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Opportunities for Using Anthropogenic CO_2 for Enhanced Oil Recovery and CO_2 Storage

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ABSTRACT: CO_2-enhanced oil recovery (CO_2-EOR) has emerged as a major option for productively using CO_2 emissions captured from electric power and other industrial facilities as part of carbon capture and storage (CCS) operations. Not only can depleting oil fields provide secure, well-characterized sites for storing CO_2, such fields can also provide a source of revenues to offset the costs of capturing CO_2 by producing incremental oil. This paper draws significantly on work by Advanced Resources International, Inc. (ARI), sponsored by the United States Department of Energy's National Energy Technology Laboratory (U.S. DOE/NETL) [Advanced Resources International, Inc. (ARI). *Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2-Enhanced Oil Recovery*; ARI: Arlington, VA, 2011; http://www.netl.doe.gov/energy-analyses/pubs/storing%20co2%20w%20eor_final.pdf] and the International Energy Agency Greenhouse Gas Research and Development Programme (IEAGHG) [Advanced Resources International, Inc. (ARI). *CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery*; ARI: Arlington, VA, Dec 2009; IEAGHG Programme Technical Report Number 2009-12], that demonstrates that CO_2-EOR offers large CO_2 storage capacity potential and could accommodate a major portion of the CO_2 captured from industrial facilities for the next 30 years. This work also demonstrates that CO_2 can be effectively and permanently stored when deployed in association with CO_2-EOR, with the amount stored depending upon the priority placed on maximizing storage. In addition to showing that CCS benefits from CO_2-EOR by providing the revenues from sale of CO_2, overcoming other barriers, while producing oil with a lower CO_2 emissions "footprint", the report demonstrates that CO_2-EOR needs CCS, because large-scale future implementation of CO_2-EOR will be dependent upon CO_2 supplies from industrial sources.

■ INTRODUCTION

Three 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"; that is, what is the potential for CO_2-EOR in the U.S. and globally, and how much CO_2 storage could result from CO_2-EOR? (2) Is CO_2 effectively stored during CO_2-EOR operations? (3) Who will benefit most from pursuing carbon capture and storage (CCS) with CO_2-EOR? This paper attempts to address these questions.

CO_2-EOR using state-of-the-art (SOA) technology is already being implemented at scale in the U.S., mostly in oil fields in west Texas, the Gulf Coast, and the Rocky Mountains. CO_2-EOR operations currently produce 284 000 barrels (38 745 tonnes) of incremental oil per day in the U.S., 4.5% of U.S. crude oil production (Figure 1).[3] CO_2-EOR has been underway for several decades, starting initially in the Permian Basin and expanding to 123 CO_2-EOR projects currently in operation in numerous regions of the country (Figure 2). In 2010, a total of 59 million tonnes of CO_2 was supplied to EOR operations in the U.S. (Table 1). Approximately 20% (13 million tonnes) of this CO_2 came from industrial sources, such as natural gas processing plants and hydrocarbon conversion facilities (e.g., coal gasification). By 2020, approximately 11.5 million tonnes of additional anthropogenic CO_2 supply will become available from large-scale integrated CCS projects in the United States Department of Energy's (U.S. DOE) portfolio,[4] assuming that all of the scheduled projects are eventually built.

A robust network of pipelines exists in the Permian Basin in west Texas that transports this CO_2 from natural CO_2 deposits and gas processing plants to the Denver City hub. In addition, numerous new CO_2 pipelines and gas processing plants have recently been placed online to deliver CO_2 to the Gulf Coast and Rocky Mountain oil fields. These include CO_2-EOR focused Denbury Resources' 515 km (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 373 km (232 mile) GreenCore CO_2 pipeline linking ConocoPhillips' Lost Cabin gas processing plant and other CO_2 sources in Wyoming to Rocky Mountain oil fields.

■ SIZE OF THE PRIZE

Typically, only about a one-third of the original oil in place in conventional oil fields is recovered with traditional primary and secondary methods. In the U.S., this leaves behind a nearly 400 billion barrel (55 billion tonnes) target for the application of

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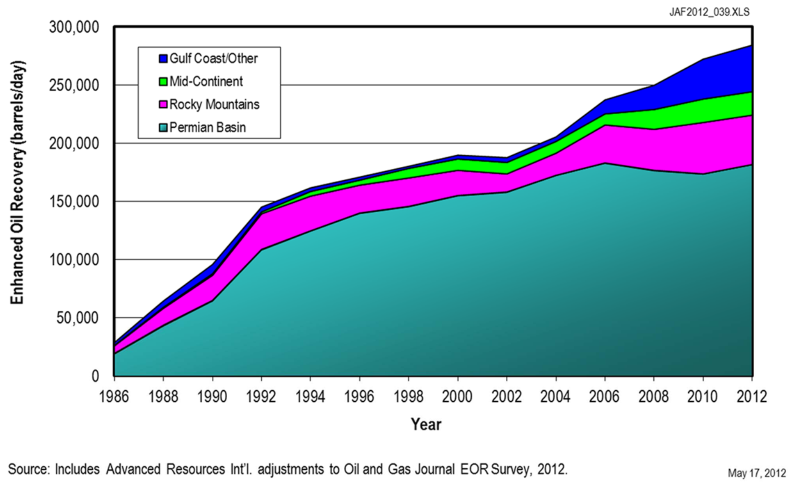

Figure 1. Domestic oil production from CO_2-EOR.

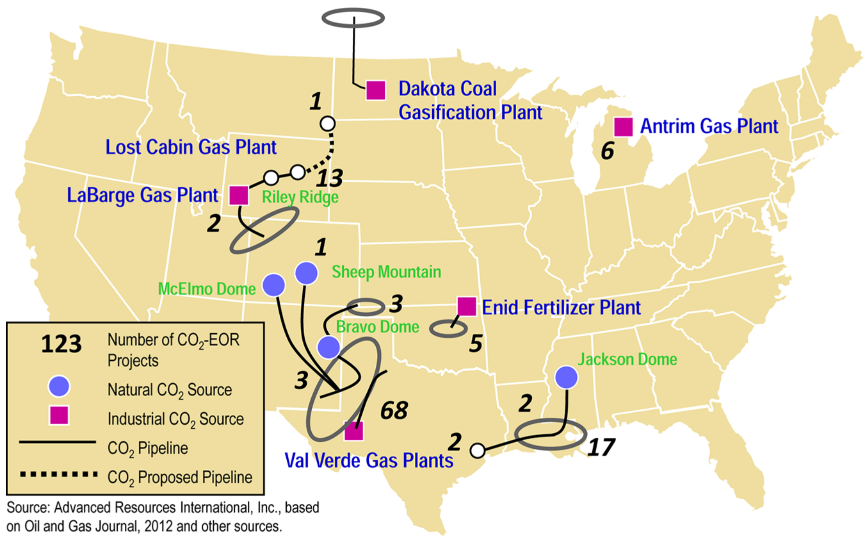

Figure 2. U.S. CO_2-EOR activity.

Table 1. Significant Volumes of Anthropogenic CO_2 Are Already Being Injected for EOR[a]

location of oil fields	location of CO_2 sources	CO_2 supply [million cubic feet per day (MMcfd)] geologic	anthropogenic
Texas, New Mexico, Oklahoma, and Utah	geologic (CO and NM), gas processing, and fertilizer plant (TX)	1600	101
Colorado and Wyoming	gas processing (Wyoming)		300
Mississippi	geologic (Mississippi)	850	
Michigan	gas processing (Michigan)		10
Oklahoma	fertilizer plant (Oklahoma)		35
Saskatchewan	coal gasification (North Dakota)		150
total (MMcfd)		2450	596
total (million tonnes per year)		47	12

[a]Source: ARI (2012). [b]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/tonne).

CO_2-EOR, plus an additional 140 billion barrels (19 billion tonnes) in residual oil zones (ROZs) below and beyond existing oil fields (discussed in more detail below) (Figure 3). Worldwide, our estimate is that the "left behind" oil resource is many times larger, in excess of 5000 billion barrels (680 billion tonnes).[2]

Application of CO_2-EOR can provide an economical means for recovering a significant portion of this "left behind" oil and for storing large volumes of CO_2 captured from industrial facilities and electric power plants, CO_2 that would otherwise be emitted to the atmosphere.

Realizing the full benefits of using CO_2 as part of a domestic or global CCS strategy requires having access to "next

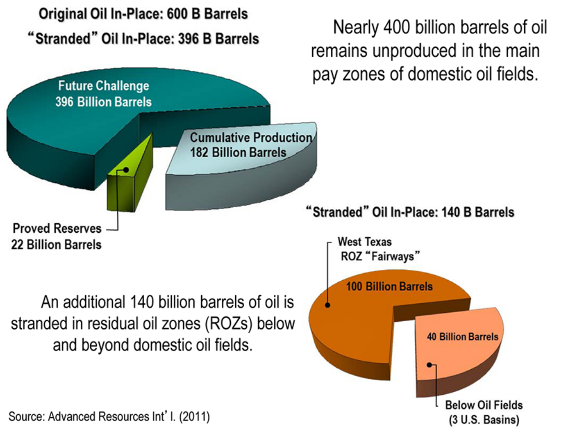

Figure 3. Large volumes of domestic oil remain "stranded" after traditional recovery operations.

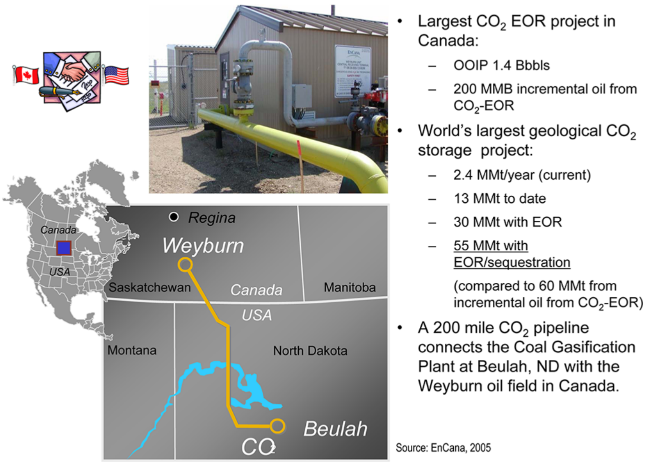

Figure 4. "Poster child" for integrating CO_2-EOR and CO_2 storage.

generation" CO_2-EOR technology. Briefly stated, "next generation" CO_2-EOR incorporates significant changes in technology and industrial practices as described in the following paragraphs.

A series of scientifically based advances in currently practiced miscible and near-miscible CO_2-EOR technology includes (1) improved conformance and mobility control, through the combination of increasing viscosity of CO_2 and plugging high permeability channels, to overcome the geologic and process limitations, such as poor sweep efficiency, unfavorable injectivity profiles, gravity override, high ratios of CO_2 to oil produced, early breakthrough, and viscous fingering, (2) locating and contacting unswept portions of the formation, through a combination of being able to see better the CO_2 plume and being able to precisely locate CO_2 injection, (3) increasing CO_2 injection based on the assumed availability of affordable CO_2, (4) achieving near-miscible behavior, and (5) improving the ability to model and predict oil production response.

CO_2 capture from advanced coal- and natural-gas-fired electric power plants, oil refineries, hydrogen plants, and coal-to-liquids (CTL) facilities is integrated with CO_2 use by CO_2-EOR. Three examples of such projects are (1) Southern Company's Kemper County integrated gasification combined cycle (IGCC) plant, which plans to provide 2.8 million tonnes/year to Denbury Resources for CO_2-EOR in oil fields in Louisiana and Mississippi, (2) Summit Energy's Texas Clean Energy IGCC project, which plans to sell 2.4 million tonnes/year for CO_2-EOR from the Permian Basin of west Texas in competition with natural sources of CO_2, and (3) the "poster child" for integrating large-scale CO_2-EOR with CCS, the Northern Great Plains Gasification plant in Beulah, ND, which captures 3 million tonnes/year of CO_2 and transports it via a 320 km (200 mile) cross-border CO_2 pipeline to two CO_2-EOR projects at the Weyburn oil field in Saskatchewan, Canada (Figure 4).

Application of CO_2-EOR to ROZs exists in the lower portions of oil reservoirs that have been hydrodynamically swept by the movement of water over geologic time. 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 remobilize and recover this oil. Work by ARI and Melzer Consulting has identified 42 billion barrels (6 billion tonnes) of oil in place below existing oil fields in three U.S. basins: Permian, Big Horn, and Williston.[5−7] 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 aerially extensive "ROZ fairways" (Figure 5).[8] Melzer Consulting and ARI estimate that about 100 billion barrels (14 billion tonnes) of oil in place exists in the ROZ "fairways" of the Permian Basin alone, of which, on the basis of preliminary modeling, 13 billion barrels (2 billion tonnes) is economically recoverable oil from the ROZ below oil fields and 20 billion barrels (3 billion tonnes) is economically recoverable oil from the ROZ "fairway". 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. Over 6500 barrels (1500 tonnes)/day are currently being produced from the ROZ in the Permian Basin.[9]

The deep, light oils common to Gulf of Mexico (GOM) offshore oil fields are amenable to miscible CO_2-EOR technology. 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. Thus, advances in technology are required for undertaking the challenge of deploying innovative designs and advanced CO_2-EOR technology in offshore oil fields.

United States' Potential. In the U.S., the "size of the oil prize" for "next generation" CO_2-EOR technology is 100 billion barrels (14 billion tonnes) of economically recoverable oil, assuming an oil price of \$85/barrel, a delivered CO_2 price of \$40/tonne, and a requirement to meet a return on investment hurdle of 20% (Table 2).[1,10] The purchased CO_2 requirements (CO_2 demand) to recover 100 billion barrels of oil with CO_2-EOR is 33 billion tonnes or gigatonnes.

Important to recognize is the fact that current/planned CO_2 supplies can only provide 4−7 gigatonnes, including 2.1−2.6 gigatonnes from natural sources and 0.7−3.0 gigatonnes from natural gas processing facilities (the high end includes LaBarge reserves), with other industrial facilities contributing 1.1 gigatonnes.[4] CO_2-EOR can accelerate the capture and storage of anthropogenic CO_2, and the full potential for CO_2-EOR can only be realized if this is the case. The Weyburn integrated CO_2-EOR and CO_2 storage project and the Summit's Texas

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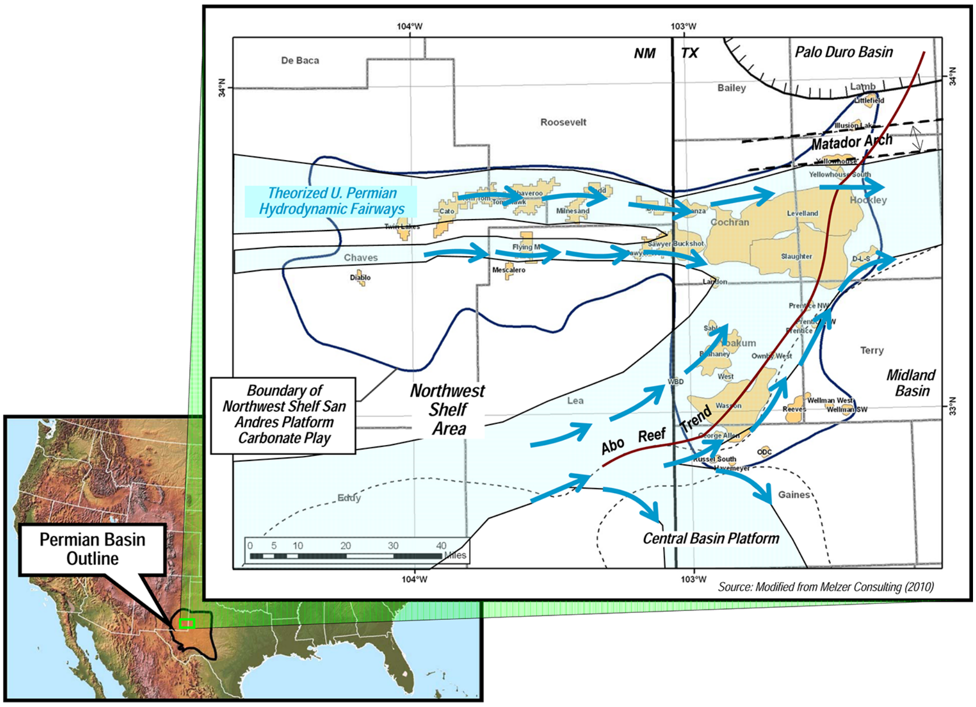

Figure 5. Map of Permian Basin ROZ fairways.

Table 2. Impact of Applying "Next Generation" CO_2-EOR Technology to U.S. Oil Fields and ROZ "Fairways"[a]

resource area	economic oil recovery (billion barrels)[b]	demand for CO_2 (billion tonnes)
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

[a]Source: ARI (2011). [b]At \$85/barrel and \$40/tonne, the economic oil recovery is the CO_2 market price with 20% rate of return (before tax). The demand for CO_2 represents the amount of CO_2 that would need to be purchased to facilitate the incremental oil production.

Clean Energy IGCC Project are just two examples of the new "model" for CCS linking industrial sources of CO_2 for commercial deployment for CO_2-EOR.

With natural CO_2 sources estimated at less than 3 gigatonnes, this means that the "size of the CO_2 use and storage prize" in the U.S. is over 30 gigatonnes. This is equal to 35 years of CO_2 emissions captured from 140 GW of coal-fired power.

Global Potential. In 2011, ARI prepared for the International Energy Agency Greenhouse Gas Research and Development Programme (IEAGHG), an assessment of worldwide CO_2 storage and oil recovery potential offered by CO_2-EOR. The study assessed 54 large world oil basins for CO_2-based EOR, using two complementary methodologies:[2] (1) high-level, first-order assessment of CO_2-EOR and associated storage potential, using U.S. experience as the analogue, and (2) 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 use (and storage) prize" from applying CO_2-EOR to already discovered oil fields is nearly 1300 billion barrels (180 billion tonnes) of incremental oil recovery with an associated 370 gigatonnes of CO_2 storage potential (Table 3). This is

Table 3. Technical Oil Recovery and CO_2 Storage Potential from the Major Oil Basins of the World Using "Next Generation"[a] CO_2-EOR Technology[b]

region	CO_2-EOR (billion barrels)	demand for CO_2 (billion tonnes)
Asia Pacific	47	13
Central and South America	93	27
Europe	41	12
former Soviet Union	232	66
Middle East/north Africa	595	170
North America/other	38	11
North America/United States	177	51
South Africa/Antarctica	74	21
total	1297	370

[a]Includes potential from discovered and undiscovered fields but not future growth of discovered fields. The demand for CO_2 represents the amount of CO_2 that would need to be purchased to facilitate the incremental oil production. [b]Source: IEAGHG Programme/ARI (2009).

equivalent to use (and storage) of captured CO_2 from about 1800 GW 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 km (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 east and southeast Asia, provide major opportunities for use of CO_2 by CO_2-EOR. Growing shale gas production could also be a source of CO_2, from produced gas cleanup of shale gas that is

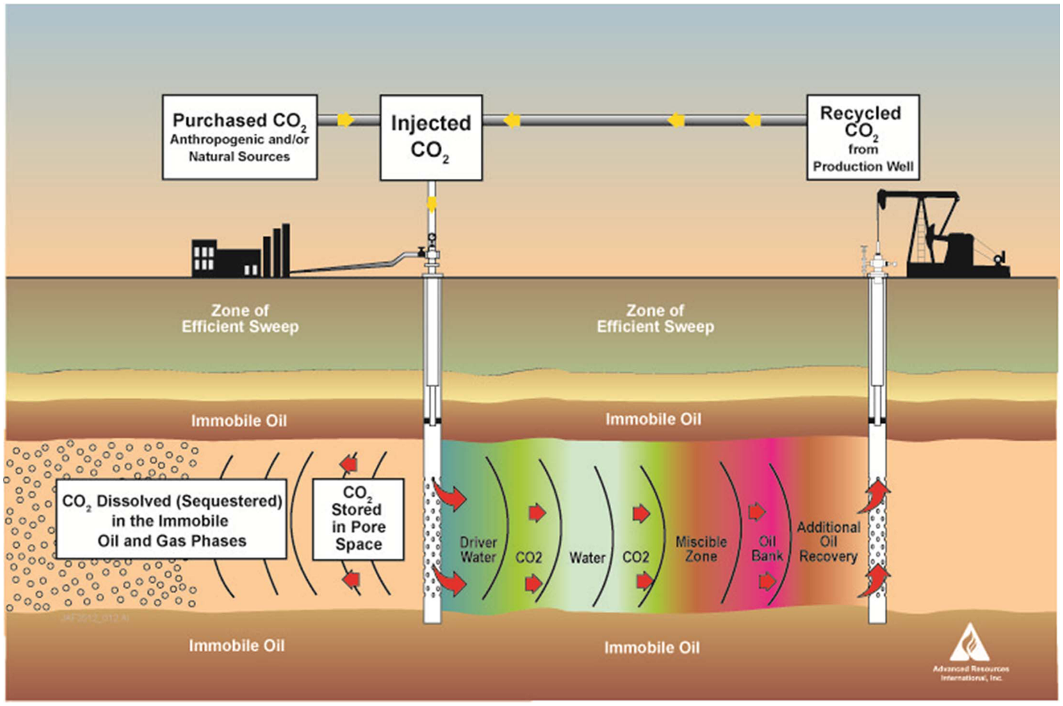

Figure 6. CO_2-EOR technology: a closed-loop system.

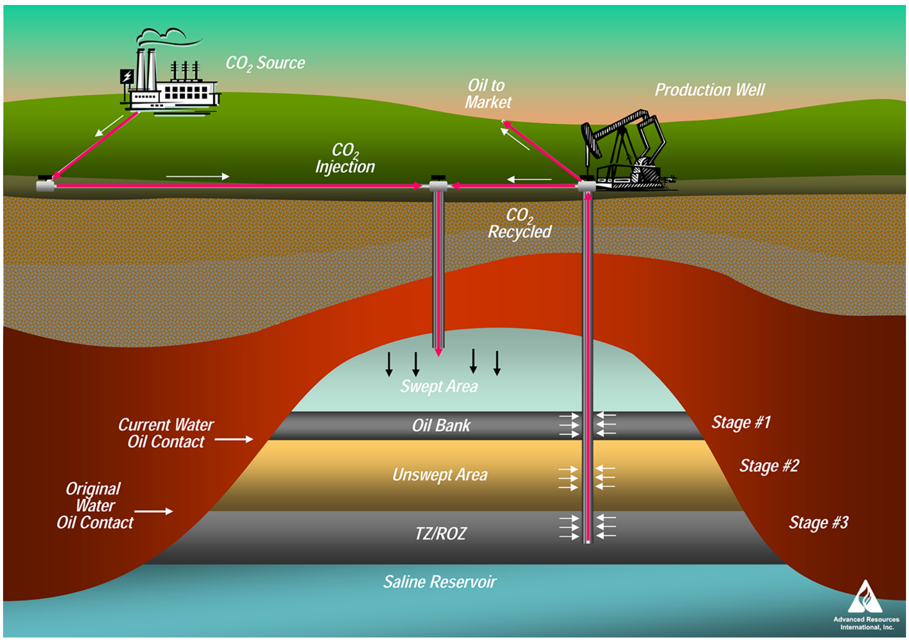

Figure 7. Integrating CO_2-EOR and CO_2 storage could increase CO_2 storage potential.

high in CO_2 content, from shale gas used in new GTL projects for onsite power/CO_2 co-generation using shale gas, and/or from CO_2 capture from gas-fired power generation.

■ STORING CO_2 DURING CO_2-EOR OPERATIONS

The operation of a CO_2-EOR project is essentially a closed-loop system (Figure 6). 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 in successive cycles. At the end of a CO_2 flood, essentially all of the CO_2 that is originally purchased is stored in the reservoir when the operator closes the field at pressure.

At a typical ratio of 1 tonne of CO_2 injected and stored for every 2.5 barrels of oil recovered, the carbon balance of the incremental oil produced with CO_2-EOR is essentially neutral when using CO_2 that would otherwise have been vented to the atmosphere.

Moreover, some approaches for CO_2-EOR that attempt to increase CO_2 storage can store more CO_2 than is associated with the CO_2 emissions over the lifecycle of the incremental oil produced from CO_2-EOR, including emissions from consumption. Basins that have produced large volumes of oil and

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that have significant potential for CO_2-EOR also possess favorable opportunities and large capacity for non-EOR storage.[11] Substantial opportunities are likely to exist for co-locating CO_2-EOR and CO_2 storage operations in deep saline formations using the same CO_2 injection wells and surface infrastructure used for CO_2-EOR. Moreover, additional storage capacity should exist in reservoirs targeted for CO_2-EOR after CO_2-EOR operations are complete. 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 7).

■ BENEFICIARIES FROM PURSUING CCS WITH CO_2-EOR

Finally, CO_2-EOR provides a market and revenues for the CO_2 captured from industrial facilities and electric power plants. The value created by applying CO_2-EOR technology would be shared by numerous stakeholders. Assuming an oil price of \$85/barrel for west Texas intermediate and a CO_2 market price of \$40/tonne, the following revenue streams would result from recovering the 100 billion barrels of potential domestic oil with "next generation" CO_2-EOR technology.

Federal/state treasuries would be a large beneficiary, receiving \$21.30 of the \$85/barrel oil price in the form of severance, *ad valorem*, and corporate income taxes. Total revenues to federal/state treasuries would equal \$2130 billion.

Electric power and other industrial companies would receive \$13.20 of the \$85/barrel oil price from the sale of CO_2. Total revenues from the sale of CO_2 would equal \$1320 billion.

The U.S. oil industry would receive \$19.80 of the \$85/barrel oil price for return of and return on capital investment or \$1980 billion. Private mineral owners would receive the remainder of the proceeds, equal to \$7.70/barrel or \$770 billion.

The general U.S. economy would be the largest beneficiary, receiving \$23.00 of the \$85/barrel of oil price in the form of wages and material purchases, amounting to \$2300 billion.

With potential oil recovery of 100 billion barrels, the CO_2-EOR sector, over the course of 30−40 years, would generate domestic economic activity equal to \$8.5 trillion in the U.S. alone (Table 4). As important, 30 billion tonnes of anthropogenic CO_2 that would have otherwise been vented to the atmosphere would be permanently stored. While not all of this potential is likely to be produced, it certainly provides an "upside" indication for the "size of the prize" for the potential of CO_2-EOR if industrial sources of otherwise emitted CO_2 would be productively used.

Table 4. "Value Chain" of "Next Generation" CO_2-EOR (U.S. Only)[a]

revenue recipient	value chain function	revenues per barrel (\$)	total[b] (\$ billion)
power/industrial companies	sale of CO_2[c]	13.20	1320
federal/state treasuries	severance/income taxes	21.30	2130
U.S. economy	services, materials, and sales	23.00	2300
other	private mineral rights	7.70	770
oil industry	return of/on capital	19.80	1980
	total	85.00	8500

[a]Source: ARI (2011). [b]Assuming 100 billion barrels of economically feasible oil recovery, with an oil prices of \$85/barrel and CO_2 sales price of \$40/ton. [c]Of the 33 billion tonnes and \$1320 billion overall market for CO_2, anthropogenic CO_2 captured from power and other industrial plants would be 30 billion tonnes and \$1200 billion.

■ CONCLUSION

The information set forth in this paper argues that CO_2-EOR 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 also 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.

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Notes

The authors declare no competing financial interest.

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