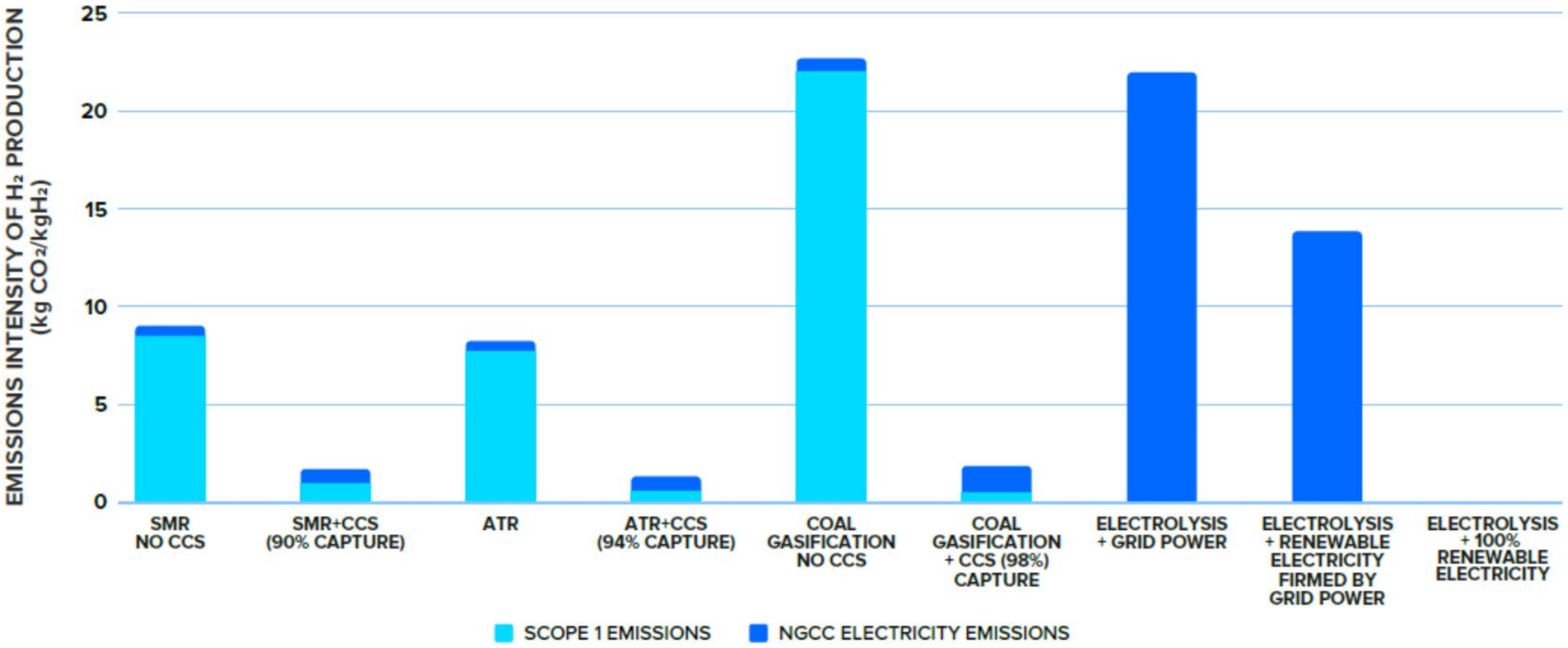
- Natural gas processing and Hydrogen gas manufacturing → What make these industries good candidates?

- Because CO_2 has to be captured anyways (e.g., CO_2 has to be < 2.5% for commercial natural gas) → so, CCS is a good option for that, especially:
  - If CO_2 is used for EOR/EGR (revenue generation)
  - If CO_2 is used to create clean hydrogen – called blue hydrogen (otherwise it is not justified) → basically CCS would justify H_2 as a clean fuel (burn H_2 get H_2O!)

If you are curious about H_2 (seen as the future fuel)

- Estimates that H_2 demand may exceed 500 million tons by 2050
- To produce hydrogen:
  - Electrolysis powered by renewable energy (green H_2)
  - Use biomass
  - Use fossil fuels (e.g., coal gasification -→ expose coal to steam and some O_2) → get hydrogen + CO_2 → CO_2 needs to be CCS [blue hydrogen]
  - Many blue H_2 projects are in development

Global Status of CCS 2021, Global CCS Institute



Assumes emissions intensity of natural gas combined cycle of 400 kgCO_2/MWh, 55 kWh/kgH_2 for electrolysis; 37 per cent of production from grid firmed electrolysis utilises zero emissions renewable electricity. Electricity required for methane and coal production pathways are full-lifecycle including power used in methane and coal production (9). Fugitive emissions from natural gas and coal production are not explicitly considered and will add to total lifecycle emissions from fossil pathways. Lifecycle emissions from construction and maintenance of renewable generation facilities are also not considered and will add to the emission intensity of those production pathways. SMR= Steam Methane Reformation. ATR = Autothermal Reformation. NGCC = Natural Gas Combined Cycle electricity generation.

FIGURE 23 EMISSIONS INTENSITY OF HYDROGEN PRODUCTION TECHNOLOGIES

Global Status of CCS 2021, Global CCS Institute

- Not only industrial sources are fit for CCS

Air is also another source for CO_2 capture….

- A number of DA-CCS projects are operating or in development.
- For example, 1 Mtpa project is in development in the Permian Basin in Texas
  - Expected to be operational by 2025
  - Developers: Carbon Engineering& Oxy Low Carbon Ventures
  - Capture facility is in proximity of CO_2 transport and storage infrastructure!

Global Status of CCS 2021, Global CCS Institute

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Where? (two sides)

- Geographically? (on the map)
- Which geologic formations? (where underground)

Geographically

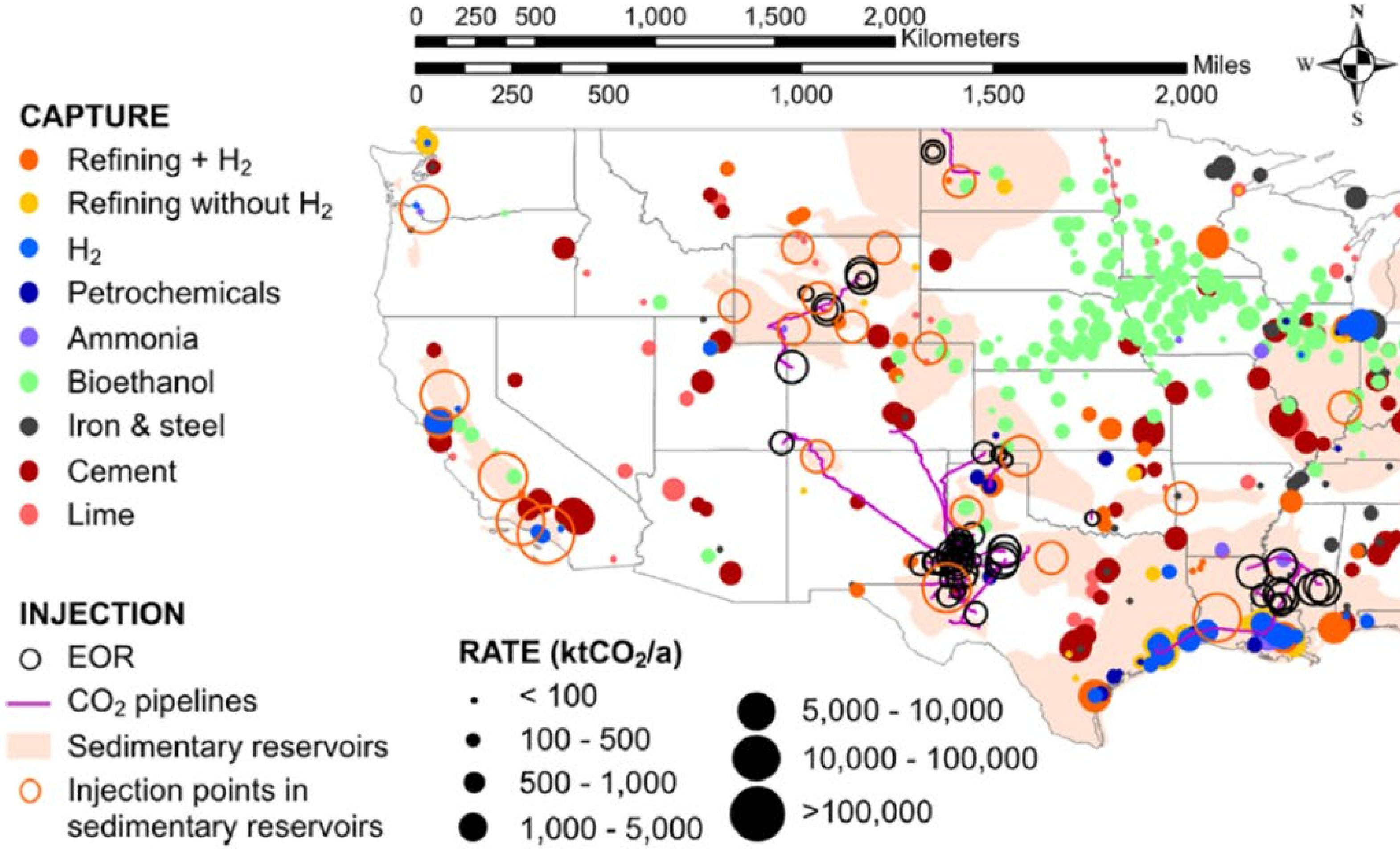
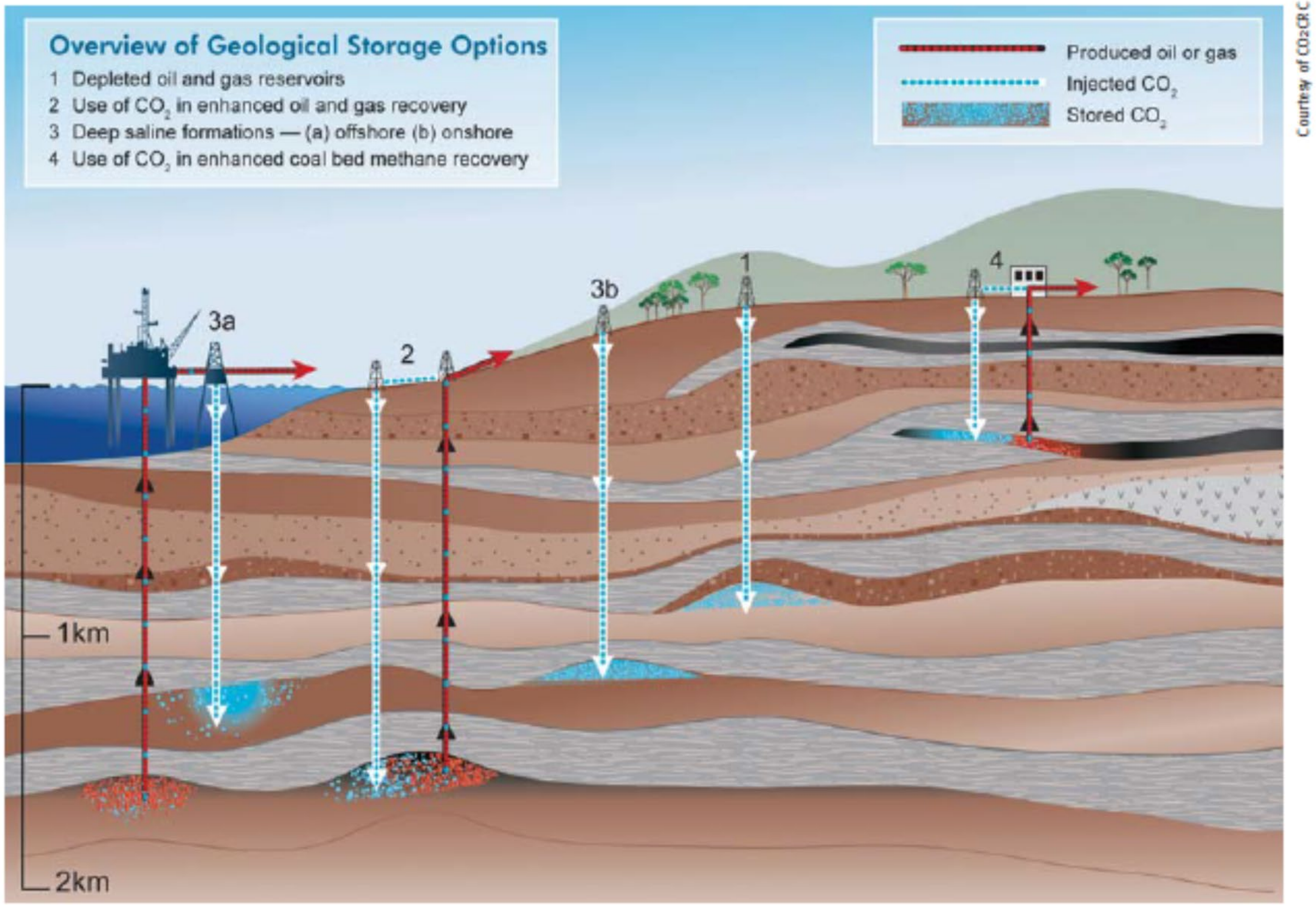


Figure 4. Geographical distribution of the CO_2 capture opportunities from industrial point sources (closed circles) in the United States along with EOR and dedicated geological sequestration opportunities (open circles).

Pilorgé, H., McQueen, N., Maynard, D., Psarras, P., He, J., Rufael, T., & Wilcox, J. (2020). Cost analysis of carbon capture and sequestration of process emissions from the US industrial sector. Environmental Science & Technology, 54(12), 7524-7532.

Which formations?

- Saline formations
- Oil and natural gas reservoirs
- Unminable coal seams
- Organic rich shales
- Basalt formations



Geological Storage Options.

This text is a faithful summary, by GreenFacts, of the IPCC Special Report on Carbon Dioxide Capture and Storage. A longer, more detailed summary can be found on www.greenfacts.org/en/co2-capture-storage/.

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The U.S. alone has way more than enough to store the global CO_2 capture targets….(based on estimates)

- Let's do a calculation for the CO_2 that need to be sequestered globally
- Total underground storage capacity 3400 Gt of Carbon = 12600 Gt of CO_2 capacity
- By 2100, if globally we need to store 20 Gt CO_2 per year (max) * 80 years = 1600 Gt CO2 by the year 2100
- It means the US has enough storage for (12600/1600) → the US has about 700 years worth of storage space!

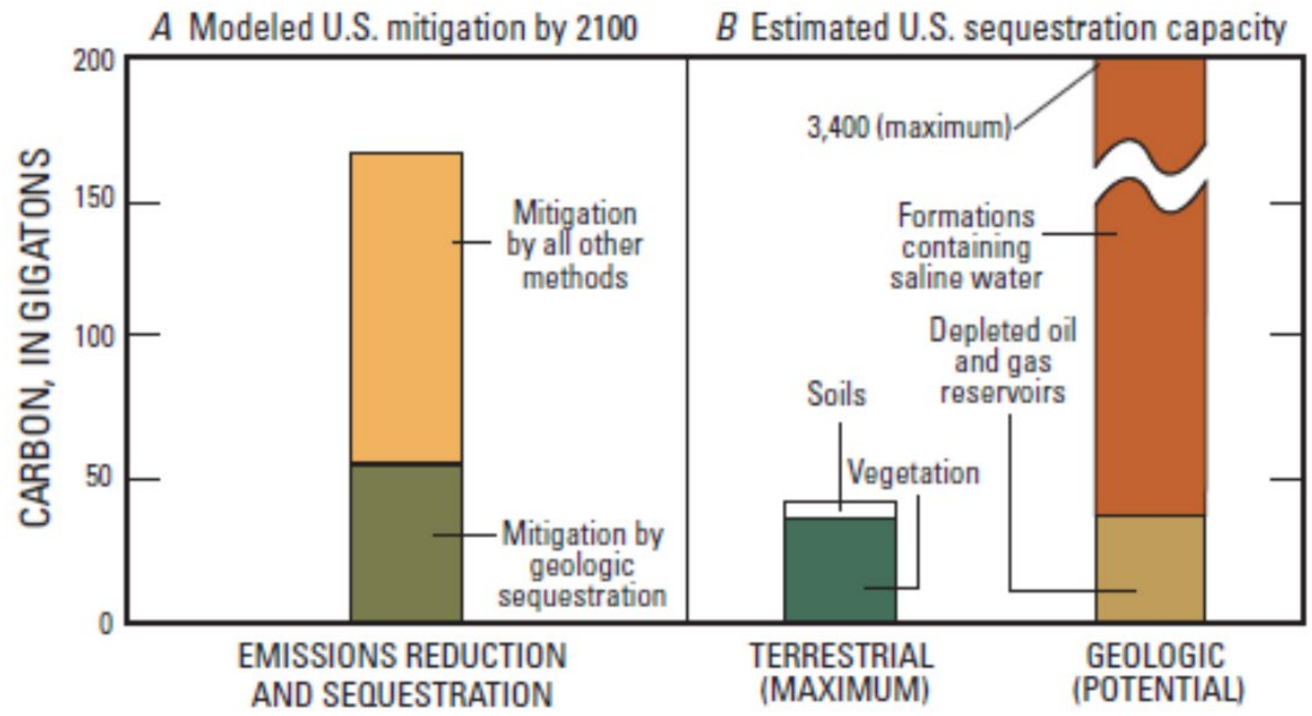

Figure 4. Estimated U.S. atmospheric CO_2 (as carbon) mitigation needs and potential sequestration capacities: *(A)* Cumulative U.S. CO_2 emissions reduction and sequestration needed by 2100 to help stabilize atmospheric CO_2 at 550 parts per million (model results from U.S. Climate Change Science Program); *(B)* Estimated U.S. CO_2 sequestration capacity. (The estimate of ~3,400 gigatons carbon for potential geologic storage is equivalent to ~12,600 gigatons CO_2, as estimated by the U.S. Department of Energy. Terrestrial sequestration is not expected to approach the estimate shown. Uncertainties in estimated terrestrial and geologic sequestration are substantial.)

https://pubs.usgs.gov/fs/2008/3097/pdf/CarbonFS.pdf

Table A-1. Estimates of U.S. Storage CO_2 Capacity

(in billions of metric tons)

Formations	Low	Medium	High
Oil and Natural Gas Reservoirs	186	205	232
Unmineable Coal Seams	54	80	113
Saline Formations	2,379	8,328	21,978
Total	2,618	8,613	22,323

Source: NETL, *Carbon Utilization and Storage Atlas*, 5th ed., August 20, 2015, https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf (data current as of November 2014).

Notes: The low, medium, and high estimates correspond to a calculated probability of exceedance of 90%, 50% and 10% respectively, meaning that there is a 90% probability that the estimated storage volume will exceed the low estimate and a 10% probability that the estimated storage volume will exceed the high estimate. Numbers in the table may not add precisely due to rounding.

Saline formations are key for CCS….we will have a lot of discussion about it later

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Let us analyze this map? What do we see?

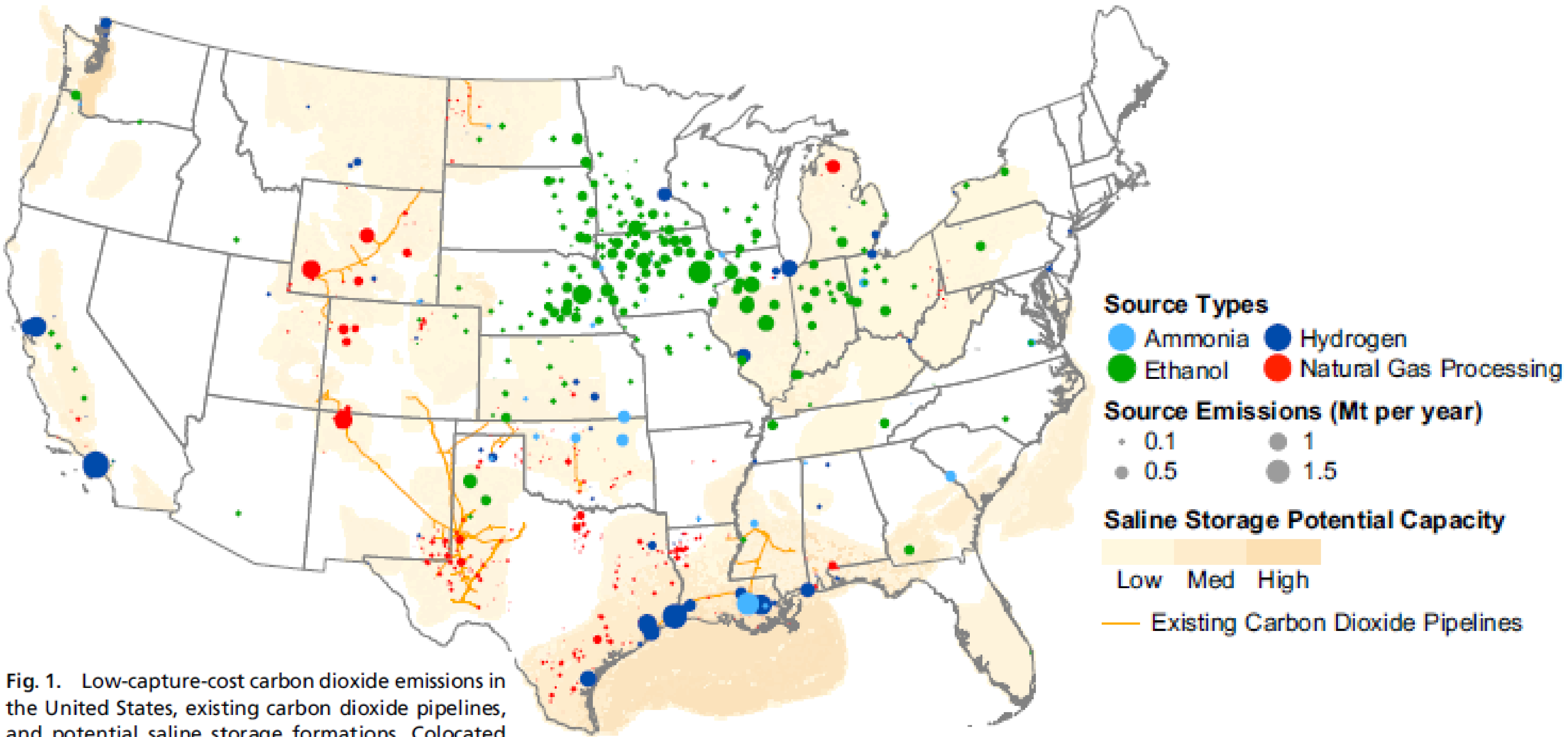
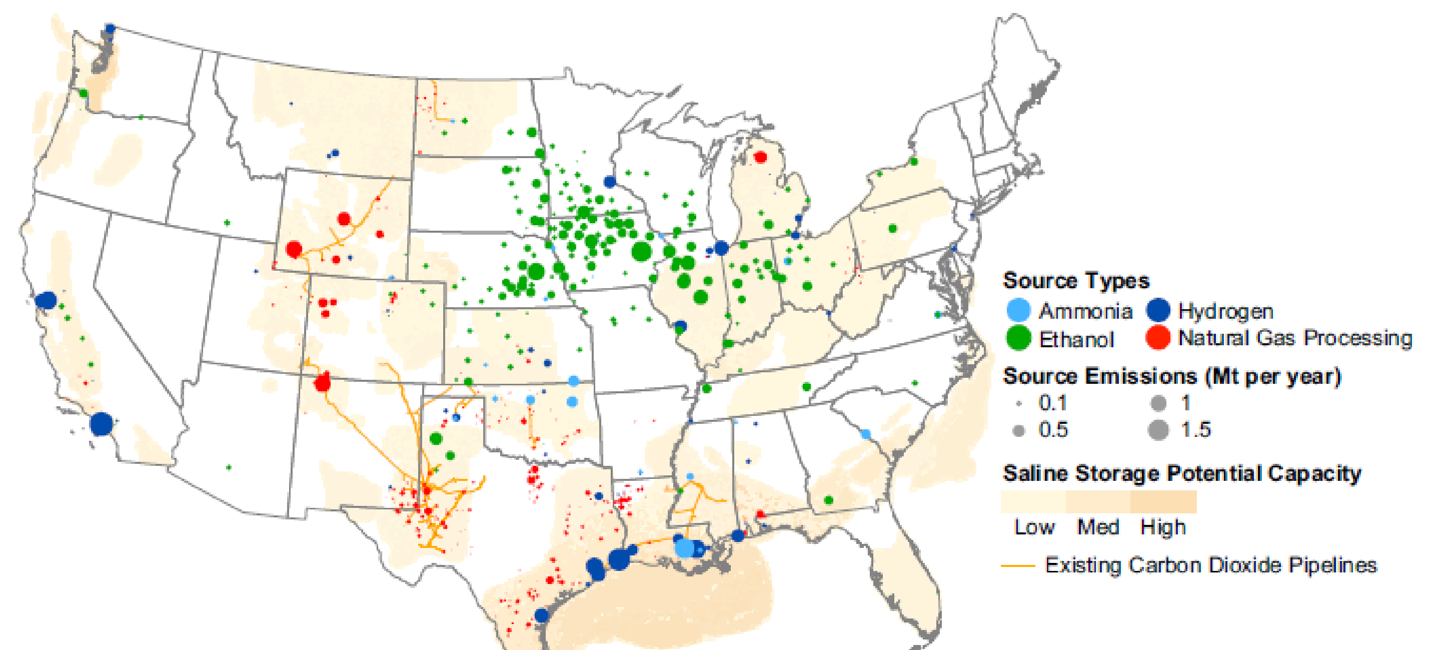


Fig. 1. Low-capture-cost carbon dioxide emissions in the United States, existing carbon dioxide pipelines, and potential saline storage formations. Colocated

Edwards, R. W., & Celia, M. A. (2018). *Proceedings of the National Academy of Sciences, 115*(38), E8815-E8824.

Let us analyze this map? What do we see?

- The Midwest “stands-out”:
  - A large number of low-capture CO_2 cost facilities (bioethanol plants) in Midwestern States
    - They have ~50% of the total low-capture cost facilities in the US
    - ~ 40 million tons CO_2 /year is emitted from these facilities
  - HOWEVER:
  - these facilities are not near CO_2 transport pipelines and they are also not close to saline formations for storage



Edwards, R. W., & Celia, M. A. (2018). *Proceedings of the National Academy of Sciences*, *115*(38), E8815-E8824.

So what?

- A regional pipeline **network** is needed to transport the CO_2 from these facilities for injection in saline formations.
- That is what is actually happening right now……
- Notes:
  - ~210 bioethanol refineries exist in the US → about 40 of these facilities sell their CO_2 for EOR, food and beverage, and dry ice industries (CCUS) --→ but the rest need to be stored to minimize the carbon footprint of bioethanol

Edwards, R. W., & Celia, M. A. (2018). *Proceedings of the National Academy of Sciences*, *115*(38), E8815-E8824.

Two CO_2 pipelines proposed in Iowa

Summit Carbon Solutions	Navigator CO_2 Venture
• Transports 12 million tons of CO_2 per year from ethanol, fertilizer, and other Agriculture Industries for storage in North Dakota • Connects 30 facilities in 5 states (Iowa, Minnesota, North Dakota, South Dakota, and Nebraska) • Costs $4.5 billion • Storage in North Dakota	• Moving in the opposite direction for storage in Illinois • 1200 miles of pipelines in 5 states (Nebraska, Iowa, South Dakota, Minnesota, and Illinois)

Big Picture CCUS

- CO_2 emissions (we are in trouble)
- Options to achieve net zero emissions by 2050?
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- Ok, seems like CCS is a must → Which emission sources should we target for CCS projects
- Where to sequester the CO_2 captured?
- Do we have enough underground storage capacity?
- Recent CCS developments in the Midwest and why?
- CCS hubs (networks)?
- CCS is not pie in the sky
- There is momentum for CCS like never before → Why? (incentives)
- Concluding Remarks

CCS Networks

- It is about the the economy of scale:
  - In the past, a capture plant would have its own pipeline and injection wells. This only works for large emitters.
  - Small emitters (≤ 0.2 Mt/year) would benefit from a hub (projects sharing infrastructure)
  - Let us see example of the difference this strategy makes……

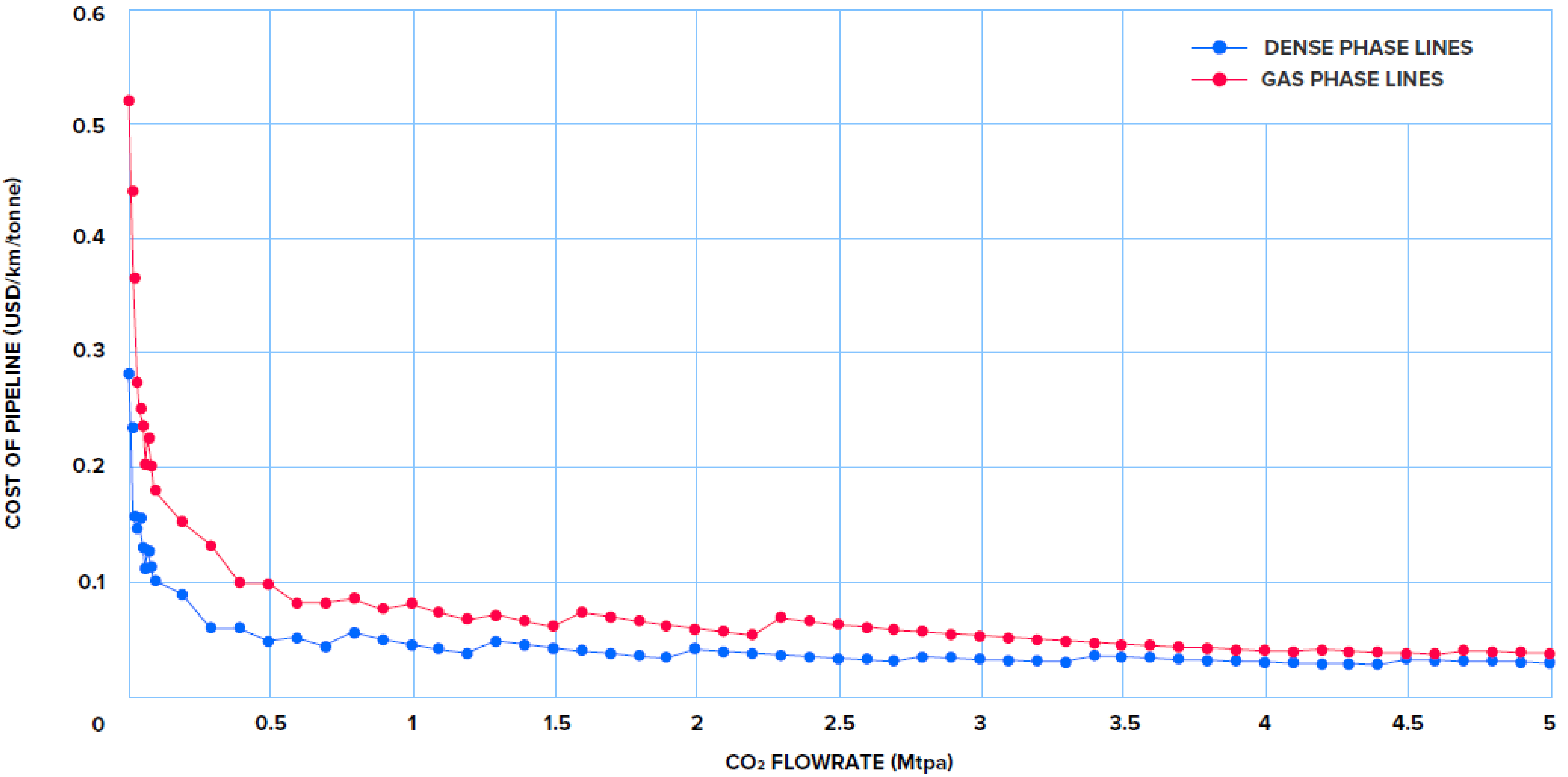

FIGURE 22 INDICATIVE COSTS OF CO_2 PIPELINES - DENSE PHASE (>74 BAR) AND GAS PHASE

Global Status of CCS 2021, Global CCS Institute

Example of a proposed “carbon hub”

Environmental Science & Technology pubs.acs.org/est Article

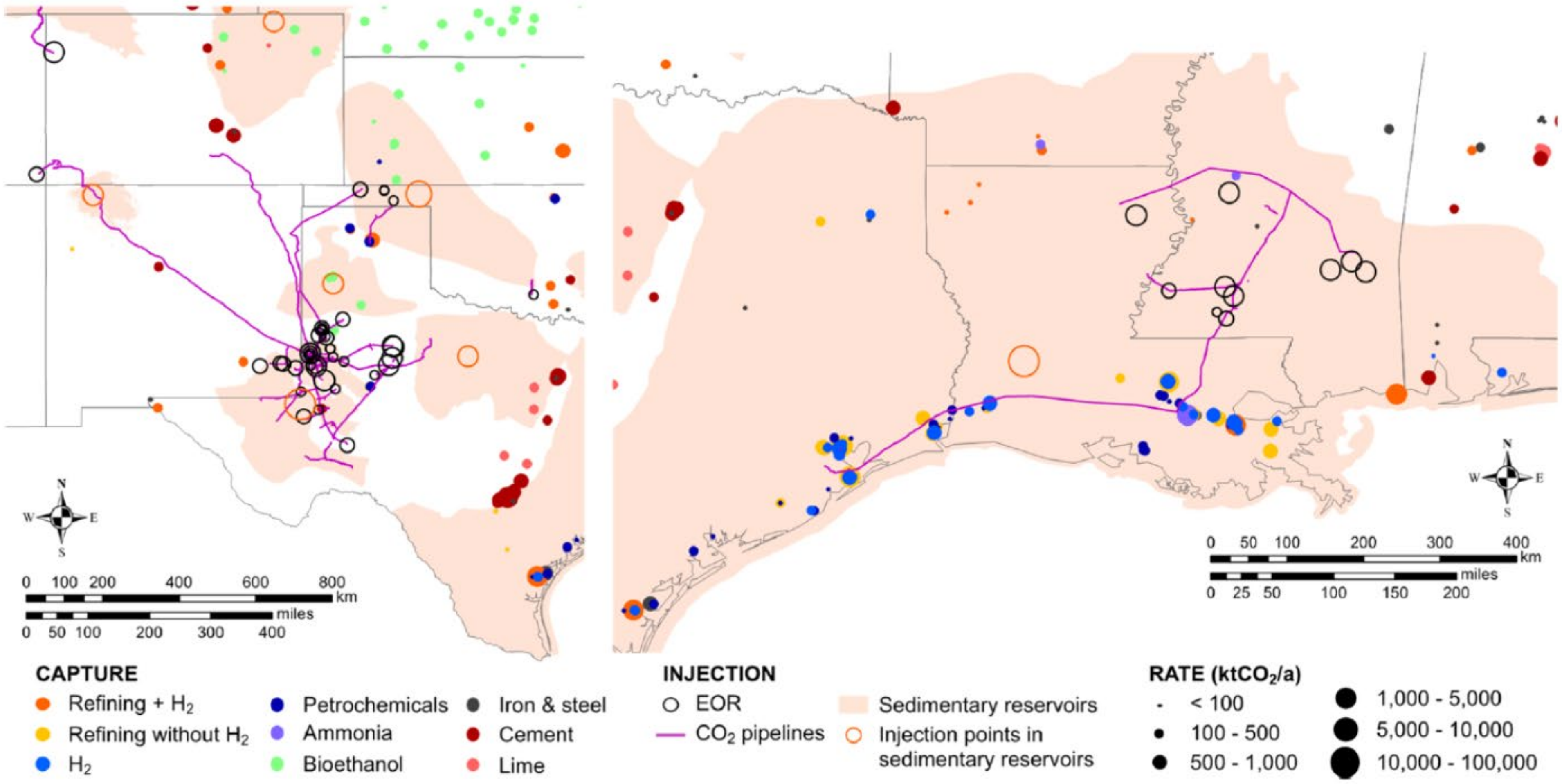

Figure 6. Demonstrated “carbon hub” potential with CO_2 capture and neighboring sink opportunities surrounding existing CO_2 pipelines in the Permian Basin (left) and Gulf Coast (right) regions.

By the way, we need alot of pipelines for CCS

- Currently the US has ~ 5,000 miles of CO_2 transport pipelines
- By 2050, ~ 27,000 miles of CO_2 pipeline network would be needed

Big Picture CCUS

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It is not that recent!

Table 13.1. Existing large-scale storage operations

Project	Leader	Location	CO_2 source	CO_2 sink
Sleipner (1996)	Statoil	North Sea, Norway	Gas processing	Saline formation
Weyburn (2000)	Pan Canadian	Saskatchewan, Canada	Coal gasification	EOR
In Salah (2004)	BP	Algeria	Gas processing	Depleted gas reservoir
Snovit (2008)	Statoil	Barents Sea, Norway	Gas processing	Saline formation

Sleipner:

- Gas field located 250 km of the Coast of Norway
- The natural gas produced has ~ 9% CO_2 (not good quality – needs to be < 2.5%)
- Separate CO_2, compress it, and inject it 800 m below seabed (1 million CO_2 ton/year)
- The storage formation is 250 m thick

https://sequestration.mit.edu/pdf/2009_CO2_Capture_and_Storage_Ch13_book.pdf

Global Status of CCS 2021, Global CCS Institute

Observations?

Table B-1. Large Scale CO_2 Injection Projects in the United States

Project	CO_2 Source	Type	Injection Status	Volume Injected (in tons)	Funding Source and Amount
Illinois Industrial Carbon Capture and Storage Project (ADM Facility) Decatur, IL	Ethanol fermentation plant	Saline storage	Active injection and sequestration	1.3 million	ARRA $141,405,945 (funding includes Illinois Basin Project)[a]
Air Products Project Port Arthur, TX	Steam methane reformers	EOR	Active injection	5 million	ARRA $284,000,000[b]
Michigan Basin Project Otsego County, MI	Natural gas processing plant	EOR	Active injection	1.5 million	RCSP $1,019.414[c]
Petra Nova Plant Thompsons, TX	Coal-fired power plant	EOR	Active injection	1.4 million per year	ARRA $167,000,000 and FY2016 Consolidated Appropriations Act $23,000,000 ($190,000,000 total)[d]
Citronelle Project Citronelle, AL	Coal-fired power plant	Saline storage	Completed Sept. 2014; post-injection monitoring	110,000	RCSP $76,981.260[e]
Illinois Basin Decatur Project (ADM Facility) Decatur, IL	Ethanol fermentation plant	Saline storage	Completed Nov. 2014; post-injection monitoring	1 million	RCSP $141,405,945 (funding includes Illinois Industrial Project)[f]
Cranfield Project Natchez, MS	Natural	EOR with saline storage	Completed Jan. 2015; post-injection monitoring	4.7 million	RCSP $76,981.260[g]
Bell Creek Field Project Crook County, WY	Natural gas processing plants	EOR	Completed; post-injection monitoring	3 million	RCSP $95,453,751[h]
Farnsworth Unit Ochitree County, TX	Ethanol and fertilizer production plants	EOR	Completed; post-injection monitoring	800,000	RCSP $65,618,315[i]
Kevin Dome Project Toole County, MT	None	Saline storage	Project suspended	No injection	RCSP $67,000,000[j]

Injection and Geologic Sequestration of Carbon Dioxide:
Federal Role and Issues for Congress
January 24, 2020, Congressional Research Services

Source:
Ethanol and natural gas, you remember why?

Purpose:
Mostly EOR

The Decatur, IL facility is the first in the nation to obtain Class VI permit for injections into saline aquifer

Source of funding:
RCSP

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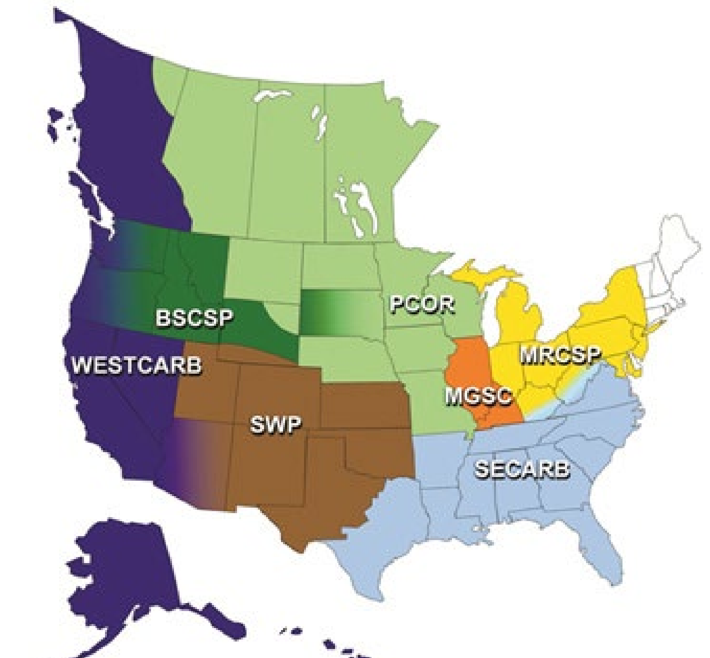
What is RCSP?
Demonstration facilities o prove viability of CO_2 storage – DOE-led effort

- RCSP – Regional Carbon Sequestration Partnership Initiative
- Implemented through the DOE (National Energy Technology laboratory (NETL)) and partners with > 400 organizations, in 43 states and 4 Canadian provinces
- Implemented large (at least 1 million tons of CO_2/year) and small CCS projects
  - Cranfield Project (SECARB) (Mississippi)
  - Citronelle Project (SECARB) (Alabama)
  - Illinois Basin Decatur CO_2 Project (MGSC)(Illinois)
  - Bell Creek Field Project (PCOR Partnership)(Montana)
  - Farnsworth Unit, Ochiltree Project (SWP)(Texas)
  - Michigan Basin Project (MRCSP) (Michigan)
  - Kevin Dome Project (BSCSP) (Montana)



https://netl.doe.gov/

Examples to demonstrate the importance of the MRCSP

- The Midwest Regional Carbon Sequestration Partnership (MRCSP) formed in 2003 had the goal to determine the feasibility of CCUS in the Midwest.
- Battelle led and completed this reserach effort in 2021.
- The program consisted of 3 R&D phases:
  - Phase 1 (2003-2005): identified CO_2 emission sources in the region, assessed storage potential in geologic formations and identified locations for demonstration projects
  - Phase 2 (2005 – 2010): conducted 3 pilot field scale validation tests to demonstrate the efficacy and safety of the geologic sequestration system
  - Phase 3 (2008-2019): focused on large scale implementation of CCUS technologies to prepare for commercialization
- Outcome of this ~20 year program:
  - Project demonstrated the technical and economic feasibility of CCUS projects in the Midwest
  - The CO_2 used for EOR generated 1.1 million barrels of oil
  - Over the duration of 20 years, 1.6 million metric tons were captured and safely stored in deep geologic formation

https://www.battelle.org/insights/case-studies/case-study-details/bringing-carbon-capture-utilization-and-storage-(ccus)-to-commercial-scale-through-the-midwest-regional-carbon-sequestration-partnership-(mrcsp)

Back to CO_2 projects around the world

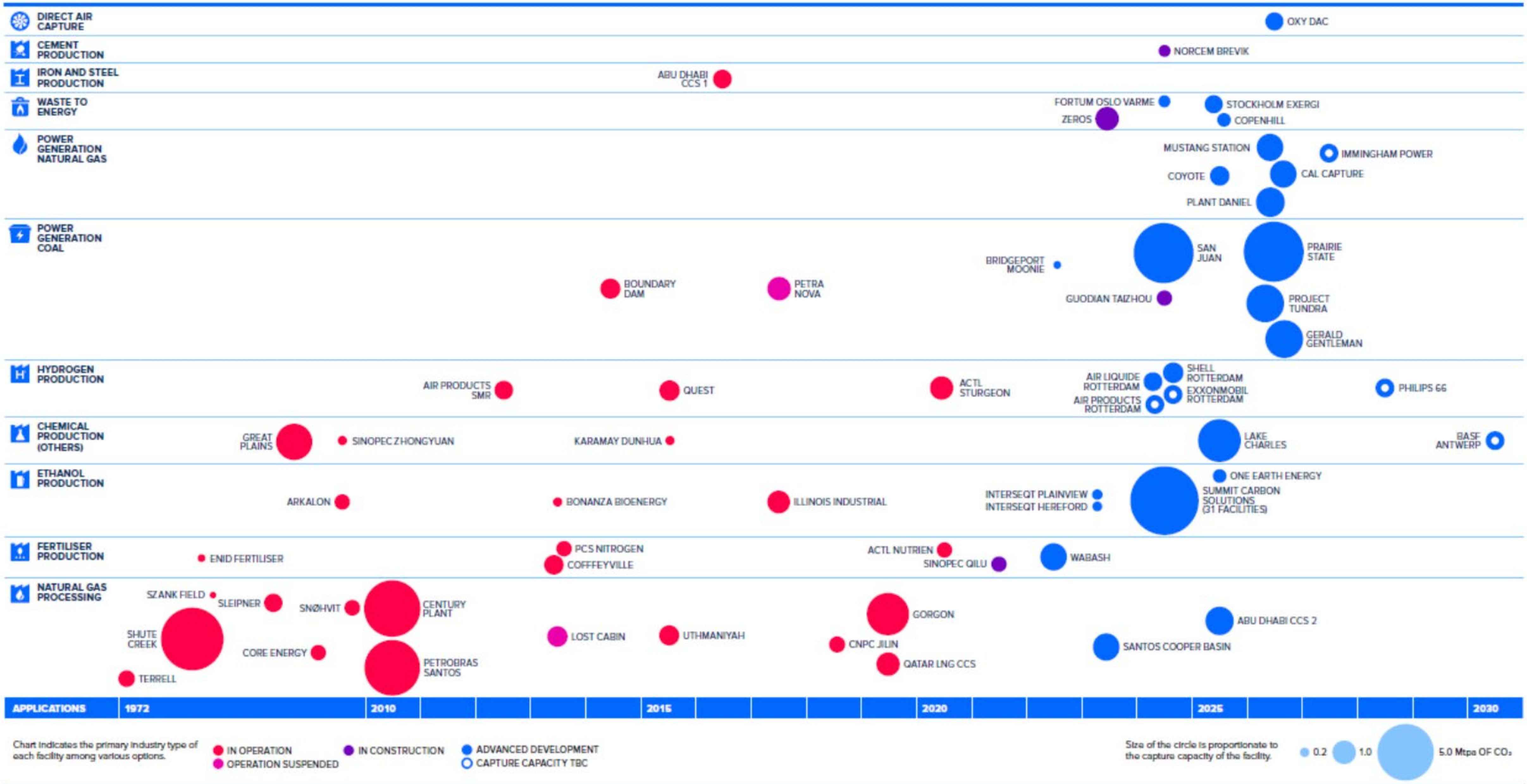
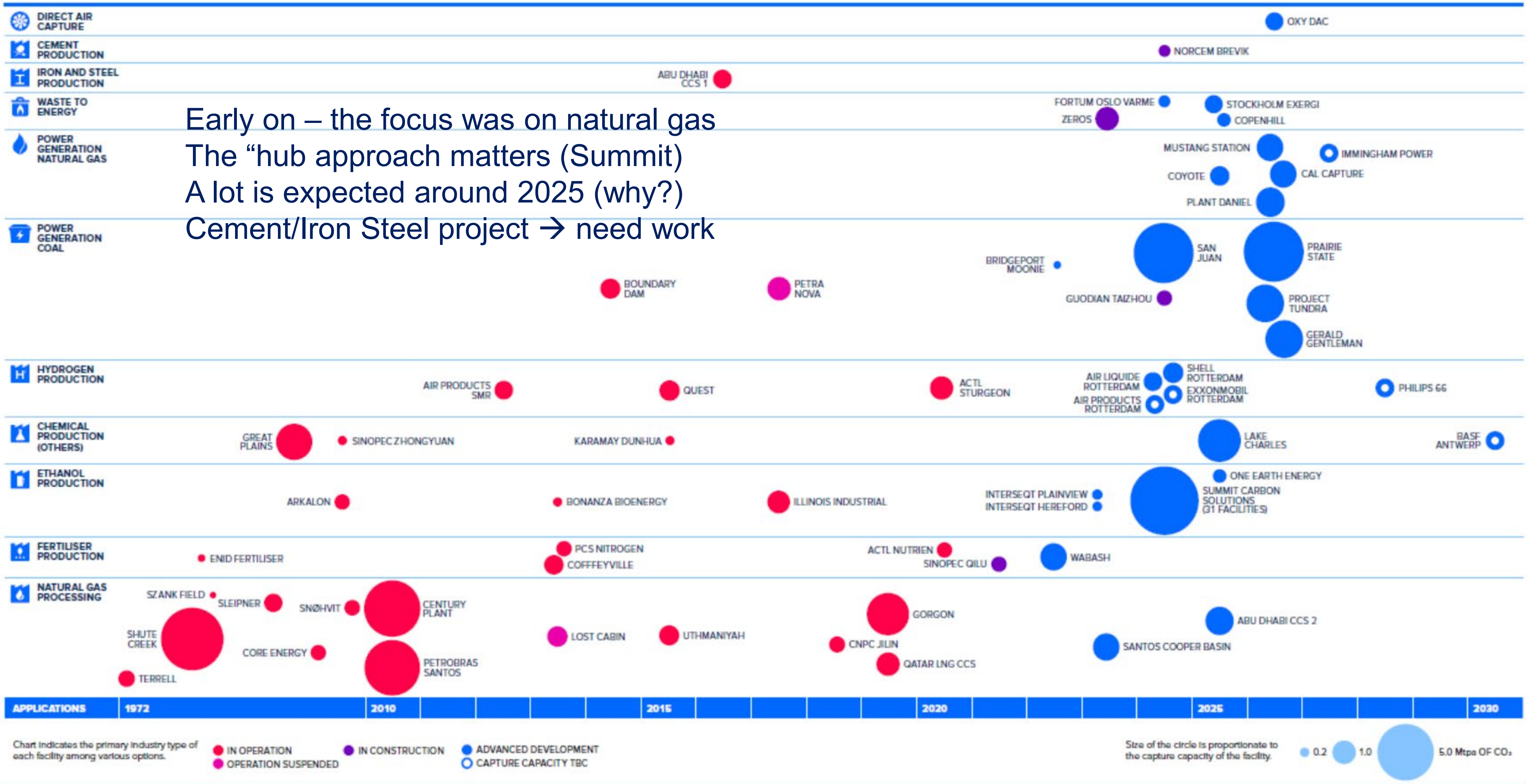


FIGURE 9 CCS PROJECTS BY SECTOR AND SCALE (BY CO_2 CAPTURE CAPACITY) OVER TIME

Global Status of CCS 2021, Global CCS Institute

Early on – the focus was on natural gas
The “hub approach matters (Summit)
A lot is expected around 2025 (why?)
Cement/Iron Steel project → need work



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Global Status of CCS 2021, Global CCS Institute

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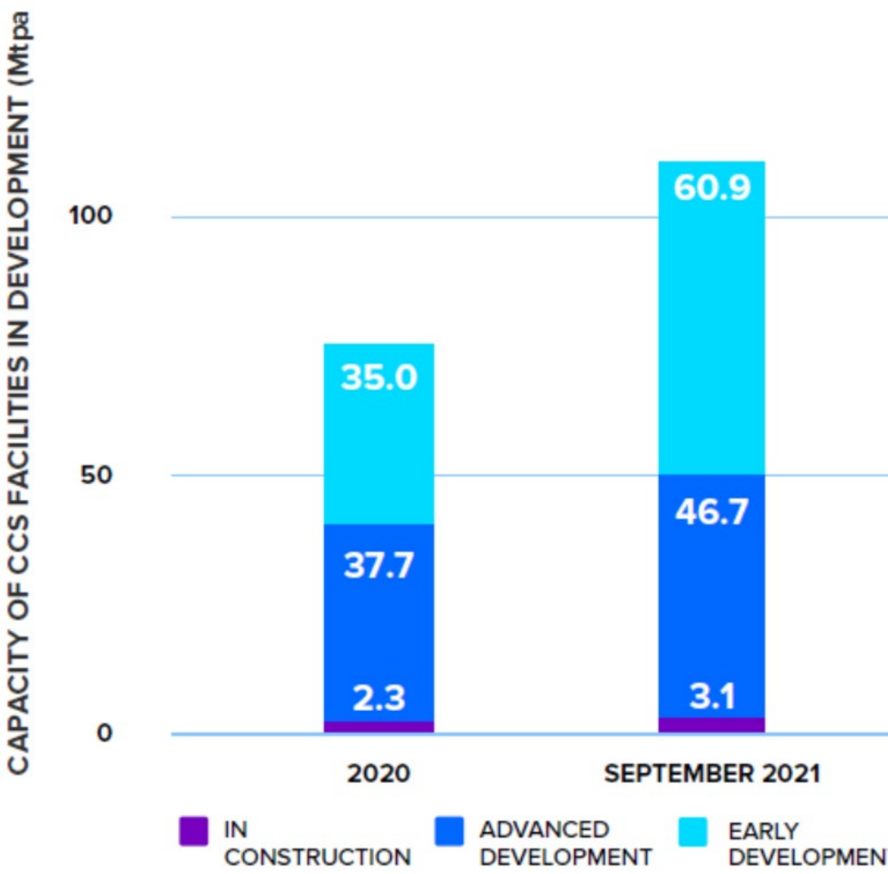
- Concluding Remarks

There is a boom in CCS projects

- ~ 108 facilities in the pipeline
- Capacity of CCS projects ~ doubled in 1 year
- 71 projects were added in the first 9 months of 2021 – this is really a big momentum there (36 of these projects are in the US)



	OPERATIONAL	IN CONSTRUCTION	ADVANCED DEVELOPMENT	EARLY DEVELOPMENT	OPERATION SUSPENDED	TOTAL
Number of facilities	27	4	58	44	2	135
Capture capacity (Mtpa)	36.6	3.1	46.7	60.9	2.1	149.3

FIGURE 6 COMMERCIAL CCS FACILITIES IN SEPTEMBER 2021 BY NUMBER AND TOTAL CAPACITY

Global Status of CCS 2021, Global CCS Institute

Why? Major contributing factors to the boom in CSS

- Strengthened climate goals and CCS is a major component to achieve these goals
- Growth in interest in producing hydrogen fuel with low CO_2 footprint (50 CCS project and underdevelopment for Hydrogen production facilities)
- The DOE efforts to advance the technology and science is paying off:
  - Funding, strategizing, and assessing CCS projects (developed Best Practices Manuals for CCS – treasure trove)
- The recent infrastructure bill (the impact is not there yet – assigned $12 billion for CCUS)
- The 45Q Tax Credit
- California Low Carbon Fuel Standard

Section 45Q of the Internal Revenue Code

- "45Q" tax credit.
- Congress passed amendments in February 2018 to incentivize CCUS projects.
- To receive the credit, the CCUS project must begin construction in 2024.
- The credit will be received for 12 years once the projects is in service.

Edwards, R. W., & Celia, M. A. (2018). Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. *Proceedings of the National Academy of Sciences*, *115*(38), E8815-E8824.

What is the credit? And what does it depend on?

Table 1 : The 45Q tax credit for CCS [35]

	Plant size in $ktCO_2/yr$			Relevant level of tax credit (USD/tCO_2)							
	Power plants	Industrial facilities	DAC	2020	2021	2022	2023	2024	2025	2026	Onwards
Geologic storage	Min. 500	100	100	34	36	39	42	45	47	50	Indexed to inflation
CO_2-EOR-storage	Min. 500	100	100	22	24	26	28	31	33	35	
Utilization dependent on actual emissions reductions	25–500	25	25	22	24	26	28	31	33	35	

It depends on:

- Source of captured CO_2
- Minimum amount to be captured (called Plant size in the table – unit is in 1000 ton/year capture)
- Pathway of CO_2 after capture

Havercroft I, Townsend A. *The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers*. Global CCS Institute. 2019. https://www.globalccsinstitute.com

California LCFS

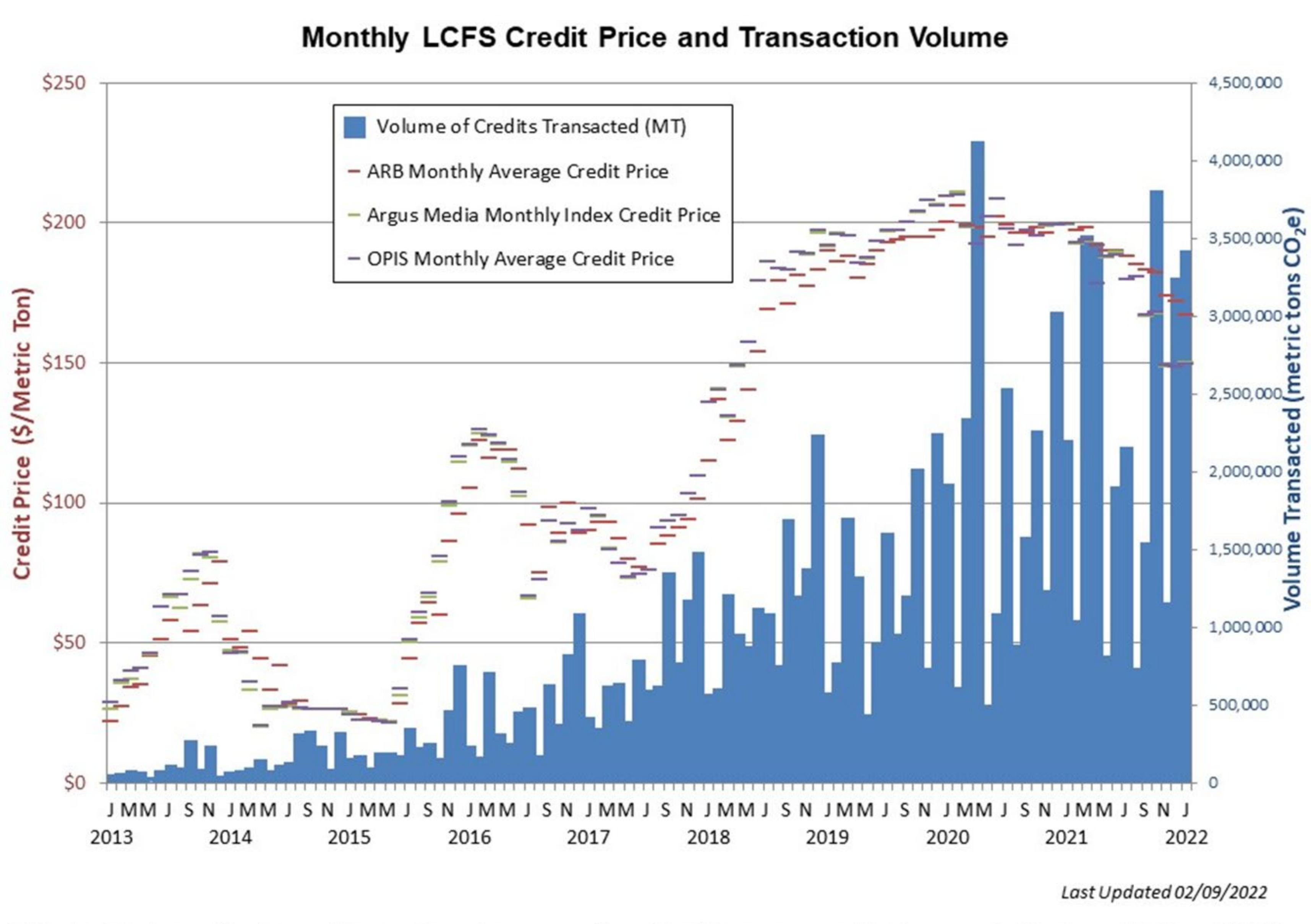
Figure 3: Different types of CCS projects that can qualify to generate credits under the LCFS

	DIRECT AIR CAPTURE PROJECTS	CCS AT OIL & GAS PRODUCTION FACILITIES	CCS AT REFINERIES PROJECTS	ALL OTHER CCS PROJECTS (E.G. CCS WITH ETHANOL)
Location of CCS project	Anywhere in the world	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California
Storage site	Onshore saline or depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-EOR			
Credit method	Project-based	Project-based, under the Innovative Crude Provision	Project-based, under the Refinery Investment Credit Program	Project-based or fuel pathway
Earliest date which existing projects eligible	Any	2010	2016	Any
Requirements	Project must meet requirements specified in the CCS Protocol			
Additional restrictions	None	Must achieve minimum CI or emission reduction	None	None

The LFCS (existed since 2009) and was amended in 2018 to include CCUS projects

Applies to any CCUS operator that sell fuel in California

Source: Global CCS Institute, 2019 Policy Report – The LCFS AND CCS Protocol: An overview for policymakers and project developers



This chart tracks credit prices and transaction volumes over time. Monthly average credit prices reported by Argus Media and OPIS [used with permission] are shown along with CARB monthly average price.

https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard

- The LCFS credit has been trading between $122/tCO_2$ and $190/tCO_2$!!

Credits are earned if a fuel has a carbon intensity lower than the carbon intensity set by alifornia in a given year (deficit will be generated if the fuel carbon intensity exceeds the target)

LCFS Compliance Schedule for 2011 to 2020 for Gasoline and Fuels Used as a Substitute for Gasoline

Year	Average Carbon Intensity (gCO_2E/MJ)
2010	Reporting Only
2011	95.61
2012	95.37
2013	97.96
2014	97.47
2015	96.48
2016	95.49
2017	94.00
2018	92.52
2019	91.03
2020 and subsequent years	89.06

https://www.transportpolicy.net/standard/california-fuels-low-carbon-fuel-standard/

Figure 9: Comparison of the eligibility requirements and scope of the LCFS and 45Q

	LCFS	45Q
GEOGRAPHIC SCOPE	Any location globally, provided sequestration site is onshore and transport fuel sold in California (except for DAC projects)	Any location in the United States
TYPES OF CCS PROJECT	Any fuel production facility or Direct Air Capture facility that captures CO_2 and either stores it in a dedicated geological site or uses it for CO_2-EOR	Any industrial or Direct Air Capture facility that either stores CO_2 in a dedicated geological site or uses it for CO_2-EOR or other utilization purposes
MINIMUM PROJECT SIZE	Any project size, except for projects applying under the Innovative Crude Provision which must meet minimum size thresholds	Projects are required to meet the following annual minimum capture thresholds in tonnes of CO_2: Power generators (500,000); Industrial and Direct Air Capture plants (100,000); Industrial Pilot Plants (25,000)
EMISSIONS COVERED	Carbon dioxide, methane, nitrous oxide, volatile organic compounds and carbon monoxide	Carbon dioxide and carbon monoxide
QUALIFICATION PERIOD RESTRICTIONS	None	Only facilities for which construction begins before January 1 2024 are eligible
CREDIT GENERATION DURATION	Duration of the injection period	12 years
CREDIT BUFFER & INVALIDATION	Operators must contribute between 8% and 16.4% of credits generated to a Buffer Account and retire credits to cover any leaks that occur up to 50 years post-injection	IRS is currently consulting on the approach to the recapture of tax credits in the event of leakage
PERMANENCE REQUIREMENTS	Demonstrated through receiving and maintaining Permanence Certification under the LCFS	IRS is currently consulting on the permanence requirements

There is potential to "stack" LFCS credit with federal 45Q tax credit

Other states are working to provide CCS incentives

- 116^{th} Congress efforts (2019-2021)

Table 2. Carbon Sequestration Related Legislation in the 116th Congress

Bill Number	Short Title	Major Carbon Sequestration Related Provision
H.R. 1166	USE IT Act	Would amend the Clean Air Act by directing EPA to conduct certain carbon capture research activities. Would require DOE to submit a report to Congress on the potential risks and benefits to project developers associated with increased storage of CO_2 in deep saline formations and recommendations for federal policy changes to mitigate identified risks. Would direct the Council on Environmental Quality (CEQ) to prepare a report including information on permitting and review of CCS projects and issue guidance on development of CO_2 pipelines and storage projects.
H.R. 3607	Fossil Energy Research and Development Act of 2019	Would amend the Energy Policy Act of 2005 to direct DOE to carry out a program of R&D and demonstration for CCS. Would direct DOE to conduct large-scale carbon sequestration partnerships through RCSP.
H.R. 5156	Carbon Capture and Sequestration Extension Act of 2019	Would amend Section 45Q of the Internal Revenue Code to extend the deadline for the start of construction of a qualified facility to January 1, 2025.
S. 383	USE IT Act	Would amend the Clean Air Act by directing EPA to conduct certain carbon capture research activities. Would require DOE to report to Congress on the potential risks and benefits to project developers associated with increased storage of CO_2 in deep saline formations and recommendations for federal policy changes to mitigate identified risks. Would direct CEQ to prepare a report including information on permitting and review of CCS projects and issue guidance on development of CO_2 pipelines and storage projects.
S. 1201	EFFECT Act	Would amend the Energy Policy Act of 2005 to direct DOE to carry out CCS research and development programs. Program requirements would include conducting research to support sites for large volume storage of CO_2 and accompanying infrastructure and continuation of a demonstration program for large-scale carbon storage validation and testing. Would require DOE to submit a report to Congress on CCS activities. Would establish an optional program to transition large-scale carbon sequestration demonstration projects into integrated commercial storage complexes.
S. 1790	National Defense Authorization Act for FY 2020	As passed in the Senate, would amend the Clean Air Act by directing EPA to conduct certain carbon capture research activities. Would require DOE to report to Congress on the potential risks and benefits to project developers associated with increased storage of CO_2 in deep saline formations and recommendations for federal policy changes to mitigate identified risks. Would direct CEQ to prepare a report including information on permitting and review of CCS projects and issue guidance on development of CO_2 pipelines and storage projects. These provisions were not included in the final version of the legislation (P.L. 116-92.)
S. 2302	America's Transportation Infrastructure	Would amend the Clean Air Act by directing EPA to conduct certain carbon capture research activities. Would require DOE to report to Congress on the potential risks and benefits to project developers

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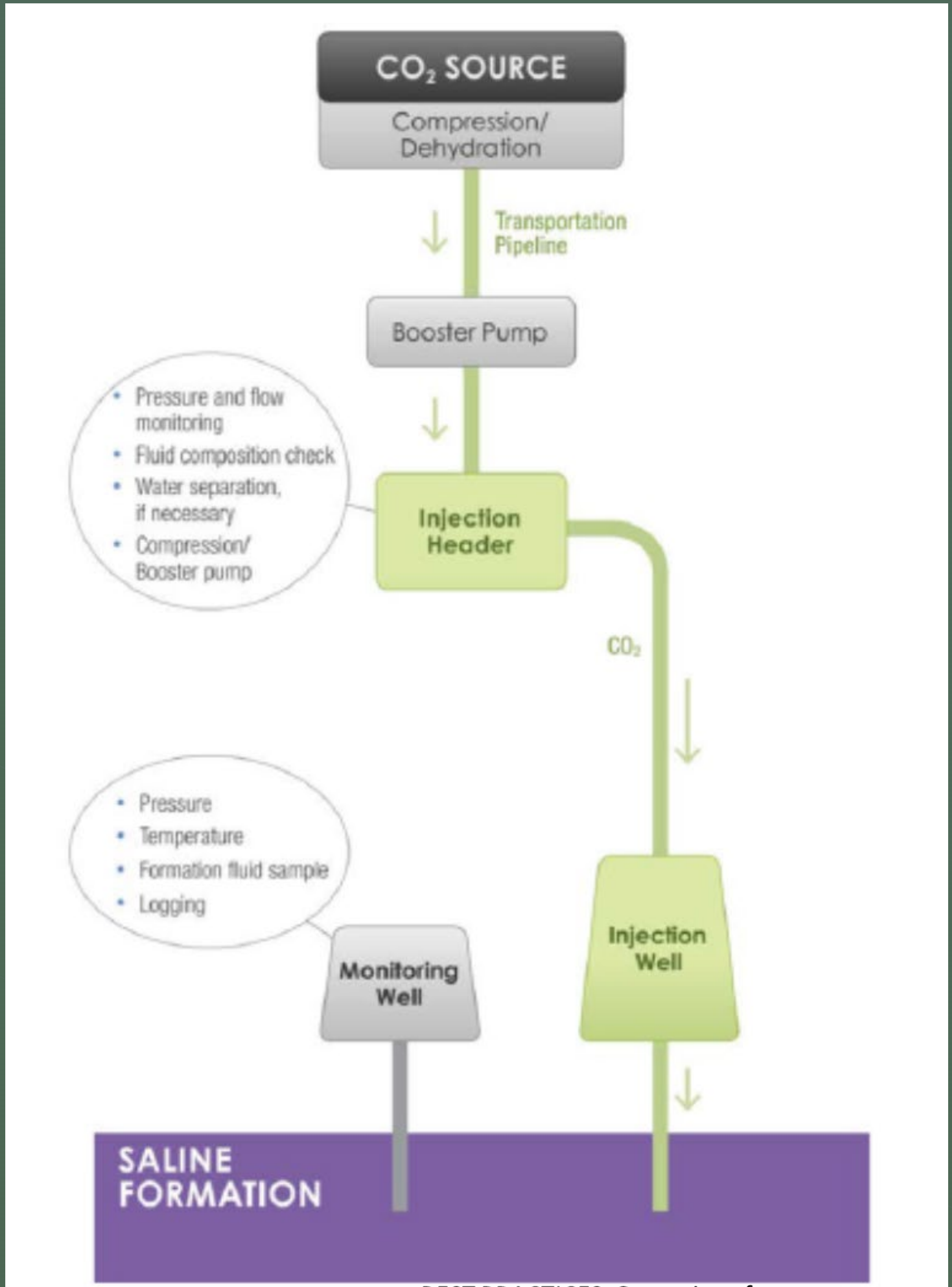
- Concluding Remarks

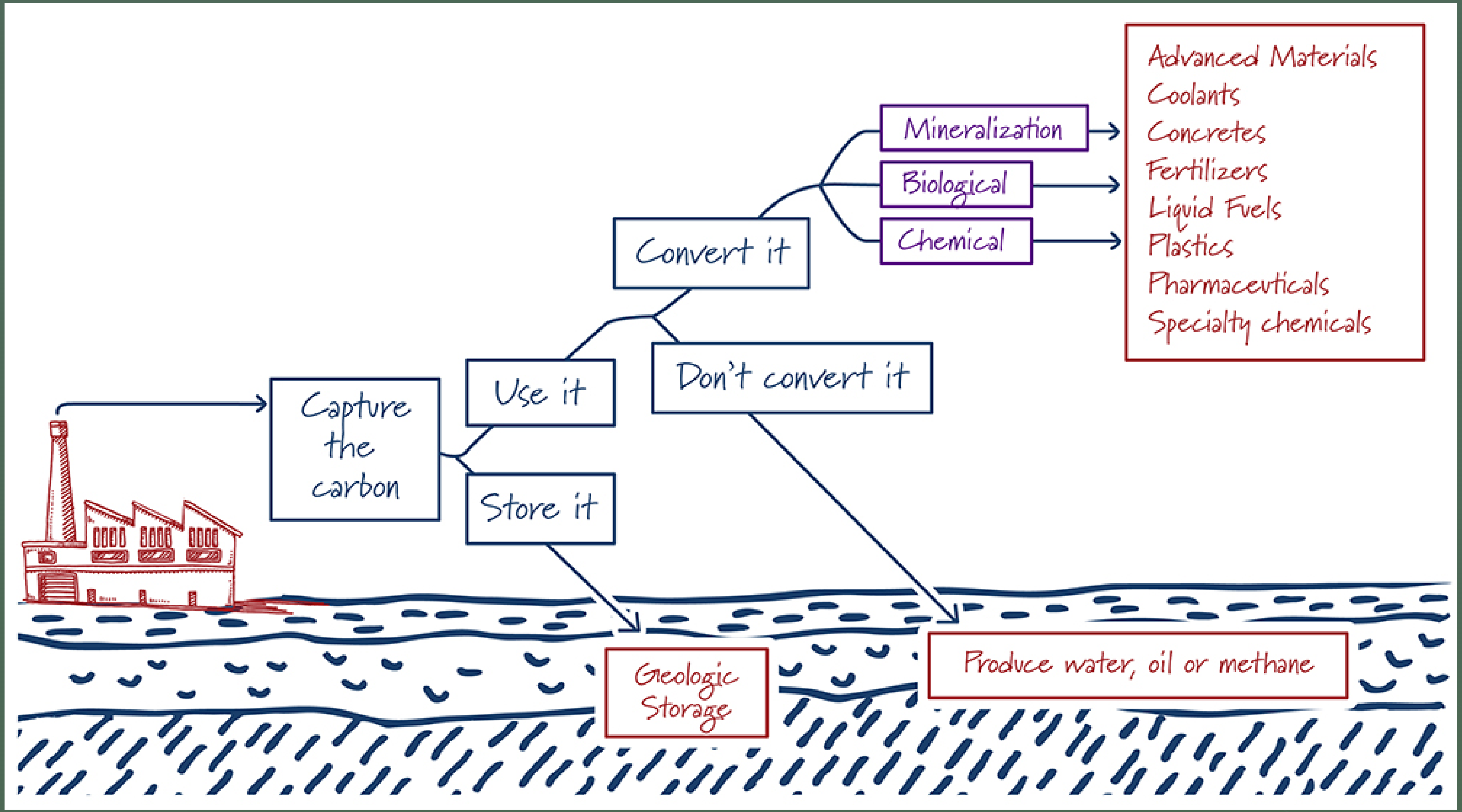
- CCSU is not a silver bullet for solving the climate issues – but it is a key component & considerable CCS projects are underway
- All components of CCS are commercial. The challenge is the **scale (we need to scale up to Giga tons of CO_2 capture) → so need to be able to store CO_2 safely at this gigantic scale of capture**
  - Thus site characterization and post-injection monitoring would be key!

Done with the overview, let us begin the journey



BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

CO_2 Capture



https://clearpath.org/tech-101/carbon-capture-101/

Capture

- What is the main purpose of capture?
- What are the CO_2 capture systems (i.e., where do we capture along the process?)
- What are the capture technologies?

Purpose

- Concentrate the CO_2 stream
- Remember that comes at a significant energy requirements if the stream is dilute

Examples

Capture energy requirement (% more input per GJ)

NGCC	PC	IGCC	Hydrogen Plant
• 11 – 22% • (16%)	• 24 – 40% • (31%)	• 14 – 25% • (19%)	• 4 – 22% • (8%)

NGCC = Natural gas-fired combined-cycle (NGCC) plant
PC = Pulverized coal
IGCC = Integrated gasification combined cycle
Value in ( ) is the representative value

IPCC Special Report on Carbon Capture and Storage, 2005

Capture

- What is the main purpose of capture?
- What are the CO_2 capture systems (i.e., where do we capture along the process?)
- What are the capture technologies?

Capture Systems

- Post-Combustion Capture
- Oxy-Combustion Capture
- Pre-Combustion Capture

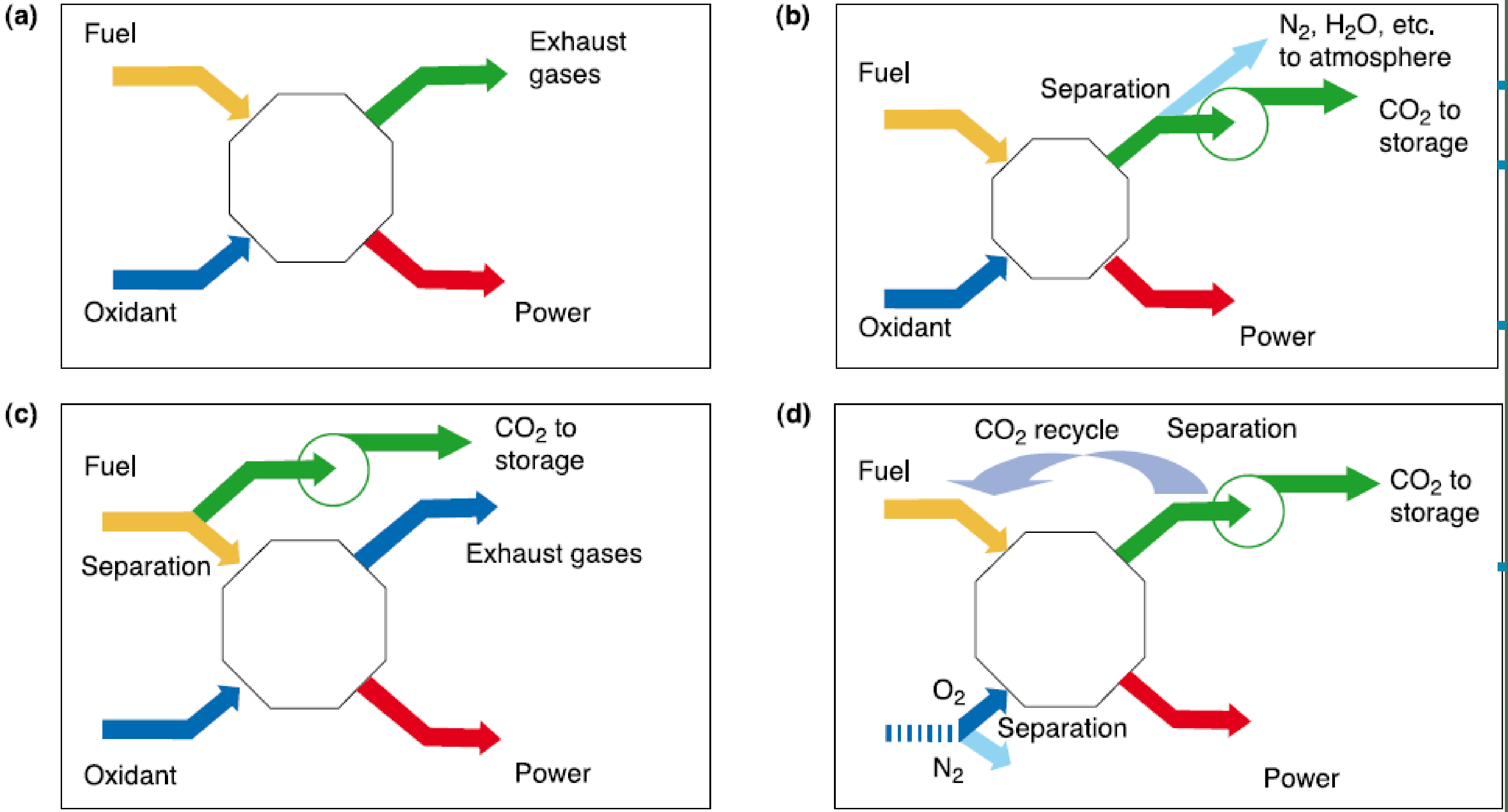


Figure 1.3 a) Schematic diagram of fossil-fuel-based power generation; b) Schematic diagram of post-combustion capture; c) Schematic diagram of pre-combustion capture; d) Schematic diagram of oxyfuel combustion

A) business as usual

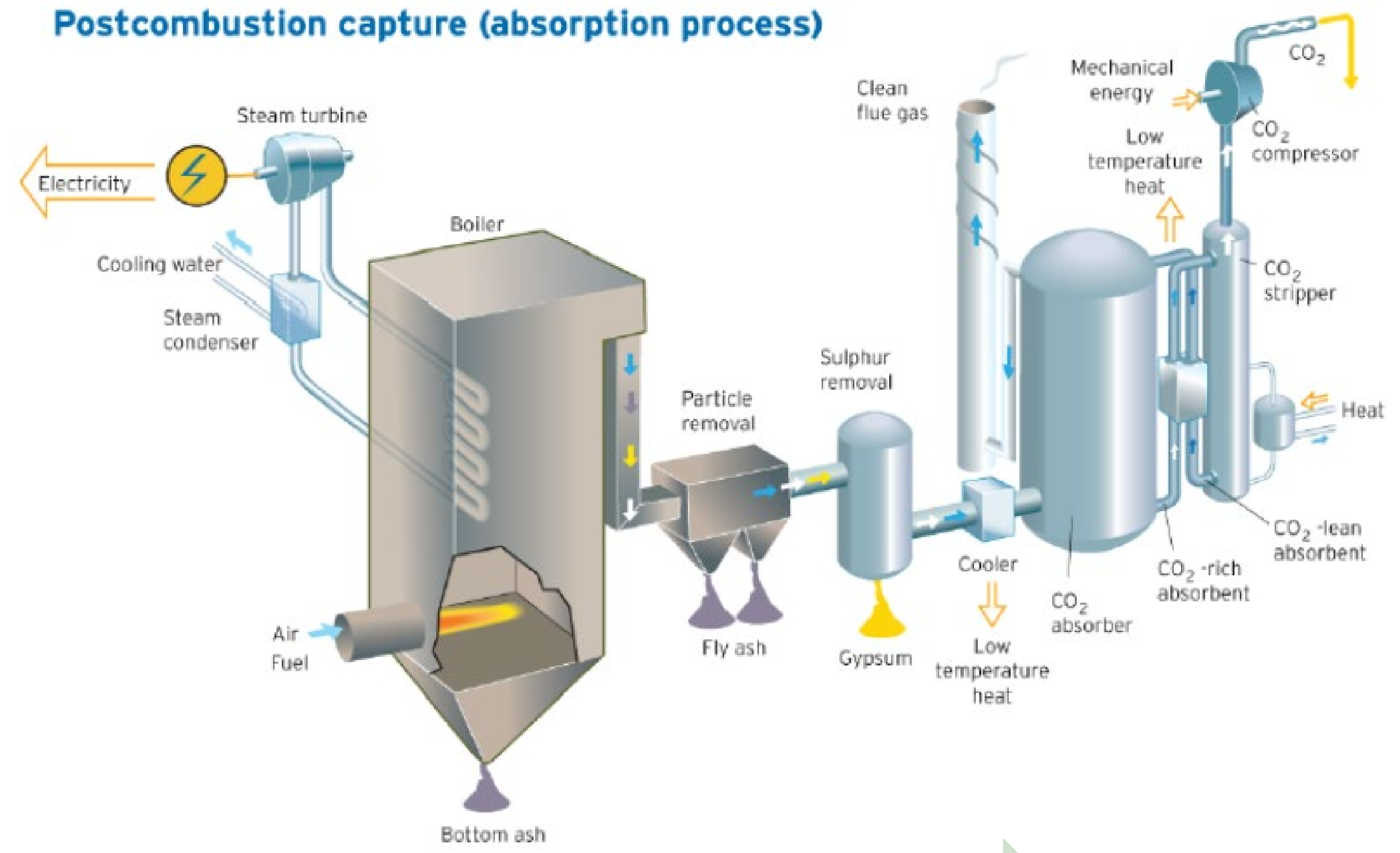
B) Post-combustion capture: burn the fuel in air and capture CO_2 from the flue gas (3-15% CO_2)

D) Oxy-fuel combustion: mix O_2 not air with the fuel (separate oxygen not CO_2) → flue gas will be a highly concentrated CO_2 stream (nitrogen (significant portion of flue gas) is gone)

C) Pre-combustion capture: like gasification . For example, heat coal with steam and O_2 (partial oxidation)→ get CO, Hydrogen → convert the CO to CO_2 → separate the CO2 and get concentrated H2 gas stream fro energy production (*remember the blue hydrogen?*)

IPCC Special Report on Carbon Capture and Storage, 2005

Example of a Post-Combustion Capture System



Source: Vattenfall, 2010[57]

CO_2 is absorbed with amine scrubber (most common – operate at 40 - 60 °C)

Clean gas is released to the atmosphere

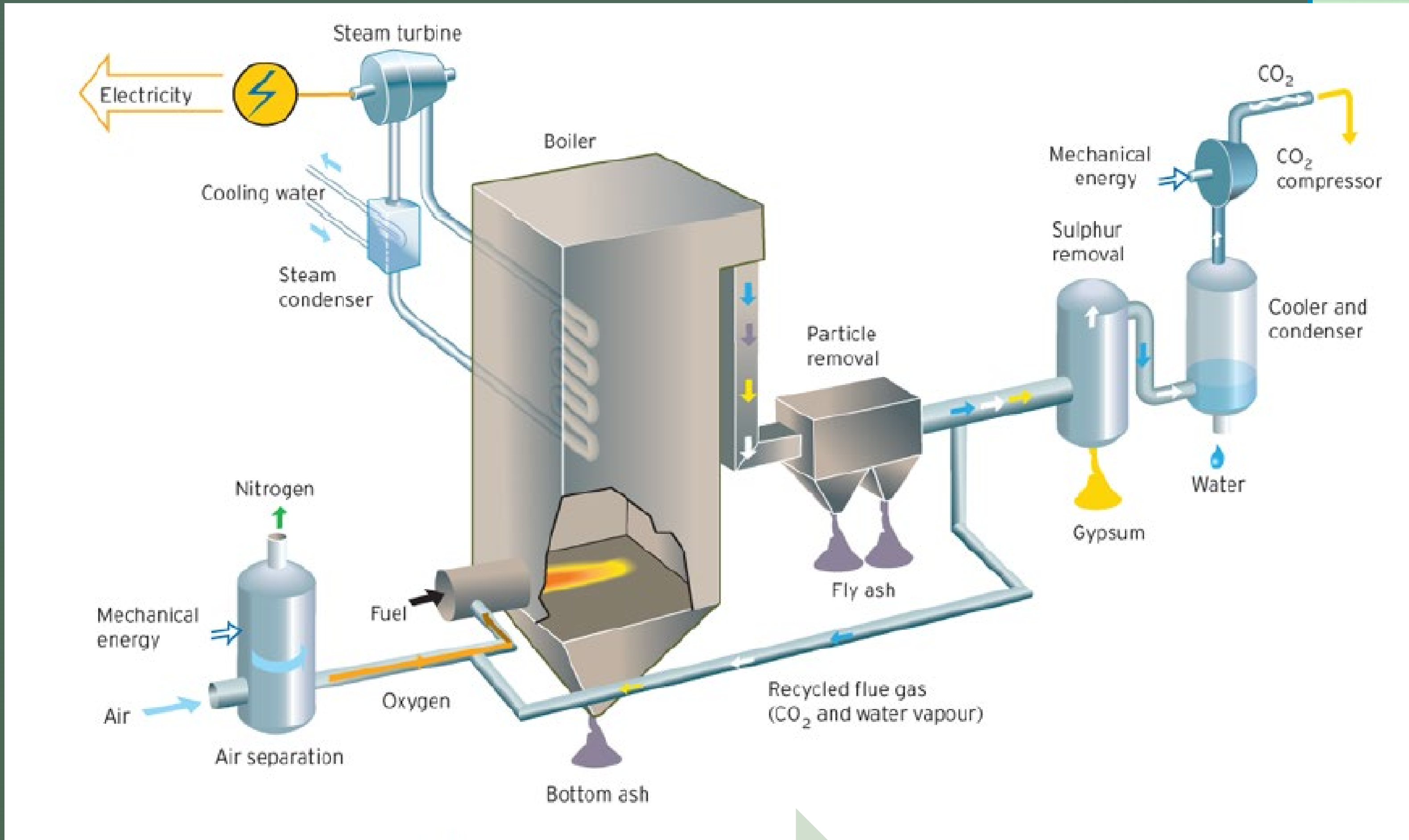
CO2 rich sorbent is stripped (high T = 100 – 140 °C) to release CO_2

The scrubbing liquid is cooled down and returns to the absorber to separate more CO_2

The CO_2 is then dried and compressed to a supercritical fluid for transport

Vidas, H. et al., 2012. Analysis of the costs and benefits of CO2 sequestration on the US outer continental shelf. OCS Study BOEM, 100.

Example of a Oxy-Fuel Combustion Capture System



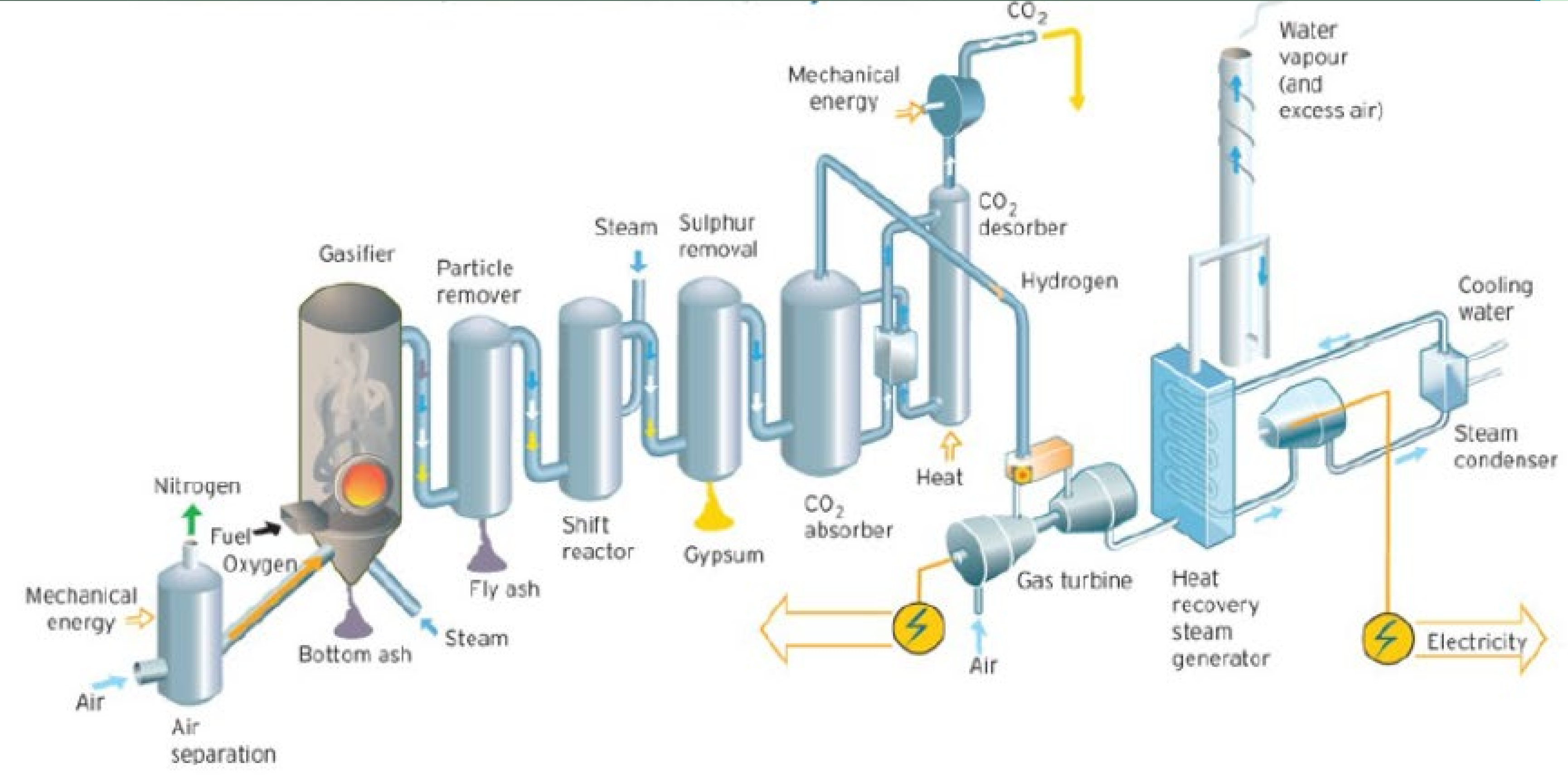
Source: Vattenfall, 2010[70]

- Fuel is oxidized with pure oxygen
- Flue gas is mainly CO_2 + H_2O + other impurities (but N_2 is not present)
- Remove particles and desulfurize the gas
- Dehydrate the gas (cooling the gas will result in water condensation)
- Compress and transport

Vidas, H. et al., 2012. Analysis of the costs and benefits of CO2 sequestration on the US outer continental shelf. OCS Study BOEM, 100.

Pre-Combustion Capture System

Vidas, H. et al., 2012. Analysis of the costs and benefits of CO2 sequestration on the US outer continental shelf. OCS Study BOEM, 100.



Source: Vattenfall, 2010 [75]

- Start with Pyrolysis: Fuel is heated in steam and pure oxygen
- The solid fuel is partially oxidized →Syngas = mainly CO + H_2
- Convert the CO into CO_2 in the water shift reactor (steam ~ 300 C reacts with CO to form CO_2)
- Capture the CO_2 using a system similar to the post-combustion capture (amine scrubber of Seloxol solvent scrubber)

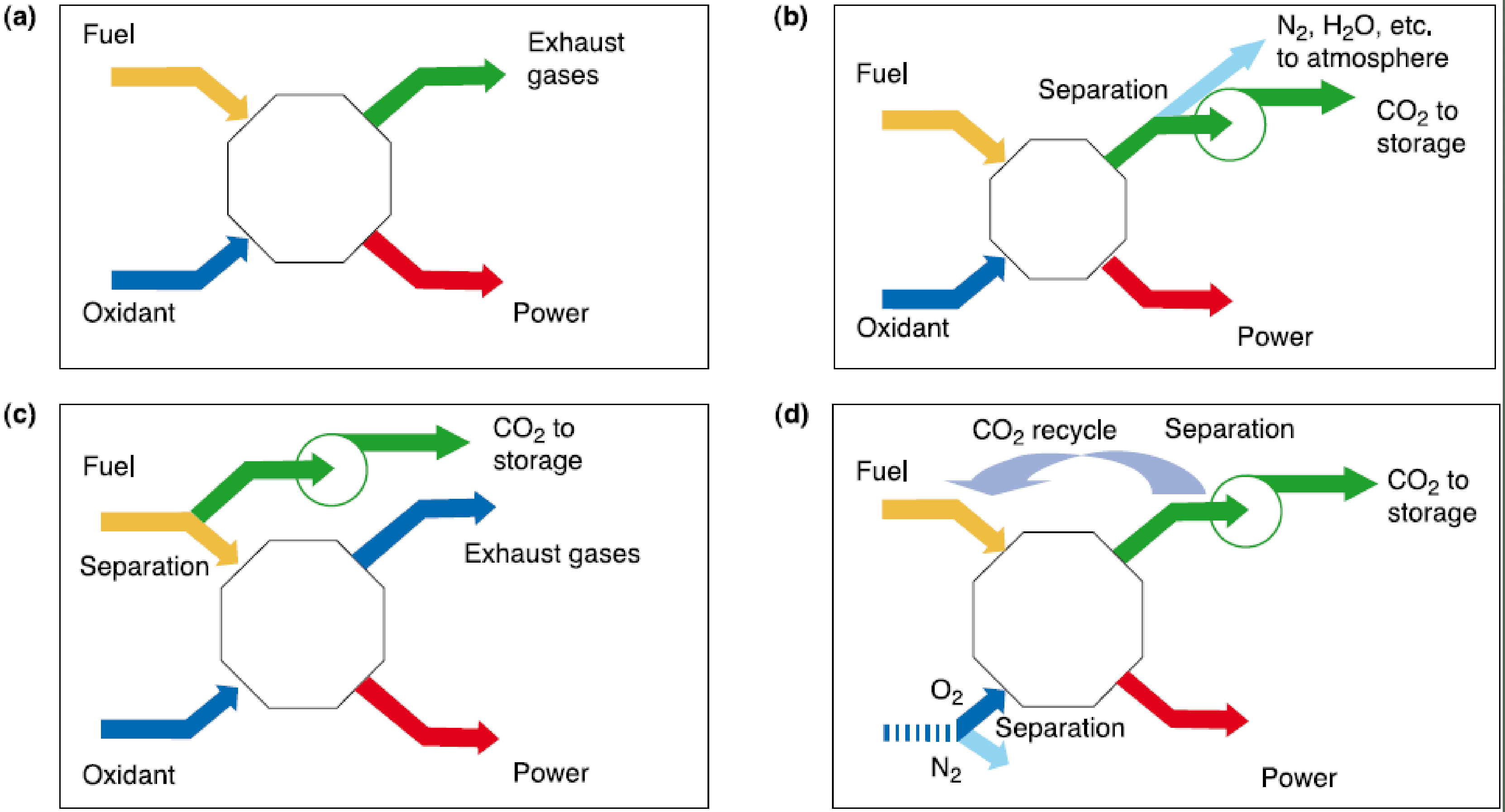


Figure 1.3 a) Schematic diagram of fossil-fuel-based power generation; b) Schematic diagram of post-combustion capture; c) Schematic diagram of pre-combustion capture; d) Schematic diagram of oxyfuel combustion

IPCC Special Report on Carbon Capture and Storage, 2005

Capture

- What is the main purpose of capture?
- What are the CO_2 capture systems (i.e., where do we capture along the process?)
- What are the capture technologies?

Capture technologies

- Absorption (i.e., scrubbing the flue gas with a liquid solvent) – mature technology – used since 1940’s
- Adsorption (i.e., use solid media to adsorb CO_2 (need high surface area)
- Membrane separation
- Chemical looping

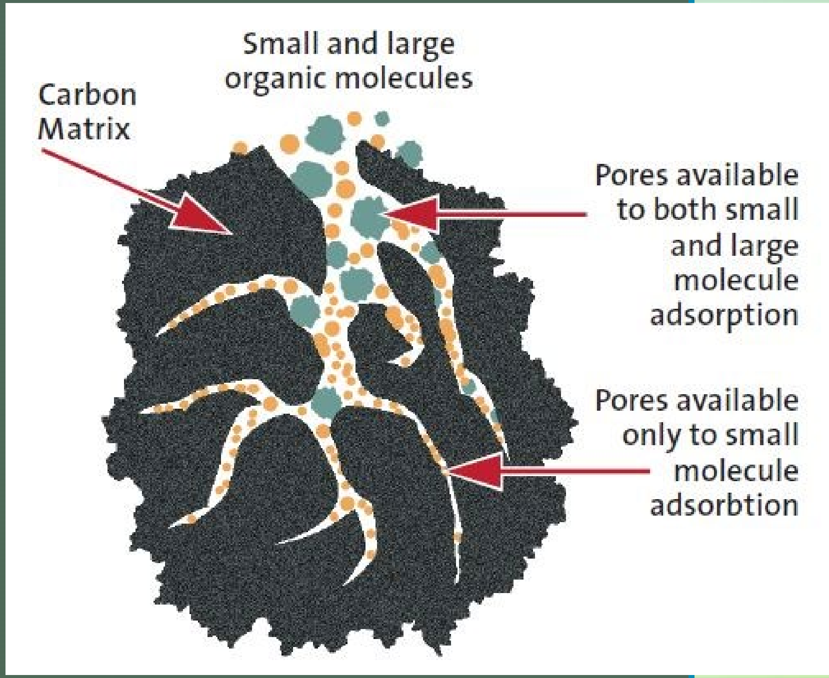
Liquid Solvents (Absorption/Scrubbers)

- Solvents:
  - Chemical solvents:
    - Chemical bond to capture CO_2
    - Work well for low partial pressure CO_2 in the flue gas
    - Usually amine-based solvents are used, *monoethanolamine* (MEA) is the most utilized
  - Physical solvents:
    - Van der Waals forces to capture CO_2
    - Preferred for high partial pressure CO_2 streams (follow Henry' law)
    - glycol-based Selexol™ and methanol-based Rectisol® systems are most commonly used

Technology Readiness and Costs of CCS, 2021, Global CCS Institute

Solid Adsorbents

- Example sorbents:
  - Granular activated carbon (cons: non-selective)
  - Chemically modified Metal organic frameworks (huge surface area to volume ratio)
- Adsorption forces:
  - Physical sorption: van der Waals forces
  - Chemical sorption: modify the solid with selective functional groups – chemical sorption
- Regeneration?
  - Temperature swing adsorption (TSA) – increase T to release the gas
  - Pressure swing adsorption (PSA) – operate the sorbent column at high pressure and then reduce pressure to release the captured gas
  - Vacuum swing adsorption(VSA) – apply vacuum to pull the gas



https://www.elgalabwater.com/activated-carbon

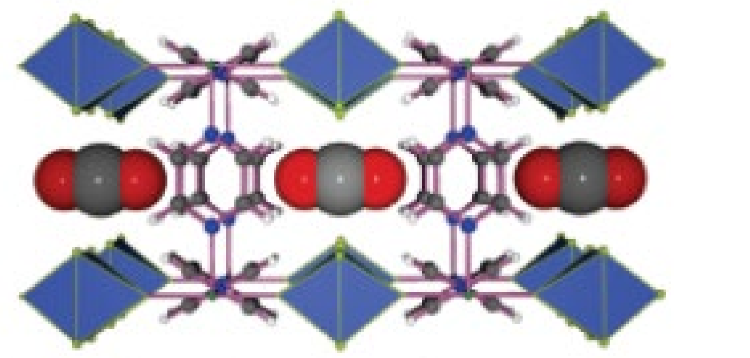
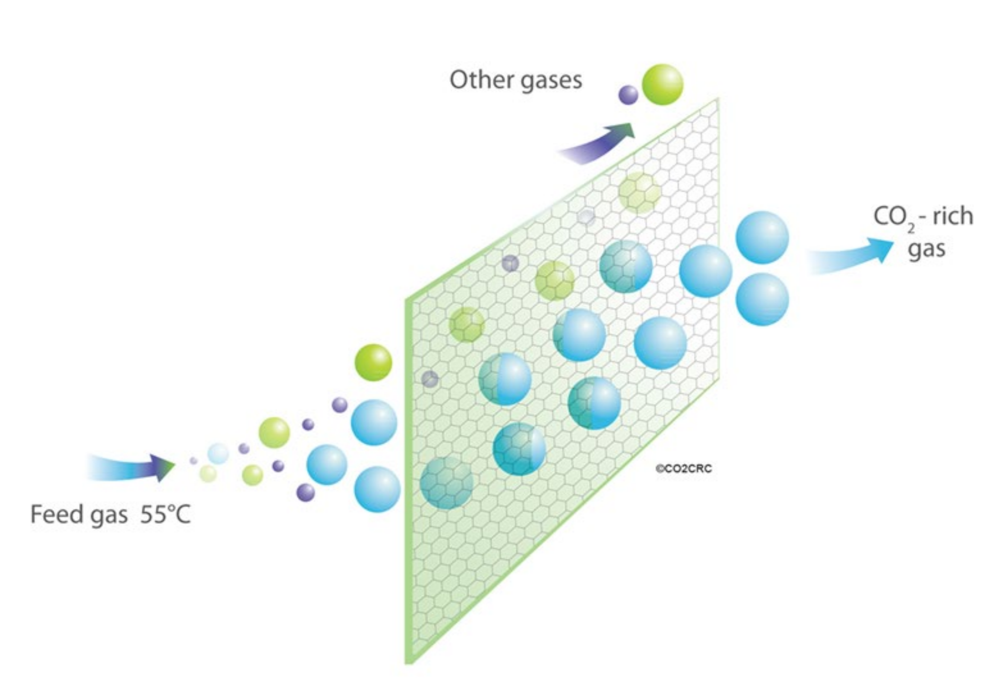


Figure 2.5. Experimental proof by x-ray diffraction of CO_2 molecules in designer nanopores in an advanced adsorbent, KAUST-7. | Reprinted with permission from Bhatt, P. M., et al. 2016. "A fine-tuned fluorinated MOF addresses the needs for trace CO_2 removal and air capture using physisorption." *J. Am. Chem. Soc.* 138(29), 9301–9307. Copyright 2016 American Chemical Society.

Accelerating breakthrough innovation in carbon capture, utilization, and storage, 2017, DOE

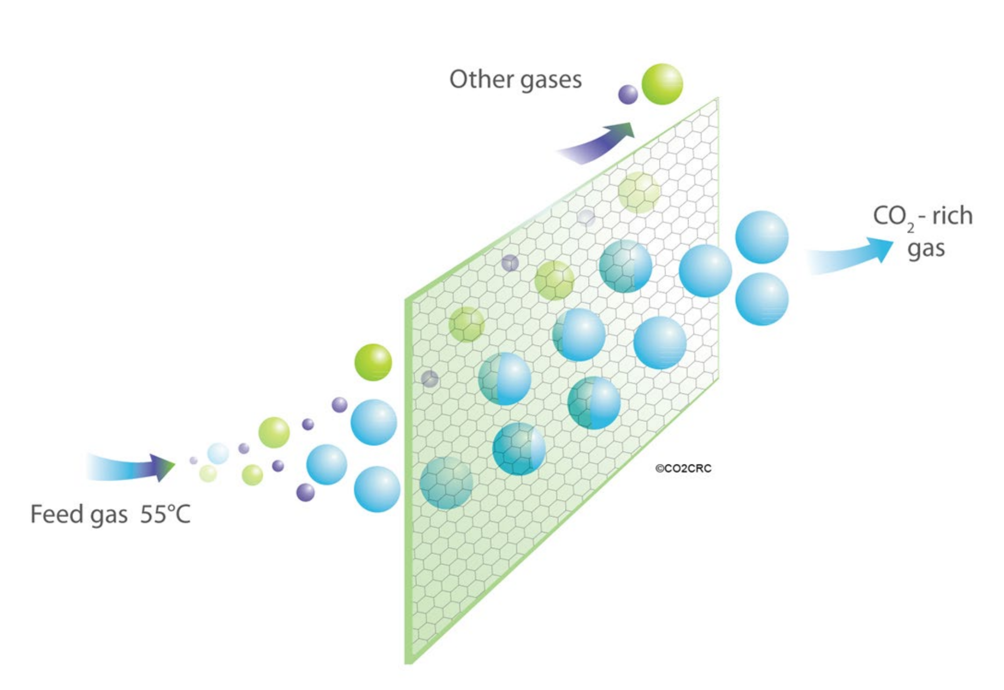
Membranes (physical separation)

How do membranes separate gases?

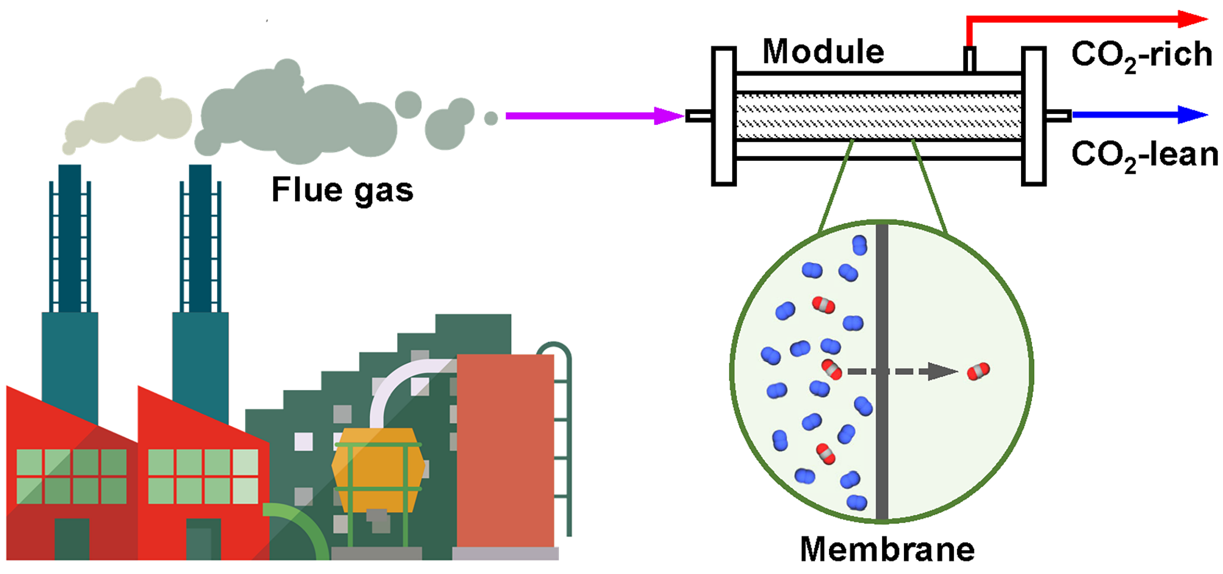


Membranes (physical separation)

- Separation depends on semi-permeable membrane pore size as well as permeability (diffusivity and solubility of CO_2 into the membrane matrix)
- Membrane materials (polymers and ceramic)



https://sites.google.com/site/ccsspring2015group1/website-builder



https://www.mdpi.com/2077-0375/10/11/365

Table 3.1 Capture toolbox.

Separation task	Process streams[a]		Post-combustion capture		Oxy-fuel combustion capture		Pre-combustion capture	
	CO_2/CH_4		CO_2/N_2		O_2/N_2		CO_2/H_2	
Capture Technologies	**Current**	**Emerging**	**Current**	**Emerging**	**Current**	**Emerging**	**Current**	**Emerging**
Solvents (Absorption)	**Physical solvents** **Chemical solvents**	Improved solvents Novel contacting equipment Improved design of processes	**Chemical solvents**	Improved solvents Novel contacting equipment Improved design of processes	n. a.	Biomimetic solvents, e.g. hemoglobine-derivatives	**Physical solvent** **Chemical solvents**	Improved chemical solvents Novel contacting equipment Improved design of processes
Membranes	**Polymeric**	Ceramic Facilitated transport Carbon Contactors	Polymeric	Ceramic Facilitated transport Carbon Contactors	Polymeric	Ion transport membranes Facilitated transport	Polymeric	Ceramic Palladium Reactors Contactors
Solid sorbents	Zeolites Activated carbon		Zeolites Activated carbon	Carbonates Carbon based sorbents	Zeolites Activated carbon	Adsorbents for O_2/N_2 separation, Perovskites Oxygen chemical looping	Zeolites Activated carbon Alumina	Carbonates Hydrotalcites Silicates

Discussion points:

- Capture stream composition
- Solvents won't work with oxy-fuel
- Emerging technologies -→ why? (improve selectivity and reduce energy needed for regenartion or c

IPCC Special Report on Carbon Capture and Storage, 2005

Chemical looping

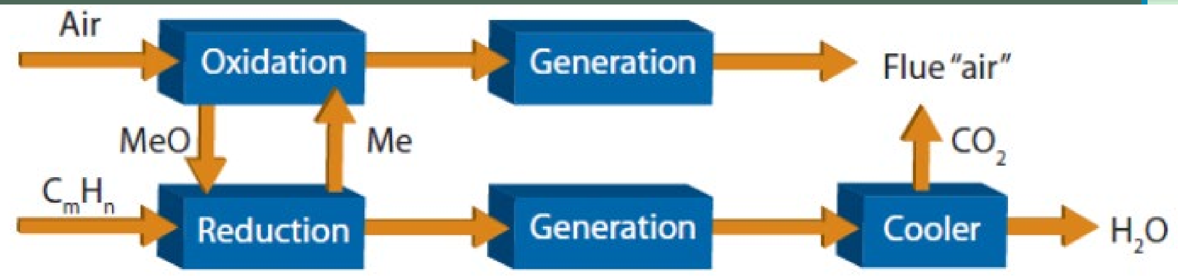


Figure 13: Chemical looping combustion.

- Split the combustion of fossil fuel into two reactions, oxidation and a reduction reaction of a metal? (that cycling of oxidized/reduced metal will supply oxygen needed for oxidizing the carbon)
- How?
- Reactor 1 (oxidation of a metal): metal reacts with O_2 under pressure and temperature (T = 400 – 500 °C) → Metal oxide (MeO) forms
- Reactor 2 (reduction of metal oxide): Metal oxide (MeO) + natural gas at 500 – 900 ºC → oxidation of the fuel to CO_2 -→ mainly CO2 stream because we did not oxidize with air
- Recycle the metal/metal oxide between the reactors
- Calcium oxide is the most promising base materials for this process (abundant) -→ sometimes the process is called "calcium looping"

Carbon capture and storage – Unni Berge et al., Zero, Norway

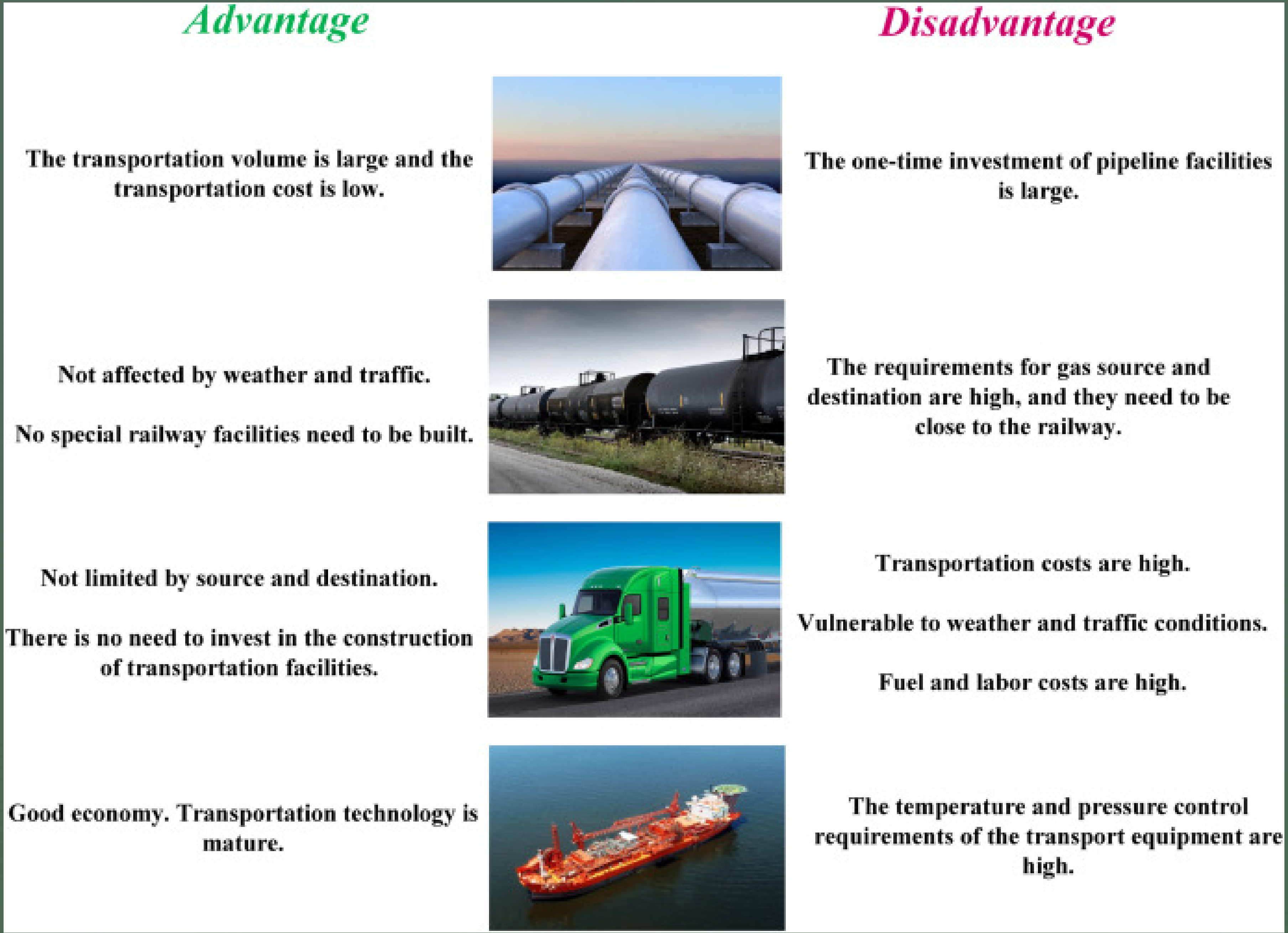
Which capture technologies are used for DAC?

Table 4. Companies Working to Commercialize Systems of Direct Air Capture technology [72].

Company	Type of System	Type of Technology	Type of Regeneration	Purity/ Application	Scale
Carbon Engineering Ltd.	Liquid solvent	Potassium hydroxide solution/calcium carbonation	Temperature	99%	Pilot 1 tonne per day
Climeworks	Solid sorbent	Amine-functionalized filter	Temperature or vacuum	99%w/dilution depending on the application	Demonstration 900 tonne per year
Global Thermostat	Solid sorbent	Amine-modified monolith	Temperature and/or vacuum	99%	1000 tonne per year
Infinitree	Solid sorbent	Ion-exchange sorbent	Humidity	3–5% algae	Laboratory
Skytree	Solid sorbent	Porous plastic beads functionalized with benzylamines	Temperature	Air purification, greenhouses	Appliance

CO_2 Transport

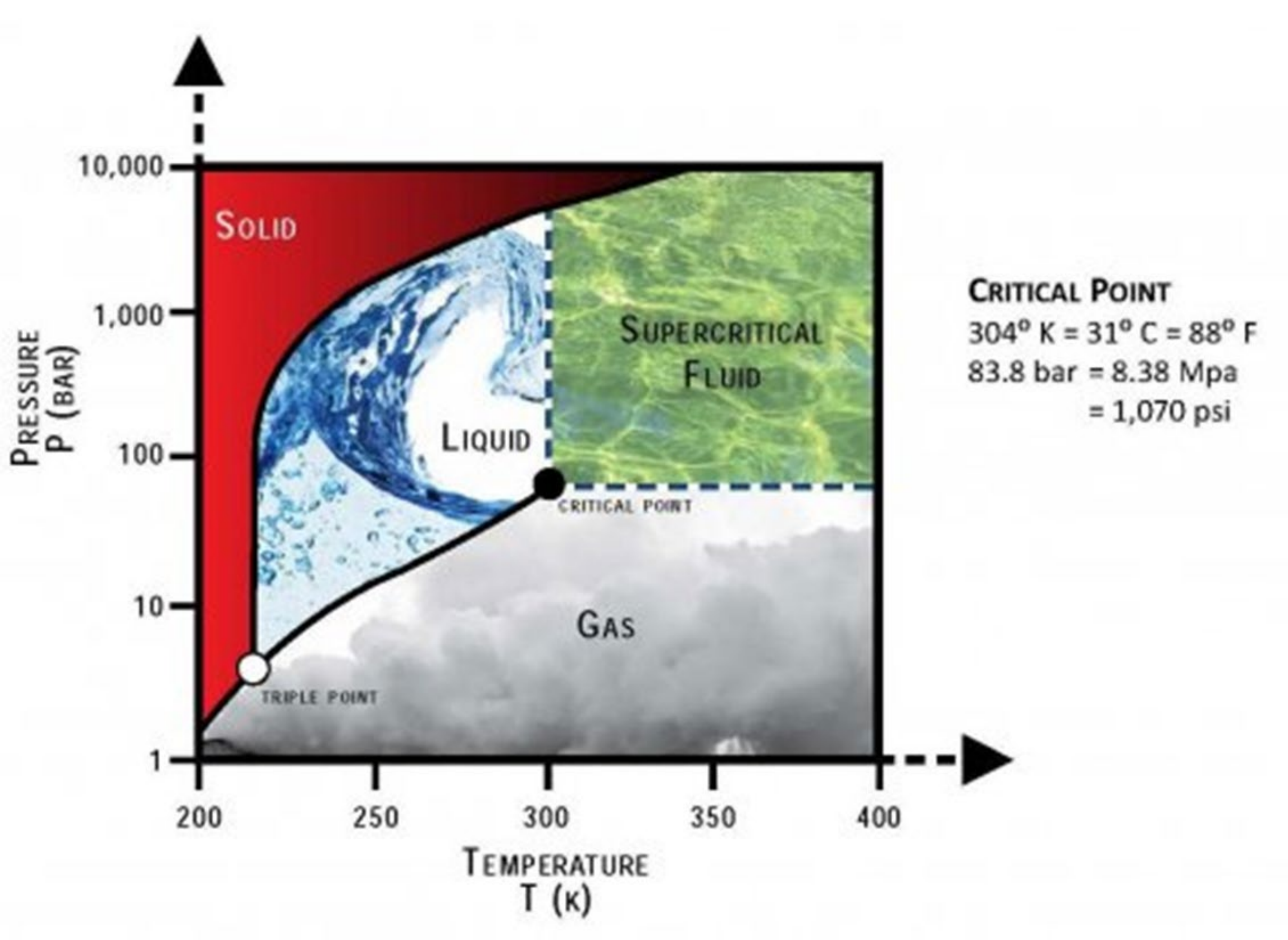
https://betterenergy.org/blog/state-work-group-urges-administration-include-co2-pipeline-networks-national-infrastructure/



Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. *Journal of Cleaner Production*, *266*, 121994

CO_2 exist in different phases depending on T & P

- Trucks/Rail or Tankers Transport Conditions:
  - Cryogenic tanks – liquefied CO_2 at - 20 °C (253 K) & 2 MPa (20 bar)



https://www.energy.gov/supercritical-co2-tech-team

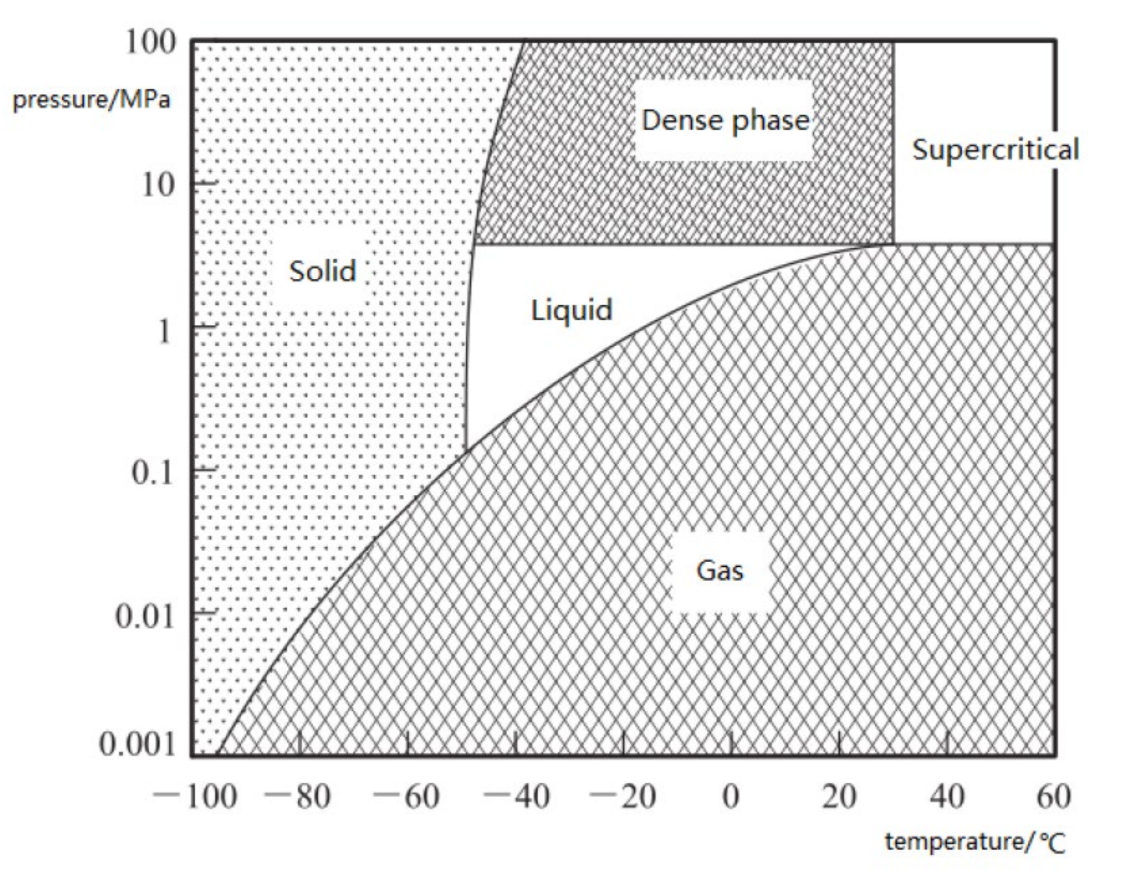
- Let us focus the rest of discussion on pipeline for CO_2 Transport

Transport in which form?

Phases of Transport:

- Gaseous transport
- Liquid transport
- Dense-phase transport
- Supercritical transport
- Solid Transport

- Which are more economical for pipeline transport?
  - Short distance transport → preference is gaseous (compressed but still gas) or liquid transport
  - Long distance transport → dense-phase and supercritical transport are favorable



Wang, H. Earth and Environmental Science 310 (2019) 032033

Components (it is all about controlling Pressures and Temperatures)

- Gaseous Transport: compressors and pipeline
- Liquid Transport: (no need to compress – just need to cool the gas and have a pump to transport it)

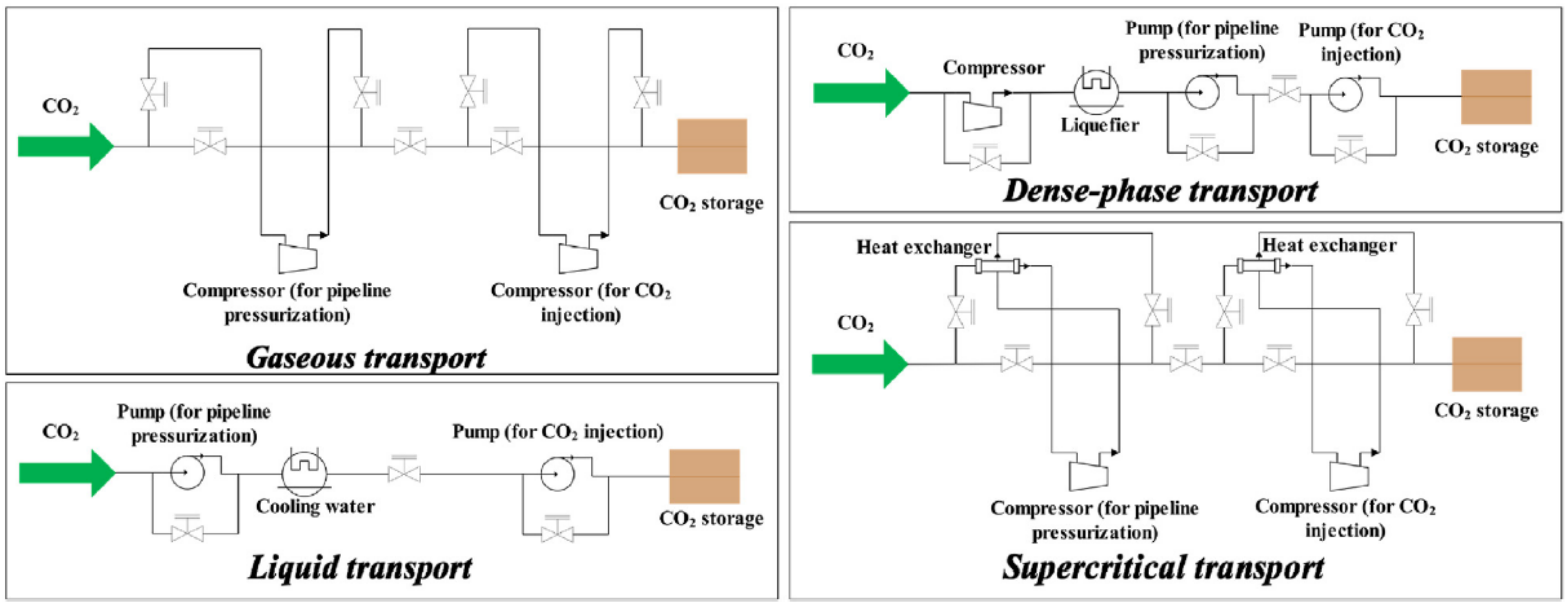


Fig. 4. Four process flow diagrams suitable for large-scale CO_2 pipeline transport (Zheng et al., 2018).

Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. *Journal of Cleaner Production*, *266*, 121994

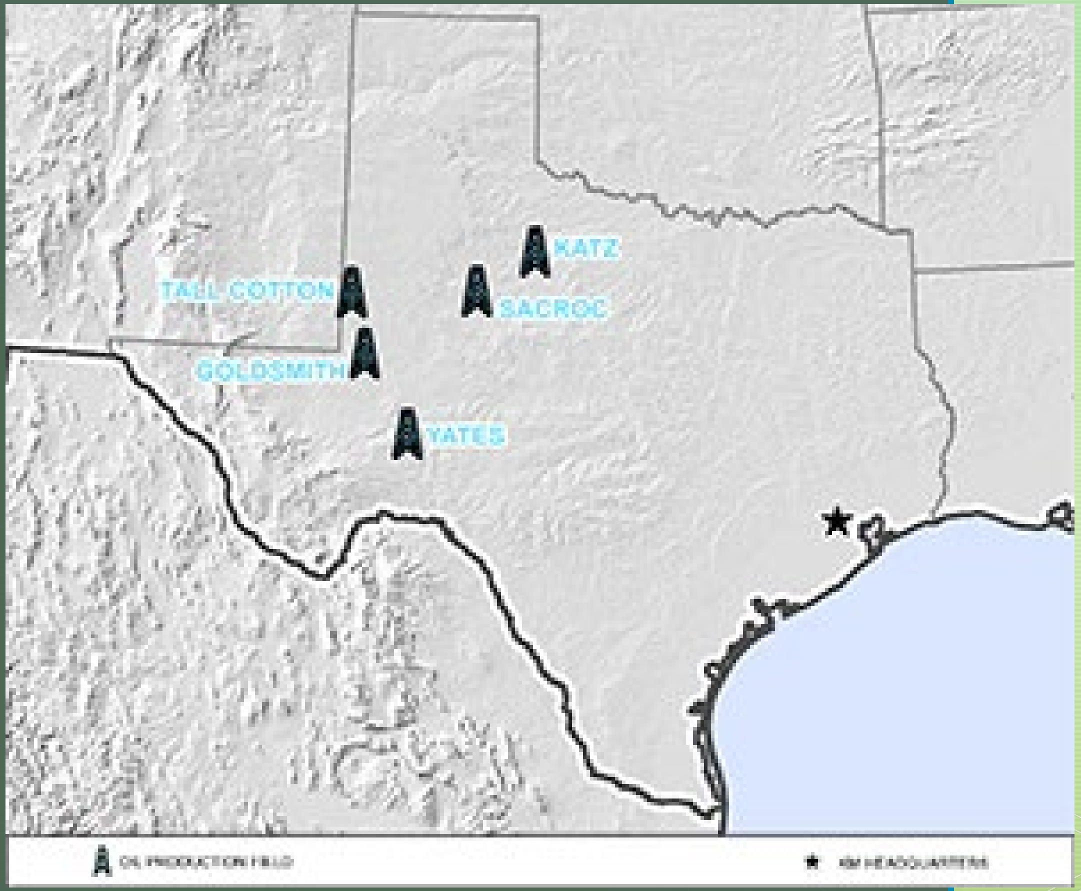
Compressors

- Compressor station is a key component in transporting gases from one location to another.
- Booster compressor: as the gas flows in the pipe, friction & elevation difference can slow the gas movement and reduce pressure → thus, compressor stations are there to maintain the pressure of the gas along the length of the pipeline.
- Cooling: heat can be generated because of gas compression (every 100 psi raises T by 7-8 °C) → so compressor can have cooler to dissipate the excess heat (like a car radiator).
- Compressors usually are fueled by natural gas (air quality people ☺) or some can be electrically powered.
  - Emissions vent into the atmosphere → need to follow the emission standards→ states and EPA regulate emissions from compressor stations under statutes in the Clean Air Act

https://extension.psu.edu/understanding-natural-gas-compressor-stations

Let us put it together -> Example pipeline used for EOR

- SACROC: one of the largest and oldest oil fields in the US.
- They use CO_2 for EOR
- CO_2 pipeline:
  - Transport ~4.2 million ton CO_2/year
  - Highest pressure 9.6 MPa (~96 bars) – dense-phase
  - The main pipe section is 290 km long with a diameter (OD) of 16 inches
  - Steel pipeline (X65 – Yield stress = 448 MPa)
- Compressors:
  - 6 compressors along the pipeline (including one at the SACROC injection site)
  - Total compressor power = 60 MW
  - Compressors are not equally spaced

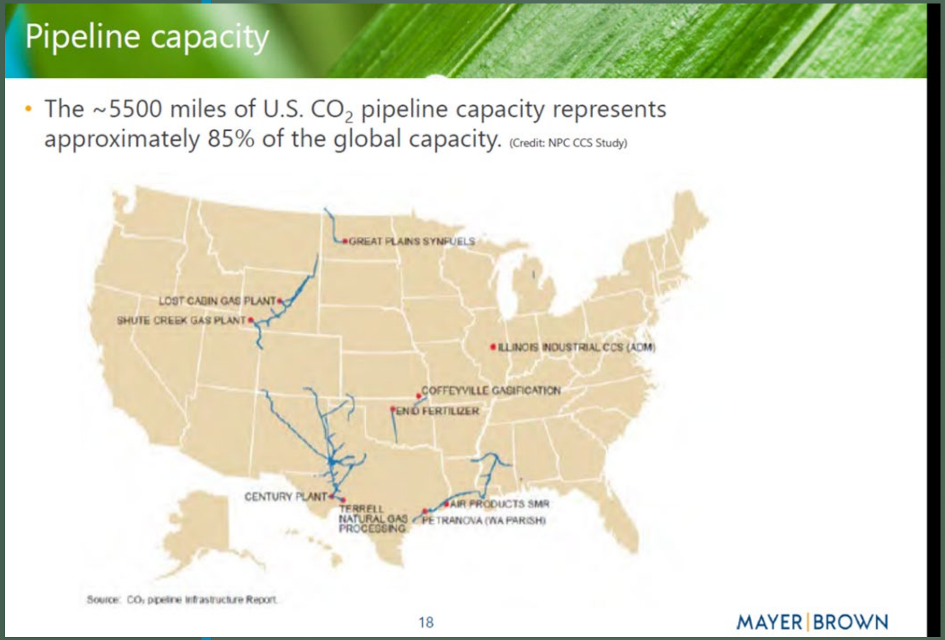


https://www.kindermorgan.com/Operations/CO2/Index

IPCC Special Report on Carbon Capture and Storage, 2005

Pipeline capacity needed?

What we have? Mainly for EOR



What we need

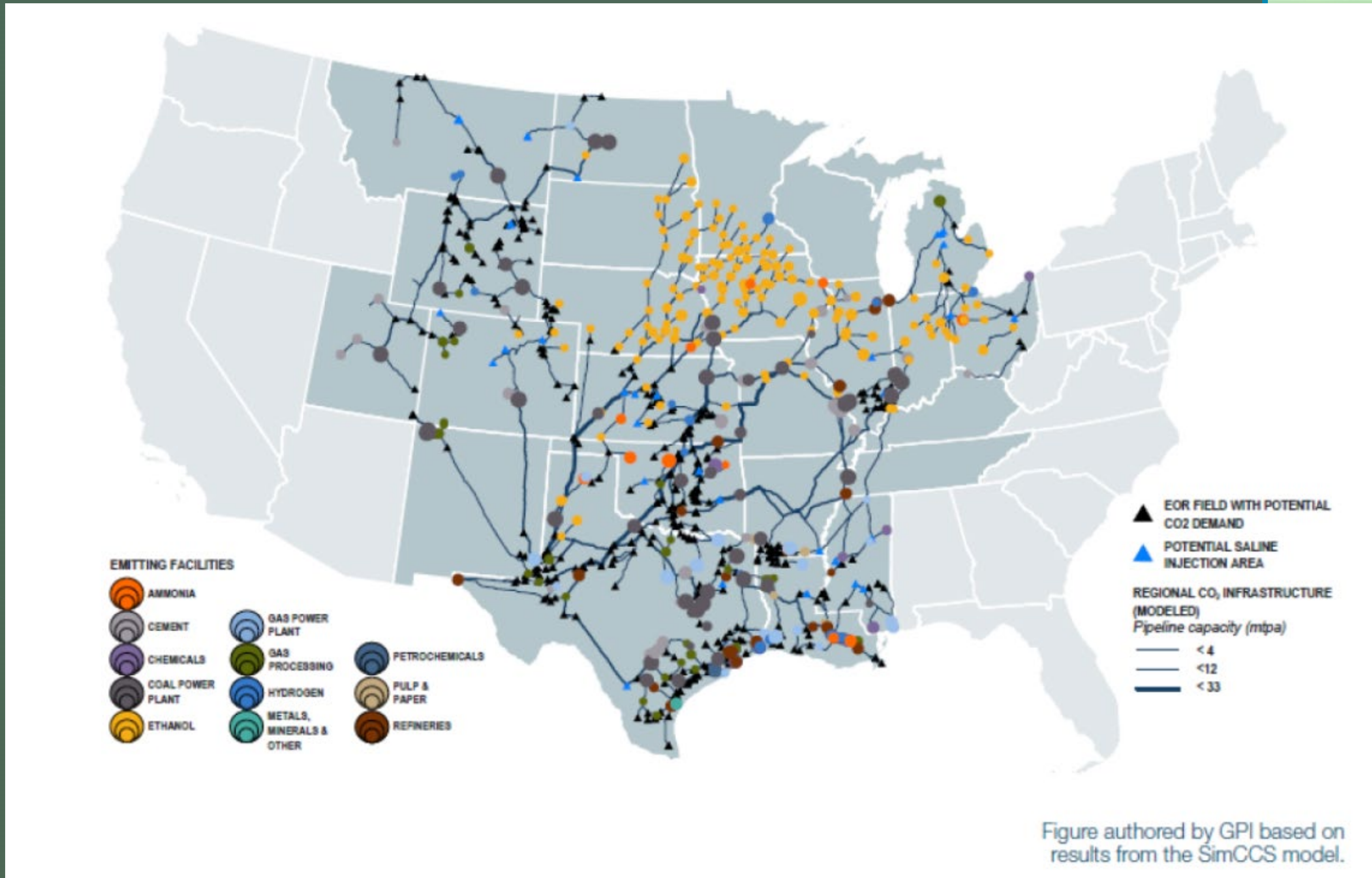


Figure 7. Optimized transportation network for economy-wide carbon capture and storage in the mid-continent of the United States

Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration, 2021

Pipeline Considerations

- Dry CO_2 should be transported (minimal moisture to not corrode the pipes).
- CO_2 gas is more dense than air → if it leaks from the pipeline, it will accumulate close to the ground → high concentrations could be harmful to environment and living species exposed to it.
- If the transport line is above the ground surface, it needs to be wrapped with insulation materials to protect from changes in atmospheric conditions (mainly Temp).

CO_2 Storage (Injection into Deep Formations)

Carbon Storage Atlas 5th Edition, DOE's NETL, https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

Storage

- Why do we need to inject CO_2 deep underground? (in other words, why depth of injection matters)?
- Trapping mechanisms in the geologic formations?
- Ok, Let us inject CO_2 in the geologic formation → Injection Wells
  - History of injection
  - Types of Injection wells & their regulatory framework
  - Class VI well components & construction
  - Miscellaneous considerations for Class VI wells

The main reason is to be able to store more CO_2

- CO_2 takes up much less volume the deeper we go
- 100 units of volume in the atmosphere occupies only 0.32 units at 800 meters (~2600 feet) deep -→ can fit much more CO_2 in a given volume
- The density sharply change at this depth
- What else do we get from this diagram?

https://netl.doe.gov/

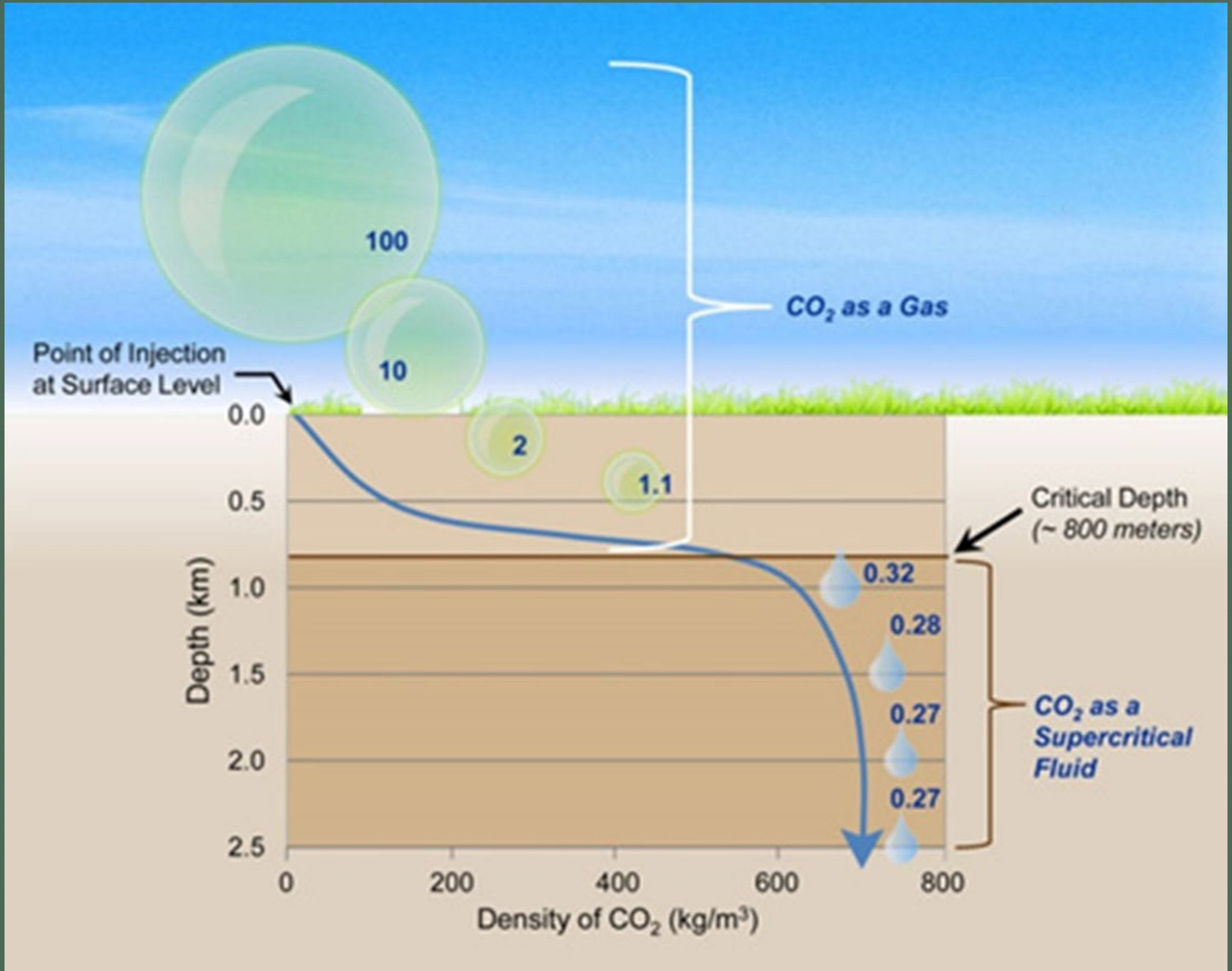
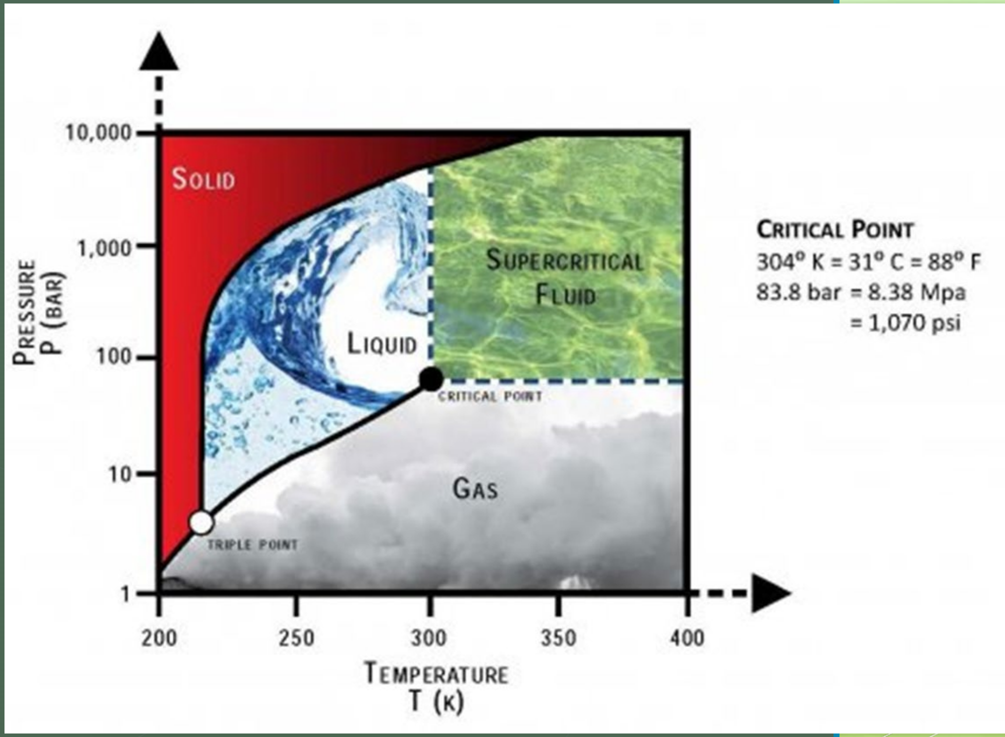


Illustration of Pressure Effects on CO2 (based upon image from CO2CRC). The blue numbers show the volume of CO2 at each depth compared to a volume of 100 at the surface

At the injection conditions CO_2 is a supercritical fluid

- Supercritical CO_2 fluid (T > 31.1 C (88 F) and P >72.9 atm (1057 psi)
- These T & P conditions exists ≥ 800 m (~2600 ft) below ground → so, CO_2 will remain in the subsurface as supercritical fluid
- So what? Why that matters?
- It impacts CO_2 trapping (enables one of the most important trapping mechanism) and transport in the subsurface after injection
- At this condition CO_2 has liquid like properties and gas-like properties:
  - Gas-like properties: viscosity is like that of gases (lower than liquid)
  - Liquid-like properties → more dense than gas phase (but less than water)
    - However, it is less dense than the liquid in the subsurface formations (e.g., saline formation) → It is more buoyant and will float o the top of the liquid in these formations



https://www.energy.gov/supercritical-co2-tech-team

Storage

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- Trapping mechanisms in the geologic formations?
- Ok, Let us inject CO_2 in the geologic formation → Injection Wells
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Let us first remember what are the candidate geologic formation for CO_2 injection

- Basalt formations
- Unminable coal seams
- Organic shale formations
- Depleted (or active) oil and gas reservoirs
- Saline formations (most promising)

Basalt Formations

- Basalt = deposits of volcanic lava → porous and permeable → rich in magnesium and magnesium → Key of how they trap CO_2
- CO_2 reacts with Calcium → mineralization (formation of stable carbonate minerals like calcite and dolomite → what does that mean?
- It means CO_2 became solid -→ permanent storage!!

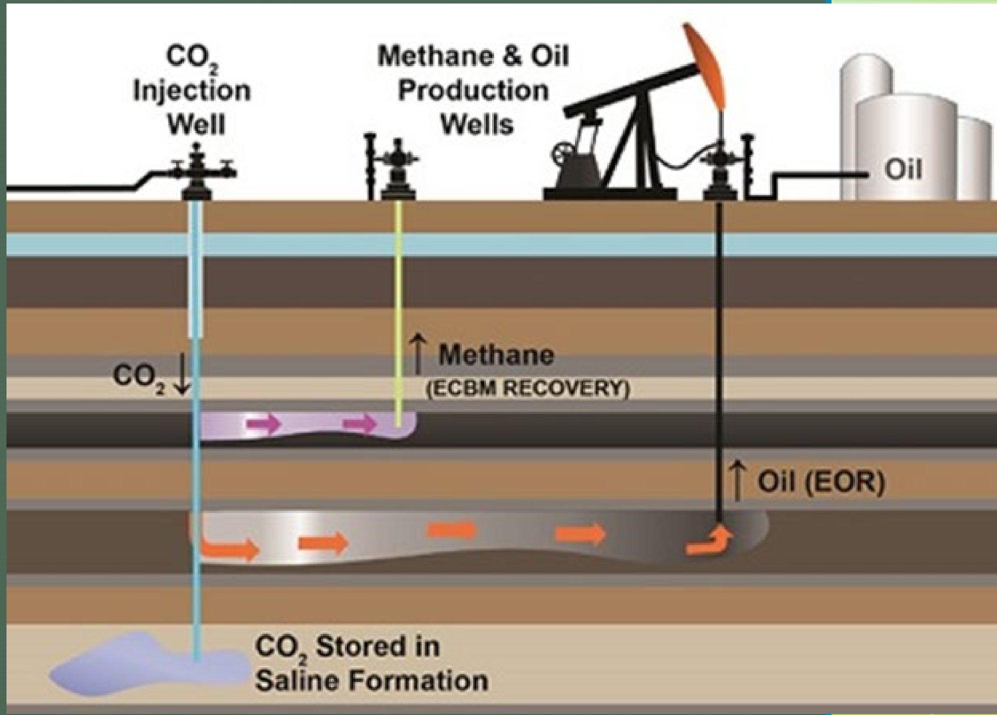
https://netl.doe.gov/

The trapping mechanisms is mineralization

Unminable Coal Seams

- Uneconomical coal mines (either too thin or too deep)
- When we say coal → what could be the trapping mechanism?
- Adsorption is how CO_2 gets trapped inside the coal pores (CO_2 has twice as much affinity for carbon than CH_4)
- In some cases, if coal contains methane in it → injection of CO_2 will result in CH_4 recovery (called enhanced coal bed methane (EBCM) recovery

The trapping mechanisms is adsorption



https://netl.doe.gov/

Organic shale formations

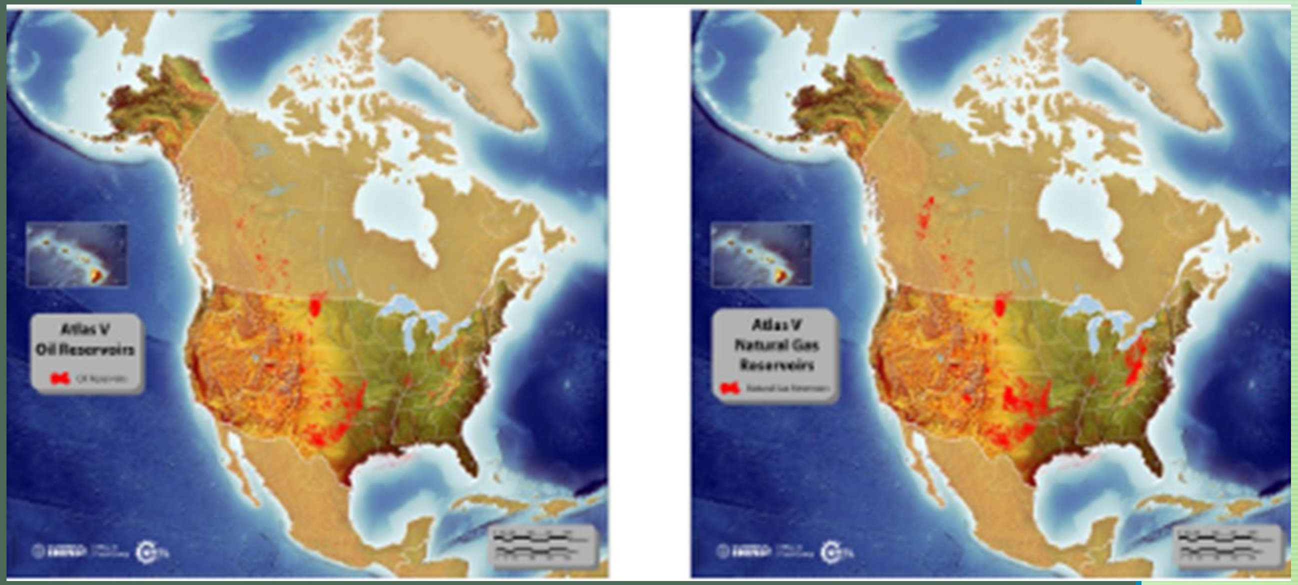
https://netl.doe.gov/

- Shale is clay-rich rock (very low permeability and low porosity)
- Organic shale means it contains > 1% organic materials
- Thus, injected CO_2 can adsorb to the organic matter (in fact organic shale has natural gas trapped in it)

The trapping mechanisms is adsorption & confinement by low and permeability

Oil and Natural Gas Reservoirs

- Ideal → we know they work → They stored oil and gas for millions of years → thus, they presumably can store CO_2 as well!
- Active or abandoned wells can be used (in active wells, not all CO_2 injected will be recovered, ~40-60% will be stored)



https://netl.doe.gov/

The trapping mechanisms is somewhat similar to saline formations → let's us wait a bit more

Saline Formations

- They are widespread and exist sub-seabed and sub-terranean
- Have the larges storage capacity and there is a lot of focus on them
- Deep reservoirs
- The pores are filled with saline water (Total Dissolved Solids (TDS) > 10,000 mg/L) → the CO_2 injected will be less dense and will float to top of the reservoir

https://netl.doe.gov/

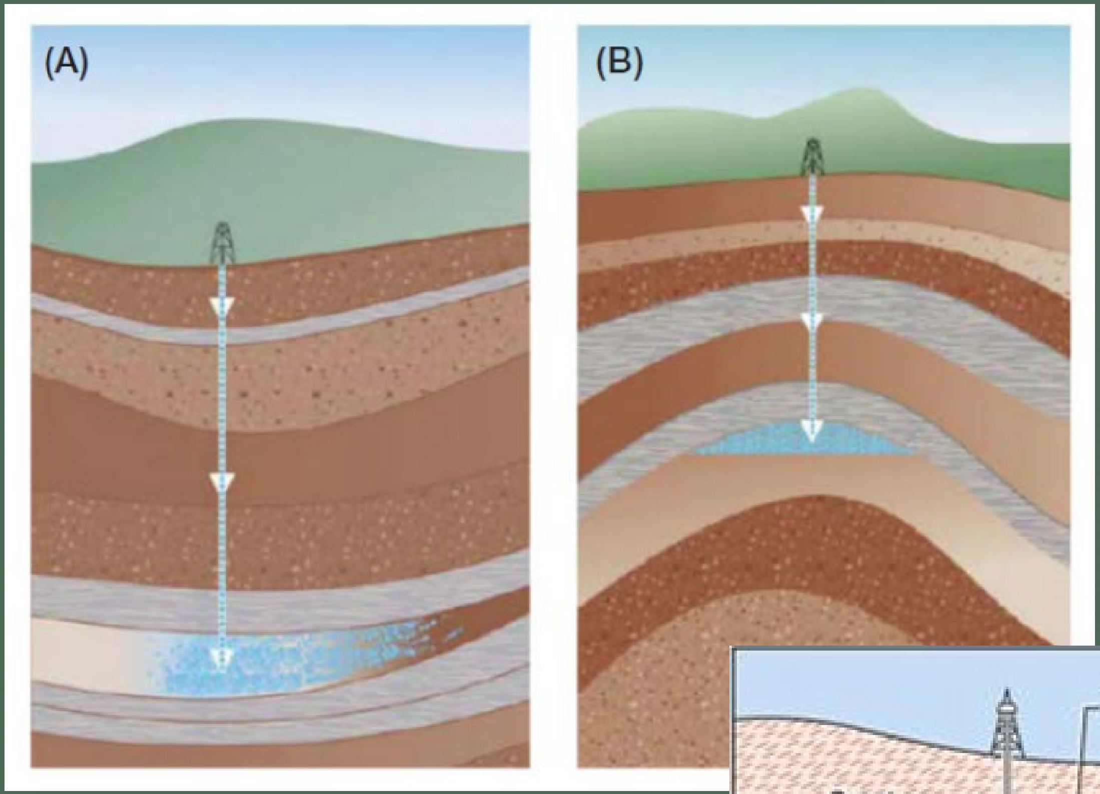
The trapping mechanisms is ……..?

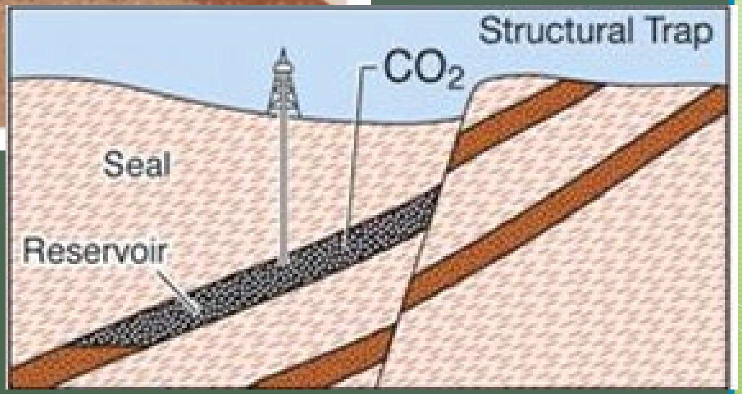
We have a couple of trapping mechanisms and they happen at different time scales

- Trapping Mechanisms
  - Physical (structural and stratigraphic)
    - Anticline Trap
    - Fault Trap
    - Pinchout Trap
  - Dissolution Trapping
  - Capillary Trapping
  - Mineralization

a) Structural and Stratigraphic Trapping (Physical Trapping – Primary mechanism)

- Caprock (low permeability layer) exist above the saline reservoir → prevents upward migration of the injected CO_2.
- Lateral migration is prevented by the structural and stratigraphic barriers.
  - First why do we need to limit lateral movement?
  - Let's talk about some examples

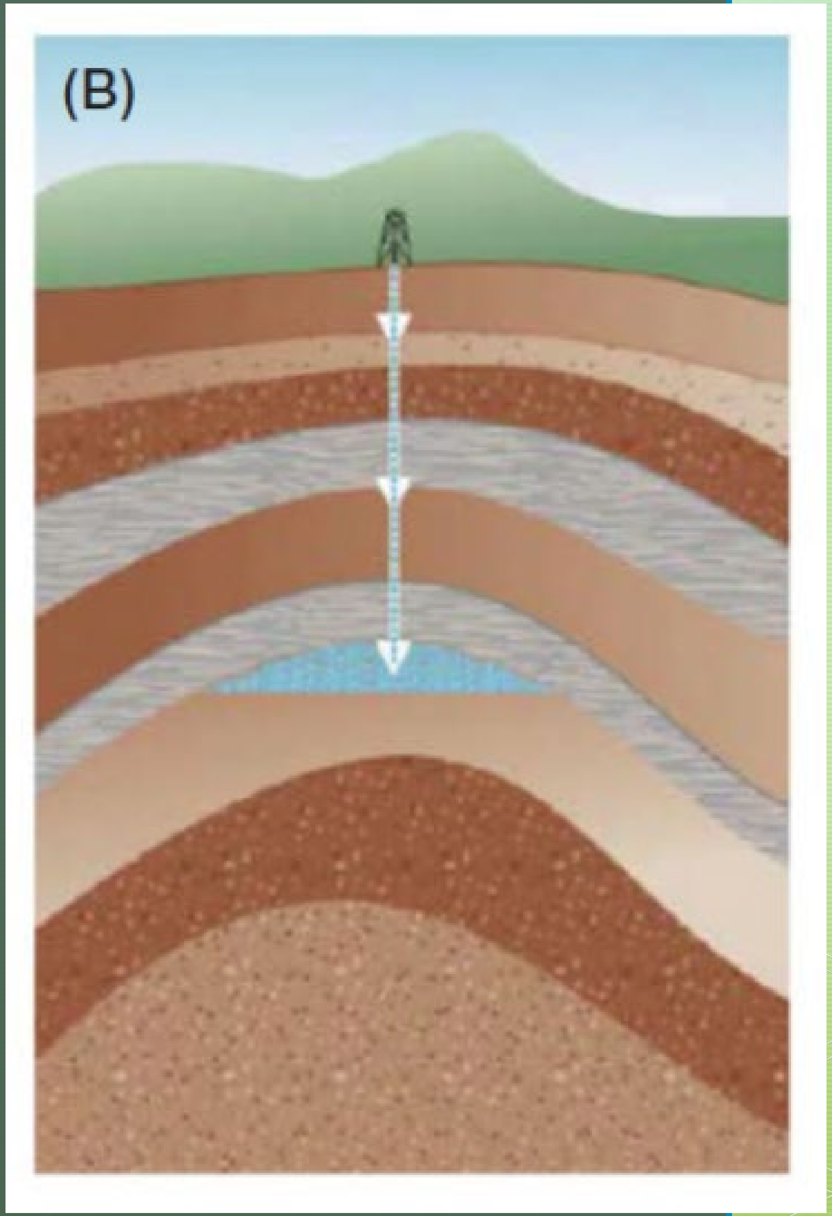




Best Practices: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects, 2017, DOE, NETL

Anticline structural traps

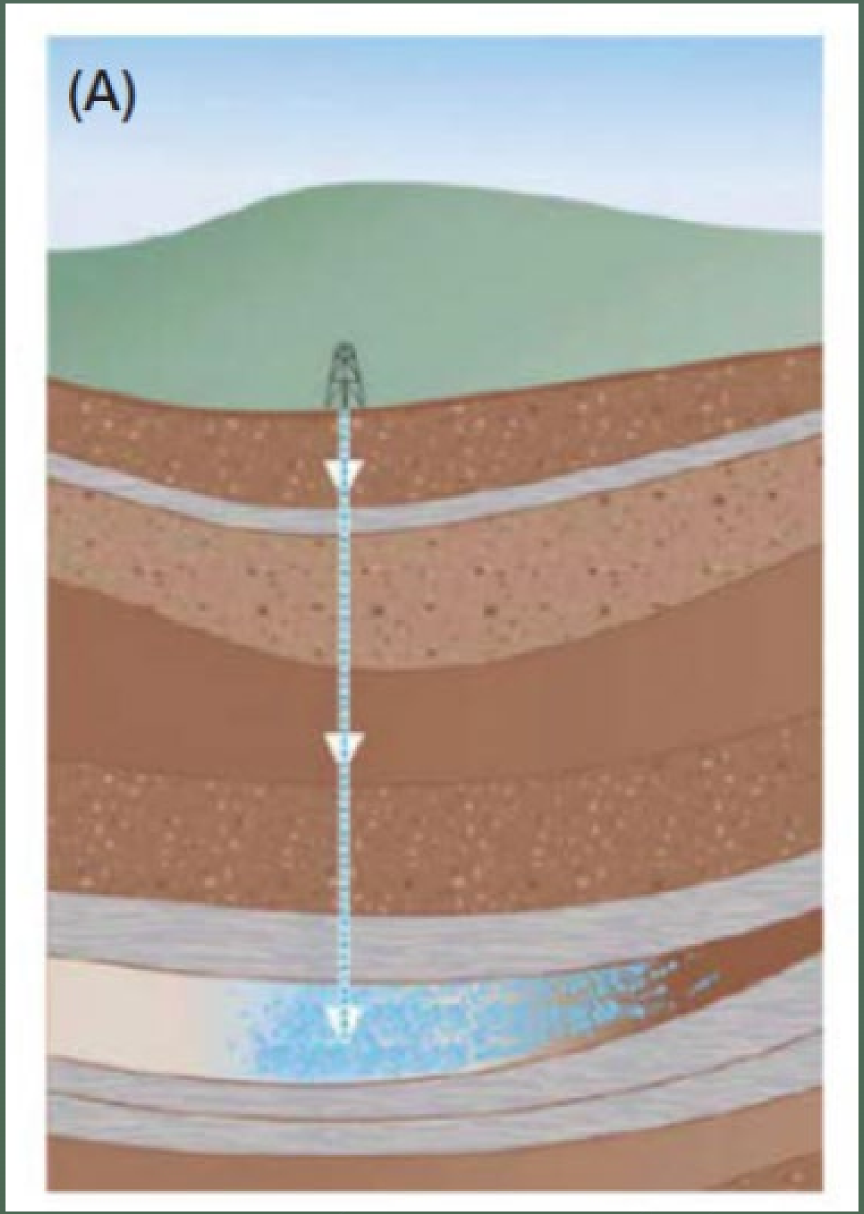
- Anticline structural trap (rock folding making a dome):
    - CO_2 less dense than the saline water → floats to the top of the saline reservoir → gets trapped (can't move upward or laterally (no where to go → can't sink and all the caprock is there is all the other directions



Best Practices: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects, 2017, DOE, NETL

Pinchout stratigraphic trap

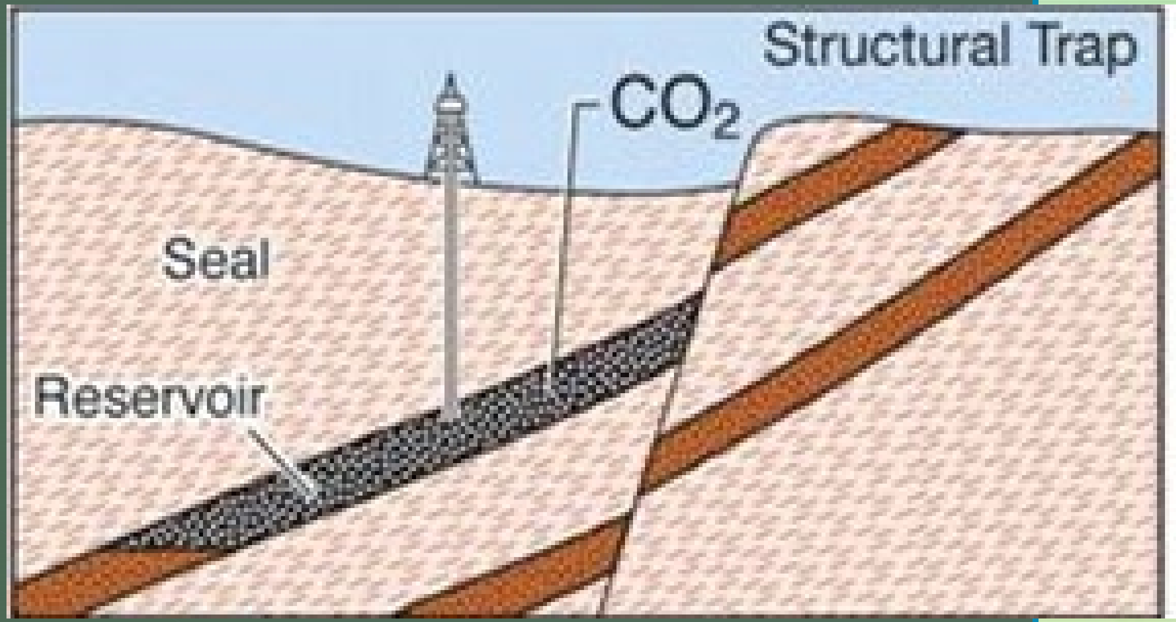
- Caprcok prevents upward migration of CO_2
- The layer of the saline reservoir gets thinner (pitchout) → prevents lateral migration of CO_2 → How?
- The thinner part of the saline formation is more compact, less porous and permeable → fluid is trapped!



Best Practices: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects, 2017, DOE, NETL

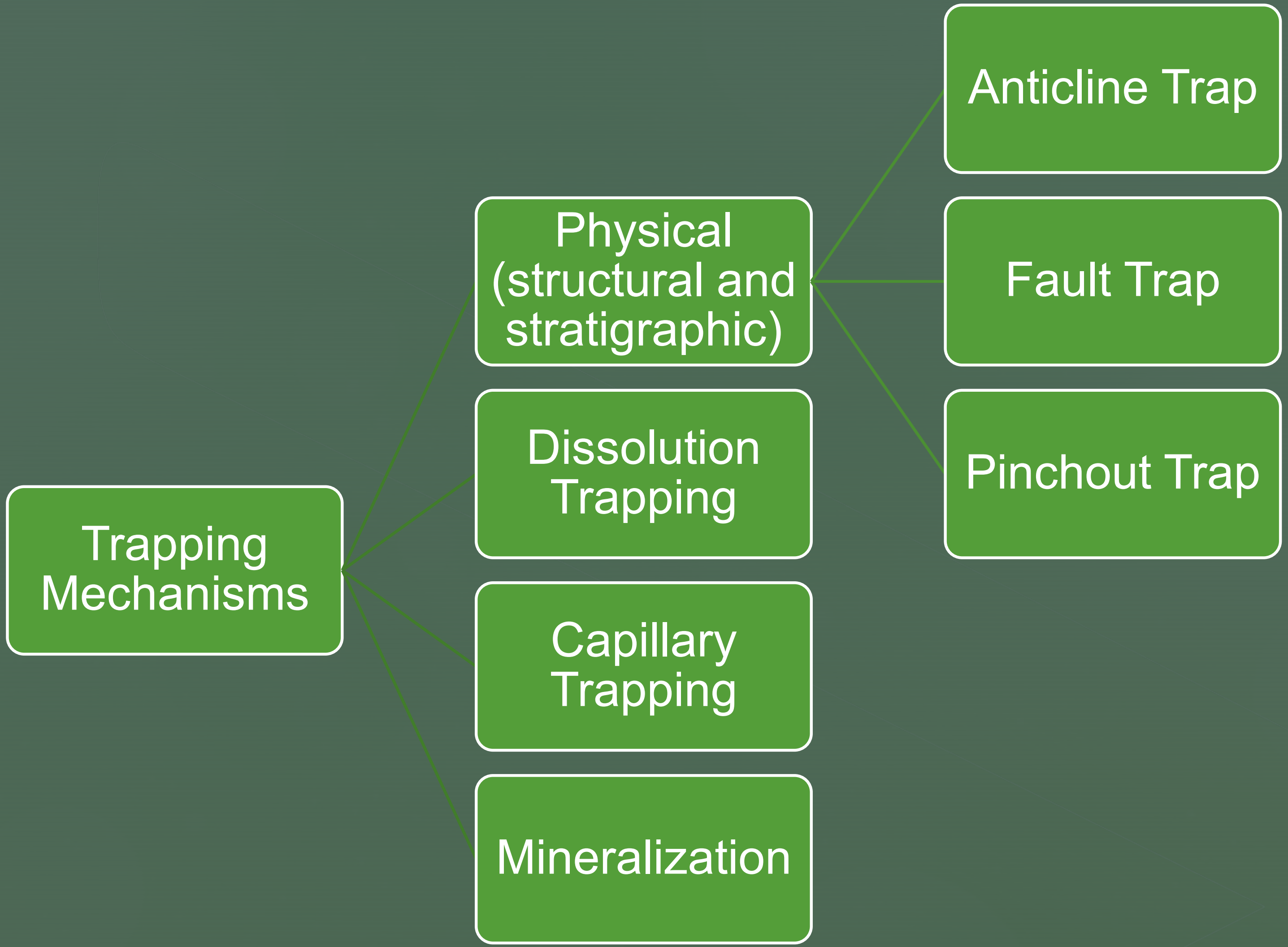
Fault Structural Trap

- Fault → leaves no place (vertically or laterally) for the CO_2 to move



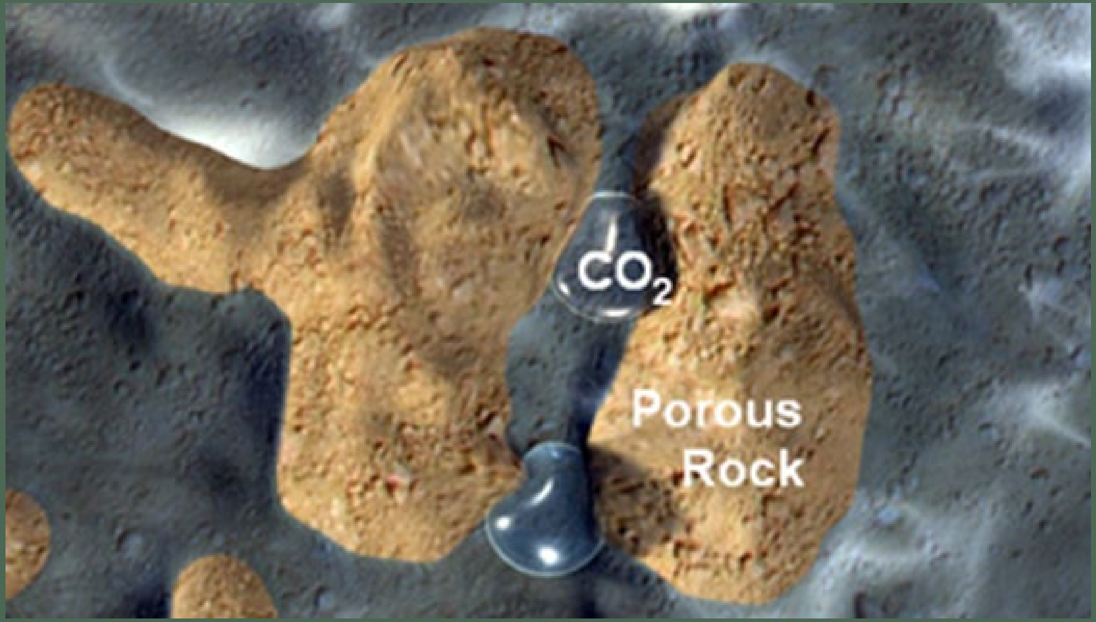
https://netl.doe.gov/

We have a couple of trapping mechanisms and they happen at different time scales



Capillary (Residual) Trapping

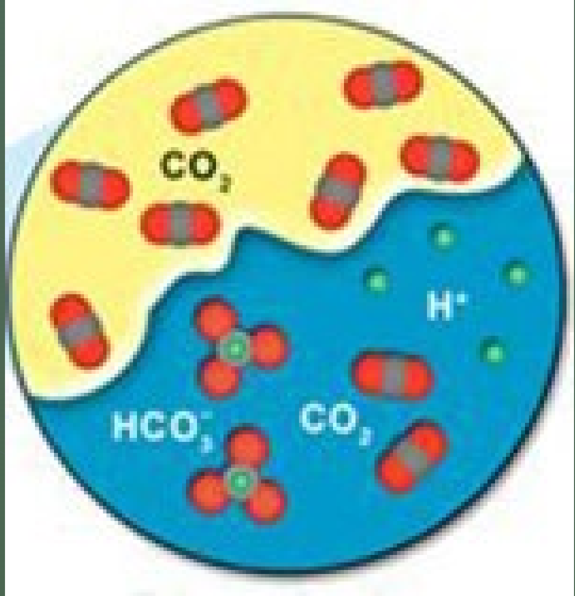
- CO_2 migrates out of the pore space → some CO_2 will get stuck inside because of capillary forces → saline water will return and displace the CO_2 that left the pore and will trap whatever CO_2 fraction that was not able to leave the pore space



https://www.co2captureproject.org/co2_trapping.html

Dissolution trapping

- CO_2 (supercritical state) is immiscible with the saline water → it takes years to dissolve very slowly → but eventually some dissolution will take place → when it dissolves, CO_2 is trapped in the liquid phase

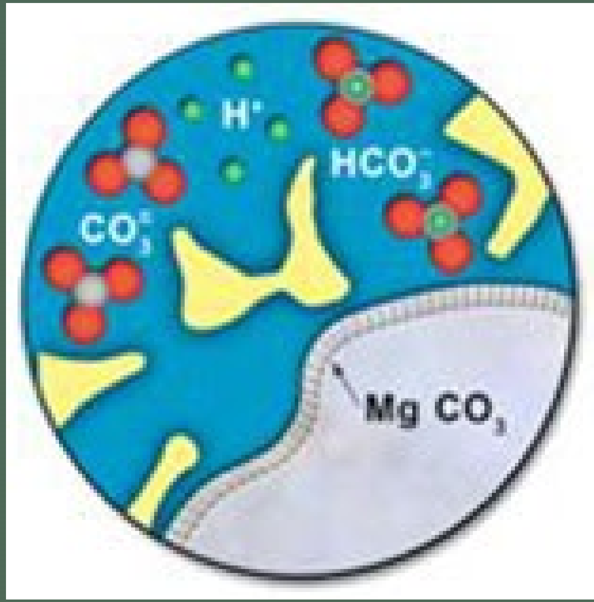


https://netl.doe.gov/

Mineral Trapping

- Takes centuries
- CO_2 reacts with minerals in the saline reservoir rocks and form solid carbonate minerals (e.g. form magnesium carbonate)
- (permeant trapping!) → like what??

Basalt formations



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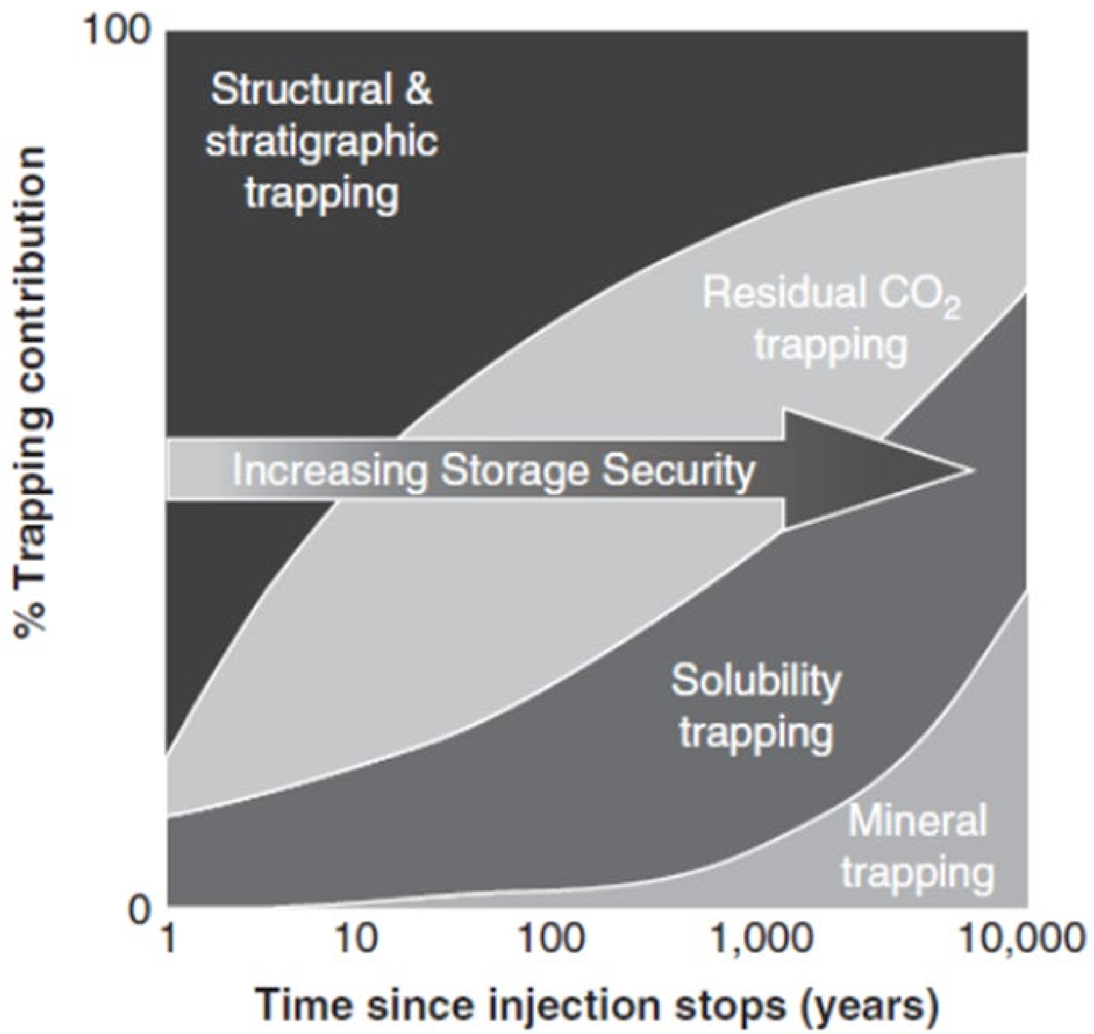
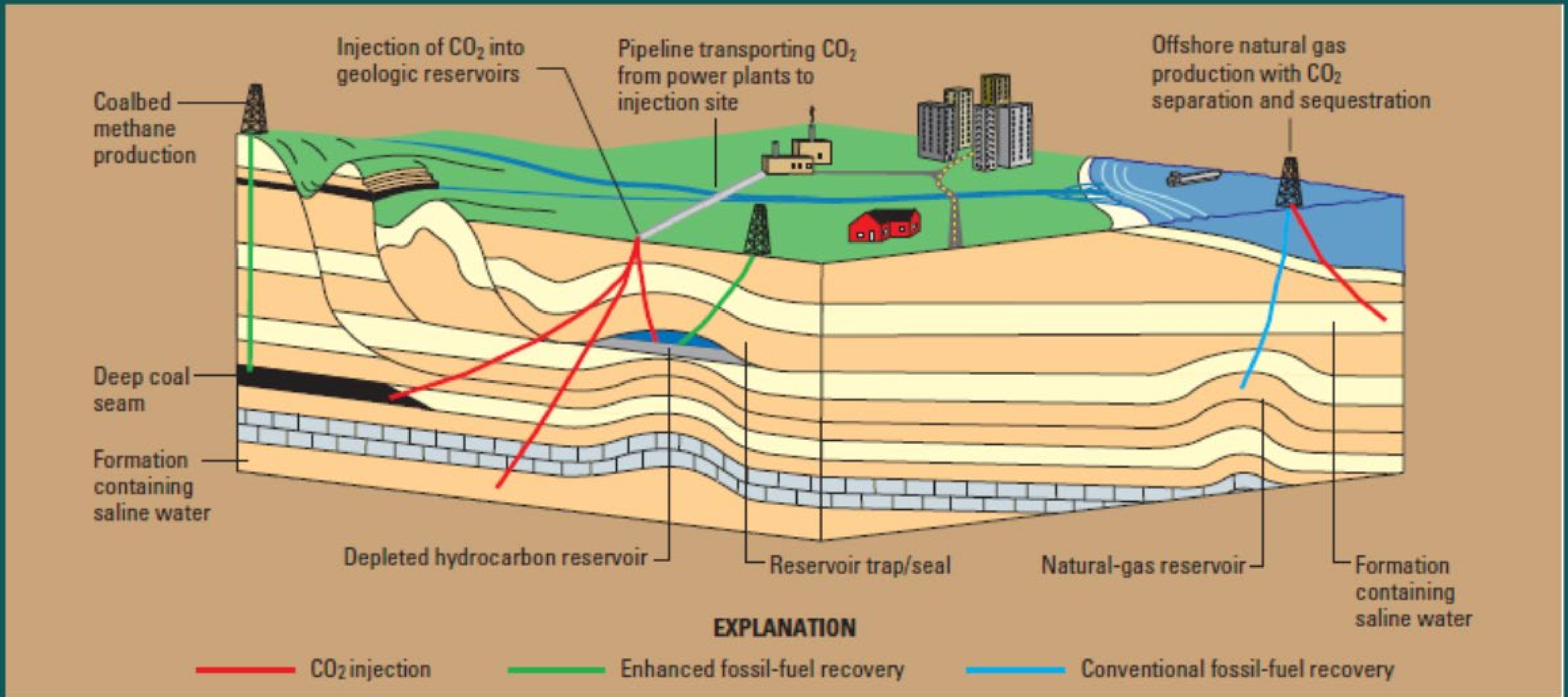


Figure 13.3. Schematic of the influence of different trapping mechanisms over time

https://sequestration.mit.edu/pdf/2009_CO2_Capture_and_Storage_Ch13_book.pdf



	Oil and gas reservoirs	Formations containing saline water	Unmineable coal beds
Advantages:	• Well-characterized volume • Known seal • Potential fuel recovery to offset cost	• Largest capacity (~250 to 900 gigatons carbon) • Wide distribution	• Adjacent to many large power plants (CO_2 source) • Potential fuel (methane) recovery to offset cost
Disadvantages:	• Smallest capacity (~25 gigatons carbon) • Limited in number • Requires infrastructure to transport CO_2	• Poorly characterized • Greatest geologic uncertainty • Unknown seal effectiveness	• Poorly characterized • Difficult to define "unmineable" coal • Potential coal resources may be rendered unusable
Environmental issues:	Potential for mobilization of ground-water contaminants; leakage of CO_2 and CO_2-saturated saline water; induced seismicity		
Regulatory issues:	Determination of rules affecting injection wells; multiple regulatory jurisdictions (State, Federal, local); post-injection ownership and liability		

Figure 3. Types of geologic CO_2 sequestration, their advantages and disadvantages, and potential environmental and regulatory issues. Offshore natural-gas production and CO_2 sequestration are currently occurring off the coast of Norway, where the gas produced contains a high concentration of CO_2 that is removed and injected into a nearby formation containing saline water.

Table 3 - CO_2 storage options of commercial and pilot/demonstration CCS facilities. Notes: DGOF: Depleted gas and oil field, SF: saline formation, EOR: CO_2- enhanced oil recovery (Global CCS Institute 2020).

SCENARIO		DEVELOPMENT	CONSTRUCTION	OPERATION	COMPLETED
COMMERCIAL FACILITIES					
Onshore	DGOF	1			
	SF	12		3	1
	EOR	9	3	21	
Offshore	DGOF	6			
	SF	9		2	
	EOR			1	
PILOT & DEMONSTRATION PROJECTS					
Onshore	DGOF	1		1	4
	SF	3	1	3	10
	EOR		1	8	4
Offshore	DGOF				1

Most of the new development projects are in SF
Older ones were for EOR
DGOF = depleted gas and oil formation

Technology Readiness and Costs of CCS, 2021, Global CCS Institute

Factors to consider when choosing a geologic formation for CO_2 injection

- **Capacity:** how much pore space (openings within rocks)
- Injectivity: depends on the permeability (relative ease – interconnectedness of individual pores) with which the fluid can move within the pore spaces of rock
  - Having a lot of pores but they are not connected well would not be ideal
- Integrity: ability to confine the injected fluid by having an impermeable seal (caprock)

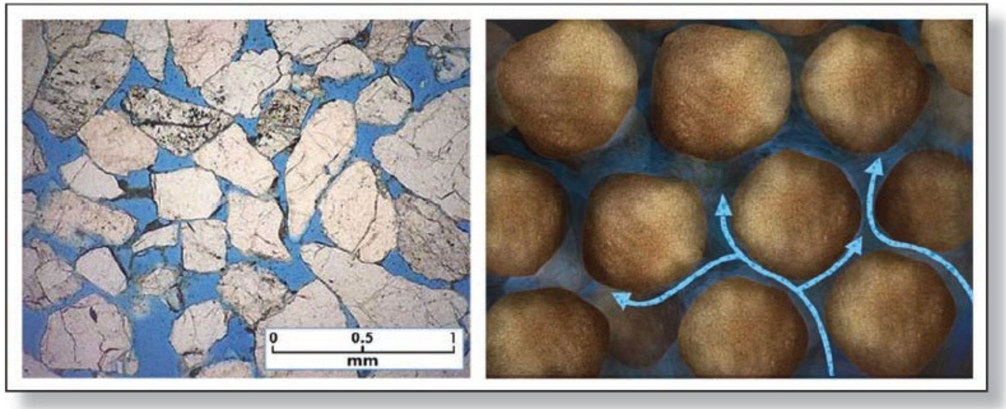


Figure 2-2. Microscopic Schematic of Rock Porosity and Permeability.

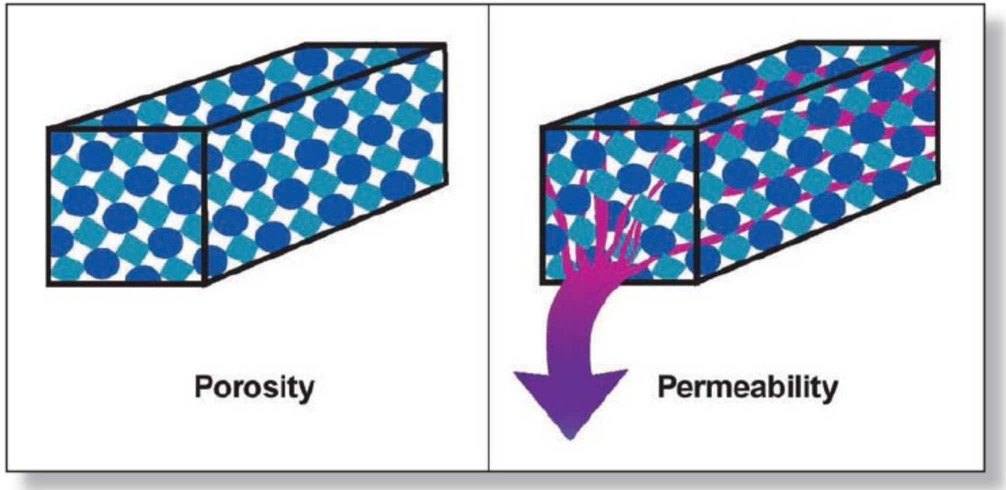


Figure 2-1. Porosity in Rocks and Rock Permeability.

Best Practices for Geologic Storage Formation Classification: Understanding Its Importance and Impacts on CCS Opportunities in the United States, 5th Edition, NETL, DOE, 2010

Storage

- Why do we need to inject CO_2 deep underground? (in other words, why depth of injection matters)?
- Trapping mechanisms in the geologic formations?
- Ok, Let us inject CO_2 in the geologic formation → Injection Wells
  - History of injection
  - Types of Injection wells & their regulatory framework
  - Class VI well components & construction
  - Miscellaneous considerations for Class VI wells

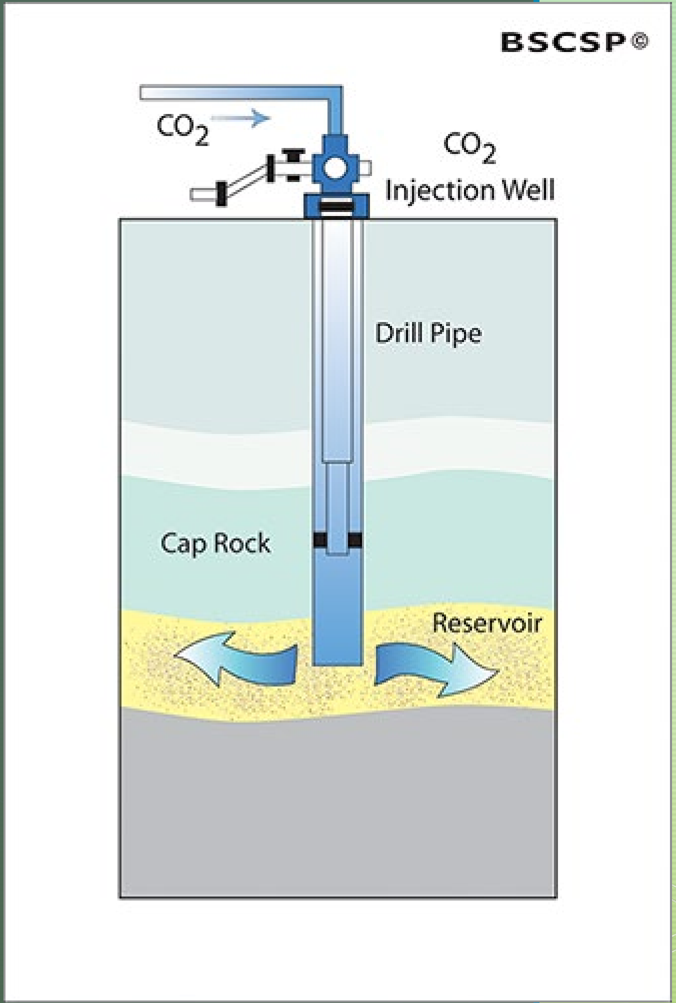
Injection of CO_2 is not new

https://permianpartnership.org/

- Acid-Gas Injection
  - Mixture of H_2S and CO_2 (acid gases, CO_2 is the dominant gas in the mix)
  - Acid gases are byproduct of oil and gas production – need to be removed to meet natural gas transportation and quality
  - Acid gas is separated, compressed and injected underground
- Enhanced Oil Recovery (EOR) – done a lot in the Permian basin – mature technology – started in 1970s
- The three sisters (acid gas, EOR, and CO_2 for storage)

Types of injection wells

- Injection wells are regulated under the Safe Drinking Water Act, the Underground Injection Control Program (UIC)
- The goal of the regulations is to protect the underground drinking water sources (USDW)
- Six well types are regulated under the UIC program:
  - Class I: wells for injecting hazardous of non-hazardous industrial and municipal wastes below USDW
  - Class II: wells for injecting brine and other fluids (including CO_2) for enhanced oil recovery (EOR)
  - Class III: wells for injecting fluids associated with mining of minerals
  - Class IV: wells for injecting hazardous or radioactive wastes into or above USDW (used for groundwater remediation)
  - Class V: experimental technology wells
  - Class VI (added by the EPA in 2010): new class of injection wells for CO_2 geologic storage



https://www.bigskyco2.org/node/123

Table 1. EOR and Permanent GS Injection Wells

	Enhanced Oil Recovery	Geologic Sequestration
EPA Well Class	Class II	Class VI
Purpose	Injecting CO_2 into aging oil fields for EOR	Injecting CO_2 into geologic formations for permanent CO_2 storage
Number of Wells	134,650	2
CO_2 Volume Injected	68 million tons/year (as of 2014)	1.3 million total (one project in IL [2019 data])
SDWA Primacy States	40 (16 under §1422 24 under §1425)	1

Notes: Number of permitted EOR wells is approximate and based on 2018 EPA data. CO_2 volume based on most recent data available. SDWA = Safe Drinking Water Act.

Congressional Reserach Services, June 2020

- EPA delegated primary regulatory authority ("Primacy") for Class VI well to only two states so far → any guess which ones?
- North Dakota and Wyoming (recent)
- Where are these 2 class VI wells?

Region	State	County	Permittee/Permit Applicant[a]	Proposed CO_2 Injection Rate[b]	Maximum CO_2 Injection Rate[b]	Maximum Total CO_2 Injection Volume[b]	Current Status of Permit[c]	Current Project Phase[d]
5	IL	Macon	Archer Daniels Midland	0.3 million metric tons/year	n/a*	1.0 million metric tons*	Active [Learn more about the permit]().	Post-Injection
	IL	Macon	Archer Daniels Midland	1.0 million metric tons/year	1.2 million metric tons/year	6.0 million metric tons	Active [Learn more about the permit]().	Injection
	IN	Vigo	Wabash Carbon Services, LLC	n/a	n/a	n/a	Pending	Pre-Construction
				n/a	n/a	n/a	Pending	Pre-Construction
	OH	Lorain	Lorain Carbon Zero Solutions, LLC	n/a	n/a	n/a	Pending	Pre-
6	LA	Cameron	Hackberry Carbon Sequestration, LLC	n/a	n/a	n/a	Pending	Pre-Construction
9	CA	Fresno	Mendota Carbon Negative Energy Project ProjectCo LLC	n/a	n/a	n/a	Pending	Pre-Construction
	CA	Kern	Carbon TerraVault 1, LLC	n/a	n/a	n/a	Pending	Pre-Construction
				n/a	n/a	n/a	Pending	Pre-Construction
	CA	Kern	Carbon TerraVault 1, LLC	n/a	n/a	n/a	Pending	Pre-Construction
	CA	Kern	San Joaquin Renewables LLC	n/a	n/a	n/a	Pending	Pre-Construction

- The two permits were issued in 2017 for injecting CO_2 from the ADM ethanol plant into saline formations

https://www.epa.gov/uic/class-vi-wells-permitted-epa

How different is Class II from Class VI wells?

- They both inject CO_2 in geologic formations but Class VI has a primary different purpose than Class II → so, their minimum permitting requirements are different
- Some differences for Class VI (thoughts before we discuss):
  - Purpose is the long-term storage of CO_2
  - Higher injection pressures and volumes (high risks of leaks and inducing seismic activity)
  - Class VI regulations require more comprehensive site characterization as well as construction, operation, and post closure requirements
  - Class VI has a larger Area of Review (AoR) and include how CO_2 plume flows underground

Table 1 Mandatory Technical Requirements for CO_2 Injection Well (NETL, 2009)
Tablica 1. *Obvezni tehnički zahtjevi za bušotine za utiskivanje CO_2 (NETL, 2009)*

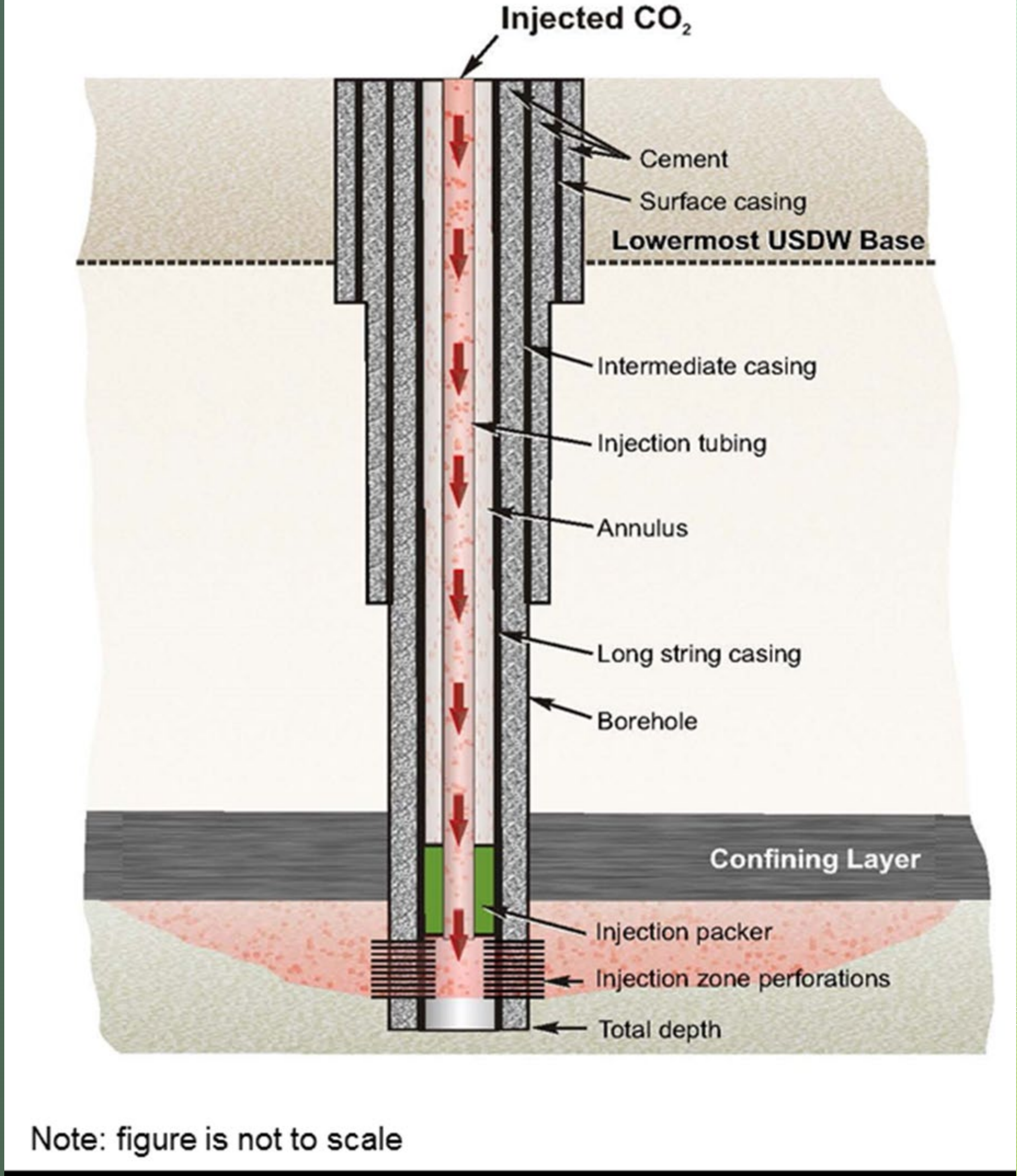
Technical Requirements for CO_2 Injection Well (Class VI)	
Siting	Extensive site characterization needed, including well logs, maps, cross-sections, USDW locations, determine injection zone porosity, identify any faults, and assess seismic history of the area.
Fluid Movement	No fluid movement to a USDW.
Area of Review (AoR)	Determined by computational model and reevaluated during project duration.
Construction	Two layers of corrosion-resistant casing required and set through lowermost USDW. Cement compatible with subsurface geology.
Operation	Injection pressures may not initiate or propagate fractures into the confining zone or cause fluid movement into USDWs. Quarterly reporting on injection, injected fluids and monitoring of USDWs within the AoR. Must report changes to facility, progress on compliance schedule, lose of mechanical integrity, or noncompliance with permit conditions. Permit valid for 10 years.
Mechanical Integrity Test (MIT)	Continuous internal integrity monitoring and annual external integrity testing.
Monitoring	Analyze injectant. Continuous temperature and pressure monitoring in the target formation. Plume tracking required.
Closure	50 day notice and flush well. Must be plugged to prevent injectant from contaminating USDWs.
Proof of Containment and Post-Closure Care	Post-closure site care for 50 years or until proof of non endangerment to USDWs demonstrated. (No-migration petition demonstration; fluids remain in injection zone for 10 000 years).
Financial Responsibility	Periodically update the cost estimate for well plugging, post injection site care and site closure, and remediation to account for any amendments to the area of review and corrective action plan. EPA is also proposing that the owner or operator submit an adjusted cost estimate to the Director if the original demonstration is no longer adequate to cover the cost of the injection well plugging, post-injection site care, and site closure.

Storage

- Why do we need to inject CO_2 deep underground? (in other words, why depth of injection matters)?
- Trapping mechanisms in the geologic formations?
- Ok, Let us inject CO_2 in the geologic formation → Injection Wells
  - History of injection
  - Types of Injection wells & their regulatory framework
  - Class VI well components & construction
  - Miscellaneous considerations for Class VI wells

Schematic of a typical Class VI well

- At a glance, it has multiple layers of casings and cementing to prevent leakage and contact of CO_2 with the USDW
- CO_2 is injected through the innermost tubing that runs through the innermost string casing (long string casing)
- Injection packer seals the innermost tubing from the innermost casing
- Summary of components: casing, cement, tubing, injection packer, wellhead



https://cadmusgroup.com/articles/permitting-framework-for-geologic-sequestration-wells/

Now, let us construct a well and talk about the components as we go!

Well Pad

- Should have enough space for all activities including construction (e.g., drilling rig, well casings, etc.), maintenance, and monitoring
- Should be easily accessible by heavy equipment and trucks
- Size of well pad: example 200 ft x 150 ft for the Decatur, IL CO_2 injection project

https://www.dreamstime.com/photos-images/oil-well-pad.html

Well drilling

- Drilling methods for CO_2 injection projects are pretty similar to the ones used in the oil industry
- Materials handling during drilling operations:
    - Drill cuttings (large volumes to be handled
    - Drilling fluids (lubricate and cool the drill bits, help remove drill cuttings out of the wellbore)
    - Produced water (wastewater generated from drilling activities)

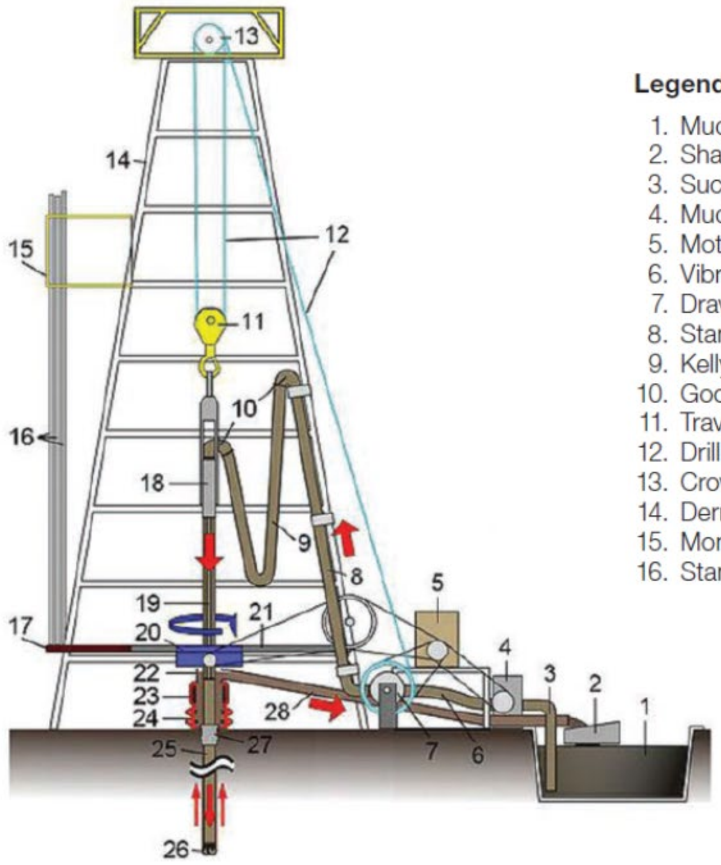


Figure 4-1: Example of a Mud Rotary Drilling Rig

(List created by TetraTech based on: http://en.wikipedia.org/wiki/File:Oil_Rig_NT8.jpg)

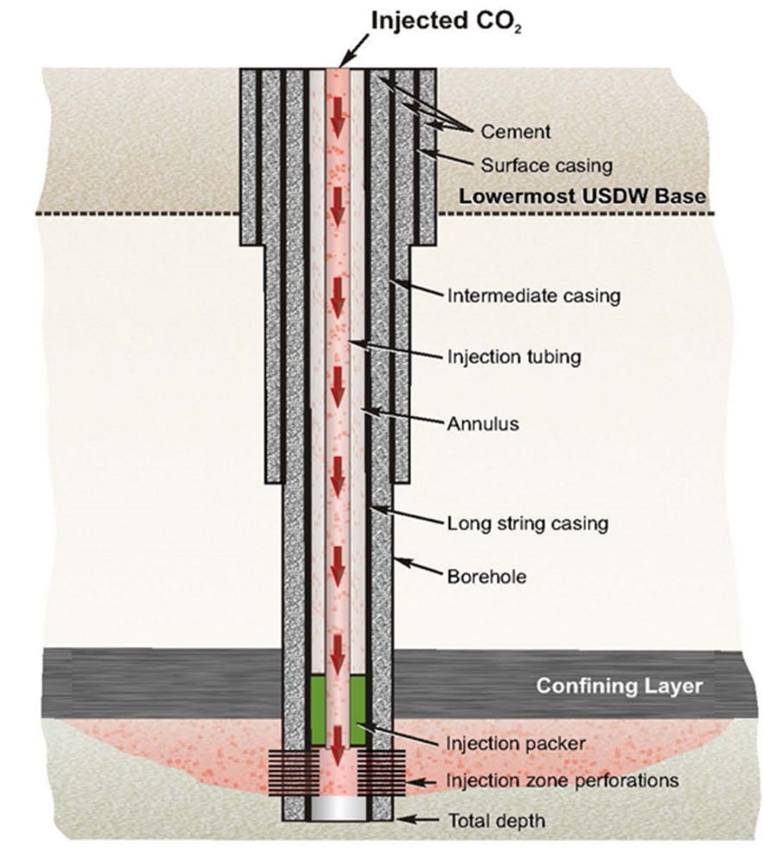
BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

As the wellbore is being drilled, casing and cementing are being installed

- Let’s talk about them!

Well Casing

- Purpose:
  - Maintain the borehole integrity during drilling
  - Barrier between CO_2 and USDW
- Casing materials are selected to handle the mechanical stresses and the corrosive nature of native surrounding fluids (e.g., brine in saline formation) and CO_2
  - Material options: 316 stainless steel, fiberglass, or lined carbon steel with glass reinforced epoxy
- More than one casing is usually needed
- Long string casing has perforations in the injection zone to allow the injected fluids to flow out to the storage formation
- All spacing between casings must be filled with cement:
  - Space between the casing and geologic formation
  - Space between intermediate casing and surface casing
  - Space between long string casing and intermediate casing

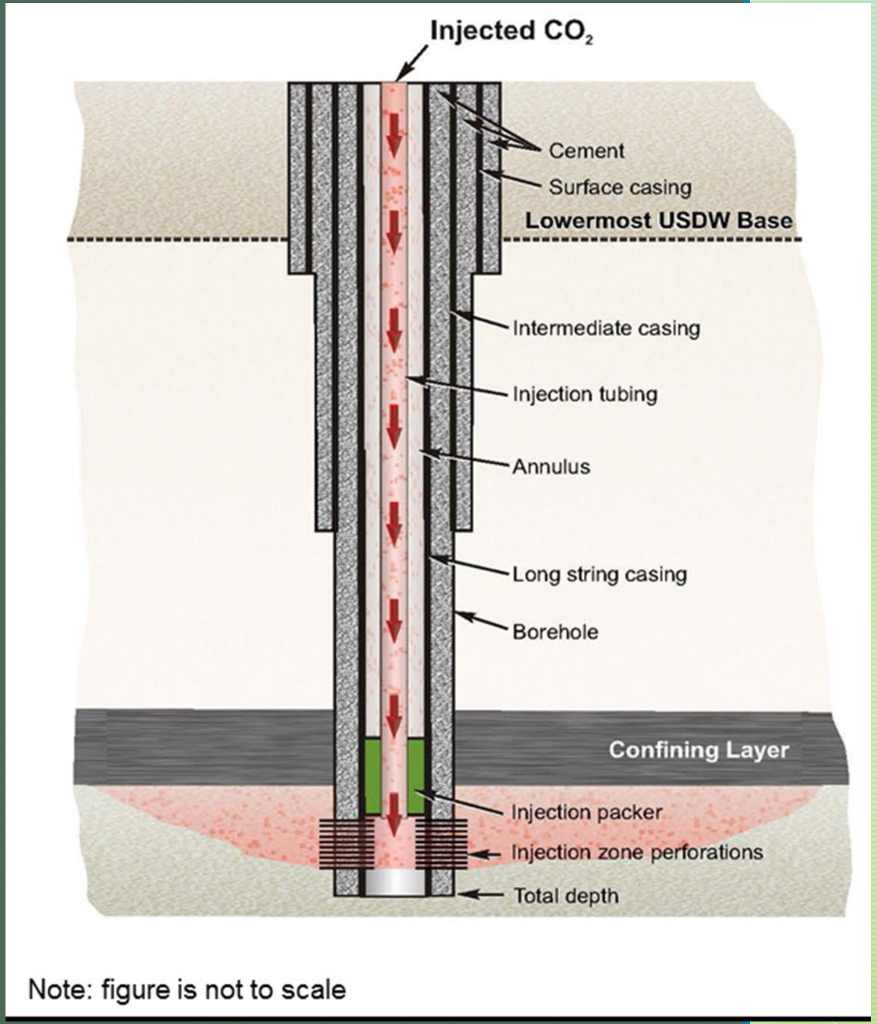


Note: figure is not to scale

https://cadmusgroup.com/articles/permitting-framework-for-geologic-sequestration-wells/

Cement

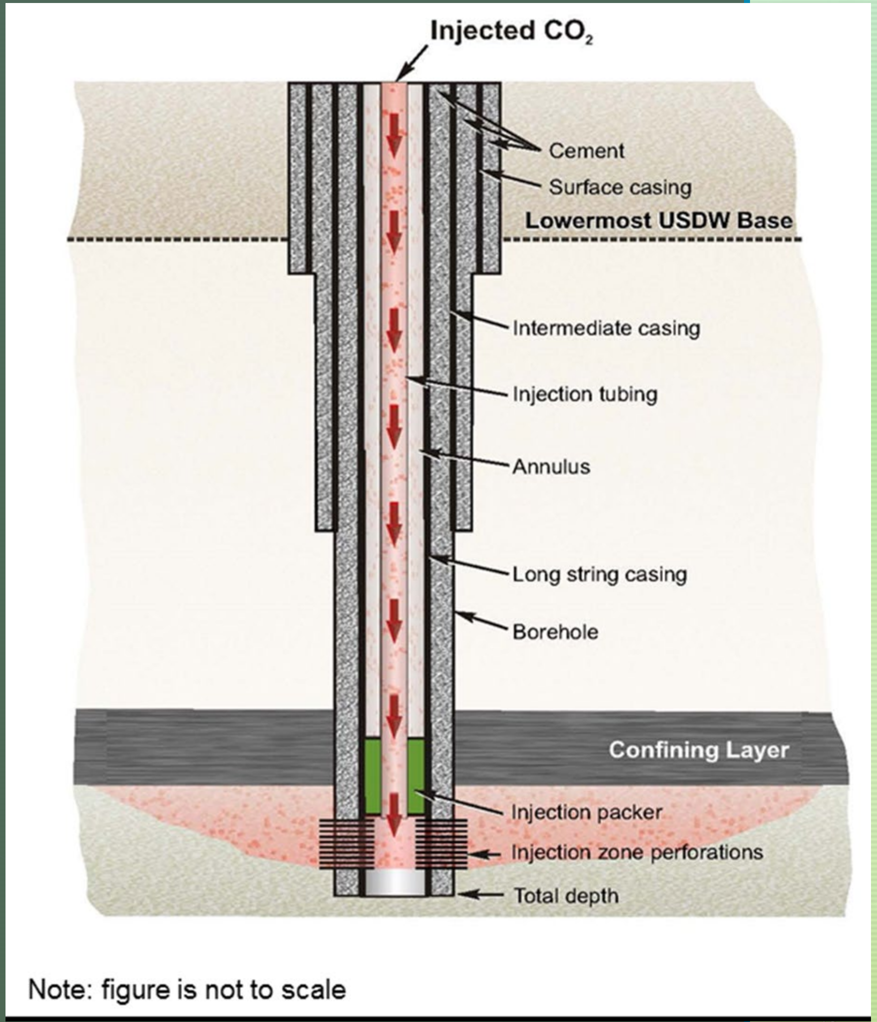
- Why it is needed?
  - Provide structural support for the casing
  - Prevent leakage of CO_2
  - Prevent contact of casing with corrosive formation fluids
- Regular cement is sufficient but CO_2-resitant cement would be better



https://cadmusgroup.com/articles/permitting-framework-for-geologic-sequestration-wells/

Tubing

- Barrier between the injected fluid and the long string well casing
- Runs from the ground surface down to the injection zone
- Designed to withstand all stresses the chemical nature of the fluid injected (e.g., 316 stainless steel, fiberglass, or lined carbon steel with glass reinforced epoxy)
- The space between the tubing and the long string casing must be filled with a non-corrosive packer fluid
- In summary → There are two barriers between the CO_2 and geologic formation above the injection zone (to protect USDW):
  - the tubing and
  - the long string casing



https://cadmusgroup.com/articles/permitting-framework-for-geologic-sequestration-wells/

Packer

- Sealing device to prevent CO_2 migration from injection zone into the annulus between long string casing and the injection tubing
- Packer materials should be resistant to (compatible with) fluids that it will come in contact with
- Packers are typically made from hardened rubber that is nickel plated)

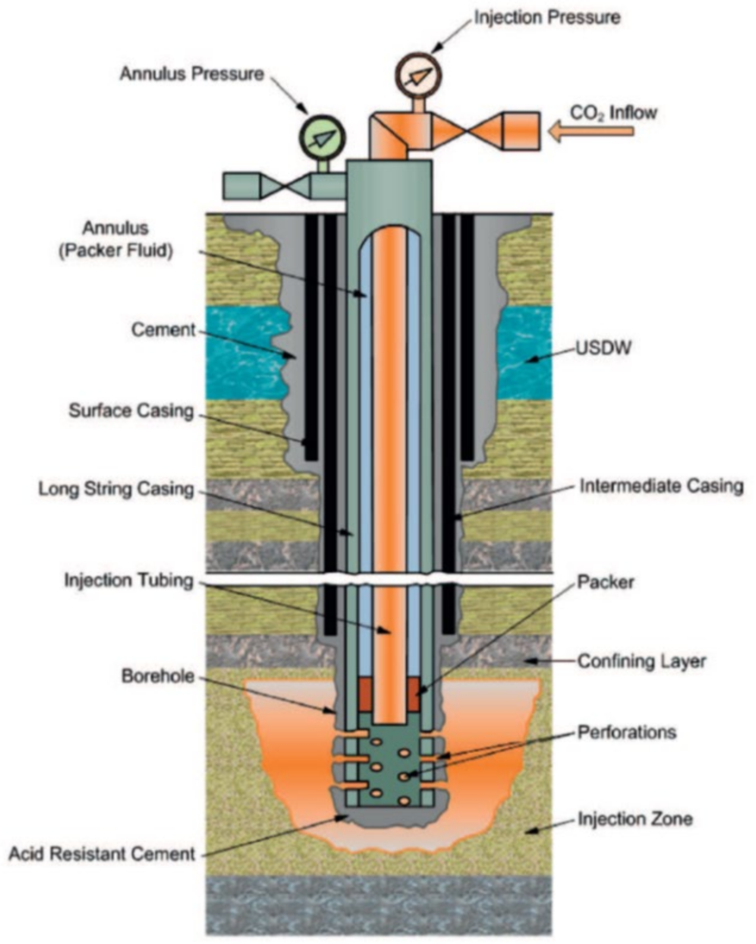


Figure 2 Schematic of a CO_2 Injection Well (Gaurina-Međimurec, 2011)
Slika 2. *Shematski prikaz bušotine za utiskivanje CO_2 (Gaurina-Međimurec, 2011)*

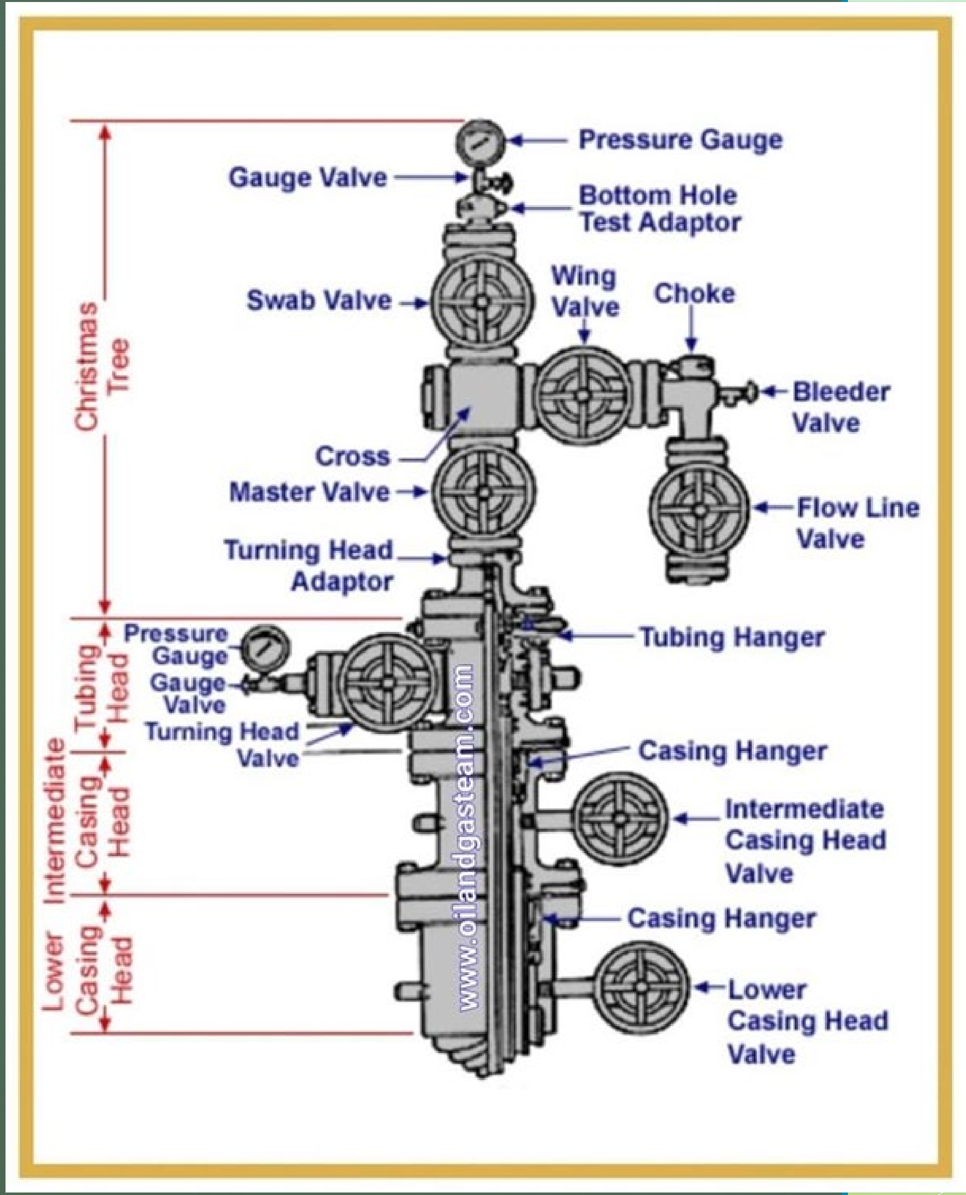
Wellhead

The well is completed by installing a wellhead and a Christmas tree

https://www.usgs.gov/media/images/co2-injection-well-mississippi

Wellhead

- Purpose: casing hanger (holds the casings and tubing in place), seal the annular space, control the CO_2 injection flows and pressures
- Typically designed to withstand pressures up to 10,000 psi (or more)
- It has a “Christmas tree” → an assembly of valves and pressure gauges

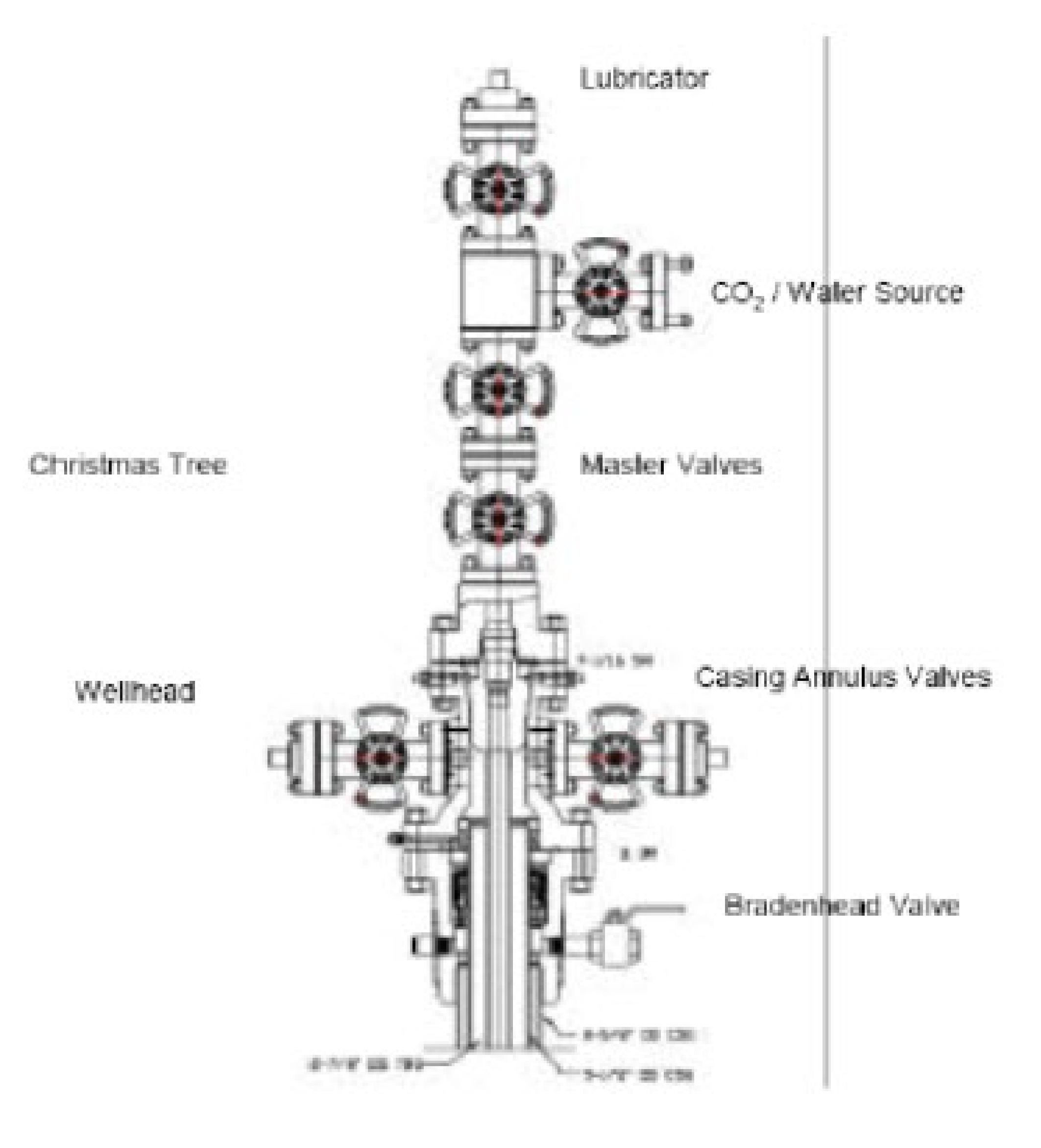


http://www.ingenieriadepetroleo.com/christmas-tree-oil-wellhead/

Some of the valves on the Christmas tree:

- CO_2 is injected through the Christmas tree
- Master valve: allows isolation of the injection tubing from the CO_2 source
- Lubricator valve → for running wireline tools through it for monitoring purposes

- Casing valves on the wellhead allows for monitoring CO_2 in the annulus spaces between casings



Geologic CO2 sequestration technology and cost analysis EPA Technical Support Document 2008

- The valves can be mechanically or manually operated
- SCADA (Supervisory Control and Data Acquisition) system is used to monitor the system performance and shut down the system automatically if problems are detected

The well construction is complete!

One final note on well construction

- The UIC Class VI wells have standard construction performance requirements that must be followed
- There are many guidelines and manuals for well construction

Table 4-4: API and ASTM Well Construction Specifications

API Specification	ASTM Specification	Construction Application
5CT		Casing and Tubing
5L		Line Pipe
6A		Wellhead and Christmas Tree Equipment
6D		Pipeline Valves
10A	C150	Well Cement
10D		Bow-Spring Casing Centralizers

BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

Storage

- Why do we need to inject CO_2 deep underground? (in other words, why depth of injection matters)?
- Trapping mechanisms in the geologic formations?
- Ok, Let us inject CO_2 in the geologic formation → Injection Wells
  - History of injection
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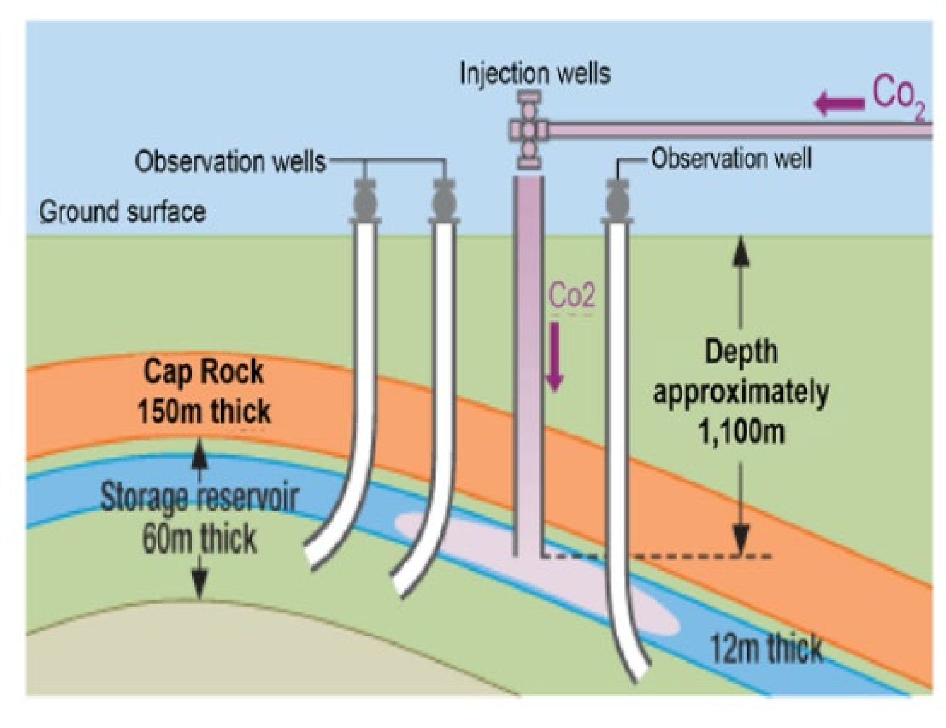
  - Miscellaneous considerations for Class VI wells

a) Well Design

- Injection wells are the most likely route of CO_2 leaks in a CCS project
- Thus, they need to be carefully designed and constructed to maintain integrity for the entire well life!
- We have more than just injection wells:
  - CCS injection site has at least one well and one monitoring well (a lot of monitoring done here).
  - The number and locations of the monitoring wells are determined based on the project objectives and regulatory requirements



T. Wilberforce, A.G. Olabi, E.T. Sayed et al.
Science of the Total Environment 761 (2021) 143203

b) Injection

- Operational stages of wells:
  - Start-up operation: pressure the well through gradual increase in injection rate until the permitted operational rate is reached (this stage might take a while)
  - Standard operation: operate at target injection rates
  - Note: monitoring is key to ensure well integrity throughout the system operation
- Injection pressure:
  - Has to be higher than the reservoir fluid pressure
  - Safe injection pressures are set by the regulatory agencies to prevent fracturing the confining zone

Minimum Operating, Monitoring, and Reporting Requirements Under the UIC Permit

Characteristic	Operating Limits	Monitoring		Reporting
		Frequency	Type	Frequency
Injection Pressure Maximum	1,818 psi	Weekly	—	Monthly
Annulus Pressure	—	Weekly	—	Monthly
Flow Rate	—	Weekly	—	Monthly
Cumulative Volume	—	Weekly	—	Monthly
Annulus Liquid Loss	—	Quarterly	—	Quarterly
Chemical Composition of Injectate	—	Annually	Grab	Annually

https://netl.doe.gov/sites/default/files/2018-02/FE00006821-Class-VI-Injection-Permit--Salient-Features-and-Regulatory-Challenges_Final.pdf

C) Well Closure ("plugging and abandoning")

- Before site closure, the operator needs to demonstrate non-endangerment to USDW to the UIC program Director
- Place cement plugs over all parts of the injection well and corrosion resistant cement maybe needed
- The monitoring wells will also need to be plugged at the end of the monitoring period

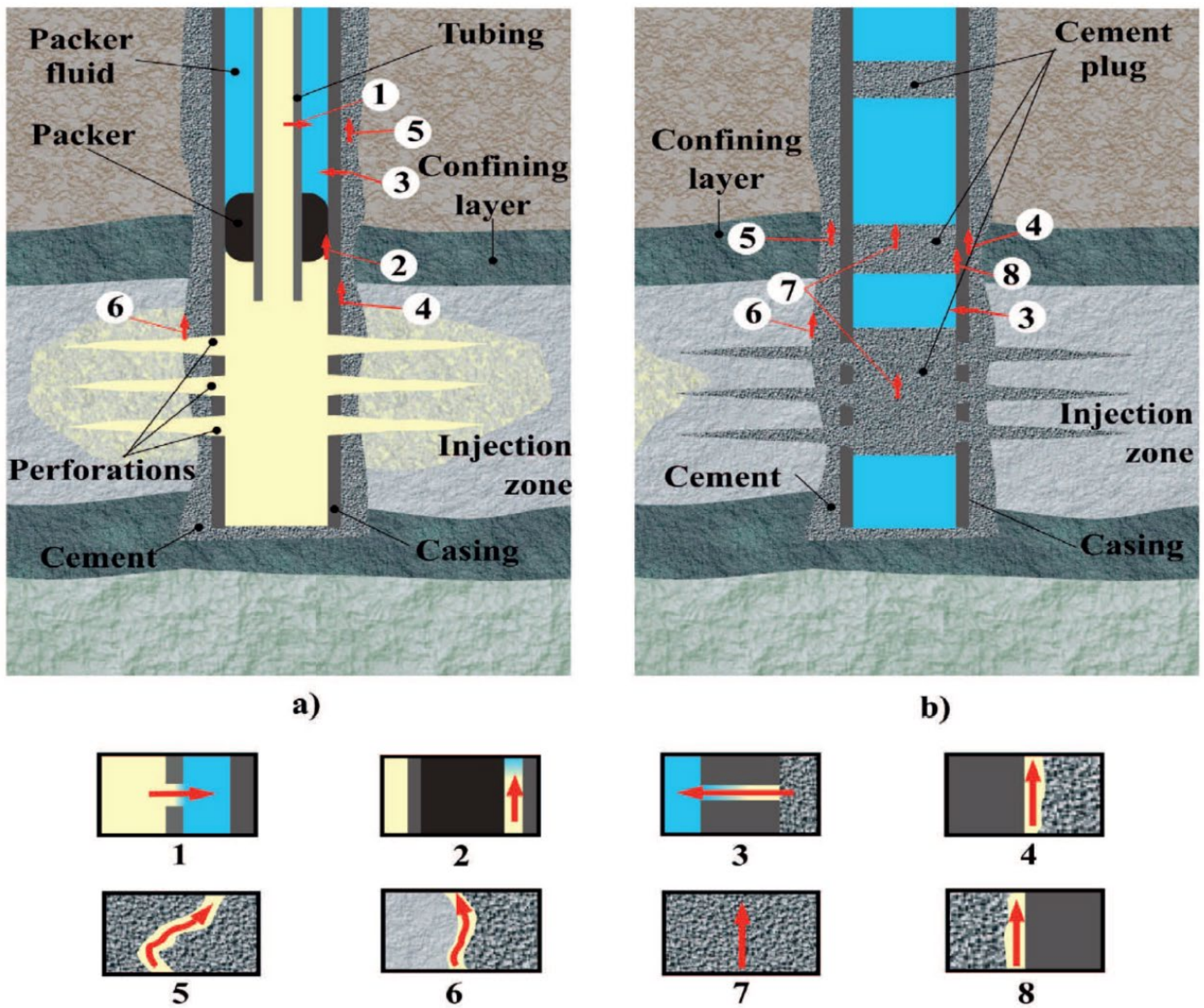
BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

We have been talking about leaks for a while…. Let us see potential CO_2 leakage pathways

Potential Leakage Pathways (for active and abandoned wells)

Leakage pathways

- 1) corrosion of the tubing
- 2) around the packer
- 3) corrosion of the casing
- 4) between cement and outside of the casing
- 5) cement fracture in the annulus
- 6) leakage in annular region between cement and formation
- 7) through the cement plug (abounded well)
- 8) between cement and outside casing (in case of abandoned wells)



Possible Leakage Pathwys in an Active CO_2 Well (a) and Abandoned Well (b)
Mogući putevi migracije fluida u aktivnoj (a) i napuštenoj (b) bušotini

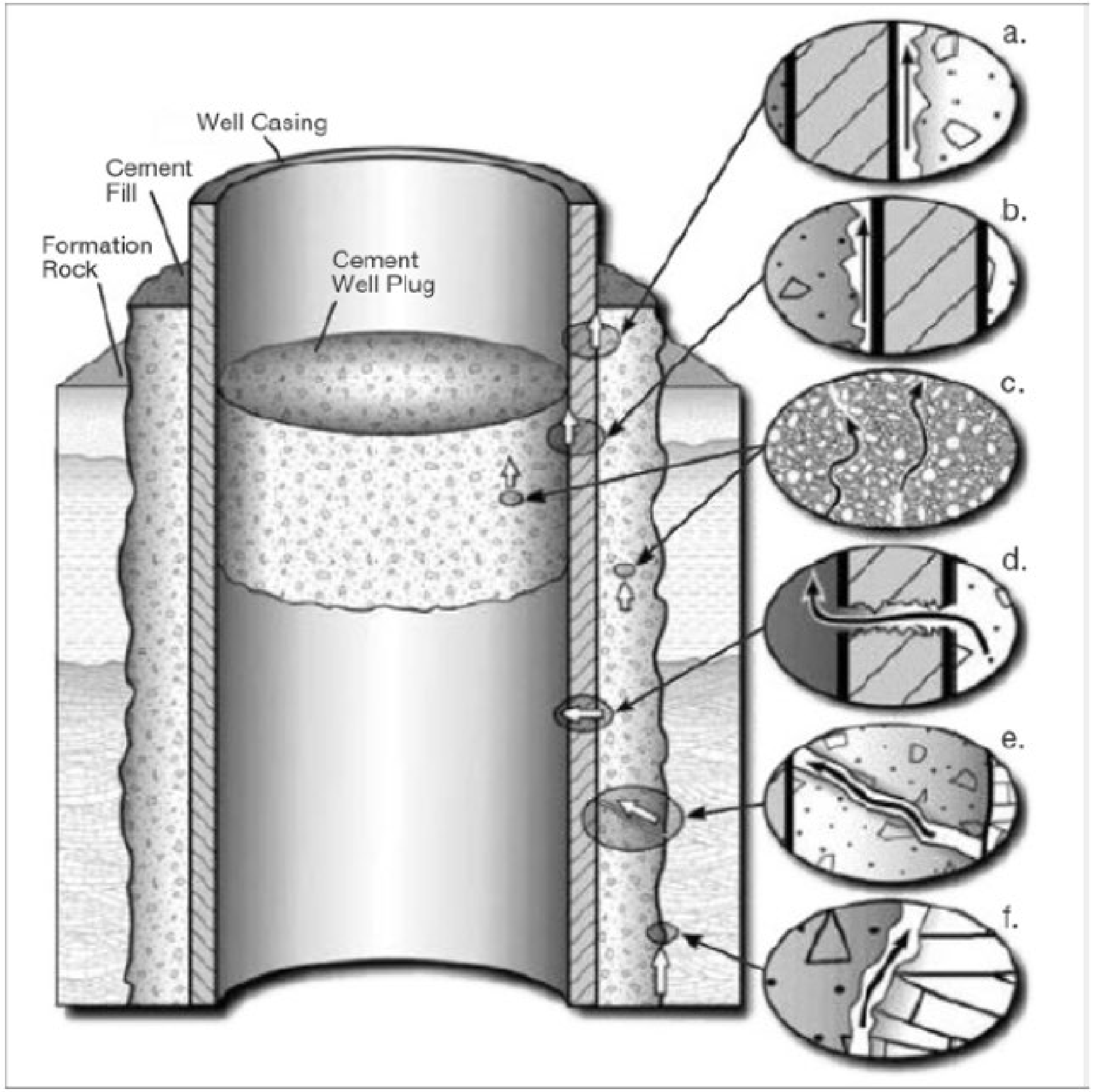


Figure 2-3: Potential leakage pathways for CO_2 in a well: the casing-cement interface (paths a and b), within the cement (c), through the casing (d), through fractures (e), cement-formation interface (f)

(from Celia et al., 2004)

BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

How come cement leaks?

Mechanism of degradation of cement in the wellbore because of CO_2 injection

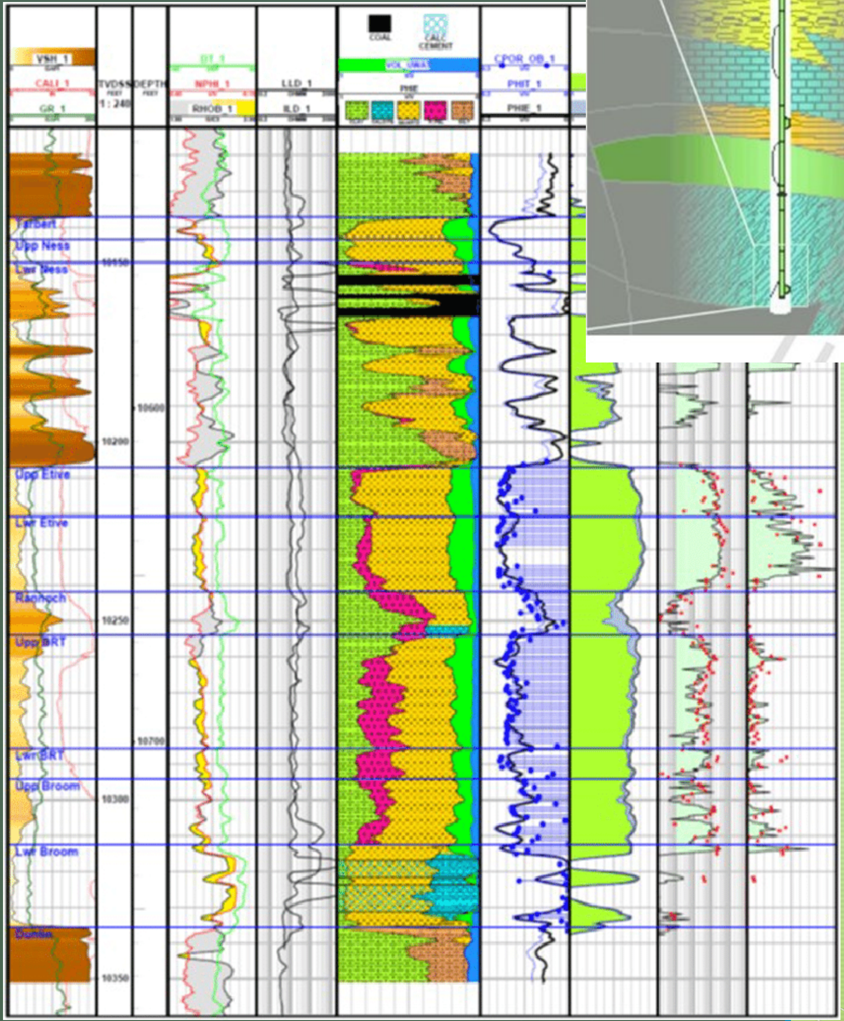
- No CO_2 environment:
  - Cement + water → hydration products form such as calcium hydroxide and calcium silicate hydrate gels (this is the main cement binding material)
- In CO_2-rich environment:
  - CO_2 + water → carbonic acid (H_2CO_3)
  - H_2CO_3 + cement → rapid degradation of cement because the H_2CO_3 reacts with the binding materials (calcium silicate gels) → volume expansion happens -→ cracks happen and some of the reaction byproducts will leave the cement matrix → cement is weakened and compressive strength decreases drastically

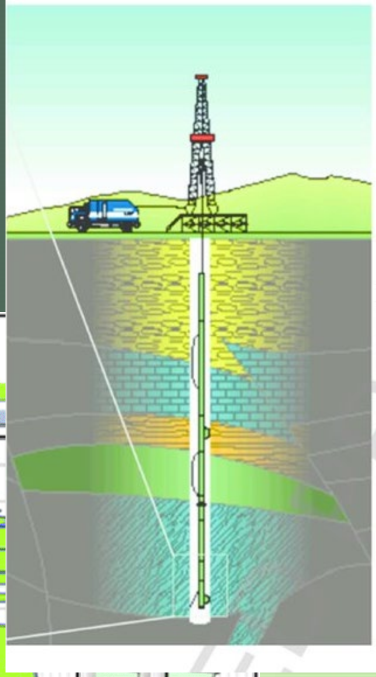
Is there a way to remediate or prevent degradation of cement in case of leaks?

- Use acid-resistant cement
- Use fillers (e.g., fly ash, silica fume) to reduce amount of Portland cement used
- Add materials (like latex) to reduce permeability of the cement or that permeability can be reduced by controlling the water ratio of the cement slurry

d) Well Integrity

- Well integrity tests are conducted throughout the life cycle of the injection well to ensure:
  - Mechanical soundness & ability to sustain pressures
  - Lack of defects and corrosion of well components
- Integrity tests →
  - Pressure tests
  - Wireline logs (insert through the Christmas tree)
    - Sends acoustics waves downhole and collect the signal intensity with depth → properties of media will be reflected in signal characteristics
    - Can get info on density of cement, cement contamination by gases or liquids, bonding with the casing





https://www.researchgate.net/figure/Interpretation-of-the-wireline-log-suite-from-considerably-updip-of_fig2_331189204

d) Injection site characterization prior to well construction

- Purpose of site characterization:
  - To determine whether the site is suitable for injecting CO_2
  - The chacateization data are inputs for well design, modeling to predict CO_2 plume transport (which helps determine the area of review), and help design the monitoring program
- What kind of characterization is performed?
  - Geologic, geophysical and engineering evaluations (porosity, thickness, permeability, stratigraphy, structure, where is the groundwater, seismic history, and more….)

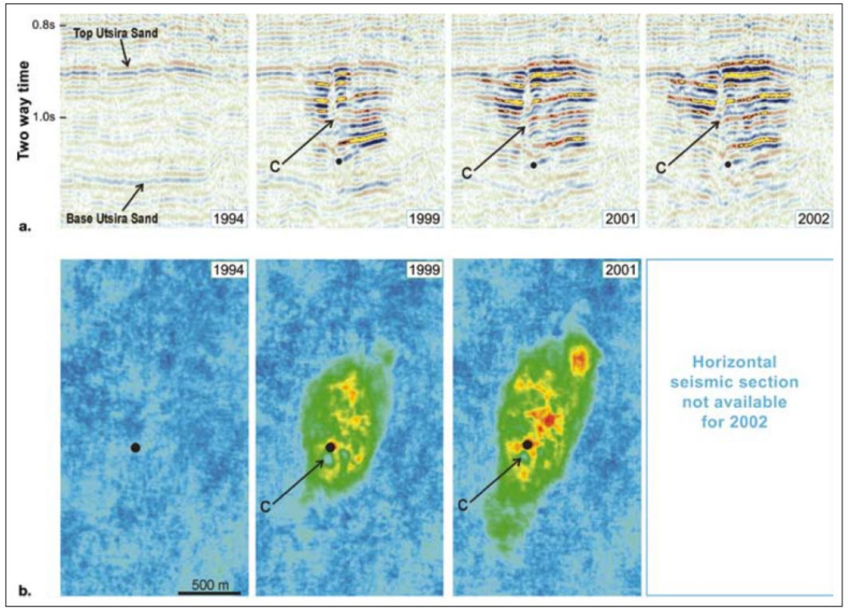
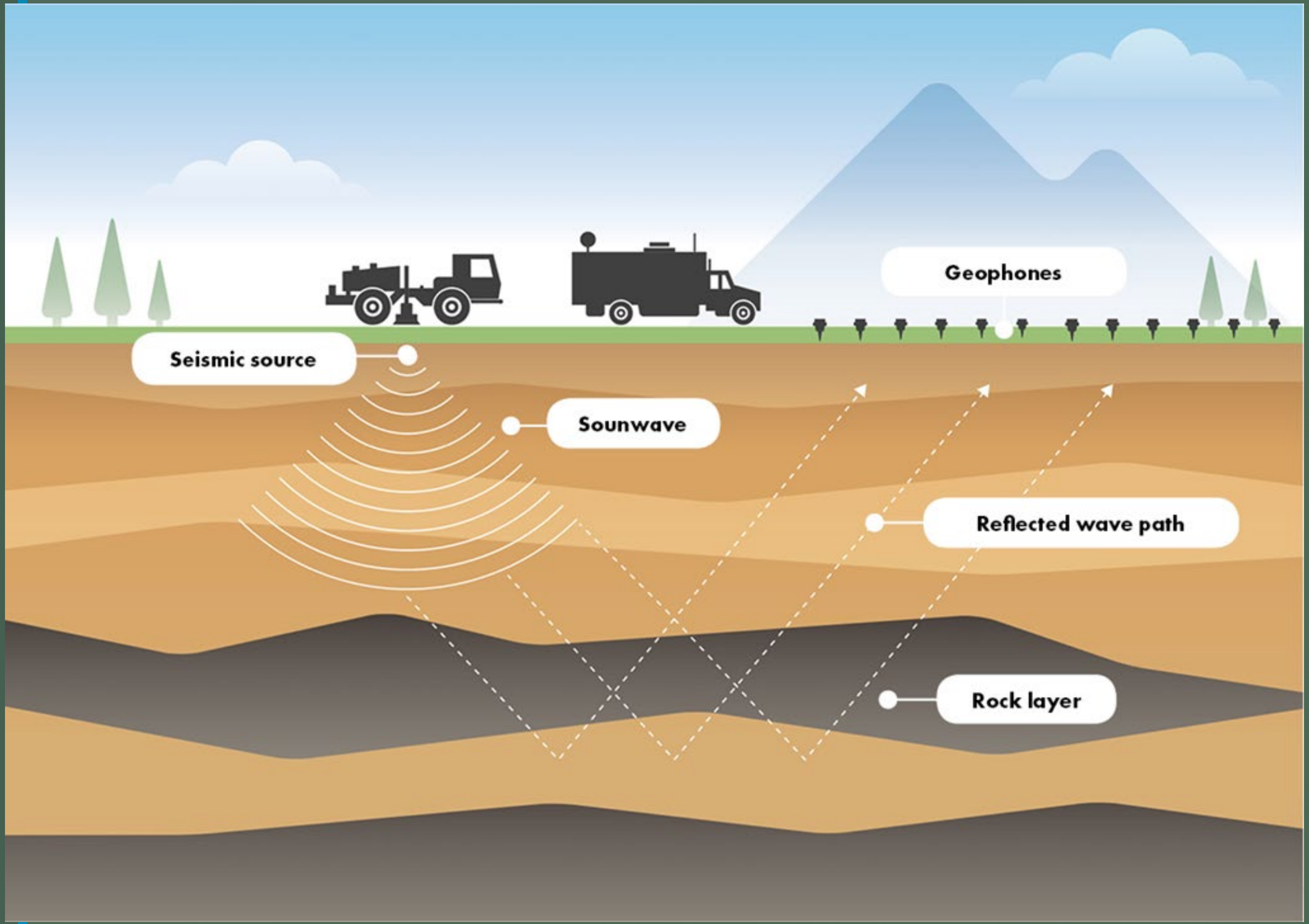


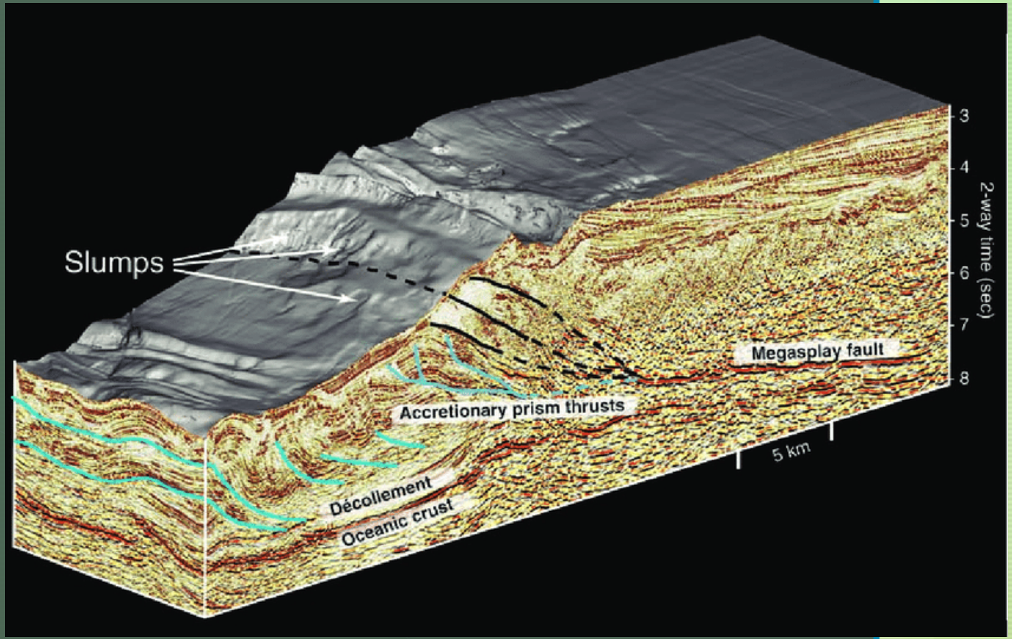
Figure 5.16 (a) Vertical seismic sections through the CO_2 plume in the Utsira Sand at the Sleipner gas field, North Sea, showing its development over time. Note the chimney of high CO_2 saturation (c) above the injection point (black dot) and the bright layers corresponding to high acoustic response due to CO_2 in a gas form being resident in sandstone beneath thin low-permeability horizons within the reservoir. (b) Horizontal seismic sections through the developing CO_2 plume at Sleipner showing its growth over time. The CO_2 plume-specific monitoring was completed in 2001; therefore data for 2002 was not available (courtesy of Andy Chadwick and the CO2STORE project).

IPCC Special Report on Carbon Capture and Storage, 2005c

Example of characterization tools: Seismic Surveys



https://www.scisnack.com/2019/10/23/what-seismic-data-tell-us-about-rocks-below-our-feet/



Moore, G. F. et al. (2007) Science, 318(5853), 1128-1131.

Monitoring

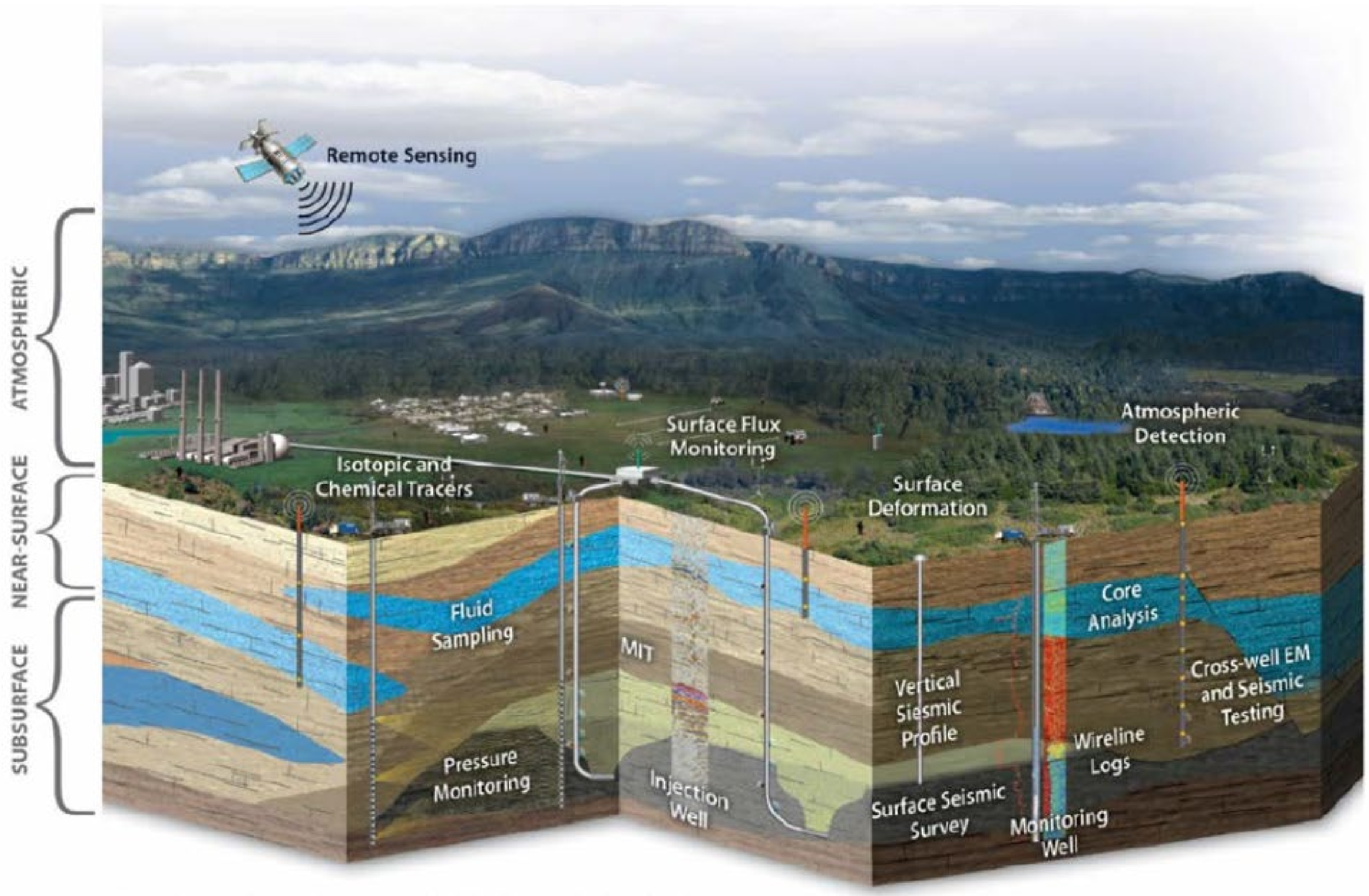


Figure 5-1: Examples of Various Field Monitoring Techniques

Backround Image Courtesy of Schlumberger Carbon Services

BEST PRACTICES: Operations for Geologic Storage Projects, 2017, DOE, NETL

Why monitoring?
(it is called monitoring, verification and accounting (MVA))

- Needed for regulatory compliance to ensure "safe. Effective, and permeant storage CO_2"
- Tracks key operational parameters (e.g., injection pressures and flow rates) and optimize operations
- Ensures CO_2 remains in the injection zone (i.e., detect leaks in the subsurface or above surface)
- Another side of the coin is: verify well integrity
- For accounting: CCS projects gain tax credits (45Q and LFCS credits) → monitoring is a means of accounting for the quantity of CO_2 injected and any negative back emissions in case of leakage (this way CCS operators can comply and demonstrate that they are abiding by these programs)

At which stage of the CCS project do we need to monitor?

- The monitoring program will have three key stages:
- 1) Pre-injection (after well is constructed and before starting to inject CO_2)
  - To establish baseline conditions for the site before the well starts to operate
  - Includes sampling groundwater, surface water bodies, atmospheric conditions, soil chemistry, among others
  - Better to monitor over several seasons to establish solid baseline conditions
- 2) Injection
  - To detect any changes to the site (changes in baseline conditions) as a result of project activities
- 3) Post-injection
  - To ensure the injected CO_2 is not well contained within the AoR and no changes are happening to the conditions of the system

Where to monitor and How?

- Atmospheric monitoring
- Near-Surface monitoring (this is where the USDW)
- Sub-surface monitoring

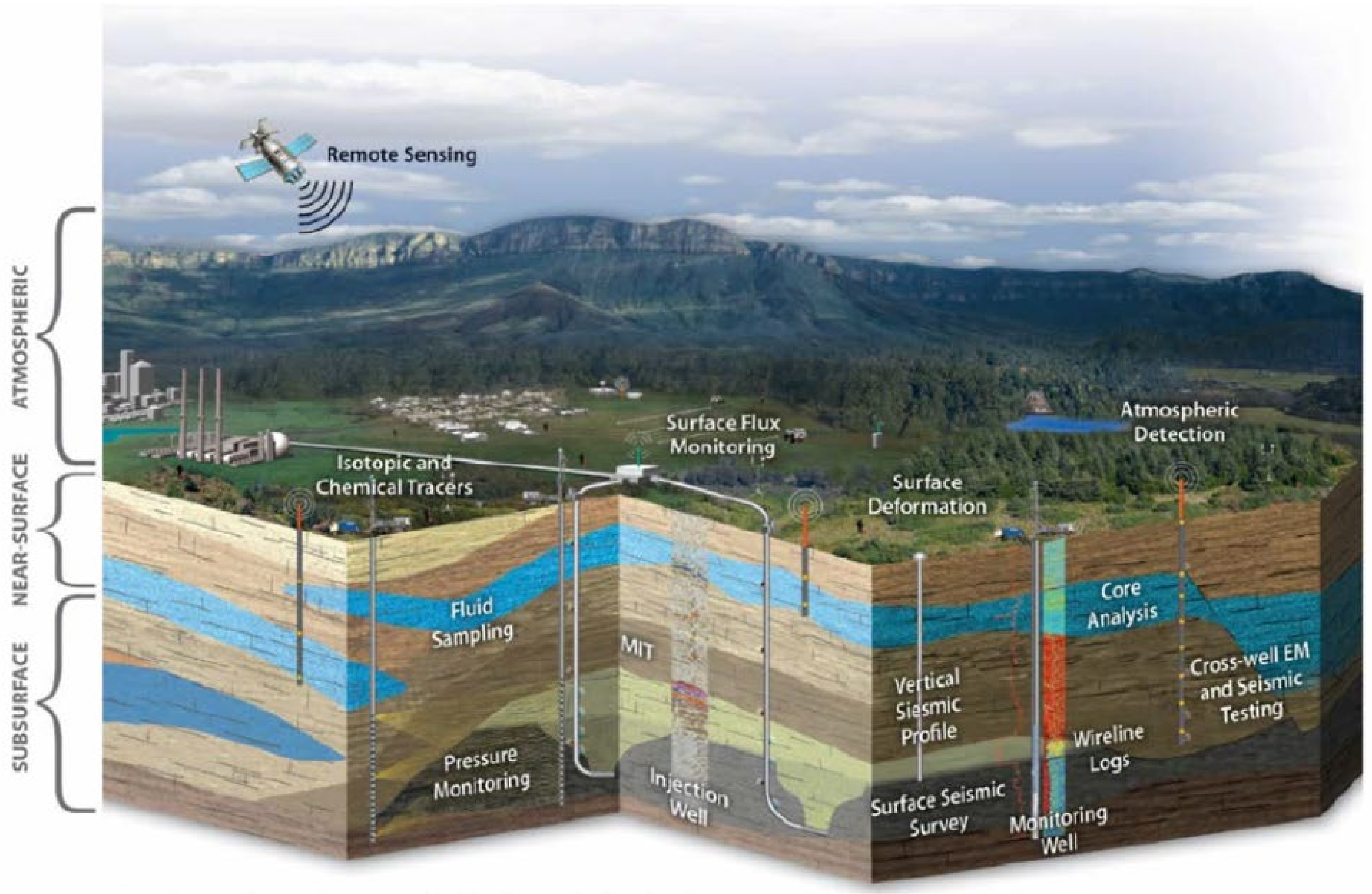


Figure 5-1: Examples of Various Field Monitoring Techniques

Backround Image Courtesy of Schlumberger Carbon Services

Atmospheric Monitoring

Purpose: Quantify CO_2 levels in- and flux into- the atmosphere

Regulatory Context: Atmospheric monitoring is needed for compliance with the Greenhouse Gas Reporting Program 40 CFR Subpart RR

"This rule requires reporting of greenhouse gases (GHGs) from facilities that inject carbon dioxide underground for geologic sequestration"

- Optical sensors: based on Infrared spectroscopy
- Atmospheric tracers (to distinguish if CO_2 detected is from natural sources or leaking from underground):
  - Examples, isotopes of CO_2, radon, noble gases
  - Inject the tracer and see if you can detect it in the subsurface and near surface
- Eddy co-variance: detect possible CO_2 flux (mass/time.area) from terrestrial ecosystems to the atmosphere based on covariance of CO_2 concentrations and vertical wind speeds

Table 3: Summary of Atmospheric Monitoring Techniques

Atmospheric Monitoring Techniques	
Monitoring Technique	**Description, Benefits, and Challenges**
Optical CO_2 Sensors	Description: Sensors for intermittent or continuous measurement of CO_2 in air. Benefits: Sensors can be relatively inexpensive and portable. Challenges: Difficult to distinguish release from natural variations in ambient-CO_2 emissions.
Atmospheric Tracers	Description: Natural and injected chemical compounds that are monitored in air to help detect CO_2 released to the atmosphere. Benefits: Used as a proxy for CO_2, when direct observation of a CO_2 release is not adequate. Also used to track potential CO_2 plumes. Challenges: In some cases, analytical equipment is not available onsite, and samples need to be analyzed offsite. Background/baseline levels must be established. Tracers may not behave the same as CO_2 along the migration pathway.
Eddy Covariance	Description: Flux measurement technique used to measure atmospheric CO_2 concentrations at a specified height above the ground surface. Benefits: Can provide continuous data, averaged over both time and space, over a large area (hundreds of meters to several kilometers). Challenges: Specialized equipment and robust data processing are required. Natu flux may mask release signal.

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Near-Surface Monitoring

- **Purpose:** measure CO_2 levels in the vadose and groundwater zones (see figure) → to detect possible migration from the injection zone
- **Regulatory context:** UIC Class VI regulations
- **Monitoring tools:**
- Note: the following monitoring tools do not directly detect CO_2, rather they detect changes in the subsurface due to presence of CO_2 (e.g., geochemical changes)
  - Soil-gas methods (measure CO_2 flux right above the ground surface)
  - Groundwater quality monitoring (e.g. pH, carbonates, alkalinity, salinity, etc.)
  - Ecosystem stress monitoring (changes that happen to the ecosystem in this zone due to CO_2 leaks

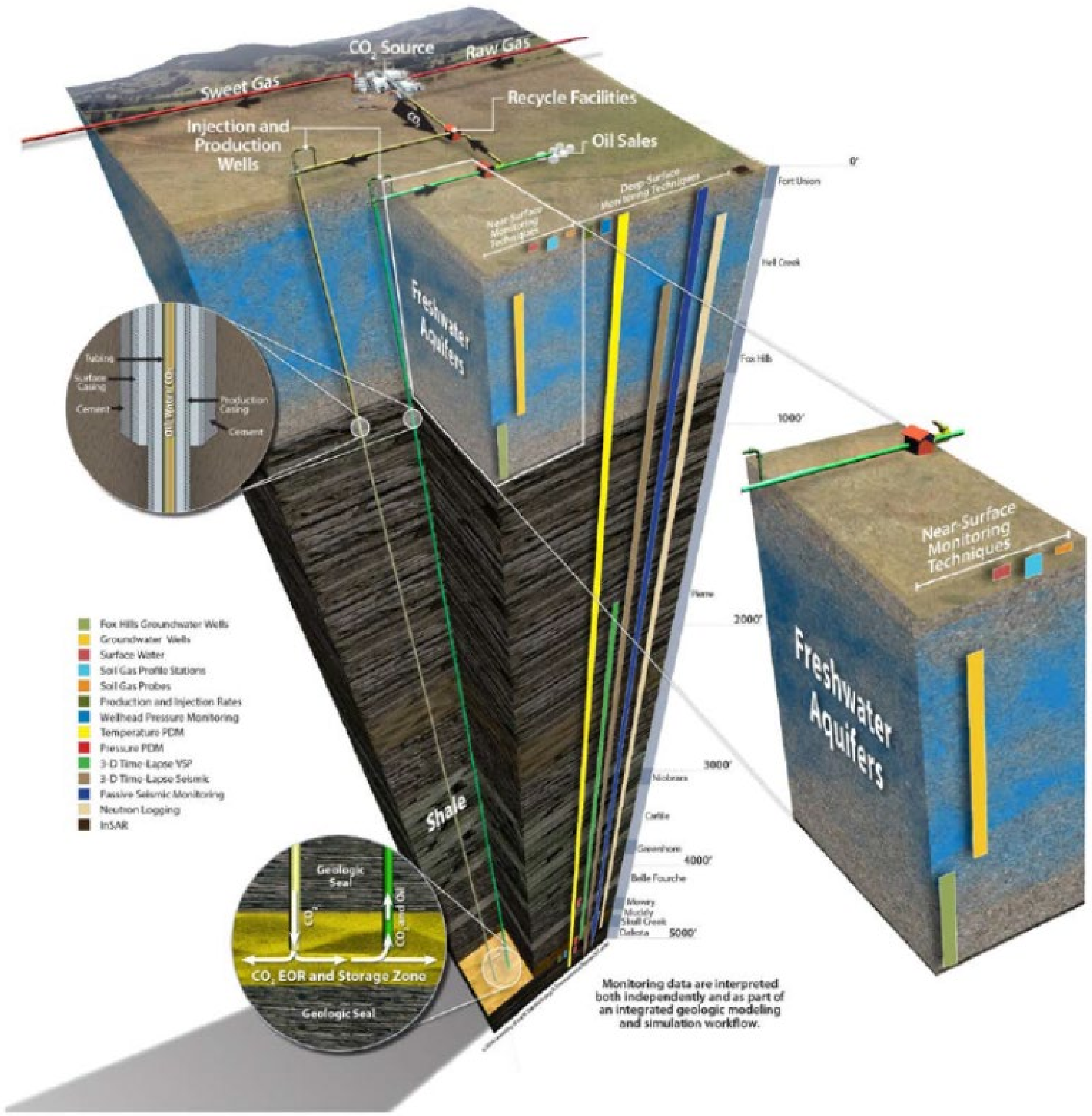

Figure 10: Near-Surface Monitoring in Relation to Other Subsurface Monitoring Techniques (EERC)

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Near-Surface Monitoring

Monitoring Technique	Description, Benefits, and Challenges
Geochemical Monitoring in the Soil and Vadose Zone	**Description:** Sampling of soil gas for CO_2, natural chemical tracers, and introduced tracers. Measurements are made by extracting gas samples from shallow wells or from/with flux accumulation chambers placed on the soil surface and/or with sensors inserted into the soil. **Benefits:** Soil-gas measurements detect shifts in gas ratios or elevated CO_2 concentrations above background levels that may provide indications of gas releases from depth. Tracers aid in identification of native vs. injected CO_2. Flux chambers can quickly and accurately measure local CO_2 fluxes from soil to air. **Challenges:** Potential for interference from surface processes producing false positives as well as missing signal is significant. Significant effort for potential lack of significant results. Relatively late detection of release. Considerable effort is required to avoid cross-contamination of tracer samples. Natural analogs suggest that migration may be focused in small areas and flux chambers provide measurements for a limited area.
Geochemical Monitoring of Shallow Groundwater	**Description:** Geochemical sampling of shallow groundwater above CO_2 storage reservoir to demonstrate isolation of the reservoir from USDWs. Chemical analyses may include pH, alkalinity, electrical conductivity, major and minor elements, dissolved gasses, tracers, and many other parameters. Sensor probes/meters, as well as titration test kits, can be used to test/sample in the field. **Benefits:** Mature technology, samples collected with shallow monitoring wells. Sensors may be inserted into the aquifer. Address major regulatory concern regarding migration reaching USDWs, and may have value in responding to local concerns, which typically elevate concerns about groundwater. **Challenges:** Significant effort for potential lack of significant results. Reactive transport modeling of CO_2 migration shows that signal may be retarded and attenuated so that high well density and long sampling periods are required to reach an insignificant result. Many factors other than fluids from depth can change or damage aquifer water quality, and detailed assessment of aquifer flow system may be needed to attribute a change to signal either to migration or to other factors. Gas solubility and associated parameters (pH, alkalinity) are pressure sensitive, so that obtaining samples representative of the aquifer fluids requires careful sampling. Carbon isotopes may be difficult to interpret due to complex interactions with carbonate minerals in shallow formations.
Surface Displacement Monitoring (Includes Remote Sensing)	**Description:** Monitor surface deformation caused by reservoir pressure changes or geomechanical impacts associated with CO_2 injection. Measurements made with satellite-based radar (SAR/InSAR) and surface- and subsurface-based tiltmeters and GPS instruments. Data allow modeling of injection-induced fracturing and volumetric change in the reservoir. **Benefits:** Highly precise measurements over a large area (100 km x 100 km) can be used to track pressure changes or geomechanical impacts in the subsurface associated with plume migration. Tiltmeter technology is mature, and has been used successfully for monitoring steam/water injection and hydraulic fracturing in oil and gas fields. GPS measurements complement InSAR and tiltmeter data. **Challenges:** Tiltmeters and GPS measurements require surface/subsurface access and remote data collection. InSAR methods work well in locations with level terrain, minimal vegetation, and minimal land use, but must be modified for complex terrain/varied conditions. Surface displacement responds also to groundwater withdrawal and recharge and to non-injection related process such as local to regional subsidence and uplift. Movement may not indicate risk, must be coupled with complex 3-D geomechanical models to make results actionable.
Ecosystem Stress Monitoring (Includes Remote Sensing)	**Description:** Satellite imagery, aerial photography, and spectral imagery are used to measure vegetative stress resulting from elevated CO_2 in soil or air. Ground-based study is required to develop understanding of signal to train the image processing and validate anomalies detected. **Benefits:** Imaging techniques can cover large areas, at relatively high frequency and low cost, and image processing can be automated. Vegetative stress is proportional to soil CO_2 levels and proximity to CO_2 release. **Challenges:** Detection only possible after sustained CO_2 emissions have occurred. Shorter duration release may not be detectable. Natural variations in site conditions make it difficult to establish reliable baseline. Changes not related to CO_2 release can lead to false positives. Variable sensitivity of vegetation to CO_2 and small areas of focus release can lead to missed signal.

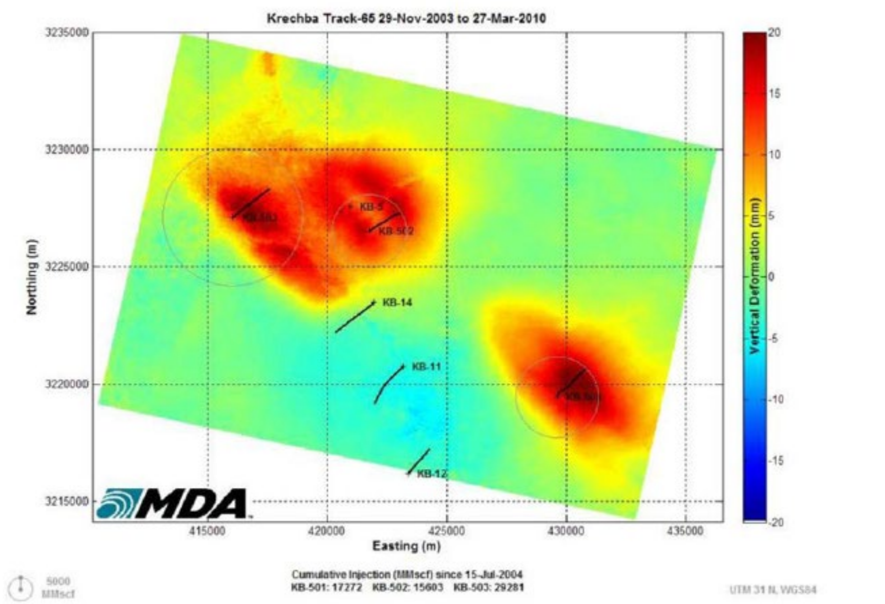

Figure 14: Satellite Image of Cumulative Surface Deformation at Krechba (In Salah) Due to CO_2 Injection *(Mathieson et al., 2011)*

https://www.osmotech.it/en/flux-chamber/

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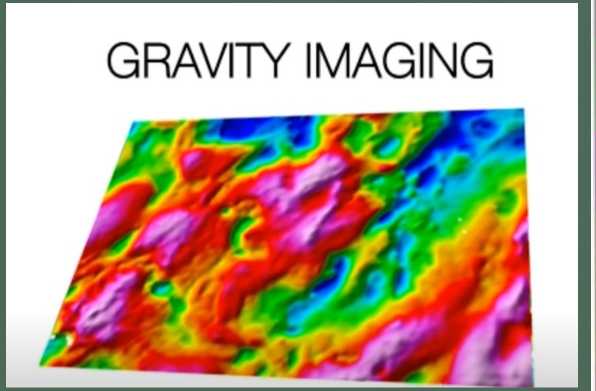
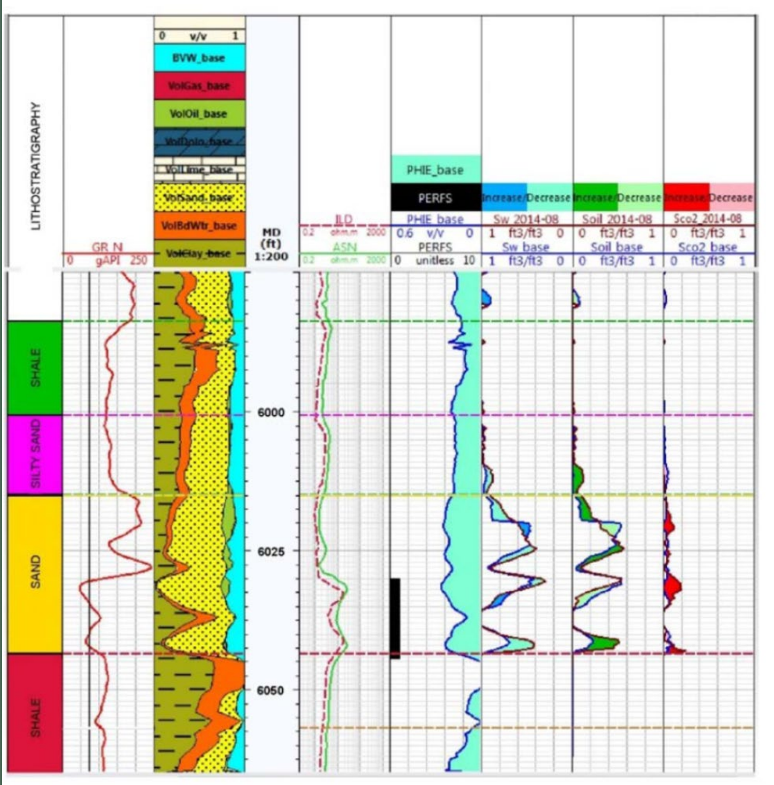
Subsurface Monitoring

- **Purpose:** detect and monitor impacts of CO_2 injected and its migration in the subsurface
- **Regulatory context:** UIC Class VI regulations
- **Monitoring include (a lot):**
  - Seismic surveys
  - Well logging:
    - Vertical profile of different characteristics (of the well materials itself or the surrounding) as a function of depth
    - Either extract samples from the bore or send instrument down for measurements
  - Tracer studies and fluid sampling
  - Gravity surveys (measure changes in the gravitational forces→ that can be translated to different properties of materials in the subsurface)





Carbon Storage Atlas 5th Edition, DOE's NETL, https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf

Monitoring Technique	Description, Benefits, and Challenges
Emerging Wellbore Tools	**Description:** Emerging wellbore technologies include smart sensors for geologic storage monitoring applications and subsurface tracer applications. Tools include harmonic pulse testing of reservoirs, modular borehole monitoring, and novel tracers. **Benefits:** Demonstrate reservoir integrity through pressure response during pulse testing. The modular borehole monitoring (MBM) concept is a multi-functional suite of instruments designed to optimize subsurface monitoring. Geochemical changes associated with the interaction of injected tracers and supercritical CO_2 provide insight concerning migration of CO_2 through the reservoir. **Challenges:** Reservoir noise interference and signal-to-noise ratio may be an issue.
Seismic Geophysical Methods	**Description:** Seismic geophysical methods use acoustic energy to image the subsurface. Differences between the acoustic properties of CO_2 and other fluids enable the plume monitoring by seismic methods. Active seismic methods (surface seismic reflection, VSP, crosswell) require a source and receiver. Passive seismic methods use natural subsurface processes that emit acoustic energy from fracture development or slip on a fault. **Benefits:** Substitution of CO_2 for brine under many conditions creates a strong change in seismic velocity ideal for time-lapse quantification from pre-injection baseline (brine-filled) pores to pores partly filled with CO_2. Reflection seismic under the right conditions is useful both for time-lapse monitoring of a CO_2 plume and for identification of any out-of-zone CO_2 accumulation indicating a release. Surface seismic surveys can assess large areas a measurements). Borehole seismic (crosswell, VSP) surveys can provic Passive seismic (microseismic monitoring) can be used to detect natu the injection zone and adjacent horizons, and to track the migration of **Challenges:** Repeatability of seismic survey needed for time-lapse su Geologic complexity and a noisy recording environment can degrade c in baseline fluids can reduce detection of CO2. Borehole seismic meth the distance between wells containing the source and receivers may l constraints. A comprehensive knowledge of reservoir geomechanical events for migration of the pressure front.

Gravity Methods	**Description:** Use of gravity measurements to monitor changes in density of fluid resulting from injection of CO_2, which is substituted for brine or other reservoir fluids. **Benefits:** Gravity measurement provides a direct assessment of the parameter wanted, mass of CO_2, unlike all other measure which are proxies and must be converted by modeling into an estimate of mass. **Challenges:** Technology is still maturing. Limited detection and resolution unless gravimeters are located just above reservoir, which significantly increases cost. Noise and gravity variations (tides, drift) need to be eliminated to interpret gravity anomalies due to CO_2.
Electrical Methods	**Description:** Based on the resistivity contrast between injected CO_2 and more conductive brine, can be used in time-lapse. Technology used in the oil and gas industry to detect hydrocarbons. Electrical methods used in geologic storage projects are (1) electrical resistance tomography (ERT) and electromagnetic (EM) tomography that images spatial distribution of resistivity i reservoir by measuring potential differences and (2) controlled-source electromagnetic (CSEM) surveys that measure induced electrical and magnetic fields. **Benefits:** Electrical techniques provide resistivity distribution in the subsurface, which can be interpreted to estimate CO_2 saturation distribution. Data resolution is dependent on electrode spacing for ERT techniques. Crosswell ERT is more sensitive to changes in near-wellbore resistivity. Surface-downhole ERT and CSEM measurements increase the lateral extent and provic data on CO_2 plume tracking. ERT and CSEM do not interfere with other subsurface monitoring techniques operating within the well casing (e.g., wireline logging, borehole seismic). **Challenges:** May not detect contrast between CO_2 and hydrocarbons. ERT, EM tomography, and CSEM surveys require non-conductive well casings and multiple monitoring wells. Deployment and inversion are less mature than other technologies.

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Monitoring Technique	Description, Benefits, and Challenges
Wireline Deployed Well Logging Tools	**Description:** Mature technology in which tools lowered into wells on wireline cables (so that the tool is in communication with the surface) are slowly moved up the well collecting data designed to monitor the condition of the wellbore and changes in fluids in the near-wellbore environment. Examples of logs used in geologic storage monitoring include acoustic (sonics), resistivity, borehole diameter logging, and pulsed neutron capture. **Benefits:** Commercial technology used to assess the condition of the well casing and cement and changes in near-wellbore fluid or formation composition. Under favorable conditions, log response may be highly sensitive to CO_2 outside the wellbore. No need to perforate well to detect CO_2. **Challenges:** Area of investigation limited to near the wellbore. Sensitivity of tool to fluid change varies; only under optimum conditions are tools sensitive to dissolved CO_2 or changes in minerology. Working fluids in wells may affect log results. Logging requires wells that penetrate the interval of interest and mobilization costs may be substantive, limiting repeated surveys. If a well is perforated in an area charged with CO_2 access, the well requires pressure management. Both wireline and well casing may corrode, especially in the presence of CO_2, requiring management via metallurgy or corrosion inhibition.
Wellbore Deployed Pressure and Temperature	**Description:** A large array of gauges is available to measure pressure and temperature. Technology is mature. Gauges are deployed at wellhead and can be permanently installed on casing, semi permanently deployed on tubing, or intermittently emplaced on slickline. Wireline communications are standard with the casing and tubing deployments; the intermittent emplacement may either be on wireline or use internal memory and be retrieved. Gauges may be deployed both on injection wells and on monitoring wells distant from injection intervals. **Benefits:** Reservoir pressure is a key parameter in the EPA UIC Class VI Program, and because of the complex temperature and pressure effects on fluid density, direct measurements at the reservoir may be needed to augment and calibrate standard wellhead pressure measurements. Measurements of reservoir response to changes in injection pressure is a mature tool for assessing fluid flow and hydrologic properties and is a key input for history-matching simulation models. **Challenges:** Gauges must be in communication with the reservoir. If the gauge is run inside of the casing, then the well must be perforated and thus the entire well is potentially exposed to corrosive fluids, increased pressure, and potential changes in wellbore fluids that may alter monitoring technologies run from inside of it (e.g., seismic). Gauges run outside of casing are not retrievable, must be carefully placed to exclude cement between the gauge and the reservoir, and must have an umbilical back to the wellhead that is a potential leakage path
Wellbore-Based Fluid Monitoring Tools	**Description:** Geochemical sampling is required under EPA's UIC Class VI to quantify the composition of the injected fluid. Fluid sampling can also be conducted at wells distant from injection wells to assess breakthrough of CO_2 or rock-CO_2 water reactions using surface or downhole samplers. **Benefits:** Modeling the response of the reservoir to injection. **Challenges:** Assessing chemistry of CO_2-brine pore fluids in the rock matrix presents many challenges related to pressure and temperature dependence of solubility and the complexity of accurately sampling mixed density-mixed viscosity brine and CO_2 in the well construction.

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Table 4.1 Monitoring types, broadly grouped into deep and shallow focused

Monitoring technique	Primary purpose	Testing sites									
		Sleipner	Snovit	K12-B	In Salah	Ketzin	Weyburn	Nagaoka	Otway	Frio	Cranfield
Deep focused											
2D/3D/4D surface seismic	Imaging the CO_2 plume. Detection of leakage in overlying rocks.	X	X		X	X	X	X	X		
Vertical seismic profiling (VSP) and other well seismic	High resolution imaging over the reservoir.					X	X		X		
Cross-hole seismics	Imaging the CO_2 plume between boreholes. Detection of leakage in overlying rocks.						X	X		X	X
Microseismics	Passive detection of CO_2 injection induced seismic events.				X	X	X		X		X
Surface gravity	Measuring gravimetric effect of CO_2 plume in the subsurface.	X									
Pressure and temperature methods	Monitoring injection and hydraulic/thermal connectivity between wells/strata.	X	X	X	X	X	X	X	X		X
Geophysical logs	Detection of CO_2 breakthrough and saturation changes around boreholes. Well bore integrity.			X	X	X	X	X	X		
Electrical resistivity tomography (ERT)	Imaging the CO_2 plume between boreholes. Detection of leakage in overlying rocks.					X					X
Electromagnetic methods (EM)	Imaging the CO_2 plume between boreholes. Detection of leakage in overlying rocks.	X				X				X	

(*Continued*)

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Table 4.1 Continued

Monitoring technique	Primary purpose	Testing sites									
		Sleipner	Snovit	K12-B	In Salah	Ketzin	Weyburn	Nagaoka	Otway	Frio	Cranfield
Fluid chemistry sampling	Detecting of CO_2 plume breakthrough and saturation changes. Reservoir geochemical evolution.			X	X	X	X	X	X	X	X
Tracers	Tags the CO_2 plume with unique signature for identification of injected CO_2 leakage.			X	X	X			X	X	X
Monitoring shallow aquifers	Mainly geochemical analysis to detect CO_2 leakage into potable water.				X				X		
Tiltmeters and satellite interferometry (InSAR)	Monitors CO_2 injection related ground displacement.				X						
Shallow focused											
Multibeam echosounding, Sidescan sonar, video	Monitoring sea bed for CO_2 leakage.	X									
Bubble-stream detection, and gas sampling	Monitoring sea bed for CO_2 leakage.										
Soil gas/surface flux	Measurement of CO_2 concentration and flux.				X		X		X		X
Flux towers (eddy covariance (EC))	Detection of CO_2 leakage from the surface.						X		X		
Passive detectors/IR diode lasers	Detection of CO_2 leakage from the surface.				X		X		X		
Ecosystem monitoring	Monitoring for effects of CO_2 leakage.	X			X						
Airborne spectral imaging	Monitoring for effects of CO_2 leakage.				X	X					

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Developing Site-Specific MVA Plan

- The plan is based on risk of CO_2 leakage at a given site
- Steps:
    1. Perform risk assessment to identify risks associated with certain features, elements, or processes (FEPs) at the site (e.g., presence of abandoned wells penetrating the injection zone)

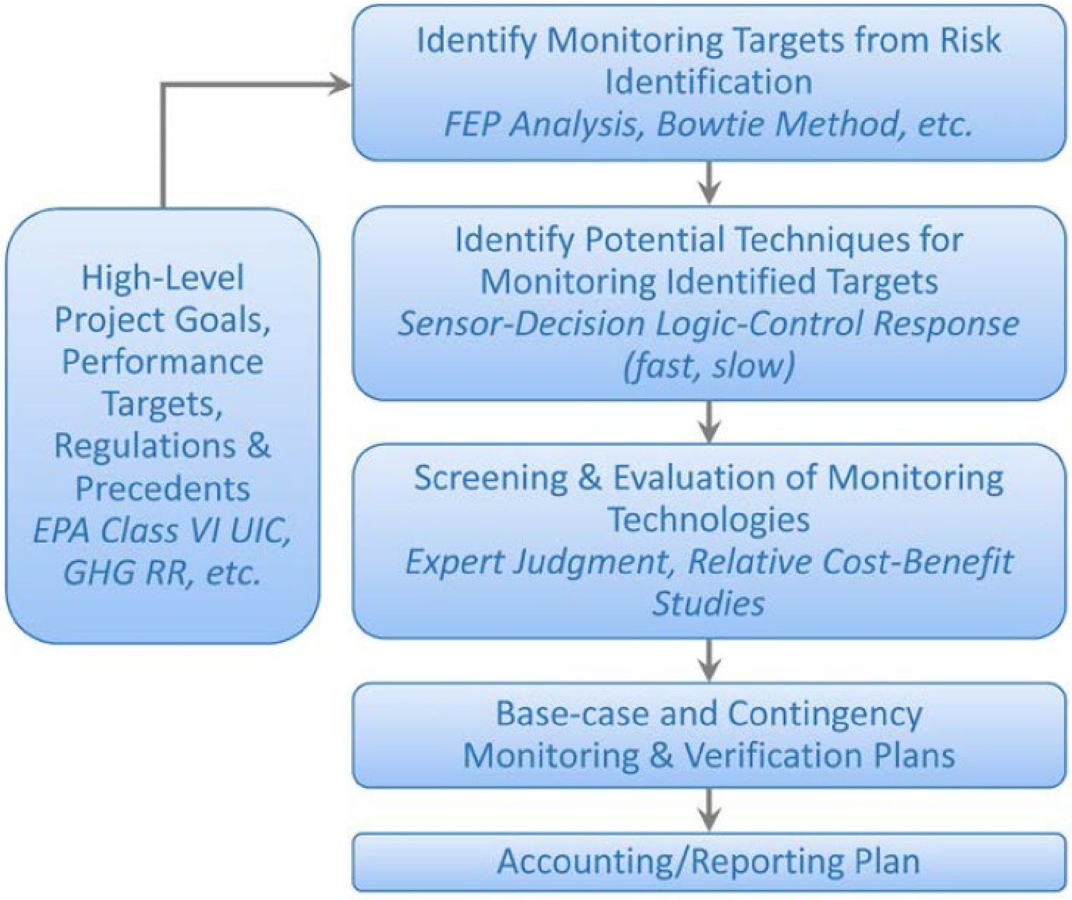

Figure 3: Workflow for the Preparation of a Risk-Based MVA Plan; Adapted from Det Norske Veritas (2010b)

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Example of FEPs identified in the Illinois Basin – Decatur Injection Project

Table 2: Risk-Related FEPs

*(Top 64 of 119 evaluated FEPs are shown, ranked by Risk = Average Severity*Average Likelihood) Courtesy MGSC*

Rank	FEP	Risk	Rank	FEP	Risk
1	Exogenous economics, supply prices	10.3	**33**	Displacement of formation fluid (capillarity)	5.3
2	CO_2 solubility and aqueous speciation	8.9	**34**	Accidents and unplanned events: External	5.3
3	Toxic geologic components (metals)	8.1	**35**	Legal/regulatory: construction, discharge, and other operations permits	5.2
4	Fractures and faults	7.8	**36**	Drilling and completion activities: Project	5.2
5	Compressor procurement	7.8	**37**	Thermal effects on the injection point in the formation	5.2
6	Legal/regulatory: Underground Injection Control permit	7.7	**38**	CO_2 release to the atmosphere	5.1
7	Schedule and planning	7.4	**39**	Actions and reactions – SIGs and NGOs, national/ international	5
8	Compression facility construction	7.2	**40**	Over-pressuring	5
9	Undetected features	7.2	**41**	Shallow gas, drift gas	5
10	Human activities in the surface environment: onsite	7	**42**	Stress and mechanical properties	5
11	Mechanical processes and conditions	7	**43**	Sealing and closure of boreholes	4.9
12	Mineral precipitation	7	**44**	System performance	4.9
13	Seal failure (in wells)	6.9	**45**	Unplanned CO_2 release to the atmosphere	4.9
14	Legal/regulatory: Property rights and trespass	6.8	**46**	Meteorology, weather	4.9
15	Seismicity (Induced earthquakes)	6.5	**47**	Land and water use	4.8
16	Undefined specification	6.3	**48**	Soils and sediments	4.8
17	Contamination of groundwater by CO_2	6.2	**49**	Mineral dissolution – caprock	4.7
18	Actions and reactions – local community	6	**50**	Support from MGSC partners	4.7
19	Near-surface aquifers and surface water bodies	6	**51**	Seal: Geologic, additional	4.6
20	Reservoir pore architecture	5.9	**52**	Support from government – political basis	4.6
21	Reservoir geometry	5.8	**53**	Support from government – technical basis	4.6
22	Accidents and unplanned events: Project	5.7	**54**	Model and data issues	4.5
23	Mineral dissolution – reservoir	5.7	**55**	Monitoring or verification wells	4.4
24	Community characteristics	5.7	**56**	Data acquisition activities at well	4.4
25	Heterogeneity in reservoir	5.6	**57**	Blowouts	4.3
26	Seal: Geologic, primary (caprock)	5.6	**58**	Lithification and diagenesis	4.3
27	Heterogeneity of overlying aquifers	5.5	**59**	Construction and operations activities	4.3
28	Mineral dissolution – borehole	5.5	**60**	Formation pressure	4.3
29	Pressure effects on caprock	5.5	**61**	CO_2 injectate quantity and rate	4.3
30	Formation damage	5.4	**62**	Legal and regulatory framework	4.3
31	Well lining and completion	5.4	**63**	Post-project monitoring of storage	4.2
32	Lithology	5.3	**64**	Actions and reactions – SIGs and NGOs, local regional	4.1

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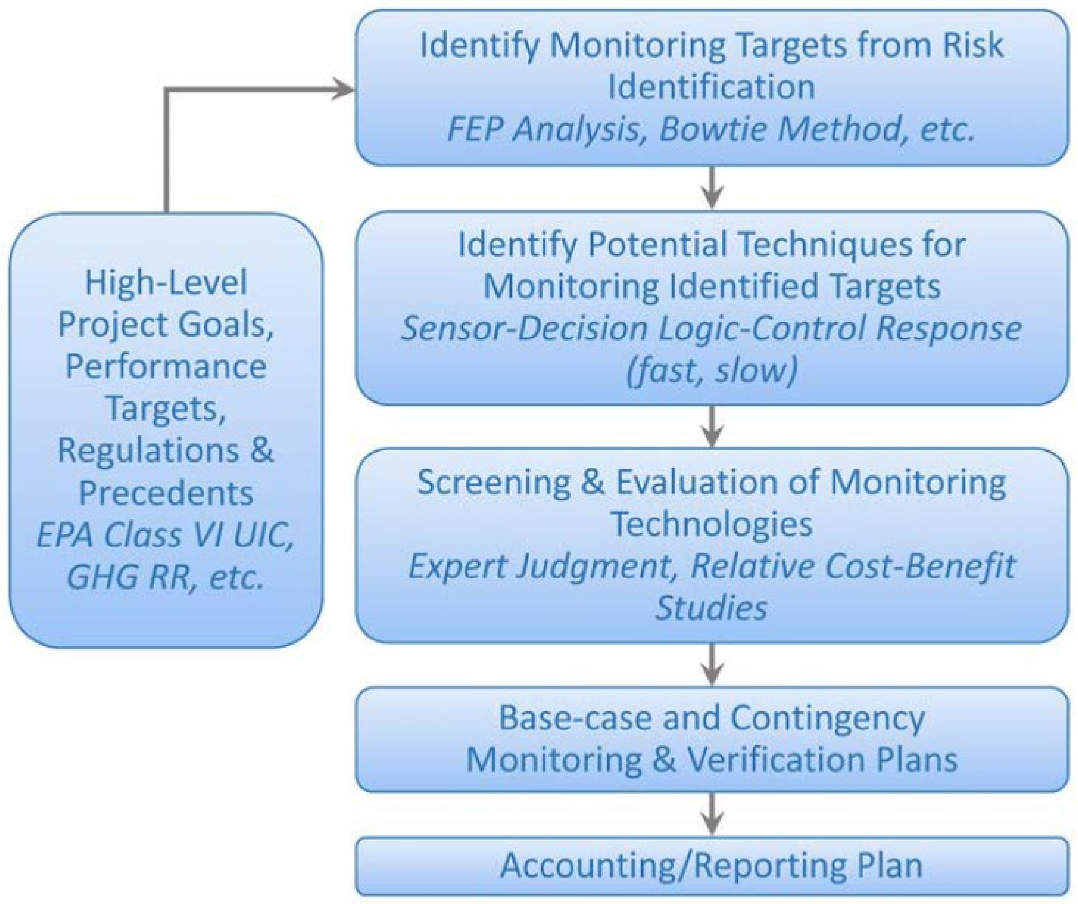
Developing Site-Specific MVA Plan

- The plan is based on risk of CO_2 leakage at a given site
- Steps:
  1. Perform risk assessment to identify risks associated with certain features, elements, or processes (FEPs) at the site (e.g., presence of abandoned wells penetrating the injection zone)
  2. Based on step 1, what monitoring kind of monitoring would be needed based on the ranking of different risks
  3. Screen options for cost-effective monitoring techniques (there is a lot of monitoring techniques to choose from)
  4. Select the monitoring techniques and prepare a plan for monitoring during normal operations and when there is contingency
  5. Describe the procedure for accounting and reporting (e.g., using mass balances based on CO_2 received and $CO_{2\ s}$tored). The plan should specific monitoring frequency and recordkeeping



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