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CO_2-driven Enhanced Oil Recovery as a Stepping Stone to What?

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ABSTRACT: This paper draws heavily on the authors' previously published research to explore the extent to which near term carbon dioxide-driven enhanced oil recovery (CO_2-EOR) can be "a stepping stone to a long term sequestration program of a scale to be material in climate change risk mitigation." The paper examines the historical evolution of CO_2-EOR in the United States and concludes that estimates of the cost of CO_2-EOR production or the extent of CO_2 pipeline networks based upon this energy security-driven promotion of CO_2-EOR do 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. The paper notes that the evolving regulatory framework for CCS makes a clear distinction between CO_2-EOR and CCS and the authors examine arguments in the technical literature about the ability for CO_2-EOR to generate offsetting revenue to accelerate the commercial deployment of CCS systems in the electric power and industrial sectors of the economy. The authors conclude that the past 35 years of CO_2-EOR in the U.S. have been important for boosting domestic oil production and delivering proven system components for future CCS systems. However, though there is no reason to suggest that CO_2-EOR will cease to deliver these benefits, there is also little to suggest that CO_2-EOR is a necessary or significantly beneficial step towards the commercial deployment of CCS as a means of addressing climate change.

KEY WORDS: carbon dioxide capture and storage; geologic CO_2 storage; CO_2-driven enhanced oil recovery; climate change; greenhouse gas emissions mitigation

1. Introduction

This paper explores the extent to which near term carbon dioxide-driven enhanced oil recovery (CO_2-EOR) can be "a stepping stone to a long term sequestration program of a scale to be material in climate change risk mitigation."[1] This paper will draw heavily upon our previously published research and our conclusion that, "The greatest impact associated with CO_2 storage in value-added reservoirs may be derived from their ability to produce more domestic oil and gas, rather than their limited ability to fundamentally lower the cost of employing CCS [carbon dioxide capture and storage] as a means of addressing climate change (Dooley et al., 2007)." CO_2-EOR indeed offers benefits to the body of knowledge needed to implement CCS, including useful experience in handling and injecting CO_2, but CO_2-EOR, as commonly practiced today, does not constitute CCS and it does not necessarily represent a fundamental step towards the development of a long-term, commercial scale geologic sequestration industry. This appraisal stands in stark contrast to statements encountered in the literature regarding the singular importance of CO_2-EOR in stimulating the early market for CCS technologies, including:

- Enhancing U.S. energy security (ARI, 2010; SSEB, 2006; Steelman and Tonachel 2010)
- Stimulating economic development and employment growth (Task Force on Strategic Unconventional Fuels, 2007; ARI, 2010; SSEB, 2006; Steelman and Tonachel 2010)
- Delivering non-climate environmental protection benefits (ARI, 2010; Steelman and Tonachel 2010)
- Lowering the cost of deploying CCS for large stationary point sources like fossil fired power plants (ARI, 2010; CCAP, 2004; Fernando et al., 2008); and
- Accelerating the deployment of the "essential" backbone for a national CO_2 pipeline network that would be used by later CCS adopters (ARI, 2010; ICF, 2009; Kelliher, 2008).

Though it runs contrary to conventional wisdom regarding the foundational nature of CO_2-EOR for commercial scale CCS deployment, our research suggests that CO_2-EOR is dissimilar enough from true commercial-scale CCS – in the vast majority of configurations likely to deploy – that it is unlikely to significantly accelerate large scale adoption of the technology. Additionally, past experience with CO_2-EOR operations and the incentives that have driven the development of the industry over the past four decades do not directly translate to form a robust basis for informing public policy or investment in a world defined by stringent and mandatory greenhouse gas (GHG) emissions reduction intended to stabilize atmospheric concentrations of these gases and avert the worst aspects of anthropogenic climatic change. This paper presents what the authors believe to be some of the critical, though seldom discussed,

[1] Quote taken from the scoping document sent out by MIT to participants of this July 2010 conference, for which this paper was invited.

complexities surrounding many of the purported benefits of expanded CO_2-EOR, as well as a discussion of why CO_2-EOR may not be the stepping stone to full-scale CCS deployment that many assume (or hope) it will be.

2. CO_2-EOR and CCS

Before embarking on analyses of the purported cost savings potential, energy security, and environmental benefits of CO_2-EOR, it is important to briefly clarify the distinction between CO_2-EOR and CCS. CO_2-EOR represents the process by which CO_2 is injected into depleting oil fields for the purpose of enhancing the recovery fraction of the oil that remains in the field following primary and secondary production methods (Meyer, 2007). According to recent survey data by Koottungal (2010), there are 129 CO_2-EOR projects operating around the world, with 114 of those in the U.S. Given the lack of binding GHG constraints in the countries where these CO_2-EOR operations are taking place, one must assume that each of these projects is focused on optimizing oil recovery. The vast majority of CO_2-EOR projects inject CO_2 produced from natural underground accumulations; in the U.S. and Canada, naturally-sourced CO_2 provides an estimated 83% of the CO_2 injected for EOR, with anthropogenic sources providing the rest (Moritis, 2010).

Though it shares some technical characteristics and methods with CO_2-EOR, CCS represents technologies focused on a different objective: the long-term isolation of CO_2 in the deep subsurface as a means of mitigating the risks of global climate change. There are a number of potential target geologic formations being examined for sequestering CO_2 deep in the subsurface including depleted oil and gas fields, as well as deep saline-filled reservoirs (IPCC, 2005). Depleted oil and gas fields are attractive options given their proven capability of securely trapping fluids and gas over geologic timescales, but carry with them additional concerns and risks because of the number of wellbore penetrations. A number of studies have examined the candidate CO_2 storage resources available around the world, and deep saline formations (DSFs) consistently provide the bulk of the CO_2 storage potential, orders of magnitude higher than the volumes likely to be found in depleted oil and gas fields (Dahowski et al., 2005; Dahowski et al., 2010; IPCC, 2005; NETL, 2007; Takahashi et al., 2009). For CCS to truly make a difference in the global challenge to reduce emissions, storage in DSFs has been shown repeatedly to be the primary reservoir application for CCS (Edmonds et al., 2007; IPCC, 2005; MIT, 2007; Wise et al., 2007). Still, CCS coupled with CO_2-EOR could be attractive in locations with significant available capacity and where conditions are amenable to both long-term CO_2 storage and EOR (see for example Ambrose et al., 2008; ARI, 2010).

However, CO_2-EOR as commonly practiced today does not meet the emerging regulatory thresholds for CO_2 sequestration, and considerable effort and costs may be required to bring current practice up to this level. Of the four large complete end-to-end commercial CCS facilities on the planet today, only one employs CO_2-EOR: the Dakota Gasification - Weyburn CCS project. Given that the world today lacks the kind of long term commitment to progressively tighter greenhouse gas constraints (a requirement to stabilize atmospheric CO_2 concentrations, see Wigley, et al., (1996)) that would be needed to motivate large scale CCS deployment, the fact that only the Dakota Gasification - Weyburn CCS project makes use of its CO_2 for EOR suggests that CO_2-EOR represents one of a larger set of possible CCS configuration rather than a critical stepping stone for component CCS technologies. The In Salah, Sleipner, Snøvit and (in the near future) Gorgon CCS projects all dispose of their CO_2 into "non-value-added" DSFs and therefore do not generate revenue via recovered hydrocarbons. If the rents associated with selling CO_2 for use in CO_2-EOR were so compelling and necessary for CCS projects then it seems counterintuitive that the majority of these early CCS facilities fail to make use of this valuable revenue stream.

There are likely a number of reasons for this, including the complexity of CO_2-EOR projects and their need for additional injection and production infrastructures that are often overlooked in discussions that equate CO_2-EOR to CCS. Figure 1 for example shows the extensive infrastructures for oil, water and CO_2 required to make CO_2-EOR economically viable at the Weyburn field. Koottungal (2010) states that there are 170 CO_2 injector wells and 320 oil production wells at Weyburn. This large infrastructure should be compared to the much smaller infrastructures required to store CO_2 in deep geologic structures at Sleipner and Snøvit where, due to the high permeability at these sites, both projects are able to inject more than $1MtCO_2$/year via a single injector well (Michael et al., 2010). Even at In Salah where the average permeability of the storage formation is up to three orders of magnitude lower than the conditions at Sleipner and Snøvit, CO_2 storage on the order of $1MtCO_2$/year is accomplished through only three directional injector wells (Michael et al., 2010). The Gorgon CO_2 storage facility in Australia will be injecting close to $5MtCO_2$/year into a relatively low permeability deep saline formation (average permeability of 25 mD) through 9 injector wells along with four water production wells which will be used to manage reservoir pressure (Michael et al., 2010).

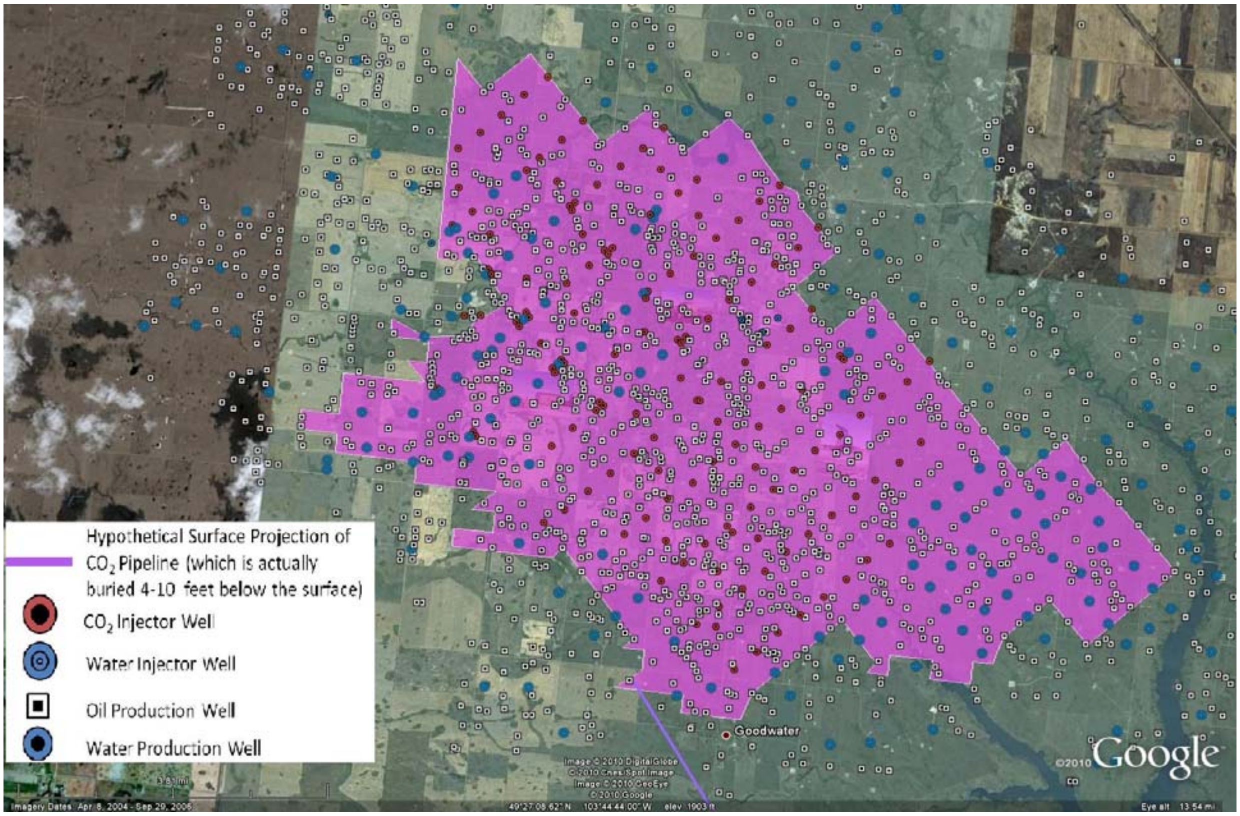


Figure 1: Areal View of Weyburn CO_2-EOR Field and Key Oil, Water, and CO_2 Well Infrastructures (for a description of the data and methods use to prepare this figure please see Dooley, 2009)

Even with nearly 40 years of operational experience, and even with a growing number of projects utilizing anthropogenic CO_2, it is only the Dakota Gasification - Weyburn CCS project that represents a complete end-to-end CO_2-EOR based CCS deployment. No other CO_2-EOR projects are viewed as CCS projects due to missing operational and CO_2 monitoring elements that are critical to demonstrating the effectiveness of the process for safely isolating CO_2 away from the atmosphere for the purpose of addressing climate change. The Weyburn project has incorporated significant risk assessment and extensive monitoring programs to verify the secure storage of the injected CO_2 (IEAGHG, 2005) which are critical aspects of the regulatory concept of a “complete end-to-end CCS project” which lies at the core of the distinction between CO_2-EOR and CCS.

3. The Threshold for Generating Tradable GHG Emission Reduction Credits

It is important to note that deploying GHG emissions reduction strategies is not simply an altruistic enterprise. The purpose of implementing any GHG emissions reduction strategy or technology is to obtain certified documentation that an entity's GHG emissions have been reduced by a specific verifiable quantity. This is especially true when it comes to capital-intensive single purpose technological systems like CCS. One employs these GHG emission reduction technologies to ensure compliance with some form of binding regulation in order to avoid penalties that would be levied for noncompliance. Certification processes are certain to demand rigor beyond simply establishing that CO_2 has been injected into the deep subsurface in order to issue certified GHG emissions reductions credits for CCS projects. Moreover, the degree of regulatory rigor applied is heightened by the need to foster economic efficiency and credibility in the implementation of the GHG emissions reduction policy by requiring that each ton of verified emissions reduction from any certified emissions mitigation activity be equivalent to and interchangeable with any other ton of verified reduced emissions.

Thus, as noted by Jaramillo et al., (2009) in terms of climate mitigation, the test for CO_2-EOR is not as simplistic as establishing that the use of CO_2 from anthropogenic CO_2 sources for CO_2-EOR results in lower overall GHG emissions than CO_2-EOR using CO_2 sourced from natural domes. The issuance of certified and fungible GHG emissions credits for any mitigation / offset project will likely be based upon net avoided emissions within a defined system boundary such that additional emissions created in the process of the mitigation opportunity are subtracted from the gross offset generated. In simple terms, CCS derived GHG emission reduction credits will be based on the net volume of CO_2 injected less the emissions associated with running the CCS project. Lifecycle analysis tools will likely be needed to understand the *net avoided* emissions for a CO_2-EOR project – accounting for both the net CO_2 stored in the reservoir as well as the additional emissions resulting from the CO_2-EOR processes, including the energy required to separate and reinject the more than 50-67% of injected CO_2 that is produced along with the oil after breakthrough (IPCC, 2005).

In reviewing the evolving body of proposed and enacted rules that would govern how CO_2 storage will be regulated in practice, it seems clear that a distinction is being drawn between the regulation of CO_2 stored in a geologic structure like a DSF versus CO_2 used for CO_2-EOR. For example, the U.S. Environmental Protection Agency (USEPA) Proposed Mandatory Reporting Rule (MRR) makes it clear that different levels of reporting will be required for conventional CO_2-EOR than will be required of what the USEPA calls geosequestration. The MRR would require the calculation of CO_2 entrained in the produced oil as well as different (albeit lesser) reporting of fugitive CO_2 emissions for CO_2-EOR based projects (USEPA, 2010). Still, the reporting threshold for geosequestration projects would be significantly higher. This was likely done to limit interference with current CO_2-EOR practices but could also present a barrier to entry for those wishing to convert CO_2-EOR projects to certified geosequestration projects if one cannot produce the appropriate baseline and historical fugitive emissions data.

The recently enacted Tax Credit for Carbon Dioxide Sequestration under Section 45Q also explicitly differentiates between injection of CO_2 into a DSF for CCS and CO_2-EOR (IRS, 2009). Further, the proposed USEPA Underground Injection Control Program Class VI CO_2 Well regulation makes it clear that abandoned wells intersecting the proposed storage reservoir that are within the area of review would need to be identified, located, and plugged prior to using the field for storage (USEPA, 2008). As noted by the IPCC (2005), this requirement reflects the fact that “storage security in mature oil and gas provinces may be compromised if a large number of wells penetrate the caprocks.” Again from the perspective of a regulator being asked to award certified, fungible GHG emission reduction credits, it is imperative that additional risks such as previously drilled wells in depleted oil and gas fields – often dozens (and sometimes hundreds) of wells per square mile – be taken into account (see Figure 2, after USGS, 1996).

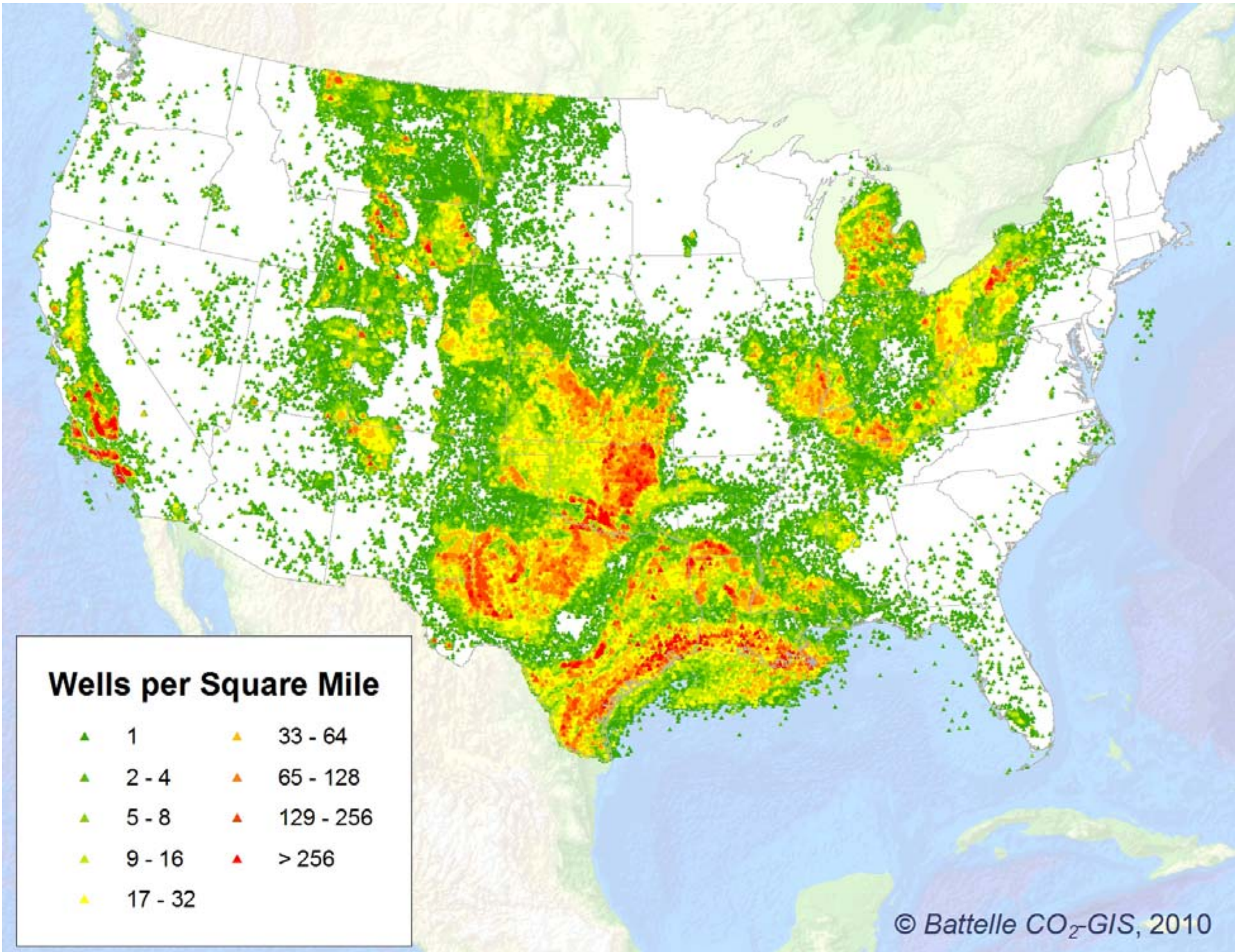


Figure 2: Well density for hydrocarbon exploration and production wells, based on data from the 1995 National Oil and Gas Assessment (USGS, 1996).

An additional factor that speaks to this regulatory distinction between CCS with CO_2-EOR is in regards to mineral ownership rights. Marston and Moore (2008) note that even after CO_2-EOR is complete and a depleted oil field is used "purely for CO_2 storage" there will still be a significant quantity of oil remaining in the reservoir. All of this stored CO_2 could eventually help mobilize some of the remaining oil and there could be future technological progress with respect to oil production techniques that could enable production of additional oil from the field. Thus according to Marston and Moore (2008), “pore space available for CO_2 storage” in a depleted oil field should only be construed as those pores that have been liberated of their formation fluids (oil, water and gas); while the pores that contain residual hydrocarbons after production could still be considered a valuable mineral right. Thus there is potentially an added level of complexity for those selecting to store CO_2 in depleted hydrocarbon formations in that who "owns" the reservoir (whether the mineral, water, or surface rights owner) is based in part upon the presence or absences of valuable minerals in the formation.

The emerging differentiated regulatory treatment of CO_2-EOR is clear, though whether it is problematic or burdensome remains to be seen. These regulations recognize that the gap between simply injecting CO_2 to increase oil recovery and injecting it to ensure that it will never enter the atmosphere is not trivial and cannot be simply addressed by simple mass balance of the volumes of CO_2 injected and produced in a given CO_2-EOR flood. At its core, this "gap" represents a set of activities that would not be undertaken on a business-as-usual EOR project, and may incur significant cost. As noted by the IPCC (2005) "current monitoring for EOR is designed to assess the sweep efficiency of the solvent flood and to deal with health and safety issues." For the purposes of climate mitigation, there would also be requirements for pre-injection activities such as field characterization and mitigation of leakage pathways (including abandoned wells); co-injection activities such as groundwater monitoring, injectate monitoring by multiple methods, iterative reservoir modeling, and efforts to optimize for CO_2 storage and security, rather than oil recovery alone; and post-injection activities such as continued monitoring, modeling and site closeout. Thus, the implication in much of the technical literature that CO_2-EOR is essentially identical to geologic CO_2 storage – except that one "gets paid" for CO_2 injected into the oil field – is simply not true. The requirements necessary to qualify CO_2-EOR as a geosequestration project are not trivial and involve significant work and cost throughout each stage of the project.

4. On the Wisdom of Extrapolating from 40 years of CO_2-EOR in West Texas

While we are all generally comfortable extrapolating from past experiences in our day-to-day lives, significant alterations to the paradigm under which past decisions were made may well result in very different outcomes for future decisions. Nevertheless, much of the technical, legislative, and public policy dialogue about the prospective role of CO_2-EOR is based on a largely implicit extrapolation of the growth of CO_2-EOR in the United States and in particular in West Texas over the past four decades. However, there is relatively little attention paid to the underlying drivers for this significant expansion of CO_2-EOR in the U.S. during this period.

Expansion of CO_2-EOR in the United States was not exclusively driven by some combination of specific gravity of the oil, remaining original oil in place, depth to the oil bearing formation, temperature of the oil bearing formation, the permeability of the formation, the degree of heterogeneity within the oil bearing formation or the many other technical factors which are often used to compute the theoretical potential of

EOR fields to store anthropogenic CO_2 (Gozalpour et al., 2005; IPCC, 2005; Meyer, 2007). Instead, the principal drivers were economic and political. For example:

- Mandelker (1992) makes it clear that federal efforts to explicitly support CO_2-EOR go back to the early 1970s: "Since the oil shocks of the late 1970s whenever the political climate has been right, steps to encourage domestic EOR have been taken [by the federal government]."

- While OTA (1978) makes it clear that direct federal support for enhanced oil recovery -- specifically including CO_2-driven EOR – can be traced back to at least 1976 when the Emergency Petroleum Allocation Act was amended to provide price incentives for "bona fide tertiary enhanced recovery (EOR) techniques." The report goes on to note that the President's 1977 National Energy Plan called for decontrolling the price of domestic oil produced via EOR which would provide a significant monetary incentive to begin seriously exploring ways to deploy nascent EOR production technologies on a large scale.

- As detailed by (Dooley et al., 2009a), there were substantial federal subsidies that funded a significant portion of the existing large CO_2 pipeline network supporting current CO_2-EOR in the United States. As documented in that paper, U.S. oil companies paid $88.5 billion (in constant 2005 US$) between 1980-1985 in Windfall Profits Taxes (WPT) which provided a strong incentive to produce more oil from existing fields rather than bringing new fields into production. Norman (1994) states unequivocally that, "There is no question that for crude oil produced from Permian basin oil fields, this [substantially lower] WPT rate differential favored CO_2 flood development."

- During the period 1994-2005, the Internal Revenue Service paid out an estimated $1.3 to $1.9 billion (in constant 2005 US$) under the Section 43 Enhanced Oil Recovery Tax Credit, which directly subsidized the creation of new CO_2-EOR floods, the expansion of existing CO_2-EOR projects, and associated purchases of CO_2 (Dooley, et al., (2009a).

While there was clearly a lag between the application of these federal subsidies[2] and the production of oil from CO_2-EOR floods and while there was certainly significant private funding invested into these fields and their associated infrastructure, there can be no doubt that federal subsidies in the name of energy

[2] It is also worth noting that there were and in many cases still are significant state level subsidies for CO_2-EOR based domestic oil production in the name of domestic energy security or regional economic growth (Martin, 1992).

security played a decisive role in establishing the existing CO_2-pipeline network. As can be seen from Figure 3, more than 60% of the existing 3900 miles of CO_2 pipeline in the United States was built in the 1980s with the vast majority of these CO_2 pipeline built in and around West Texas (Dooley et al., 2009a).

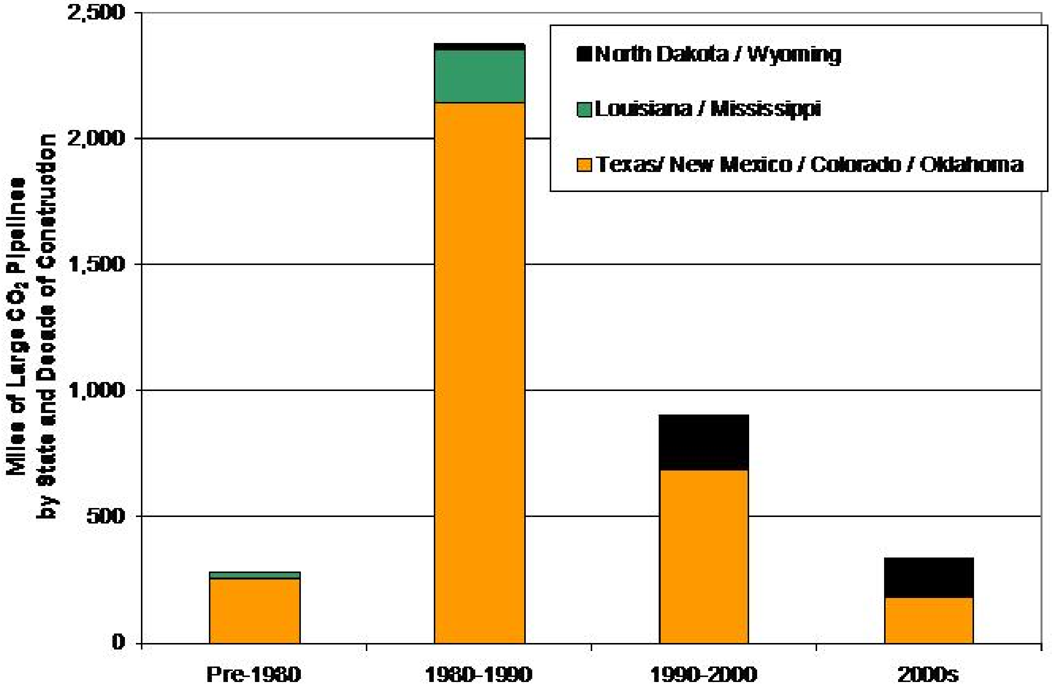


Figure 3: Additions to the US CO_2 Pipeline Infrastructure by decade and by region (taken from Dooley et al., 2009a)

These existing CO_2 pipelines are important "sticky" pieces of capital; they are unlikely to be relocated and their O&M costs are small compared to their construction costs (McCollum and Ogden, 2006; Norman, 1994; Smith, 2009). These existing CO_2 pipelines represent an implicit subsidy for any given CO_2-EOR flood that accesses these existing lines as the new CO_2 flood does not need to pay the entire cost of producing CO_2 from a dome and delivering it to a given field. Thus, it is not clear to the extent to which it is appropriate to extrapolate field level CO_2-EOR production cost data in areas that are served by these existing CO_2 pipelines to regions of the U.S. where there is CO_2-EOR potential but no extant pipeline infrastructure.

5. Is There a Need to Build Out a National CO_2 Pipeline Network before CCS Can Deploy?

The largely overlooked role of the federal government's past subsidization of the existing CO_2-pipeline network in the name of energy security is germane to discussions of the future role of CO_2-EOR as a means of reducing greenhouse gas emissions as there are numerous analyses that suggest there is a need to build out a large CO_2 pipeline network like what exists in West Texas in order for CCS technologies to deploy.

Figure 4 shows three recently published estimates of large continental CO_2 pipeline networks that the authors of these studies say would be needed before 2030 and whose existence would facilitate the commercial deployment of CCS. It is difficult to understand the rationale for a CO_2 pipeline network on this scale. In our bottom-up modeling of CCS deployment in the U.S., we employ an assumption that individual CCS facilities will construct and operate their own dedicated CO_2 pipeline system (Dahowski et al., 2005; Dahowski et al., 2010; Dooley et al., 2006). This assumption of dedicated source-to-sink CO_2 pipeline networks has been criticized as too simplistic in that it overestimates the amount of CO_2 pipeline needed by forgoing the purported cost savings associated with networked CO_2 pipeline systems. However when we employ this assumption in our modeling (see Table 1 for an example of the results of this bottom-up modeling), we see a national CO_2 pipeline system that would plateau at perhaps 30,000 miles which would deploy over the course of many decades. This 30,000 miles would be enough to decarbonize the vast majority of existing large CO_2 point sources in the U.S., including fossil fuel fired baseload power plants and large swaths of industry (Dahowski and Dooley, 2004; Dooley et al., 2009a; Dooley et al., 2005; Wise et al., 2010a). Assuming that future CO_2 sources will largely be built on brownfield sites and/or use proximity to CO_2 storage reservoirs as a siting criterion, the 30,000 miles of one-to-one pipelines we have estimated in our previous work could potentially represent an upper limit on total CO_2 pipeline that needs to be built. In light of this, estimates of 66,000 miles (ICF, 2009) or 73,000 miles (Kelliher, 2008) seem to overestimate the deployment of CO_2 transport infrastructure by a factor of two or more.

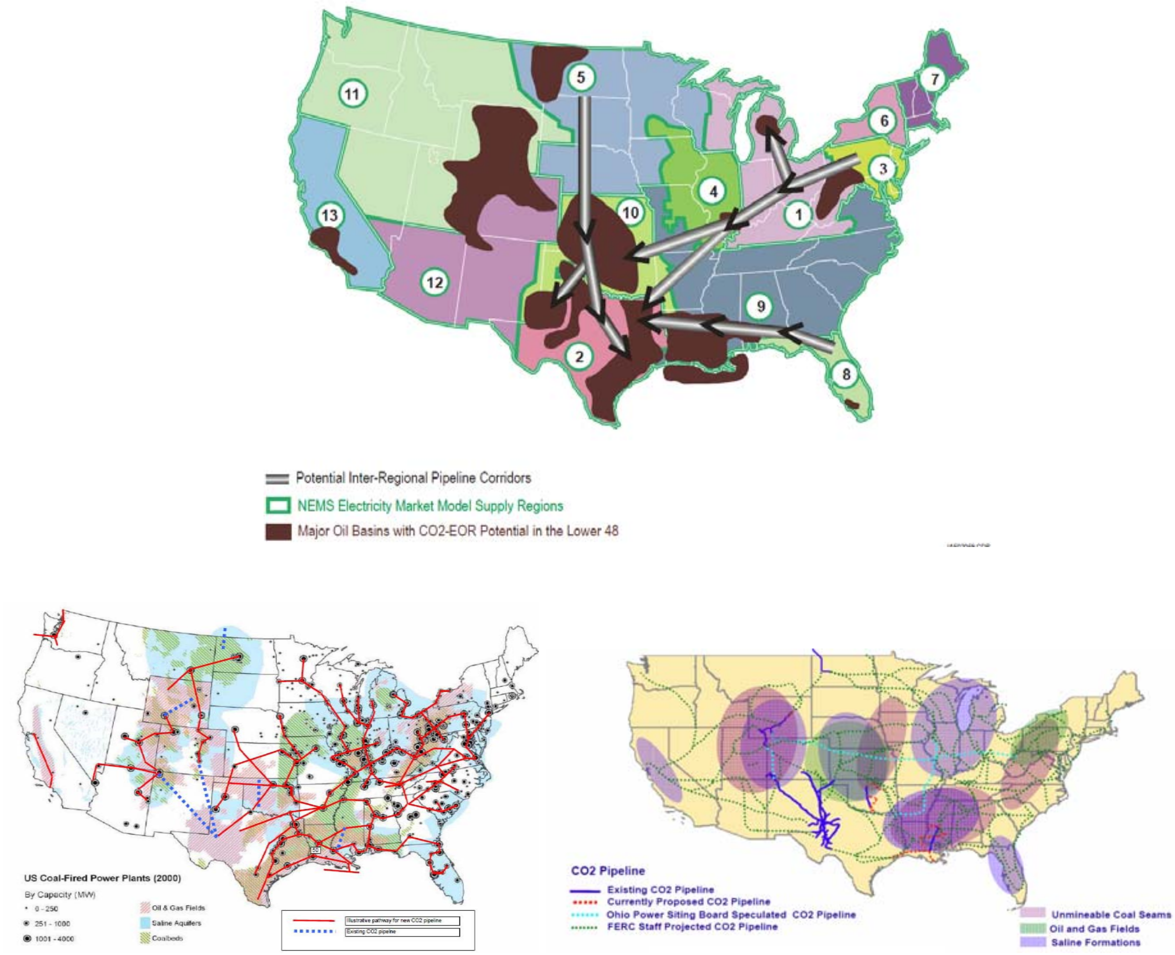


Figure 4: Three views of the need for a large national CO_2 pipeline network by 2030 (top figure, major CO_2 pipeline corridors for CO_2 EOR by 2030 (ARI, 2010), figure in the lower left projection of 66,000 miles of CO_2 pipeline need by 2030 (ICF, 2009); figure in the lower right projection of 73,000 miles of CO_2 pipeline needed by 2030 (Kelliher, 2008)

Others have based their estimates of the need for a large national CO_2 pipeline network upon simple volumetric calculations that compare the volume of oil moved around the world today and its associated infrastructure to the volume of CO_2 that would need to be stored in the future and then state that it would require roughly the same pipeline infrastructure (see for example MIT, 2007; Smil, 2008). Unfortunately, these volumetric comparison-based estimates fail to appreciate the distinction between high and low value-added commodities; oil and natural gas consumers in New York City, Boston, Chicago and Peoria are willing to pay to have these high value-added commodities shipped over large distances so that they can use them to create further value-added products and services. The same cannot be said about pipeline quality CO_2, especially when CCS systems deploy to the extent that there are billions of tons of CO_2 needing to be stored annually. At these scales, CO_2 becomes a waste product that has zero (or as will be discussed below more than likely a negative) value associated with it. Economic analysis suggests that one will likely seek to dispose of the CO_2 as close to the point of generation as feasible, subject to site suitability factors and non-transport cost variables.

Table 1: Rates of CCS Adoption and the Build Out of CO_2 Pipeline Infrastructure under WRE450 and WRE550 Atmospheric CO_2 Stabilization Policies (data taken from (Dooley et al., 2009a)

	WRE 550 Stabilization	**WRE 450 Stabilization**
Average annual number of power plants adopting CCS 2010-2030	1-3 per year	~ dozen per year
CCS Adoption by high purity CO_2 point sources 2010-2030	(relatively) slower adoption of CCS by high purity CO_2 point sources	(nearly) all high purity CO_2 point sources decarbonized within a decade
Average growth in CO_2 pipelines 2010-2030	~ 300 miles/year	<900 miles/year
Average source-sink pipeline length	Tens of miles	Tens of miles
CO_2 Pipelines in Operation 2030	<10,000 miles (i.e., doubling existing CO_2 pipeline system)	~22,000 miles
CO_2 Pipelines in Operation 2050	~16,000 miles	~28,000 miles

Our detailed modeling of CCS adoption across the United States in response to an economic-based climate policy (e.g., a carbon tax or a cap and trade) suggests a temporally and spatially heterogeneous pattern of CCS adoption in response to the climate policy (see for example, Dooley et al., 2005; Wise et al., 2007). This is important and suggests that it is highly likely that the "optimal" placement of a CO_2 pipeline network might only be apparent in hindsight many decades from now. In fact, a recent study by Johnson and Ogden (2010) indicates that only in later phases of CCS deployment for climate mitigation purposes do networked pipelines begin to make economic sense and that for the early to middle stages of deployment, direct pipelines between each source and sink are more cost effective. Further, it particularly does not make a lot of sense from a climate mitigation perspective to develop a long-term transportation backbone to deliver CO_2 to a currently attractive promising area of CO_2-EOR production without establishing that large additional suitable storage capacity exists in the area that can handle storage demand over the long term.

In looking to the future, it is also worth considering the extent to which there are likely to be federal subsidies that would accelerate CO_2 pipeline development. The currently available Section 45Q tax credit provides a subsidy of potentially up to \$10/tonCO_2 for no more than 75 MtCO_2 from anthropogenic sources used for CO_2-EOR (IRS, 2009). Moritis (2010) reports that 17% of the CO_2 used for CO_2-EOR in the United States in 2008 came from anthropogenic (non-dome) sources. That would imply approximately 9 MtCO_2/year of anthropogenic CO_2 is already being used for CO_2-EOR and thus if these existing facilities alone applied for the Section 45 Tax Credit, the entire authorized amount would be exhausted in a little more than 8 years. This would do little to incentivize development of new technologies or infrastructure that would help migrate from early CO_2-EOR based applications to CCS deployed by baseload power plants injecting their CO_2 into non-value-added DSF reservoirs.

The authors remain skeptical of arguments for expanded CO_2-EOR that are, at their core, extrapolations of what happened in the past in an effort to address energy security concerns, a fundamentally different motivation than stabilizing atmospheric concentrations of GHGs.

6. Cost Savings Associated with CO_2-EOR for CCS: Why Share Rents with Your Commodity Supplier?

A core argument made in support of the proposition that CO_2-EOR will provide a bridge to larger CCS deployment is that the revenue associated with selling CO_2 to an EOR operator would result in substantial income for power plants or other large anthropogenic CO_2 point sources that could be used to lower the overall cost of employing CCS and therefore speed the large scale commercial adoption of CCS as a means of addressing climate change. For example:

- "Revenues from CO_2 sales to the oil industry can offset some of the costs of CO_2 capture from both natural gas- and coal-fired power plants, as well as other industrial facilities producing large volumes of CO_2." (ARI, 2010)

- A 2004 report from the Center for Clean Air Policy (CCAP, 2004) projected that as much as 17.5 GW of new IGCC+CCS power plants could be built by 2020 with the incremental cost of these plants being offset by a market and a positive price for all the CO_2 captured by this vast new fleet of power plants. This report's modeling suggested the scale of the rents associated with selling CO_2 for CO2-EOR could be so profitable that "Regional wholesale [electricity] prices decrease by 1 percent to 5 percent in the regions in which enhanced oil recovery credits are available."

- While a 2008 report from the World Resources Institute (Fernando et al., 2008) asserted that "[CO_2-driven] EOR can create benefits of up to $55 per ton of CO_2 (excluding the cost of the wells and CO_2 recycling), which can potentially offset part or even total capture costs … [this] cost advantage could potentially encourage early adopters of CCS technology … [and] may be a way to spearhead commercial deployment and an infrastructure build-out for regular carbon capture and permanent sequestration."

Assertions such as these stem from the fact that CO_2-EOR is undertaken as a profitable endeavor, motivated by revenues from the recovered oil. At present there is a positive price for pipeline quality CO_2 in regions of the U.S. that already employ CO_2-EOR. This positive price has been rising in the past several years along with oil prices. The flawed logic that extrapolates this current situation into the future assumes that (1) the positive price for pipeline quality CO_2 will persist for a significant period of time into the future and (2) the rents associated with the production of a valuable commodity like oil would be shared with the upstream supplier of pipeline quality CO_2, a low value-added commodity.

Both of these premises hinge on whether pipeline quality CO_2 remains a scarce resource relative to the demand. Figure 5 shows supply and demand for pipeline quality CO_2 under a scenario (illustrated at t=0) in which CO_2 supply is scarce relative to demand resulting in a positive price for CO_2 as well as a scenario (t=1) in which the supply of pipeline quality CO_2 is far in excess of any potential demand for this basic commodity. In this second situation, the price paid for pipeline quality CO_2 should drop and eventually become negative. That is, the suppliers of pipeline quality CO_2 (e.g., a large power plant that employs CCS as a means of reducing its GHG emissions) would have to pay a disposal fee rather than be able to demand payment for their CO_2. There would no longer be "buyers" willing to purchase their CO_2.

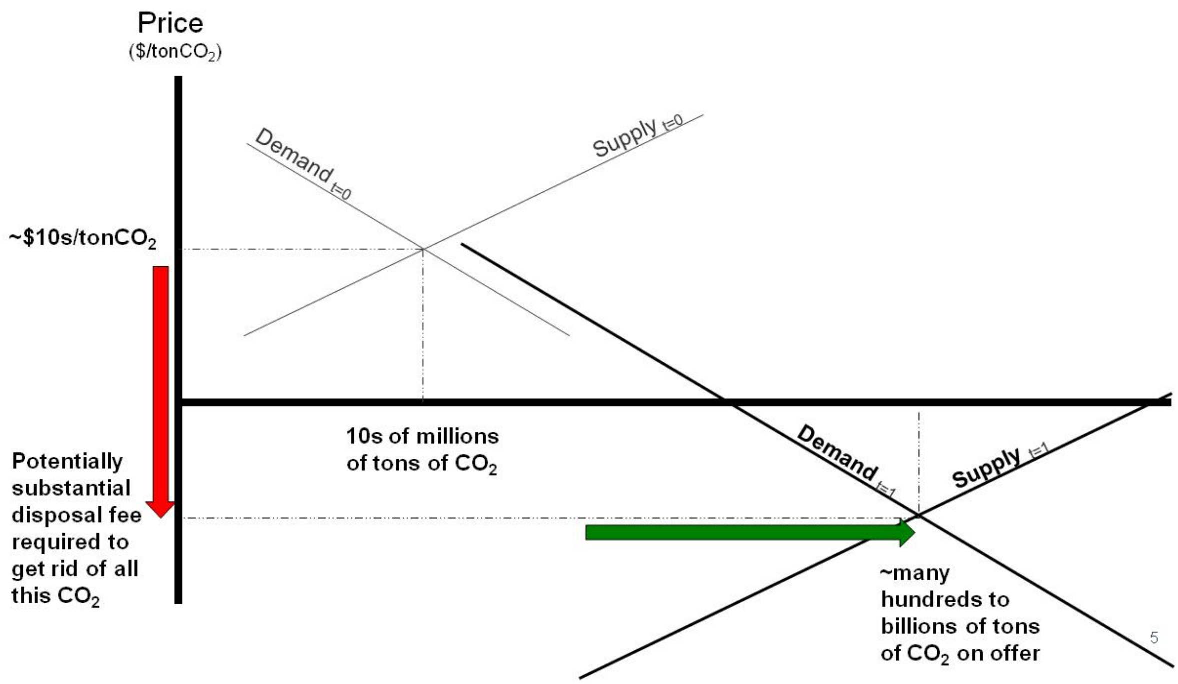


Figure 5: Illustration of supply and demand for pipeline quality CO_2 and the resulting price paid under two scenarios of assumed scarcity (taken from Dooley, 2004)

If pipeline quality CO_2 remains scarce, then it is reasonable to assume that the supplier (i.e., the anthropogenic CO_2 point of origin which might be different from the entity that delivers pipeline quality CO_2 at the boundary of a CO_2 flood) will have some ability to set the price of pipeline quality CO_2 and receive some positive price (i.e., payment) for supplying this commodity. While potentially dated, Norman (1994) examined the market for pipeline quality CO_2 in West Texas in the early 1990s and found the market to be oligopolistic in nature (i.e., a small number of sellers were able to control supply and therefore influence the price paid). This is what one would expect in a market characterized by scarcity and high barriers to entry. However when CCS systems are deployed on a large scale because of GHG emissions constraints, a very different market structure for pipeline quality CO_2 should exist. When the supply of pipeline quality CO_2 on offer significantly exceeds demand, the rents from CO_2-EOR do not accrue to the upstream supplier of CO_2-EOR. Under these market conditions, while CO_2-EOR may remain profitable, the revenue streams would no longer accrue to the anthropogenic CO_2 point source supplier and the cost of capturing the CO_2 would not be offset. For a more rigorous treatment of the evolving pricing of pipeline quality CO_2 for CO_2-EOR in a greenhouse gas constrained world readers are encouraged to consult Leach et al. (2009).

7. Matching CO_2 Supply and Demand for CO_2-EOR

This simplified "Economics 101" discussion of supply and demand and resulting prices for CO_2-EOR is not merely a macroeconomic phenomenon. There is also reason to question the scale and sustainability of revenues received by individual facilities selling CO_2 to individual EOR projects. Here we present preliminary results of work to be formally presented this fall on the role of CO_2-EOR when applied to a large CO_2 point source such as a power plant (Davidson, Dooley and Dahowski 2010).

Previous evaluations of economy-wide CCS deployment have typically applied a simplifying assumption that 100% of the potential storage capacity for a given formation is available on the first day of the analysis, as well as an assumption that the assumed injection rate impacts only the number of wells required to inject a given volume of fluid per year and is thus considered exclusively as a cost driver rather than a technical one. However, as discussed by Dahowski and Bachu (2006), storing CO_2 in a field undergoing CO_2-EOR is subject to a set of constraints to which storage in DSFs is not, and these constraints – particularly variable demand for CO_2 – may strongly influence the ability of an EOR field to serve as a baseload storage formation for commercial scale CCS projects undertaken as a means of addressing climate change mitigation targets. While each EOR field will be unique and will respond to CO_2 stimulation in different ways based on reservoir-specific characteristics and project design, Figure 7 illustrates the general pattern of high initial demand for new CO_2 coupled with a decrease in demand as recycled CO_2 is used for an increasingly larger portion of the total injection volume. This behavior is consistent with most current CO_2-EOR practices and is critical to understanding the impact on commercial-scale CO_2 storage in EOR fields. Again readers are encouraged to consult Leach et al. (2009) which models the same temporal dynamic; SSEB 2006 and IPCC 2005 also both make explicit reference to the changing demand for "new" CO_2 as the CO_2 flood matures and more CO_2 is recycled.
Here we apply the CO_2 demand profile shown in Figure 7 to a hypothetical 1000 MW IGCC+CCS which produces 6 $MtCO_2$ per year. We further assume that the IGCC is employing CCS as an alternative to paying an assumed significant disincentive associated with venting CO_2 to the atmosphere. In order to avoid penalties associated with emitting CO_2 not used by the CO_2-EOR project, excess CO_2 will need to be stored in a suitable nearby deep saline formation under this scenario.

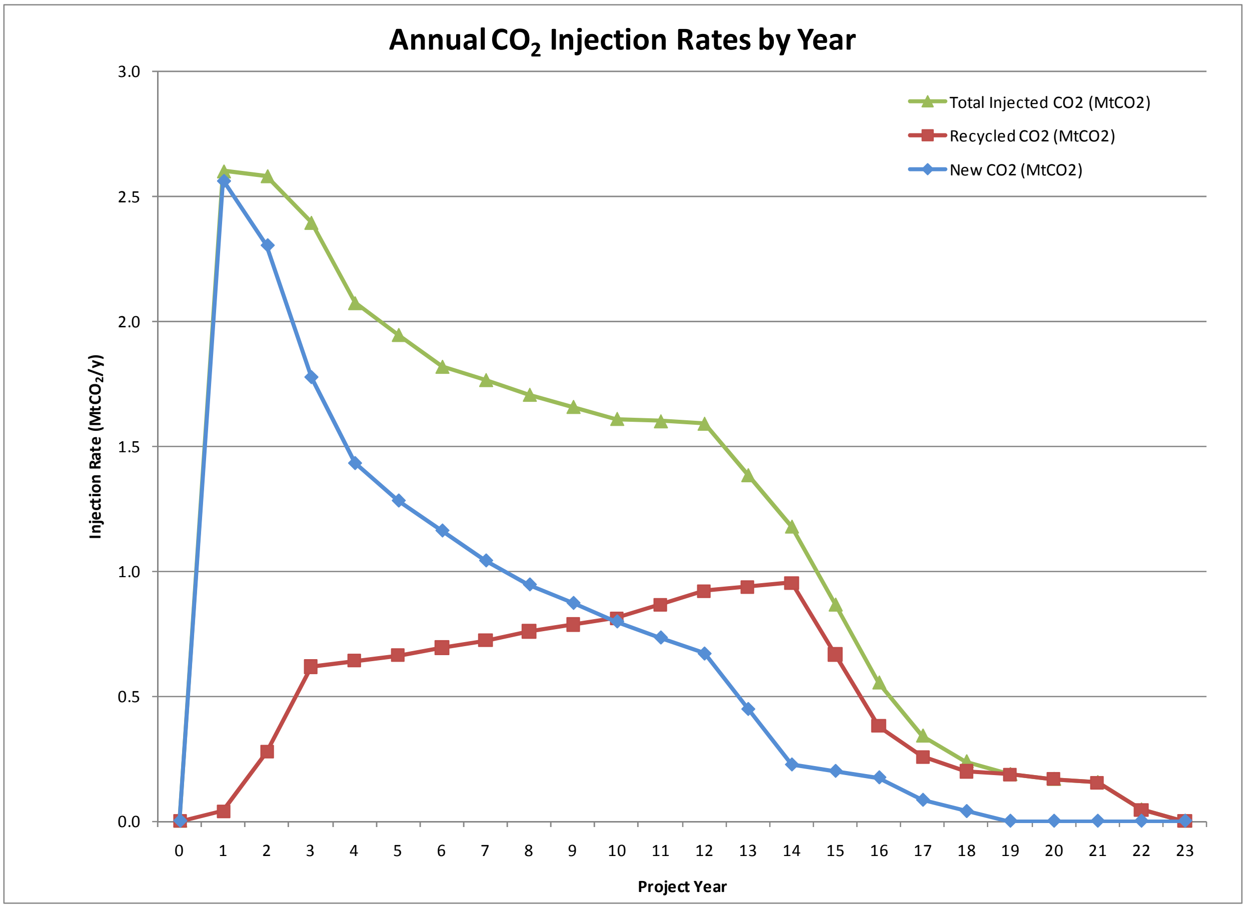


Figure 7. CO_2 demands from a typical west Texas CO_2-EOR project, assuming 20 injection wells per project (Davidson et al., 2010 forthcoming; after Jarrell et al., 2002)

Preliminary modeling indicates that during the first year of injection, this large IGCC+CCS would rely on the "back-up" deep saline formation-based storage for over 50% of its storage needs with the remaining CO_2 utilized in the CO_2-EOR project. The reliance on deep saline formation based storage grows annually, reaching 90% within 15 years and 100% within 20 years (Figure 8). The only way to counteract this inherent declining demand for "new" CO_2 for the flood (i.e., CO_2 derived from the IGCC source rather than via recycling) is to link multiple CO_2 flood-ready projects together to enable a larger fraction of total storage in EOR fields rather than the backup DSF.

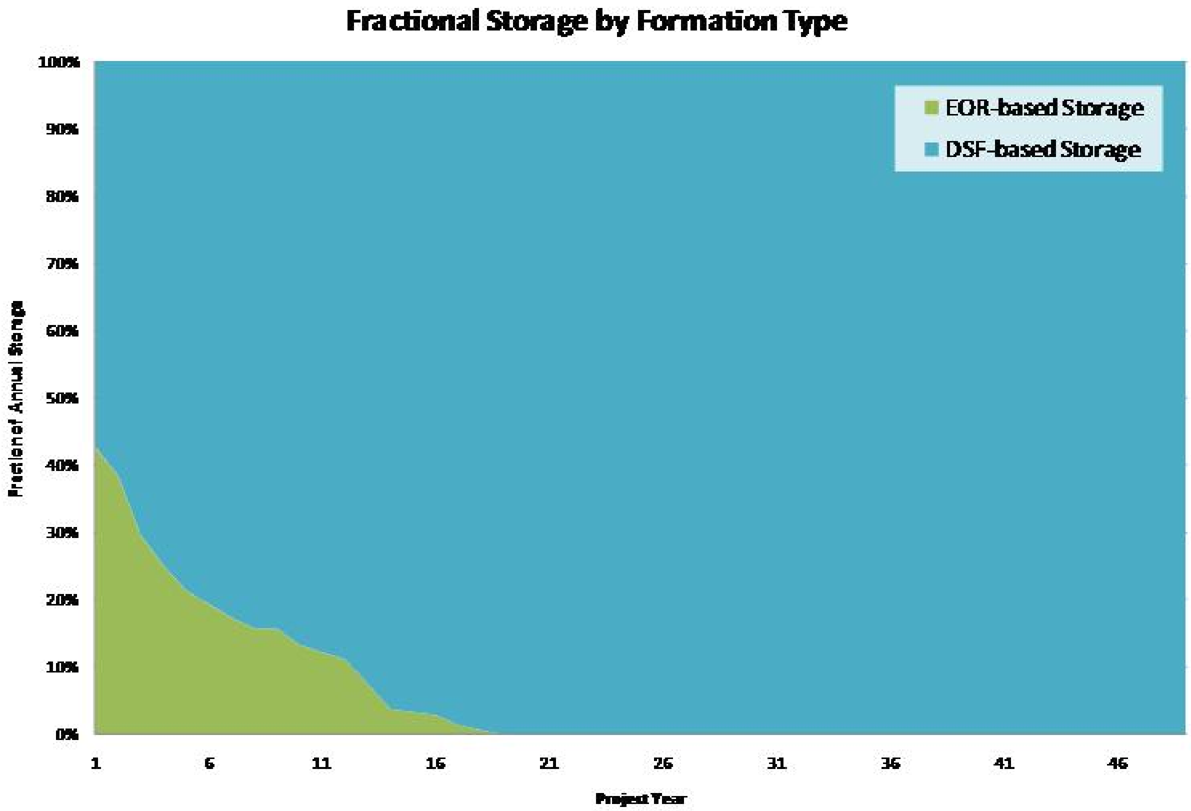


Figure 8: Annual CO_2 Stored by Formation Type for Hypothetical 1000 MW IGCC+CCS storing in a single EOR project and employing a DSF for supplemental storage of the CO_2 not demanded by the EOR project.

As can be seen in Figure 9, those costs need to be captured in the analysis of the economic benefit of CO_2-EOR as it relates to accelerating the deployment of CCS because not fully capturing the cost associated with these additional infrastructures can have a profound effect on the perceived cost reduction potential of CO_2-EOR based storage.

We have also begun to estimate the costs associated with storage in each field type – including revenues from incremental EOR production – along with the cost of CO_2 capture and compression over the assumed 50-year life of this IGCC+CCS facility. In the first year of operation, the assumed offsetting EOR revenues could reduce the net cost *to society* of employing CCS by over 70% (i.e., regardless of which entity(s) captures the incremental EOR revenues) for the IGCC plant relative to simply storing in a DSF, but this savings is halved within the first few years, and decreases until it disappears altogether by the middle of the second decade. This suggests that, under a single-project scenario such as this, EOR-based CCS is not likely to have more than a modest impact on the cost of electricity generated by a large IGCC plant seeking to store the CO_2 produced from round-the-clock operations over its lifetime.

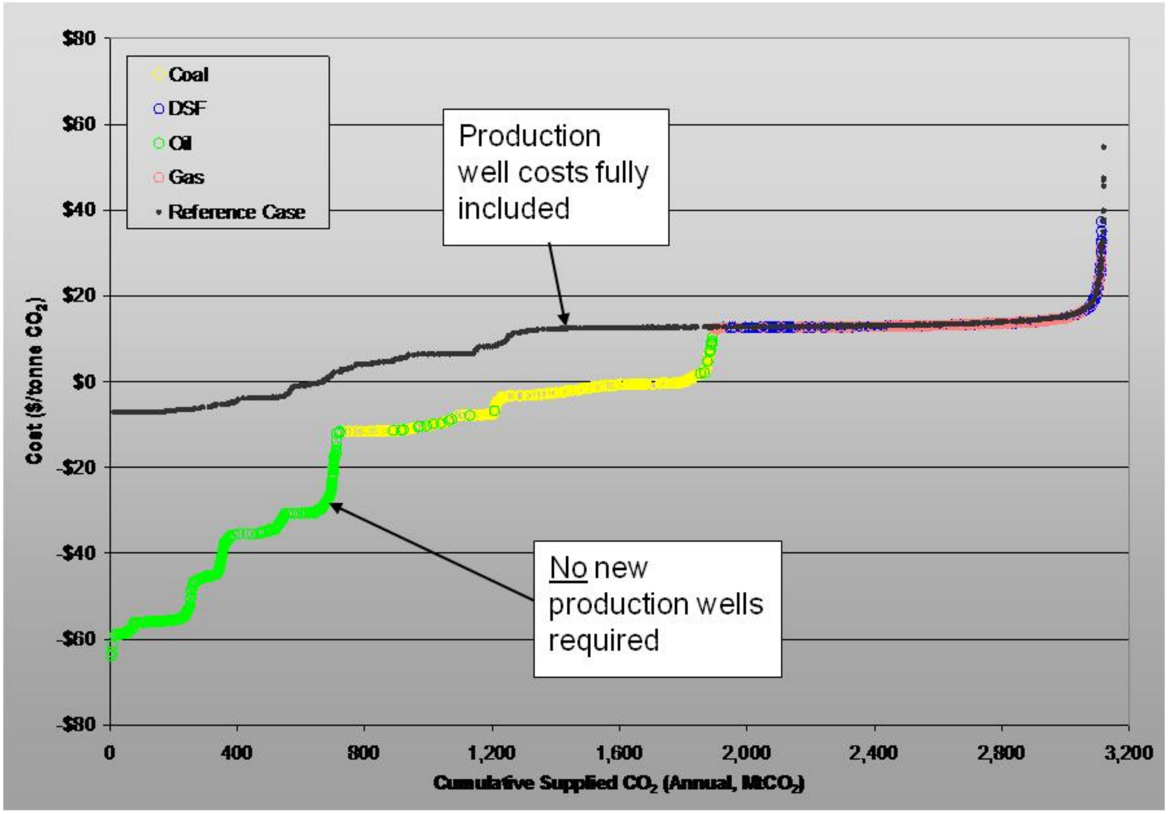


Figure 9. The impact on the cost of transport and storing CO_2 in the US depending upon modeling assumptions regarding the amount of additional infrastructure needed for CO_2-EOR and ECBM based storage options (Dahowski, et al., 2005)

8. A Final Note on CO_2-EOR and Energy Security

As noted above to many, CO_2-EOR looks just like CCS but in fact differs in some fundamental ways. It entails more complexity than is often discussed, and in many cases it is unlikely to appreciably offset the cost of CO_2 emissions mitigation. But can it still provide value by decreasing U.S. reliance on imported oil? Again, the answer is more nuanced and less straightforward than typically presented (ARI, 2010; SSEB, 2006; Steelman and Tonachel 2010) .

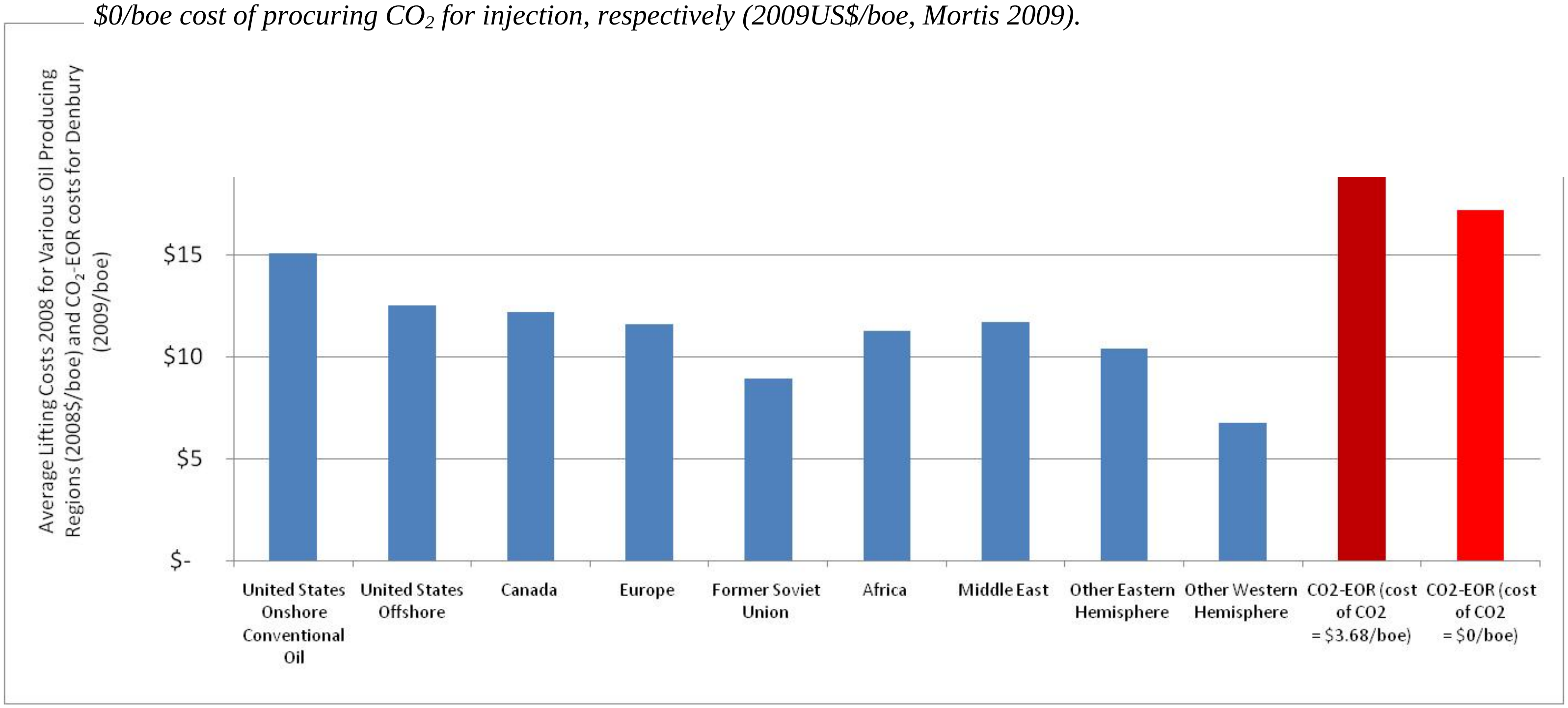
Ample technical literature supports the conclusion that, absent a global commitment to significantly reduce GHG emissions, the world will expand its use of unconventional hydrocarbon resources (e.g., oil shale, tar sands, coal-to-liquids) to replace declining conventional oil production (Dooley et al., 2009b; IPCC, 2007; US Climate Change Science Program, 2007). Given the energy intensity of producing transportation fuels from many of these unconventional hydrocarbon resources (see for example the comprehensive analysis of Brandt and Farrell, 2007), the expansion of unconventional hydrocarbon production in a world without stringent GHG emissions constraints will certainly lead to increased GHG emissions.

However, the imposition of climate policies can fundamentally alter the composition of energy resources that the world draws upon to augment declining conventional oil resources. In order to stabilize atmospheric concentrations of GHGs, the cost associated with releasing these gases to the atmosphere must increase in real terms over time (Wigley et al., 1996). As the cost of emitting GHGs to the atmosphere increases, the energy- and GHG-intensity of these unconventional hydrocarbons will make them less competitive with other options such as biomass-derived fuels and electric passenger vehicle (Dooley et al., 2009b; Luckow et al., 2010; Wise et al., 2010b). This undermines the assertion that there is a beneficial synergy between the need to continue producing crude oil and climate mitigation that can uniquely delivered by CO_2-EOR, despite claims by groups as diverse as the Natural Resources Defense Council (Steelman and Tonachel 2010), Advanced Resources International (ARI, 2010), and the Southern States Energy Board (SSEB, 2006). Fundamentally, this assertion relies on extrapolation of past trends into the future, but if the world is serious about stabilizing atmospheric concentrations of GHGs, simply asserting that the world needs more fossil-derived transportation fuels because electric vehicles and biofuels have not been competitive in the past does not support the conclusion that CO_2-EOR is an inherently beneficial activity that must be sustained and expanded.

There is also no economic or technical justification for assuming that domestically produced CO_2-EOR oil will directly displace oil imported from nations considered hostile to the United States and its allies as argued by Steelman and Tonachel (2010), ARI (2010), and SSEB (2006). Figure 10 shows the average total lifting costs for producing a barrel of oil (including taxes) from major oil producing regions of the world as reported by EIA (2009). As Figure 10 demonstrates, the U.S. tends to be a high cost producer of oil relative to other nations. Figure 10 also includes data for Denbury's CO_2-EOR operating costs for the second quarter of 2009 (Moritis 2009), along with a hypothetical estimate for CO_2-EOR operating costs based upon these Denbury data with the added assumption that delivered pipeline quality CO_2 is free for a CO_2 flood operator.[3] The data in Figure 10 strongly suggest that in a global oil market, increased

[3] This assumes that the EIA's (2010) definition of lifting costs is similar to the costs that Moritis (2009) reports for Denbury. The data reported by Moritis are more detailed than those provided by the EIA making it difficult to verify direct comparability between the datasets. The costs reported by Mortis are comparable to similar figures presented by SSEB (2006) for "Typical CO_2-EOR per Barrel Costs" for a 1st of a kind and an nth of a kind CO_2-EOR flood.

Figure 10: Comparing CO_2-EOR to average oil production costs. Blue bars show 2008 average total lifting costs by region (2008US$/boe, EIA 2010). Red and purple bars show Denbury's reported CO_2-EOR operating costs assuming a $3.68/boe and $0/boe cost of procuring CO_2 for injection, respectively (2009US$/boe, Mortis 2009).



domestic CO_2-EOR driven oil production – even if there were no cost to the CO_2-EOR producer associated with acquiring pipeline quality CO_2 – could just as easily displace oil production from the Gulf of Mexico or lower the marginal global price of crude oil.[4]

Figure 11 shows the historical and projected contribution of domestically produced CO_2-EOR produced oil as a fraction of the nation's annual oil consumption over the 50 year period 1980-2030. The historical data here are from Moritis (2010) and show that domestically produced CO_2-EOR oil grew from virtually nothing in the early 1980s to the point where it now accounts for approximately 2% of US annual oil consumption. The projected data come from the Annual Energy Outlook (EIA, 2010) and reflect EIA's belief that future higher oil prices along with some technical improvement should increase the share of U.S. oil consumption met by domestically produced CO_2-EOR crude to slightly less than 8% by 2030 under the EIA's Reference Case (i.e., no climate policy). Domestically produced CO_2-EOR crude is clearly an important and growing component of the nation's energy portfolio and it is expected to continue its contributions into the future.

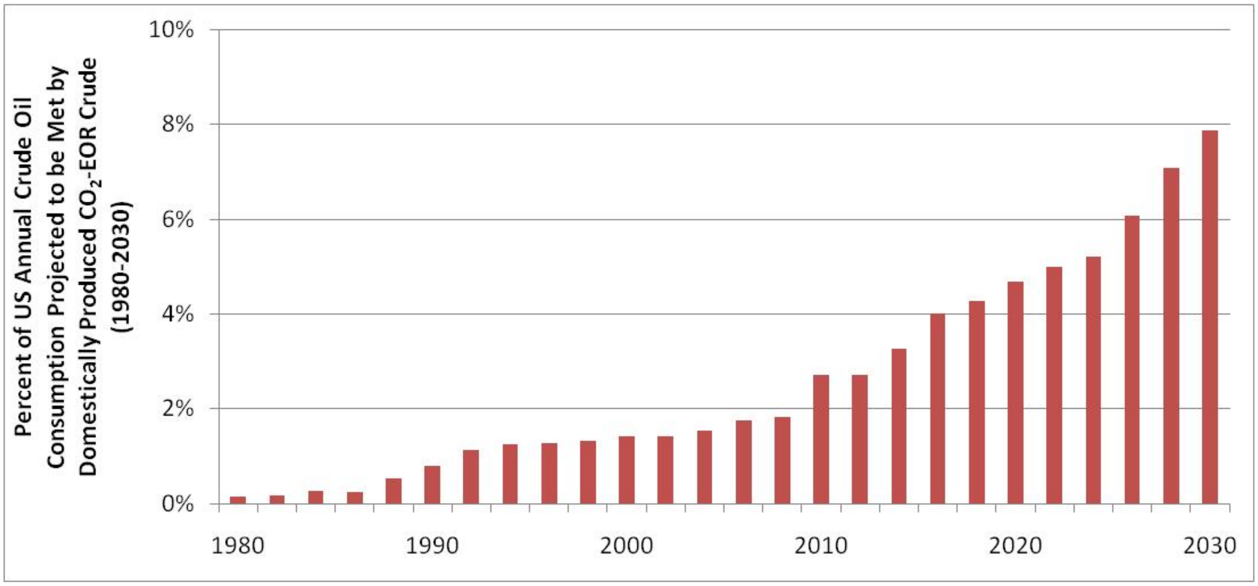


Figure 11. Fraction of U.S. Annual Oil Consumption Met by Domestically Produced CO_2-EOR Crude over the period 1980-2030 (historical data are from Moritis (2010) while future projections are from the Reference Case from EIA (2010))

[4] As noted by Huntington (2006), "The nation is vulnerable to another major [oil] disruption [and the attendant negative economic and security consequences] not because the economy imports oil but primarily because it uses a lot of oil, primarily for gasoline and jet fuel. Even if domestic production could replace all oil imports, which I am not advocating, the economy would remain vulnerable to the[se] types of disruptions."

Figure 12 attempts to put the data in Figure 11 about the growing importance of CO_2-EOR as a source of domestically produced crude oil into a larger economic and geopolitical framework. Figure 12 shows the average annual U.S. dependence on imported oil along with selected efforts to make the U.S. energy independent or less reliant on imported oil over the period 1950-2030. One can see that these efforts to reduce U.S. oil imports have not delivered on their stated goals and have become significantly less ambitious over time. It is also clear from Figure 12 that to date large geopolitical and economic forces have driven significant swings in the degree to which the U.S. imports foreign oil; these swings have often been large and have occurred over relatively short time periods.   For example, U.S. dependence on imported oil went from 46% in 1977 to 27% in 1985 and back up to 46% by 1996. This large swing in import dependence dwarfs the 7% reduction in oil imports by 2030 forecasted by Steelman and Tonachel (2010) if one assumes that all additional U.S. oil produced by the recommended aggressive expansion of CO_2-EOR production displaces imports, barrel for barrel.

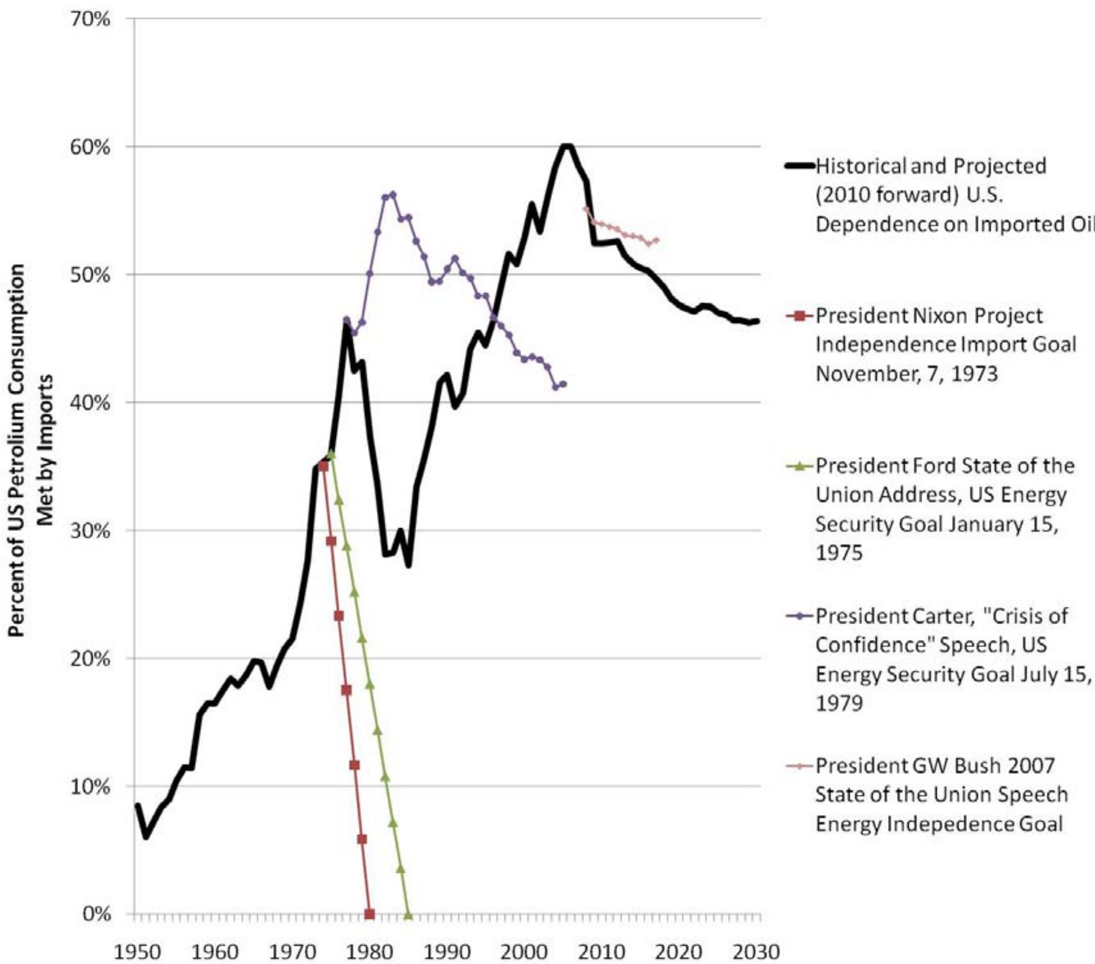


Figure 12: U.S. Historic and Projected Dependence on Foreign Oil and Selected Presidential Energy Security Initiatives (1950-2030)

9. Concluding Comment

It is clear that CO_2-EOR is an important and growing aspect of the United State's energy resource base. The contribution that CO_2-EOR makes to the U.S. economy should not be underestimated or undervalued. It is also clear from the work of Meyer (2007), IPCC (2005) and others that the more than 35 years of experience in using CO_2 for enhanced oil recovery has led to the development of numerous materials, technologies and industrial best practices that should be directly transferable to the large scale commercial adoption of CCS across the global power and industrial economies.

The purpose of this paper is not to call into question the significance of CO_2-EOR as a means of producing oil from domestic fields that are in decline. Rather, the goal was to examine key aspects of conventional wisdom that draws no distinction between CO_2 injection into marginal oil fields to increase hydrocarbon production and the injection, verification and long-term monitoring of CO_2 to ensure retention as a method of complying with binding GHG emissions limits under a future climate policy. This paper has sought to bring some level of rigor to what is often an overly simplified discussion by explicitly distinguishing between the economics of CO_2-EOR and the economics and operational requirements of large scale CCS deployment. CO_2-EOR may offer an opportunity to jumpstart climate protection-motivated CCS deployment in the electric power and other industrial sectors. But overall, it is unlikely to serve as a major stepping stone to commercial-scale CCS deployment. The fact that only one of 129 current CO_2-EOR projects worldwide is regarded or certified as a CCS project, and only 1 of the 4 current commercial scale CCS projects utilizes the CO_2-EOR process, provides significant empirical evidence that CO_2-EOR is not a mandatory step on the path to CCS deployment; it is a useful and in many ways beneficial option for CCS where available and where the extra requirements to document stored CO_2 prove worthwhile, but CO_2-EOR is not core to the deployment of CCS technologies.

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