The Carbon Capture Conundrum: Public Need vs Private Gain

A Public Policy Perspective on Atmospheric Carbon Dioxide Reduction

by

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Abstract

Under the banner of “climate mitigation,” the U.S. Congress has enacted legislation to subsidize technological-commercial “carbon dioxide removal” (CDR). Yet, a review of the scientific literature on CDR shows that, in practice, the methods Congress is supporting generally emit more CO_2 into the air than they remove. Lawmakers in the U.S. and elsewhere are considering further subsidies. Such legislation is based on a premise that carbon is a potential asset to be captured and sold. This finance-driven rather than science-driven approach to climate mitigation policy makes biophysics subservient to market concerns. A chief result has been subsidies for increased oil production using “anthropogenic” CO_2. In their actions, lawmakers are eschewing both science and public need. What is vital on both scores is not merely carbon “removal” but an absolute *net reduction* of atmospheric CO_2.

Lawmakers inclined toward the market perspective can find support for technological-commercial CDR practices. Some scientific papers report that such procedures represent “climate mitigation” because they produce fewer carbon emissions than conventional oil production, and will “displace” conventional production. Other papers advance the argument that “negative emissions technologies” – such as direct air capture – can result in “net-zero” emissions. A central issue in many scientific studies is commercial viability: scientific papers that undertake a *financial* analysis find that the techno-industrial CDR procedures are not now commercially viable. Based upon a market frame, these papers call for government subsidies to develop a market for captured carbon, and, eventually, commercial profitability.

However, scientific studies that use a biophysical frame directly address the question of net CO_2 reduction. They show that the technological-commercial CDR procedures reviewed *are net atmospheric CO_2 additive* (that is, they emit more CO_2 than they remove). Our review of over 200 scientific studies on CDR revealed reasons for this apparent divergence of expert opinion. Studies by proponents of technological-industrial CDR methods miss crucial information for public policy-making. Some analyze only part of the CDR process “life cycle,” omitting parts crucial to policymakers. Most base their “climate mitigation” conclusions upon “carbon accounting” schema that look at CO_2 flow rather than atmospheric stock, and invoke unsupported economics assumptions about “displacement” of conventional oil production.

Moreover, the scale of techno-commercial carbon capture and storage at this time is infinitesimal in relation to the scale of the problem. The preponderance of scientific literature elides or ignores the biophysical impacts and potential adverse effects of operating such procedures at the scale needed to avoid exceeding the international 1.5º C target limit for global warming: earthquakes prompted by vast volumes of CO_2 stored underground; groundwater contamination; “fugitive emissions” that pollute the air. Energy consumption at scale is also often slighted: one industrial CDR process would annually demand an amount of energy nearly equal to all electricity generated in the U.S. in 2017; another would require a land area 10 times the size of Delaware for energy generation alone. To upscale any of the methods in existing or pending legislation to a meaningful level of CO_2 reduction would entail the construction of an infrastructure and pipeline network far larger than that which now exists for fossil fuel production and delivery. Most studies also avoid discussion of the “wartime level of effort” that would be required to achieve CO_2 reduction at scale and in time to make a difference.

CDR legislation enacted to date and the 8 bills making their way through Congress now (see Appendix) do not support *biological methods* of carbon drawdown and sequestration. Preliminary research suggests that biological methods are not only more effective at atmospheric CO_2 reduction; they also provide co-benefits such as soil nutrient restoration, air and water filtration, fire management and flood control, and may also be more effective and efficient in terms of resource usage.

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1. Introduction and Background

Carbon dioxide removal (CDR)[1] as a means of climate change mitigation is gaining attention among U.S. lawmakers. Congress has passed legislation to subsidize industrial CO_2 removal methods, and lawmakers are taking up additional measures to finance further expansion. This legislative attention is motivated by several drivers: mounting concern about the acceleration of climate change and its widening impacts; scientific reports that proffer "negative emissions technologies" as a mitigation method; appeals by advocates for and investors[2] in industrial-commercial CDR[3]; the influence of fossil fuel interests[4]; advocates for prolonging fossil fuel production[5] (for example, via "clean coal" and "green oil" [6]); and oil companies seeking to acquire and hold CDR patents and intellectual property[7].

Although interest in CDR goes back more than a decade[8], attention has increased since the release of reports on the topic by the Intergovernmental Panel on Climate Change (IPCC) in 2014 and 2018.[9] The IPCC in its 2018 report invoked "negative emissions technologies" (NETs) to create "pathways" that might be followed in order to avoid "overshooting" the internationally agreed-upon global warming target range of 1.5°- 2ºC. NETs – also called "carbon dioxide removal" methods – include both biological methods (such as reforestation, forest management, wetlands restoration and others) and engineered-technological methods (such as drawing CO_2 out of ambient air via mechanical-chemical processes). In line with the IPCC report, the U.S. National Academies of Sciences (NAS) soon followed suit with its own "negative emissions technologies" report (draft in 2018; final in 2019). A pivotal premise of the NAS report on NETs that goes generally unremarked-upon is its emphasis that commercial opportunity in the "international market" and "economic rewards" are of central concern. Here is what the report says:

> This report's statements about the *need* for an emissions reduction of a particular amount

[1] We use the term "carbon dioxide removal" (CDR), because it is being widely adopted in international discussions of atmospheric carbon dioxide reduction. Note that this term does not include "geo-engineering," which refers to interventions, like solar radiation management (SRM), designed to limit the amount of sunlight/energy reaching the planet's surface. This distinction is also consistent with the 2015 report of the National Academies of Sciences on "Climate Intervention". Also, note that the term "negative emissions technologies" (NETs) is often used interchangeably with CDR in much of the literature.

[2] Some "Direct Air Capture" investors & ventures: Bill Gates, Occidental Petroleum, Chevron -- Carbon Engineering ; Seagram's heir Edgar Bronfman Jr. -- Global Thermostat; Gary Comer, Lands End Founder -- Kilimanjaro Energy.

[3] Gunther 2011, Gunther 2012, Vidal 2018, Chalmin 2019, Rhodium Group 2019, Chichilnisky 2019, Mufson 2019, Temple 2019, Nagabhushan and Thompson 2019, Diamandis 2019.

[4] Marshall 2019; Morgan 2019, Muffett and Feit 2019, Cresswell 2019, ExxonMobil 2019a, Tabuchi 2019.

[5] E.g., see Realmonte et. al., (2019): "Moreover, DACCS enables delaying the phaseout of fossil-based electricity generation until after 2050;" and Mendelevitch (2013).

[6] U.S. Dept. of Energy (2017) "Two DOE-Supported Projects Receive Awards for Carbon Capture Technologies", December 7, 2017; Hackett, Dave, Stillwater Associates (2018) "Carbon Capture and Utilization for Enhanced Oil Recovery, March 28, 2018; Azzolina, NA, Peck, WD, Hamling, JD, Gorecki, CD (2016). "How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites" *International Journal of Greenhouse Gas Control*, Vol 51, 369–379.

[7] Soltoff 2019, ExxonMobil 2019b, Parsons 2018

[8] "Carbon Capture and Storage" has found favor with public leaders of both progressive and conservative political persuasions. The attractiveness of the idea that we can bury the carbon that we've produced has been alluring, and arguments that government should support technological capture by private businesses persuasive. President Obama, Chancellor Merkel and Prime Minister Gordon Brown had all worked to advance CCS. (See e.g., "The illusion of clean coal" and "Carbon capture and storage: Trouble in store", *The Economist*, March 5, 2009.) The Obama administration advocated and Congress funded a number of Department of Energy initiatives to develop and advance CCS. "Energy security" was generally cited as a reason government should subsidize the development and operation of CCS-EOR.

[9] Intergovernmental Panel on Climate Change (2014) *Climate Change 2014: Mitigation of Climate Change***.** Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. Intergovernmental Panel on Climate Change (2018) *Global Warming of 1.5°C; Summary for Policymakers*; October 2018. https://www.ipcc.ch/sr15/chapter/spm/

> should not be interpreted as normative statements (a value judgment on what should be), but rather as statements about the action required *given a decision to meet the Paris agreement or to provide NETs to the international market created by such a decision by most nations, many corporations, and several U.S. states and local governments*…The committee believes that its conclusions and recommendations are generally robust, simply because the economic rewards for success would be so large. (Emphasis in original.)

U.S. lawmakers' actions in passing legislation to subsidize technological-commercial NETs are based on this type of finance-driven rather than science-driven approach to climate mitigation policy. Doing so makes biophysics subservient to market concerns.

Concurrent with legislative actions, among scientists, and increasingly among the informed public, there is growing alarm about the rising atmospheric concentration of carbon dioxide, which is seen as the "most important"[10] greenhouse gas driving global warming. Atmospheric CO_2 recently surpassed 400 parts per million (ppm). Before the industrial age the level was 280 ppm.[11] Globally, CO_2 annual emissions have reached nearly 37 billion tons[12] (gigatons), a level that scientists warn cannot be continued or increased if we are to avoid exceeding the 1.5° Celsius threshold and the resultant climate-change impacts.

Responses to the reports of excess concentration of atmospheric CO_2 range from calls to decarbonize global energy sources to advocacy for CDR (removal of the excess CO_2 that human activity has already emitted). Some CDR advocates call for technological removal methods; others point to the advantages and co-benefits of biological methods. Seeing an opportunity for "market solutions," commercial interests, investors and, in some cases, scientists, have launched startups to develop and promote mechanical-chemical technologies for carbon removal. Fossil fuel interests have moved to reframe an old oil production method as a new climate mitigation technique.

This paper concerns technological-industrial methods to remove CO_2 because that approach has enjoyed the most legislative success in the United States thus far, even though many scientists and others argue that biological methods could be widely deployed and effective, or that energy decarbonization is the most fundamental need and would be the most fruitful path to take.[13]

This report is designed for public policymakers. The approach of this study is to address collective need, hence -- in legislative terms -- public purpose. The scientific consensus is that there is excess CO_2 in the air; the collective need – hence, the public purpose – must be to *reduce the atmospheric concentration of CO_2*. While CDR technologies may "remove" CO_2, that is not the same thing as an overall *reduction* of atmospheric CO_2. I.e., what is required biophysically is not simply "removal" but absolute "reduction".

The contribution of this paper lies in the intersection of public purpose and biophysics. Our research methodology combines the lens of public policy with the perspective of biophysics in order to examine the literature on carbon dioxide removal (CDR), focusing mainly on engineered technologies for CDR. This paper is intended to (a) review and summarize the CDR literature –

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[10] "So far as radiative forcing of the climate is concerned, the increase in carbon dioxide has been the most important (contributing about 60% of the increased forcing over the last 200 years)…" pg xxxvii; Intergovernmental Panel on Climate Change (1990) *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press.

[11] World Economic Forum https://www.weforum.org/agenda/2019/06/chart-of-the-day-these-countries-create-most-of-the-world-s-co2-emissions/

[12] Global Carbon Project; "Global Carbon Budget" https://www.globalcarbonproject.org/carbonbudget/19/highlights.htm. Also: "Global greenhouse gas emissions will hit yet another record high this year"; Chris Mooney & Brady Dennis, *Washington Post*, Dec. 3, 2019.

[13] There is a vast literature on this position, too voluminous to cite here.

primarily scientific papers but also journalistic reporting – through a public policy lens: specifically, the collective need objective of *net atmospheric CO_2 reduction*; and (b) illuminate scientific findings that have not previously been brought to the forefront for policymakers. Without this approach, both lawmakers and the public are denied the necessary context within which to make considered decisions about how to vote.

1.1. This report will make the following over-arching points:

1. Technological-commercial methods of CDR generally emit more CO_2 into the atmosphere than they remove and thus are, in their very essence, counter-productive in terms of the public purpose goal of *net atmospheric CO_2 reduction*. This is primarily because the captured carbon is used to produce more oil. Congress should stop subsidizing these counter-productive, commercial practices that foster carbon lock-in[14].

2. The body of existing scientific literature on engineered CDR technologies contains conflicting conclusions about whether any particular method effects "climate mitigation". This inconsistency in conclusions is generally due to three factors: differing underlying assumptions; differing frameworks for analysis and differing objectives.

3. The scale of technological-commercial carbon capture and storage at this time is infinitesimal in relation to the excess concentration of CO_2 in the atmosphere. Most literature that addresses scale frames it as a ***financial*** problem – massive amounts of investment are needed – and as a challenge for government to address through public financial investment. In this paper, we, instead, address the ***biophysical*** issues related to scale: the limited (or counter-productive) CO_2 impact of technological-commercial CDR methods; the enormous resource usage required; and the "dis-benefits" that would arise from scaling up to a meaningful level.

   Only a few studies have acknowledged the massive mobilization and infrastructural buildout that would be needed to scale up to significant[15] impact -- a level of "wartime mobilization" as some have termed it. Scaling up to an operational level to have significant impact on atmospheric CO_2 would: 1) entail an immense infrastructure build-out across the country (including a vast new pipeline network[16]); 2) consume massive amounts of energy and use large amounts of land; and 3) likely have significant harmful results such as earthquakes caused by underground storage of enormous amounts of CO_2, as well as potentially significant "fugitive emissions" and groundwater contamination. Many authors who either disregard or slight these issues argue that government should subsidize techno-commercial methods at this time as a "stepping stone" or "on ramp" to larger future operations. However, it is incumbent upon lawmakers to do their "due diligence" and undertake an in-depth and serious examination of the implications and impacts of scaling-up.

4. Public subsidy in the near-term of commercial CDR methods would create long-term "lock-in" of the fossil fuel industry as the holder of the expertise and owner of the infrastructure that would be necessary should government decide that scaling up on a wartime

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[14] Re: "carbon lock-in", see: SEI, IISD, ODI, Climate Analytics, CICERO & UNEP (2019) and Erickson et. al. (2015).
[15] Mac Dowell et. al., (2017) calculate that a rate of sequestration of 2.5 Gt per year is needed by 2030, increasing to 8-10 Gt CO_2 per year by 2050, and escalating after that.
[16] Some authors claim that direct air capture would not require a vast pipeline buildout because CO2 can be drawn out of the air anywhere, but others note that pipelines would still be needed to transport the captured CO2 to suitable underground storage locations.

mobilization level is necessary due to a declared climate emergency. Government will have to rely on the fossil fuel industry to solve the problem that their products produced.

5. As things now stand, policymakers -- and the public – are deprived of the necessary context to be able to evaluate the full range of choices for CDR. To obtain a full context, it is necessary to evaluate the effectiveness of biological methods -- in addition to the technological methods reviewed in this paper -- on an apples-to-apples basis. I.e., a standardized output analysis; a standardized resource usage analysis (particularly energy and land); and an analysis of the ancillary effects of each method are needed. Such a comparison does not now exist. Toward this end, this paper proposes the development of a "Resource Return on Resource Investment" (RRORI) tool, which potentially could serve as a basis for not only comparing methods, but also for setting standards for public policy formulation on CDR, taking into consideration *all* methods – biological and technological.

1.2. CDR Methods Addressed in this Report

There are a variety of possible methods for achieving carbon dioxide removal (sometimes called "negative emissions"), including engineered technologies and biological methods. We focus on engineered technological methods – particularly as designed for commercial application -- because these have received the most traction in terms of public policy and legislation in the United States (and to some extent in Europe). The methods of atmospheric carbon dioxide removal addressed [17] in this report are:

- **<u>Point-source carbon capture technologies</u>: Carbon Capture and Storage (CCS**; also called Carbon Capture and Sequestration) and Carbon Capture Utilization and Storage (**CCUS**). Both CCS and CCUS capture carbon dioxide at a point of emissions, generally smokestacks. The captured carbon is either stored underground or used for commercial applications (e.g. for oil production via "enhanced oil recovery"), or both. The Congressional Research Service defines CCS as

  > a process that involves capturing man-made carbon dioxide (CO_2) at its source and storing it permanently underground. (CCS is sometimes referred to as CCUS—carbon capture, *utilization*, and storage.)[18].

  Note that "point-source" capture does not remove CO_2 that is already in the atmosphere, and hence cannot, in itself, reduce the stock of atmospheric carbon dioxide. Its aim is to prevent additional CO_2 emissions from being released into the atmosphere. That objective is undercut if the captured carbon dioxide is used for new oil production (see discussions of "enhanced oil recovery" below).

- **<u>Atmospheric carbon capture technologies</u>: Direct Air Capture (DAC)** which has been defined as

  > the process of pulling carbon dioxide molecules from ambient air as opposed to removing them from waste streams, where they exist in considerably greater concentrations. Because it must collect CO_2 from the ambient air, where carbon dioxide exists in extremely low concentrations relative to industrial point sources, DAC is…is far more energy intensive. [19]

Error! Reference source not found. is a depiction of engineered technological CDR methods.

[17] This report examines only engineered CDR methods that are the focus of legislative and public policy interest in the U.S. at this time. Thus, we do not address, for example, "enhanced weathering," "ocean fertilization", Bioenergy with Carbon Capture and Storage (BECCS) or other methods that are often discussed in the academic literature.
[18] Congressional Research Service, "Carbon Capture and Sequestration (CCS) in the United States", Aug. 9, 2018.
[19] Definition of DAC in CIEL, *Fuel to the Fire* (2019)

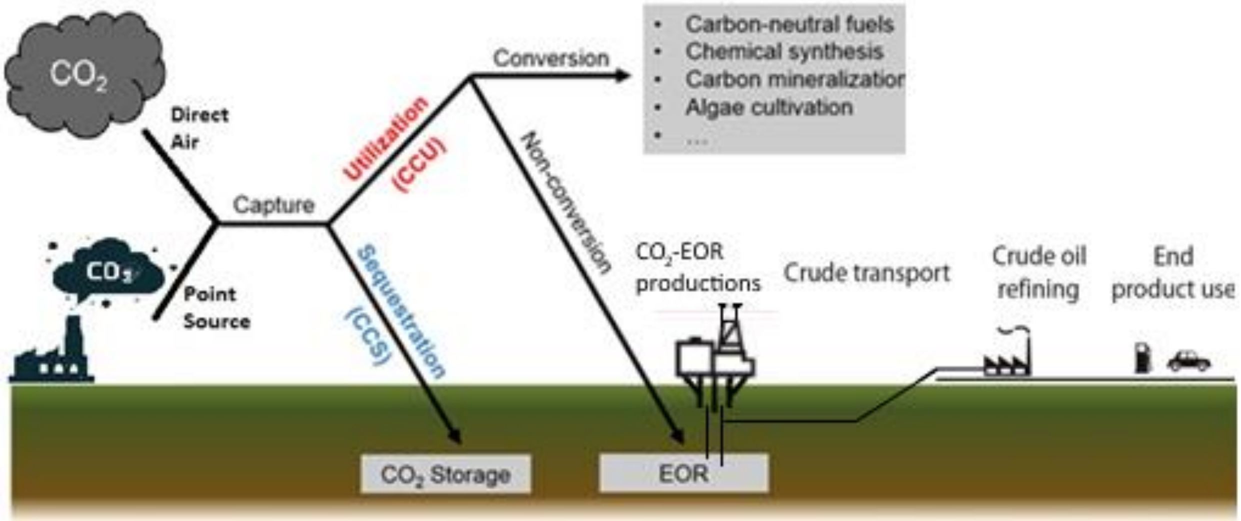

Figure 1.1: Engineered-technological Carbon Dioxide Removal (Image credit: Adoption of [Wikipedia depiction]() and Stewart & Haszeldine (2014) "Carbon Accounting for Carbon Dioxide Enhanced Oil Recovery", pp 26)

1.3. Further methods, not addressed in this report: Biological Methods of Carbon Dioxide Removal and Sequestration

There are also biological methods of CDR that are based processes that naturally remove CO_2 from the atmosphere and sequester it in soil and biomass. These include:

- **Forests:** reforestation, afforestation and averting deforestation.
- **Farming:** soil and biomass carbon sequestration through regenerative farming and other improved agricultural methods.
- **Grasslands:** restoration.
- **Wetlands:** restoration.

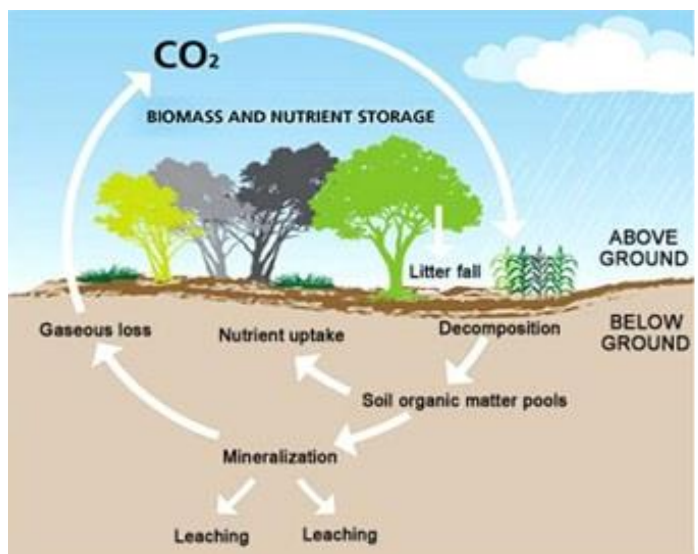

Figure 1.2: Biological Systems for Carbon Dioxide Removal and Sequestration (Image credit: https://climatechange.lta.org/enhancing-carbon-sequestration/)

Preliminary research suggests that biological methods are not only more effective at atmospheric CO_2 reduction; they also provide co-benefits such as soil nutrient restoration, air and water filtration, fire management and flood control, and may also be more effective and efficient in terms of resource usage.[20]

However, biological methods of carbon dioxide removal are not the subject of this paper because it is technological methods that have gained legislative traction in the U.S. Further work in needed to compare technological and biological methods on a standardized basis.

[20] (E.g., see: Moomaw et. al. 2019, Moomaw 2017, Bastin et. al., 2019, Griscom et. al, 2017, Fargione et. al., 2018, Dooley et.al. 2018, Lal 2018, Bai et. al., 2019, Kane 2015, Rumpel 2018, Smith et. al., 2019, Wright 2017, Nature Conservancy 2016, Zomer et. al., 2016, Zomer et. al., 2017, Johnson (undated), Houghton & Nassikas 2018, Smith 2016).

This report is designed for the current policy environment in the United States, but may also be useful in other nations that are considering legislative action on carbon dioxide removal (CDR). The organizing principle for this paper is that *reducing the amount of CO_2 in the atmosphere* is the *public policy goal* – the societal need. That principle may seem obvious, but this driving purpose can easily get lost among the competing demands, interests and complexities (Sekera 2017) faced by policy-makers who are attempting to take action to avert the worst consequences of climate change.

In order to achieve the **public purpose goal of net atmospheric CO_2 reduction**, policy-making must take into consideration thermodynamic imperatives and biophysical constraints. There are two fundamental questions whose answers can effectively guide policymaking. One is the threshold question of whether a particular method actually reduces atmospheric CO_2 or not. The second pertains to the amount and kind of resources (especially energy) consumed by a CDR method in relation to results achieved. Lastly, policymakers need also to take into account the ancillary effects: co-benefits or adverse side-effects (dis-benefits) that can result from each method.

1. **Net carbon balance:** does the process *remove* more CO_2 than is *emitted* by the process?
2. **Resource usage:** how much energy is consumed by a process? how much land is required?
3. **Ancillary effects:** what are side effects of each method – its co-benefits or dis-benefits?

Not a financial analysis
This paper does not address financial matters such as costs or ascribed financial value. Rather, it addresses the essential, foundational question of whether particular methods of carbon dioxide removal will likely achieve or thwart the goal of net reduction of atmospheric CO_2. This question must be answered biophysical and thermodynamic terms: **1.5 Celsius is a biophysical metric, not a financial metric.**

It is the aim of this report to aid policy-makers to step back and become more familiar with the scientific research on CDR and, as one scientist said, "to apply science to societal needs."[21]

2. Approach and Methodology

In our study we conducted a literature review of over 200 papers, reports and articles using a public policy perspective. Our analysis of CDR methods focuses primarily on scientific research and reports, but also examines journalistic reporting about carbon dioxide removal. The following points explain our approach and methodology.

1. **Public purpose approach**. The approach of this study is to address **collective need**, and hence –in legislative terms -- **public purpose**. The scientific consensus is that there is excess CO_2 in the air; the collective need – hence the public purpose -- must be to reduce the atmospheric concentration of CO_2. This means that the objective is an absolute, net, reduction of atmospheric CO_2, not a *relative* reduction in the amount of CO_2 emitted or hypothetically emitted – which is an approach that some scientific studies use.

[21] Chabbi et al 2017.

2. **Biophysical perspective**. Our analysis thus focuses on biophysical considerations. While the scientific literature of course employs a biophysical analysis, many of the scientific reports also overlay a market framework to draw their conclusions about the viability of particular CDR methods. In some scientific papers, commercial viability is the ultimate criterion and is adopted as an analytic lens. Many studies call for public subsidy, which they argue is necessary to move towards market success. But market dynamics and commercial viability are not the lenses of the analysis herein. Our approach is not a cost-analytic one. Nor does it consider, as some scientific studies do, hypothetical constructions and potential market incentives, such as a carbon tax, carbon pricing, or carbon credits.

3. **Consistent bases for comparisons**. The body of existing scientific literature that compares methods of CDR contains inconsistent conclusions, generally because of differing objectives, differing underlying assumptions and differing frameworks for analysis. The welter of seemingly conflicting findings is not useful for policy-makers. Therefore, our methodology is to examine the literature by using a consistent basis for understanding and evaluating studies in order to offer policymakers both an apples-to-apples comparison of methods as well as an analysis that looks at *impacts* in terms of public purpose.

   Given the above considerations and objective, the approach we take is to compare CDR methods based on three dimensions:
   - **(I) Impact on Carbon Balance –** Does the process result in net atmospheric carbon dioxide reduction?
   - **(II) Resource Usage –** What is the quantity of resources – particularly energy and land – needed to operate at scale?
   - **(III) Ancillary effects –** What are the side effects of carbon removal technologies, particularly in terms of other biophysical gains or losses?

   "Impact on Carbon Balance" is the threshold measure for assessing whether the public policy goal of net atmospheric CO_2 reduction is achieved. The measure to evaluate carbon balance impact can be expressed as a ratio[22]:

$$\gamma_{CO2} = \frac{total\ CO_2\ emitted}{total\ CO_2\ removed}$$

where:
γ_{CO2} = impact on carbon balance
total CO_2 emitted = the amount of CO_2 emitted by the full LCA process
total CO_2 removed = the amount of CO_2 removed by the full LCA process

A ratio of γ_{CO2} greater than 1 means that the process is adding more CO_2 to the atmosphere than it is removing. It would therefore not meet the public purpose of atmospheric carbon dioxide reduction.

Another way to express net reduction is in terms of stock and flow. Net reduction means an *absolute reduction* in the total *stock* of atmospheric carbon. A *relative reduction* of the continuously generated carbon *flows* is not enough. Many scientific papers look at flow but not stock reductions, and, in doing so, argue that a carbon dioxide reduction has taken place.

[22] Ratio suggested in communication with Robert K. Kaufmann, Professor of Earth and Environment, Boston University.

Resource Usage: Output Standardization. Studies differ in their claims and estimates about resource usage, particularly energy and land, and in their claims and estimates about outputs (CO_2 removal) that can be achieved. A chief reason for these discrepancies is that studies differ in their assumptions about *inputs* (resource usage) and thus make conflicting projections about *output* (amount of CO_2 that can be removed by a particular method). And an obverse problem arises in the ways that studies look at resource usage itself: differing studies make assumptions about outputs (amount of CO_2 removed) and therefore make differing claims or estimates about the amount of resources required. Both of these problems create confusion when trying to understand the "bottom line" in terms of resource usage. In order to overcome these problems in a way that can be useful for policymakers, our approach is to *standardize for outcome*. It is then possible to analyze studies of each CDR method in terms of resource inputs.

Our approach is to examine CDR methods in terms of the removal of 1 Gt (gigaton) per year. For comparison, global annual CO_2 emissions were nearly 37 Gt in 2019; U. S. annual CO_2 emissions in 2017 were approximately 5.3 Gt.[23] Thus, 1 Gt removal is minimal for any appreciable impact. Also, a number of scientific studies examine impacts at the 1 Gt level, although, once again, there is little consistency among scientific reports.

4. **Address the "scale" issue from a public purpose perspective.** "Scale" is an issue that we also approach from a public policy perspective, which most scientific papers do not. The issue is twofold. First, the amount of CO_2 that is being captured and stored through CCS/CCUS and DAC currently is negligible in comparison to the scale of the problem (Mac Dowell 2017; Minx et al 2018; Fuss et al 2018; Nemet et al 2018; Honegger & Reiner 2017; Jacobson 2019; Herzog 2011). Secondly, when scaling up to have significant impact on the stock of CO_2 in the atmosphere, there are enormous biophysical implications and impacts that many papers ignore or slight.

   Our approach in this paper is to address those issues head-on. We look at what would be required to have a modest impact -- 1 Gt per year reduction of atmospheric CO_2 stock. We use this standard to report on energy consumption and land use, infrastructure requirements, etc. Also, we look at ancillary effects – so-called "dis-benefits" -- which would become tremendously larger if CCS and DAC were operated at scale and the captured CO_2 were buried underground.

   Most scientific papers on CDR gravitate toward a *financial* framework: they discuss the need to "scale up" CDR processes and argue that public funding is necessary for this up-scaling because the engineered-technological methods are not commercially viable. This *financial approach* to scaling elides or slights major biophysical issues, such as resource consumption and adverse side-effects. (A few writers do address these issues related to scaling up; see Discussion section.)

   In this paper we bring the resource consumption and biophysical impact issues to the forefront; thus, our approach is to address the issue of scale in ways that are most relevant for policy-makers and the public – even before the issue of financial cost is considered.

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[23] Fleming, Sean (2019) "Chart of the day: These countries create most of the world's CO2 emissions"; World Economic Forum, 7 June 2019.

3. Principal Results / Findings

This section summarizes some of the principal findings; details can be found in the Discussion section. Our general observation, from a public policymakers' perspective, is that many of the scientific studies on CDR are abstruse: papers are written in terminology designed for specialists; units of measurement are indecipherable by the non-scientist; and emissions are categorized and labeled differently in different studies.[24]

(1) Conflicting terminology: CCS vs. CCUS

The CDR literature generally explains that the abbreviation CCS means "Carbon Capture and Storage" (or sometimes "Carbon Capture and Sequestration") – implying that the captured carbon is stored or sequestered in perpetuity. The literature also generally explains that CCUS means that the captured carbon is "utilized" for making a product. In reality, the two terms – CCS and CCUS – are used interchangeably. And in reality, whichever term is used, the captured carbon is predominantly used to produce more oil.[25] The term CCUS was created to emphasize the potential commercial viability of engineered technologies to capture carbon. As Veld et. al. (2013) explain, the U.S. Energy Department did a "re-branding' of CCS to CCUS: "Recognizing perhaps the political advantage in emphasizing that captured CO2 can generate economic value, the US Department of Energy (DOE) has in fact…re-branded CCS to CCUS the U standing for utilization, mostly in CO2-EOR projects." Although most reports on CCUS proffer the idea that the captured carbon can be used for a variety of products, from carbonated drinks to cement-making to synfuels production, the only significant "utilization" of captured CO_2 to date in the United States is for enhanced oil recovery (EOR), which is often called CO_2-EOR in the scientific literature on the topic (Nunez-Lopez et. al. 2019).[26]

In theory, the term "CCS" would only apply to a process in which captured CO_2 is merely injected into underground strata for perpetual storage rather than being "utilized" for the commercial production of products. However, as most studies acknowledge, simply injecting captured carbon into the earth is not commercially viable. The only way that such a process for carbon sequestration can be function in reality is for it to be operated as a public service, like water treatment or waste disposal (Kolbert 2017, Buck 2018, Temple 2019).

(2) Contradictory conclusions on whether technological-commercial CDR is a climate mitigation solution

There is no consensus in the literature about whether engineered CDR technologies represent climate change "mitigation". Some papers argue that CCS (and CCUS) and DAC effect mitigation; other studies argue and show that they do not. The reasons for these discrepancies include: differing underlying assumptions, differing frameworks for analysis and differing objectives of each study.

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[24] From Stewart & Haszeldine (2014): "Often studies attempt to summarise emission factors or storage factors using a different units e.g (Kg CO2 e/bbl), (kg CO2 /Mwh), (m3 CO2 / m3 oil). Although these units can be converted, it has the potential to cause confusion when comparing the results from life cycle assessments."

[25] Foehringer Merchant, Emma (2018) "With 43 Carbon-Capture Projects Lined Up Worldwide, Supporters Cheer Industry Momentum," Greentechmedia, Dec. 11, 2018. Roberts, David (2019) "Could squeezing more oil out of the ground help fight climate change?" *Vox*, Dec. 6, 2019. Also see https://co2re.co/FacilityData to check for the usage of CO2 from the CCS projects. Filtering the data for largescale CCS projects there was in fact only one project ('Illinois Industrial Carbon Capture and Storage', injection however already ended in the past: https://sequestration.mit.edu/tools/projects/decatur.html). All the others in the list mention the use of EOR and actually also the capture capacity (annual Mt of CO2) that involves EOR could be added.

[26] "Carbon dioxide-enhanced oil recovery (CO_2-EOR) is a technology most commonly applied in the third and final stage of the development of mature oil fields to enhance oil production. For this reason, it is also referred to as a type of tertiary recovery… The technology targets the residual oil in depleted oil reservoirs with the injection of CO_2. (Nunez-Lopez et. al. 2019).

Following are explanations of some of the major inconsistencies among the studies.

a. "Life cycle analysis" (LCA). LCA is a crucial concept for evaluating whether a particular CDR process results in a ***net reduction of atmospheric CO_2***. LCA is discussed in detail below, but the crucial point is that, for a public policy assessment, a **full** life cycle analysis – sometimes called "cradle to grave" LCA – is essential. That is, only studies that examine CO_2 generation from the beginning, or "birth" of the CDR process, to its end, or "grave," are relevant for judging whether that CDR method results in a net reduction of atmospheric CO_2. Full life cycle analysis of technologically captured post-combustion CO_2 includes: sourcing and processing for capture, transporting, injection into an underground reservoir, producing oil, and the consumption of that oil. This process puts more CO_2 into the atmosphere than it takes out. Many scientific studies use only a partial LCA; thus, their findings and conclusions differ from those that undertake a full LCA. Only studies that use a full LCA are relevant to the collective need of atmospheric CO_2 reduction.

b. Type of greenhouse gas. The plethora of scientific studies on "carbon dioxide removal," "negative emissions," "carbon capture and storage" and "geoengineering" (to name a few of the labels) report their measurements and findings in terms of different types of gasses. This heterogeneity makes it difficult to compare the studies' findings, and adds to the confusion in policy debates. This report is expressly and exclusively about carbon dioxide – "CO_2" – for two principal reasons. First, CO_2 is the greenhouse gas the IPCC indicates as the most important in terms of radiative forcing.[27] Second, it is the gas that technological-industrial methods are aimed at capturing. Thus, this report does not address greenhouse gases (GHGs) in general, which, in addition to CO_2 include methane and nitrous oxide. (It is important to note that the technological CDR methods do not address the increasing problem of excess *methane* emissions.) And lastly, many reports speak in terms of "carbon" or "CO_2 equivalents;" we convert those findings into the equivalent amount of CO_2.

(3) Carbon accounting conventions matter crucially

"Carbon accounting conventions" refers to the schema various scientific studies employ to "account for" the production and disposal (or use) of CO_2 emissions in an overall CDR process.

The components of the carbon accounting schema generally are:

- The Life Cycle Analysis boundary
- The "displacement" assumption
- The "efficiency factor"

As noted above, **LCA** is a crucial concept for evaluating whether a particular CDR process results in a *net reduction of atmospheric CO_2*. E.g. if the combustion of CCS-EOR-produced-oil by the final consumer is included in the framework of analysis, it is clear that there is a net addition to atmospheric CO_2, whereas if a study looks only at the carbon emissions relating to a specific part of the CDR process (as in a partial LCA), lower emission results are reported.

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[27] Intergovernmental Panel on Climate Change (1990) *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press

A full CO_2 accounting can only be obtained through a full "Life Cycle Analysis": where the carbon originally starts out, where it ends up, and how much is generated from the overall process.

And finally there are the **displacement argument** and **the efficiency factor**. The displacement argument rests on an unsupportable assertion about "demand for oil". The efficiency factor is a mathematical component employed in some CDR analyses; it varies based on the researcher's assumptions and reference points.

LCA, the displacement assumption and the efficiency factor are further explained in the Discussion section below.

(4) The threshold question: Does the process remove more CO_2 than is emitted by the process?

Significant finding: The two principal technological-industrial methods of "carbon dioxide removal" – CCS-EOR and DAC when powered by fossil fuels – are both net additive. I.e., they add more CO_2 to the atmosphere than they remove. Furthermore, *any* technological method in which the captured CO_2 is used for EOR will be net additive.

- **(a) CCS-EOR[28] is net-additive for full LCA**: No paper we reviewed that looks at the full LCA of CCS-EOR claims that there is an *absolute* reduction of atmospheric CO_2. Various papers draw differing boundaries in terms of carbon emissions accounting. Some of them argue that CCS-EOR can contribute to *relative* reductions. Yet, we did not find any paper that disagreed with the results of Jaramillo et. al. (2009) who carried out a full LCA for several EOR projects and found clear net additive results. This full LCA study found that "between 3.7 and 4.7 metric tons of CO_2 are emitted for every metric ton of CO2 injected" underground. Papers that argue that CCS with EOR is an effective climate mitigation method are based on truncated Life Cycle Analyses (omitting "upstream" or "downstream" CO_2 emissions or both), unsupported economics assumptions and postulates about substitution and "displacement." In contrast, studies that use a full life cycle analysis, eschew the displacement assertion and are empirically based demonstrate that the full process puts more CO_2 into the atmosphere than it takes out.

- **(b) Fossil-fuel powered DAC is net additive:** Direct air capture operations that use fossil fuels as their power source are, in most studies,[29] shown to be net-additive in terms of atmospheric CO_2. This is because of the large amounts of energy required to power the machinery and process that captures the CO_2 from ambient air. A widely-cited study showed that DAC emits from 1.5 to 3.4 tons of CO_2 for every ton captured.[30]

[28] The term CCS-EOR is used in this paper to mean CO_2 EOR. Other substances, such as water, can also be used for EOR, sometimes in addition to CO_2, but these other methods are not relevant to this paper.

[29] Some research has suggested that under "best case" scenarios fossil-fuel powered DAC could be net reductive; see details in Discussion section of this paper.

[30] Based on Smith et al. 2016 pg 47: 156 EJ/yr required to capture ~3.3 Gt Ceq/yr. Calculations performed by S. Davis. 8-19-19; personal communication. Calculations showed the emissions ratio associated with gas as the DAC power source to be 1.46 to 1 [rounded to 1.5 to 1); the ratio with coal as DAC power source is 3.44 to 1. Alternatively, renewable energy sources could be used, which could result in net reduction of atmospheric CO_2. However, the question is whether renewable energy power should be consumed by DAC rather than used for direct energy production for the nation.

(5) The predominant "utilization" of captured CO_2 is Enhanced Oil Recovery (EOR)

In theory captured CO_2 could be used for products other than oil. A number of studies point out other potential uses for captured CO2.[31] However, there is no significant alternative demand for captured CO_2 at this time[32] or in the foreseeable near-future.[33] In fact, direct air capture operations that had announced they would be using their captured CO_2 for other products, such as synfuels, carbonated beverages and greenhouses, are having difficulty finding buyers. Some are now changing plans and will be selling their captured CO_2 to the oil industry for EOR. For example, Carbon Engineering[34] has announced that it is partnering with Occidental Petroleum to build a new DAC plant in the Permian Basin (Texas) for the purpose of EOR. This operation will be taxpayer-subsidized, both federally and at the state level.[35] And another DAC startup – Global Thermostat – has announced plans to partner with ExxonMobil.[36]

Some papers acknowledge that Enhanced Oil Recovery in the future will be entirely dependent upon "anthropogenic" CO_2 because it is not politically, socially or financially feasible to continue to use naturally-occurring deposits of CO_2 for EOR. One paper that emphasizes this point is "Opportunities for Utilizing Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage"[37]. As this paper states: "The report demonstrates that CO_2-EOR needs CCS; because large-scale future implementation of CO2-EOR will be dependent on CO2 supplies from industrial sources".

> **"…CO_2-EOR needs CCS because large-scale future implementation of CO_2-EOR will be dependent on CO_2 supplies from industrial sources."**

That paper concludes:

> [N]ot only does CCS need CO_2-EOR to ensure viability of CCS, but CO_2-EOR needs CCS to ensure adequate CO_2 to facilitate CO_2-EOR production growth. This will become even more apparent as even more new targets for CO_2-EOR become recognized. Therefore, the "size of the prize" is large, the oil produced has a lower CO_2 emission footprint than most other sources of oil, with the injected CO_2 stored securely, and CO_2-EOR can provide a market-driven option for accelerating CO_2 capture, with widely distributed economic benefits. (Godec et. al. 2013)

(6) Resource usage – energy and land

The "direct air capture" method of carbon dioxide removal when operated at scale could consume a quantity of energy approaching the total electricity generation for the U.S. For example, to remove 1 gigaton (one billion tons) of CO_2 from the ambient air could, according to one report, consume" 3,417 terawatt-hours of electricity annually -- "an amount that is nearly equivalent to all electricity generated in the United States in 2017." Other studies also show similar estimates, ranging from 3,156 to 5,049 terawatt hours, as discussed below.

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[31] For example: Steven J. Davis et. al. (2018) "Net-zero emissions energy systems", *Science 360.*

[32] Foehringer Merchant, Emma, "With 43 Carbon-Capture Projects Lined Up Worldwide, Supporters Cheer Industry Momentum," Greentechmedia, Dec. 11, 2018. Also when filtering for large-scale CCS projects in the U.S. at the CCS website, all projects are EOR-related (https://co2re.co/FacilityData).

[33] See e.g., Mac Dowell et. al. (2017); Schafer et. al. (2015) and CIEL (2019) *Fuel to the Fire*

[34] A DAC startup in which Bill Gates originally invested (Vidal 2018, Morgan 2019, Gunther 2011).

[35] The facility "will be designed to qualify for both the US federal 45Q tax credits, and California's Low Carbon Fuel Standard credits." "Oxy and Carbon Engineering partner to Combine Direct Air Capture and Enhanced Oil Recovery storage."

[36] James Temple; "Another major oil company tiptoes into the carbon removal space" MIT Technology Review June 28, 2019. "ExxonMobil's deal with a startup developing ways to suck carbon dioxide from the air marks another sign of the oil and gas sector's growing interest."

[37] Godec, Michael L., Vello A. Kuuskraa & Phil Dipietro (2013) "Opportunities for Utilizing Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage," *Energy & Fuels*.

Yet, even this large amount omits some downstream components of the DAC life cycle process like the energy requirements for transportation or sequestration of the captured CO_2.

CCS is more energy-efficient than DAC, since CCS captures the CO_2 as it comes out of smokestacks. However, a recent study argues that public investments in renewables development would have better "energetic" returns than public investments in CCS *not even considering CCS used for EOR*. Sgouridis et. al. (2019) have shown that investments in "**renewable technologies** generally provide a better **energetic return than CCS**". They conclude that "<u>renewables plus [battery] storage provide a more energetically effective approach</u> to climate mitigation than constructing CCS fossil-fuel power stations." (Emphases added.)

Regarding land requirements, there are three types of land requirements associated with industrial CDR methods:

- Surface land for the industrial **capture** process;
- Surface land for pipelines to **transport**;
- Subterranean land for geological **storage**.

Most reports on direct air capture (DAC) elide or ignore the land requirements of this method, which become enormous when operating at scale, particularly if powered by renewable energy.

Another surface land requirement that lacks a prominent place the scientific literature is the requirement for land acquisition for pipelines to transport the CO_2 to injections sites – whether that be for enhanced oil recovery or for injection into caverns. Significant amounts of land would need to be acquired and occupied for pipeline buildout. One Gt of CO_2 capture would entail building new pipeline capacity even larger than the existing petroleum pipeline system.[38] And pipelines have other "disbenefits" such as the potential for "blowouts".

Legislation would be required to assure standards are in place to avert or reduce leakage and earthquakes from underground storage sites. And even then, diligent, long-term monitoring and government-funded oversight would be required. Experience thus far with the "45Q" tax credit for CCS indicates discrepancies in industry reporting about how much CO_2 was actually stored (see Discussion section for details).

(7) Ancillary effects

The literature on CDR shows a number of "dis-benefits," including:

- Blowouts – of pipelines or other equipment
- Earthquakes – resulting from underground storage of CO_2 under high pressures
- "Fugitive emissions" – leakage of CO_2 from pipelines, storage or elsewhere
- Pipelines extending over many thousands of miles across the U.S.
- Aquifer acidification
- Air pollution and health damage

(8) The problems of scale

The scale issue is twofold. First, the amount of CO_2 that is being captured and stored through CCS/CCUS and DAC currently is negligible in comparison to the scale of the problem (Mac Dowell 2017; Minx et al 2018; Fuss et al 2018; Nemet et al 2018; Honegger & Reiner 2017; Jacobson 2019; Herzog 2011). Secondly, when scaling up to have

[38] David Fridley, Fellow, Post-Carbon Institute; Staff Scientist (retired), Lawrence Berkeley Laboratory; personal communication, personal communication, Sept. 17, 2019.

significant impact on the stock of CO_2 in the atmosphere, there are enormous biophysical implications and impacts that many papers ignore or slight.

Over the last 250 years, since the beginning of the industrial revolution, the stock of atmospheric CO_2 has vastly increased: Compared to pre-industrial levels which were at 280 ± 10 ppm (a level that existed for several thousand years[39]) we are currently (2018) at a global atmospheric CO_2 level of 407ppm.[40] Globally, CO_2 annual emissions have reached nearly 37Gt annually[41] and U.S. annual CO_2 emissions in 2017 were approximately 5.3 Gt.[42] or nearly 15% of global emissions.[43]

There is not consensus on precisely what level of atmospheric CO_2 is "safe", or what levels would enable us to avoid exceeding the 1.5° Celsius or 2° Celsius targets. Estimates have ranged from 350ppm[44] to 507ppm[45]. According to one report (Kemp 2019),

> Science advisers on the Intergovernmental Panel on Climate Change have estimated the limits imply an atmospheric CO2 concentration of no more than 450 parts per million (for 2 degrees) or 430 ppm (for 1.5 degrees).

A study by MacDowell et. al., (2017) puts a spotlight on the scale issue and **calculates that a sequestration rate of 2.5 $GtCO_2$ per year is needed by 2030 and the amount must increase significantly after that**.

4. Discussion

Dimensions on which methods are compared

We discuss and analyze CDR methods based on four dimensions: We first assess CDR methods in terms of **Impact on Carbon Balance –** the threshold question of whether a process removes more CO_2 from the atmosphere than is emitted by the process**.** Next, we look at **Resource Usage**, particularly energy and land. We then review the **Ancillary Effects** -- co-benefits and "dis-benefits" of various methods, and lastly, we look at the relevance of scale.

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[39] IPCC, "The carbon cycle and atmospheric carbon dioxide" https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf . According to the IPCC, "the present atmospheric CO2 concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years" and most importantly it is caused by human action: Atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2, and about 75% of these emissions are due to fossil fuel burning. IPCC "The Carbon Cycle and Atmospheric Carbon Dioxide " (https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf)

[40] Lindsey, Rebecca (2019) "Climate Change: Atmospheric Carbon Dioxide, Sept. 19, 2019 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide.

[41] Global Carbon Project; "Global Carbon Budget" https://www.globalcarbonproject.org/carbonbudget/19/highlights.htm; "Global greenhouse gas emissions will hit yet another record high this year"; Chris Mooney & Brady Dennis, *Washington Post*, Dec. 3, 2019.

[42] Fleming, Sean (2019) "Chart of the day: These countries create most of the world's CO2 emissions"; World Economic Forum, 7 June 2019.

[43] Fleming, Sean (2019) "Chart of the Day: These countries create most of the world's CO2 emissions" *World Economic Forum*, 7 Jun 2019. https://www.weforum.org/agenda/2019/06/chart-of-the-day-these-countries-create-most-of-the-world-s-co2-emissions/ . Also: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#cumulative-co2-emissions

[44] Bill McKibben citing esteemed NASA scientist James Hansen in 2007. McKibben, Bill (2007) "Remember This: 350 Parts Per Million" *Washington Post*, Dec. 28, 2007.

[45] "How much CO2 at1.5° C and 2° C?" July 2018, https://www.metoffice.gov.uk/research/news/2018/how-much-co2-at-1.5c-and-2c

4.1. Impact on carbon balance

"Impact on Carbon Balance" is the threshold measure for assessing whether the public policy goal of net atmospheric CO_2 reduction is achieved. The measure to evaluate carbon balance impact can be expressed as a ratio[46]:

$$\gamma_{CO2} = \frac{total\ CO_2\ emitted}{total\ CO_2\ removed}$$

where:
γ_{CO2} = impact on carbon balance
total CO_2 emitted = the amount of CO_2 emitted by the full LCA process
total CO_2 removed = the amount of CO_2 removed by the full LCA process

A ratio of γ_{CO2} greater than 1 means that the process is adding more CO_2 to the atmosphere than it is removing. It would therefore not meet the public purpose of atmospheric carbon dioxide reduction.

In this section we discuss whether, and the extent to which, various methods of CDR emit more CO_2 than is removed by the process, i.e., yield a ratio of greater than 1. We begin by explaining that one reason that technological-commercial methods of CDR yield a ration of greater than 1 is because the captured carbon is generally used to produce additional oi.

CO_2 that is captured via technological CDR methods is primarily used for Enhanced Oil Recovery (EOR).

Review of both scientific literature and journalistic reporting shows that the predominant use of carbon that is captured via technological CDR methods is Enhanced Oil Recovery (EOR). Figure 4.1 shows that the vast majority of captured CO_2 that has been injected for subterranean storage was first used for oil production via EOR. Utilization for purposes other than oil production are negligible, and likely to be so for the foreseeable future (e.g., see Mac Dowell et. al., 2017).

[46] Ratio suggested in communication with Robert K. Kaufmann, Professor of Earth and Environment, Boston University.

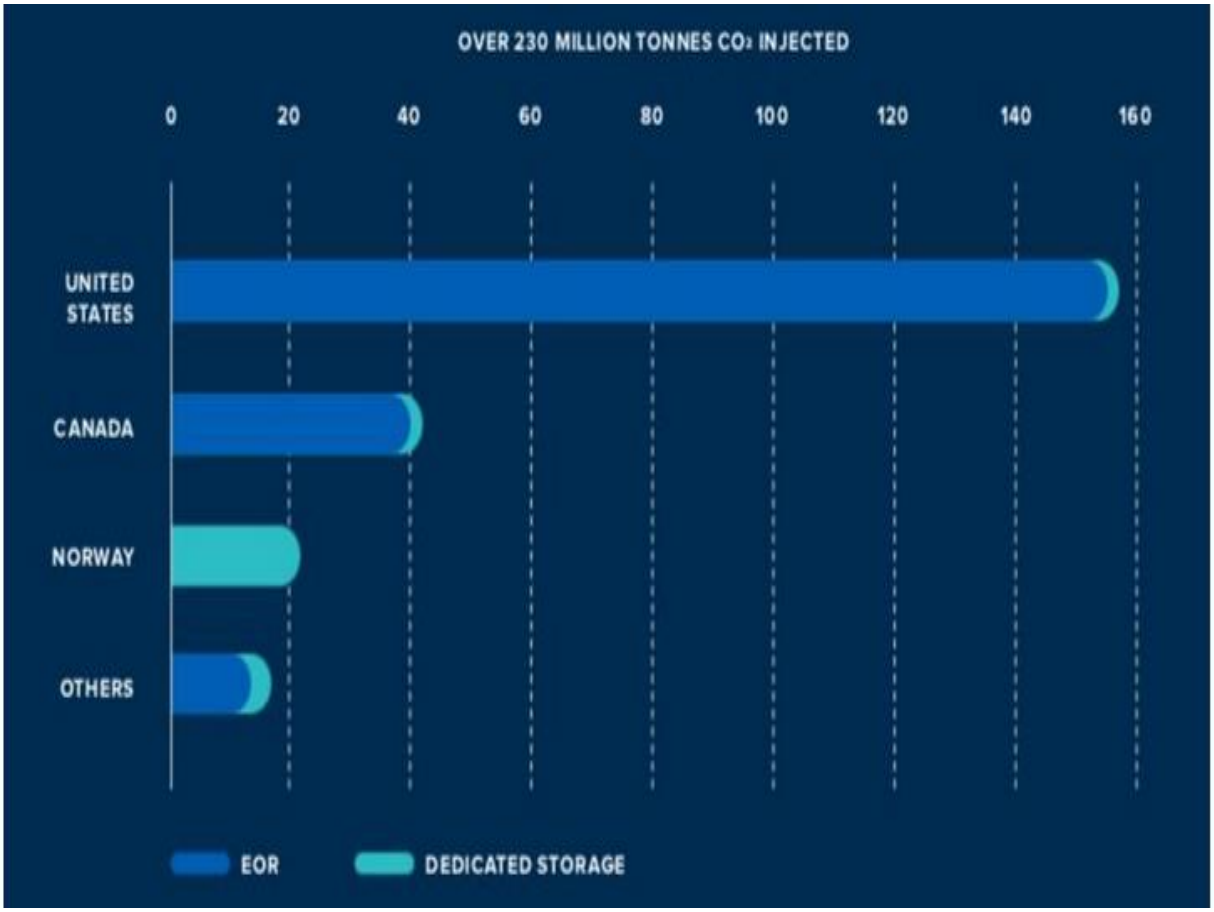

Figure 4.1: Overview of cumulative CO_2 injection in major countries (approximate): dedicated for storage and respective share that was first used for CO_2-EOR. 'Others' include Algeria, Brazil, China, Saudi Arabia, UAE, Australia, Germany, France (Source: Global CCS Institute)

The article[47] displaying the above bar chart explains that:

> Carbon capture has seen the most success in the United States, where so far projects have stored nearly 160 million metric tons of carbon dioxide. According to the report, 10 of the world's operating CCS facilities are located in the U.S. (one is a capture facility located in the U.S., but the carbon dioxide is injected across the border in Canada). The U.S. has several large-scale facilities, but only one of those projects is a large-scale CCS power facility: Petra Nova in Texas. **In the U.S., most captured carbon has gone to enhanced oil recovery**, a process that pushes out more oil from a producing well after the extractor has already used primary and secondary methods. That added revenue from EOR helped Petra Nova's economics. It's also used at other plants like the Great Plains Synfuels Plant in North Dakota. (Emphasis added.)

A recent article that reports on alternative views about EOR, Roberts (2019) also provides a graphic display of the proportion of CO_2 that goes toward fossil fuel production. See Figure 4.2.

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[47] Foehringer Merchant, Emma, "With 43 Carbon-Capture Projects Lined Up Worldwide, Supporters Cheer Industry Momentum," Greentechmedia, Dec. 11, 2018. https://www.greentechmedia.com/articles/read/carbon-capture-gains-momentum#gs.nnjkhy

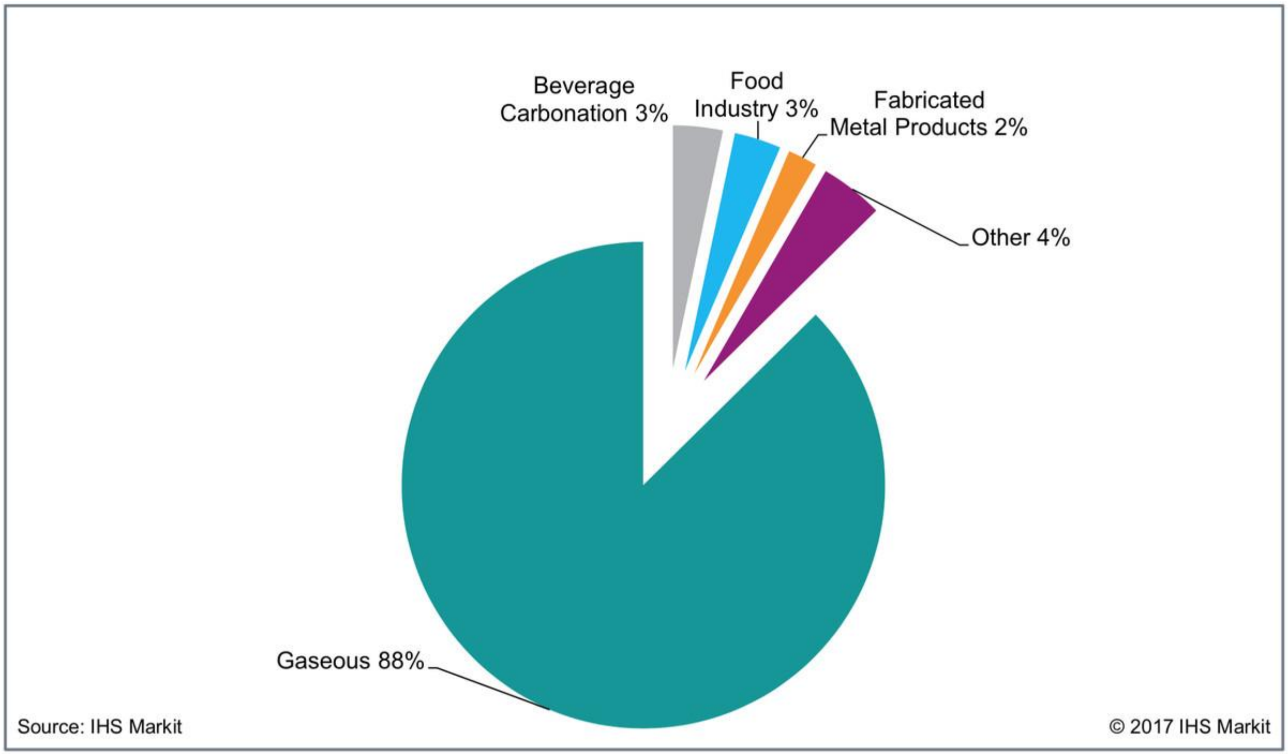

Figure 4.2: [Graphic display of CO_2 use globally](). According to the source, "gaseous" means "direct use of CO_2 to boost fossil fuel recovery". (Source: Roberts 2019)

In theory, captured CO_2 could be used for products other than oil. A number of studies point out other potential uses for captured fossil CO_2 including cement production, carbonated beverages and synfuels for hard-to-decarbonize sectors.[48] However, there is no significant alternative demand for captured CO_2 at this time[49] or in the foreseeable near-future.[50] In fact, direct air capture operations that had announced they would be using their captured CO_2 for other products, such as synfuels, carbonated beverages and greenhouses, are having difficulty finding buyers. Some are now changing plans and will be selling their captured CO_2 to the oil industry for EOR. For example, Carbon Engineering[51] recently announced that it is partnering with Occidental Petroleum to build a new DAC plant in the Permian Basin (Texas) for the purpose of EOR. This operation will be taxpayer-subsidized, both federally and at the state level.[52] And another DAC startup – Global Thermostat – has announced plans to partner with ExxonMobil.[53]

Following are additional sources that pertain to use of captured CO_2.

The largest CCS facility in US that uses CO_2 captured from fossil-fueled power plants is Petra Nova in Texas. It **sells its captured CO_2 for enhanced oil recovery**. According to "Carbon Capture and Sequestration in the United States," by the Congressional Research Service (2018) --

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48 For example: Davis et. al (2018) and Soltoff (2019).

49 Foehringer Merchant, Emma, "With 43 Carbon-Capture Projects Lined Up Worldwide, Supporters Cheer Industry Momentum," Greentechmedia, Dec. 11, 2018. Also when filtering for large-scale CCS projects in the U.S. at the CCS website, all projects are EOR-related (https://co2re.co/FacilityData).

50 See e.g., Mac Dowell et. al. (2017); Schafer et. al. (2015) and CIEL (2019) *Fuel to the Fire*

51 A DAC startup in which Bill Gates originally invested (Vidal 2018, Morgan 2019, Gunther 2011).

52 The facility "will be designed to qualify for both the US federal 45Q tax credits, and California's Low Carbon Fuel Standard credits." "Oxy and Carbon Engineering partner to Combine Direct Air Capture and Enhanced Oil Recovery storage."

53 James Temple; "Another major oil company tiptoes into the carbon removal space" [MIT Technology Review]() June 28, 2019. "ExxonMobil's deal with a startup developing ways to suck carbon dioxide from the air marks another sign of the oil and gas sector's growing interest."

> The Petra Nova plant in Texas is the only U.S. fossil-fueled power plant currently generating electricity and capturing CO2 in large quantities (over 1 million tons per year).

And, as *Fuel to the Fire* (pg 15) points out:[54]

> [E]ven with government incentives, as of December 2018 there were only two large-scale fossil energy power plants with carbon capture units operating: the Boundary Dam project in Canada and the Petra Nova plant in the United States. Both are coal-fired, and both use the captured carbon dioxide for EOR.

Schafer et. al. (2015) note that, outside of EOR, demand for CO_2 as a marketable commodity is extremely small.[55]

> **Demand for long-term, chemically stable CO2-based products is very likely to remain extremely small compared to current anthropogenic emissions of CO2** (Kember et al., 2011). Consequently, carbon capture and utilisation (CCU) projects may be important as a step towards developing closed-cycle perspectives in the private sector and general public, and towards adding value to some of the CO2 that is captured by various processes, but are not likely to have a large impact on global atmospheric CO2 concentrations. (Emphasis added.)

In a paper that suggests a framework for analyzing CO2 utilization for uses other than EOR, Bennett et al (2014) find that other options are extremely limited due to scale challenges, and may not produce significant lasting climate mitigation benefit.

The Center for International Environmental Law summarized the situation in their 2019 report[56]:

> **Increasingly, proponents of carbon capture claim that captured CO2 can be used in the production of other products, including plastics, petrochemicals, synthetic fuels, and cements**. As noted by the Global CCS Institute, however, "**the market for products derived from non-EOR use of CO2 is small relative to what is needed to be stored.**" The Norway-based research group NORCE, which actively advocates for CCUS, echoed this view in a presentation at the 2018 climate negotiations in Katowice, Poland, observing that EOR is "currently the only commercially ready process allowing for simultaneous utilization and storage (CCUS) of industrial-scale volumes[.]" (Emphasis added.)

Several studies have emphasized that CCS-EOR using "anthropogenic CO_2" (e.g., coming from power plants) is not financially feasible for commercial businesses unless they obtain government subsidies. As one paper points out[57] the added costs of point source carbon capture would significantly raise the cost of power generation, and hence electric bills for customers.

> Of the three surviving "pilot" CCUS projects in North America, all have gone over budget…and the cumulative costs for CCUS could more than double the electricity-rate costs for residential and commercial consumers.

Yet, a number of papers have argued that CCS-EOR is a climate mitigation method and "reduces" CO_2 emissions. Here are three:

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[54] Fuel to the Fire footnotes:
61 See e.g., Petra Nova: Carbon Capture and the Future of Coal Power, nrg, https://www.nrg. com/case-studies/petra-nova.html (last visited Dec. 21, 2018) (noting a $190 million grant from the US Department of Energy).
62 See id.; *Boundary Dam Carbon Capture Project*, SaskPower, https://www. saskpower.com/our-power-future/ *infra*structure-projects/carbon-capture-and-storage/boundary-dam-carbon-capture-project (last visited Feb. 8, 2019).
63 See id.; nrg, *supra* note 61.

[55] Schaefer, Stefan et al. Eds. (2015) "The European Transdisciplinary Assessment of Climate Engineering (EuTRACE),".

[56] CIEL (2019) *Fuel to the Fire* pg 15

[57] David Johnson (undated), "Why Not Soil Carbon?" https://www.csuchico.edu/regenerativeagriculture/_assets/documents/research-david-johnson-atmospheric-co2-reduction-final.pdf

1. "Opportunities for Utilizing Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage"[58]

   As the Abstract of this paper states: "The report demonstrates that CO_2-EOR needs CCS; because large-scale future implementation of CO2-EOR will be dependent on CO2 supplies from industrial sources". The paper concludes:

   > [N]ot only does CCS need CO2-EOR to ensure viability of CCS, but CO2-EOR needs CCS to ensure adequate CO2 to facilitate CO2-EOR production growth. This will become even more apparent as even more new targets for CO2-EOR become recognized.
   >
   > Therefore, the "size of the prize" is large, the oil produced has a lower CO2 emission footprint than most other sources of oil, with the injected CO2 stored securely, and CO2-EOR can provide a market-driven option for accelerating CO2 capture, with widely distributed economic benefits.

2. "Negative emission technologies: What role in meeting Paris Agreement targets?"[59]

   > [W]e conclude that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios…
   >
   > Scenarios and projections of NET's future contribution to CDR that allow Paris targets to be met thus appear optimistic on the basis of current knowledge and should not form the basis of developing, analyzing and comparing scenarios of longer-term energy pathways for the European Union (EU).

3. "Potential of CO2-EOR for Near-Term Decarbonization
   In this paper Nunez-Lopez & Moskal (2019) argue that, in their early stages, certain CO2-EOR projects can be carbon-negative. However, the authors create and use a "dynamic life cycle analysis" – which relies on an economic "demand" postulate (discussed below) -- and a limited "gate to grave" project boundary to make their argument.

Given that such studies argue that CCS-EOR "reduces emissions" and is therefore "climate mitigation" – what is the basis for this claim? We address this question next.

4.1.1. Carbon Accounting Conventions: Life Cycle Boundary, Displacement Postulate and Efficiency Factor

A number of papers have argued that CCS-EOR is a climate mitigation method because, in their calculations, the procedure "reduces" CO_2 emissions (e.g., see Cooney et. al. 2015; Azzolina et. al. 2016; Faltinson and Gunter (2011); Godec et.al. (2013); Nagabhushan, Deepika & Waltzer, Kurt (2016)[60] and Nunez-Lopez & Moskal (2019)).

What is the basis for this claim?

In sum, the argument that CCS-EOR is a climate mitigation technique relies on a "carbon accounting" schema, the chief elements of which are:

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[58] **Godec**, Michael L., Vello A. Kuuskraa & Phil Dipietro (2013) "Opportunities for Utilizing Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage," *Energy & Fuels*.

[59] **EASAC (European Academies, Science Advisory Council**) (2018) *Negative emission technologies: What role in meeting Paris Agreement targets?*; February 2018.

[60] Note that this report, by the Clean Air Task Force, contains an arithmetic error that leads to an erroneous calculation, and over-estimation, about the amount of emissions reduction they argue takes place.

- a partial "Life Cycle Analysis" (LCA), omitting CO2-emission part(s) of the process;
- a postulate about "displacement": a claim that production from CO_2-EOR wells displaces production conventional oil wells;
- efficiency ratio (conversion factor) assumptions.

Following is a discussion of these elements.

4.1.1.1. *Life Cycle Analysis and "project boundaries"*

"Life Cycle Analysis" (LCA) is a commonly-used analytic approach in carbon dioxide removal studies. LCA is a crucial concept for evaluating whether a particular CDR process results in a *net reduction of atmospheric* CO_2.

However, researchers define the "life cycle" to be analyzed (often called the "project boundary") differently, depending on their research objectives. In some cases, the objective is to assure "oil production" goals.[61] Using a partial LCA does not make these studies "wrong," but such studies do not address the needs of public policymakers attempting to *reduce* the stock of atmospheric CO_2.

For public policy purposes a "full LCA" for CCS-EOR must include all parts of the process, including "upstream" (power plant energy sourcing and generation) and "downstream" (EOR oil production and combustion) – sometimes called a "cradle to grave" LCA. That is, only studies that examine CO_2 generation from the beginning, or "birth" of the CDR process, to its end, or "grave," are relevant for judging whether that CDR method results in a net reduction of atmospheric CO_2. Figure 4.3 illustrates a full life cycle.

Many studies use only a partial LCA that omits either the upstream part or the downstream part, or both. Some study "boundaries" begin at the point that CO_2 is purchased from the emitting facility (the power plant) and end at the point the CO_2 is injected into the ground for EOR.[62] Faltinson and Gunter (2011) made the argument that only "project-life cycles" (that is, *a partial* LCA) should be considered: "Project-life-cycle emissions attributed to CO_2 EOR should include fugitive emissions directly related to the CO_2-EOR project only, and not include downstream emissions common to all sources of oil supply." Studies that use only a partial LCA report findings and reach conclusions different from those that undertake a full LCA.

The significant consideration for public policy-makers is this: only studies that encompass the <u>full</u> LCA ("cradle to grave") are relevant to the public purpose -- net reduction of atmospheric CO_2.

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[61] E.g., Nunez-Lopez et al. (2019) "Abstract**:** This study evaluates the potential of carbon dioxide-enhanced oil recovery (CO2-EOR) to reduce greenhouse gas emissions **without compromising oil production goals**. A novel, dynamic carbon lifecycle analysis (d-LCA) was developed and used to understand the evolution of the environmental impact (CO2 emissions) and mitigation (geologic CO2 storage) associated with an expanded carbon capture, utilization and storage (CCUS) system, from start to closure of operations."

[62] The relevance of LCA boundary definitions is also emphasized by Cuellar-Franca and Azapagic (2015) who refer to the studies of Jaramillo et. al. (2009) and Hertwich et. al. (2008) with similar system boundaries of a "cradle-to-grave" design of CO_2-EOR projects. Yet, Hertwich et. al. (2008) did not involve aspects from refining the extracted oil and the combustion of refined petroleum products.

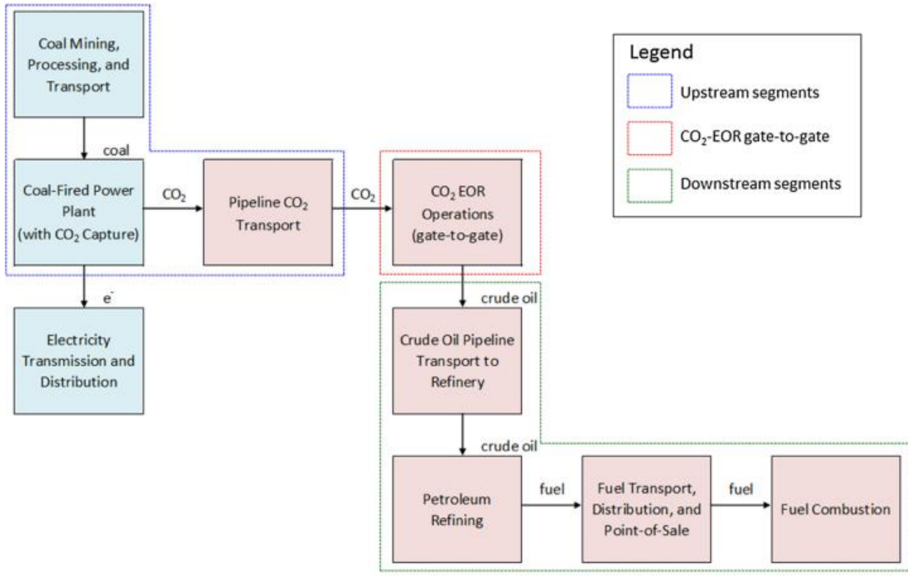

Fig. 1. System boundaries for evaluating the life cycle CO_2 emissions associated with CO_2-EOR.
[Source: Adapted from Cooney et al. (2015)]

Figure 4.3: Example of LCA frames - a full LCA comprises all three colored parts, a partial one relies only on a subset (Source: Azzolina et. al. (2016) "A life cycle analysis of incremental oil produced via CO2 EOR")

4.1.1.2. ***The "displacement" postulate***

The second significant factor that affects conclusions about whether or not CCS-EOR is net additive or reductive in terms of atmospheric CO_2 is the concept of "displacement." Studies that conclude that CCS-EOR reduces atmospheric CO_2 rely on the assertion that the oil produced by EOR "displaces" rather than adds to conventionally-produced oil. The argument generally is that there is a given amount of "demand" for oil and that meeting the demand via CO_2-EOR displaces a certain amount of conventional oil production. Faltinson and Gunter (2011) made the argument that:

> World oil production is determined by world oil demand and if CO_2-EOR projects were not undertaken, some other source of oil would step forward and fill the gap. Therefore, executing CO_2-EOR projects will not result in incremental aggregate refining and consumption emissions.

Numerous subsequent CO_2-EOR studies made similar claims. As Kolster et. al. (2017) point out: "using the displacement assumption" results in a finding of "net negative emissions from CO_2-EOR.[63]

Evidence for the displacement assumption is lacking, and the assertion has been questioned or challenged by a number of CDR researchers. E.g., Jaramillo et.al., (2009) conclude:

> A thorough understanding of ultimate displacement is necessary before anyone can suggest that CO2-EOR is a sequestration technique… It is clear, that without displacement of a carbon intensive energy source CO2-EORsystems will result in net carbon emissions.

Veld et. al. (2013) challenge the displacement argument. In their research, they found that:

[63] From Kolster, et al 2017 "For CO2-EOR, the LCAs differ most significantly on the accounting treatment of produced oil. An assumption of additionality assumes that producing oil via CO2-EOR will add to the global supply of oil and therefore LCAs should include emissions from the combustion of the resulting petroleum products (i.e., diesel fuel). Additionality results in CO2-EOR with net positive emissions.[24,29] The alternative assumption of displacement assumes that EOR-derived oil displaces oil that would have come from another source. Displacement results in net negative emissions from CO2-EOR."

> a key result is that the introduction of EOR may not displace any conventional production at all, though it necessarily will delay the development of some new sources of production. The implication is that, unless EOR projects utilize on average as much CO2 per incremental barrel produced as the CO2 generated when that barrel is consumed, they may not reduce carbon emissions overall.

Moreover, a 2019 report by the Center for International Environmental Law (CIEL)[64] not only rebutted the displacement argument, but pointed out that the U.S. Department of Energy has actually made the argument that CCS-EOR will *add to US oil production*.

> Some EOR proponents argue that the emissions from the produced oil can be ignored because oil from EOR will displace other, purportedly more carbon-intense oil from the markets. In the US context, however, the Department of Energy's analysis did not assert EOR would reduce US domestic oil production. Indeed, DOE argued that "increasing domestic oil production" would be an "important co-benefit" of promoting CO2- EOR.
>
> Claims that oil from CO2-EOR would displace more carbon-intensive oil on global markets, instead of adding to the abundant supplies of government-subsidized oil on those markets, rely heavily on assumptions and forecasts that are, at best, highly disputed. While optimistic supporters claim that over 80% of the oil produced via new EOR will displace oil that would have been produced anyway, other projections suggest a much lower displacement value, closer to 50%. In that case, the proposed emissions benefits of EOR disappear.

Claims that CO_2-EOR-produced oil displaces more carbon-intensive oil on global markets, instead of adding to the supply, rely heavily on assumptions and forecasts that are casually accepted by some scientists.

The displacement argument rests on a conventional approach to economics that confuses **"demand for oil" with *need for energy***. There is no empirical justification for an argument of "displacement,' which is based on market-centric, mainstream economics axioms. In fact, oil "demand" is a variable whose level can be increased or decreased by a number of factors, including public policy. Numbers of countries, states and cities are acting to constrain the demand for oil and other fossil fuels as they move their societies and economies to other ways[65] of meeting their energy ***need***.

4.1.1.3. ***The "efficiency factor"***

Thirdly, the displacement argument is, further, reliant upon assumptions about the "efficiency factor" (also called the "crude recovery ratio," "utilization rate" and "net utilization"). As noted in a paper by the International Energy Agency (2015), "net utilization is a key factor in determining the emissions from CO2-EOR projects." [66]

The "efficiency factor" of the CO_2-EOR process is a production ratio of how much oil is produced (or theoretically produced in some modeling studies) compared to the amount of CO_2 purchased for injection, a factor that is also referred to as "EOR process efficiency" (Hussain et al., 2013) or "crude recovery ratio" (Cooney et al, 2015).

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[64] CIEL, *Fuel to the Fire* (2019). pg 17.

[65] E.g., Germany's "Energiewende" policy http://www.energiewende-global.com/en/; Wettengel, Julian (2019) "Renewables supplied 40 percent of net public power in Germany in 2018", cleanenergywire.org; Jan 2. 2019. Baker, Mike (2020) "To Fight Climate Change, One City May Ban Natural Gas to Heat Homes" New York Times, January 6, 2020.

[66] IEA (2015) "Storing CO2 through Enhanced Oil Recovery – Combining EOR with CO2 storage (EOR+) for profit"

The deliberations about what efficiency factor is appropriate to apply delve into intricate technicalities about the amount of oil that is produced by a particular amount of CO_2 injected. The argument is that even though the net reduction of carbon is higher for saline injection (i.e., no utilization) than for CO_2-EOR (Jaramillo et al., 2009; Cuéllar-Franca & Azpagic, 2015) the carbon benefits are calculated as being based on the efficiency of the CO_2 usage (Dismukes et al., 2019). The benefits of CO_2-EOR as a CDR method are lower if there is a higher number of barrels of oil produced (e.g., five) per ton of CO2 purchased for injection (bbl/tCO2), and the 'benefits increase if the efficiency decreases' to a lower order, e.g. 1-3 bbls of oil produced per ton of CO2 injected (Dismukes et al., 2019). The crude recovery ratio of 4.6-6.5 bbl/tCO2 that was reported by Jaramillo et al. (2009) was criticized by Cooney et. al. (2015) (which refers to estimates from Murrell and DiPietro), and by Azzolina et. al. (2016), which refers to lower recovery ratios than Jaramillo et al. The paper by Azzolina et. al. states that the Jaramillo et al. (2009) paper "greatly exaggerates the efficiency, which, in turn, significantly reduces the amount of CO2 that is estimated to be stored in the reservoir." [67] Importantly, however, the finding of Jaramillo et. al. (2009) that CO_2-EOR projects are net CO_2 emitting was not rejected by other estimates of the CO_2 utilization rate. This fact is also reflected in the study by Azzolina et. al., (2016) which shows values for life-cycle GHG estimates that are above zero, and hence net additive.

The relevant bottom line for the present paper is that studies draw on factors such as efficiency ratios to estimate relative reductions ascribed to various methods, and different assumptions result in differing conclusions.

Moreover, most discussions of the "efficiency factor" point out that climate mitigation benefits can be higher if oil production is "inefficient". For example, EOR oil production of 1-3bbls of oil gained for each ton of CO_2 injected is less efficient but reflects higher emissions reduction than EOR oil production where 3-5bbls of oil are gained per ton of CO_2 injected. Such arguments about the efficiency of the oil production are not inadmissible but miss the point that the end result is higher concentration of CO_2 in the atmosphere. It is necessary to rethink the whole issue of oil production, which indispensably leads to more atmospheric carbon, than ways of carbon accounting that are engrossed with efficiency factor analysis.

See Appendix B for summaries of some of the studies that either discuss or rely on the displacement assumption and discuss the efficiency factor.

4.1.2. Carbon Capture at Emissions Source (CCS/CCUS)

CCS/CCUS is net-additive. Full life cycle analyses of CCS/CCUS shows that this method emits more CO_2 into the atmosphere than it removes, largely because the captured CO_2 is used to produce oil. The method is therefore "net additive": it adds to the stock of CO_2 already in the atmosphere.

The only CCS/CCUS process that is widely practiced at the current time in the U.S. is CO_2-EOR, which uses the captured carbon to produce more oil. That process, called "enhanced oil recovery" (EOR) injects CO_2 into oil wells with "stranded assets" – oil that cannot be extracted through conventional methods. CCS (also called CO_2-EOR) has been employed in the United States for decades, utilizing naturally-occurring CO_2. Only in the last several years has CO_2-EOR using "anthropogenic" CO_2 been promoted as a method of "climate mitigation."

Full "life cycle analysis" of technologically captured post-combustion CO_2 includes: sourcing and processing for capture, transporting, injection into an underground reservoir, producing oil, and the

[67] The result which Azzolina et al. (2016) report an efficiency factor of 2.28 bbl/tCO2, or a net-life cycle emission factor of 0.438 tCO2/bbl. Inverting it yields a value of 2.28 bbl/tCO2.

consumption of that oil. This process puts more CO_2 into the atmosphere than it takes out. Studies that omit any part of the life cycle do not supply the information policymakers need, namely whether there is a net reduction of atmospheric carbon dioxide or not.

The primary studies showing this method to be net additive are:

- Jaramilo et. al. (2009) "Live cycle inventory of CO2 in an enhanced oil recovery system.
- Azzolina et. al. (2016) "How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites".
- Armstrong and Styring (2015) "Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction".
- Dismukes, David E. Michael Layne & Brian F. Snyder (2018) "Understanding the challenges of industrial carbon capture and storage: an example in a U.S. petrochemical corridor"

Following is a brief summary of each of these studies:

1. "Life cycle inventory of CO_2 in an enhanced oil recovery system"[68]

This empirical study shows that "between 3.7 and 4.7 metric tons of CO_2 are emitted for every metric ton of CO2 injected" underground. Thus, this study indicates that **3.7 to 4.7 times as much CO_2 is emitted into the air by the process than is stored by the process.**

This full life cycle analysis study of five operational CO_2-EOR projects in the US, Jaramillo et. al. (2009) included: sourcing and transport of the coal used to generate electricity at a power plant; coal gasification; power generation with point source capture of CO_2; CO_2 transport to the injection field; CO_2-EOR operation; crude oil transport; crude oil refining operation; and end-user combustion. Especially important is the inclusion of petroleum product combustion, which partial "life cycle analysis" studies omit. Combustion of the produced petroleum amounts to about a half of the total emissions in the analyzed projects.

Another important point, which Jaramillo et. al. 2009 make, is that about 93% of all produced oil is used as combustible; only a small share of 7% is used in non-combustible ways. (This number also appears in several studies and does not seem to be a point of disagreement).

2. "How green is my oil?"[69]

This study that argues that CCS with EOR can be used to "reduce" greenhouse gas emissions because it comes from the perspective of relative flow and not absolute stock of CO_2. It argues that because oil produced by the EOR method has lower emissions than conventionally produced oil, and that EOR-produced oil "displaces" conventionally-produced oil, the process represents climate mitigation. The first assertion is based on the study's choice of carbon accounting conventions; the second is based on an unproven economic assumption (see "displacement postulate" discussion earlier). Nevertheless, even this study demonstrates that – if the displacement assumption is eschewed – the overall process puts more CO_2 into the atmosphere than it removes. A close reading of this report reveals that this study indicates that CCS **emits 1.5 times as much CO_2 as it removes.**[70]

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[68] Jaramillo, P, Griffin WM & McCoy ST; 2009; "**Life cycle inventory of CO2 in an enhanced oil recovery system**"; Environmental Science & Technology; 43 (21): 8027-8032.

[69] Azzolina, NA, WD Peck, JA Hamling , CD Gorecki (2016), How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites," *International Journal of Greenhouse Gas Control*; 51 (2016) 369–379.

[70] This calculation does not integrate the "displacement" argument that is generally advanced in this paper. Azzolina, NA, WD Peck, JA Hamling , CD Gorecki (2016), How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites," *International Journal of Greenhouse Gas Control*; 51 369–379.

3. "Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction"[71]

This study includes a full LCA of CO_2-EOR, which in this paper is termed EHR: "enhanced hydrocarbon recovery". The authors find that

> EHR will remain a means for economic benefit but cannot be considered as a mitigation technology **as it ultimately emits more carbon dioxide than it sequesters** through product use. (Emphasis added.)

4. "Understanding the challenges of industrial carbon capture and storage: an example in a U.S. petrochemical corridor"[72]

This study discusses the problem of incomplete LCA studies and notes that the usage of CO_2 for EOR shows a lower carbon reduction compared to saline injection. It discusses the findings of studies that show CCS-EOR to be net additive, and also brings up the irony of CCS-EOR accounting conventions: CCS-EOR operations that are *more* efficient in using CO_2 for EOR are *less* useful in using CO_2 for climate mitigation.

> The EOR process traps CO_2 in the reservoir and can therefore be a mechanism of carbon storage (Godec, Kuuskraa, and Dipietro 2013; Hill, Hovorka, and Melzer 2013), however, the use of EOR as a means of CCS is not without controversy. The fact that the carbon is being utilised to produce additional hydrocarbons, the primary human-induced contributor to climate change, may be considered problematic because it increases the supply of crude, potentially decreasing costs and increasing emissions (De Coninck 2008), although we are unaware of an empirical estimate of this mechanism. Further, the net carbon reduction of injection for EOR is lower than the net benefit of saline injection (Jaramillo, Griffin, and McCoy 2009; Cuéllar-Franca and Azapagic 2015), but the degree of carbon benefit depends critically on the efficiency of CO_2 use. **If CO_2 is highly efficient** such that there are five or more barrels of oil produced per tonne of CO_2 purchased, **then carbon benefits may be very low** (Jaramillo, Griffin, and McCoy 2009). **However, if the efficiency is low,** on the order of 1–3 bbls of oil per tonne of CO_2, **the life cycle benefits of EOR increase significantly** (Azzolina et al. 2015; Cooney et al. 2015; Cuéllar-Franca and Azapagic 2015).

Another report promoting CCS, acknowledges that the process at a coal-fired power plant is net CO_2 additive. According to this report about the financial success of the largest carbon capture plant in the U.S.,

> considering the emissions of the gas-fired turbine that powers the carbon capture system and the emissions from the additional petroleum products resulting from EOR, the total impact of the carbon capture system is actually **an estimated 2% increase in CO2 emissions**.[73] (Emphasis added.)

A further note: the following studies did not conduct an original full life cycle analysis (LCA) but they underscored or cited the relevant findings of Jaramillo et. al. (2009):

- Seto and McRae (2011): LCA of a number of CO_2 EOR scenarios suggest that these projects will increase the amount of CO_2 in the atmosphere, and are not viable solutions for long-term greenhouse gas mitigation.
- North and Styring (2015): An LCA of EOR (Jaramillo study) confirmed that CO_2-EOR would result in a net increase in CO_2 emissions unless the oil recovered could be used to displace an energy producer with even greater CO_2 emissions per mole of carbon combusted.

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[71] Armstrong, Katy and Peter Styring (2015) "Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction" *Frontiers in Energy Research*, 3 March 2015.

[72] Dismukes, David E., Michael Layne & Brian F. Snyder (2018) "Understanding the challenges of industrial carbon capture and storage: an example in a U.S. petrochemical corridor;" International Journal of Sustainable Energy, 4 July 2018.

[73] ScottMadden Management Consultants; "Billion Dollar Petra Nova Coal Carbon Capture Project a Financial Success But Unclear If It Can Be Replicated"; https://www.scottmadden.com/insight/billion-dollar-petra-nova-coal-carbon-capture-project-financial-success-unclear-can-replicated/ Note: the US Dept. of Energy provided $190 million in funding. And the state of Texas provided additional funding.

- Hovorka & Tinker (2010): LCA shows CO_2 EOR projects to have "a significant net carbon emission."
- McCoy (2011): Concurs with Jaramillo paper and outlines the net additive effect of CO_2-EOR as a reason for seeking other public policy measures to remove carbon.

Note: When CO_2 is captured directly from the emissions source and is simply injected into underground storage, the process is likely net CO_2 reductive. However, "[R]enewable technologies generally provide a better energetic return than CCS" (Sgouris et. al. 2019). And CCS requires significant land usage for pipelines and, underground, for geological storage (see details in sections on Dis-Benefits and Problems of Scale).

"Efficiency penalty"
A further note on point-source capture: there is an "efficiency penalty" that arises in connection with capturing CO_2 as it is emitted from power plants. This "efficiency penalty" is entirely different from the "efficiency factor" discussed earlier. The efficiency penalty refers to the added energy required to power CDR equipment at power plants. Powering the machinery to capture the CO_2 entails the combustion of additional fossil fuels, and accompanying additional emissions. The efficiency penalty has been estimated at from 10% to 40% (Oil Change International 2017), referring to the added fuel consumption required over and above normal operations without carbon capture. Most fossil-fueled power plants do not perform carbon capture presently in large part because of the added expense associated with this efficiency penalty. Heinberg (2018) reports that CCS equipment "cannibalizes up to a third of the power produced" – that is, the power plant must either generate extra power to run the carbon capture machinery, or take a loss in terms of the quantity of power produced for sale.

4.1.3. Direct Air Capture (DAC)

DAC (fossil-fuel powered)
"Direct Air Capture" operations that use fossil fuels as their power source are, in most studies,[74] shown to be net-additive in terms of atmospheric CO_2. This is because of the large amounts of energy required to power the machinery and process that captures the CO_2 from ambient air. It is so energy-intensive mainly because CO_2 – at 400 parts per million in the air – is a mere trace. So, it is much more difficult to extract CO_2 this way than to capture it at the source of emissions (e.g., power plant smokestacks), where it is much more concentrated. A widely-cited study showed that DAC **emits from 1.5 to 3.4 tons of CO_2 for every ton captured.**[75]

[74] One report's "best case" scenarios, based on solid sorbent process and other factors, suggests that DAC could be CO_2 reductive: National Academies of Sciences, *Negative Emissions Technologies* (2019). DAC has differing energy requirements partially depending on whether the process uses a liquid for absorption or a solid for adsorption. The latter has lower temperature requirements and thus lower energy requirements. The report by the National Academies of Sciences (2019) (pp 218-219) presents findings for a solid adsorption process in which projections range from net reductive by a factor of 0.13 to net additive by a factor of 2.7.

[75] Based on Smith et al. 2016 pg 47: 156 EJ/yr required to capture ~3.3 Gt Ceq/yr. Calculations performed by S. Davis. 8-19-19; personal communication. Calculations showed the emissions ratio associated with gas as the DAC power source to be 1.46 to 1 [rounded to 1.5 to 1); the ratio with coal as DAC power source is 3.44 to 1. Alternatively, renewable energy sources could be used, which could result in net reduction of atmospheric CO_2. However, the question is whether renewable energy power should be consumed by DAC rather than used for direct energy production for the nation.

DAC, if it operated at significant scale[76] and if powered by fossil fuels would consume an amount of energy nearly equivalent to the total U.S. electricity generated in 2017.[77] It is this remarkably inefficient energy usage that results in CO_2 emissions from DAC exceeding the amount captured.

An analysis by House et. al.[78] concluded that: DAC "can only be viable (i.e., net CO_2 negative) if powered by non-CO_2 emitting sources." Others have made a similar case. Yet, given the enormous energy requirements for extracting CO_2 from ambient air, the question for policymakers is whether to use taxpayers' money and public incentives to direct renewable energy to DAC or to support the development and deployment of renewables to power homes, offices, businesses and cars in order to keep CO_2 emissions from entering the atmosphere in the first place.

Note that **the above DAC estimates are for capture only, and do not include energy requirements and resulting emissions for transporting the CO_2 to underground storage or for keeping it stored there in perpetuity**.

DAC-EOR

As noted above, DAC is reported to be net additive when the power source is fossil fuels, even without considering the potential use of the captured CO_2 for EOR. Far more emissions would result from a DAC-EOR process. Some DAC operations are moving in this direction despite initial stated intentions to produce other products. For example, Carbon Engineering[79] had stated that its captured CO_2 would be used to make synfuels, but in 2019 announced that it is partnering with Occidental Petroleum to build a new DAC plant in the Permian Basin (Texas) to produce oil through EOR. This operation will be taxpayer-subsidized, both federally and at the state level.[80] And another DAC startup – Global Thermostat – has announced plans to partner with ExxonMobil.[81] Graciela Chichilnisky, a co-founder and CEO of Global Thermostat, notes that "The gas captured at [Global Thermostat's DAC operations]… is available for use in applications such as enhanced oil recovery…"[82]

4.2. Resource Usage

As explained in the Methodology section, the approach of this paper in reviewing the CDR literature is to standardize output in order to compare resource input requirements.

Studies differ in their claims and estimates about resource usage, particularly energy and land, and in their claims and estimates about outputs (CO_2 removal) that can be achieved. A chief reason for these discrepancies is that studies differ in their assumptions about *inputs* (resource usage) and thus make conflicting projections about *output* (amount of CO_2 that can be removed by a particular

[76] 1 gigaton of CO_2 removal is the "significant scale" level examined in this report. Much of the literature on CDR is concerned with gigaton-level removal objectives.
[77] Climate Advisers (2018)
[78] House, Kurt Zenz, Antonio C. Baclig, Manya Ranjan, Ernst A. van Nierop, Jennifer Wilcox, & Howard J. Herzog; "Economic and energetic analysis of capturing CO_2 from ambient air**,"** PNAS, December 5, 2011.
[79] A DAC startup in which Bill Gates originally invested.
[80] The facility "will be designed to qualify for both the US federal 45Q tax credits, and California's Low Carbon Fuel Standard credits." Global Carbon Institute, 5 Jun 2019: "Oxy and Carbon Engineering partner to Combine Direct Air Capture and Enhanced Oil Recovery storage."
[81] James Temple; "Another major oil company tiptoes into the carbon removal space" MIT Technology Review June 28, 2019. "ExxonMobil's deal with a startup developing ways to suck carbon dioxide from the air marks another sign of the oil and gas sector's growing interest."
[82] Chichilnisky, Graciela (2019) "Direct Air Capture: The Key To Reversing Climate Change" *Biofuels Digest*, Nov. 20, 2019.

method). And an obverse problem arises in the ways that studies look at resource usage itself: differing studies make assumptions about outputs (amount of CO_2 removed) and therefore make differing claims or estimates about the amount of resources required. Both of these problems create confusion when trying to understand the "bottom line" in terms of resource usage. In order to overcome these problems in a way that can be useful for policy-makers, our approach is to *standardize for outcome*. It is then possible to analyze studies of each CDR method in terms of resource inputs.

Our approach is to examine CDR methods in terms of the removal of 1 Gt (gigaton) per year. For comparison, global annual CO_2 emissions were nearly 37 Gt in 2019; U. S. annual CO_2 emissions in 2017 were approximately 5.3 Gt.[83] Thus, 1 Gt removal is minimal for any significant impact. Also, a number of scientific studies examine impacts at the 1 Gt level, although, once again, there is little consistency among scientific reports.

4.2.1. Energy

Energy required to remove 1 Gt CO_2

Summary:

The "direct air capture" method of carbon dioxide removal when operated at scale could consume a quantity of energy approaching the total electricity generation for the US. For example, to remove 1 gigaton (one billion tons) of CO_2 from the ambient air could, according to one report, consume "3,417 terawatt-hours of electricity annually -- "an amount that is nearly equivalent to all electricity generated in the United States in 2017.**"** Other studies also show similar estimates, ranging from 3,156 to 5,049 terawatt hours, as discussed below.

Yet, even this large amount omits some downstream components of the DAC life cycle process like the energy requirements for transportation or sequestration of the captured CO_2.

CCS is more energy-efficient than DAC, since CCS captures the CO_2 as it comes out of smokestacks. However, a recent study argues that public investments in renewables development would have better "energetic" returns than public investments in CCS *not even considering CCS used for EOR.*

Detailed discussion

4.2.1.1. CCS: Point source capture

CCS is more energy-efficient than DAC, since CCS captures the CO_2 as it comes out of the source of emission – generally power plant smokestacks. However, a recent study argues that public investments in renewables development would have better "energetic" returns than public investments in CCS *not even considering CCS used for EOR*. Sgouridis et. al. (2019)[84] have shown that investments in "renewable technologies generally provide a better **energetic return than CCS**". They found the energetic return on CCS projects to range from 6.6:1 and 21.3:1, whereas the energetic return on renewable electricity ranges from 9:1 to 30+:1. They conclude that

[83] Fleming, Sean (2019) "Chart of the day: These countries create most of the world's CO2 emissions"; World Economic Forum, 7 June 2019.

[84] Sgouridis et al (2019) "Comparative net energy analysis of renewable electricity and carbon capture and storage" *Nature Energy*. 8 April 2019.

"Therefore, renewables plus [battery] storage provide a more energetically effective approach to climate mitigation than constructing CCS fossil-fuel power stations." [Emphases added.]

4.2.1.2. *Direct Air Capture, fossil-fuel powered*

Several studies of DAC have concluded that that the direct air capture CDR method, when fossil-fueled, is thermodynamically counter-productive.

One of the most frequently-cited studies of DAC is by the American Physical Society (Socolow et. al. 2011), which reported 12.5 GJ (gigajoules) of energy to capture 1 ton of CO_2. Similarly, Climate Advisers[85] reports 12.3 GJ per ton of CO_2 captured, and they point out: "At this rate, achieving 1 Gt of removals could require 3,417 terawatt-hours of electricity annually—an **amount that is nearly equivalent to all electricity generated in the United States in 2017."** [Emphasis added.] (This amount does not include the additional energy consumption that would be associated with transport, injection/sequestration or end-product processing.) Yet, a wide range of energy usage is reported in the literature. The "Negative Emissions Technologies" study by the National Academies of Sciences (2019, p 216) reported that the lower-energy-using method of DAC (solid sorbent) could require from 1.92 to 23.09 GJ of energy per ton of CO2 captured.

An analysis by House et. al.[86] concluded that: DAC "can only be viable (i.e., net CO_2 negative) if powered by non-CO_2 emitting sources." (See discussion below on DAC – Renewables-Powered").

Some scientists argue that DAC can be *financially* viable, regardless of thermodynamic outcomes, particularly if government investment is directed to developing the technology. Several authors of scientific reports have financial interests in or ownership of DAC startup businesses.

Socolow et. al. (2011), Smith et. al. (2016), Climate Advisors (2018), House et. al. (2011), Realmonte et. al. (2019) and The U.S. National Academies of Sciences (2018) are briefly summarized here:

1) Socolow et. al. (2011) is one of the most frequently-cited reports on direct air capture. This report, published by the American Physical Society, found that, if 100% efficiency is assumed, the "primary energy requirement" for capturing and compressing 1tCO_2 is 9.9 GJ. Assuming a conversion factor for electricity efficiency of 40% (per Socolow et al. 2011) yields 1tCO_2 an energy requirement of 12.5GJ. (Socolow et. al. 2011, p. 40)

   However, as highlighted in their report on DAC, the American Physical Society focuses purely on estimates of capturing and compressing CO_2. The authors state that the estimates in their report only reflect *capture* costs and do not deal with CO_2 beyond the boundary of the capturing facility. Hence, the energy estimates do not account for further transport, sequestration or end-product processing (p. ii).

   > The cost estimates in this report are *capture* costs. They do not include the cost of dealing with CO2 beyond the boundary of the capture facility. Specifically, the costs of sequestering the captured CO2 from the atmosphere have not been estimated. The principal sequestration strategy under discussion today is injection of CO2 in geological formations for multi-hundred-year storage. The cost of geological storage is expected to be smaller than the capture cost even

[85] Climate Advisers (2018) "Creating Negative Emissions; The Role of Natural and Technological Carbon Dioxide Removal Strategies", June 2018.

[86] House, Kurt Zenz, Antonio C. Baclig, Manya Ranjan, Ernst A. van Nierop, Jennifer Wilcox, & Howard J. Herzog; "Economic and energetic analysis of capturing CO_2 from ambient air," PNAS, December 5, 2011.

for capture from flue gas, but its commercialization at very large scale will require the resolution of formidable reservoir-engineering, regulatory, and public acceptance challenges. It was beyond the scope of this report to investigate post-capture management of CO2 in any detail. (Socolow et al 2011.)

2) Smith et. al. (2016) reported that the energy requirements to remove ~3.3 gigatons of carbon equivalents[87] by DAC would equate to 29% of total global energy use in 2013:

> The energy requirements of amine DAC deployed for net removal of ~3.3 Gt Ceq yr^{-1}would amount to a global energy requirement of 156 EJ yr^{-1} if all energy costs are included. This is equivalent to 29% of total global energy use in 2013 (540 EJ yr^{-1}), and a significant proportion of total energy demand in 2100 (which the IPCC AR5 scenario database estimates will be~500–1,500 EJ yr^{-1}), which will be a major limitation unless low-GHG energy could be used, or the energy requirements significantly reduced. (Smith et al., 2016)

Translating these figures into 1 gigaton of CO_2 removal – the standard we are using in this report – yields 3,580.9 terawatt hours,[88] which is slightly more than the figure of 3,417 terawatt hours reported by Climate Advisers (discussed earlier and below), and equates to nearly the total amount of electricity generated in the U.S. in 2017.

Smith et. al. (2016) bases its values on the results of the Socolow (2011) report, and hence also do not include transportation and downstream elements.

In order to translate scientific notation for wide readership, Climate Advisers (2018) converted "gigajoules" into US energy usage:

> Direct Air Capture; Resource Intensity: …the technology is very energy-intensive… Processing, transporting and injecting CO2 has additional energy requirements, potentially raising the per tCO2 energy intensity to 12.3 GJ. At this rate, achieving 1 Gt of removals could require 3,417 terawatt-hours of electricity annually—an amount that is nearly equivalent to all electricity generated in the United States in 2017. (Climate Advisers, 2018)

This paper cites the Socolow et. al. (2011) study above,[89] and as noted, the energy usage estimate omits energy that would be consumed by parts of the process that are excluded from the study, e.g., transportation, geological injection, combustion of any fuels produced from the captured CO_2.

3) House et. al. (2011) review a number of published analyses on DAC and undertake an empirical analysis of operating commercial DAC processes. The authors conclude that: DAC "can only be viable (i.e., net CO_2 negative) if powered by non-CO_2 emitting sources." In summarizing their research on DAC energy requirements, the authors find that removing 1 gigaton of CO_2 using direct air capture could require from 3,156 terawatt hours to 5,049 terawatt hours. This is commensurate with the findings of 3,580.9 terawatt hours from Smith et. al. (2016) and 3,417 terawatt hours from Climate Advisers (2018), which pointed out that this amount was nearly as much as all the electricity generated in the U.S. in 2017.

4) Realmonte et. al. (2019) advocate for the development of DAC, and model scenarios for that development under various "techno-economic assumptions" (detailed in **Error! Reference source not found.**). Their projection of 300 EJ/yr by 2100 portends substantial energy usage: this projection would equate to 55.56 billion MWh to capture 1Gt/CO_2yr.[90]

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[87] The 3.3 Gt estimate this study represents the upper bound of the range.

[88] Smith et al. 2016 pg 47; calculations performed by S. Davis, co-author, Smith et. al. Personal communication 8-19-18.

[89] The number in Socolow et. al. is 12.5 GJ (pg 40); Climate Advisors does not give a reason for using 12.3 GJ instead.

[90] If 1.5Gt/yr -> 300EJ/yr then 1Gt/yr -> 200EJ/yr = 55.56 billion MWh.

However, this represents only a partial Life Cycle Analysis that leaves out energy requirements for processing and use of the captured CO2 (e.g., for EOR, synfuels or other carbon-emitting uses.) Moreover, one scenario modeled incorporates the use of waste heat – "We include the use of waste heat to operate the amine-based plants, recovering it from energy-intensive industries and renewable power plants." – an assumption that is favorable to desired outcomes but not supportable by current practices. Others have critiqued this paper for making unrealistic assumptions.[91] The paper concludes that **DAC is a means to delay the phaseout of fossil fuels**:

> **"DACCS enables delaying the phase-out of fossil-based electricity generation until after 2050."**

5) The U.S. National Academies of Sciences (2018)[92] study addresses a large panoply of CDR methods, which in this report are called "negative emissions technologies." Its coverage of DAC makes a distinction between liquid solvent and solid sorbent approaches. The latter requires lower temperatures to accomplish the chemical binding needed and therefore uses less energy. The study reports a wide range of 1.93 to 23.09 GJ (gigajoules) per ton of CO_2 captured (pg 216) for *solid* sorbent DAC systems. The range would be significantly higher for liquid solvent systems. For comparison, the widely-cited Socolow et. al. study (2011) reported 9.9 to 12.5 GJ per ton of CO_2.

For additional details on research energy usage for fossil-fueled DAC see **Error! Reference source not found.**.

4.2.1.3. Direct Air Capture – Renewables Powered

House et al (2011) argued that DAC "can only be viable (i.e., CO_2 negative) if powered by non-CO_2 emitting sources." Others have made a similar case. Yet, given the enormous energy requirements for extracting CO_2 from ambient air, the question for policymakers is whether to use taxpayers' money and public incentives to direct renewable energy to DAC or to support the development and deployment of renewables to power homes, offices, businesses and cars in order to keep CO_2 emissions from entering the atmosphere in the first place.

According to the energy requirements shown in Smith et. al. (2016), it would require all of the wind and solar power generated in the U.S. in 2018 to capture just 1/10th of a gigaton of CO_2.[93]

Calculations in paper on DAC by Realmonte et. al. (2019), also indicate that DAC would use all available renewable energy. Commenting on this paper, David Fridley[94] notes that

> In terms of energy requirements as shown in the paper, for electricity alone, around 500 TWh would be needed to capture 1 Gt of CO_2, and to avoid creating additional offsetting emissions, this electricity would need to come from renewable sources, specifically variable renewable generation as mentioned in the study. 500 TWh, however**, is more than total renewable generation in the US** (375 TWh in 2018), about 27% of the world total, and is nearly double the

[91] David Fridley; Fellow, Post-Carbon Institute; Staff Scientist (retired), Lawrence Berkeley Laboratory; personal communication Aug. 2019.

[92] *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. U. S. National Academies of Sciences, Engineering, and Medicine 2018; The National Academies Press.

[93] Calculations by Steven J. Davis, Smith et al 2016 co-author; personal communication 8-19-19: Wind – 275 TWh generated in U.S.; CO2 capture capability: 76.8 million tons of CO2. Solar – 96 Twh generated in U. S.; CO2 capture capability 26.8 million tons of CO2.

[94] Fellow, Post-Carbon Institute; Staff Scientist (retired), Lawrence Berkeley Laboratory; personal communication Aug. 2019.

> increment in renewable generation growth between 2017 and 2018 globally (which was less the increment between 2016 and 2017).

Fridley and Heinberg (2018) address the energy problem in scaling-up DAC, estimating that scaling the DAC process "to remove, say, 1 billion tons of CO2 (1/37th of global emissions) would require 61 TWh, or **more than all the solar power generation in the U.S. in 2017.**"

4.2.1.4. *Direct Air Capture, Utilization and Storage (DACUS)*

As noted above, some DAC plants are now planning to utilize their captured CO_2 for EOR, but since these operations are yet to get fully underway, there is a lack of empirical research about energy usage. Of course, the energy consumed would be in addition to that consumed by the capture process that was enumerated above.

A 2012 article[95] about three DAC startups – Carbon Engineering, Global Thermostat and Kilimanjaro Energy – reported that all three firms initially had planned to sell their captured CO_2 to the oil industry, contrary to later statements from these companies that they intended to use their captured CO_2 for other products.

> Three startup companies led by prominent scientists are working on new technologies to remove carbon dioxide from the atmosphere. The scientific community is skeptical, but these entrepreneurs believe the process of CO2 removal can eventually be profitable and help cool an overheating planet…. All three startups intend to get their businesses rolling by selling CO2 to the oil industry.

4.2.2. Land

Land required to remove 1 Gt CO_2

<u>**Summary**</u>

Most reports on direct air capture (DAC) elide or ignore the land requirements of this method, which become large when operating at scale. CCS also has significant land requirements that are not addressed in many of the reports on this method.

An important note for policymakers is that, while studies of biological CDR methods generally cite land requirements as a potential barrier, few studies point to the tremendous land requirements for renewables-powered DAC.

There are three types of land requirements associated with industrial CDR methods:
- Surface land for the capture process;
- Surface land for pipelines to transport CO_2;
- Subterranean land for geological storage.

There are not large land requirements for the CCS/CCUS capture process itself, but for DAC – particularly if powered by renewables – the land requirements are enormous to operate at scale. The other surface land requirement that usually lacks a prominent place the scientific literature is the requirement for land acquisition for pipelines to transport the CO_2 to injections sites – whether that be for enhanced oil recovery or for injection into caverns. And lastly there is the subterranean "land" that is required for storage in perpetuity.

[95] Marc Gunther (2012) "Rethinking Carbon Dioxide: From a Pollutant to an Asset" Yale e360 February, 23, 2012.

4.2.2.1. *Land use: CCS-EOR compared to photovoltaic*

Groesbeck et. al. (2018)[96] compared land use for CCS-EOR (when the CO_2 capture is from coal-fired electricity plants) with land use for photovoltaic (PV). The study found that land use for CCS-EOR was greater than that for PV and found that:

> the use of coal to provide climate-neutral power **cannot be justified** because the potential for far more effective use of land with PV. This study showed that solar photovoltaic technology is a far superior use of land for climate neutral electricity generation than any technology coupled to coal….**Carbon capture and storage and enhanced oil recovery** can improve coal performance, but for all cases the results **clearly show that PV is a far more effective use of land.** (Emphasis added.)

4.2.2.2. *Direct Air Capture*

To operate at scale (capturing 1 Gt of CO_2), a DAC facility powered by natural gas would require a land area more than five (5) times the size of the city of Los Angeles. This projection is based on the National Academies of Sciences report on *Negative Emissions Technologies* (2019)[97] The report goes on to explain that, if solar is used to replace the fossil fuel power source, then the required land area expands dramatically. Thus, to remove 1Gt of CO_2 would require a land area ten (10) times the size of the state of Delaware.[98] And this does not count the land required for transport and storage after the CO2 has been captured.

Socolow et. al. (2011)[99] did note the substantial land requirements for DAC. A 30-kilometer (19 miles) long "direct air capture" structure would be needed just to balance out the CO_2 emitted from a single coal-fired power plant. And that does not count the emissions from consuming the oil that would be produced by utilization of the captured CO_2 for EOR.

> The physical scale of the air contactor in any DAC system is a formidable challenge. A typical contactor will capture about 20 tons of CO2 per year for each square meter of area through which the air flows. Since a 1000-megawatt coal power plant emits about six million metric tons of CO2 per year, a DAC system consisting of structures 10-meters high that removes CO2 from the atmosphere as fast as this coal plant emits CO2 would require structures whose total length would be about 30 kilometers. Large quantities of construction materials and chemicals would be required. It is likely that the full cost of the

[96] Groesbeck, James Gunnar & Joshua M. Pearce (2018) "Coal with Carbon Capture and Sequestration is not as Land Use Efficient as Solar Photovoltaic Technology for Climate Neutral Electricity Production" *Nature; Scientific Reports.*

[97] National Academies of Sciences, *Negative Emissions Technologies* (2019) pg 224. Calculations: 7 km^2 for 1 million tons of CO2 = 7,000 km^2 for 1 Gt removal of CO2. 7,000 km^2 = 1,729,738 acres, or 2702 sq mi. The city of Los Angeles is 503 sq. mi. NAS report pg 224: "Direct air capture systems have significantly fewer land requirements than do afforestation/ reforestation and BECCS approaches, and because they do not require arable land their impacts on biodiversity would be much smaller. Consider the Amazon rainforest as an example. The net primary production of the Amazon is approximately 270 km2 per Mt/y CO2. With a land area of 5.5 million km2, this equates to an annual CO2 removal of about 20 Gt CO2. As discussed later in this section, the land area requirement for the equivalent CO2 removal using direct air capture is roughly 40 times smaller at **7 km2 per Mt CO2** if powered by natural gas. If you consider a temperate deciduous forest with a net primary production of 390 km2 per Mt/y CO2 and an average tree density of 200 per acre, a single tree acts to remove (net), on average, 50 kg CO2/y; in this sense, a 1 Mt CO2 direct air capture system does the work of 20 million tree equivalents, or a forest spanning 100,000 acres."

[98] "If solar is used to offset 25 percent of the electric and thermal requirements, an additional 3,600 acres of total land area is required. In the theoretical limit where solar power and the Conservation Stewardship Program (CSP) are used to offset all electric and thermal requirements, total land use escalates to 14,500 acres, or roughly 58.6 km2. One-hundred such facilities (representing 100 Mt CO2 removal per year) would require a land area roughly the size of Delaware." National Academies of Sciences 2019, pg 226). [Note: 1 Gt = 1Mt x 1,000.]

[99] Socolow, R. et al. (2011) *Direct air capture of CO2 with chemicals: a technology assessment for the APS Panel on Public Affairs*.; American Physical Society, June 1, 2011

benchmark DAC system scaled to capture six million metric tons of CO2 per year would be much higher than alternative strategies providing equivalent decarbonized electricity.

*4.2.2.3. **Geological storage***

The "storage" aspect of the CCS/CCUS or DAC process requires injection into some kind of underground geological formation. The longevity of such storage can depend on the suitability of sites for long-term CO_2 storage,[100] and can be affected by seismic activity and leakage.

If captured CO_2 is used for EOR, the CO_2 is injected into an oil well where it is meant to remain in perpetuity. Other locations for storage are saline formations (aquifers) and "unminable coal seams" (Herzog 2011). As the Congressional Research Service (CRS) (2018)[101] points out, storage sites require certain features to reduce the extent or likelihood of leakage, a layer of caprock being crucial. In addition, possible storage caverns must be examined and selected based on other qualities such as **porosity, permeability and potential for leakage**.

The quantity of storage capacity is also a major question. The CRS (2018) cites U.S. Dept. of Energy estimates that storage capacity in the U.S. may range from 2,618 to 21,978 Gt of CO_2, (most being in saline formations). However, the IPCC (2005) estimated only 2,000 Gt of *worldwide* storage capacity. As Herzog (2011) notes, "the exact quantity [of geological storage capacity] is highly uncertain." Seto and McRae note that most storage capacity is in saline aquifers (which can lead to water contamination).[102] A report by the European science academy (EASAC)[103] raises questions about the estimated capacity vs practical capacity:

> Regarding capacity potentially available, estimates show that geological sequestration in depleted oil and gas reservoirs, coal beds and saline aquifers has a global 'theoretical' capacity of 35,300 GtCO2, an 'effective' capacity of 13,500 GtCO2 and a 'practical' capacity of 3,900 GtCO2 (Dooley, 2013).

Permanence and safety of storage are also major issues. Both the CRS and the European science academy (EASAC) raise questions about these issues.

Here is CRS:

> For CCS to succeed, it is assumed that each reservoir type would permanently store the vast majority of injected CO2, **keeping the gas isolated from the atmosphere in perpetuity. That assumption is untested,** although part of the DOE CCS R&D program has been devoted to experimenting and modeling the behavior of large quantities of injected CO2. Theoretically—and without consideration of **costs, regulatory issues, public acceptance, infrastructure needs, liability, ownership, and other issues**—the United States could store its total CO2 emissions from large stationary sources (at the current rate of emissions) **for centuries**. (Emphasis added.)

And here is EASAC

> Benson *et al.* (2012) emphasise that environmental risks of geological sequestration appear manageable, but regulations will be required to govern site selection, operating guidelines, and the monitoring and closure of a sequestration facility. Public perception of the safety and effectiveness of geological

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[100] "Mineralization" of CO2 -- "solid storage" -- is also discussed in the literature as a possibility. But there are hurdles; the feasibility of this approach is uncertain; and carbon dioxide removal at scale could result in burying "mountains" of solidified carbon (Clemens 2019; Barnard 2019).

[101] "Carbon Capture and Sequestration in the United States," Congressional Research Service, 2018.

[102] Seto & McRae (2011) [102] (DOI: 10.1021/es102240w) "While depleted oil and gas reservoirs and unminable coal seams are attractive targets for injection because the additional recovery of oil and natural gas (which would otherwise remain trapped in the subsurface) can partially offset costs associated with capture, their capacities are small compared to those of saline aquifers (coal seams: 3-200 GtCO2; oil and gas reservoirs: 675-900 GtCO2; saline aquifers: 1000-10 000 Gt CO2 ([14]). Under most scenarios, saline aquifer storage will be the ultimate target because storage requirements necessary to manage the climate problem are expected to exceed the capacity of oil and gas reservoirs."

[103] EASAC (European Academies, Science Advisory Council) (2018) *Negative emission technologies: What role in meeting Paris Agreement targets?*; February 2018.

> sequestration will likely be a challenge until more projects are underway with an established safety record, especially when the storage site is onshore rather than offshore. Recent debate in Germany over the use of porous sedimentary rocks containing saltwater has focused on dangers of leakage, so that the presence of suitable impermeable strata above the reservoir, speed of carbonation into solid forms and resistance to any unexpected earthquakes become issues.

Further, as Bruhn et. al., (2016)[104] advise, storage may not actually be "permanent," but rather only for a limited time. This study also discussed the wariness of the European public about underground storage of CO_2:

> Since the safety and permanence of geological storage of CO2 are still perceived to be uncertain, CCS has encountered public opposition in some countries (Brunsting et al., 2011; de Coninck and Benson, 2014; Selma et al., 2014). Consequently, due to a spectrum of reasons ranging from technical difficulties, lacking business cases and public opposition, CCS demonstration plants across Europe have largely been cancelled or postponed.

Legislation would be required to assure standards are in place to avert or reduce leakage and earthquakes. And even then, diligent, long-term monitoring and government-funded oversight would be required. Experience thus far with the "45Q" tax credit for CCS indicates discrepancies in industry reporting about how much CO_2 was actually stored. Clean Water Action reviewed[105] industry claims for the 45Q tax credit and found that companies reported one amount to the IRS – nearly 60 million tons – to obtain their tax credits and another amount to EPA – 3 million tons – to certify that they actually permanently sequestered and stored the CO_2. So, companies could only document the "secure geological storage" of a small fraction of the tonnage claimed to be stored for tax credit claims.

Moreover, there may be legal obstacles to geological storage of CO_2. The following is from the 2015 report by the International Energy Agency (pp 14-15):

> The laws and regulations that apply to CO2-EOR operations have evolved to address the issues associated with oil and gas operations, not CO2 storage. In the **United States, for example, property law places limits use of the subsurface that, while allowing for efficient oil recovery, present barriers to CO2-storage** (Marston, 2013). **Without changes to the laws and regulations that apply to CO2-EOR, it may not be possible to reconcile the practice of CO2-storage with that of CO2-EOR**. (Emphasis added.)

*4.2.2.4. **Pipelines***

CCS expansion and DAC would require building pipelines across US land to transport CO_2 from capture sources to injection sites.[106]

Significant amounts of land would need to be acquired and occupied for pipeline buildout. And pipelines have other "disbenefits" such as the potential for "blowouts". Figure 4.4 is a map of

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[104] Bruhn, Thomas, Henriette Naims & Barbara Olfe-Kräutlein (2016) "Separating the debate on CO2 utilisation from carbon capture and storage" Environmental Science & Policy, 60 (2016) 38-43.

[105] John Noel (2018) [Carbon Capture and Release: Oversight Failures in Section 45Q Tax Credit for Enhanced Oil Recovery](); Clean Water Action; May 2018. Among the findings:

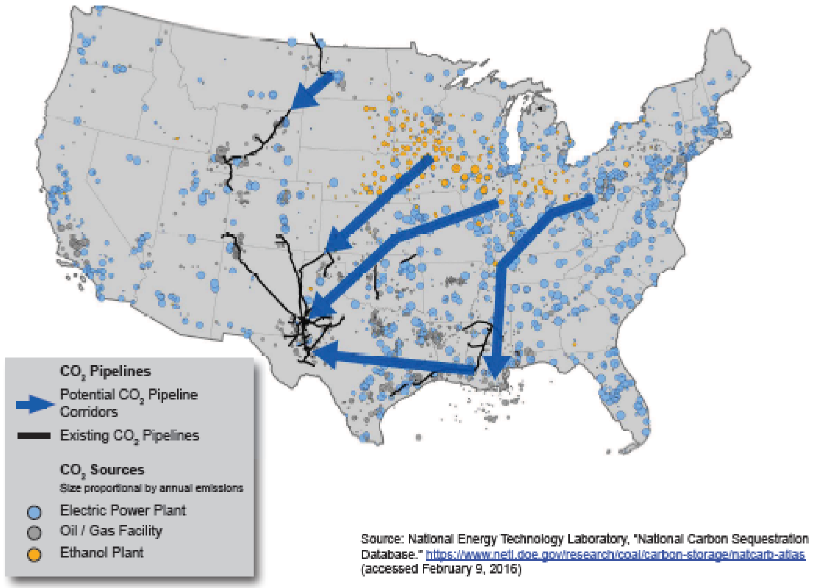
- ***59,767,924:*** *metric tons of CO2 claimed to IRS as captured for tax credit as of May 10, 2017.*
- ***3 million:*** *metric tons of CO2 reported to EPA for sequestration verification as of August 5, 2017.*
- ***$597 million up to $1.3 billion:*** *value of claimed credits.*

[106] DAC advocates argue that "mobile" DAC units could be moved to wherever injections sites are. However, this argument does not address the large land requirements in order for DAC to operate at scale.

pipelines proposed by the "State CO_2-EOR Deployment Work Group" in their 2017 report on "Policy Recommendations for Development of American CO_2 Pipeline Networks".

21st Century Energy Infrastructure:
Policy Recommendations for Development of American CO_2 Pipeline Networks

Figure 2: Potential Regional CO_2 Pipeline Corridors (Illustrative Purposes Only)



Source: National Energy Technology Laboratory, "National Carbon Sequestration Database." https://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas (accessed February 9, 2016)

The five potential priority CO_2 trunk pipeline corridors suggested by this map are:

- **North Dakota to Montana, Wyoming and Colorado.** Moving CO_2 from coal gasification, coal and natural gas-fired power generation and ethanol production southwest into southeastern Montana, connecting the existing North Dakota-Saskatchewan and Wyoming-Colorado-Montana pipeline systems;
- **Upper Midwest to the Permian Basin.** Moving CO_2 from ethanol, fossil power generation, fertilizer production and other industries in the corn-producing heartland of the Upper Midwest into the vast potential and proven reservoirs of the Permian Basin of Texas and New Mexico;
- **Illinois Basin-Midwest to the Permian Basin.** Moving CO_2 from Midwestern ethanol production, fossil power plants and other industries to midcontinent oilfields in Oklahoma, Kansas and Arkansas and the Permian Basin;
- **Louisiana Gulf Coast to the Permian Basin.** Moving CO_2 from the cluster of refining, petrochemical and other industrial facilities in Louisiana to oilfields along the Louisiana and Texas Gulf Coast and on into the Permian Basin; and
- **Ohio River Valley-Lower Midwest to Gulf Coast.** Moving CO_2 from fossil power generation, steel production, and other industries in the industrial and manufacturing heartland of the Lower Midwest to Midwestern oilfields and down to onshore and offshore fields of the Gulf Coast of Alabama, Mississippi and Louisiana.

Page 10 Prepared by the State CO_2-EOR Deployment Work Group

Figure 4.4: Recommendations for Publicly-Subsidized CO_2 Pipelines (Source: "State CO_2-EOR Deployment Work Group" 2017)

Commenting on a draft of the present paper, David Fridley[107] underscored the problem of pipeline buildout in that 1 Gt of CO_2 capture would entail building new pipeline capacity even larger than the existing petroleum pipeline system, which has been built over 150 years. As Fridley explains:

> To inject CO_2 into sequestration sites, the CO_2 must first be compressed to a supercritical state (fluid) for transport and injection. At supercritical pressures, CO_2 reaches the density of 630 kg/m3 (which is less than petroleum, but much higher than the 1.977kg/m3 in its gaseous state). At this density, 1 Gt of CO_2 would turn into the equivalent of 27.4 million b/d of liquid, and this compares to the current US petroleum pipeline system of about 21 million b/d capacity. According to the DOE CO_2 pipeline

[107] Fellow, Post-Carbon Institute; Staff Scientist (retired), Lawrence Berkeley Laboratory; personal communication Aug. 2019. Commentary on draft of the present paper, September 17, 2019.

infrastructure report, the majority of CO_2 pipelines operate in the Permian Basin, and even at full capacity running 24/7, they would carry at most 115 Mt/year (actual utilization is certainly lower). So the gap between what we have and would need even for 1 Gt is vast.

The chart below [Figure 4.5] is from David Hughes (former geophysicist with Natural Resources Canada, also with Post-Carbon Institute) who then scaled these numbers to compare the various SSP climate models and the amount of CCS/BECCS that is being assumed. As you can see, nearly every scenario entails a volume of sequestration that vastly exceed the current GLOBAL oil handling infrastructure. It's patently infeasible.

And this, of course, also begs the question of the "induced demand" to mine the ores, process them, and build all the pipelines, compressors and so forth that such a new huge infrastructure would require. But…**__this is usually hidden as a monetary cost__**, not a new source of CO_2 emissions. (Emphasis added.)

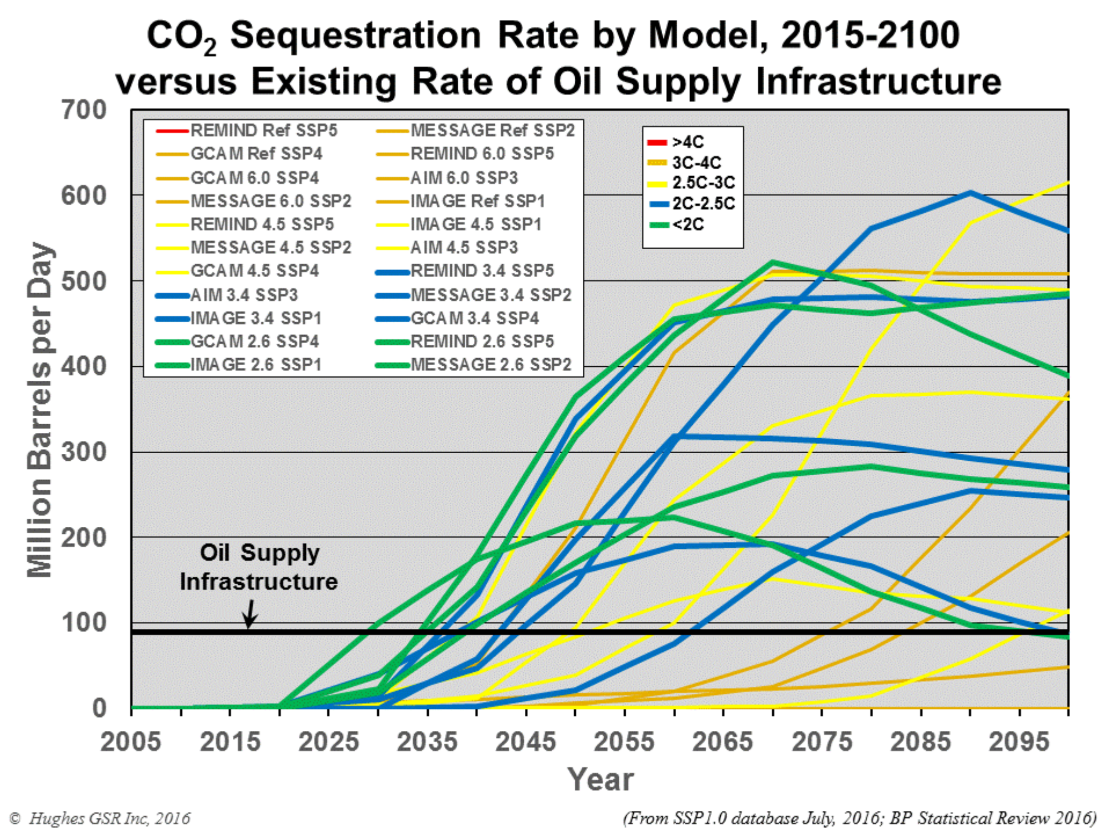


Figure 4.5: CO_2 sequestration rate models (Source: SSP database, 2016)

Similarly, Mac Dowell et. al. (2017) stress the enormous infrastructure buildout that would be required for CO_2 capture and storage to operate at scale. They compare "global anthropogenic emissions [of] about 35.5 Gtco$_2$ per year" (at the time the paper was written) with global oil production and (converting between bbl and Gt) find that "**global CO_2 production today is approximately a factor of 10 greater than global oil production today**, and, at current rates of growth, may be as much as a factor of 20 greater in 2050" (emphasis added). They explain:

> Given that CCS is expected to account for the mitigation of approximately 14–20% of total anthropogenic CO_2 emissions, in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. In other words, we have 35 years to

> deploy an industry that is substantially larger than one which has been developed over approximately the last century…
>
> … This is an exceptionally challenging task, similar in scale to wartime mobilization

4.3. Ancillary effects

When comparing the impacts of CDR methods, it is important for policy-makers to consider "ancillary effects" – impacts and effects in addition to those covered above (which dealt with carbon balance impact and resource usage). The discussion in this section is organized in two categories: "Benefits" and "Dis-benefits" – the latter being a term used in some quarters to refer to harmful impacts or effects.

4.3.1. Co-Benefits

"Energy security"

A number of researchers and advocates of technological carbon capture argue that CDR linked to enhanced oil recovery will enhance United States' energy security. This rationale was pointed out by Dooley, J.J. et. al. in 2010, which cited the "energy security-driven promotion of CO_2-EOR", and adds that

> there can be no doubt that federal subsidies in the name of energy security played a decisive role in establishing the existing CO_2-pipeline network.

The energy security argument was made as recently as April 2019 by bi-partisan Senate group. The following is from a "Democratic News" release of April 5, 2019:[108]

> The Senators' said in part, "As the world transitions towards a carbon constrained economy, investment in CCUS technology will spur economic development and ensure energy security while protecting the environment from carbon dioxide emissions and maintaining global leadership role in research and development."

A booklet by the U. S. Dept. of Energy[109] stresses the potential for CCS-EOR to foster U. S. energy security, explaining:

> the significant potential of CO2 EOR to contribute to the nation's future oil supply. Increasing the volume of technically recoverable domestic crude oil could help reduce the Nation's trade deficit and enhance national energy security by reducing oil imports, add high-paying domestic jobs from the direct and indirect economic effects of increased domestic oil production

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[108] Manchin And Bipartisan Group Of Senators Urge Support For DOE Carbon Capture Technology Programs; April 5, 2019; https://www.energy.senate.gov/public/index.cfm/2019/4/manchin-and-bipartisan-group-of-senators-urge-support-for-doe-carbon-capture-technology-programs

[109] National Energy Technology Laboratory / U. S. Dept. of Energy (undated) "Carbon Dioxide Enhanced Oil Recovery; Untapped Domestic Energy Supply and Long Term Carbon Storage Solution".

4.3.2. "Dis-benefits"

The literature on CDR shows a number of "dis-benefits", including:

- Blowouts – of pipelines or other equipment;
- Earthquakes – resulting from underground storage of CO_2 under high pressures. (Industry's term, normally used in the scientific literature, is "seismic events".);
- "Fugitive emissions" – leakage of the CO_2 from pipelines, storage or elsewhere;
- Pipelines extending over many thousands of miles across the U.S.;
- Aquifer acidification;
- Air pollution and health damage.

Johnson[110] summarized some of the "dis-benefits" of industrial carbon removal methods:

> Besides for the contingencies related to capture, the proof of concept for how to utilize or store the captured CO2 coming from CCUS plants, still remains an issue. Transportation and geo-storage of captured CO2 from a CCUS system carries the potential for **migration and leaks, increased seismic activity, and aquifer acidification.** The long-term liability issues related to geo-storage will be shouldered by the taxpayer with mechanisms similar to the liability structures in the nuclear energy industry. (Emphasis added.)

Clean Water Action has prepared a summary[111] of some of the environmental risks of CO_2-EOR, **Carbon Dioxide EOR - A Threat To Water and the Environment - Nov 2017.pdf**, which is excerpted here:

What is CO_2-EOR?

CO2-EOR includes several specific oil production methods that involve the injection of CO2 into oil-bearing formations through injection wells. It's important to note that CO2 injection is usually combined with other injected fluids or gases. Together these technologies account for approximately 5% of US oil production associated with more than 13,000 CO2 injection wells. The main CO2-EOR technologies include:

- *Continuous CO2 injection;*
- *Continuous CO2 injection followed by water injection;*
- *Water-alternating-gas (WAG) injection, the most common form of CO2-EOR, in which either fresh water or produced water (oil field wastewater) is injected in intervals between CO2 injections;*
- *WAG followed by gas, in which a cheaper gas such as nitrogen is injected following the CO2 injection cycle.*

Environmental Risks of CO_2-EOR

CO2-EOR presents many of the same environmental risks and threats to drinking water as other oil and gas production activities including hydraulic fracturing and conventional drilling. While proponents sometimes claim that CO2-EOR is safer or cleaner than other drilling, there are significant risks and environmental problems that call that assertion into question. Among the threats to drinking water that CO2-EOR shares with other forms of production:

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[110] David Johnson (undated)"Why Not Soil Carbon?" https://www.csuchico.edu/regenerativeagriculture/_assets/documents/research-david-johnson-atmospheric-co2-reduction-final.pdf

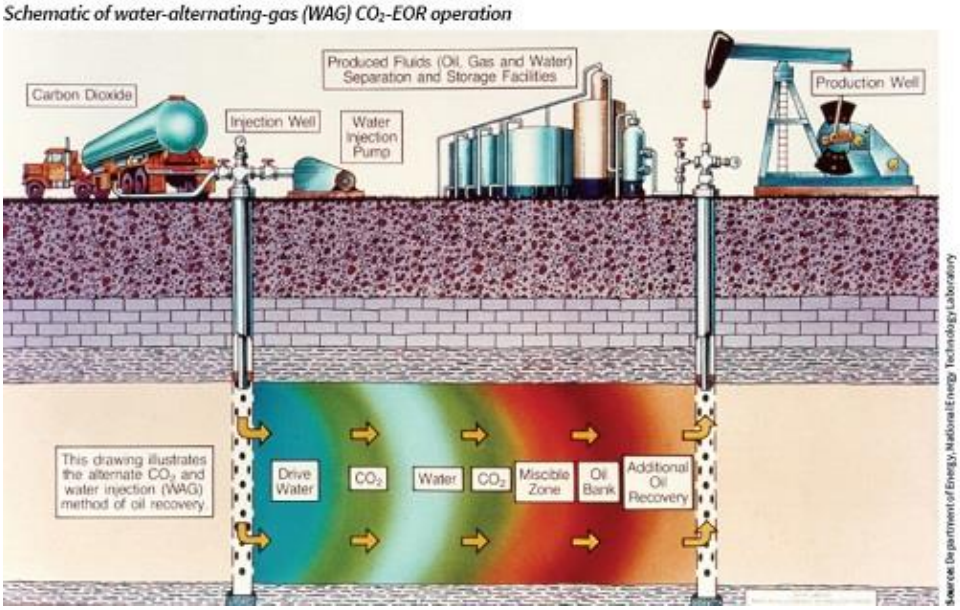
[111] https://www.cleanwaterfund.org/publications/carbon-dioxide-enhanced-oil-recovery-co2-eor

- *Improper disposal and spills of chemicals, produced water and other wastes impacting surface and/or groundwater, air, and land;*
- *Well failures, leaks or breaches causing groundwater contamination;*
- *Migration of chemicals, wastewater or oil and gas through natural pathways or idle/abandoned wells; and*
- *Water consumption, acquisition, and competition with other uses.*

CO2-EOR also presents unique threats to water and the environment, which can make this production technique potentially more environmentally harmful than other methods.

- *Since EOR often occurs in older oil fields, outdated well construction standards not designed for CO2-EOR conditions may increase risk of equipment or well failures.*
- *Blowouts from CO2-EOR injection can and do occur. While there is a lack of comprehensive data on the risk or frequency of blowouts, numerous CO2-EOR blowouts have been recorded over the last 30 years.*
- *When CO2 reacts with water in oil-producing formations, carbonic acid is produced, creating a corrosive environment. This reaction increases the risk of degradation and corrosion of equipment, and amplifies the threat of leaks and blowouts.*
- *The acidic environment can mobilize and dissolve elements and compounds that can impact drinking water sources, such as boron, barium, calcium, chromium, strontium, depending on the formation.*
- *Blowouts can pollute the surface environment if produced fluids, oil, and drilling muds are brought up the well are discharged. In 2011, a 37-day long blowout of a Denbury Resources well in the Tinsley Field, Mississippi, resulted in the removal of 27,000 tons of contaminated soil and 32,000 barrels of contaminated fluids.*

Schematic of water-alternating-gas (WAG) CO_2-EOR operation



- *Blowouts can also impact air quality. In addition to reversing any potential climate benefits of CO2 injection, large CO2 releases can harm local wildlife and people. The Tinsley Field blowout led to health impacts for first responders and oil field workers, and the asphyxiation of animals in the area.*

Finally, since CO2-EOR often extends the life of an oil field, sometimes by decades, the threats to water, air, land, and health, are all extended. Research has found that older oil fields have increased environmental (including climate) impacts, as dirtier, harder to reach oil is produced. More energy is required to extract and refine crude from older oilfields. Additionally, as equipment ages, the likelihood of failures, spills, and leaks increases.

Proponents of EOR, often claim that extending the life of an oil field is preferable to drilling new wells, yet that assumption may not always be true.

Air pollution and Health Damage

Jacobson (2019)[112] studied two carbon capture facilities, one a point-source capture at a power plant and the other a direct air capture facility, and concluded that these methods are inefficient in carbon capture and, he stresses, also add to air pollution and adverse health impacts. In his study of the two plants, Jacobson found that even ignoring the emissions from EOR, the CCS and DAC facilities captured only a negligible fraction of either point source or ambient air CO_2 removals. He finds that, besides their inefficiencies in atmospheric CO_2 reduction, the processes also emit other greenhouse gasses, producing air pollution and resulting in health damage.

Leakage and Questions of Storage Permanence

Leakage of CO_2 from underground storage is a significant concern. Many studies, including those that advance CCS as a climate mitigation method, point to the risk of leakage. Storage strata require certain qualities in order to minimize the amount or likelihood of CO_2 escaping from storage. For example, there must be a layer of impermeable "cap rock" above the porous rock into which the CO_2 is injected. (Herzog 2011). But even with the desired criteria met, leakage, and even "massive release" events are possible. Moreover, storage must be monitored indefinitely into the future through "long-term stewardship" as Herzog calls it. A further concern is "Liability [for] environmental or health problems." (Herzog 2011.)

Bruhn et. al. (2016) advise that CCS storage is not necessarily permanent:

> [H]opes that CCU could represent a promising perspective for contributing to mitigation efforts should not be exaggerated and considerations of CCU in climate politics need to account for the largely varying and technology specific temporary storage times of CO2 and its specific substitution potential. Consequently, we call for accounting mechanisms and legislations for CCU that acknowledge the different storage durations and efficiency gains of CCU technologies.

Venting and Flaring

Another matter of concern to public policy makers considering government support for technological-industrial methods of CDR is the "venting" of CO_2 into the atmosphere. This is discussed in several studies, including Stewart & Haszeldine (2015):

> [W]e find that the largest contribution to offshore emissions is from flaring or venting of reproduced CH4 and CO2. These can already be greatly reduced by regulation.

4.4. The Problems of Scale

"Scale" is a twofold issue, with numerous associated problems. First, the amount of CO_2 that is being captured and stored through CCS/CCUS and DAC currently is negligible in comparison to the scale of the problem (Mac Dowell 2017; Minx et al 2018; Fuss et al 2018; Nemet et al 2018; Honegger & Reiner 2017; Jacobson 2019; Herzog 2011). Secondly, when scaling up to have significant impact on the stock of CO_2 in the atmosphere, there are enormous biophysical implications and impacts that many papers ignore or slight. Some of these were summarized above, in the section on Ancillary Effects.

[112] Jacobson, Mark Z.(2019) "The Health and Climate Impacts of Carbon Capture and Direct Air Capture"; *Energy & Environmental Science*, 2019, DOI:10.1039/C9EE02709B

Over the last 250 years, since the beginning of the industrial revolution, the stock of atmospheric CO_2 has vastly increased: Compared to pre-industrial levels which were at 280 ± 10 ppm (a level that existed for several thousand years[113]) we are currently (2018) at a global atmospheric CO_2 level of 407ppm.[114] Globally, CO_2 annual emissions have reached nearly 37Gt annually[115] and U.S. annual CO_2 emissions in 2017 were approximately 5.3 Gt[116] or nearly 15% of global emissions.[117]

There is no consensus on precisely what level of atmospheric CO_2 is "safe", or what levels would enable us to avoid exceeding the 1.5° Celsius or 2° Celsius targets. Estimates have ranged from 350ppm[118] to 507ppm[119]. According to one report (Kemp 2019),

> Science advisers on the Intergovernmental Panel on Climate Change have estimated the limits imply an atmospheric CO2 concentration of no more than 450 parts per million (for 2 degrees) or 430 ppm (for 1.5 degrees).

A study by Mac Dowell et. al. (2017)[120] puts a spotlight on the scale issue and **calculates that a sequestration rate of 2.5 $GtCO_2$ per year is needed by 2030 and the amount must increase significantly after that**.

> [I]n order to reduce global CO_2 emissions to 80% of 1990 levels by 2050, **it will be necessary to reduce anthropogenic emissions by approximately 42 $GtCO_2$ per year by 2050** compared to a 1990 baseline in line with the IEA and IPCC scenarios. To achieve this, it is anticipated that, amongst other things, it will be necessary to sequester a cumulative 120–160 $GtCO_2$ in the period to 2050, or 16–20% of the cumulative mitigation challenge. **This corresponds to a rate of CO2 sequestration of approximately 2.5 $GtCO_2$ per year by 2030, increasing to 8–10 GtCO2 per year by 2050** with further increases in the rate of sequestration in the period to 2100.

This study pointed to two problems with technological methods in particular. First, the CO_2 "utilization" argument falls short because the amount of CO_2 that needs to be removed and permanently sequestered so far exceeds potential demand for captured CO_2 that such utilization would make only a "negligible contribution" to CO_2 removal. Secondly, (and as described above) the infrastructure requirements technological carbon capture and storage would be enormous: in order to sequester a significant amount of CO_2 in sufficient time to meet projected level of CO_2 reduction needed, "the CCS industry will need to be larger by a factor of 2-4 in volume terms than

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113 IPCC, "The carbon cycle and atmospheric carbon dioxide" https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf . According to the IPCC, "the present atmospheric CO2 concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years" and most importantly it is caused by human action: Atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2, and about 75% of these emissions are due to fossil fuel burning. IPCC "The Carbon Cycle and Atmospheric Carbon Dioxide " (https://www.ipcc.ch/site/assets/uploads/2018/02/TAR-03.pdf)

114 Lindsey, Rebecca (2019) "Climate Change: Atmospheric Carbon Dioxide, Sept. 19, 2019 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide.

115 Global Carbon Project; "Global Carbon Budget" https://www.globalcarbonproject.org/carbonbudget/19/highlights.htm; "Global greenhouse gas emissions will hit yet another record high this year"; Chris Mooney & Brady Dennis, *Washington Post*, Dec. 3, 2019.

116 Fleming, Sean (2019) "Chart of the day: These countries create most of the world's CO2 emissions"; World Economic Forum, 7 June 2019.

117 Fleming, Sean (2019) "Chart of the Day: These countries create most of the world's CO2 emissions" *World Economic Forum*, 7 Jun 2019. https://www.weforum.org/agenda/2019/06/chart-of-the-day-these-countries-create-most-of-the-world-s-co2-emissions/ . Also: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#cumulative-co2-emissions

118 Bill McKibben citing esteemed NASA scientist James Hansen in 2007. McKibben, Bill (2007) "Remember This: 350 Parts Per Million" *Washington Post*, Dec. 28, 2007.

119 "How much CO2 at1.5° C and 2° C?" July 2018, https://www.metoffice.gov.uk/research/news/2018/how-much-co2-at-1.5c-and-2c

120 Mac Dowell et. al. (2017) "The role of CO2 capture and utilization in mitigating climate change" Nature Climate Change, Vol 7, 5 April 2017.

the current global oil industry." Mac Dowell et. al. concluded that technological-commercial methods of CDR "may prove to be a costly distraction, financially and politically, from the real task of mitigation."

The European Academies, Science Advisory Council (EASAC) has also issued cautions in regard to the scale issue. Their 2018 paper, "Negative emission technologies: What role in meeting Paris Agreement targets?"[121] notes the "limited potential" of atmospheric CO_2 removal:

> [W]e conclude that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios…
>
> Scenarios and projections of NET's future contribution to CDR that allow Paris targets to be met thus appear optimistic on the basis of current knowledge and should not form the basis of developing, analyzing and comparing scenarios of longer-term energy pathways for the European Union (EU).

Also see the information on scale requirements by David Fridley in the "Pipelines" section above.

'Wartime mobilization' scale

A few authors who have addressed the scale issue from a biophysical perspective have emphasized that the scale of effort that would be needed is equivalent to "wartime mobilization".

Here is how Mac Dowell et (2017) al describe it:

> Given that CCS is expected to account for the mitigation of approximately 14–20% of total anthropogenic CO_2 emissions, in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. **In other words, we have 35 years to deploy an industry that is substantially larger than one which has been developed over approximately the last century**, resulting in the sequestration of 8–10 GtCO2 per annum by 2050[22] with a cumulative CO_2 storage target of approximately 120–160 GtCO2 in the period to 2050[17] and between 1,200–3,300 GtCO2 over the course of the twenty-first century[13]. **This is an exceptionally challenging task, similar in scale to wartime mobilization**…(emphases added).

The Climate Investigations Center (2019) "Carbon Capture: Expensive Pipe Dream or 'Holy Grail'?" described the "massive amounts of costly infrastructure" that would be required in order to operate at scale. Even the former CEO of ExxonMobil, Lee Raymond, stressed the challenge while speaking at a 2007 National Petroleum Council event: "it is a huge, huge undertaking… and the cost is going to be very, very significant."[122]

Joseph Romm, editor of "Climate Progress," wrote in 2008[123] that "450[ppm] needs a World War II-scale effort starting in the next decade."

Michael Barnard, a writer and consultant on energy and climate strategy, has put the scale issue in graphic terms. Writing about direct air capture (2019), "Air Carbon Capture's Scale Problem: 1.1 Astrodomes for a Ton of CO2," Barnard notes:

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[121] **EASAC (European Academies, Science Advisory Council**) (2018) *Negative emission technologies: What role in meeting Paris Agreement targets?*; February 2018.

[122] Climate Investigations Center (2019) https://climateinvestigations.org/carbon-capture-sequestration-ccs/

[123] Romm, Joseph (2008) "What is the safe upper limit for atmospheric CO2?" Grist, Jan. 1, 2008.

> for a million ton per year solution [far short of the 1 Gt (one billion) level] would [require] constructing a kilometer long, 20-meter high, 8-meter thick wall of fans…"

and…

> If we wanted to just deal with 10% of our annual increase in CO2, we'd need to filter the air out of 44 billion Houston Astrodomes or 32 million Grand Canyons. And think of all the electricity we'd need for the fans and heating the water.

Scaling up: the "stepping stone" argument.

Some authors and observers have argued that government should subsidize CCS-EOR in order to develop and scale-up the technology in order to have CCS *without* EOR at some time in the future, presuming that CO_2 concentrations will become so large as to precipitate a "climate emergency".

Those who have made the "stepping stone" argument include Boot-Handford and colleagues (2014), who stated that despite the caveats "it may still be worth undertaking CO2-EOR as a stepping stone to rapid building of large numbers of capture plants connected to pipeline networks, connected to multiple storage sites which will reach their full potential after the additional oil production is exhausted", and Hu and Zhai (2017) who also see the concerns about CO_2-EOR technology but find it "an economically feasible option as a short-term solution to facilitate CCS deployment and technological learning". Accepting the risks of CO_2-EOR and its additive emissions, these authors claim there is value in supporting CO_2-EOR as a way to promote technological and infrastructural development. (See **Appendix** for more information on these two reports.)

The stepping stone argument has been challenged by, among others, Dooley et. al. (2010) who found that:

> this energy security-driven promotion of CO2-EOR do[es] not provide a robust platform for spurring the commercial deployment of carbon dioxide capture and storage technologies (CCS) as a means of reducing greenhouse gas emissions.

and further that:

> there is also little to suggest that CO2-EOR is a necessary or significantly beneficial step towards the commercial deployment of CCS as a means of addressing climate change.[124]

Those who make the stepping stone argument neglect or slight the adverse side-effects associated with scaling up, which we have summarized above.

[124] Dooley J, Dahowski R, Davidson C. CO2-driven enhanced oil recovery as a stepping stone to what? Technical Report PNNL-19557, Pacific Northwest National Laboratory; 2010.

5. Legislation Passed and Pending

Carbon Dioxide Removal Legislation Passed by or Pending in the U.S. Congress

The U.S. Congress in 2018 enacted a significant expansion of an existing tax credit for carbon dioxide removal. This expanded "**45Q" tax credit**[125] loosened the qualifications and increased the subsidy for industrial-commercial carbon capture. One source at the time predicted that the legislation would likely be "the largest subsidy given to the fossil fuel industry by the United States government."[126] Claimants for these funds had previously claimed 60 million $MtCO_2$ for IRS tax credits, but reported to the EPA only 3 million $MtCO_2$ as permanently stored, an anomaly found in a study by Clean Water Action.[127]

Additional federal subsidies under the **"USE IT Act"** and the **"EFFECT Act"** are moving through Congress, along with other bills that have been introduced, summarized below.

5.1. Legislation Passed

5.1.1. 45Q tax credit

Enacted in 2018

Expanded and extended a previous tax credit for carbon capture: tripled the amount of the tax credit; removed a cap on CO_2 tonnage qualifying for the credit; extended the credit to direct air capture.[128] Of special note is that 45Q incentivizes counter-productive action in terms of atmospheric CO_2 reduction by increasing the amount of the credit for EOR, thus making it more profitable than sequestration:

> **Under 45Q, selling to EOR is more profitable than saline sequestration.**[129] The latter pays $50 per ton in tax credits. EOR gets $35 in credits plus the delivered cost of the CO_2, which, depending on the price of oil, could be anywhere between $15–30 a ton. The deal is further sealed when you consider the preference for cash over tax credits and the regulatory difficulties of acquiring permits for saline sequestration wells. [Emphasis added.]

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[125] An environmentalist analysis of the 45Q legislation: Expanding Subsidies for CO2-EOR. An industry summary: Three Things to Know.

[126] Redman 2017 http://priceofoil.org/2017/10/24/expanding-subsidies-for-co2-enhanced-oil-recovery-a-net-loss-for-communities-taxpayers-and-the-climate/

[127] Noel 2018 https://www.cleanwateraction.org/sites/default/files/docs/publications/Carbon%20Capture%20and%20Release%20-%20Clean%20Water%20Action%20-%20May%202018%20-%20Web%20Resolution.pdf

[128] National Law Review (2019) "Enhancements to the New Section 45Q Tax Credit" May 3, 2019.

[129] Matt Lucas (2108) "45Q Creates Tax Credits for carbon capture. Who benefits?" Carbon 180.

5.2. Legislation Pending

5.2.1. USE IT Act (Utilizing Significant Emissions with Innovative Technologies Act)[130]

Provides public funding for:
* commercial development of carbon capture;
* promotion and development of direct air capture for private sector and commercial uses;
* facilitating the construction of pipelines for CO_2 transport;
* use of captured carbon for Enhanced Oil Recovery.

5.2.2. EFFECT Act (Enhancing Fossil Fuel Energy Carbon Technology Act)

The EFFECT ACT would direct the Department of Energy's Office of Fossil Energy to establish four new research and development (R&D) programs focused on coal and natural gas technology, carbon storage, carbon utilization, and carbon removal.

Following is from senate.gov[131]

The EFFECT Act would expand the DOE's fossil energy research and development (R&D) objectives and establish new R&D programs for carbon capture, utilization, storage, and removal, including:

- A Coal and Natural Gas Technology Program for the development of transformational technologies to improve the efficiency, effectiveness, costs, and environmental performance of coal and natural gas use.
- A Carbon Storage Validation and Testing Program to conduct research, development and demonstration for carbon storage and establish a large-scale carbon sequestration demonstration program, with the possibility of transitioning to an integrated commercial storage complex.
- A Carbon Utilization Program to identify and assess novel uses for carbon, carbon capture technologies for industrial systems, and alternative uses for coal.
- A Carbon Removal Program for technologies and strategies to remove atmospheric carbon dioxide on a large scale, including an air capture technology prize competition.

5.2.3. Fossil Energy Research and Development Act of 2019

This bill expands Department of Energy (DOE) research, development, and demonstration programs for fossil energy.[132] The bill authorizes DOE programs including:

- carbon capture technologies for power plants, including technologies for coal and natural gas;
- carbon storage;
- carbon utilization, including to assess and monitor potential changes in life cycle carbon dioxide and other greenhouse gas emissions;
- carbon dioxide removal from the atmosphere;
- methane leak detection and mitigation; and
- identifying and evaluating novel uses for light hydrocarbons produced during oil and shale gas production.

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[130] USE IT Act (S.2602), U.S. Senate ; Rathi, Akshat (2018) "A bipartisan US group introduced another bill to support a controversial climate technology" qz.com April 1, 2018;
Barrasso, John, U.S. Senator (2019) "USE IT Act: Reducing Emissions Through Carbon Use Innovation, Not Regulation"; March 18, 2019; Carbon Capture Coalition Hails Bipartisan Introduction of the USE IT Act Feb. 13, 2019

[131] https://www.energy.senate.gov/public/index.cfm/2019/4/manchin-murkowski-capito-cramer-daines-bill-authorizes-full-suite-of-carbon-capture-utilization-storage-and-removal-technology-programs

[132] Congress.gov Fossil Energy Research and Development Act of 2019

5.2.4. LEADING Act of 2019 (Launching Energy Advancement and Development through Innovations for Natural Gas Act)[133]

This bill is intended to make carbon capture commercially viable. It directs the Department of Energy (DOE) to establish a program to award funding to construct and operate facilities for capturing carbon dioxide produced during the generation of natural gas-generated power.

5.2.5. Carbon Capture Improvement of 2019

Amends the Internal Revenue Code to provide for the issuance of tax-exempt facility bonds for the financing of carbon dioxide capture facilities.[134]

5.2.6. Clean Industrial Technology Act of 2019

The "Clean Industrial Technology Act of 2019" is meant to: "incentivize innovation and to enhance the industrial competitiveness of the United States" and would support "carbon capture technologies" for this purpose.[135]

5.2.7. SEA FUEL Act, 2019 (Securing Energy for our Armed Forces Using Engineering Leadership Act) [136]

Provides funding for research and deployment of direct air capture and blue carbon technologies and conversion to fuels and other materials. Directs the Departments of Defense and Homeland Security to "pioneer" these technologies.

5.2.8. CLEAN Future Act (Climate Leadership and Environmental Action for our Nation's Future Act)[137] (drafted Jan. 2020)

This legislation would provide several types of subsidies and incentives for technological-commercial CDR, and establishes a program for taxpayer-funded purchases of low-carbon industrial products (which could be made with captured CO_2.) The proposed legislation also contains numerous other provisions unrelated to CDR; the bill is meant to be an alternative to the Green New Deal[138] (Grandoni 2020).

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[133] Congress.gov [Launching Energy Advancement and Development through Innovations for Natural Gas Act of 2019](#)
Senator Crenshaw website: [Crenshaw Introduces Bipartisan Carbon Capture Legislation](#)
[134] Congress.gov [Carbon Capture Improvement Act of 2019](#)
[135] Congress.gov [The Clean Industrial Technology Act of 2019](#)
[136] "Bipartisan Bill to Improve Military's Energy Security Included in NDAA"; December 17, 2019; https://www.whitehouse.senate.gov/news/release/bipartisan-bill-to-improve-militarys-energy-security-included-in-ndaa
[137] [Clean Future Act](#) legislative framework Memo.
[138] The Green New Deal Resolution supports biological methods of carbon drawdown and sequestration.

6. Conclusion

This report summarized and highlighted scientific literature and journalistic reporting on technological-industrial methods of carbon dioxide removal (CDR), focusing on findings that are most relevant for public policy. The organizing principle for this document is that *reducing the concentration of CO_2 in the atmosphere* is the *public purpose goal* – the purpose for which legislative action would be considered or taken. This public purpose derives from collective need, which in turn derives from the scientific virtual-consensus that excess atmospheric CO_2 is the most important GHG driving global warming and climate change.[139] This study also addressed two other questions of direct relevance and major significance for public policymakers and legislators: What is the quantity of resources (particularly energy and land) required to operate at scale? What are the ancillary impacts of various CDR methods, particularly when operating at scale?

From a public purpose perspective, and given the foregoing analysis of technological CDR methods, the literature does not support the use of public funds to subsidize the development of technological-commercial CDR, and most particularly, those methods that have been shown to emit more CO_2 than they remove, thereby adding to the existing stock of atmospheric CO_2.

Government's new assignment: reduce atmospheric CO_2

Given the urgency of reducing atmospheric CO_2, voices from many quarters – industry, the investor community, political leaders, as well as climate scientists – have called for government action. Financing the removal of atmospheric carbon has been declared a responsibility of the state.

Indeed, the U.S. Congress has already acted. Legislators from both political parties have been persuaded to make a major public investment in carbon capture technology: lawmakers in 2018 enacted subsidies for carbon capture and storage in the form of a tax credit to industry. Additional subsidies are currently moving through both chambers of Congress.

Legislation enacted and pending contravenes known science and ignores natural methods of atmospheric carbon removal. [140]

Legislative action thus far has relied on the premise that commercial operations and market forces can meet the collective need to reduce atmospheric CO_2. Lawmakers have banked on the presumption that the government's role is simply to subsidize private ventures in order to bring down their cost of CO_2 removal, making commercial operations for carbon re-use viable. Such logic leads directly back to carbon dependency. It also disregards known risks of CCS technology and foregoes benefits of alternative methods being ignored.

At hand are proven natural carbon removal and storage methods that rely on the intrinsic capacities of vegetation (photosynthesis) and soil sequestration: retaining and restoring forests and improved forest management; restoring wetlands and grasslands; regenerative farming techniques and improved farm soil management; creation of a "green infrastructure" using many varieties of vegetation. Forests annually remove the largest amount of CO_2 from the planet's atmosphere; wetlands and soils store the greatest quantities accumulated over hundreds of years. Natural

[139] "So far as radiative forcing of the climate is concerned, the increase in carbon dioxide has been the most important (contributing about 60% of the increased forcing over the last 200 years)…" pg xxxvii; Intergovernmental Panel on Climate Change (1990) *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press.

[140] Legislation to support biological methods of CDR is in the discussion stage or has gained little traction.

processes currently remove 55% of our annual emissions.[141] Government support to more widely deploy and enhance natural processes of carbon capture and sequestration could move us back toward carbon balance, and at less jeopardy than technological-commercial methods.

However, if massive government-funded carbon removal *is* essential, then a more coherent assessment of alternative methods is needed than has yet taken place in the public policy arena. The question of energy requirements must be addressed as well questions of land and water use, among others. Lawmakers need an apples-to-apples comparison[142] and assessment of natural and technological methods to make reasoned policy choices for carbon removal and storage.

Is CO_2 a commodity to be gathered and sold, or a substance to be sequestered?

In their final analyses, the majority of papers on technological-industrial CDR methods are market-centric, oriented around the presumption that carbon is a potential asset to be captured and sold. Government's role is seen as market-making: subsidize the development of CDR technologies ostensibly so that they can reach commercial viability, and remove regulatory barriers (e.g., for pipeline construction). The oft-stated assertion is that taxpayer subsidy will lead, at some point in the future, to commercial viability. There is, however, no evidence presented to support the prediction that government subsidy will lead to market viability (notwithstanding calls for "carbon pricing" and other market interventions.)

Carbon dioxide *reduction* is a public service to meet an urgent public need

There is another way for policymakers and lawmakers to think about government's role in atmospheric CO_2 reduction: as a public service. This alternative view focuses on the societal need: <u>Reduce atmospheric CO_2 as safely and expeditiously as possible</u>. This means sequestering – not selling – CO_2. Climate mitigation is not a market matter.[143]

Indeed, some people have alluded to this alternative way of thinking about meeting this collective need. The World Resources Institute (Milligan et al, 2018b), for example, wrote of carbon removal as a "public good." One of the early developers of direct air capture, Klaus Lackner, has said that CO_2 should be treated like sewage; it needs to be removed and disposed of like sewage or garbage (Temple 2019; Kolbert 2017).

CDR cannot work as a profit-generating enterprise if it is to succeed in *actually reducing* atmospheric CO_2. Captured CO_2 must simply be sequestered, not sold. Since it cannot produce profit, carbon dioxide *reduction* must be collectively financed: it is a public service to meet an urgent public need.[144] If CDR technologies are publicly financed, then the accompanying or resultant intellectual property and patents should be held in the government's name.

[141] Moomaw, William and Danna Smith, The Great American Stand; US Forests and the Climate Emergency 2017, pg 10.

[142] As evidenced in this report, numerous studies exist. But they contain inconsistent findings and exist in formats – in both language and notation -- that are not accessible to non-science policy-makers. Moreover, they do not provide a standardized basis for comparison and evaluation of various methods from a public purpose perspective.

[143] See: Missing in the Mainstream; Sekera (2017).

[144] CO_2 has been classified as a pollutant under the Clean Air Act; see Supreme Court rulings in 2007 and 2014. Subsequently, the EPA issued rules regulating CO2 as a pollutant. Still, some argue that CO_2 is should instead be viewed as a valuable commodity. Scientists and journalists have reported on CO_2 as a "waste" and the need for "waste disposal", and on the view of carbon dioxide removal as a public service, or a "public good". See: Kolbert, Elizabeth (2017) "Can Carbon-Dioxide Removal Save the World?" *New Yorker*, Nov. 20, 2017; Buck, Holly Jean (2018) "The Need for Carbon Removal" *Jacobin Magazine*, July 2018; Mulligan, James, Ellison, Gretchen, Gasper, Rebecca & Rudee, Alexander (2018b) "Carbon Removal in Forests and Farms in the United States," *World Resources Institute,* Sept. 2018; Magill, Bobby (2016) "CO2, Climate Change Seen As Waste Disposal Challenge" *Climate Central*, Sept. 13, 2016. Re: Supreme Court decisions, see National Resources Defense Council (2007) and Barnes (2014).

Public options
We suggest two potential courses of governmental action, one for direct air capture and one for CCS (point source capture).

DAC:
If government subsidy (whether in the form of tax credits, direct financing, "prize" awards, or loans) is used to support any form of atmospheric carbon dioxide capture or removal, the accompanying or resultant intellectual property, and any patents, would be held in the government's name. If taxpayers are paying for the development and use of technology for DAC, then the taxpayers should be the owners of that technology, and the technical expertise should be resident in the public domain.

CCS:
In economics terminology, harmful power-plant emissions are a "negative externality. The cost of ending or preventing these "externalities" should be borne by the producer. Hence, public law should require that all fossil fuel power facilities use carbon capture technology to prevent the CO_2 from entering the atmosphere. The cost should be entirely borne by the owners of the power facility – not the utility customers (state regulators would need to ensure that the expense is not passed on to the ratepayers). The law should clearly state that no public funding could be used subsidize this point-source capture. Of course, this requirement would substantially reduce the profitability of fossil fuel power generation. But, after decades of talk about properly assigning externality costs, it is arguably time to move from talk to action.

Storage:
In a public service context, all CO_2 captured through technological methods (whether CCS or DAC) would be injected underground and stored in perpetuity. As explained in the sections on Scale and Ancillary Effects above, in order to have any significant impact on the level of atmospheric CO_2, this would require massive effort, along the lines of "wartime mobilization", including infrastructure buildout and pipelines for transport to underground storage sites. It also would require long-term monitoring for blowouts, "fugitive emissions", "seismic events" (earthquakes), groundwater contamination, and other ancillary effects. As a public service, the cost would be borne by taxpayers.

However, before embarking on any such legislation for technological methods, policymakers and lawmakers need also to examine and evaluate biological methods of carbon drawdown and sequestration.

Immediate legislative action needed:
As noted earlier, the most important finding for policymakers is that some "carbon dioxide removal" (CDR) methods emit more CO_2 into the atmosphere than they remove, thereby adding to the already existing stock of atmospheric CO_2. Yet these methods have been subsidized under legislation passed in 2018, and would be further subsidized with pending legislation.

In order to restrict public subsidies to methods that are net CO_2 *reductive*, **Congress could include language along the following lines in any CDR legislation:**

1. **"No funding appropriated, or tax liability reduced, under this Act may be used to support any process related to enhanced oil recovery, or for any other process that results in the production of fossil fuels."**

2. “No funding appropriated, or tax liability reduced, under this Act may be used to support any CO_2 direct air capture process that uses fossil fuel as its power source.”

3. “No funding appropriated, or tax liability reduced, under this Act may be used to support any process in which the CO_2 emitted by the process exceeds the CO_2 removed by the process over its entire life cycle.”

This standard can be expressed as a ratio: $\gamma_{CO2} = \frac{total\ CO_2\ emitted}{total\ CO_2\ removed}$

A ratio greater than 1 means that the process adds more CO_2 to the atmosphere than it removes.

Comparison and evaluation of biological vs technological-commercial methods

As things now stand, policymakers -- and the public – are deprived of the necessary context to be able to evaluate the full range of choices for CDR. To obtain a full context, it is necessary to evaluate the effectiveness of biological methods and well as the technological methods reviewed in this paper on an apples-to-apples basis. Such a comparison does not now exist.

To accomplish this, an examination of biological methods analogous to that used in the present study can be conducted, allowing all biological and technological methods to be compared on an apples-to-apples basis. The questions to be addressed are:

- **Impact on Carbon Balance**
  Does the process remove more CO_2 than is emitted by the process?
- **Resource Usage**
  How much energy is consumed by a process? How much land is required?
- **Ancillary effects**
  What ae the side effects of the process, particularly in terms of other biophysical gains or losses?

With the above information on both biological and technological methods, a tool for effective comparison could be constructed:

- **Resource Return on Resource Inputs (RRORI)** [145]
  What is the “return” on the resource inputs of energy and land in terms of:
  a) atmospheric carbon dioxide reduction?
  b) other biophysical gains or losses?

The development of a “Resource Return on Resource Investment” (RRORI) tool could serve as a basis for setting standards for public policy formulation on CDR.

[145] This concept borrows from the concept of “EORI” – Energy Return on Investment – developed by systems ecologist Charles A. S. Hall.

* * *

"Moral hazard, betting, and hubris"

In an overview of a series of papers on CDR with regard to the policy landscape, Minx et al (2018), stated their view, which we find an apt summary for policymakers:

> **[T]hree issues in particular stand out in need of future ethical analysis. These are first, that NETs might create a *moral hazard* against mitigation; second (and relatedly), that an implicit policy *bet* on NETs that are unproven at scale may lock in worse climate-related harms if they failed to deliver; and third, that the sheer scale of NETs deployment observed in mitigation scenarios is staggeringly *hubristic*.**

As Minx[146] concludes

> "**There is an urgent need for the international community <u>not</u> <u>to further increase but reduce its dependence on technologies for carbon removal from the atmosphere</u>. To achieve this, we need to reduce greenhouse gas emissions much more rapidly."**

[146] Minx quoted in LaFollette News (2018) "Nemet, colleagues review negative emission technologies for reducing CO2," Robert M. La Follette School of Public Affairs, University of Wisconsin-Madison, May 22, 2018.

Appendices

Appendix A: **Literature Review: Technological-Industrial Methods of CDR - Relevant to Impact on Net Carbon Balance**

Following are studies that pertain to the question of whether a process is net additive or net reductive.

Jaramillo, P, Griffin WM & McCoy ST; **2009**; "**Life cycle inventory of CO2 in an enhanced oil recovery system**"; Environmental Science & Technology; 43 (21): 8027-8032.

Finds that Empirical study of five CCS-EOR that "between 3.7 and 4.7 metric tons of CO2 are emitted for every metric ton of CO2 injected." Based on an empirical study of five CCUS-EOR operations in the U.S.

Veld, Klaas van't, Charles F. Manson and Andrew Leach (**2013**) "The Economics of CO2 Sequestration Through Enhanced Oil Recovery" *ScienceDirect*, Energy Procedia 37 (2013) 6909-6919.

Challenges the "displacement" argument.
"a key result is that the introduction of EOR may not displace any conventional production at all, though it necessarily will delay the development of some new sources of production. The implication is that, unless EOR projects utilize on average as much CO2 per incremental barrel produced as the CO2 generated when that barrel is consumed, they may not reduce carbon emissions overall."

Faltinson, J. and B. Gunter (**2011**) "Net CO2 Stored in North American EOR Projects**"** *Journal of Canadian Petroleum Technology*, July-Aug 2011, 55-60.
Advocates CO2-EOR as "promising", making the argument that "World oil supply is determined by world oil demand, and CO2-EOR oil will simply displace other oil from higher-cost sources – i.e., not be produced in addition to it." However, this argument is problematic. First, it makes a category error: there is a global demand for energy, not necessarily for oil. Second, there is a lack of evidence to support the displacement assertion, as has been pointed out by numerous authors.

Cooney, G, J. Littlefield, J. Marriott, T Skone, **(2015)** "Evaluating the Climate Benefits of CO_2-Enhanced Oil Recovery Using Life Cycle Analysis;" *Environmental Science & Technology*, 2015, 49 (12), pp 7491–7500.

Examines the CO2-EOR process from the standpoint of the "crude recovery ratio" and displacement effects. Concludes that calculations based on assumptions about these variables present "an interesting challenge for policymakers" who will "have to decide which entity receives credit for the sequestered carbon, the power plant or the EOR operator" and notes that "the economic incentives would change for EOR operators in the presence of a price on carbon."

A critical parameter is the crude recovery ratio, which describes how much crude is recovered for a fixed amount of purchased CO_2. When CO_2 is sourced from a natural dome, increasing the crude recovery ratio decreases emissions, the opposite is true for anthropogenic CO_2. When the CO_2 is sourced from a power plant, the electricity coproduct is assumed to displace existing power. With anthropogenic CO_2, increasing the crude recovery ratio reduces the amount of CO_2 required, thereby reducing the amount of power displaced and the corresponding credit. Only the anthropogenic EOR cases result in emissions lower than conventionally produced crude. This is not specific to EOR, rather the fact that carbon-intensive electricity is being displaced with captured electricity, and the fuel produced from that system receives a credit for this displacement.

Nunez-Lopez, Vanessa, Ramon Gil-Egui and Seyyed A. Hosseini (**2019**) "Environmental and Operational Performance of CO2-EOR as a CCUS Technology" *Energies* 2019, 12, 448

As summarized in its conclusion, this study "demonstrates the variability of the net carbon balance of CCUS systems. Net carbon balance not only varies among different EOR settings, but it also varies depending on the strategy selected to develop reservoirs with the same geologic setting. In addition, net carbon balance also varies significantly through time, as projects mature." The researchers argue that with sufficient passage of time – as more and more CO2 is injected and less and less remaining oil is pumped out, and under a particular set of operating conditions, the CO2-EOR process could eventually become net-reductive.

Godec, Michael L., Vello A. Kuuskraa & Phil Dipietro (2013) "Opportunities for Utilizing Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage," *Energy & Fuels*.

As the Abstract states: "The report demonstrates that CO2-EOR needs CCS; because large-scale future implementation of CO2-EOR will be dependent on CO2 supplies from industrial sources".

The paper concludes:

> The information set forth in this paper argues that CO_2 enhanced oil recovery deserves to be a major part of a worldwide carbon management strategy. Growth in production from CO_2-EOR is now limited by the availability of reliable, affordable CO_2. There are more prospective CO_2-EOR projects than there is CO_2 to supply them. If increased volumes of CO_2 do not result from CCS, then these benefits from CO_2-EOR will not be realized. Thus, not only does CCS need CO_2-EOR to ensure viability of CCS, **but CO_2-EOR needs CCS to ensure adequate CO_2 to facilitate CO_2-EOR production growth**. This will become even more apparent as even more new targets for CO_2-EOR become recognized.
>
> Therefore, the "size of the prize" is large, the oil produced has a lower CO_2 emission footprint than most other sources of oil, with the injected CO_2 stored securely, and CO_2-EOR can provide a market-driven option for accelerating CO_2 capture, with widely distributed economic benefits.

EASAC (European Academies, Science Advisory Council) (2018) *Negative emission technologies: What role in meeting Paris Agreement targets?*; February 2018.

[W]e conclude that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios…

Scenarios and projections of NET's future contribution to CDR that allow Paris targets to be met thus appear optimistic on the basis of current knowledge and should not form the basis of developing, analyzing and comparing scenarios of longer-term energy pathways for the European Union (EU).

Fuss, Sabine, William F. Lamb, Max W. Callaghan, et. al. (2018) **"Negative emissions—Part 2: Costs, potentials and side effects,"** *Environmental Research Letters* 13 (2018) 063002; 22 May 2018.

This report notes the problematic character of DAC in terms of CO2 emissions:

- "It is important to note that if DACCS is powered with coal, the CO2 emissions from fueling the plant would be greater than the CO2 captured (National Academy of Sciences 2015)."

- "It is difficult to compare the costs of DAC reported in the literature due to their differing boundary conditions in addition to the fact that many of the reported estimates are the costs of CO2 capture and not the costs of capturing the avoided CO2. [...] Hence, if a DAC plant is designed to capture on the order of 1 Mt CO2 yr−1, it may ultimately avoid only a fraction of this due to the emissions generated from the use of natural gas to provide energy to the plant."

Anderson & Peters 2016

Anderson, Kevin & Glen Peters; 2016; "**The Trouble with Negative Emissions**"; 14 October 2016 sciencemag.org • Science; Vol 354 Issue 6309; 182-183

Essay on the general difficulty in handling climate change and emissions. Warns that negative emissions technologies "**are not an insurance policy but rather a…high-stakes gamble"**

> "Negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble. There is a real risk they will be unable to deliver on the scale of their promise. If the emphasis on equity and risk aversion embodied in the Paris Agreement are to have traction, negative-emission technologies should not form the basis of the mitigation agenda. This is not to say that they should be abandoned. They could very reasonably be the subject of research, development, and potentially deployment, but the mitigation agenda should proceed on the premise that they will not work at scale. The implications of failing to do otherwise are a moral hazard par excellence"

Greenpeace 2015

Ash, Kyle et. al. *Carbon Capture Scam (CCS)*; Greenpeace, April 15, 2015.

A study and report by Greenpeace that strongly warns against public subsidy of CCS.

> Supporters of carbon capture for oil extraction claim that oil produced with CO2 injection is going to get produced somewhere else anyway, and therefore would actually be 'green' oil because it keeps CO2 from a coal plant from entering the atmosphere. Is this "clean coal" for "green oil"? This sounds confusing because it makes no sense for many reasons, one being that injected CO2 comes back up the well with the oil.
>
> …The CCS myth posits that the economy could continue to burn fossil fuels without the harmful effect of global warming. Burning fossil fuels for electricity is the number one source of anthropogenic carbon dioxide, the most predominant greenhouse gas and most problematic climate pollutant over the long term.[1] Burning coal is the number one source of CO2 from the

electricity sector.[3] The proposed carbon rule from the US Environmental Protection Agency (EPA) regarding future power plants would affect only new coal plants.

CATF 2016

Nagabhushan, Deepika & Kurt Waltzer (2016) "**The Emission Reduction Benefits of Carbon Capture Utilization and Storage using CO2 Enhanced Oil Recovery**;" Clean Air Task Force.

A report that advocates CO2-EOR, whose analysis rests on calculations that contain a fundamental arithmetical error. The error was corrected in a later version of the report posted to the web, but the conclusion remained the same.

CATF 2019

Nagabhushan, Deepika & John Thompson (2019) "**Carbon Capture & Storage in the United States Power Sector; The Impact of 45Q Federal Tax Credits**;" Clean Air Task Force, February 2019.

Carbon Capture & Storage in The United States Power Sector
The Impact of 45Q Federal Tax Credits , Nagabhushan & Thompson, Clean Air Task Force, Feb. 2019.

An analysis with multiple problems: a mis-representation of the 2015 International Energy Agency report; an unsupported assumption about CO_2 reduction; and, like their 2016 report, is based on a "Life Cycle Analysis" that looks at only part of the life cycle. Also, it is only concerned with the power sector; it leaves out the larger picture of fossil fuel consumption generally. It advocates for CCS-EOR, but based on a faulty analysis.

Hertwich, Edgar G. et. al. (2008) "Life-cycle Assessment of Carbon Dioxide Capture for Enhanced Oil Recovery" Chinese Journal of Chemical Engineering, 16(3) 343-353.

This paper reports on a potential system design for CCS-EOR and concludes that a power plant with carbon capture has lower GHG emissions than a comparable plant without CCS. A life cycle analysis is not included.

Stewart & Haszeldine 2015

Can producing oil store carbon? Greenhouse Gas footprint of CO2EOR, offshore North Sea
R Jamie Stewart, and R Stuart Haszeldine Environ. Sci. Technol., Just Accepted Manuscript• Publication Date (Web): 19 Mar 2015

Examines an offshore CO2-EOR project, but makes some generalized observations:

> **[We} find that the largest contribution to offshore emissions is from flaring or venting of reproduced CH4 and CO2.** These can already be greatly reduced by regulation. If CO2 injection is continued after oil production has been optimised, then offshore CO2EOR <u>has the potential</u> <u>to be carbon negative - even when emissions from refining, transport and combustion of produced crude oil are included</u>. The carbon intensity of oil produced can be just 0.056-0.062 tCO2e/<u>bbl **if flaring/venting is reduced by regulation**</u>. This compares against conventional Saudi oil 0.040tCO2e/bbl, or mined shale oil >0.300tCO2e/bbl.
>
> **The primary reason for the varying conclusions relates to inclusion or exclusion of the large contribution to emissions made by the combustion of produced petroleum products, and the principal of additionality**. Jaramillo et al., (2009) who looked at 5 onshore North American CO2 EOR projects found that when emissions from the full system boundary, from coal mining to final product combustion are included, then **onshore CO2 EOR projects have historically been net emitters of CO2**. They assumed that oil produced through CO2EOR is

> additional to the global system and therefore emissions from the combustion of the final petroleum products should be included in the study, which resulted in overall net emissions. **Other studies** such as Faltison and Gunter., (2011)12 64 who have analysed emissions and CO2 stored at 8 onshore US CO2EOR fields, **argue that oil produced through CO2EOR will displace oil produced through other sources** and **emissions from final product combustion should therefore not be included**. [Emphases added.]

Hu, Bingyin and Haibo Zhai (2017) "The cost of carbon capture and storage for coal-fired power plants in China" *International Journal of Greenhouse Gas Control*, 65 (2017) 23-31.

> CO2-EOR could be an economically feasible option as a short-term solution to facilitate CCS deployment and technological learning, **though there is a concern about the net increase in life cycle CO2 emissions via CO2-EOR operations (Jaramillo et al., 2009**). Based on the probabilistic analysis, the deterministic results presented in Fig. 3 are more likely to be underestimated than to be overestimated. [Emphasis added.]

Boot-Hanford, M.E. et. al. (2014) "Carbon capture and storage update" Energy & Environmental Science, 2014, 7,130.

Makes the "stepping stone" argument. But also discusses problems with "carbon budget double accounting," and lack of mandates to monitor storage for leakage.

> Four CO2 injection projects are currently in operation, with a further nine planned to be operating by 2016. Of these, about 75% intend to undertake CO2-EOR where, using conventional injection and production plans, 3 tonnes of CO2 produce one additional barrel of oil. The **primary purpose of those projects is to produce oil rather than to dispose of CO2**. This can have a benefit in that **such projects encourage and enable the development of efficient and low-cost CO2 capture technology**, and such projects may fund the building of pipeline transportation networks for CO2. However, viewed from the objective of CCS, such projects have two significant disadvantages: the first problem is that CO2-EOR objects fall under industrial legislation; **consequently there is no mandate to undertake details or extensive CO2 monitoring through the lifetime of the project to demonstrate and predict secure long-term retention**. Second, the carbon budget overall becomes conflicted **by double counting**. CO2 captured from combustion of coal or gas at a power station cannot be regarded as free from emissions, available to be used to release additional fossil fuel, which itself will produce CO2 upon combustion. **In North America the additional oil is not conventionally regarded as producing an emission, because oil production is regarded as free of emission, until the end user undertakes combustion. By contrast in Europe these additional emissions will be explicitly counted** as part of the carbon budget and if CO2 emissions credits are to be claimed, then monitoring validation of CO2 storage will be required.
>
> **Even with these practical difficulties of emissions offsetting, it may still be worth undertaking CO2-EOR as a stepping stone** to rapid building of large numbers of capture plants connected to pipeline networks, connected to multiple storage sites which will reach their full potential after the additional oil production is exhausted. [Emphases added.]

Hussain et al. 2013

Hussain, Daniar, David A. Dzombak, Paulina Jaramillo & Gregory V. Lowry (2013) International Journal of Greenhouse Gas Control, 16; 129-144, 21 April 2013.

The study in effect acknowledges that CCS-EOR has an additive impact on carbon balance, yet it defends the idea of EOR oil due to its "relatively lower" emissions. The general sense is that: "The petroleum industry will continue to pursue tertiary oil recovery when it makes economic sense, and the tremendous inertia in the global energy infrastructure requires examining approaches to utilize existing fossil fuel resources while reducing associated GHG emissions."

As noted in the "Acknowledgements," this study was financially supported by "American Pioneer Ventures, a firm founded by author Daniar Hussain and advisor Steven Milliaris." APV "consults to Pioneer Energy, which is developing portable EOR technology."

Dismukes et al 2018

Dismukes, David E. Michael Layne & Brian F. Snyder (2018) "Understanding the challenges of industrial carbon capture and storage: an example in a U.S. petrochemical corridor;" International Journal of Sustainable Energy, 4 July 2018.

This study touches on the controversy of EOR produced oil. "The fact that the carbon is being utilised to produce additional hydrocarbons, the primary human-induced contributor to climate change, may be considered problematic because it increases the supply of crude, potentially decreasing costs and increasing emissions (De Coninck 2008), although we are unaware of an empirical estimate of this mechanism. Further, the net carbon reduction of injection for EOR is lower than the net benefit of saline injection (Jaramillo, Griffin, and McCoy 2009; Cuéllar-Franca and Azapagic 2015), but the degree of carbon benefit depends critically on the efficiency of CO2 use." … The basic narrative concerns carbon reduction, but not removal: "So, while industrial CCS applications may be limited in both number and geographic scope, they can reduce or avoid a tremendous amount of carbon emissions on a per project basis."

Azzolina 2016

Azzolina, NA, WD Peck, JA Hamling , CD Gorecki (2016), [How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites,"]() *International Journal of Greenhouse Gas Control*; 51 (2016) 369–379.

This study provides alternative ranges for CO_2 storage in combination with EOR depending on varying assumptions. Several LCA scenarios are investigated (up-stream, gate-to-gate, downstream). The study comments on and criticizes the choice for crude oil recovery ratios in Jaramillo et al. (2009). An analysis with regard to the efficiency factor and LCA specifications draw on the following points:
… specification upstream:

- 1) base case with 975 kg CO2/MWh for electricity generation;
- 2) coal, mining, processing with an average emission factor of 18kg CO2e/MWh;
- 3) average value for net efficiency: 30% … adjusted emission factor of 18/0.3=60 kgCO2e/MWh;
- 4) pipeline transport of 100 to 1000km with an average of 500km
- 5)
    - i) mentioning crude oil recovery ratio (@Cooney) and paper of Murrell & Dipietro (2013) for estimates
    - ii) stating that Jaramillo's paper aassumes crude recovery ratios from 4.6 to 6.5 bbl/t CO2, which applies to less than 2% of sites and greatly

exaggerates the efficiency, which, in turn, significantly reduces the amount of CO2 that is estimated to be stored in the reservoir

… specification downstream:

- 6) 7% of the carbon per barrel of oil remains in noncombustible products (such as asphalt and petrochemical feedstocks).
- 7) CO2 capture and storage: rate of 90% CO2 capture are often cited in the literature.

Suebsiri et. al. 2006

Suebsiri, J.;Wilson, M.; Tontiwachwuthikul, P. Life-cycle analysis of CO2 EOR on EOR and geological storage through economic optimization and sensitivity analysis using theWeyburn Unit as a case study. Ind. Eng. Chem. Res. **2006**, 45, 2483–2488. [CrossRef]

"This article focuses on applying life-cycle analysis (LCA) of CO2 storage from delivery to the oil field through the production, transportation, and refining of the oil and identifies opportunities for optimization."

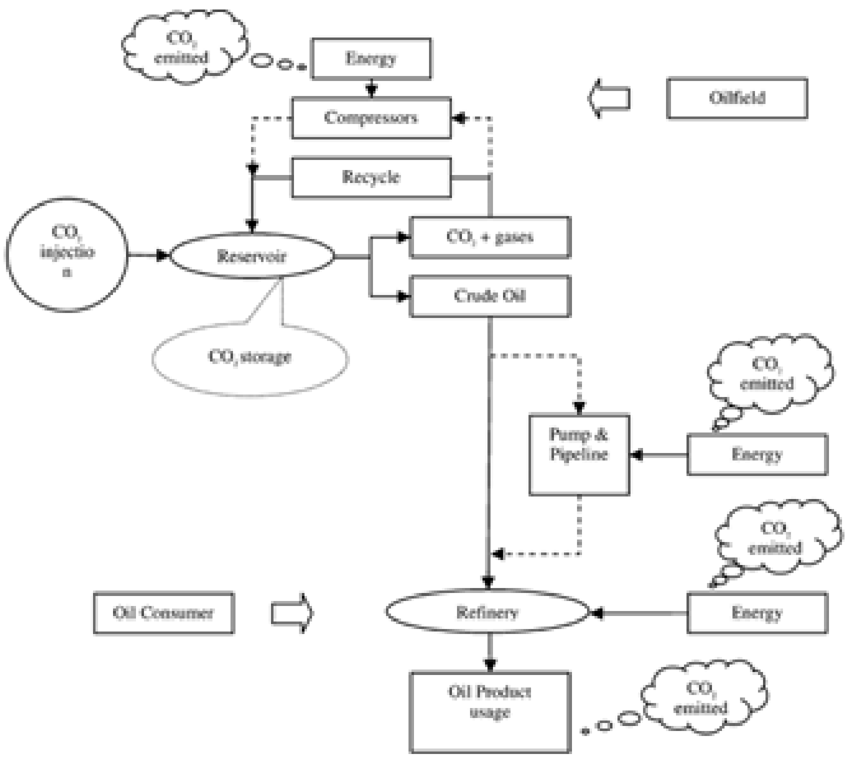


Figure 3. Schematic of the CO_2 stream from the oilfield through the oil consumer.

The result is net additive, yet the authors see this outcome as "very desirable. The argument relies on a relative carbon reduction compared to conventional oil production: "CO2 EOR and storage is, however, a very desirable process for achieving CO2 emissions reductions… In other words, according to a full life-cycle analysis, the emissions of CO2 from oil produced from a CO2-based EOR operation are only two-thirds of the life-cycle emissions of conventional oil production." The general conclusion of this paper is that EOR has the capacity to store 30% of the total CO2 emissions from the EOR process through the refinery and end usage.

Hovorka and Tinker 2010

Hovorka, S. and Tinker, S.W., "**EOR as sequestration: Geoscience perspective:** presented at the Symposium on the Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Storage," Cambridge, MA, July 23, 2010 (http://mitei.mit.edu/system/files/110510_EOR_Report_1.pdf). GCCC Digital Publication Series #10-12.

The study shows awareness for the carbon additive nature of CO2-EOR, and acknowledges the findings of Jaramillo et. al. 2009: "Jaramillo and others (2009) have completed a lifecycle analysis based on current WAG floods, showing that such CO2 EOR projects have a significant net carbon emission. The carbon emissions profile is variable among the five fields assessed."

Herzog 2011

Herzog, Howard J. (2011) "Scaling up carbon dioxide capture and storage: From megatons to gigatons"; Energy Economics 33, (2011) 597-604.

This paper begins in the abstract with a naturalization of oil production as necessary for societal needs and argues for CCS as a desirable solution "Carbon dioxide (CO2) capture and storage (CCS) is the only technology that can reduce CO2 emissions substantially while allowing fossil fuels to meet the world's pressing energy needs."

The paper analyzes the current state of CCS in a systematic way, identifies hurdles in its further promotion and how to address these. The core difficulties mentioned are **costs, infrastructure, subsurface uncertainty, and legal and regulatory issue**. The paper states that the availability of storage capacity for up-scaling CCS could pose a problem ". It is not yet proven that enough storage capacity exists to support CCS at the gigaton scale, and the cost of CCS mitigation may be more than is politically acceptable for the next couple of decades"

Cuellar-Franca & Azapagic 2014

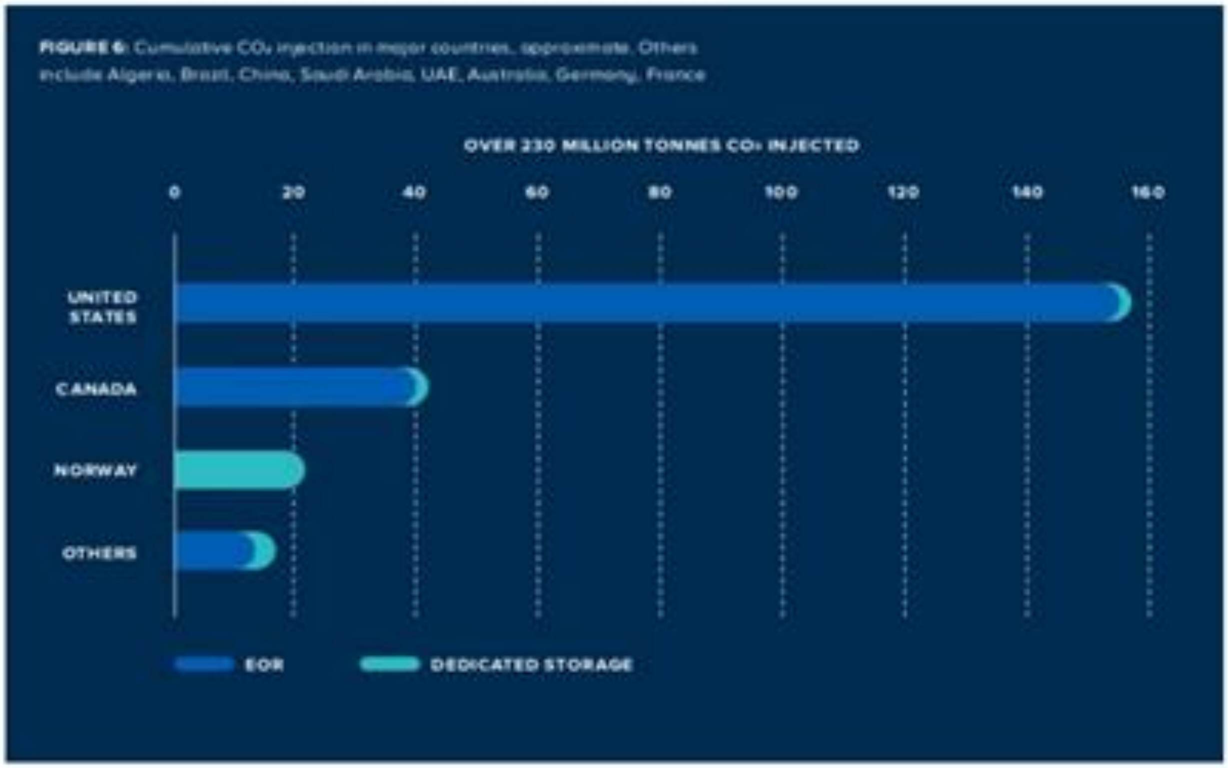
Cuellar-Franca, Rosa M. & Adisa Azapagic (2014) "Carbon capture, storage and utilization technologies: A critical analysis and comparison of their life cycle environmental impacts;" *Journal of CO_2 Utilization,* 19 December 2014.

The paper studies warming potentials, acidification, and total impacts, listing 16 different LCA studies. Of these, two study the cradle-to-grave impact of CCS EOR: (i) Hertwich et al. (2008), and (ii) Jaramillo et al. (2009), both of which show the process to be net additive, although to different degrees (due to different CO_2 capturing options and other EOR practices assumed).

Foehringer Merchant 2018 -

Foehringer Merchant, Emma (2018) "With 43 Carbon-Capture Projects Lined Up Worldwide, Supporters Cheer Industry Momentum" GreentechMedia, December 11, 2018.

This article reviews the status of carbon capture projects



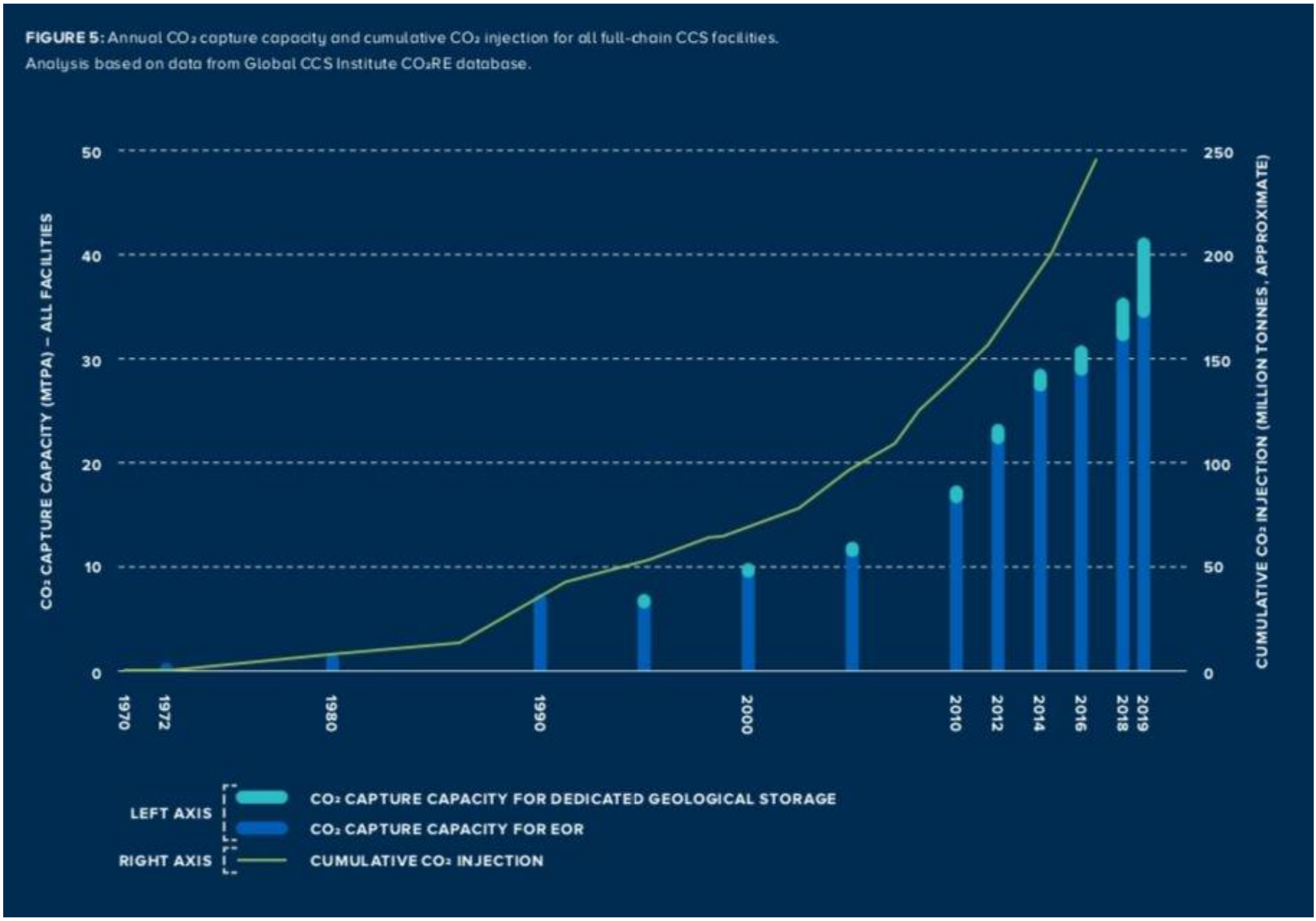
Source: Global CCS Institute

"But carbon capture as an industry depends on a continued reliance on fossil fuels, since carbon dioxide is so commonly used in EOR."

"Though carbon-capture capacity increased between 2010 and 2019, relatively few projects use geological storage."

"Only in Norway have carbon-capture projects mostly used geological storage."

"Australia's Gorgon project could help change that. When fully online, as it's slated to be in 2019, the project will be the largest geological storage facility in the world."



International Energy Agency (IEA) 2015

[“Storing CO2 through Enhanced Oil Recovery; Combining EOR with CO2 storage (EOR+) for profit,”] International Energy Agency, 2015.

Communicates a market-oriented approach to EOR activities:
“Novel ways of conducting CO2-EOR could help achieve a win-win solution for business and for climate change mitigation goals, offering commercial opportunities for oil producers while also ensuring permanent storage of large quantities of CO2 underground” (p.6)
Acknowledges that thus far the role of EOR is globally limited, as only 300,000 barrels per day are produced, which amounts to 0.35% of the global oil consumption (p. 11) and that almost all operating CO2-EOR projects are located in the mid-west of the U.S. (p. 11).
The report argues that by an improved EOR methodology (Maximum Storage EOR+) it would be possible to achieve net reductive results, even assuming that EOR oil adds to conventional oil. But EOR+ is an envisioned method, not an existing one.

Redman 2017

Redman, Janet (2017) Expanding Subsidies for CO2-Enhanced Oil Recovery: A Net Loss for Communities, Taxpayers, and the Climate, Oil Change International; October 24, 2017

A report that analyses the 45Q tax policy. Key findings and conclusion:

- “The proposed law would result in at least an additional 400 thousand barrels per day (kbpd) of CO2-enhanced oil production.”
- The additional production would “directly lead to as much as 50.7 million metric tons of net CO2 emissions annually that would otherwise not be emitted.”
- “Subsidizing and expanding the fossil fuel industry is not – and will never be – a solution to the climate crisis.”

von der Assen 2013

von der Assen, Niklas, Johannes Jung & Andre, Bardow (2013) “Life-Cycle Assessment of Carbon Dioxide Capture and Utilization: Avoiding the Pitfalls”

This paper argues that a holistic LCA analysis is mandatory and provides a systematic framework for LCA of CCU to avoid the pitfalls that are addressed in the paper. Finding only two LCA studies of CCU: **(i**) Aresta & Galatola (1999**)** and (ii) Jaramillo et al. (2009)

Appendix B: **Literature Review: Displacement Postulate and Efficiency Factor**

Following are brief summaries of some of the studies that either discuss or rely on the displacement assumption and discuss the efficiency factor.

1. Nunez-Lopez, Vanessa, Ramon Gil-Egui and Seyyed A. Hosseini (2019) "Environmental and Operational Performance of CO2-EOR as a CCUS Technology" *Energies* 2019, 12, 448.

This paper touches on one reason there is significant "variability" in study findings --

> This variability is mostly due to the efficiency of the EOR process, which controls oil recovery and associated carbon storage. Most studies on carbon lifecycle analysis of CO2-EOR use a range for EOR efficiency, commonly stated in barrels of oil produced per ton of CO2 purchased. Such simplifications provide a narrow view of carbon lifecycle variability of CO2-EOR.

As summarized in its conclusion, this study "demonstrates the variability of the net carbon balance of CCUS systems. Net carbon balance not only varies among different EOR settings, but it also varies depending on the strategy selected to develop reservoirs with the same geologic setting. In addition, net carbon balance also varies significantly through time, as projects mature." The researchers argue that with sufficient passage of time – as more and more CO_2 is injected and less and less remaining oil is pumped out, and under a particular set of operating conditions – the CO_2-EOR process could eventually become net-reductive.

2. Veld, Klaas van't, Charles F. Manson and Andrew Leach (**2013**) "The Economics of CO2 Sequestration Through Enhanced Oil Recovery" *ScienceDirect*, Energy Procedia 37 (2013) 6909-6919.

> Challenges the "displacement" argument:
> "a key result is that the introduction of EOR may not displace any conventional production at all, though it necessarily will delay the development of some new sources of production. The implication is that, unless EOR projects utilize on average as much CO2 per incremental barrel produced as the CO2 generated when that barrel is consumed, they may not reduce carbon emissions overall."

3**. Faltinson,** J. and B. Gunter (**2011**) "Net CO2 Stored in North American EOR Projects**"** *Journal of Canadian Petroleum Technology*, July-Aug 2011, 55-60.

> Advocates CO_2-EOR as "promising", making the argument that "World oil supply is determined by world oil demand, and CO_2-EOR oil will simply displace other oil from higher-cost sources – i.e., not be produced in addition to it." However, this argument is problematic. First, it makes an error in an economics assumption: there is a global demand for energy, not necessarily for oil. Second, there is a lack of evidence to support the displacement assertion, as discussed earlier.

4. Cooney, G, J. Littlefield, J. Marriott, T Skone, (**2015)** "Evaluating the Climate Benefits of CO_2-Enhanced Oil Recovery Using Life Cycle Analysis;" *Environmental Science & Technology*, 2015, 49 (12), pp 7491–7500.

Examines the CO_2-EOR process from the standpoint of the "crude recovery ratio" and displacement effects. Concludes that calculations based on assumptions about these variables present "an interesting challenge for policymakers" who will "have to decide which entity receives credit for the sequestered carbon, the power plant or the EOR operator" and notes that "the economic incentives would change for EOR operators in the presence of a price on carbon."

Note that this paper discusses the point that "increasing EOR efficiency increases GHG emissions…"

> A critical parameter is the crude recovery ratio, which describes how much crude is recovered for a fixed amount of purchased CO_2. When CO_2 is sourced from a natural dome, increasing the crude recovery ratio decreases emissions, the opposite is true for anthropogenic CO_2. **When the CO_2 is sourced from a power plant, the electricity coproduct is assumed to displace existing power.** With anthropogenic CO_2, increasing the crude recovery ratio reduces the amount of CO_2 required, thereby reducing the amount of power displaced and the corresponding credit. Only the anthropogenic EOR cases result in emissions lower than conventionally produced crude. This is not specific to EOR, rather the fact that carbon-intensive electricity is being displaced with captured electricity, and the fuel produced from that system receives a credit for this displacement. [Emphasis added.]
>
> …EOR operators currently purchase CO2 for use in EOR. As with any other purchased input, it is in the operator's economic interest to optimize the use of CO2, meaning that their goal is to produce as much crude as feasible per unit of CO2 purchased and injected. Under this scheme, as illustrated by the two natural dome cases in Figure 3, increasing the EOR efficiency actually reduces the GHG emissions on a functional unit basis. The opposite is true if the source of that purchased CO2 is a fossil power plant. **Increasing the EOR efficiency increases the GHG emissions f**or the functional unit, **because of the reduction in displacement credit** for electricity. [Emphasis added.]

Appendix C: **Literature Review: Direct Air Capture – Resource Usage**

A. Socolow et al 2011

Socolow, R. et al. (2011) ***Direct air capture of CO2 with chemicals: a technology assessment for the APS Panel on Public Affairs.;*** American Physical Society, June 1, 2011.

This report by the American Physical Society found that, if 100% efficiency is assumed, the "primary energy requirement" for capturing and compressing 1tCO_2 is 9.9 GJ. Assuming a conversion factor for electricity efficiency of 40% (per Socolow et al.) yields 1tCO_2 an energy requirement of 12.5GJ. (Socolow et al p. 40)

However, as highlighted in their report on DAC, the American Physical Society focusses purely on estimates of capturing and compressing CO_2. The authors state that the estimates in their report only reflect *capture* costs and do not deal with CO_2 beyond the boundary of the capturing facility. Hence, the energy estimates do not account for further transport, sequestration or end-product processing (p. ii).

> The cost estimates in this report are *capture* costs. They do not include the cost of dealing with CO2 beyond the boundary of the capture facility. Specifically, the costs of sequestering the captured CO2 from the atmosphere have not been estimated. The principal sequestration strategy under discussion today is injection of CO2 in geological formations for multi-hundred-year storage. The cost of geological storage is expected to be smaller than the capture cost even for capture from flue gas, but its commercialization at very large scale will require the resolution of formidable reservoir-engineering, regulatory, and public acceptance challenges. It was beyond the scope of this report to investigate post-capture management of CO2 in any detail.

B. Smith et. al. 2016

Smith, P., S.J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato et al. (2016) **"Biophysical and Economic Limits to Negative CO2 Emissions."** ***Nature Climate Change*****;** **London** Vol. 6, Iss. 1, Jan 2016.

This study reported that the energy requirements to remove ~3.3 gigatons of carbon equivalents[147] by DAC would equate to 29% of total global energy use in 2013 –

> The energy requirements of amine DAC deployed for net removal of ~3.3 Gt Ceq yr^{-1}would amount to a global energy requirement of 156 EJ yr^{-1} if all energy costs are included. This is equivalent to 29% of total global energy use in 2013 (540 EJ yr^{-1}), and a significant proportion of total energy demand in 2100 (which the IPCC AR5 scenario database estimates will be~500–1,500 EJ yr^{-1}), which will be a major limitation unless low-GHG energy could be used, or the energy requirements significantly reduced.

Translating these figures into 1 gigaton of CO_2 removal – the standard we are using in this report – yields 3,580.9 terawatt hours,[148] which is slightly more than the figure of 3,417 terawatt hours reported by Climate Advisers (discussed earlier and below), and equates to nearly the total amount of electricity generated in the U.S. in 2017.

[147] The 3.3 Gt estimate this study represents the upper bound of the range. .

[148] Smith et al. 2016 pg 47; calculations performed by S. Davis, co-author of Smith et. al. Personal communication 8-19-18.

Smith et. al. (2011) bases its values on the results of the Socolow (2011) report, and hence also do not include transportation and downstream elements.

C. Climate Advisers 2018

Climate Advisers (2018) "Creating Negative Emissions; The Role of Natural and Technological Carbon Dioxide Removal Strategies", June 2018
[Creating Negative Emissions: The Role of Natural and Technological Carbon Dioxide Removal Strategies](https://www.climateadvisers.com/creating-negative-emissions-the-role-of-natural-and-technological-carbon-dioxide-removal-strategies/)

https://www.climateadvisers.com/creating-negative-emissions-the-role-of-natural-and-technological-carbon-dioxide-removal-strategies/

In order to scientific notation for wide readership, Climate Advisers converted "gigajoules" into US energy usage:

> **Direct Air Capture**
> ***Resource Intensity:***
> …the technology is very energy-intensive...Processing, transporting and injecting CO2 has additional energy requirements, potentially raising the per tCO2 energy intensity to 12.3 GJ. At this rate, achieving 1 Gt of removals could require 3,417 terawatt-hours of electricity annually—an amount that is nearly equivalent to all electricity generated in the United States in 2017.

This paper cites the Socolow et. al. study above,[149] and as noted, the energy usage estimate omits energy that would be consumed by parts of the process that are excluded from the study, e.g., transportation, geological injection, combustion of fuels produced from the captured CO_2.

D. House et al 2011

House, Kurt Zenz, Antonio C. Baclig, Manya Ranjan, Ernst A. van Nierop, Jennifer Wilcox, & Howard J. Herzog; **"Economic and energetic analysis of capturing CO_2 from ambient air,"** PNAS, December 5, 2011

> This paper reviews a number of published analyses on DAC and undertakes an empirical analysis of operating commercial DAC processes. The authors conclude that: DAC "can only be viable (i.e., net CO_2 negative) if powered by non-CO_2 emitting sources."
>
> In summarizing their research on DAC energy requirements, the authors find that removing 1 gigaton of CO_2 using direct air capture could require from 3,156 terawatt hours to 5,049 terawatt hours. This is commensurate with the findings of 3,580.9 terawatt hours from Smith et. al. (2016) and 3,417 terawatt hours from Climate Advisers (2018), which pointed out that this amount was nearly as much as all the electricity generated in the U.S. in 2017.

E. Realmonte et al. 2019

Realmonte, Giulia, et. al. (2019) "**An inter-model assessment of the role of direct air capture in deep mitigation pathways,**" Nature Communications Vol 10, Article number 3277.

[149] The number in Socolow et. al. is 12.5 GJ (pg 40); Climate Advisors does not give a reason for using 12.3 GJ instead.

This paper advocates for the development of DAC, and models scenarios for that development under various "techno-economic assumptions".

> Here we conduct the first inter-model comparison on the role of DACCS in 1.5 and 2 °C scenarios, under a variety of techno-economic assumptions…Our scenarios' average DACCS scale-up rates of 1.5 $GtCO_2$/yr would require considerable sorbent production and up to 300 EJ/yr of energy input by 2100.
>
> …The key factor governing the role of DACCS compared to other mitigation and negative emissions strategies is the rate at which DACCS capacity can be ramped up. Such a massive deployment requires a major refocusing of the manufacturing and chemical industries for sorbent production, and a large need for electricity and heat.

The projection of 300 EJ/yr by 2100 portends substantial energy usage: this projection would equate to 55.56 billion MWh to capture 1Gt/CO_2yr.[150] However, this represents only a partial Life Cycle Analysis that leaves out energy requirements for processing and use of the captured CO2 (e.g., for EOR, synfuels or other carbon-emitting uses.) Moreover, one scenario modeled incorporates the use of waste heat – "We include the use of waste heat to operate the amine-based plants, recovering it from energy-intensive industries and renewable power plants." – an assumption that is favorable to desired outcomes but not supportable by current practices. Others have critiqued this paper for making unrealistic assumptions.[151].

The paper concludes that DAC is a means to delay the phaseout of fossil fuels:

> **"DACCS enables delaying the phase-out of fossil-based electricity generation until after 2050."**

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150 If 1.5Gt/yr -> 300EJ/yr then 1Gt/yr -> 200EJ/yr = 55.56 billion MWh.

151 David Fridley; Fellow, Post-Carbon Institute; Staff Scientist (retired), Lawrence Berkeley Laboratory; personal communication Aug. 2019. "In terms of energy requirements as shown in the paper, for electricity alone, around 500 TWh would be needed to capture 1 Gt of CO2, and to avoid creating additional offsetting emissions, this electricity would need to come from renewable sources, specifically variable renewable generation as mentioned in the study. 500 TWh, however, is more than total renewable generation in the US (375 TWh in 2018), about 27% of the world total, and is nearly double the increment in renewable generation growth between 2017 and 2018 globally (which was less the increment between 2016 and 2017). The proposed "scalable" scheme they describe is to build capacity to remove 1.5Gt CO2 *per year,* thus annually requiring an additional 750 TWh of renewable electricity. This is an unrealistic assumption in my view. As such, they also note that intermittent renewable generation—wind and solar--would be 50% of total generation by 2030. This is in sharp contrast to the 7% total that variable renewables now account for in global generation, with just 11 years in which to close the gap (not only on current use, but future growth in use). And this is set against a falling rate of growth in deployment of solar and wind installations in the last 2 years. ……The study omits what could be thought of as "induced demand" for materials and resources (and fossil fuel combustion) by referring to the actual construction requirements for this infrastructure **only in money terms but not material terms.** Since they posit 30,000 of the DAC1 plants (or 30,000,000 of the DAC2 type). None of this exists, so there would be significant new demand for ore mining and transport (fossil fuels), smelting and rolling (fossil fuels), manufacturing of components, transport of materials, construction equipment, maintenance, and decommissioning and rebuilding after the lifetime (the study doesn't assume a lifetime—they assume once built it will last for the rest of the century, which is not a reasonable assumption for anything mechanical that is required to operate 24/7/365.) This will involve steel, aluminum, copper for the motor windings for the fans and compressors, not to mention the pipelines and other compressors needed to sequestration, and so forth, **yet the emissions engendered by all this new activity is not deducted from the amount removed.** And given that solar and wind installations require 3-6 times more copper than conventional power plants, and that EVs are copper intensive, supplying all this additional copper is not a given.)" [Emphases added.]

F. U.S. National Academies of Sciences

---, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. National Academies of Sciences, Engineering, and Medicine 2018. Washington, DC: The National Academies Press.

This study addresses a large panoply of CDR methods, which in this report are called “negative emissions technologies.” Its coverage of DAC makes a distinction between liquid and soled sorbent approaches. The latter requires lower temperatures to accomplish the chemical binding needed and therefore uses less energy. The study reports a wide range of 1.93 to 23.09 GJ (gigajoules) per ton of CO_2 captured (pg 216) for *solid* sorbent DAC systems. The range would be significantly higher for liquid sorbent systems. For comparison, the widely-cited Socolow et. al. study (2011) reported 9.9 to 12.5 GJ per ton of CO_2.

Appendix D: Literature Review: "Stepping Stone" Argument

Hu, Bingyin and Haibo Zhai (2017) "The cost of carbon capture and storage for coal-fired power plants in China" *International Journal of Greenhouse Gas Control*, 65 (2017) 23-31.

> CO2-EOR could be an economically feasible option as a short-term solution to facilitate CCS deployment and technological learning, **though there is a concern about the net increase in life cycle CO2 emissions via CO2-EOR operations** (Jaramillo et al., 2009). [Emphasis added.]

Boot-Hanford, M.E. et. al. (2014) "Carbon capture and storage update" Energy & Environmental Science, 2014, 7,130.

> CO2 has been injected into the subsurface for many decades for the purpose of improving oil recovery, as mentioned in the beginning of this section. This is overwhelmingly in the USA in southern states of west Texas, Mississippi and Louisiana; although the longest duration project is at Rangely and the best-known project for
> CCS is Weyburn in Saskatchewan. Most of these 70 or so projects have been and are supplied with CO2 from natural accumulations of volcanic derivation, so provide some information on subsurface behaviour but less as an analogue for the CCS techno-economic system. …The primary purpose of those projects is to produce oil rather than to dispose of CO2. This can have a benefit in that such projects encourage and enable the development of efficient and low-cost CO2 capture technology, and such projects may fund the building of pipeline transportation networks for CO2. However, viewed from the objective of CCS, such projects have two significant disadvantages: the first problem is that CO2-EOR objects fall under industrial legislation; consequently there is no mandate to undertake details or extensive CO2 monitoring through the lifetime of the project to demonstrate and predict secure long-term retention. Second, the carbon budget overall becomes conflicted by double counting. CO2 captured from
> combustion of coal or gas at a power station cannot be regarded as free from emissions, available to be used to release additional fossil fuel, which itself will produce CO2 upon combustion.
>
> **In North America the additional oil is not conventionally regarded as producing an emission**, because oil production is regarded as free of emission, until the end user undertakes combustion. **By contrast in Europe these additional emissions will be explicitly counted as part of the carbon budget** and if CO2 emissions credits are to be claimed, then monitoring validation of CO2 storage will be required.
>
> **Even with these practical difficulties of emissions offsetting, it may still be worth undertaking CO2-EOR as a stepping stone** to rapid building of large numbers of capture plants connected to pipeline networks, connected to multiple storage sites which will reach their full potential after the additional oil production is exhausted. [Emphasis added.]

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