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CO_2 Utilization from "Next Generation" CO_2 Enhanced Oil Recovery Technology

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Abstract

CO_2-enhanced oil recovery (CO_2-EOR) has emerged as a major option for productively utilizing CO_2 emissions captured from electric power and other industrial plants. Not only can oil fields provide secure, well characterized sites for storing CO_2, they can also provide revenues to offset the costs of capturing CO_2. Though utilization of captured CO_2 emissions for enhanced oil recovery has been underway for some time, further advances in CO_2-EOR technology could significantly improve the technology's applicability as a revenue generator for CO_2 capture and a large-scale CO_2 storage option. With application of "next generation" CO_2-EOR technologies in geologically favorable settings, the volume of CO_2 stored could exceed the CO_2 content of the oil produced. The paper draws significantly on the recently completed report sponsored by the U.S. Department of Energy, National Energy Technology Laboratory (U.S. DOE/NETL) and prepared by Advanced Resources International entitled, "Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2-EOR".

The paper introduces the feasibility of applying "next generation" CO_2-EOR technologies to new, challenging areas, such as to residual oil zones (ROZs) below and beyond the structural confinement of existing oil fields and to offshore oil fields. The paper provides a case study that tracks the performance and the economics of CO_2-EOR in the Permian Basin of West Texas. While much of the information in the paper is drawn from the CO_2-EOR experiences in North American oil fields, the paper also examines the CO_2 utilization and storage potential from applying "next generation" CO_2-EOR technology to the large oil fields of the world, drawing on extensions of work performed by Advanced Resources International for the IEA Greenhouse Gas R&D Programme.

The paper concludes with two key messages. First, with application of "next generation" technologies to a broader set of oil resources, the market for utilization of CO_2 for enhanced oil recovery is much larger than previously assumed. Second, the revenues from the sale of captured CO_2 emissions, along with research that reduces the costs of CO_2 capture, can greatly accelerate the time when CCS (now CCUS) can be applied at wide scale.

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1. Introduction

Four key questions are at the heart of gaining wide-scale acceptance for using CO_2 enhanced oil recovery (CO_2-EOR) as a major carbon management strategy; namely: (1) what is the size of the prize?; (2) could CO_2-EOR, like wind and solar, provide essentially net zero carbon energy?; (3) how much of the CO_2 used for EOR will remain securely stored?; and (4) to what extent could CO_2-EOR provide a market-driven option for CO_2 capture?

1.1. The Size of the Prize

Typically, only about a one-third of the original oil in-place in a conventional oil field is recovered with traditional primary and secondary methods. In the U.S., this leaves behind a massive, nearly 400 billion barrel target for "next generation" CO_2-EOR in existing oil fields, plus an additional 140 billion barrels in residual oil zones (ROZ) below and beyond existing oil fields, Figure 1. Worldwide, our estimate is that the "left behind" oil resource is many times larger, in excess of 5,000 billion barrels. Application of CO_2 enhanced oil recovery (CO_2-EOR) provides the economically most favorable means for recovering a significant portion of this "left behind" oil and for storing massive volumes of CO_2 captured from industrial and electric power plants.

- In the U.S., the "size of the oil prize" for "next generation" CO_2-EOR technology is 100 billion barrels of economically recoverable oil, assuming an oil price of $85 per barrel,[†] a CO_2 price of $40 per metric ton, and a return on investment hurdle of 20%, Table 1.[1,2]

- The economic CO_2 demand to recover 100 billion barrels of oil with CO_2-EOR is 33 billion metric tons, Table 1.[1,2] With natural CO_2 sources estimated at less than 3 billion metric tons, this means that the "size of the CO_2 utilization and storage prize" in the U.S. is 30 billion metric tons. This is equal to 35 years of CO_2 emissions captured from 140 GWs of coal-fired power.[3]

1.2. Carbon Neutral Oil

At a typical ratio of 1 metric ton of CO_2 injected and stored for every 2.5 barrels of oil recovered, the carbon balance of oil produced with CO_2-EOR is essentially neutral, when using CO_2 that would otherwise have been vented to the atmosphere. Under special conditions, such as gravity stable CO_2 flooding, the CO_2-EOR process can store considerably more CO_2 than the carbon content of the oil, Figure 2.

Today, a significant number of activities are underway that find and bring more oil to the surface, including exploration and drilling for conventional oil. These are activities that provide no offsets to the carbon in the produced oil. Yet, no rational official, one concerned with a country's economic well-being, its energy security, and its jobs, has called for a stop to oil exploration (except in environmentally fragile areas) as long as it is done in a safe and environmentally sound way. In addition, recently Norway's Statoil announced that it has adopted a goal of achieving 60% recovery efficiency from its offshore oil fields, without use of CO_2 injection. We are not aware of any Norwegian public officials that condemned Statoil's pursuit of efficiency and conservation of the nation's oil resources.[4]

[†]In this report, all economic value numbers are expressed in U.S. dollars.

1.3. A Closed-Loop System

The operation of a CO_2-EOR project is essentially a closed-loop system, Figure 3. Initially, about half of the injected CO_2 is trapped or dissolved in the reservoir and its fluids. The CO_2 that is produced with the oil is recycled (separated and re-injected back into the reservoir), with an increasing portion of the re-injected CO_2 trapped. At the end of a CO_2 flood, essentially all of the purchased CO_2 is stored in the reservoir when the operator closes the field at pressure.

1.4. Providing Revenues for CO_2 Capture

Finally, CO_2-EOR provides a market and revenues for the CO_2 captured from industrial and electric power plants. In the U.S. alone, we estimate that the CO_2-EOR industry could provide revenues of $1.2 trillion for CO_2 capture and delivery from fossil fuel power plants and industrial facilities. In addition, with "next generation" technology, the CO_2-EOR sector, over the course of thirty to forty years, would generate domestic economic activity equal to $8.5 trillion in the U.S. alone, Table 2. As important, 30 billion metric tons of anthropogenic CO_2 that would have otherwise been vented to the atmosphere would be permanently stored.

2. Status of CO_2-EOR

CO_2-based enhanced oil recovery, using state-of-the-art (SOA) technology, is already being implemented in the U.S., particularly in the oil fields of the Permian Basin of West Texas, the Gulf Coast and the Rockies.

- CO_2-EOR currently provides about 284,000 barrels of oil per day in the U.S., equal to 6% of U.S. crude oil production, Figure 4.[5] CO_2-EOR has been underway for several decades, starting initially in the Permian Basin and expanding to 123 CO_2-EOR projects currently installed in numerous regions of the country, Figure 5.

- In 2010, a total of 62 million metric tons of CO_2 was supplied to EOR operations in the U.S., Table 3. Approximately 20% (13 million metric tons) of this CO_2 came from industrial sources, natural gas processing plants, and hydrocarbon conversion facilities (e.g., coal gasification). By 2020, approximately 14 Mt of additional CO_2 supply will become available from large-scale integrated CCUS projects in the U.S. Department of Energy's (DOE) portfolio.[3]

- A robust network of pipelines exist in the Permian Basin that transports this CO_2 from natural CO_2 deposits and gas processing plants to the Denver City Hub, Figure 5. In addition, numerous new CO_2 pipelines have recently been placed on-line to deliver CO_2 to Gulf Coast and Rocky Mountain oil fields.[5, 6] These include Denbury's 320 mile Green Pipeline along the Gulf Coast, Occidental Petroleum's new $850 million Century natural gas/CO_2 processing plant and pipeline facilities in West Texas, and Denbury's GreenCore CO_2 pipeline linking the Lost Cabin gas processing plant and other CO_2 sources in Wyoming to Rocky Mountain oil fields, Figure 5.

3. Overview of "Next Generation" CO_2-EOR Technologies

Realizing the full benefits of utilizing CO_2 as part of a CCUS strategy requires having access to "Next Generation" CO_2-EOR technology. Before proceeding further, it is useful to address the questions - - just what constitutes "Next Generation" CO_2 enhanced oil recovery and how does it differ from the CO_2-EOR technology in use today? Briefly stated, "Next Generation" CO_2-EOR incorporates four significant changes in technology and industrial practices:

- First are a series of scientifically-based advances in currently practiced miscible and near-miscible CO_2-EOR technology, including:
  - Improved sweep efficiency and mobility control (reservoir conformance),
  - Advanced technology of reservoir surveillance (monitoring and process control),
  - More efficient contact and production of the reservoir's remaining mobile (and immobile) oil,
  - Lowering the threshold minimum miscibility pressure (MMP) for shallower, heavier oil reservoirs, and
  - Significantly increasing the volumes of CO_2 injected and efficiently used.
- Second is integrating CO_2 capture from advanced coal- and natural gas-fired electric power plants, oil refineries, hydrogen plants and coal-to-liquids (CTL) facilities with CO_2 utilization by CO_2-EOR,
- Third is application of CO_2-EOR to residual oil zones (ROZs), and
- Fourth is deployment of CO_2-EOR in offshore oil fields.

3.1. Integrating CO_2 Capture and Utilization with CO_2-EOR

To a large extent, operators of integrated gasification combined cycle (IGCC) facilities, proposed CTL plants and other carbon conversion projects have already "voted with their feet" by turning to oil fields for storing CO_2. Three such projects are:

- Southern Company's Kemper County IGCC plant, which plans to provide 1.1 to 1.5 MMt/yr to Denbury Resources for CO_2-EOR in oil fields in Louisiana and Mississippi. Integrating CO_2 capture and utilization involved formulating innovative contractual terms and alternative options for CO_2 delivery.[6]
- Summit Energy's Texas Clean Energy IGCC project, which plans to sell 3 MMt/yr for CO_2-EOR from the Permian Basin of West Texas in competition with natural sources of CO_2.[6]
- The "poster child" for integrating large-scale CO_2-EOR with CCS is the capture of 150 MMcfd (~3MMmt/yr) of CO_2 from the Northern Great Plains Gasification plant in Beulah, North Dakota and its transportation, via a 200 mile cross-border CO_2 pipeline, to two CO_2-EOR projects at the Weyburn oil field in Saskatchewan, Canada, Figure 6.[7]

3.2. Residual Oil Zone ("ROZ")

No discussion of "next generation" technology would be complete without a discussion of the major volumes of oil that exist and can be recovered with CO_2-EOR from the residual oil zone (ROZ). Residual oil zones exist in the lower portions of oil reservoirs that have been hydro-dynamically swept by the movement of water over a time period of millions of years. One may label this movement of water and its displacement of oil as “nature’s waterflood”. Because the “left behind” oil in the ROZ is at or near residual oil saturation, CO_2-EOR is required to re-mobilize and recover this oil.

Work by Advanced Resources and Melzer Consulting has identified 42 billion barrels of oil in-place below existing oil fields in three U.S. basins - - Permian, Big Horn and Williston. [8,9,10] Importantly, recent work by Melzer Consulting for the Research Partnership to Secure Energy for America (RPSEA) shows that the ROZ resource also occurs beyond the outlines of existing oil fields and exists as a series of areally extensive “ROZ fairways”, Figure 7. Melzer Consulting and Advanced Resources estimate that about 100 billion barrels of oil in-place exists in the ROZ “fairways” of the Permian Basin alone. Based on preliminary modeling, we estimate there is 27 billion barrels of economically recoverable oil from the ROZ (below oil fields and from the ROZ “fairway”). The “CO_2 utilization and storage prize” offered by the ROZ resource is 13 billion metric tons, Table 1.

The viability of recovering oil from ROZs is already being demonstrated by a series of ROZ field projects - - at Seminole oil field by Hess, at Wasson Denver Unit by Occidental, and at Goldsmith oil field by Legado, among others. An important R&D goal for the U.S. (and the world) is establishing optimally efficient oil recovery and CO_2 storage in ROZs using miscible CO_2-EOR.

3.3. CO_2-EOR in Offshore Oil Fields

The deep, light oils common to Gulf of Mexico (GOM) offshore oil fields are amenable to miscible CO_2-EOR technology. With the continued discovery of oil fields in the deep waters of the Outer Continental Shelf (OCS), the size of this resource target continues to grow. However, the deployment of CO_2-EOR technology in offshore oil fields faces many challenges, including limited platform space for CO_2 recycling equipment, the expense of drilling new CO_2 injection wells, and the need to transport CO_2 from onshore sources to offshore platforms. While these barriers and challenges can be addressed with advances in technology, they add substantial costs to the oil recovery process. CO_2-EOR projects have been undertaken in a small handful of offshore oil fields in shallow GOM waters; however, currently none are operating. As such, the fourth “next generation” CO_2-EOR application involves undertaking the challenge of deploying innovative designs and advanced CO_2-EOR technology in offshore oil fields.

4. International CO_2-EOR and CO_2 Storage

In 2011, Advanced Resources prepared for the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) an assessment of worldwide CO_2 storage and oil recovery potential offered by CO_2-EOR. The CO_2 supplies for EOR were assumed to be primarily from power plants, cement plants and refineries with large-scale CO_2 pipelines transporting the CO_2 to geologically favorable oil fields. The study assessed 54 large world oil basins for CO_2-based enhanced oil recovery, using two complementary methodologies .[11]

- High-level, first-order assessment of CO_2-EOR and associated storage potential, using U.S. experience as the analog.

- Calibration of the above first-order basin-level estimates with detailed modeling of 47 large oil fields in 6 basins.

The study established that the "size of international oil and CO_2 utilization (and storage) price" from applying CO_2-EOR to already discovered oil fields is about 1,300 barrels of incremental oil recovery and 370 billion metric tons of CO_2, Table 4. This is equivalent to utilization (and storage) of captured CO_2 from about 2,000 GWs of coal-fired power for 35 years. Much of this demand can be met by large, existing anthropogenic CO_2 sources within distances of 800 kilometers (500 miles) of these oil basins. New anthropogenic sources, such as the large oil refineries and hydrogen plants being constructed in the Middle East and the high CO_2 content natural gas fields in the Far East, provide major opportunities for utilization of CO_2 by CO_2-EOR.

5. Permian Basin CO_2-EOR Case Study

The purpose of the Permian Basin CO_2-EOR case study is to provide the reader basic information by which to address the question: "What does a successful CO_2-EOR project look like?"

CO_2 injection into the Denver Unit of the giant Wasson (San Andres) oil field began in 1985, helping arrest the steep drop in oil production. Before the start of CO_2-EOR, oil production had declined from about 90,000 B/D to 40,000 B/D and was on pace to decline to below 1,000 B/D in the next 20 years. After the initiation of the CO_2 flood, oil production increased to about 50,000 B/D. Today, twenty four years after the start of the flood, the Denver Unit still produces at 30,000 B/D, Figure 8.

At the completion of the CO_2 flood, Oxy expects the Denver Unit to recover nearly two-thirds of the approximately 2 billion barrels of original oil in-place, with CO_2-EOR providing nearly 20% oil recovery efficiency (400 million barrels) on top of already high oil recovery efficiency from primary methods and the waterflood. In turn, the Denver Unit CO_2 flood will utilize over 100 million metric tons of CO_2.[6]

A broader look at Permian Basin CO_2-EOR projects shows that the CO_2 flood at the Wasson (Denver Unit) oil field, while exemplary, is not unique. Using an oil price of $100 per barrel, Occidental Petroleum, the largest CO_2-EOR operator in the Permian Basin, expects its CO_2-EOR projects to provide a net cash margin (before corporate taxes) of $56 per barrel, after subtraction of royalties, operating costs, CO_2 purchase and amortized capital, Figure 9. CO_2 purchase (plus recycling operations) constitutes the largest single cost item in the CO_2 flood. Even with delay between investment of capital and the production of oil, the EOR case study and the results from the other CO_2-EOR projects in the Permian Basin show that an economically favorable market exists for anthropogenic CO_2.

6. Summary

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. The "size of the prize" is large, the oil produced is net carbon energy, the injected CO_2 will remain stored securely, and CO_2-EOR can provide a market-driven option for accelerating CO_2 capture.

Acknowledgements

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Table 1. Impact of Applying "Next Generation" CO_2-EOR Technology to U.S. Oil Fields and ROZ "Fairways"

Resource Area	**Economic Oil Recovery (BBbls)***	**Demand for CO_2 (Billion Metric Tons)**
More efficient recovery from "lower 48" oil fields	60	17
Alaska/offshore	7	3
Residual oil zone (below oil fields)	13	5
Residual oil zone "fairways" (preliminary)	20	8
Total	**100**	**33**

*At $85 per barrel and $40 per metric ton, CO_2 market price with 20 % rate of return (before tax).
Source: Advanced Resources International, Inc. (2011)

Table 2. The "Value Chain" of "Next Generation" CO_2-EOR (U.S. Only)

Revenue Recipient	**Value Chain Function**	**Revenues Per Barrel ($)**	**TOTAL* ($ billion)**
Power/Industrial Companies	Sale of CO_2 **	$13.20	$1,320
Federal/State Treasuries	Severance/Income Taxes	$19.80	$1,980
U.S. Economy	Services, Materials and Sales	$26.50	$2,650
Other	Private Mineral Rights	$7.70	$770
Oil Industry	Return of/on Capital	$17.80	$1,780
	Total	**$85.00**	**$8,500**

*Assuming 100 billion barrels of economically feasible oil recovery; oil prices of $85 per barrel and CO_2 sales price of $40/metric tons.
**Of the 33 billion metric ton, $1,320 billion overall market for CO_2, anthropogenic CO_2 captured from power and other industrial plants would be 30 billion metric tons and $1,200 billion.
Source: Advanced Resources International, Inc. (2011)

Table 3. Significant Volumes of Anthropogenic CO_2 are Already Being Injected for EOR

Location of Oil Fields	**Location of CO_2 Sources**	**CO_2 Supply**	
		Geologic	**Anthropogenic**
Texas, New Mexico, Oklahoma, Utah	Geologic (CO, NM) and Gas Processing, Fertilizer Plant (TX)	1,600	190
Colorado, Wyoming	Gas Processing (Wyoming)	-	300
Mississippi	Geologic (Mississippi)	930	-
Michigan	Gas Processing (Michigan)	-	10
Oklahoma	Fertilizer Plant (Oklahoma)	-	35
Saskatchewan	Coal Gasification (North Dakota)	-	150
TOTAL (Million cfd)		**2,530**	**685**
TOTAL (Million metric tons per year)		**49**	**13**

* Source: Advanced Resources International, 2012
**MMcfd of CO_2 can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by $18.9 * 10^3$ (Mcf per metric ton)

Table 4. Technical Oil Recovery and CO_2 Storage Potential from the Major Oil Basins of the World Using from “Next Generation”* CO_2-EOR Technology

Region	**CO_2-EOR Oil Recovery (Billion Barrels)**	**CO_2 Storage Capacity (Billion Metric Tons)**
1. Asia Pacific	47	13
2. C. & S. America	93	27
3. Europe	41	12
4. FSU	232	66
5. M. East/N. Africa	595	170
6. NA/Other	38	11
7. NA/U.S.	177	51
8. S. Africa/Antarctica	74	21
TOTAL	**1,297**	**370**

* Includes potential from discovered and undiscovered fields, but not future growth of discovered fields.
Source: IEA GHG Programme/Advanced Resources International (2009)

Fig. 1. Large Volumes Of Domestic Oil Remain “Stranded” After Traditional Recovery Operations

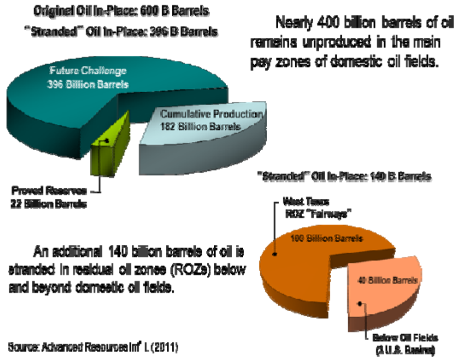


Fig. 2. Integrating CO_2-EOR and CO_2 Storage Could Increase CO_2 Storage Potential

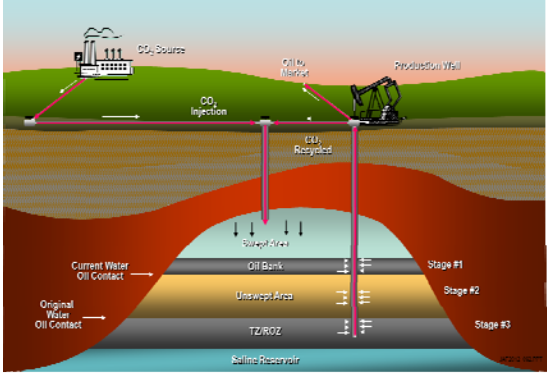


Fig. 3. CO_2-EOR Technology: A Closed-Loop System

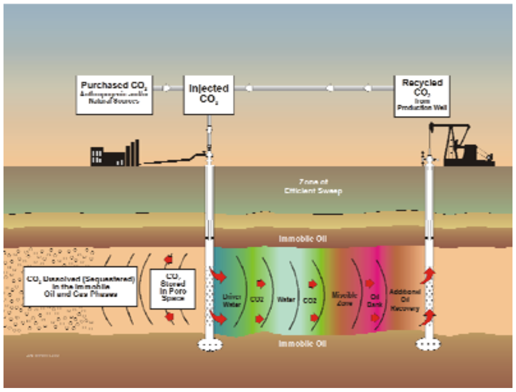


Fig. 4. Domestic Oil Production from CO_2-EOR

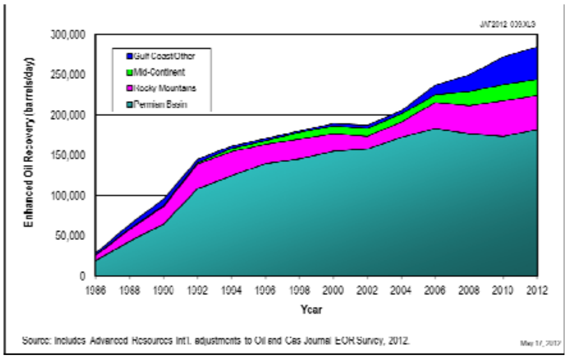


Fig. 5. U.S. CO_2-EOR Activity

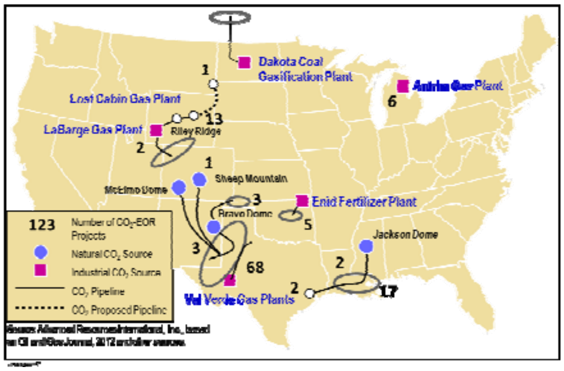


Fig. 6. "Poster Child" for Integrating CO_2-EOR and CO_2 Storage

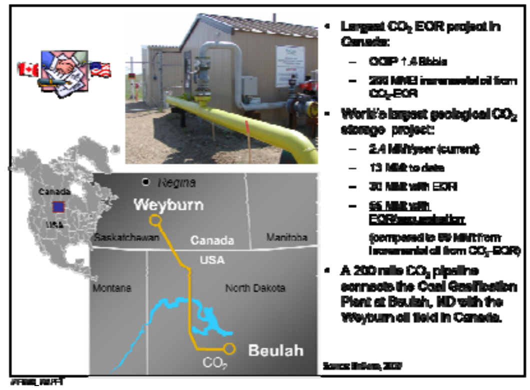


Fig. 7. Map of Permian Basin ROZ Fairways.

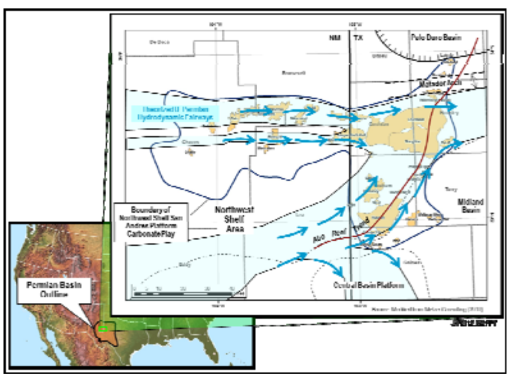


Fig. 8. CO2-EOR at Denver Unit, Wasson Oil Field.

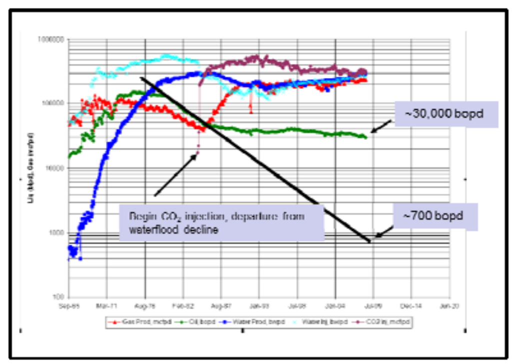
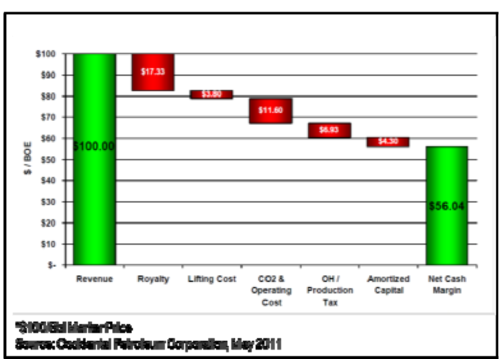


Fig. 9 Permian Basin CO2-EOR Project Cost Structure



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