CCUS Conference

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Sponsored By: The Research Council of Norway &

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“Whole Value Chain Carbon Capture, Utilization, and Storage (CCUS)”

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CO_2 for EOR – History and Technology Challenges

H. Kazemi, Professor

CSM

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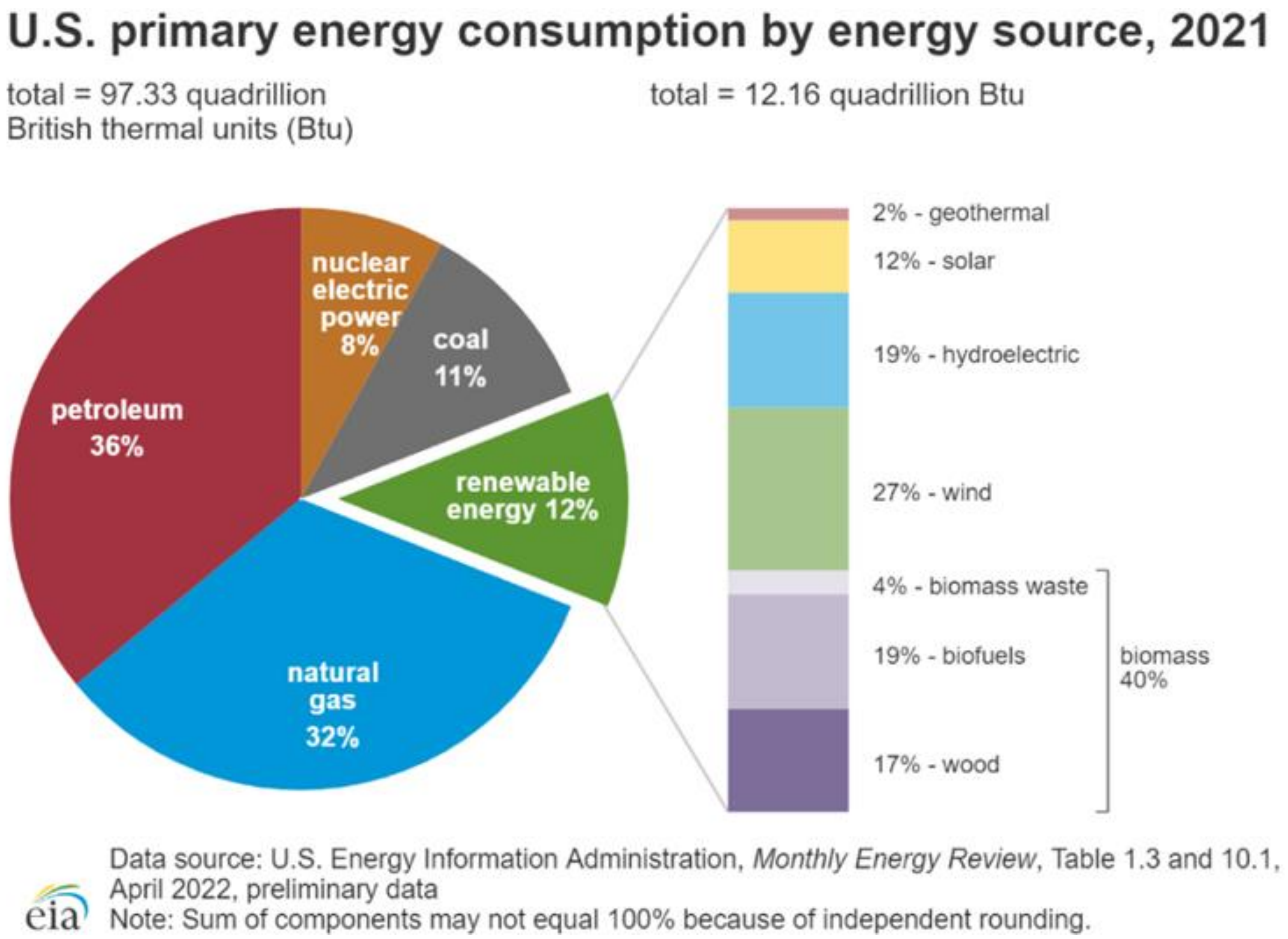


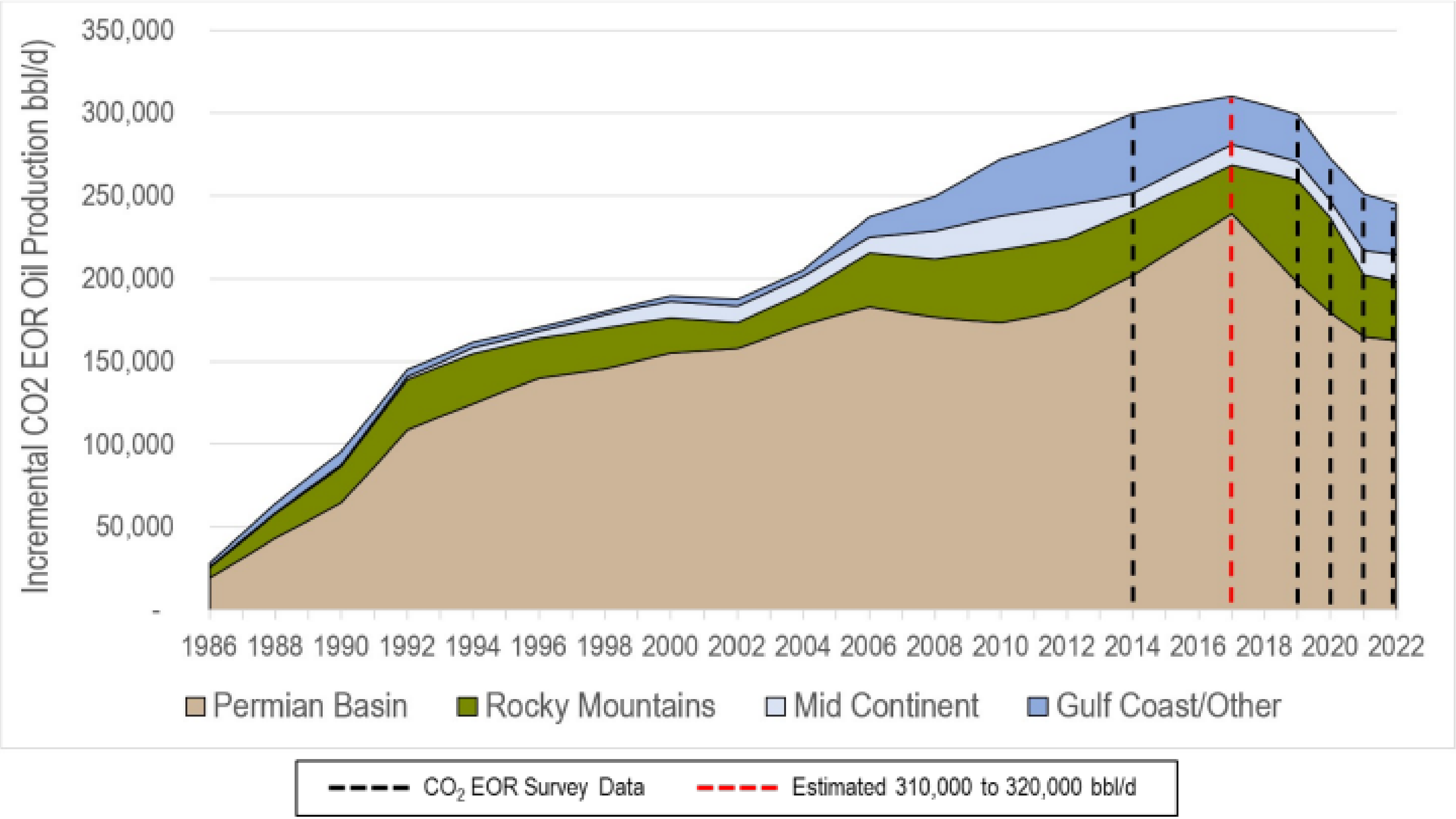
U.S. Primary Energy Consumption by Energy Source, 2021 (U.S. EIA, 2022)

CO_2 Enhanced Oil Recovery (EOR) in Conventional Reservoirs

- ***Primary Production**: Oil is produced from many production wells. The production mechanism is primarily by reservoir fluid expansion. Approximately 10 to 15% of oil in placed is produced this way.*
- ***Secondary Production:** Next injection wells are drilled to inject water to push additional amount of oil which amounts to, say, an additional 10 to 15%.*
- ***Tertiary Production:** The third phase is injecting **EOR** agents to mobilize additional oil to produce. The U.S. total EOR daily production is about 5.0 %.*
- *Today, U.S. produces **2.4 %** of its daily oil production from **CO_2**, **1.6 %** from **steam injection**, and another **1.7 %** from **hydrocarbon gas** injection. **CO_2 leads all EOR in the U.S.***

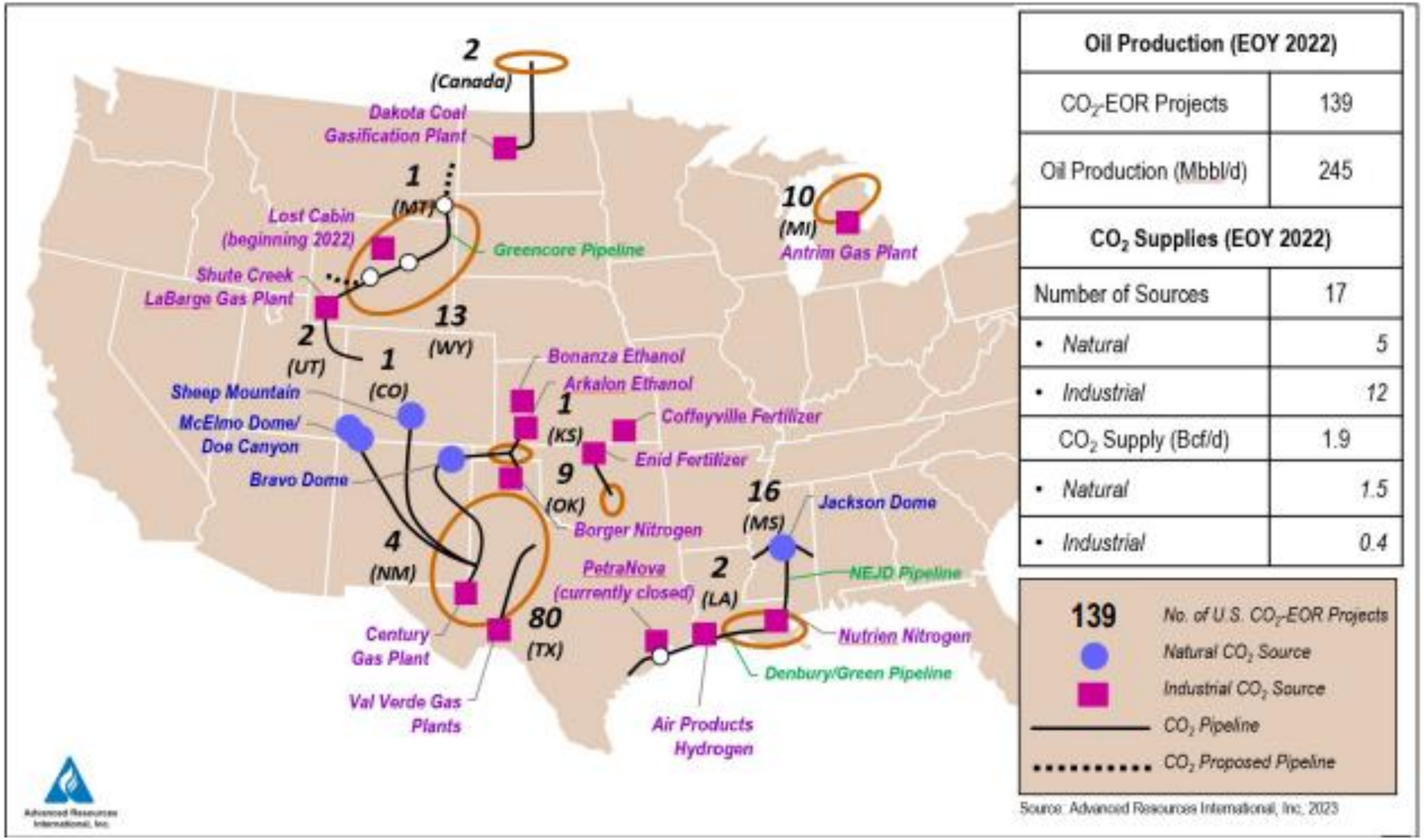
Chart of U.S. CO2 EOR Production

(Source: NETL)



CO_2 EOR Locations in the U.S. (EOY 2022)

Source: Advanced Resources International, Matt Wallace, mwallace@adv-res.com)

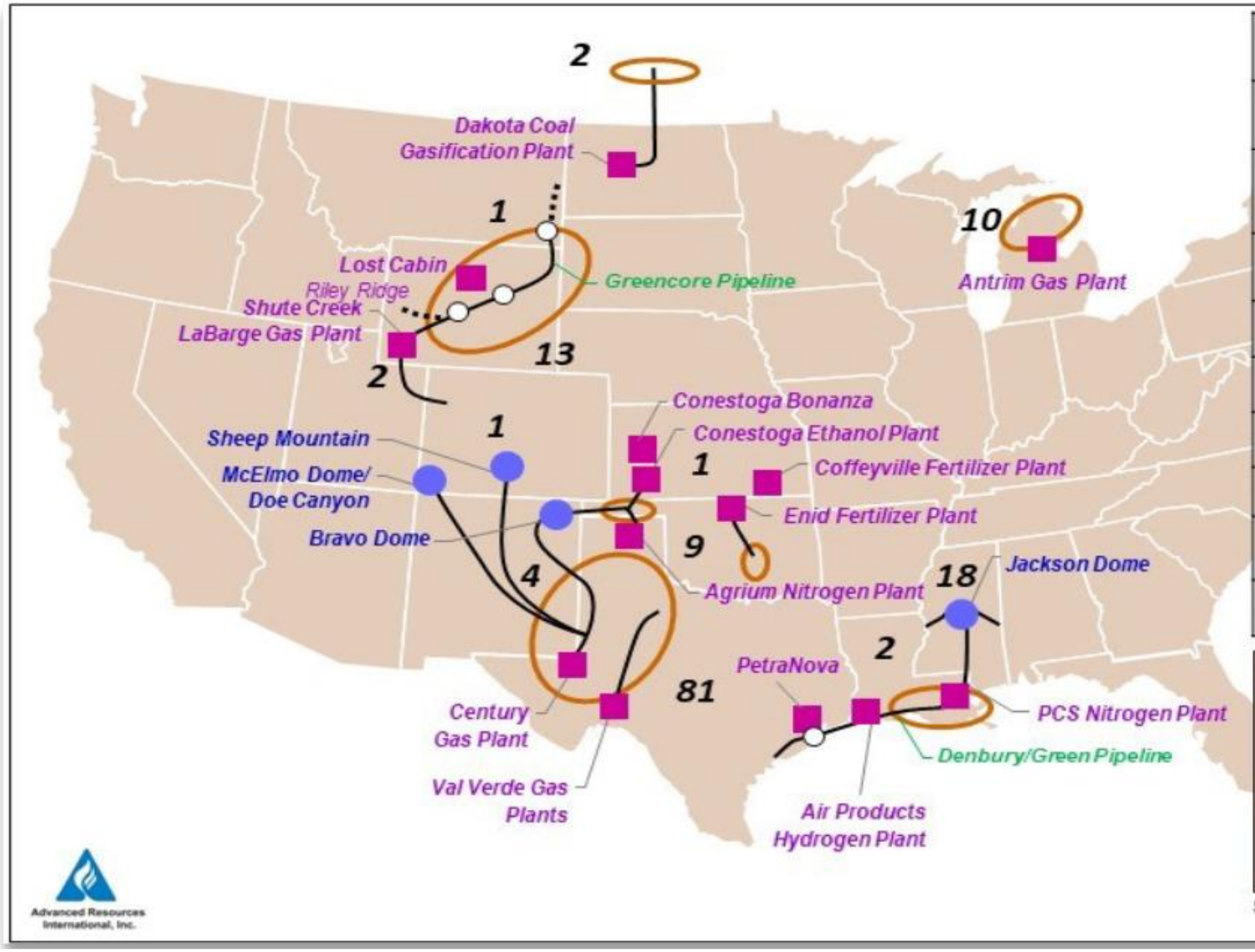


Oil Production (EOY 2022)	
CO_2-EOR Projects	139
Oil Production (Mbbl/d)	245
CO_2 Supplies (EOY 2022)	
Number of Sources	17
• *Natural*	5
• *Industrial*	12
CO_2 Supply (Bcf/d)	1.9
• *Natural*	1.5
• *Industrial*	0.4

Source: Advanced Resources International, Inc, 2023

CO_2 EOR Infrastructure in the United States (EOY 2020)

(Source: Advanced Resources International, Inc.)



Oil Production (EOY 2020)	
CO_2-EOR Projects	142
Oil Production (MBbl/d)	273
CO_2 Supplies (EOY 2020)	
Number of Sources	18
• *Natural*	5
• *Industrial*	13
CO_2 Supply (Bcf/d)	1.6
• *Natural*	1.3
• *Industrial*	0.3

142 *No. of U.S. CO_2-EOR Projects*

Natural CO_2 Source

Industrial CO_2 Source

CO_2 Pipeline

CO_2 Proposed Pipeline

Source: Advanced Resources International, Inc, 2021

Summary of CO_2 Field Projects in the U.S., 2020
(Source: Advanced Resources International)

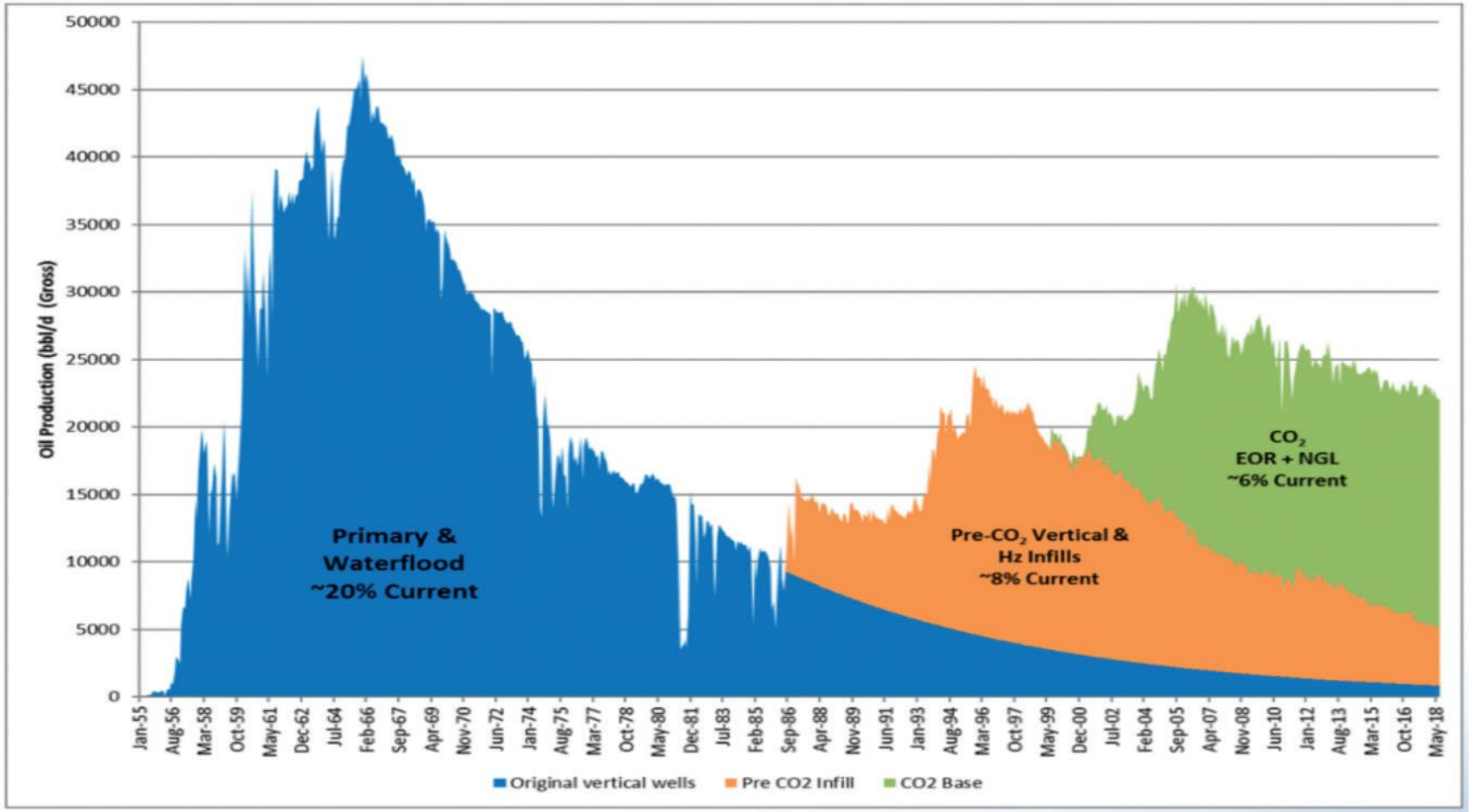
- ***Total projects 143**, **operators 23**, and **amount 273,000 STB/D**, respectively*
- ***CO_2 supply sources 18**:*

  ***Natural 5** (0.3 BCF/D), **Industrial 13** (1.6 BCF/D)*
- ***CO_2 EOR in Permian Basin** consists of 80 'active' projects (owned by 13 operators) declined from 204,000 STB/D in 2019 to 185 STB/D in 2020*
- *The **45Q tax credit** should increase the volume of industrial sources of*

  *CO_2 – specially utilization of CO_2 from **ethanol plants** across the U.S. (**map**)*

Weyburn and Midale Fields

Since 2000, industrial-grade CO_2 has travelled 205 miles (330 km) by pipeline from the Great Plains Synfuels Plant in Beulah, North Dakota, to the Weyburn and Midale oil fields where the EOR operations will eventually produce an additional 200 million barrels of oil and permanently store 44 million tonnes of CO_2 (or, 836 BCF) deep underground in the oil-producing rocks. The net utilization ratio is 4,180 scf of CO_2/barrel of EOR oil.



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GAS FLARING OF EXCESS NATURAL GAS DURING OIL PRODUCTION IN SOUTHERN IRAQ.
SOURCE: BBC AND CHAFIQ FAIZ, 2023

Steam Generators for Steam EOR, Capacity of 57 Tons/hr, Middle East

A Prudent Approach to Reduce CO_2 Emissions While Enhancing Oil Recovery Using CO_2 From a Steam Flood Project (Source: Al-Ghnemi et al., Jour. Fuels, 2025)

*"**Emissions of carbon dioxide (CO_2) resulting from steam-driven enhanced oil recovery (EOR) operations** present an environmental challenge as well as an opportunity... Using numerical simulations with realistic input data from field and laboratory measurements we demonstrate a prudent approach to reduce CO_2 emissions by capturing CO_2 from steam generators of a steam-driven enhanced oil recovery (EOR) project and injecting it in a nearby oil field to improve oil recovery in this neighboring field."*

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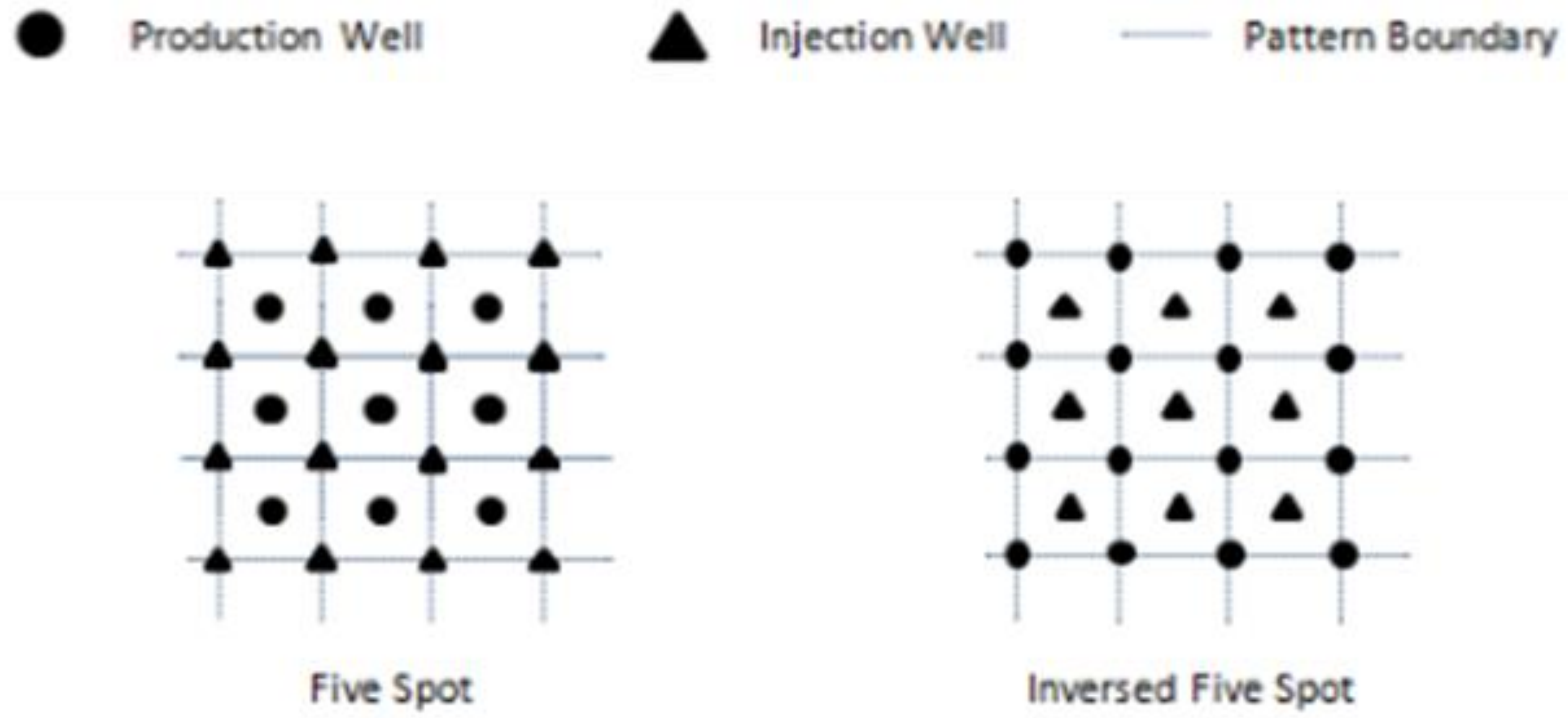
A Prudent Approach to Reduce CO_2 Emissions While Enhancing Oil Recovery Using CO_2 From a Steam Flood Project (Source: Al-Ghnemi et al., Jour. Fuels, 2025)

*"The proposed use of CO_2 as a water-alternating-CO_2 (WAG-CO_2) EOR project in a small, 144-acre, sector of a target limestone reservoir would yield **42% incremental EOR oil** while sequestering CO_2 with a **net utilization ratio (NUR) of 3100 standard cubic feet CO_2 per stock tank barrel (SCF/STB) of EOR oil in a single five-spot pattern** consisting of a central producer and four surrounding injectors.*

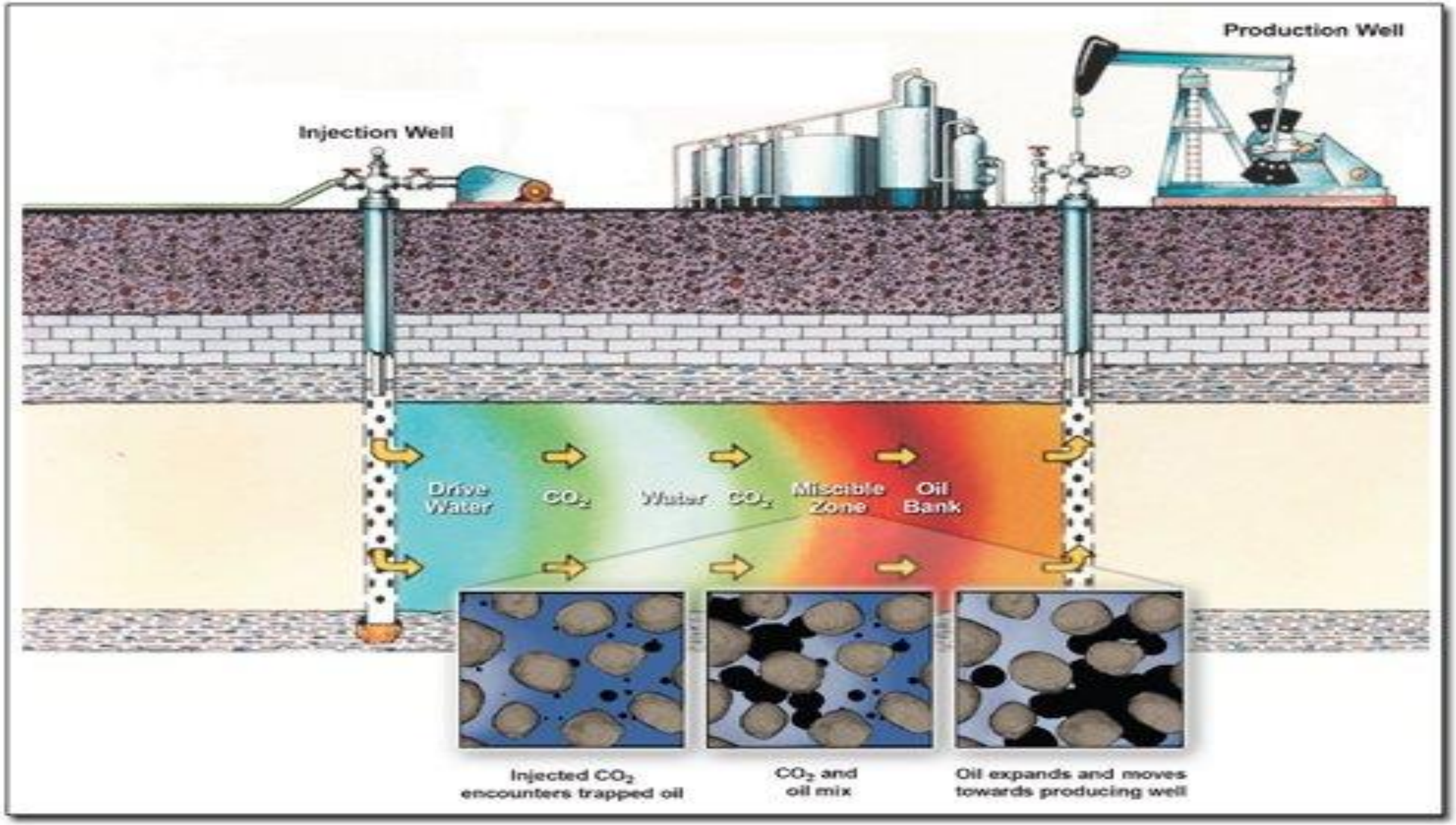
***This EOR application sequesters 135,000, 165,000, and 213,000 metric tons of CO_2 in five, ten, and twenty years** in the single five spot pattern (i.e., our sector model), respectively."*

Five-Spot Pattern vs. Inverted Five-Spot Injection-Production Patterns

(Source: Chen et al.: Flow in Porous Media)



CO_2 Enhanced Oil Recovery –The WAG Process
(Picture Source: U.S. DOE)



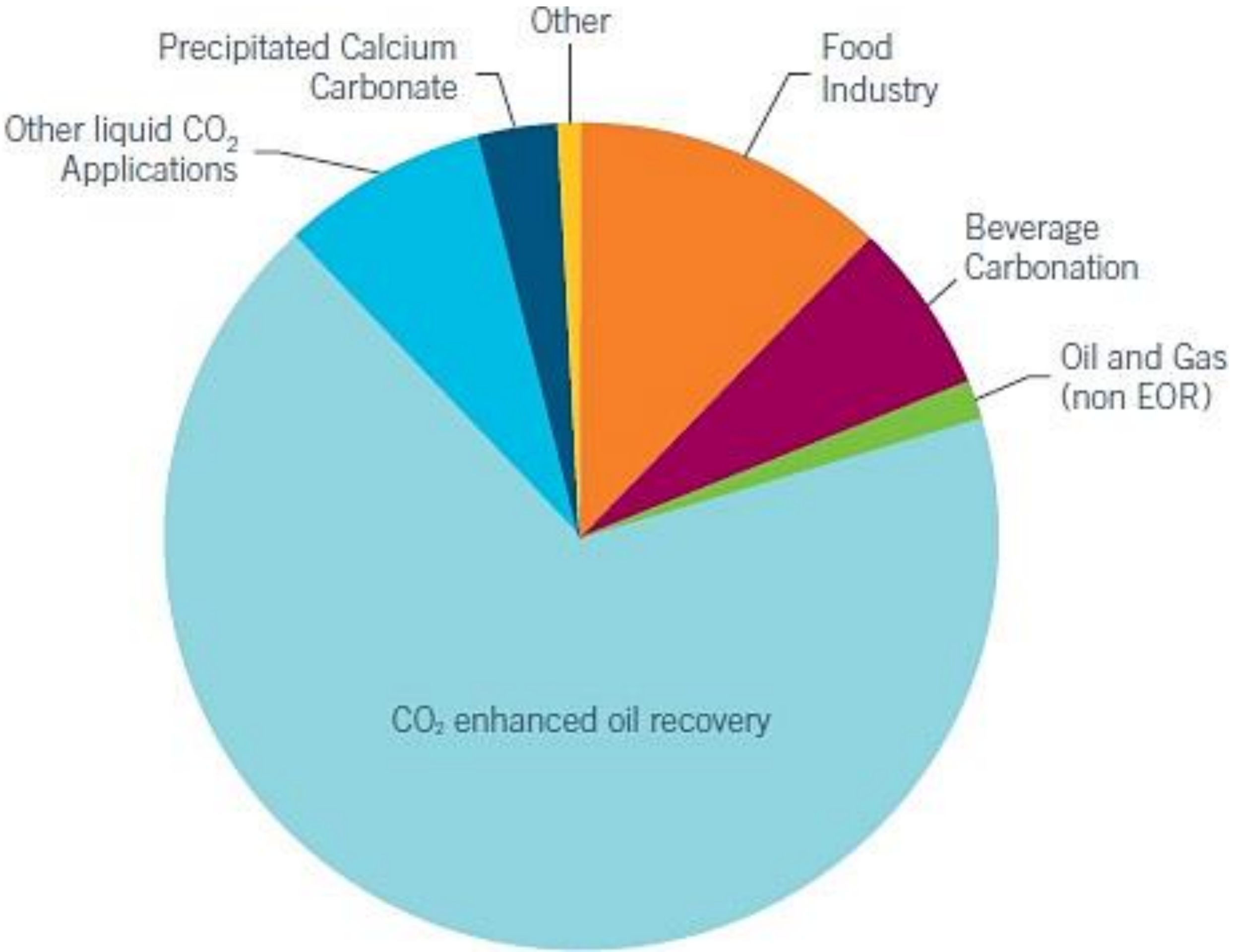
NETL and Global CCS Institute

- According to **NETL** and **The Global CCS Institute in** 2011, the global demand for CO_2 was estimated at **80 Mtpa**, of which: (1) **50Mtpa** is utilized for Enhanced Oil Recovery, almost exclusively in North America, and (2) the remaining **30 Mtpa** represents the global demand of all other uses, predominantly the mature industries of beverage carbonation and food industry uses.

- CO2 was used in oilfields in Kansas, Mississippi, Wyoming, Oklahoma, Colorado, Utah, Montana, Alaska, and Pennsylvania. In the United States CO_2 EOR production has increased to over 300,000 barrels of oil per day.

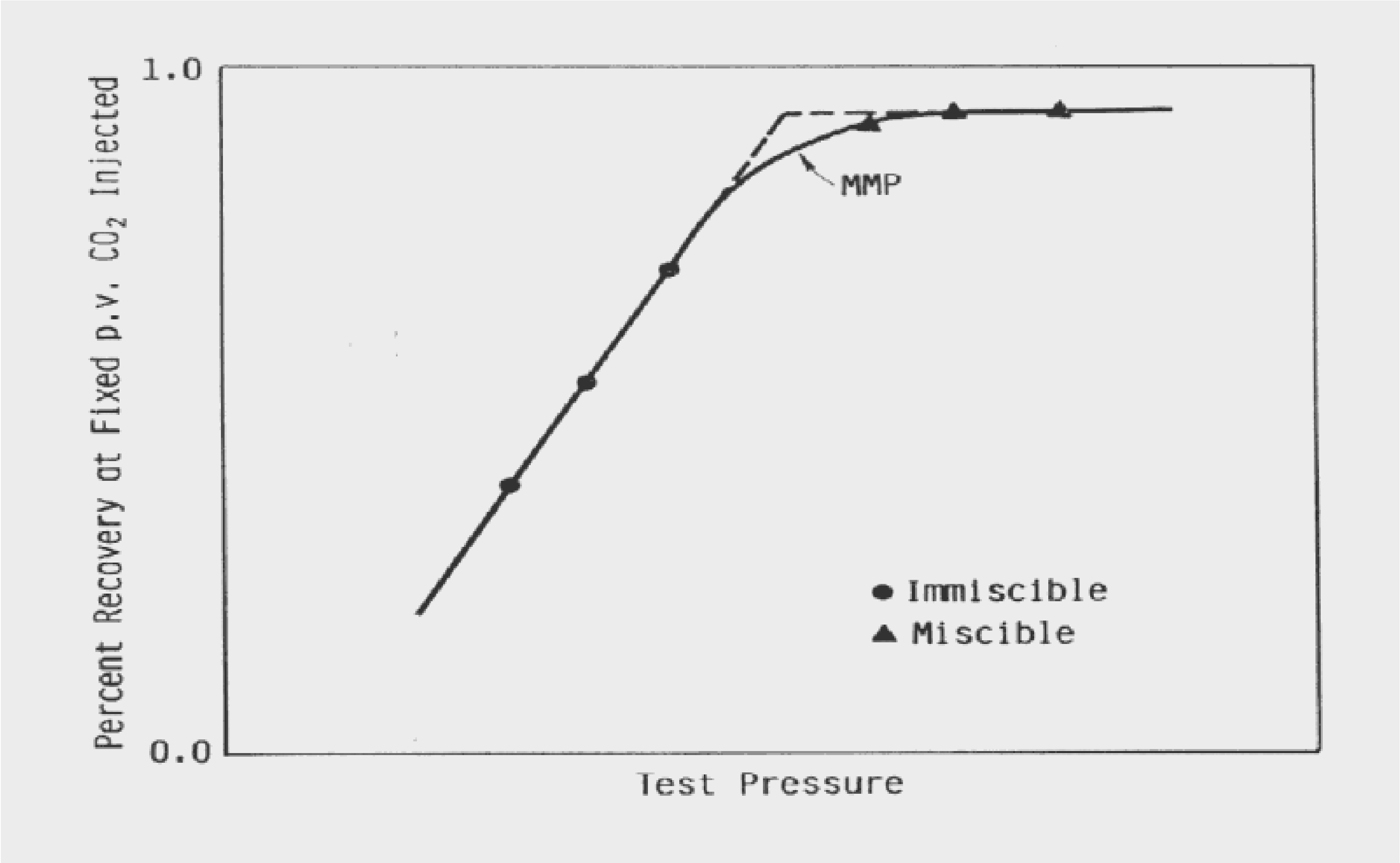
Proportion of Current CO_2 Demand by End Use

(Source: NETL)

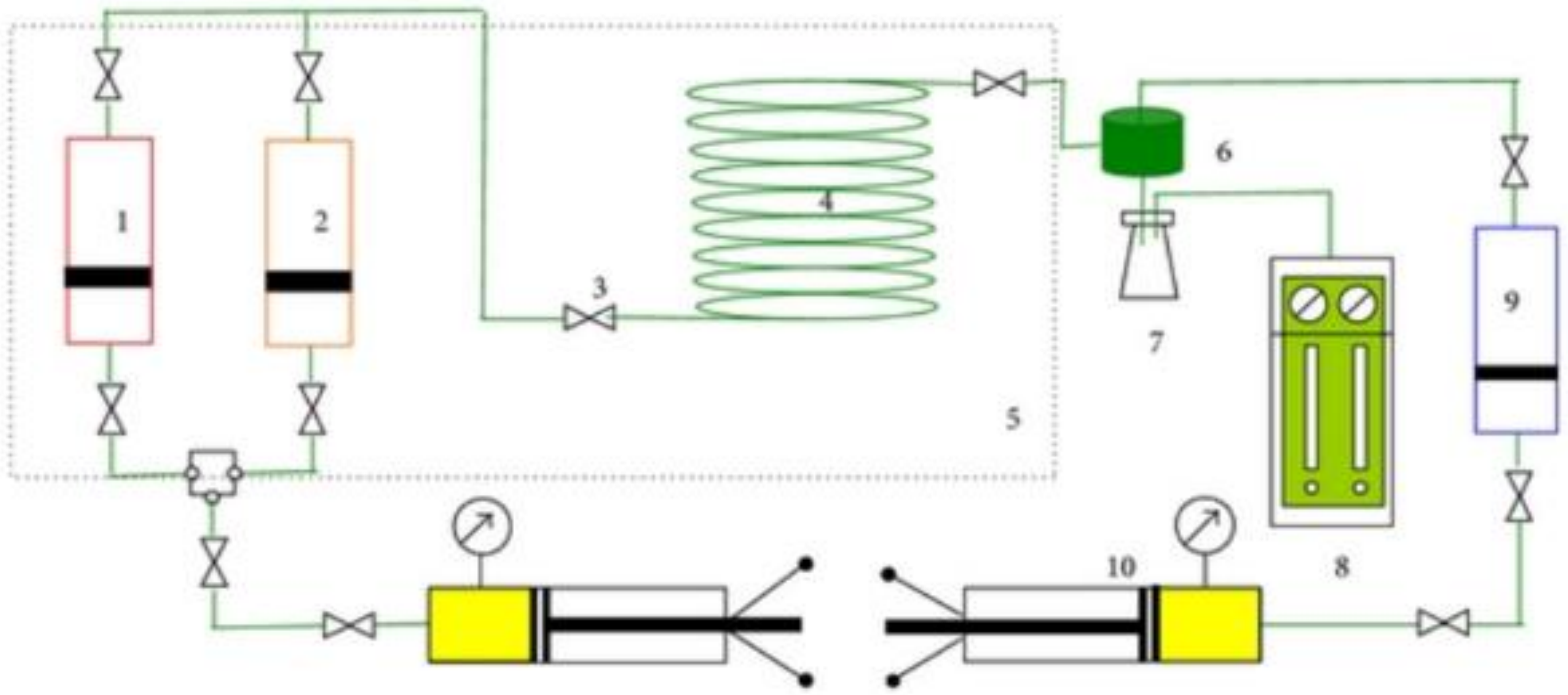


Oil Recovery in Slim Tube & Minimum Miscibility Pressure (MMP)

(Source: G. Paul Willhite, University of Kansas)



Slim Tube Schematic, Core Lab
(Source: Schlumberger)

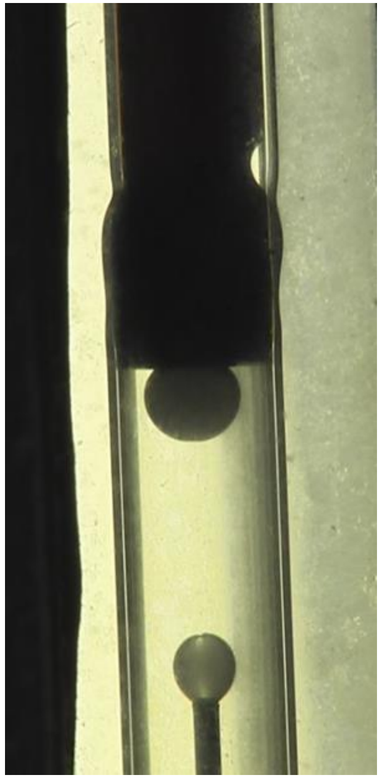


(1) Pure CO_2
(2) Reservoir oil
(3) Valve
(4) Slim tube
(5) Constant temperature air bath

(6) Back-pressure valve
(7) Separator
(8) Gasometer
(9) Nitrogen
(10) Automatic pump

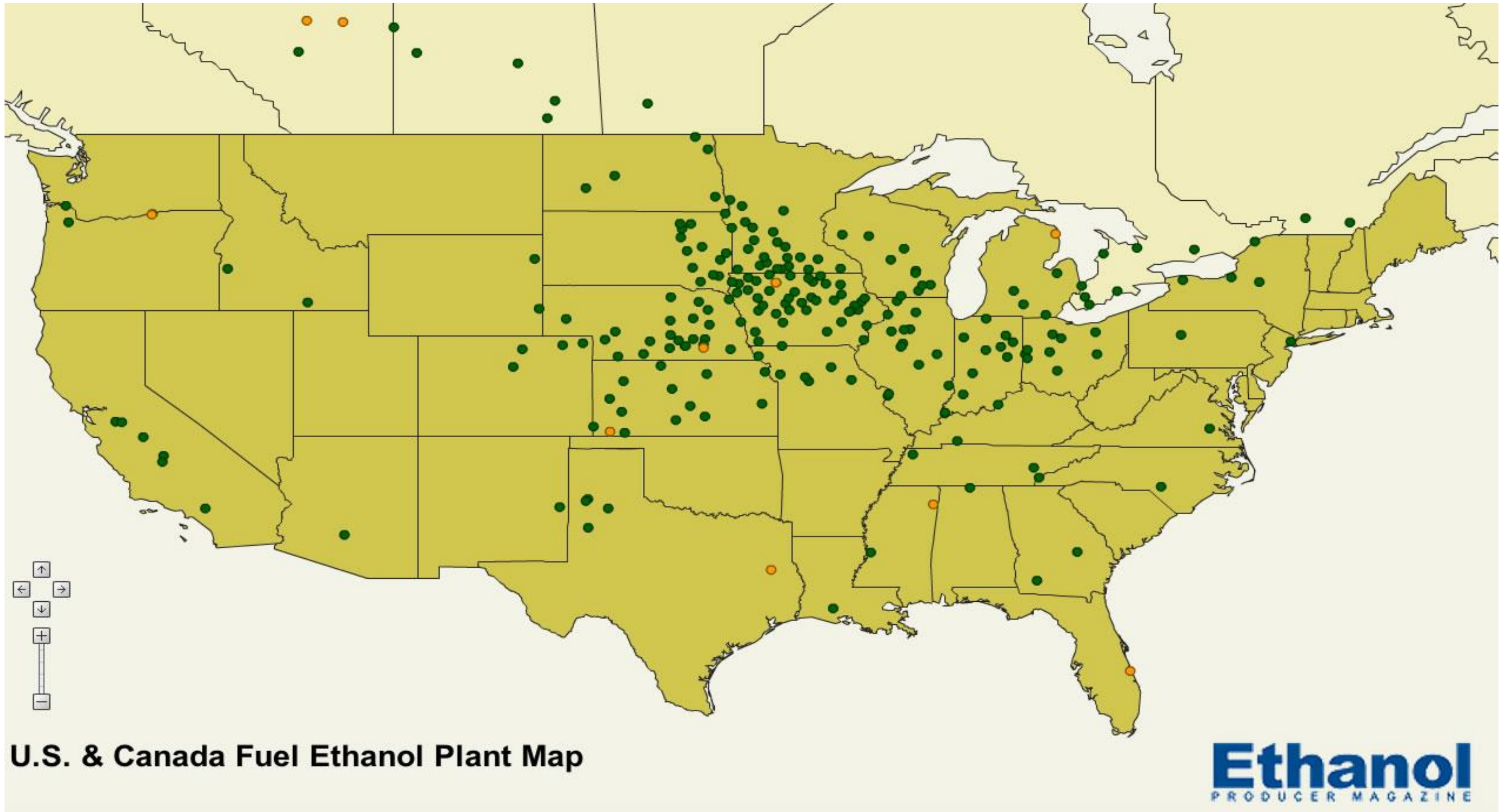
Oil Recovery in RBA & Minimum Miscibility Pressure (MMP)

(Source: Olawale Adekunle, M.S. Thesis, CSM)



Map of Ethanol Plants in the U.S. and Canada

There were 198 ethanol plants in the U.S. as of 2017, and in 2018, 60 billion liters of ethanol were produced at more than 220 ethanol production facilities in the United States and the estimated carbon dioxide (CO2) from fermentation was around 50 million metric tons (From: Renewable Fuel Association) (Source: Institute for Energy Resourcefulness)



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Great Plains Synfuels Plant

- *The **Great Plains Synfuels Plant** is a model of how coal can be used to produce energy in an efficient and environmentally responsible manner. Each day the Synfuels Plant converts about 18,000 tons of lignite coal into an average 150 million cubic feet of **synthetic natural gas** for home heating and electricity generation. (**Source: Dakota Gasification Company**)*

Great Plains Synfuels Plant

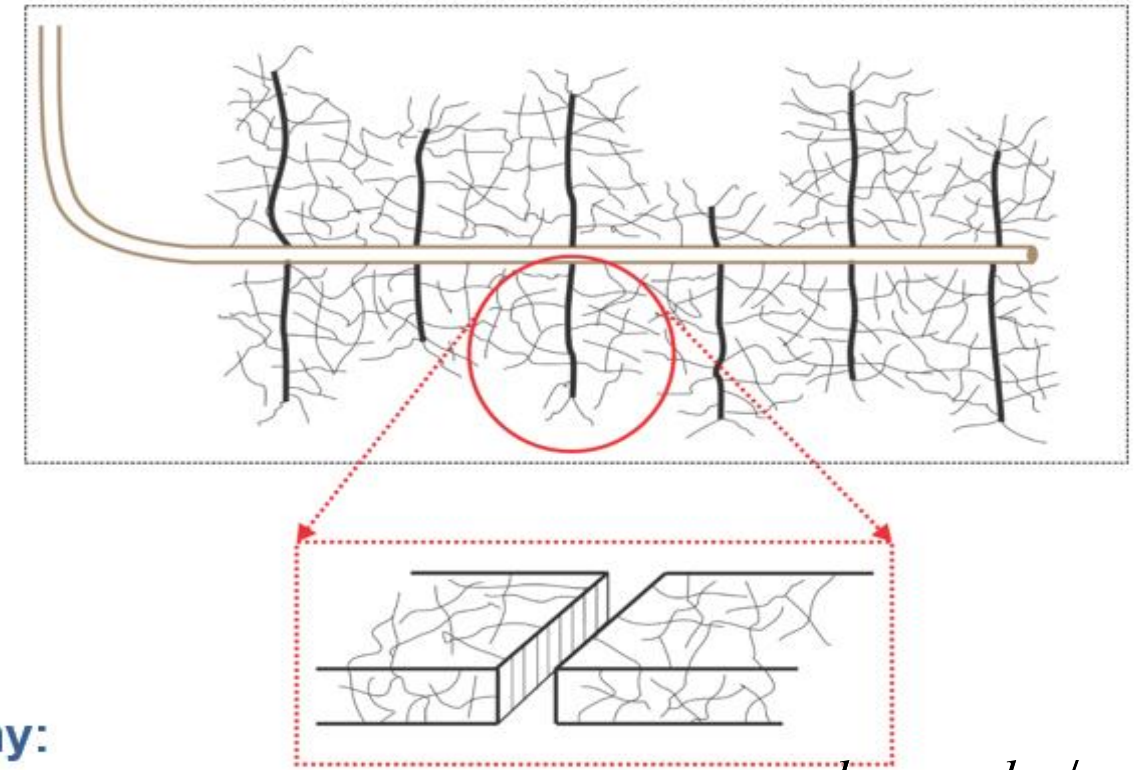
- *The **Great Plains Synfuels Plant in Beulah, North Dakota** has been in operation producing synthetic natural gas (SNG) from lignite coal for 25 years and remains the only coal-to-SNG facility in the United States. In addition to the production of SNG, the plant also produces high purity carbon dioxide (CO_2), which is distributed through a pipeline to end users in Canada for enhanced oil recovery (EOR) operations. The plant also produces and sells anhydrous ammonia, as well as the following byproducts: ammonium sulfate, krypton, xenon, dephenolized cresylic acid, liquid nitrogen, phenol, and naphtha, most of the last of which is burned as fuel in plant boilers. (**Source: U.S. National Energy Technology Laboratory**)*

CO_2 Enhanced Oil Recovery (EOR) in Unconventional Reservoirs

- ***Primary Production****: Oil is produced from many* ***hydraulic-fracture-stimulated*** *production wells. The production mechanism is primarily by reservoir fluid expansion. Approximately 4 to 8% of oil in placed is produced this way.*
- ***EOR Production:*** *Only cyclic gas injection (huff-n-puff) process produces additional amounts of oil.* ***Hydrocarbon rich-gas*** *and* ***CO_2*** *are the methods of choice.*
- *Unconventional reservoirs retain much of the injected* ***CO_2 ;*** *thus, unconventional reservoirs are suitable both for* ***CO_2-EOR (CCUS) and CO_2 storage (CCS).***

Idealization of a Dual-Porosity Environment

(Source: Mehmet Torcuk et al., 2015, CSM)

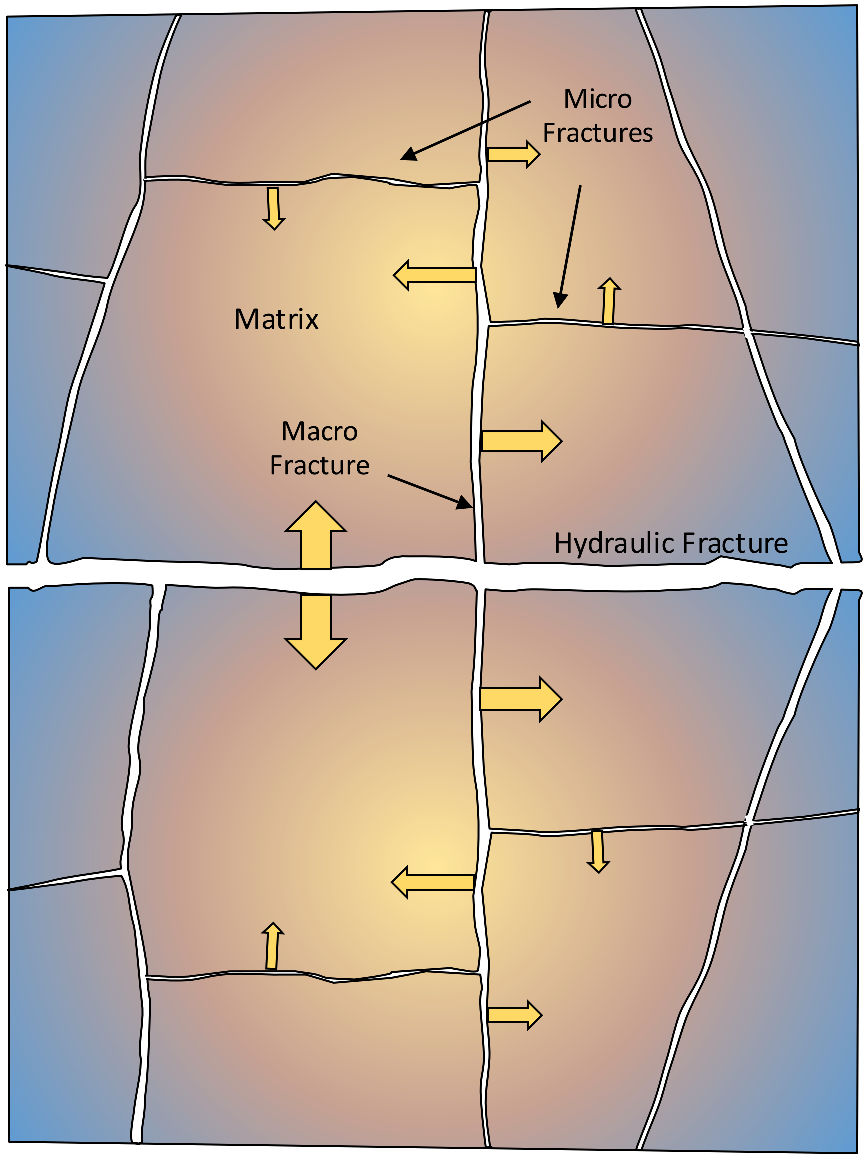


Flow Hierarchy:

$$Matrix \overset{FEEDS}{\rightarrow} Fracture \overset{FEEDS}{\rightarrow} Hydraulic\,Fracture$$

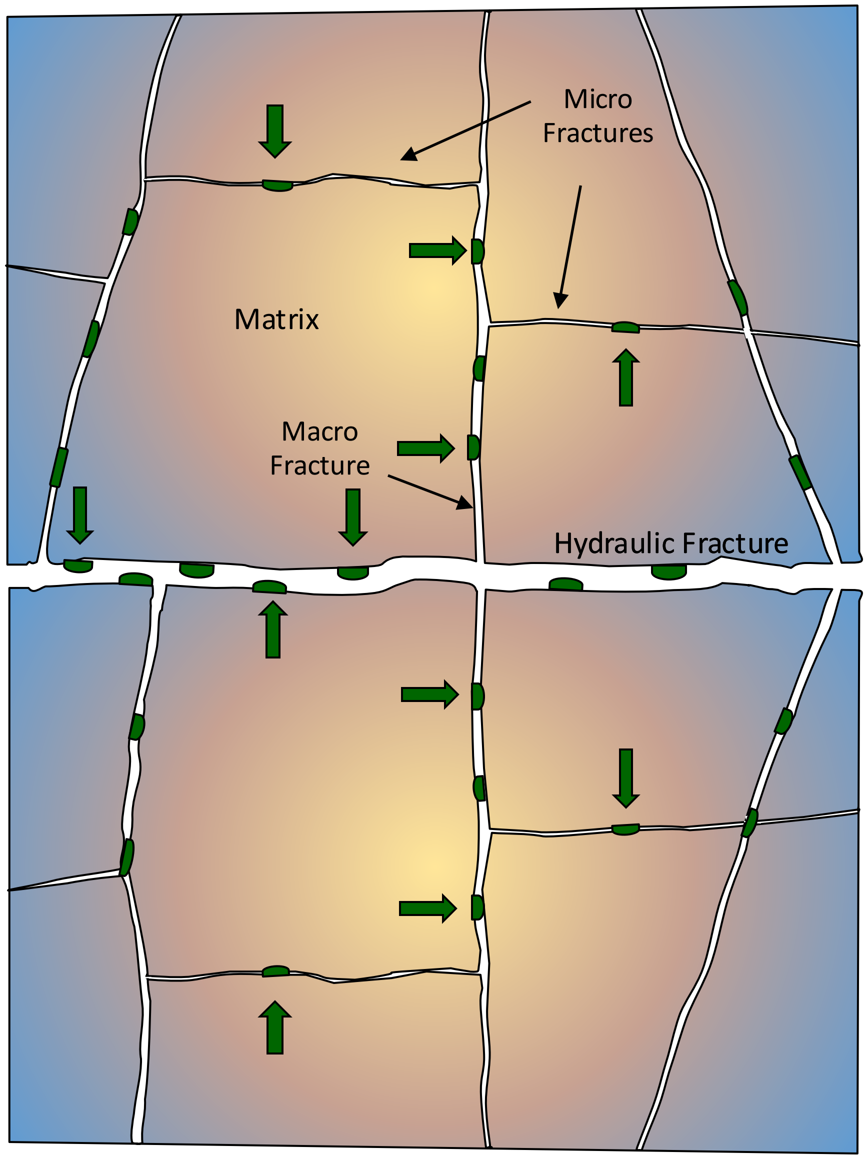
$$k_{f,eff} = k_f \phi_f + k_m$$

Cyclic gas injection 'huff-n-puff' EOR process:
CO_2 injection cycle



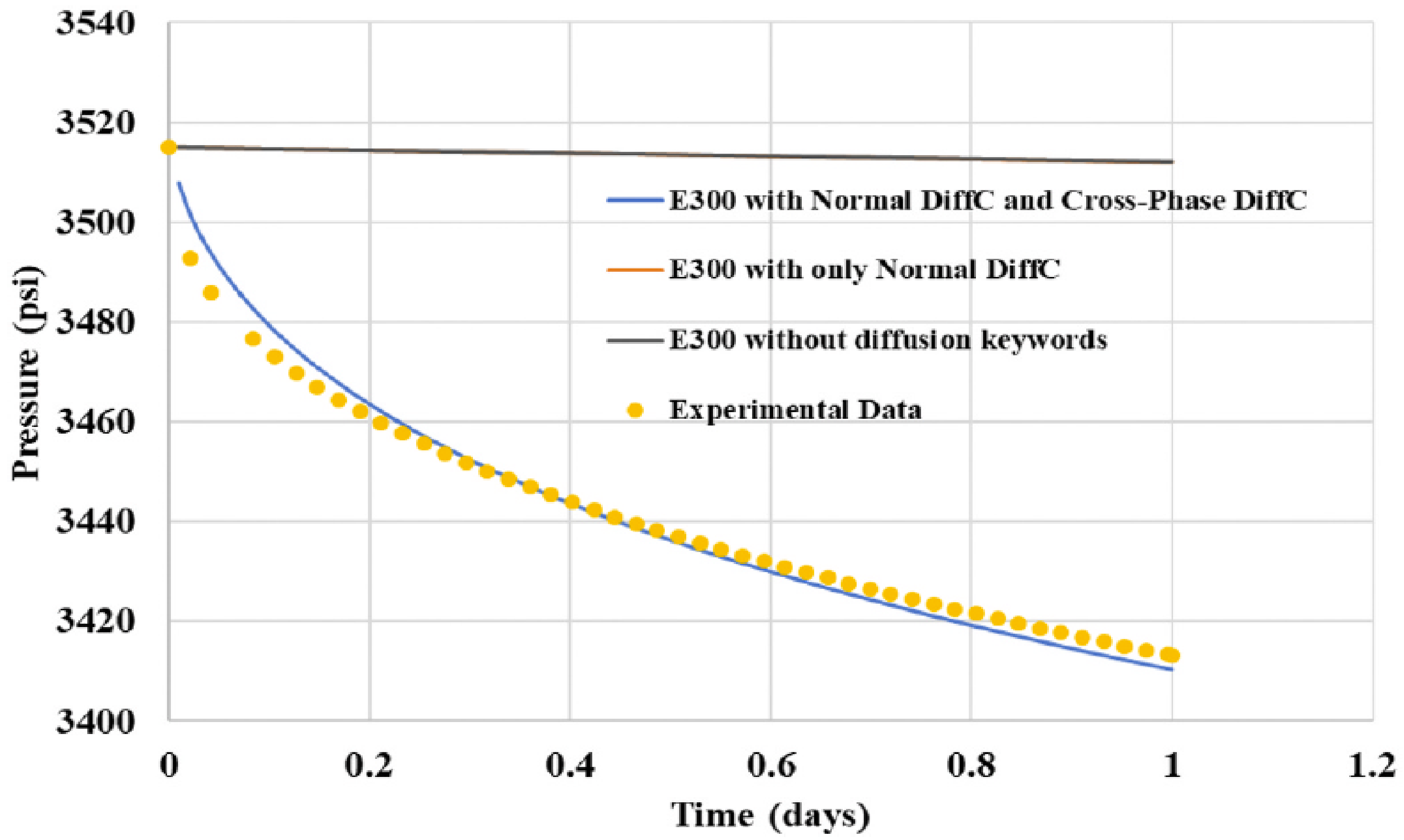
Cyclic gas injection 'huff-n-puff' EOR process:

Oil production cycle



Diffusion-driven EOR in Unconventional Shale Reservoirs

(Source: Fu et al., Journal of Petroleum Science and Engineering, 2021)



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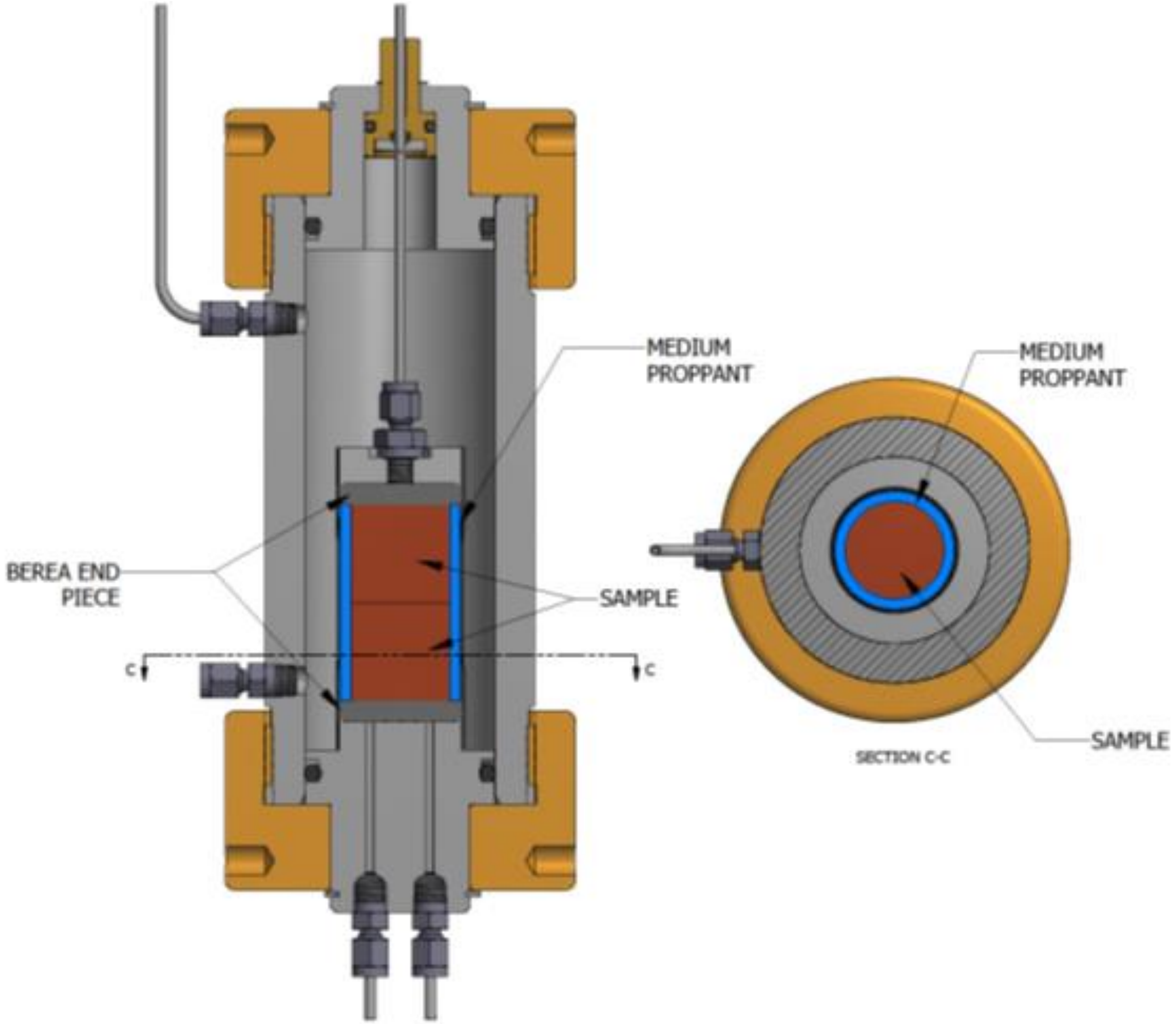
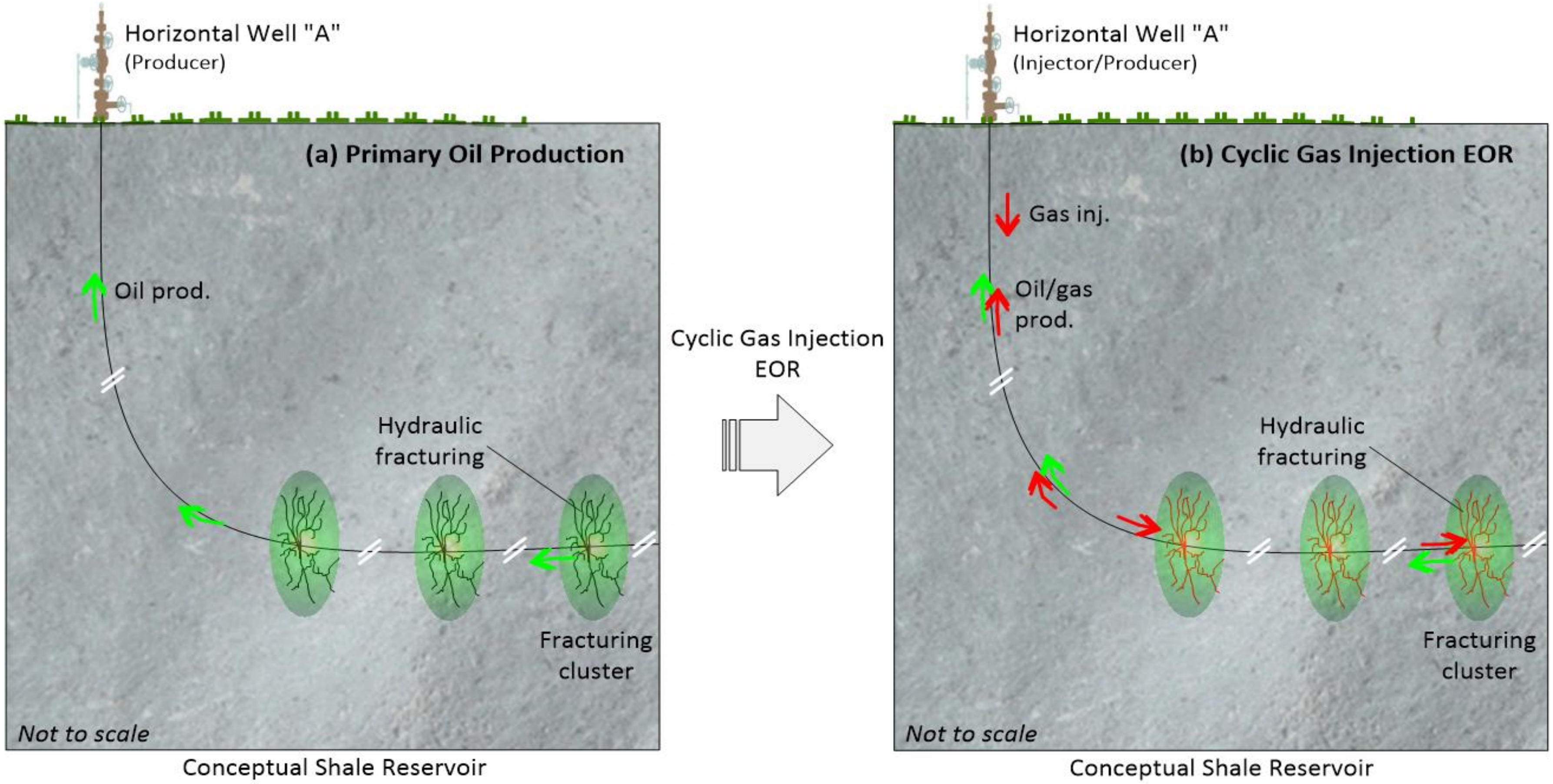
Core Lab Huff-n-Puff EOR Apparatus

(Source: Liu et al., URTeC 2018)



Idealization of CO_2 EOR via Huff-N-Puff Process

(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)



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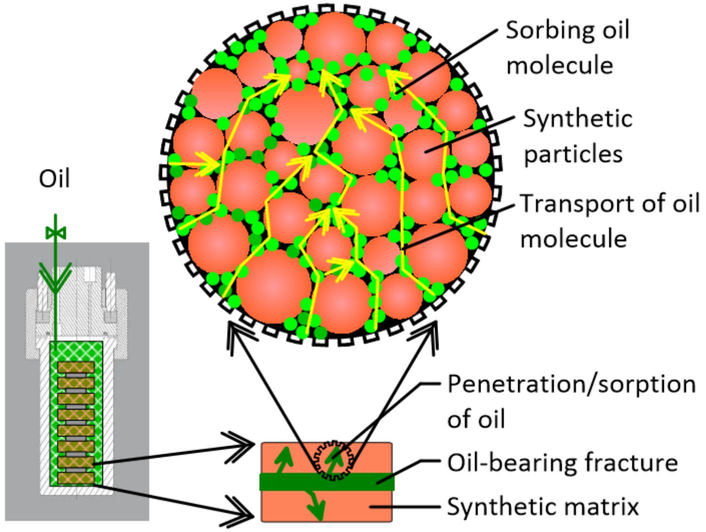
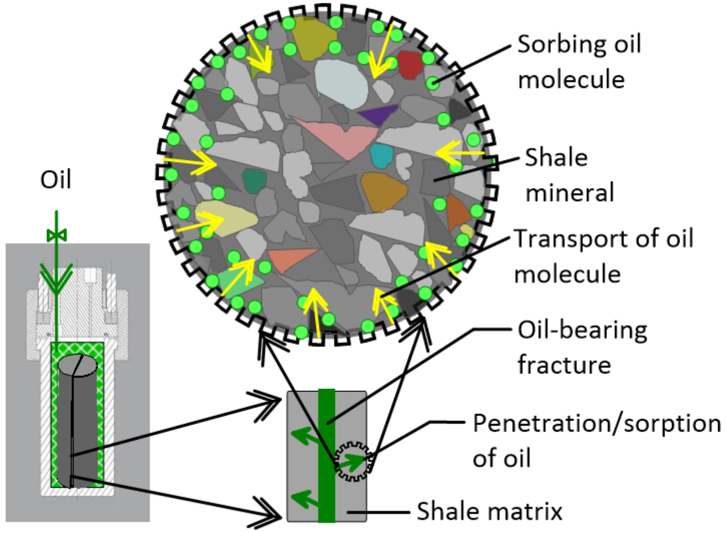
Mechanism of Oil Pressurization by Gas Infusion

(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)

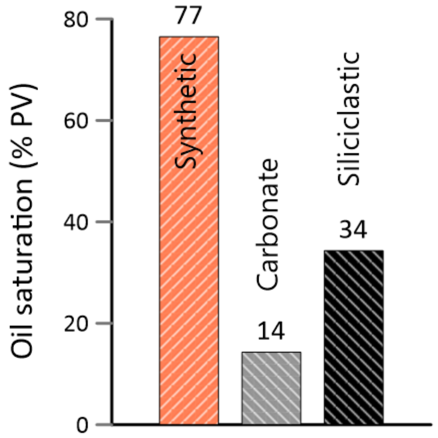
Mechanism of oil infusion [synthetic core]



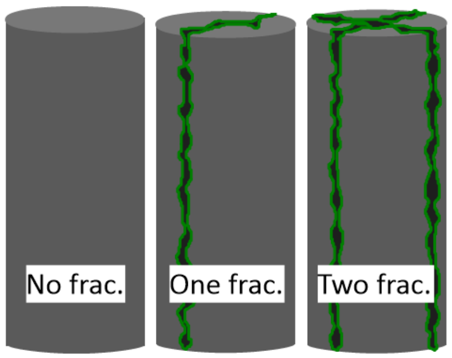
Mechanism of oil infusion [shale core]



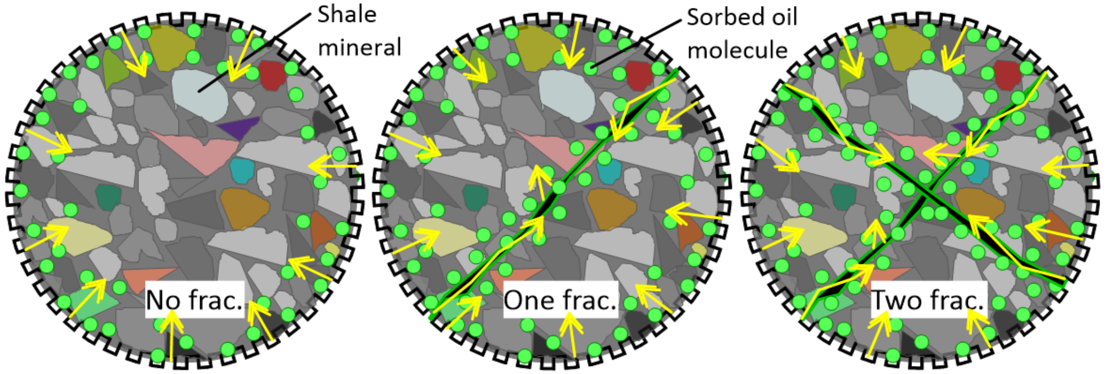
Infused oil [synthetic vs. shale core]



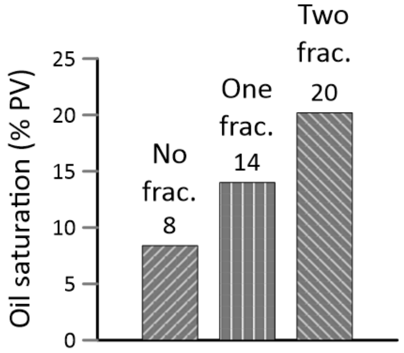
Fracture geometry [carb. core]



Mechanism of oil infusion [carb. core]



Infused oil [carb. core]



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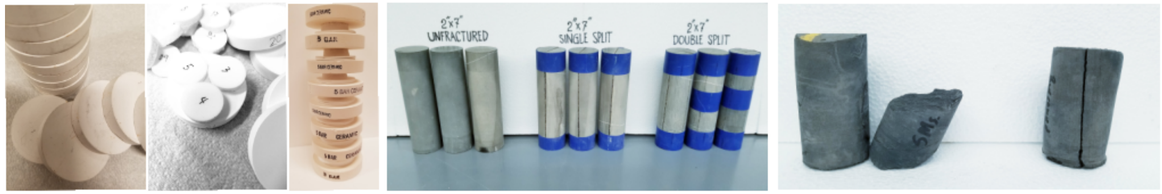
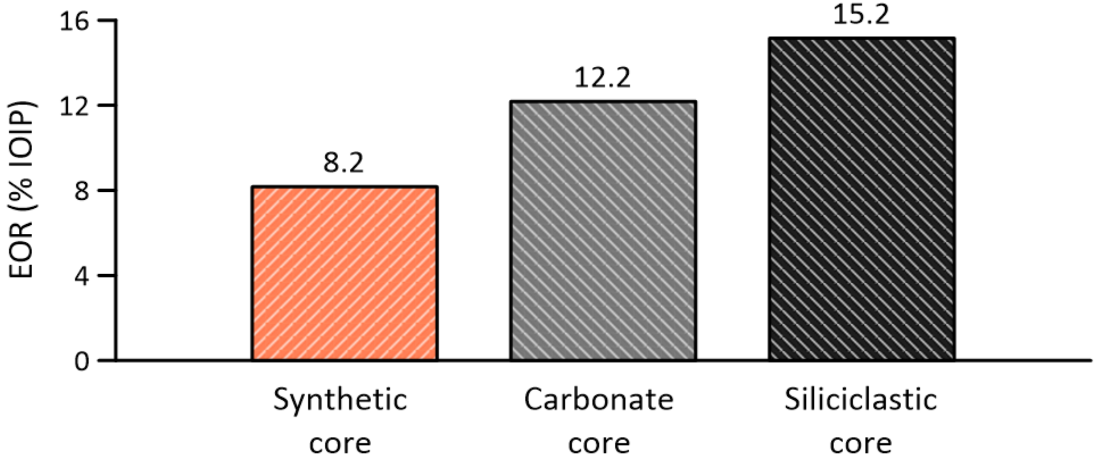
Contribution of Fractures to Gas Injection Huff-N-Puff EOR

(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)

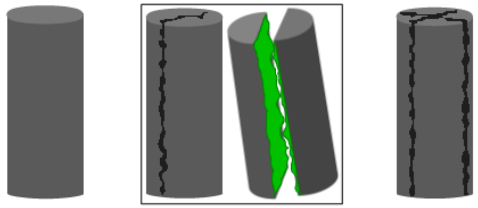
EOR comparisons:
Wolfcamp carbonate vs. siliciclastic vs. synthetic cores



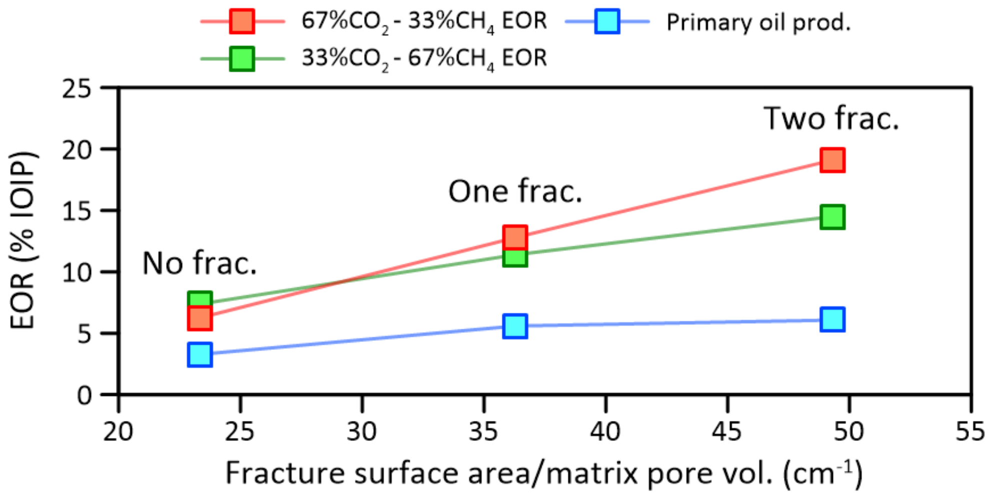
Synthetic core — Wolfcamp carbonate core — Wolfcamp siliciclastic core



EOR comparisons:
Wolfcamp carbonate cores (frac. vs. unfrac.)

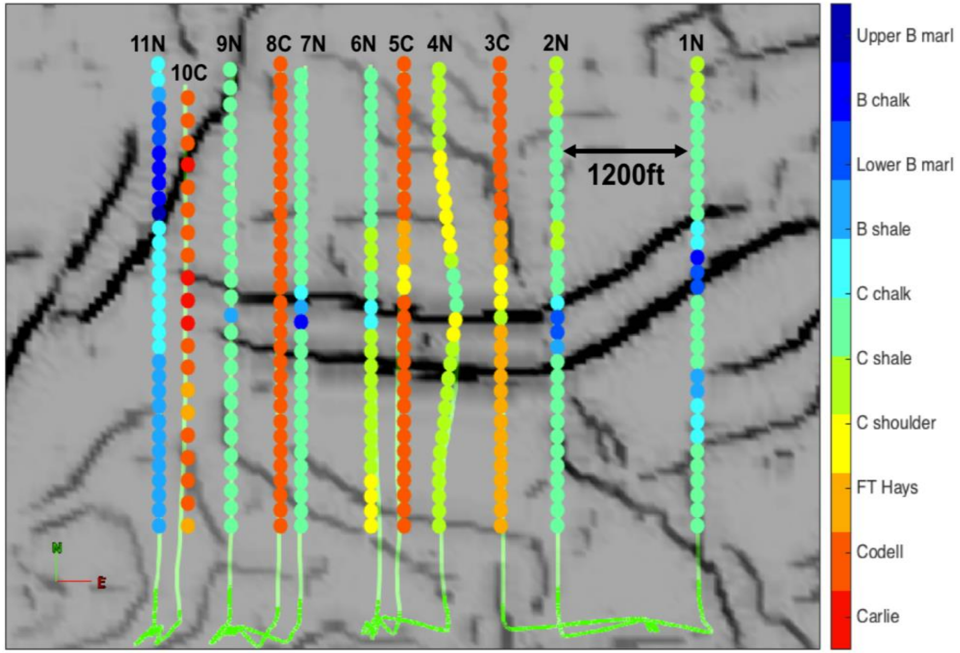


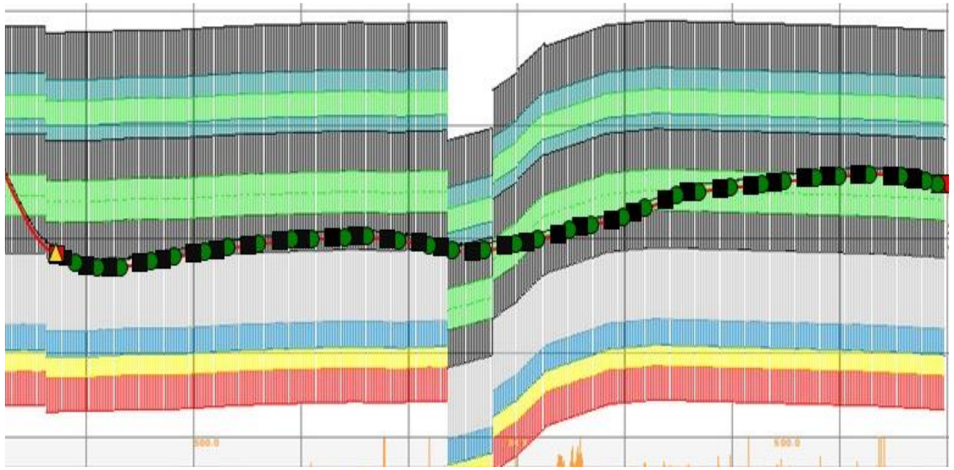
No frac. — One frac. — Two frac.



11 Wells in the 1-Square Mile Study Area and A Well Path

(Source: Yanrui Ning, PhD Thesis, 2018, CSM)





Pitcher, 2015

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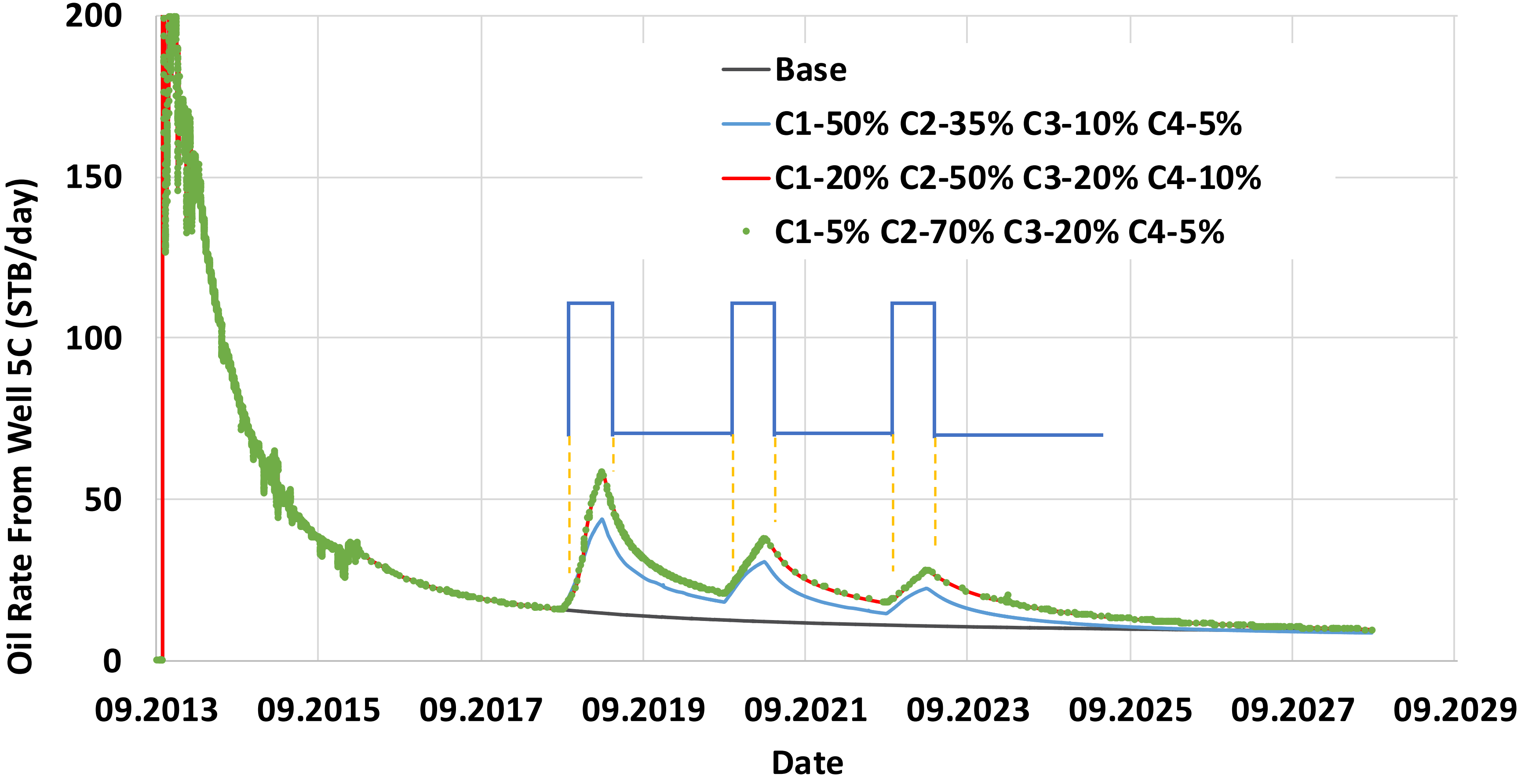
Performance of Wishbone Well 5C, after Gas Injection in Well 6N at 1.0 MMscf/D

(Source: Yanrui Ning, CSM, 2018)



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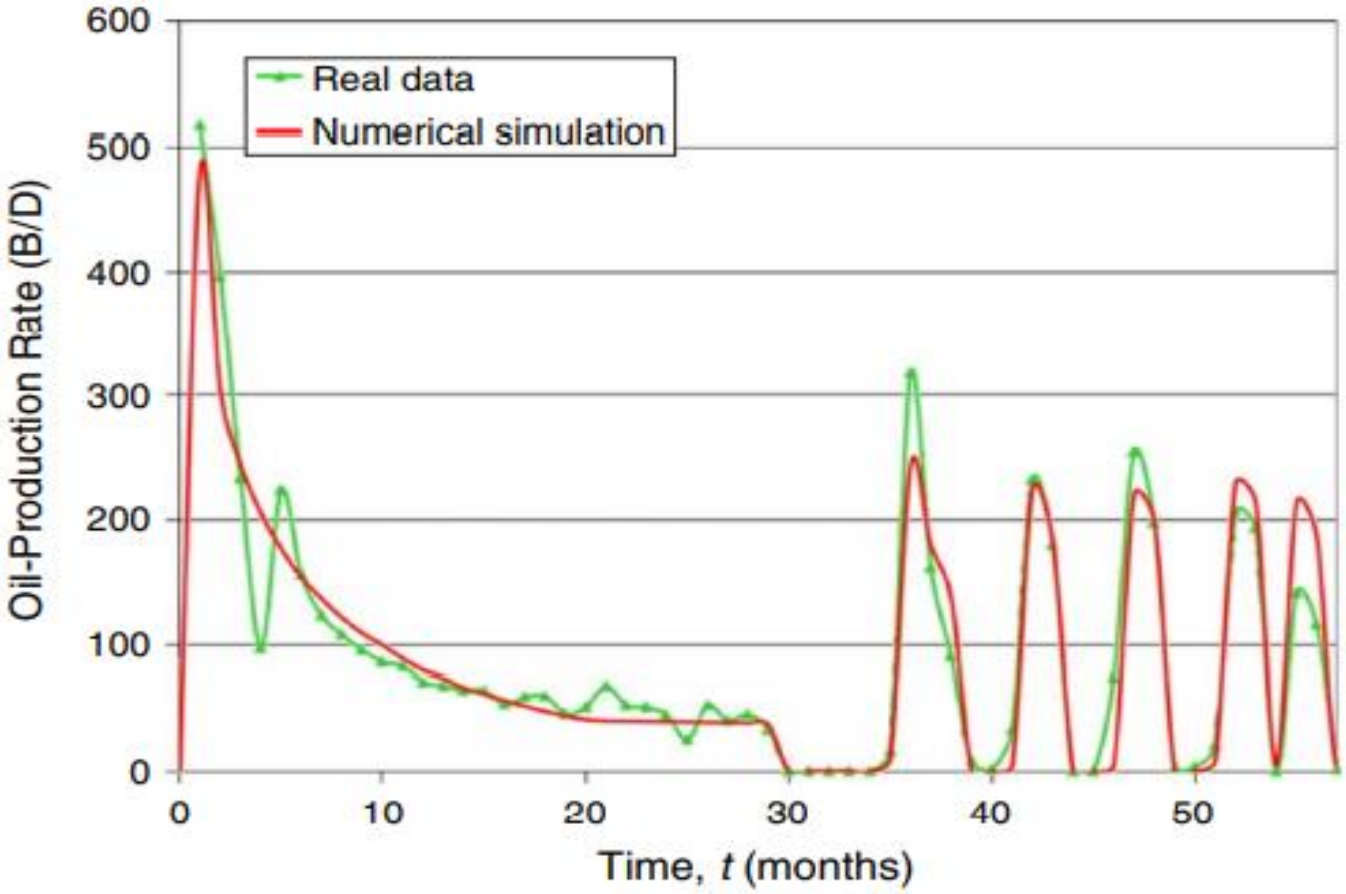
Huff-n-Puff Gas Injection EOR in An *Eagle Ford Pilot Test*

(Source: Orozco et al.: SPE Res. Eval. & Eng., Feb. 2020)



Energy Transition Dilemma

- ***Global warming*** *resulting from emission of high quantities of* ***greenhouse gases (GHG)*** *has created great concern for the Earth. The main gases responsible for the greenhouse effect include* ***carbon dioxide, methane, nitrous oxide, and water vapor*** *(which all occur naturally), and* ***fluorinated gases*** *(which are synthetic). Greenhouse gases have different chemical properties and are removed from the atmosphere, over time, by different processes.*

Energy Transition …

- *Greenhouse gases are responsible for global warming because **they trap heat that would otherwise escape from the atmosphere**. Unlike oxygen and nitrogen, the GHG gases absorb radiation and hold onto the heat. Greenhouse gases keep Earth at a temperature that can harbor life—meaning that keeping temperature at around 58 ^{o}F rather than 0 ^{o}F!*

Energy Transition …

Two key indices *defining how these gases differ from each other are:*

(1) The gas ability to absorb energy (the radiative efficiency).

(2) How long the gas stays in the atmosphere — the lifetime ***Global Warming Potential, GWP*** *(Tans et al. 2020). The GWP was developed to allow comparisons of the global warming impacts of different gases. Specifically, GWP is a measure of how much energy the emissions of one tonne of a gas will absorb over a given period, relative to the emissions of one tonne of carbon dioxide (CO_2).*

CO_2 has a GWP of 1 regardless of the time period used*, because it is the gas being used as the reference. CO_2 remains in the climate system for a very long time (Tans et al., 2020).*

The Inevitable CCS

"The 'road ahead' is challenging but Carbon Capture and Storage (CCS) is increasingly well placed to make its significant and necessary contribution to achieving net-zero emissions around mid-century."

(Brad Page, CEO, Global CCS Institute, Dec. 11, 2020, Report)

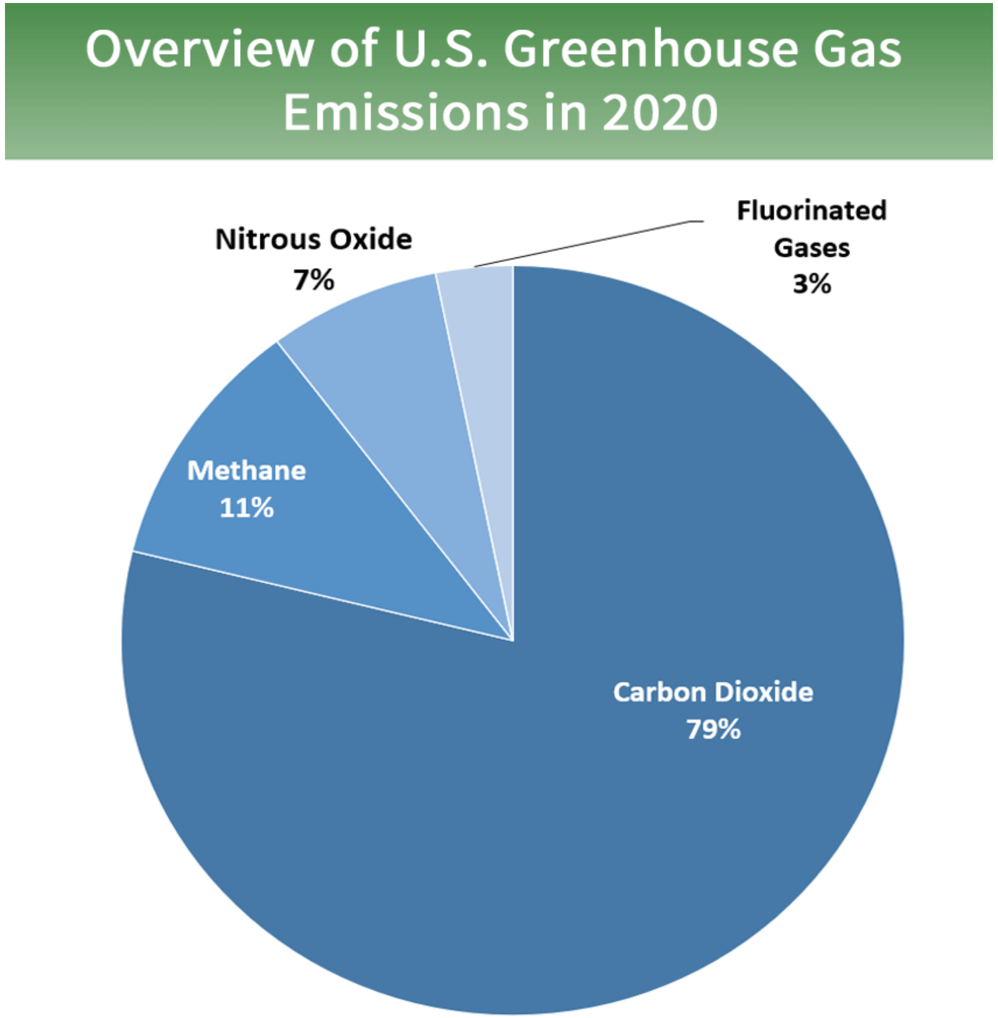
Future of Energy

***World population is increasing at a rapid pace**, and there is an increasing need for **food, clean water, clean air, and energy**. I believe **hydrocarbons** (oil and gas) will continue to be the leading fuel for the energy needs for several decades. What we really need is **managing carbon emissions**. **Thus**, I support both the Carbon Capture and Storage (**CCS**) and the Carbon Capture, Utilization, and Storage (**CCUS**) via **CO_2-EOR**.*

Energy Transition …

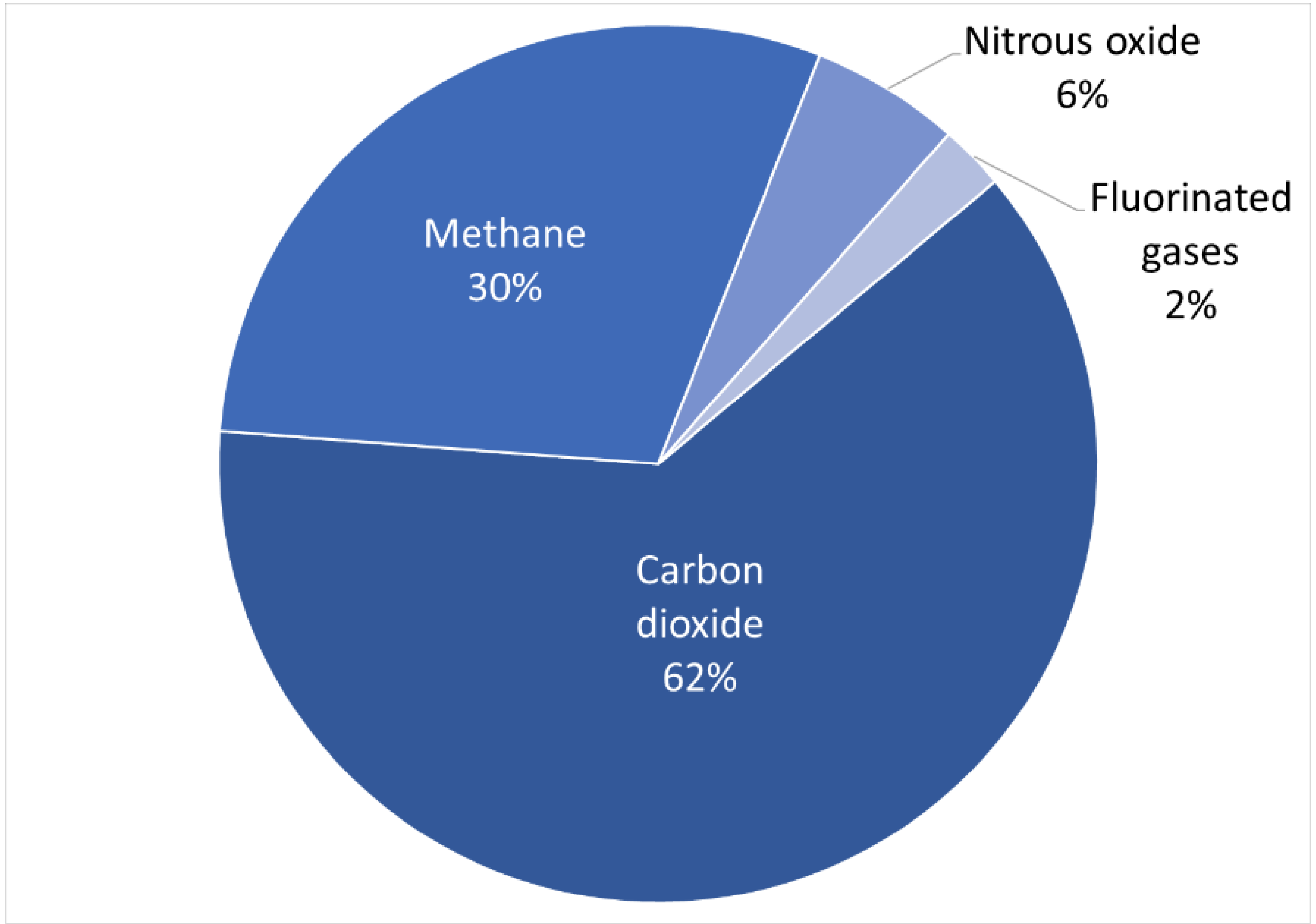
- ***Methane (CH4) is estimated to have a GWP of 28-36 over 100 years.*** *When methane GWP is measured over a* ***20-year period, the GWP ratio grows to 84-86 times.***
- *CH_4 emitted today lasts about a decade on average, which is much less time than CO_2. But CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a greenhouse gas.*

An overview of the greenhouse gas emissions (GHS) in the U.S. in 2020 in CO_2e over a period of 100 years. (US EPA)



U.S. Environmental Protection Agency (2022). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020

Replot of the U.S., 2020 greenhouse gas emissions (GHS) in CO_2e over a period of 25 years. The only change from data reported by the U.S. EPA is replacing CO_2e for methane from 25 to 86.



Steam & Hydrocarbon Gas Injection EOR

- ***U.S. oil*** *from* ***steam injection*** *is* ***2.5 %*** *of daily total oil production.*

  - it is interesting to note that if one uses lease oil to generate steam, for every bbl of oil consumed it generates 13 bbl of cold-water equivalent which produces a little over 2 bbl of oil. Thus, the net steam EOR oil is o 1 incremental barrel of oil. The oil consumed generates around 1000 pounds of CO_2*.*

- ***Hydrocarbon gas injection*** *is* ***2.0 %*** *of the daily total oil.*

  - In conventional reservoirs, gas injection is a ***gravity drainage*** *process.*

  - In unconventional shale reservoirs, it is the ***huff-n-puff*** *process.*

U.S. Pipelines

- ***U.S. has more than 2.6 million miles of pipelines*** *safely delivering trillions cubic feet of natural gas and hundreds of billion ton-miles of liquid petroleum products each year.* ***(Source: U.S. DOE, Pipelines and Hazardous Materials Safety Administration, 2018)***
- *The primary mode of* ***large-scale CO_2 transport in the United States*** *today is via pipeline, and in 2017, there were more than* ***5,000 miles of CO_2 pipelines*** *in operation.* ***(Source: Energy Equipment & Infrastructure Alliance)***
- *Approximately* ***90% of the CO_2 pipeline*** *infrastructure in the United States today is used for* ***CO_2 enhanced oil recovery (EOR)*** *operations.*

Recent CO_2 Pipeline Construction Metrics

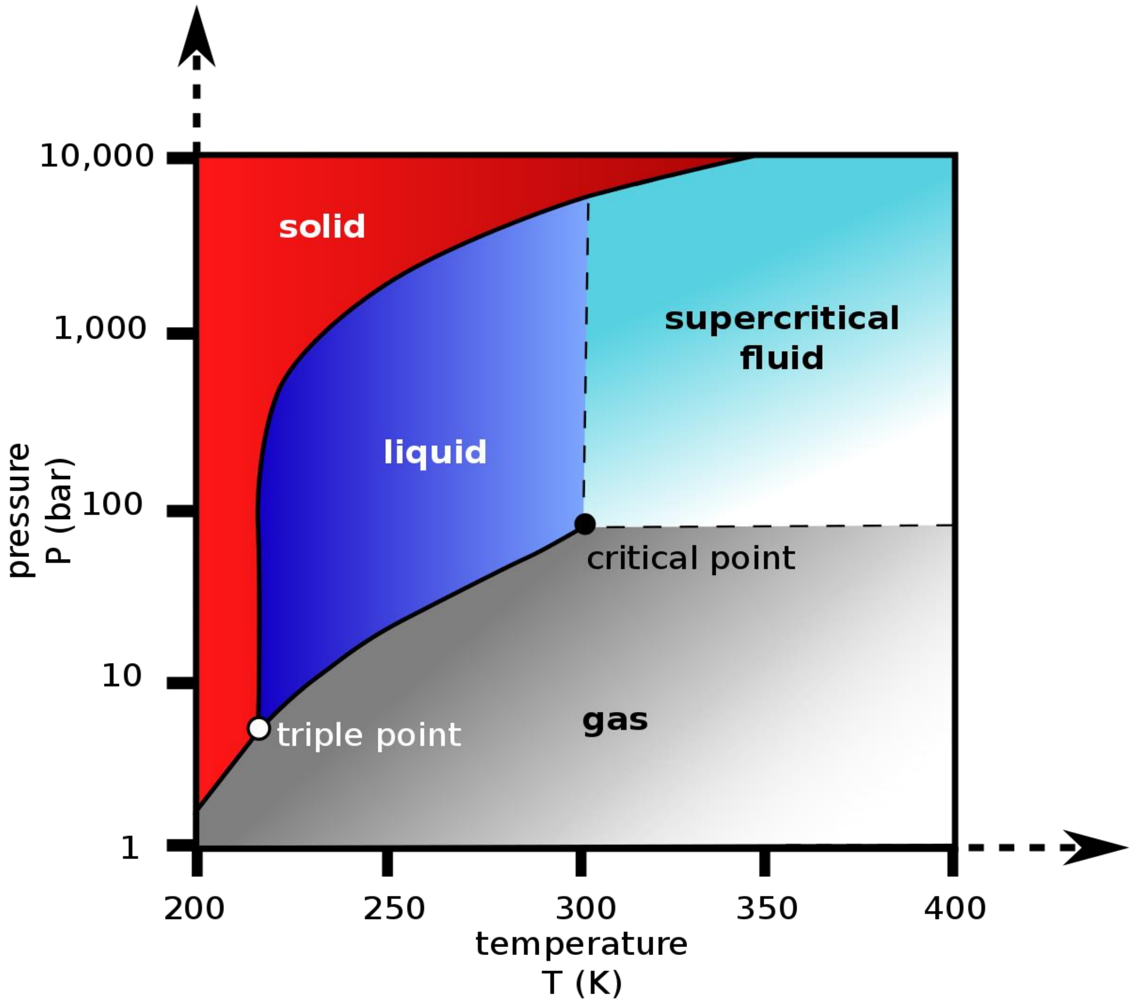
(Source: Advanced Resources International, Inc.)

***In the past 10 years**, the construction of CO2 pipeline infrastructure in the United States has been limited to establishing point-to-point pipelines that connect an identified source of CO2 to the corresponding sink(s) where the CO2 is used for either EOR or industry. The Greencore Pipeline is built across private ranchland as well as state and public lands in Wyoming and Montana and cost **$69,000** per **'diameter-inch-mile'**. Contrast this with the Webster Pipeline built in a highly concentrated industrial and suburban area just south of Houston, Texas, that cost **$199,000** per **'diameter inch-mile'**.*

Commercial CO2 pipelines typically operate at pressures between 1,200 and 2,200 psig**, with some pipelines having a maximum operating pressure of 2,500 psig to 2,800 psig. At these pressures, CO2 is in a **dense phase** - either as a **liquid** or a **supercritical fluid

Pressure-Temperature Phase Diagram for CO_2

(P_c = 1070 psia, T_c = 87.8 º F) *(From: Wikipedia)*



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CO_2 Emission from five Colorado Power Plants

Four Plants Use Coal and One Uses Natural Gas (Source: Dr. Ali Tura, CSM)

- ***Craig Power Plant:***

  7.6 Mt/yr = 396 x 10^6 scf CO_2/D = 396 MMscf CO_2/D = 66,000/2.75 BOE/D = ***24,000 BOE/D*** *(Based on CH_4)*

- ***Haydon Power Plant:***

  1.7 Mt/yr = 88.5 x 10^6 scf/D =88.5 MMscf/D = ***5,380 BOE/D*** *(Based on CH_4)*

- ***Comanche Power Plant:***

  9.3 Mt/yr = 486 x 10^6 scf/D = 486 MMscf/D = ***29,500 BOE/D*** *(Based on CH_4)*

- ***Pawnee Power Plant:***

  3.6 Mt/yr = 186 x 10^6 scf/D = 186 MMscf/D = ***11,300 BOE/D*** *(Based on CH_4)*

- ***Rawhide Energy Station:***

  1.7 Mt/yr = 88.5 x 10^6 scf/D = 88.5 MMscf/D = ***5,380 BOE/D*** *(Based on CH_4)*

Total: *1245 x 10^6 scf CO_2/D = 1.245 Bscf CO_2/D =* ***75,560 BOE/D*** *(Based on CH_4)*

US Renewable Energy Development

(Global Energy Prize News, October 30, 2020)

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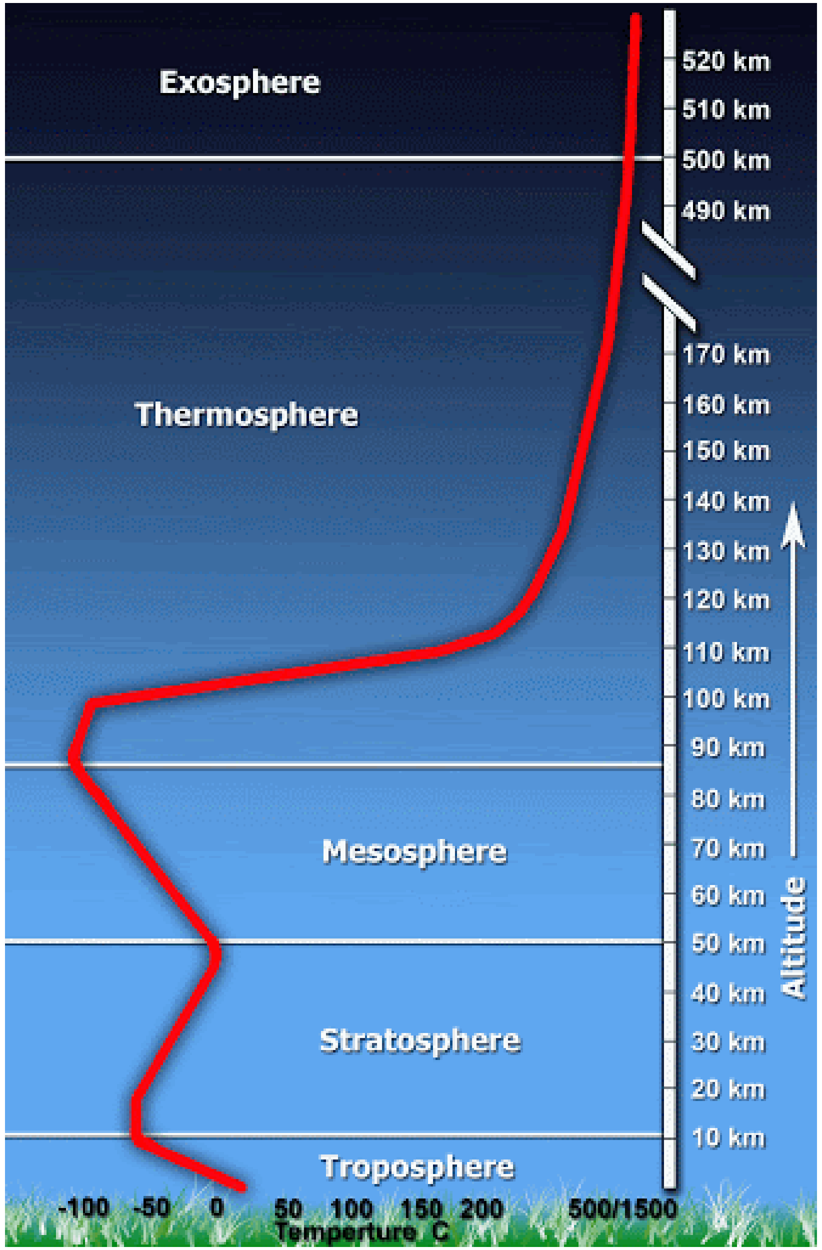
Thank you!


Exosphere
Thermosphere
Mesosphere
Stratosphere
Troposphere
520 km
510 km
500 km
490 km
170 km
160 km
150 km
140 km
130 km
120 km
110 km
100 km
90 km
80 km
70 km
60 km
50 km
40 km
30 km
20 km
10 km
Altitude
-100 -50 0 50 100 150 200 500/1500
Temperture C

The Moon and Earth's Atmosphere (NASA)