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The False Promise and Potential Health Harms of Carbon Dioxide Enhanced Oil Recovery (CO2 EOR) as a Tool of Climate Mitigation

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ABSTRACT

Using increasing amounts of newly subsidized carbon dioxide (CO_2) to remove oil from the ground is the next phase in the fossil fuel industry's bid to extend the use of fossil fuels far into the future. While the industry claims that carbon dioxide enhanced oil recovery (CO_2 EOR) is a tool of climate mitigation, it actually perpetuates oil and gas extraction and generates more greenhouse gases. Subsidized by public money through excessively generous tax credits, CO_2 EOR not only exacerbates climate change, it causes unusual public health and environmental damage. This paper explores the history and geology of CO_2 EOR, describes the public health, environmental, and climate impacts, and concludes that our commitment to future generations requires a halt to this practice.

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OVERVIEW

Carbon capture and storage (CCS) involves securing and sequestering the carbon dioxide (CO_2) that is created as a waste gas during industrial processes or energy production and that would otherwise enter the atmosphere as a greenhouse gas. Touted as a critical component of the effort to mitigate climate change, this technology has received major support by the Biden Administration.[1] Under current law, Section 45Q of the Internal Revenue Code[2] supports carbon capture by offering a tax credit for each ton of CO_2 captured and stored. In 2022, as part of the Inflation Reduction Act, these tax credits were increased and eligibility thresholds loosened, increasing incentives for carbon capture projects.[3] The 2022 Bipartisan Infrastructure Law[4] also supports direct government investments in carbon capture.

In most existing carbon capture and storage operations, the apprehended CO_2 is not simply warehoused underground but is used for an industrial purpose. Currently, the leading end-user of carbon capture technology is the oil industry, which injects liquefied CO_2 into depleted oil fields in order to dissolve crude oil that remains stuck within rock so that it can be pumped to the surface. As early as 2015, the International Energy Agency (IEA) framed this use of carbon capture as a win-win for the oil industry and for the global climate—essentially co-exploiting CO_2 storage and the final stage of oil production and creating revenue streams for each.[5] The goal of this repurposing and retooling, known as carbon dioxide enhanced oil recovery (CO_2 EOR), is to squeeze out the veritable last drop of recoverable oil from an oilfield. The assumption is that the injected CO_2 will either remain within an escape-proof underground location or will be re-captured and reused if it rises to the surface with the oil it liberates. Indeed, U.S. gas and oil companies have seized on carbon capture as a means to partially offset, on paper, their greenhouse gas emissions without ending fossil fuel extraction or combustion.

CO_2 EOR is, in fact, the only currently existing commercially available market for millions of tons of captured CO_2. Of the 12 commercial carbon-capture operations in the United States in 2021, 11 were CO_2 EOR projects.

All the evidence to date, however, indicates that no regulatory framework or system of economic incentivization can transform CO2 EOR into a meaningful tool for climate mitigation. To the contrary, CO2 EOR harms the climate by incentivizing rather than impeding the continued extraction of fossil fuels and by extracting crude oil that would otherwise remain in the ground.

At the same time, CO2 EOR poses considerable public health threats. Climate change is, of course, the greatest threat to health posed by continuing to extract and burn fossil fuels far into the future. And yet, the dangers posed by the specific toxic emissions involved in CO2 EOR are also of concern. People, livestock, and wildlife may be exposed to hazards throughout the CO2 EOR continuum, from CO2 capture to compression, transport, injection, and output from the production well. As is explored further below, the risk of adverse health effects depends on the nature and combinations of hazards, as well as the extent and duration of exposures.

Additionally, adverse health effects are likely to result from the increased energy generation and resulting pollution required to capture CO2, compress it, inject it, and recapture and reuse it. Depending on the energy source, resulting air pollutants can include nitrogen oxides and ozone. Exposures to these pollutants can increase risks of heart disease, lung disorders including cancer and asthma, premature death, low birthweight, and pre-term births, and lead to higher numbers of hospitalizations and emergency department visits.[6]

THE FUNDAMENTALS OF PETROLEUM GEOLOGY

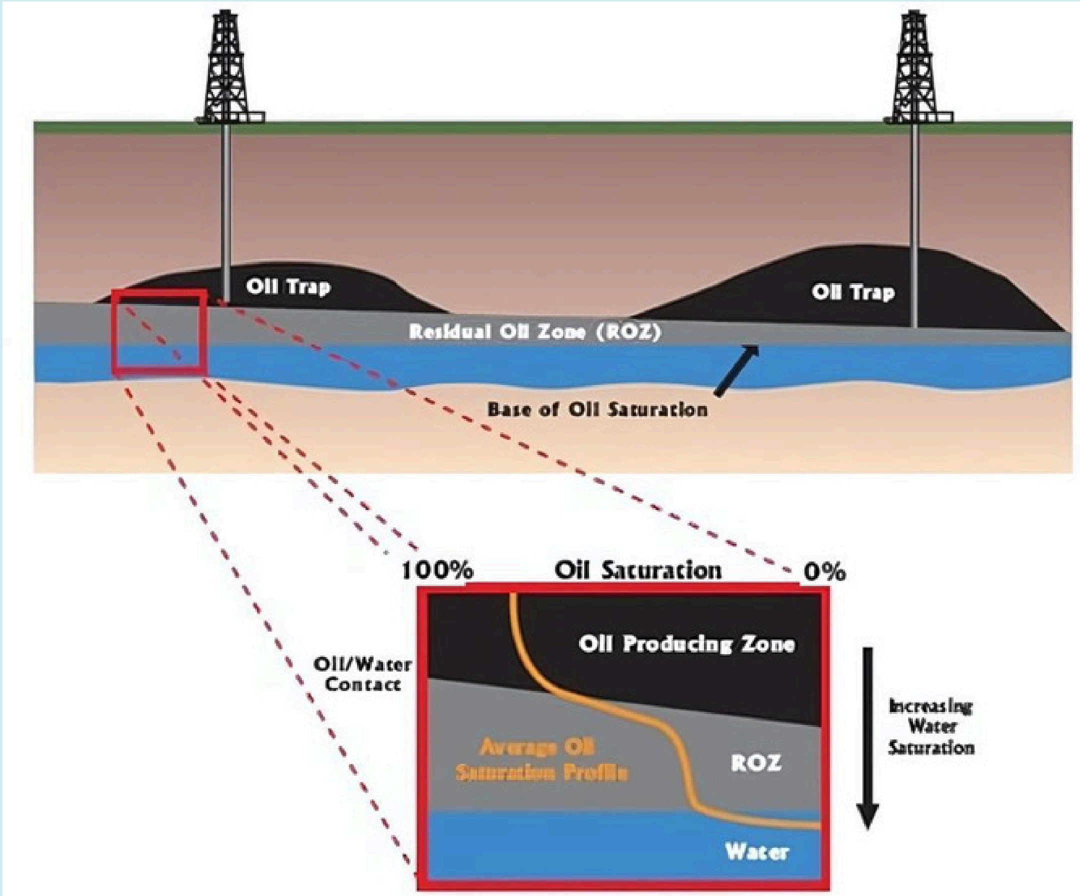
Understanding how CO2 EOR fits into the oil industry's long-term plans requires a basic knowledge of petroleum geology—including how crude oil was formed in the earth in the first place and how the oil industry extracts it.

The geologic formation of oil began between 541 million and 65 million years ago in warm shallow seas filled with extremely small plants and animals collectively called plankton, composed primarily of carbon and hydrogen. Over millions of years, this ancient plankton lived, died, settled to the sea floor, and mixed with mud, creating deep layers of sediments rich in hydrocarbons. These sediments were then covered in layers of clay, sand, and other minerals, trapping and pushing the plankton remains thousands of feet below the surface. Over millions more years, the accumulating weight of these sediments compressed and heated deeper layers, turning them into different types of rock, some porous and some nonporous, and turning hydrocarbon-rich sediments into shale. Where this shale descended deep enough to be heated to between 194°F and 320°F, the combination of heat and pressure cooked the hydrocarbons into crude oil.

When first formed, this crude oil was dispersed throughout the shale, but over millions of years some of it migrated upwards through layers of porous rock. Where this upward migration was stopped by a layer of impermeable rock—called cap rock—the oil accumulated in the porous layers just beneath the cap rock in areas called oil reservoirs. Where enough oil accumulated to make its extraction commercially viable, oil companies drill multiple wells through the cap rock to reach the oil-saturated porous rock. These wells allow oil to flow to the surface. The areas where these wells are drilled are called oil fields. In other words, crude oil is not located in underground caves but rather is soaked in varying amounts into the tiny spaces within porous rock.

The weight of the thousands of feet of rock over oil reservoirs creates pressure. When a well is first drilled through cap rock, unless controlled, the pressurized oil will rush to the surface and spray out the top of the well as a gusher. As oil is extracted from the well, this natural pressure gradually drops until no more oil flows naturally from the well. When this happens, oil companies use pumps and a variety of technologies to remove more of the oil. As more and more oil is pulled out, the rate of extraction declines. When the revenue collected from selling the oil is insufficient to pay for the pumps and other technologies needed to remove the oil, the well owner will cap the well and stop extraction. The depletion point depends on a combination of the physical nature of the oil and the reservoir rock, available extraction technology, and the price of oil. When prices are high, more oil may be extracted, but as oil prices drop, wells may be “shut in” and then abandoned.

Notably, not all the oil migrates upward through porous rock to oil reservoirs; some remains stuck in in the deeper layers of porous rock through which it migrated. These deeper layers are called residual oil zones (ROZ).



Credit: National Energy Technology Laboratory, https://netl.doe.gov/node/2686

Historically, the oil industry has not extracted oil from the ROZ, because wells drilled into these layers produced too little oil to be profitable. In some ways, the ROZ and depleted oil reservoirs are similar in that they both lack oil that can move freely. Both contain leftover oil stuck inside rock pores.

Ultimately, the amount of oil that can be extracted from an oilfield depends on complex relationships among geology, technology, and economics. While it might be technically possible to extract most of the oil in an oil reservoir, doing so might not be profitable given the high cost of the equipment, labor, and materials needed for such extraction relative to the amount of oil extracted. The following discussion describes the types of increasingly complex and expensive equipment and technology used by oil companies to extract oil as the amount of remaining oil decreases.

THE FUNDAMENTALS OF OIL FIELD DEVELOPMENT: PRIMARY, SECONDARY, AND TERTIARY RECOVERY

The geological fundamentals described above govern the three phases of technology [7] through which the oil industry extracts crude oil. **Primary recovery** involves drilling an extraction well through cap rock and relying on natural pressure and pumps to extract oil. **Secondary recovery** involves injecting water or various gases[8] underground to push oil toward extraction wells. These techniques incur additional costs: transportation, the drilling of injection wells, separation of oil and water at the surface, and reinjection of wastewater into deep disposal wells. **Tertiary recovery** involves the use of chemicals or steam to dissolve crude oil out of rock pores and requires specialized geological and technical assessments, transporting chemicals and/or heating equipment to the drill site, drilling injection wells, injecting the chemicals or steam into the ground, pumping the oil mixed with chemicals and/or water to the surface, separating the oil, water, and chemicals, and disposing contaminated water or chemicals in deep injection wells. Each of these phases is progressively more complex and expensive. These phases are described in more detail below. CO2 EOR is a technique used during tertiary recovery.

Primary recovery

The first stage of extracting crude oil relies on the lithostatic pressure of overlying rocks to push the oil up the well bore as soon as the drill breaches the impermeable cap rock. While this natural pressure lasts, the cost of extracting oil is very low, and the oil need only be captured in tanks or pipelines for transport to refineries. In the early days of the oil industry, shallow oil wells driven by natural pressure could produce hundreds of thousands of barrels per day at nominal cost.

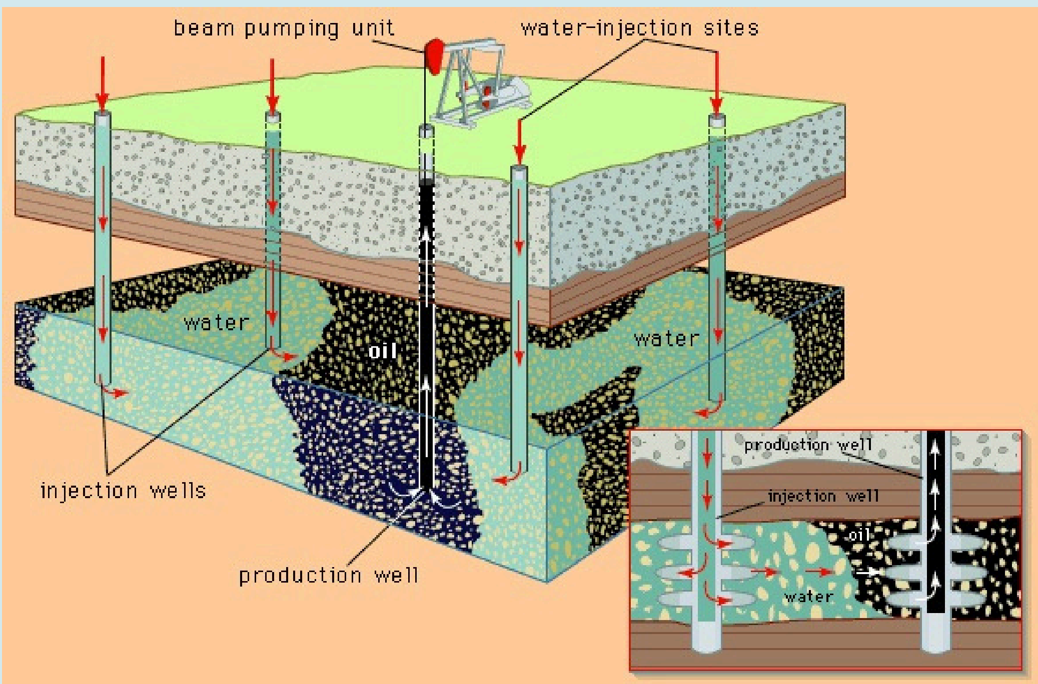
Over time, as oil is removed from the ground, the natural pressure in an oilfield drops to the point that oil stops flowing. When this happens, the oil industry installs pumps to lift oil from the ground. As pumping moves oil to the surface, oil flows through porous rock toward the well up to the point that all the free oil near the well is pumped out. Two kinds of oil are left behind: oil that is too far away to flow to the well of its own accord and oil that is stuck inside rock pores. When a combination of natural pressure and simple pumping are sufficient to bring oil to the surface, the oil industry refers to this stage of oil extraction as primary recovery. Producing crude oil using natural pressure and simple pumping is the lowest cost form of oil extraction. The low cost of production means that the petroleum fuels and other products made from this oil may be provided to global consumers at relatively low cost.

Credit: Library of Congress, https://www.loc.gov/item/2014633920/

Typically, only 5 to 15 percent of the underground oil is extracted during primary recovery. Pumping increases the costs of extraction but remains economic in many oilfields, even at very low flows, depending on the price of oil and the cost of the energy needed to run the pumps.

Secondary recovery

Once the oil flow slows to the point that too little oil is extracted to pay for the cost of pumping plus profit expectations, the oil industry begins a second phase of oil extraction. New wells are drilled around the oilfield and water or various gases are pumped in, increasing pressure and driving distant oil toward the extraction wells. Because oil and water don't mix, pumping water underground also pushes some of the oil out of rock pores toward wells. The process of using water to push oil toward oil wells is called waterflooding and is a hallmark of secondary recovery.

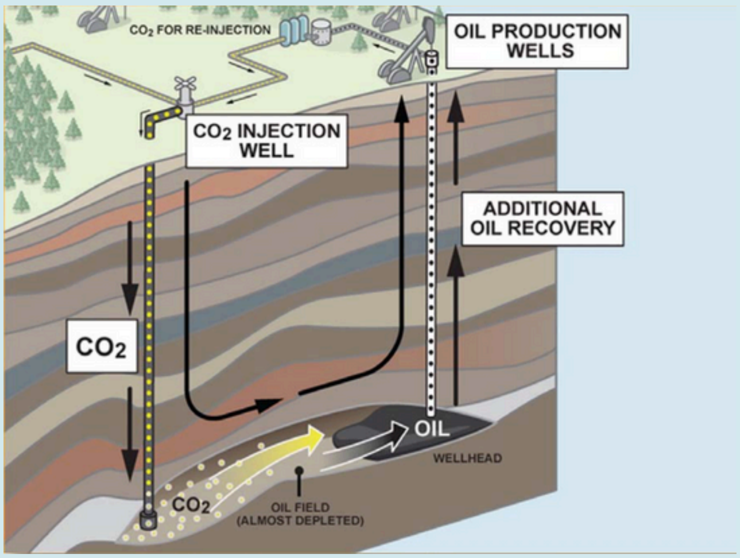


Credit: Britannica, https://www.britannica.com/technology/waterflooding

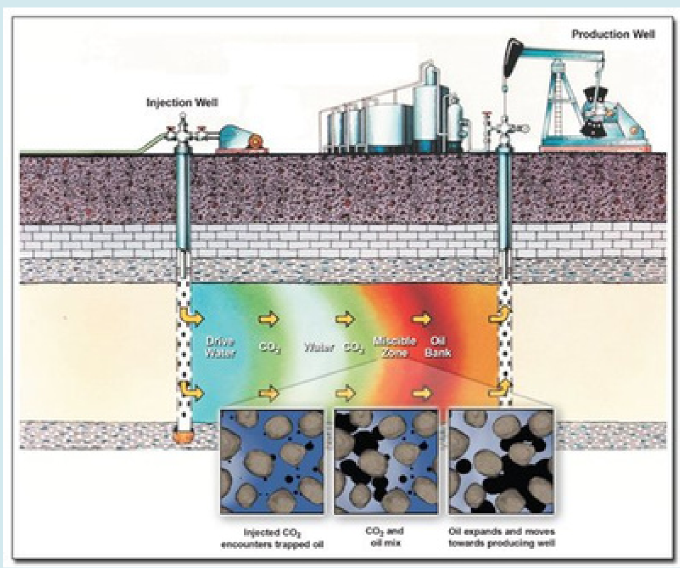
Typically, 30 to 50 percent of the initial oil in the field is extracted during this phase.

Tertiary recovery

Eventually, as distant oil is pushed towards the extraction wells, the water will reach the well bore and rise to the surface along with the oil to the point where too little oil is extracted to pay for the cost of waterflooding operations. The residual oil remains pasted to the interior walls of rock pores and can only be driven out with heat (provided by steam) or washed out with large amounts of detergent-like surfactants, polymers, alkalis, or solvents. Liquefied CO2 is one such solvent. Typically, this washing process is repeated multiple times per year for multiple years until the amount of oil extracted is too little to justify continued operation. Extraction of oil stuck in rock pores using any of these techniques is called tertiary recovery or enhanced oil recovery (EOR).



Credit: U.S. Department of Energy, https://www.energy.gov/fecm/articles/enhanced-oil-recovery



Credit: U.S. Department of Energy, https://www.energy.gov/fecm/enhanced-oil-recovery

Generally, tertiary recovery may yield an additional 30 to 60 percent of the initial oil in an oilfield, but it is the most expensive phase of oil extraction. A key factor in the cost of EOR operations is the price of the chemicals used to wash oil out of rock pores. While some fraction may be recovered and reused, a substantial portion of these chemicals diffuses away from the oilfield and/or combine chemically with the rock and is lost underground, such that supplemental chemicals must be provided throughout the course of tertiary recovery operations.

Hence, tertiary recovery is generally more economic when oil prices are relatively high and, depending on oilfield characteristics, may never be economic. The higher the price of oil, the more affordable the chemicals and equipment needed for tertiary recovery operations. However, this trend is self-limiting. As oil prices rise, demand invariably drops as consumers reduce consumption. Oil prices soon follow. If global consumers were willing and able to pay, say, $10 or more per gallon of gasoline, much more crude oil would be considered extractable. There are economic limits to fuel prices that consumers are able to bear.

The commercial life of an oilfield, then, lasts only as long oil extraction is profitable, and profitability in turn depends on the interplay between the oilfield's geology (the difficulty of extraction), the cost of technology to extract the oil given this geology, and the price that consumers are willing to pay for the oil. When all the oil that can be extracted economically from an oilfield is removed, the oilfield will cease operation. In this way, oil is a finite resource.

THE HISTORICAL ROLE OF CO2 IN ENHANCED OIL RECOVERY

Carbon dioxide naturally exists as a gas but, with enough pressure, it can be compressed into a liquid or even into what's called a supercritical state, in which distinct liquid and gas phases do not exist.[9] These fluid forms of CO2 are good solvents, meaning that, like a detergent, they can wash oil away—including the oil that inhabits microscopic rock pores.

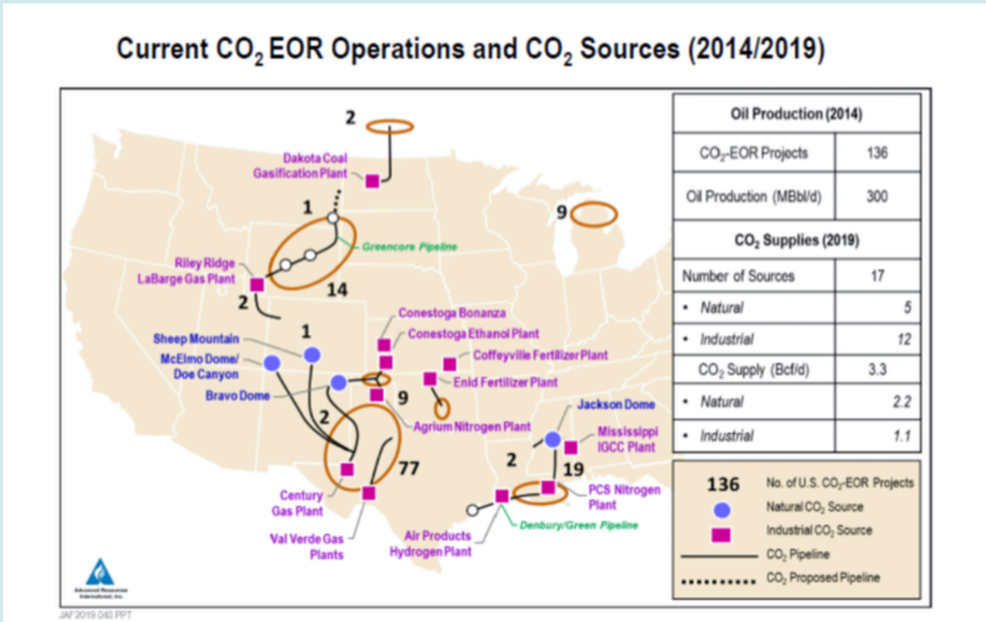
In the 1970s, the oil industry began using CO2 in tertiary recovery operations, sourcing it from naturally occurring underground CO2 deposits located mostly in Colorado and New Mexico.[10] This CO2 was generally compressed into a supercritical state and then transported by pipeline, primarily to Texas oilfields.[11] These natural CO2 deposits continue to be used for EOR operations in the Permian Basin in Texas and New Mexico, but their size is limited and fully committed to existing operations.

The historic cost of sourcing CO2 from natural deposits appears to be non-public information. However, the cost of buying CO2 is reported to account for 25-50 percent of all CO2 EOR project costs, making it perhaps the single largest operational cost for CO2 EOR. Several economic studies assume these costs[12] range from $20 to $45 per metric ton.[13]

Despite the high cost of CO2, it is currently used in CO2 EOR operations in the Permian Basin, Gulf Coast, Mountain West, and Michigan. In 2020, the oil production enabled by CO2 EOR in the Permian Basin reached 185,000 barrels per day (bpd) using CO2 primarily from naturally occurring CO2 deposits.[14] Since these natural deposits are fully committed, to increase production, the Texas EOR industry also began acquiring CO2 from the Val Verde and Century natural gas processing plants that strip CO2 from raw natural gas, although the future of these projects appears uncertain.[15]

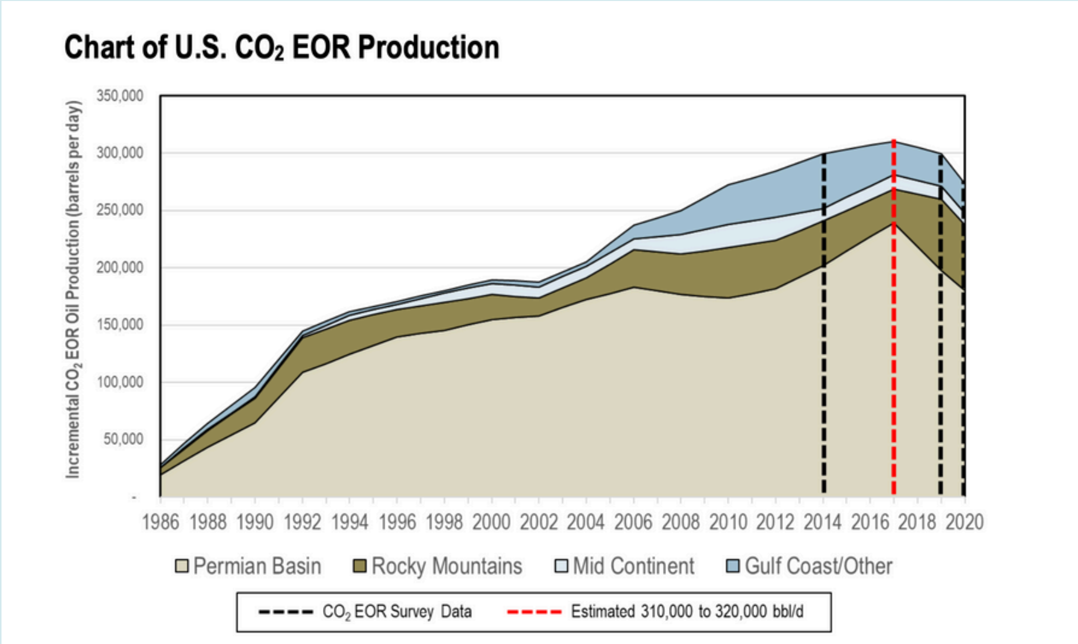
Over the past two decades, Denbury Inc., now owned by Exxon Mobil, expanded its CO2 EOR operations in the U.S. Gulf Coast region. In 2020, Gulf Coast CO2 operators sourced 83 percent of the CO2 used in Gulf Coast operations from Jackson Dome, a naturally occurring CO2 deposit in Mississippi.[16] The remaining 17 percent was obtained from three industrial sources.[17] Gulf Coast CO2 EOR crude oil production for the year totaled 39,000 bpd.[18]

In 2020, Denbury, along with other CO2 EOR companies, operated 13 projects in Wyoming, two in Utah, and one each in Colorado and Montana.[19] These projects produced a combined 37,000 bpd.[20] In southern Kansas, Oklahoma, and northern Texas, a number of of companies operated relatively small CO2 EOR fields that together produced 10,000 bpd. In Michigan, a very small EOR operation produced 1,400 bpd.[21]



Credit: Advance Resources International based on Oil & Gas Journal and other industry data, 2014/2019

Despite these efforts, the CO2 EOR industry has historically produced a nominal proportion of total U.S. oil production. Based on the most recent survey conducted by Advanced Resources International, Inc.,[22] the CO2 EOR industry's daily oil production in 2020 averaged 273,000 bpd, or about 2.4 percent of the total U.S. 2020 average daily crude oil production of 11,318,000 bpd. While CO2 EOR production increased steadily over the four decades that it has been used, this growth has been quite slow, averaging only about 75,000 bpd of new net production per decade, just 7,500 bpd per year.



Credit: Advanced Resources International, Inc., https://adv-res.com/pdf/ARI-2021-EOY-2020-CO2-EOR-Survey-OCT-21-2021.pdf

Most of the investments that created periods of market-based growth in CO2 EOR operations were approved during periods of relatively high retail oil prices,[23] including during the 1980s and early 2010s, leading to more rapid growth in the years following. Lower CO2 EOR extraction growth followed periods of low oil prices during the 1990s through early 2000s and the late 2010s. These trends indicate that growth in CO2 EOR production is tied to high oil prices. Notably, the 2020 bankruptcy of Denbury Resources Inc.[24] was attributed to low oil prices caused by the COVID-19 pandemic and the Russia/OPEC price war.[25]

In sum, high capital and operations costs for CO2 EOR have, historically restricted its growth to periods of high oil prices and to oilfields with specific geological characteristics.[26] Its slow historical growth suggests that CO2 EOR has been a marginally economic technology, profitable in few locations during periods of relatively high oil prices.

A POSSIBLE FUTURE FOR CO2 EOR: ANTHROPOGENIC CO2

The limited supply of naturally occurring CO2 has encouraged the oil industry to exploit waste CO2 created by power plants and various industrial facilities. Reliance on anthropogenic CO2 has been, up to now, marginally economic because of the prohibitive costs of capturing and transporting it to oilfields. The following are estimates of the cost ranges for capturing CO2 in different industries.[27]

Industry	Great Plains Institute Est. Ave. Cost	Great Plains Institute Range of Cost Est.	International Energy Agency Est. Costs $/ton
Coal Power Plant	$56	$46-$60	$50-$100
Gas Power Plant	$57	$53-$63	$50-$100
Ethanol	$17	$12-$30	$25-$35
Cement	$56	$40 - $75	$60-$120
Refineries	$56	$43 - $68	n/a
Steel	$59	$55 - $64	$40-$100
Hydrogen	$44	$36 - $57	$50-$80
Gas Processing	$14	$11 - $16	$15-$25
Petrochemicals	$59	$57 - $60	n/a
Ammonia	$17	$15 - $21	$25-$35
Chemicals	$30	$19 - $40	n/a

Most of these costs are well above the CO_2 historical cost estimates of \$20 to \$45 per metric ton, suggesting that they are generally too high to allow economic application of CO_2 EOR technology. While the cost of capture in some industries is relatively low, the above figures do not include the cost of permitting and building pipelines to transport CO_2 to EOR fields. The high cost of capturing and transporting CO_2 to EOR operations may explain why the oil industry historically has not developed CO_2 capture facilities except at a few carefully chosen ethanol, natural gas, processing, and ammonia plants sited relatively close to EOR operations. That said, even nearby, low-cost carbon capture projects, such as the Century Natural Gas Processing Plant in the Texas Permian Basin, have proven uneconomic.[28] CO_2 capture operations linked to high-cost capture facilities, such as those at coal power plants, have required substantial subsidies to be constructed and operated. Even with substantial subsidies, carbon capture projects at higher-cost capture facilities have also failed for economic reasons, including the project at the Petra Nova coal power plant in Texas.[29] (More on Petra Nova below.)

Using anthropogenic CO_2 presents a second challenge that arises from a mismatch between supply and demand. Whereas CO_2 is continuously captured from industrial facilities and power plants that typically operate nearly continuously, CO_2 EOR operations require CO_2 only episodically at specific points during the extraction process. Furthermore, industrial CO_2 emitters generally create CO_2 in amounts too large to store, such that captured CO_2 must be immediately pumped into pipelines whether it is needed for oil recovery or not. Any CO_2 not transported to EOR operations must then either be injected into underground sequestration wells or vented to the atmosphere. Since venting CO_2 essentially wastes all of the financial resources needed to capture it, venting is uneconomic.

Typically, CO_2 EOR operators initially inject a large amount of CO_2 into an oil reservoir and then wait weeks for it to soak into the rock, allowing it time to dissolve oil out of the pores. Next, a mixture of CO_2 and oil is extracted, the oil is separated out, and the CO_2 is injected back into the oil-bearing sediments to repeat the soak cycle. Each time CO_2 is injected underground, some of it diffuses through the rock and/or chemically combines with minerals or water and so remains underground. To repeat the cycle, CO_2 EOR operators need ever-smaller additional amounts to make up for the CO_2 lost underground.

In other words, individual CO2 EOR wells cannot absorb the continuous flow of CO2 that industrial operations provide. However, as CO2 EOR operations proliferate, CO2 demand by the oil industry may level out over time. Nonetheless, exactly matching CO2 generated and captured from industrial emitters with CO2 EOR demand would be impossible. Thus, CO2 EOR operations *must* be combined with sequestration operations that can accept CO2 unneeded for EOR, otherwise the CO2 captured at substantial cost would need to be vented to the atmosphere. If an EOR operator compensates a capture facility for vented CO2, then the operator's costs increase significantly and adversely impact the profitability of the CO2 EOR operation. On the other hand, if a CO2 capture facility receives no compensation for substantial amounts of vented CO2, it would likely be uneconomic. Thus, CO2 sequestration is a necessary component of widespread application of CO2 EOR technology.

Many oilfields appear to be unsuitable for CO2 EOR. For example, CO2 EOR tests in North Dakota failed to substantially increase oil production from fracked Bakken Formation wells due to the tendency of the CO2 to dissipate away from project wells.[30] While the application of CO2 EOR may seem straightforward, in practice its application requires substantial geological information, a sufficient supply of CO2 timed to specific stages of the operation, specialized knowledge and equipment, and considerable financial resources.

Despite its technical potential, the CO2 EOR sector has not been a growth industry. The primary reasons for limited use of this technology have been:

- *Limited natural CO2 supplies*. Natural CO2 deposits in the volumes needed have been fully committed for years, and this limited supply has capped growth of CO2 EOR.

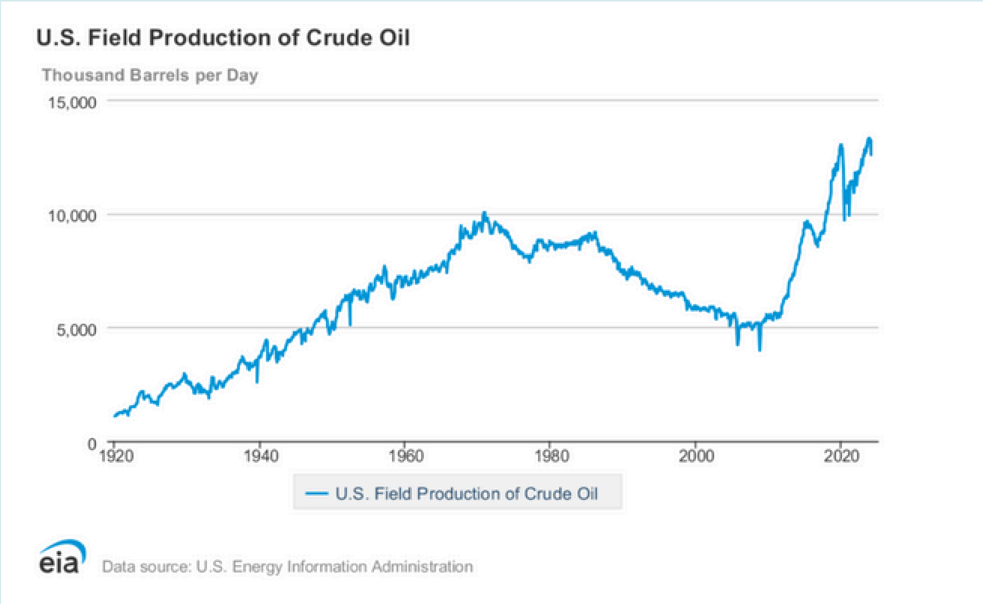
- *High cost of industrial CO2 supplies relative to oil prices*. While it is possible to capture CO2 from industrial facilities, the cost of capture has been economically prohibitive and, for some classes of CO2-emitting facilities, not technologically mature.

- *The practical and economic hurdles of creating a new high-volume carbon-capture industry suitable for oil extraction.* The widespread application of CO2 EOR would require massive amounts of CO2 from many carbon capture facilities. Even if these facilities could be economically constructed, the flows of anthropogenic CO2 from these facilities would be mismatched in terms of supply and demand profiles and geographic location.

Taken together, these forces have, historically, made CO2 EOR marginally economic and restricted growth of the CO2 EOR industry. [31]

THE SUBSIDIZED ROLE OF CO2 EOR IN FUTURE U.S. OIL EXTRACTION

For geophysical reasons, future U.S. crude oil extraction will depend on increased tertiary recovery, because new opportunities for primary and secondary recovery are disappearing. U.S. crude oil production using primary and secondary recovery in conventional oilfields peaked in November 1970 and declined until 2009.[32] This downward trend was reversed by the fracking boom.

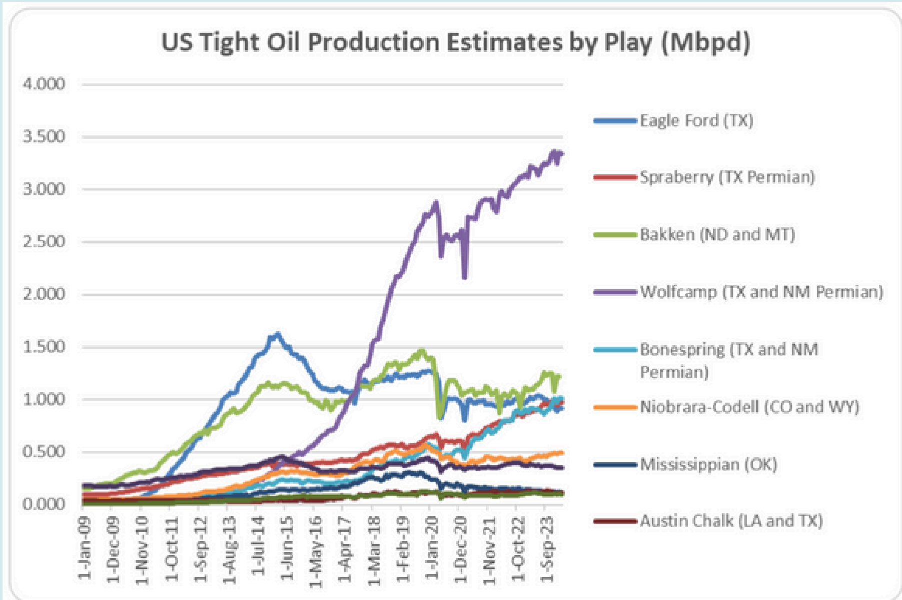


Credit: U.S. Energy Information Administration

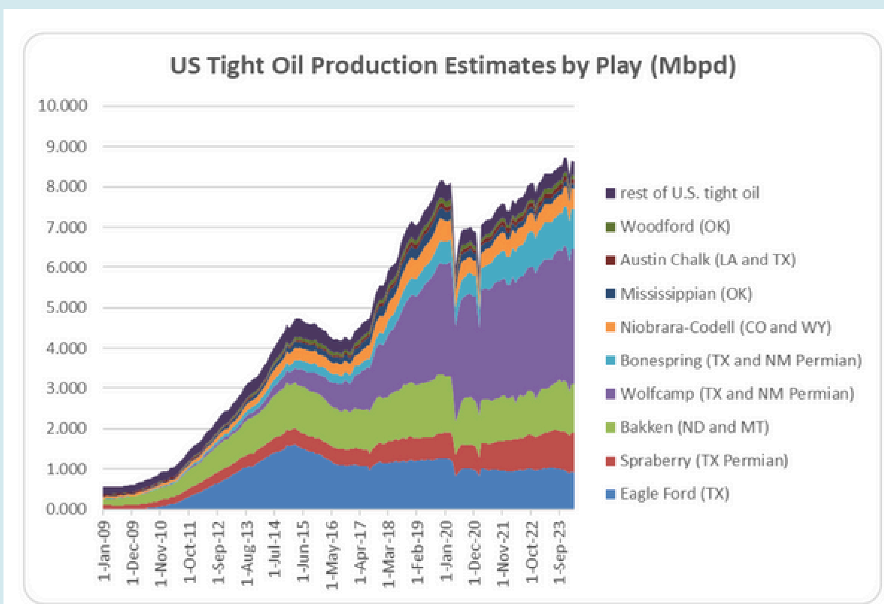
The dramatic growth in U.S. oil production over the past 15 years has been entirely due to the use of expensive hydrofracturing (fracking) technology to extract crude oil from shale, a type of dense and often uniform unfractured sedimentary rock with extremely small pores. Fracking is used to extract crude oil from oil deposits that have not previously been exploited. Fracking is applied where oil is trapped in relatively uniform layers of shale with extremely small pores and few natural fractures, such that oil cannot flow easily through the shale towards an extraction well. The oil in such fields is referred to as "tight oil" because it is bound tightly within the shale.

Fracking uses high-pressure water to fracture the shale, creating pathways for oil to flow to the well. First, a well is drilled vertically to the depth of the oil-bearing sediments and then the drill is directed to bore horizontally through the oil-bearing shale, requiring total well lengths from 10,000 to more than 20,000 feet.[33] The horizontal bores alone can extend as far as two miles underground. Next, many small explosive charges followed by high volumes of pressurized fluid (water and a mixture of chemicals) are injected into the shale layer to expand and extend its many naturally occurring cracks, bedding planes, and faults. Sand is forced into these cracks to prop them open so that oil can flow toward the well. Each fracked well produces relatively small amounts of oil,[34] operates for only a few years,[35] and may need to be re-fracked multiple times to keep the oil flowing. The high cost of fracking equipment and of drilling very long wells, together with the limited amounts of oil produced per well, means that, on average, fracking is economic only when oil prices are relatively high and credit is cheap. Although the cost of fracked wells far exceeds the cost of conventional shallow oil wells, the oil industry turned to fracking because it had already discovered and exploited essentially all the conventional oilfields in the United States.

Federal tight oil production estimates[36] show that U.S. fracked oil fields are mature or in decline, except in the Permian Basin in Texas and New Mexico.



Credit: graph by author with EIA data

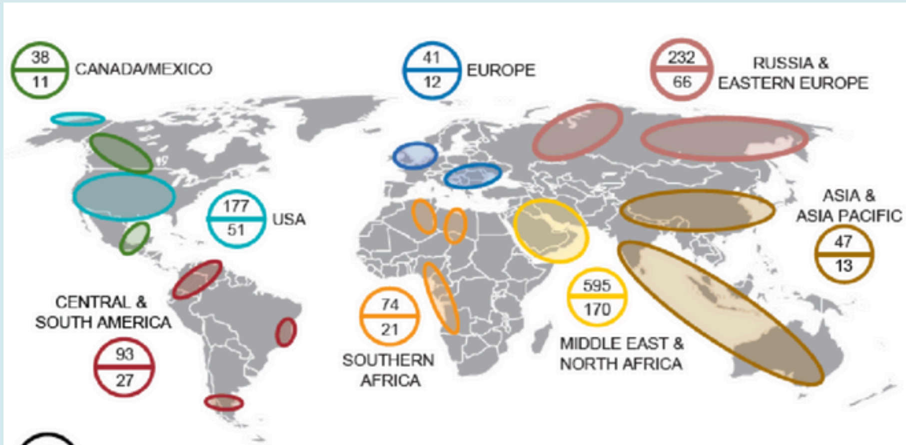


Credit: graph by author with EIA data

Forecasts predict that the Permian Basin will begin to decline within the next five years.[37] While the rate of future extraction of tight oil is unknowable, all oilfields, sooner or later, irreversibly decline. The oil industry, therefore, continuously evaluates the potential lifespan of existing oil plays and explores opportunities for future plays.

As U.S. fracked oil production declines, the oil industry will seek to pivot to a different technology to exploit oilfields in a new way. Apart from unextracted tight oil, the only quantity of oil still remaining in the ground onshore in the contiguous 48 states that could significantly extend U.S. oil production over the long-term is oil adhered within rock pores of old oilfields and within the ROZs. The only way to extract this remaining oil is through tertiary recovery, via chemical or heat-based methods. For chemical recovery, the only substance potentially available in the enormous quantities needed to substantially impact overall U.S. oil production is CO2. Hence, the U.S. oil industry is likely to attempt to pivot from fracking to CO2 EOR in states where fracked oil production is falling—and eventually throughout the nation, including in long dormant oilfields. If it is unable to extract this remaining—if expensive—pore-bound oil, the U.S. oil industry will face ongoing decline, and U.S. oil production will begin its terminal descent.

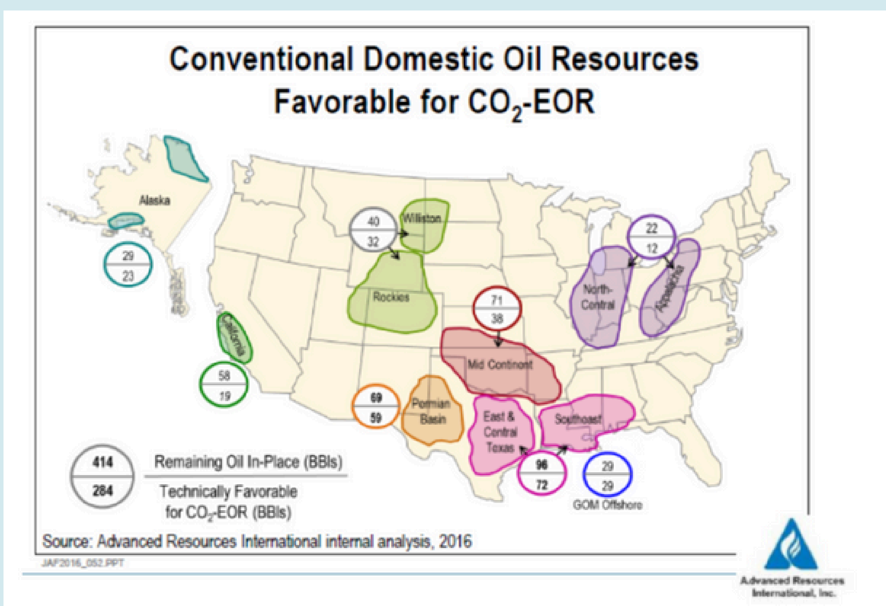
Hypothetically, the amount of crude oil that could be extracted using CO2 EOR is large. The DOE estimates that CO2 EOR could be used to extract between 84 and 181 billion barrels of crude oil in the United States, with an estimated 177 billion barrels technically recoverable using existing technology, and nearly 1.3 trillion barrels oil recoverable worldwide.[38]



Source: IEA Greenhouse Gas R&D Programme, "CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery," December 2009.

Figure 8-5. Worldwide CO_2 EOR Potential in Conventional Fields

In the Permian Basin alone, 69 billion barrels of oil are estimated to be technically recoverable from the ROZ.[39]



Given that the United States produced an average of 12.933 million barrels of crude oil per day in 2023,[40] 177 billion barrels of technically recoverable CO2 EOR oil would be the equivalent of 38 years of current U.S. crude oil production. While this potential may sound impressive, oil that is technically recoverable using CO2 EOR may very well not be economically recoverable.

In addition to the possibility that CO2 EOR might extend the life of the U.S. oil industry, the industry also sees political benefit in pursuing CO2 EOR because it claims that injecting anthropogenic CO2 underground to recover crude oil will reduce U.S. greenhouse gas emissions (this claim is examined below). CO2 EOR operators regularly describe oil extracted using CO2 EOR as low carbon oil.[41] Thus, CO2 EOR represents both a last potential major oil extraction opportunity as well as a public-relations talking point in the face of accelerating public concern about global warming.

The oil industry's solution to the high cost of CO2 EOR has been to seek federal subsidies for the capture and use of anthropogenic CO2 in EOR operations, in the name of mitigating climate change. The primary subsidy, which first went into effect in 2008, is provided by Section 45Q of the U.S. Tax Code.[42] This law currently grants those who capture CO2 a tax credit of $85 for each ton captured and sequestered (stored) underground. Additionally, it provides a tax credit of $60 per ton of CO2 captured and then used in EOR operations. Since CO2 sequestration is a necessary component of CO2 EOR operations using anthropogenic CO2, both subsidy levels support oil extraction. Although the EOR subsidy is $25 less than the sequestration subsidy, this disparity does not mean that CO2 will preferentially be sequestered. In order to beat the $85 per ton sequestration tax credit, an EOR operator could simply pay a CO2 capture facility $25 or more per ton in cash for CO2, which when combined with the $60 per ton EOR tax credit would match or exceed the sequestration tax credit.

Alternatively, an oil company could own a capture facility and use its CO2 for an EOR operation, knowing that the combined financial benefit of the $60 per ton EOR tax credit in combination with the profit from selling the oil would exceed the benefit provided by the $85 per ton sequestration tax credit.

Importantly, the 45Q tax credit is provided by the federal government without regard to the cost of capturing CO2 at particular facilities. This means that an ethanol plant with a capture cost of $30 per ton would receive the same subsidy as a coal power plant with a capture cost of $60 per ton, thereby providing a windfall to the ethanol plant. In any case, the existing 45Q tax credit could pay the entire cost of capturing CO2 at some industrial facilities, and accordingly has the potential to provide essentially free CO2 to the oil industry and thereby remove some of the economic barriers to widespread use of CO2 EOR technology.

Given that the long-term future of the oil industry may depend on expanding CO2 EOR operations, it is reasonable to expect that the oil industry will seek future 45Q tax credit increases. Notably, Exxon Mobil is on the record for seeking to increase the 45Q tax credit to $100 per ton.[43] The higher the tax credit, the more CO2 would be economic to capture and the larger the CO2 EOR industry could grow, but at the cost of either higher federal taxes or larger federal deficits, or both. Given that the 45Q program has no limitations on the dollar amount of tax credits granted, Congress has constructed a general subsidy for CO2 EOR operations that increases oil industry access to a new, affordable, and potentially very large, supply of CO2.

THE FLAWS OF CO2 EOR AS A CLIMATE MITIGATION STRATEGY

All the evidence to date indicates that no regulatory framework or system of economic incentivization can transform CO2 EOR into a meaningful tool of climate mitigation. To the contrary, and for three fundamental reasons, CO2 EOR contributes to the climate problem rather than serving as a climate solution.

CO2 EOR suffers from incomplete emissions accounting.

The simple bottom line, ignored by any model that purports to show that carbon capture is a legitimate tool to reach net zero carbon emissions, is that burning the oil recovered using CO2 EOR generally emits two or more times as much CO2 as is kept underground during CO2 EOR operations. Even if every CO2 EOR operation were entirely leakproof, with all the captured carbon eternally sequestered in the spaces into which they are injected, those molecules of CO2 serve to displace molecules of crude oil, which, by nature, do rise to the surface. The downstream carbon emissions from burning the oil so extracted, which would otherwise remain in the ground, are not accounted for in industry models. As noted by the two cofounders of the first privately funded company to make use of carbon capture in the United States, every dollar invested in renewable energy eliminates far more carbon emissions than CO2 EOR operations and does so less expensively.[44] In sum, CO2 EOR harms the climate by incentivizing rather than impeding the continued extraction of fossil fuels. Even if CO2 EOR could be made to work perfectly, renewable energy alternatives are cheaper and more effective at preventing greenhouse gas emissions. Although the oil and gas industry continues to hail CO2 EOR as an emissions-reductions strategy, this technology is more likely to increase total emissions rather than reduce them. As noted by the Institute for Energy Economics and Financial Analysis in a July 2024 report, "CCS was originally devised to support oil and gas extraction, and has a long history of under-achievement in combatting emissions, which is unlikely to change in the foreseeable future."[45]

Evidence that CO2 EOR can offer permanent CO2 sequestration is lacking

CO2 EOR operations do not, in fact, work perfectly. The potential for leaks is real. As mentioned above, as a supercritical fluid, CO2 has the dissolving properties of a liquid but the ability to move through porous solids like a gas. As a buoyant and low-viscosity fluid, it can migrate quickly through microscopic fractures in the rock. Depending on small shifts in temperature and pressure, supercritical CO2 can behave more like a liquid or more like a gas, and its behavior can change dramatically, as, for example, when smooth, laminar flow suddenly becomes turbulent with a slight change of physical condition.

As a buoyant and low-viscosity fluid, supercritical CO_2 can help drive oil out of the pores within geological formations where it would otherwise not flow. But this same property allows it to easily migrate through microscopic fractures in the rock where it is buried. As noted by geologist and science historian Naomi Oreskes, “We all know the saying that what goes up must come down, but the opposite is also largely true”; that is, what goes up tends to keep going up. Pressurized supercritical CO_2 is buoyant and tends to rise. Therefore, the ideal site for its permanent containment would be a permeable rock layer—with abundant pore spaces for the CO_2 to fill—overlaid by thick cap rock without any pores or fissures in it. Additionally, there should be no unmapped or abandoned wells in the area to serve as a fast highway to the surface. And the formation should not be vulnerable to seismic activity.

Oreskes emphasizes that there might well be places on earth that meet these qualifications and could serve as a maximum-security facility for the permanent sequestration of CO_2, but depleted oil wells likely are not these places. A search for appropriate geological storage for CO_2 also would require years-long site characterization research.[46]

Old wells, boreholes, and naturally occurring faults are the most common pathways for free-form CO_2 to escape to the surface.[47] However, even absent significant seismic activity, carbon sequestration and CO_2 EOR can create pressure build-up great enough to break through cap rock, releasing the stored CO_2. CO_2 is not only buoyant but also converts to carbonic acid in the presence of moisture. Both of these qualities enable its ability to corrode well casings, dissolve rock formations, and rise to the surface. There is no empirical data to suggest that depleted oil fields can serve as an eternal, escape-proof storage unit for pressurized, liquefied CO_2.

Unable to scale rapidly, CO_2 EOR is not a feasible tool for meaningful decarbonization within agreed-upon timelines.

As described above, CO_2 EOR has been in use for a half century and yet has not succeeded in capturing carbon at a scale anywhere close to the levels required to hit agreed-upon climate targets that would limit warming to 1.5 degrees by 2050.[48] The IEA, which itself views some uses of carbon capture technology as “critical” to this goal, has warned that incorporating carbon capture into ongoing oil and gas extraction operations is at odds with a net zero future and that carbon capture deployment of all kinds, including CO2 EOR, is well below what is required in the net zero scenario.[49]

A 2024 analysis led by a geoscience team at Imperial College London notes that all the pathways for limiting warming to 1.5 degree assume massive amounts of geological carbon storage. However, these projections are wildly unrealistic.[50] Currently, around 9 million tons of CO2 are stored underground, included in depleted oil and gas reservoirs. To stay below 1.5 degrees, the study forecasts the rate of storage would need to increase by 1000-fold in less than three decades, a rapid scaling that is "fanciful."[51]

Indeed, many CO2 EOR pilot projects are failing rather than expanding. Outfitted with carbon capture machinery and subsidized with $440 million in government grants, the Petra Nova coal plant in Texas was the sole U.S. commercial-scale power plant to capture CO2 from its emissions stack for the purposes of EOR. Never able to hit its targets for CO2 capture, and suffering repeated outages, Petra Nova shut down after three years of operation in 2020, amid plunging oil prices.[52] Mothballed for three years, it was restarted in September 2023 with the advent of higher oil prices and a 2022 increase in the 45Q tax credit. As costs of renewable energy fall further, capturing CO2 from coal- or gas-fired power plants to serve as a feedstock for CO2 EOR operations for oil extraction becomes ever more uneconomical, especially when compared to the lower cost of renewable energy and demand management programs.

Further, most of the CO2 EOR projects currently operating use CO2 extracted from natural underground deposits, not CO2 captured from industrial operations that would otherwise end up in the atmosphere. This practice represents a subsidized transfer of already sequestered CO2 from one site to another. As the IEA notes, "such practice is neither beneficial to the climate nor for the development of CCS."

Privately, the oil and gas industry itself admits that carbon capture technologies are unscalable and of limited use in reaching climate targets. In April 2024, a joint bicameral staff report from the House Committee on Oversight and Accountability Democrats and Senate Committee on the Budget, "Denial, Disinformation, and Doublespeak," revealed the fossil fuel industry's campaign to misinform and deceive the public about its commitments to mitigate the climate crisis. Notably, these efforts include statements made about carbon capture. Internal documents show that the industry publicly celebrated carbon capture technologies as a helpful tool for reducing emissions even while privately acknowledging that it is expensive, unscalable without massive investment by the federal government, and of very limited use. According to the report, "the fossil fuel industry recognizes that the rollout of [carbon capture technologies] at scale is moving too slow to reach net zero emissions by 2050 and that the reason is their own extremely modest investment, but their public claims conceal this reality....The industry's true goal is to prolong, perhaps indefinitely, the abated use of fossil fuels."[53]

In short, CO2 EOR is not a good-faith climate mitigation strategy and instead is an expensive, taxpayer-funded scheme—with a thin veneer of greenwash—to extract the last drop of oil from the ground. It may be the oil industry's last, best hope for survival.

POTENTIAL HEALTH HARMS OF CO2 EOR

CO2 EOR operations can pose health and safety risks at every stage of the process, from the point of capture and transportation via pipeline to the wellhead and the disposal of oilfield waste.

Many of these risks can arise from the CO2 itself. As a gas, CO2 is colorless and odorless. It is heavier than air and tends to hug the ground, displacing oxygen. Thus, sufficiently elevated concentrations of CO2 can cause asphyxiation due to lack of oxygen. When inhaled, the gas also has toxic properties independent of oxygen deprivation.[54]

Carbon dioxide is a byproduct of normal cellular metabolism and is transported through the blood to the lungs and kidneys, from which it is excreted. Blood levels of CO2 play a major role in regulating tissue pH (acid-base balance). Carbon dioxide combines with water in blood to form carbonic acid, excessive levels of which can lead to acidosis, with initial, acute impacts on respiratory, cardiovascular, and brain function.

Chemoreceptors in major arteries and at the base of the brain detect increases in blood CO2 levels and trigger increased respiratory rate and volume, which along with other buffering mechanisms, initially blunt the impending acidosis (when blood pH begins to fall). As these compensatory mechanisms become overwhelmed, symptoms progress and become more dangerous.

According to the National Institute for Occupational Safety and Health (NIOSH), a concentration of 4 percent CO2 (40,000 ppm)[55] in ambient air is "immediately dangerous to life and health."[56] At this concentration, in addition to rapid breathing, some people develop visual and hearing impairments that, along with confusion, can interfere with a person's ability to respond and get to safety. As CO2 concentrations rise to 5-10 percent in ambient air, rapid breathing becomes increasingly disturbing, heart rate and blood pressure increase, vision dims, and confusion worsens. Older people or those with various underlying health conditions can have reduced tolerance to CO2 concentrations in this range.[57] Physiological responses at or above 8 percent CO2 concentrations are due to a combination of oxygen deprivation and toxicity from the developing acidosis. A CO2 concentration of 10 percent can cause unconsciousness within a few minutes, and more than 10 percent can cause convulsions, coma and death within ten minutes.[58]

As detailed below, worker or community member exposures to CO2 may occur at any point throughout the carbon capture, transportation, and CO2 EOR process due to equipment or pipeline leaks or ruptures, well blowout during injection, intentional or unintentional releases from the production well, or during gas separation.

In addition to threats of CO2 exposure, CO2 EOR operations generate toxic waste and raise the risk of other chemical exposures, induced earthquakes, and groundwater contamination.

Health hazards and risks from carbon capture and processing

Potential health effects at the carbon capture and processing stage of CO_2 EOR operations are dependent to some degree on where the CO_2 is sourced and how it is collected, as the composition of the gas stream varies.

If CO_2 is collected from naturally occurring geologic sources, it may contain chemical contaminants. For example, CO_2 collected from the Jackson Dome in Mississippi contains an average of 5 percent (50,000 ppm) hydrogen sulfide (H_2S).[59] If the H_2S is not removed before transport, a pipeline rupture carrying gas from that source would release hazardous amounts of both CO_2 and H_2S. Hydrogen sulfide is far more toxic than CO_2.[60] Breathing a concentration of H_2S at just 500 ppm (0.05 percent) is sufficient to cause severe lung irritation, immediate loss of consciousness (sometimes called "knockdown") and death if exposure continues for several hours.[61] At 1,000 ppm, death is almost immediate.

If CO_2 is captured from an ethanol plant, it must be dehydrated to reduce water content. "Wet" CO_2 forms carbonic acid, which is highly corrosive in carbon steel pipes, increasing the risk of leaks and ruptures.

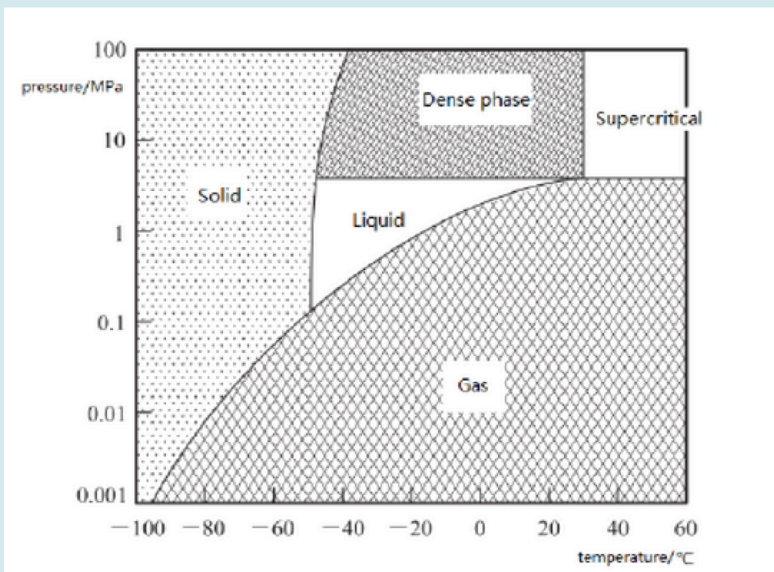
If CO_2 is captured from a power plant, it must be separated from other flue gases, usually by means of solvents, which carry health risks of their own. Ethanolamines (e.g. monoethanolamine [MEA]) are commonly used for carbon capture, although other methods are available.[62] MEA is an irritant to eyes and skin and exposure to significantly elevated inhaled levels for a sufficient duration can also lead to central nervous system effects, nasal irritation, or pulmonary edema.[63] The Occupational Safety and Health Administration (OSHA) average eight-hour permissible workplace exposure limit for MEA is 3 ppm.[64]

The manufacture of MEA raises health risks for workers and communities. MEA is made from ammonia and ethylene oxide (EtO), a highly toxic carcinogen that is used as a precursor in the manufacture of a number of chemicals and as a sterilant. Exposures in communities where EtO is used or made are often above safe levels.[65]

The amine solvents that are used to capture CO_2 from power plants degrade over time and need to be replaced and disposed of as hazardous waste. This waste contains a variety of hazardous compounds, including ammonia, carcinogens (e.g. nitrosamines), and sensitizers (e.g. aldehydes). Commonly the amine waste is incinerated or landfilled although other treatment technologies are being explored.[66] Incineration of amine waste increases hazardous air pollution. In these ways, the dangers posed by CO2 EOR operations are distributed to communities near hazardous waste landfills and incinerators.

Health hazards and risks from CO2 transport by pipeline

Carbon dioxide used for EOR is usually transported to oilfields by pipeline, sometimes over hundreds of miles and even longer pipelines are planned. To accomplish this, energy-intensive compressors first pressurize large volumes of CO2 into a supercritical or dense phase, and then these dense forms of CO2 are moved through pipelines via pumps.[67] CO2 can also be piped less economically or efficiently as a gas using compressors instead of pumps.[68]



Credit: Haixia Wang, et al (see footnote for complete citation), Creative Commons Attribution 3.0 license.

Supercritical CO2 is achieved with temperatures above 31°C (88°F) and pressures above 1070 psi, whereas dense phase CO2 is achieved with temperatures below 31°C (88°F) and pressures above 1070 psi. In its supercritical and dense phases, CO2 has a density similar to a liquid and viscosity of a gas, such that it flows through pipelines efficiently and can easily penetrate porous rock similar to a gas.[69]

Existing CO_2 pipelines are constructed of carbon steel with diameters ranging from several inches up to 30 inches.[70] Given the CCS expansion plans, even larger pipelines are contemplated. [71]

Carbon steel pipelines carrying CO_2 are highly vulnerable to corrosion from carbonic acid that forms when CO_2 reacts with water impurities not removed before compression and transport. Similarly, H_2S impurities are also corrosive to carbon steel.

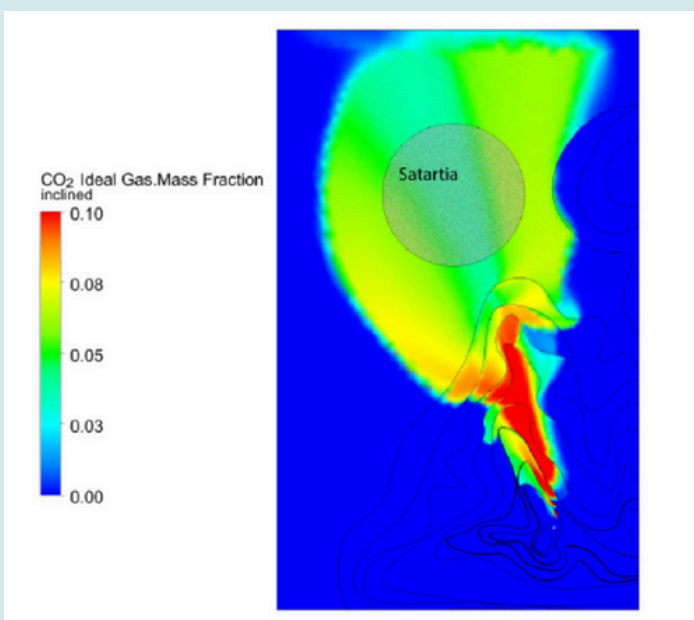
Equipment or weld failures, corrosion, land shifts around pipelines or improper operation are the most common causes of pipeline leaks or ruptures.[72] Smaller leaks, for example, from defective valves, can release varying amounts of CO_2 that can go undetected over time. Pipeline ruptures, however, are much different and can release large volumes of CO_2 quickly. Ruptures can occur across the full girth of a circumferential weld or run longitudinally as the pipeline "unzips" over long distances (also called a ductile fracture) due to the high pressure and extremely cold temperature of CO_2 as it explosively undergoes a phase change from supercritical to gas and small particles of "dry ice," when pressure is suddenly released at the site of a leak.[73] Pressurized pipeline ruptures can shoot metal shrapnel into the air and create large craters in the ground.

The volume of CO_2 released from a pipeline leak or rupture depends on the temperature and pressure within the pipe, size of the failure, distance between shutoff valves, and response time of the operator to isolate the damaged pipeline segment by closing valves. The dispersion of a colorless, odorless CO_2 cloud above ground also depends on wind speed and direction and local topography since CO_2 is heavier than air and tends to flow in low-lying areas and around more elevated ground.

A rupture in a Denbury-owned pipeline near Satartia, Mississippi carrying CO_2 for EOR illustrates the hazards and risks.[74] The February 2020 event was triggered when a 24-inch diameter CO_2 pipeline pressurized to 1336 psi sustained a full-girth rupture after a weld failed following subsidence of land following a period of heavy rain. The distance between shutoff valves was 9.5 miles and the rupture occurred 6.6 miles from the nearest upstream valve. The upstream valve was not closed until more than three hours after the rupture. Subsequently, the operator reported a release of 31,000 barrels of CO_2 into the air.

More than two dozen people were overcome within minutes, some collapsing in their homes or in their cars. Nearby cars shut off or failed to start because of lack of oxygen needed to operate internal combustion engines. People near the cloud reported a “rotten egg” smell, suggesting that there was at least a small amount of H2S in the otherwise odorless CO2 suddenly released. In addition to loss of consciousness, other victims and first responders reported people with extreme difficulty breathing, seizures, confusion, and foaming at the mouth. About 200 residents surrounding the rupture location were evacuated, and 45 people were taken to the hospital. Some victims continue to report ongoing respiratory problems and confusion not present before the incident.

Hours after the rupture and the pipeline was shut down, real-time CO2 readings in homes in Satartia, about a mile from the site of release, were as high as 2.8 percent according to monitoring by CTEH, a Denbury-hired toxicologic response firm. Subsequent diffusion modelling of the plume, using a computational fluid dynamics approach that considered the volume of CO2 released, weather conditions, and local topography, concluded that residents living in portions of the town of Satartia were likely to have been exposed during the event to time-averaged CO2 levels of 5 percent and transient concentrations of up to 10 percent.[75] As shown in the figure below, this modeling also estimated time-averaged CO2 concentrations of 10 percent as far as approximately one-half mile from the rupture site, again with transient concentrations being potentially much higher.[76]



Credit: J. Abraham, et al (see footnote for complete citation), Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Recalling that NIOSH considers a concentration of 4 percent CO_2 in ambient air to be “immediately dangerous to life and health” and previously described impacts at 5-10 percent, these estimates of air levels are consistent with symptoms reported by victims.

A number of other accidental releases of CO_2 from ruptured pipelines or well blowouts with varying impacts have been reported.[77] In April 2024, a 24-inch CO_2 pipe at a pumping station near Sulphur, Louisiana ruptured, releasing about 2500 barrels of CO_2 into the air before it was controlled several hours later.[78] No alarm or rapid response plans for nearby residents had ever been established.

Health hazards and risks from CO2 injection

In preparation for injection into oilfields, various chemicals may be added to the CO_2 depending on specifics of the well, its geology, and the makeup of the hydrocarbons targeted for recovery.[79] These can include surfactants, polymers, and alkalis that reduce the adsorption of the surfactants, among others. Sometimes nanoparticles (e.g. silicon or aluminum oxides) are added to CO_2 to form more stable foams that increase its viscosity without compromising its efficacy in mobilizing hydrocarbons.[80] These stiffened foams enable more of the oil and CO_2 to migrate more effectively from injector to producer well without bypassing portions of the residual oil. Some of these chemicals will return to the surface along with oil, gas, and water at the production well, where there can be opportunities for human and ecosystem exposures and toxicity, depending on how the water is handled and treated.

Over-pressurization of CO_2 during CO_2 EOR can induce seismicity and drive displacement of underground brines, potentially toward drinking water aquifers or abandoned oil wells resulting in releases to the surface environment.[81]

Health hazards and risks at the production well

After the CO_2 is injected and crude oil begins flowing from the production well, it must be separated from the crude oil, volatile organic compounds (VOCs), and brine that are liberated from the pore spaces along with the oil. During the separation processes, VOCs are released in flashing operations, when sharp pressure drops result in a phase change from liquid to a gas, or when loading of streams into separation and storage vessels. VOC emissions can be recovered and used, flared, or released to the atmosphere, depending on the presence and use of emission-control equipment.[82] Flaring is the practice of burning off unwanted gas. VOCs contribute to ozone formation and are likely to include benzene, a carcinogen.

Venting of excess natural gas from compression, system upsets, or pressure release during emergencies is common in oil and gas production and processing.[83] In addition to methane emissions from venting, flaring emissions include CO_2, fine particulates, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), contributing to ozone formation. Venting and flaring emissions are difficult to quantify because they are intermittent and poorly monitored and reported. A recent nationwide study using refined satellite monitoring data concluded that venting and flaring emissions are markedly underestimated and increase the regional risk of premature mortality, heart attacks, asthma exacerbations and asthma hospitalizations.[84]

Health hazards and risks from CO2 EOR produced water

"Produced water," the briny fluid that flows out of the well during oil production, can pose additional health hazards. Produced water contains naturally occurring constituents from the oil reservoir such as salts, minerals, metals, ammonia, hydrogen sulfide, organics (e.g., oil and grease, total petroleum hydrocarbons, volatile and semi-volatile organic compounds), radionuclides, and chemicals added downhole or during well drilling, production, or maintenance processes.[85] It may include polymers, solvents, petroleum products and salts, and carboxylic acids, used to control scale and iron; corrosion inhibitors; hydrochloric and hydrofluoric acid; biocides, including glutaraldehyde and formaldehyde; surfactants; nanomaterials and others.[86] However, the identity of some added chemicals remains unknown or is not publicly available.[87]

Some classes of chemicals likely to be contained in CO2 EOR produced water (e.g. biocides, surfactants) can present larger hazards because of their relatively high toxicity, frequent use, or use in large amounts.

A literature review of 129 papers that included data on chemicals detected in produced water revealed that the majority (56 percent) have no safety evaluation or toxicology studies and 86 percent lack data necessary to complete a risk assessment.[88] A few toxicity studies of complex produced-water mixtures have been published.[89] [90] [91] In one, surface water downstream of injection wells in West Virginia had significantly higher endocrine disrupting activity in laboratory tests than upstream samples. This suggests spills at or near injection wells in West Virginia had significantly higher endocrine disrupting activity in laboratory tests than upstream samples.[92] This suggests spills at or near injection wells during transport and handling. Data gaps mean that we largely lack information to determine if these chemicals would present a threat to human health or the environment when released to groundwater, surface water, air, or soil.

Produced water is subject to a complicated patchwork of federal, state, and sometimes local regulations.[93] Because of the uncertain and complex chemistry, the primary disposal option in the United States is deep well injection. Other methods include using the water for fracking, waterflooding, or well drilling; disposal in evaporation ponds or seepage pits within the oil and gas field; or transferring produced water offsite for disposal and discharge. Current treatment technologies are often not cost-competitive as compared to the options of injection well disposal or water reuse for fracking.[94] However, reuse of produced water after treatment is beginning to gain traction in some states with water shortages and where recovered minerals, such as lithium, have market value.[95]

The permissibility of these options and treatment standards are regulated in large part by the federal Clean Water Act (CWA),[96] which controls discharge to surface water, and the Safe Drinking Water Act (SDWA).[97]

These federal statutes allow some state-by-state variability in handling produced water.[98] For example, the CWA permits reuse of treated produced water “of good enough quality”[99] for irrigating crops or watering livestock in the western United States (west of the 98th meridian), because of arid conditions. The definition of “good enough quality” for CWA purposes varies by state. Standards for using produced water for irrigation or livestock watering where it is permitted largely focus on pH; total dissolved solids, salts, metals, and minerals; and oil and grease levels, without consideration of process chemicals.[100] This means that various mixtures of potentially hazardous chemicals intentionally used in EOR operations could remain unidentified in produced water that flows to soil, crops, surface- or groundwater.

Produced water kept in unlined evaporation ponds or seepage pits, allowed in some states, can potentially contaminate shallow drinking water aquifers, result in toxic dust dispersion, and release VOCs into the air.

Deep well injection in Class II wells for disposal increases risks of earthquakes and drinking water aquifer contamination.[101] The U.S. Environmental Protection Agency (EPA) maintains that Class II injection wells[102] do not threaten drinking water quality provided "that the wells are sited properly, used correctly, and tested regularly."[103] Yet it is clear that produced water injected deep underground for disposal in an area of abandoned oil wells can migrate back to the surface through old bore holes, contaminating the soil with a complex mixture of hazardous liquids—some of which could also migrate downward into drinking water aquifers or runoff into surface waters.[104]

CONCLUSIONS

In conclusion, CO2 EOR is a moral failure, a climate failure, and a threat to public health and the environment, all while being publicly funded. Morally sound public policy would not pay the polluter to pollute. It would penalize the polluter for damaging the commons. Real climate policy would cut CO2 emissions rather than guaranteeing increased atmospheric CO2 far into the future. We would reduce threats to public health and the environment rather than building in more risks to water, climate and human health. Finally, we would not fill the coffers of the fossil fuel industry using public money, particularly in the absence of any mechanisms for public accountability of either the CO2 captured and sequestered, or for the 45Q tax credits given to prop up corporations.

CO2 EOR is the last best hope for the fossil fuel industry to keep pumping oil out of the ground. It must end.

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