Joule

CellPress

COMMENTARY

Advancing Enhanced Oil Recovery as a Sequestration Asset

Sally M. Benson[1,*]
and John Deutch[2]

Sally M. Benson is a professor of energy resources engineering in the School of Earth, Energy & Environmental Sciences, co-director of the Precourt Institute for Energy, and Director of the Global Climate and Energy Project at Stanford University. Formerly, Benson was at Lawrence Berkeley National Laboratory, where she held a variety of key positions, including Deputy Director, Associate Director for Energy Sciences, and Director of the Earth Sciences Division. Benson is regarded as an authority on carbon capture and storage. She also uses energy systems analysis to help guide decisions about the most promising pathways for clean energy development.

John Deutch is an emeritus Institute Professor at the Massachusetts Institute of Technology where he has been a member of the faculty since 1970. He has served as Chairman of the Department of Chemistry, Dean of Science, and Provost. In the Carter Administration, he served as Director of Energy Research (1977–1979), Acting Assistant Secretary for Energy Technology (1979), and Undersecretary (1979–1980) in the US Department of Energy. He has been a member of the President's Nuclear Safety Oversight Committee (1980–1981), the White House Science Council (1985–1989), the President's Committee of Advisors on Science and Technology (1997–2001), and the Secretary of the Energy Advisory Board (2008–2016). John Deutch has published widely on technical and policy aspects of energy and the environment and has been a member of the board of directors or of the technical advisory committees of several energy companies.

Introduction

Avoided atmospheric CO_2 emissions could be increased by accelerating the use of advanced CO_2 enhanced oil recovery (EOR). Today, about 65 million metric tons of CO_2 are pumped underground for enhanced oil recovery, mostly in the US. About one third of this CO_2 is captured from anthropogenic sources. By doubling the amount of CO_2 pumped underground for every barrel of oil produced, avoided emissions could be increased dramatically. We propose that the US government pilot-tests a reverse Dutch auction for CO_2 EOR credits to stimulate the development of advanced CO_2 EOR. At an estimated cost of about \$25 per metric ton of CO_2, this compares favorably with other government programs designed to reduce CO_2 emissions. Effective incentives would spur investments leading to gigaton-scale reductions that offset CO_2 emissions from the transportation sector.

Carbon dioxide, CO_2, injection is an enhanced oil recovery (EOR) technique especially effective at increasing production from deep light oil reservoirs. Studies suggest a global technical potential to sequester from 60 to 360 GT of CO_2 over the next 50 years, depending on the amount of CO_2 injected underground per barrel of oil produced.[1] For context, a path to a 2°C average global temperature increase is expected to require a total of about 125 GT of CO_2 storage.[2]

Achieving gigaton scale CO_2 EOR storage goals will require innovation. This work focuses on a government incentive—a reverse Dutch auction—as a sensible policy mechanism to encourage innovation of advanced CO_2 EOR (A-CO_2 EOR), whose commercial profitability derives from both enhanced production and CO_2 storage.

The United States and other countries are struggling to find fair and cost-effective ways to reduce carbon emissions to avoid the risks of climate change. When the oil and gas industry is facing mounting criticism as a business based on conversion of hydrocarbons in the ground to carbon dioxide emissions in the atmosphere, CO_2 EOR could be a concrete and positive contribution to CO_2 emission avoidance and deserves evaluation.

Table 1. Properties and Assumptions Used in Hypothetical Analysis

Initial OIP: 180 Million Barrels	Primary and Secondary Production	Conventional CO_2 EOR at 2.5 bbl/T[a] CO_2	A-EOR at 1.25 bbl/T CO_2
Total recovery (% OIP)	33.3	50	60
Total oil recovery (million barrels)	60	90	108
CO_2 EOR oil recovery (million barrels)	0	30	48
CO_2 injected (MT)[a]	0	12.0	38.4
CO_2 emitted on use (MT)[b]	25.8	38.7	46.4
Net CO_2 emitted (MT)[b]	25.8	26.7	8.0
CO_2 emitted from incremental production (MT)[b]	–	12.9	20.7
Net CO_2 emitted from incremental production (MT)	–	0.9	−17.8

[a]MT, million metric tons; T, metric ton.
[b]0.43 metric tons emitted CO_2 per barrel of oil.

At present, CO_2-assisted EOR is about 3% of US domestic oil production or about 300,000 barrels (bbl)/day, mostly from the Permian Basin and the Gulf Coast.[3] Historically, since most of the CO_2 for EOR has come from natural CO_2 reservoirs, there has been little climate benefit. However, if CO_2 EOR using CO_2 captured from anthropogenic sources were increased about 10-fold to a level of 500 MT/year, that would reduce total US emissions by about 9.5%, not an inconsequential part of the emissions reductions that the United States is seeking to achieve by mid-century.

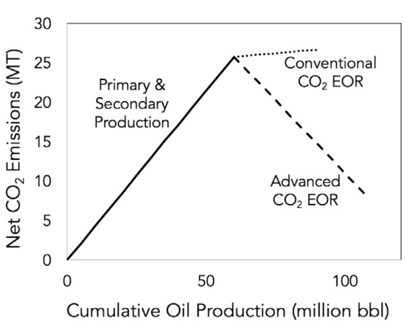

Figure 1. Net CO_2 Emissions over the Lifetime of an Oilfield as a Function of the Amount of Oil Produced

Net emissions are defined as the difference between emissions from burning produced oil (0.43 tonnes/bbl) and the CO_2 sequestered in the oil field during CO_2 EOR and A-CO_2 EOR (Table 2).

Operation and Economics of CO_2 EOR

Primary and secondary production typically recovers up to one-third of the oil-in-place (OIP) in a reservoir. A-CO_2 EOR has the technical potential for doubling the recovery of OIP compared with conventional EOR.[1] Normally a CO_2 EOR project will extend for decades with nearly all of the injected CO_2 remaining sequestered in the oil reservoir when produced CO_2 is recycled back into the reservoir.[4]

EOR projects are notorious for the high variability that reflects reservoir location and conditions. Project economics vary depending on the price of oil and the cost of CO_2 over the life of the project. Here, we use generalized results of prior studies of co-optimized CO_2 EOR plus sequestration.[5–12] For illustration, we focus on the hypothetical oil field described in Table 1 with 180 million barrels OIP. After primary and secondary production, we consider two cases: conventional CO_2 EOR and A-CO_2 EOR.

For this example, A-CO_2 EOR sequesters twice the amount of CO_2 per barrel of oil produced compared with conventional CO_2 EOR. Net emissions, defined as the emissions from burning the oil minus the amount of CO_2 sequestered from the oilfield are illustrated in Figure 1. During primary and secondary production, emissions increase linearly at a rate of 0.43 tonnes CO_2/bbl of oil produced. Once conventional CO_2 EOR begins, sequestered CO_2 nearly offsets the incremental emissions produced when the oil is burned. For A-CO_2 EOR, sequestered CO_2 exceeds the incremental emissions from burning the oil, offsetting not only current but past emissions, eventually for this example, by 70% of all the emissions from primary and secondary production (Table 1, see Figure 1).

The economics of a CO_2 EOR project is sensitive to oil price, the acquisition cost of CO_2, and additional cost associated with the EOR activity. Table 2 shows the range assumed in this work for "high," "reference," and "low" oil prices averaged over the project life. Table 2 includes the CO_2 acquisition cost and other costs associated with CO_2 EOR activity.[13] The values in Table 2 are subject to challenge but the trends of CO_2 price and margin with increasing oil prices are robust.

The margins are highly sensitive to oil price. Without an imposed charge on CO_2 emissions, Table 2 shows that the projected cost of an A-CO_2 EOR is not financially attractive to the owner/operator compared with conventional CO_2 EOR. The incremental costs to break even with traditional CO_2 EOR range from \$22 to \$32/T CO_2.

Policy Options

The preferred approach of an economy-wide greenhouse gas emissions charge is unlikely in the near term. If, in the future, a charge is adopted at sufficiently high levels, the value of using the pores in oil reservoirs for sequestration will be greater than the value of the oil displaced, and the economic motivation for CO_2 EOR production and sequestration will reverse.

In the absence of a carbon emission charge, there is no commercial

Table 2. Economic Analysis of CO_2 EOR and A-CO_2 EOR

Oil Price ($/bbl)[a]	Conventional CO_2 EOR (2.5 bbl/T)			A-CO_2 EOR (1.25 bbl/T)		
	100	75	50	100	75	50
CO_2 acquisition cost ($/T)	−39	−29	−19	−39	−29	−19
CO_2 acquisition cost ($/bbl production)[b]	−15	−12	−8	−31	−23	−15
Other related costs ($/bbl)[c]	−35	−35	−35	−56	−56	−56
Net pretax margin ($/bbl)	50	28	7	13	−4	−21
CO_2 EOR production (million barrels)	30	30	30	48	48	48
Project EOR margin ($ million)	1,488	854	219	634	−197	−1,027
CO_2 injected (MT)	12	12	12	38.4	38.4	38.4
CO_2 price to break even ($/MT)				22.25	27.35	32.45
Project margin ($/million) if credited with the social cost of carbon ($30/T) for incremental storage				1,786	955	125

[a]This range is narrower than the EIA 2017 AEO's $30 to $194 per barrel in 2030.
[b]A rule of thumb is that the acquisition CO_2 cost in $/MCF (1,000 cubic feet) is between 2% and 4% of the oil price in $/barrel. Cook, B.R. (2012) The Economic Contribution of CO_2 Enhanced Oil Recovery in Wyoming's Economy. The Enhanced Oil Recovery Institute, University of Wyoming. Working paper. p. 20.
[c]Includes royalties, allocated EOR equipment allocation, taxes, recycling cost, and other site operation and maintenance costs associated with CO_2.

justification for private industry to invest in A-CO_2 EOR technologies. In this circumstance, the government objective should be to adopt policies at reasonable cost that will encourage EOR owner/operators to explore A-CO_2 EOR to position the industry to deploy this technology more rapidly when there is an economy-wide price on carbon emissions. The government has the choice of several policy mechanisms for this purpose:

- A tax credit for EOR. Since 2008, qualifying CO_2 EOR facilities have been eligible to receive a tax credit of $10/T, with a cap of a total of 75 MT, referred to as the 45Q tax credit. In 2018, Congress raised the 45Q credit to $35/T for CO_2 EOR and $50/T for storage in saline formations and removed the cap.[14]

  The 45Q tax credit will incentivize conventional CO_2 EOR. But this tax credit mechanism is not targeted to incentivize A-CO_2 EOR. Furthermore, the use of tax credits suffers from "leakage" to financial intermediaries, and in the circumstances where oil prices are low, few oil and gas firms are in a position to take advantage directly of the incentive. Recent cuts to corporate tax rates also make tax credits less attractive than in the past.
- A direct payment also does not incentivize development of A-CO_2 EOR beyond what would be expected under market conditions. To be effective, the level of payment would need to be sufficiently high to offset the current cost of CO_2. However, the great diversity and uncertainty in the discounted net present value to owner/operators of multiyear EOR projects makes this approach more expensive than a targeted benefit.
- What is needed is a policy mechanism that allows the government the flexibility to adjust the amount of assistance provided to the firms prepared to undertake new projects at various levels of support. A reverse Dutch auction is an ideal mechanism to achieve selective encouragement of A-CO_2 EOR. In a reverse Dutch auction, the government would annually solicit bids from owner/operators of new A-CO_2 EOR multiyear projects that, over the life of the project, specify the amount of CO_2 sequestered, the ratio of CO_2 sequestered to oil production, and the amount of annual payment sought from the government (which is assumed to be constant over the life of the project). These bids will reflect each firm's willingness to implement A-CO_2 EOR. In contrast to conventional tax credit or direct payment subsidy programs that offer the same benefit to all eligible firms, in a Dutch auction the government selects the price that yields the desired cumulative amount of A-CO_2 EOR.

It is difficult to predict the outcome of such reverse Dutch auctions for CO_2 EOR credits. The sizes and prices bid will depend on the oil price. It is quite possible that a $20 per metric ton CO_2 payment would be sufficiently attractive to result in greater CO_2 EOR use in 2040 than the 700 million bbl/day predicted by the Energy Information Administration (EIA) in its 2014 Annual Energy Outlook (AEO). Rebound effects need to be evaluated that could increase oil consumption by the shift of the supply curve to a lower market clearing price.

The design of all these incentives for CO_2 EOR confronts several complications:

- Should a benefit be extended to both low-cost natural sources and high-cost anthropogenic sources of CO_2? Low-cost natural or anthropogenic sources (high-purity sources of CO_2 from refineries and ethanol plants can be compressed and dehydrated for about $20–30 T/$CO_2$) of CO_2 can jump start the process, but in the future, anthropogenic CO_2 will increasingly come from coal, oil, and natural gas combustion, which incur higher CO_2 capture, purification, and pressurization costs (ranging from $60 to $90/T CO_2 depending on the source).[15]

- The availability of a CO_2 gas pipeline distribution system is likely to be the greatest constraint to the expansion (at reasonable cost) of A-CO_2 EOR. A pipeline capacity constraint will lead to an increase in pipeline tariffs, a reduction in expected margins for A-CO_2 EOR, and hence attenuation in desired growth.
- An A-CO_2 EOR project will have a life of 10 years or more. The project entrepreneur must estimate the variability in oil prices and CO_2 acquisition cost in assessing the discounted present value of the project. Under current market conditions, there is a strong positive correlation between oil price, CO_2 cost, and return on CO_2 EOR projects.

How successful government policy will be at encouraging A-CO_2 EOR use and technology advance is uncertain for the reasons mentioned above. This uncertainty suggests that payments for A-CO_2 EOR using anthropogenic CO_2 with the Dutch auction proposal for CO_2 EOR be considered an experiment rather than a policy to be permanently adopted. A decade of experience will determine the merit of this policy incentive to encourage A-CO_2 EOR.

Experience gained from the expansion of A-CO_2 EOR will also be beneficial for assessing the costs and risks of CO_2 sequestration in deep saline formations, which have the potential for even larger amount of sequestration, but lack the financial and energy security benefits of CO_2 EOR. Let us assume a 3-year experimental program with ten projects selected per year, each with a 10-year lifetime, and 300,000 bbl/per day produced for the entire program. If the government accepted an average bid for CO_2 of \$25/T, the annual per project cost would be \$22 million for 0.88 MT of CO_2 sequestered. The total program cost over the lifetime of the program would be \$6.6 billion for 264 MT of CO_2 sequestered. The expense of the proposed CO_2 EOR program should be compared with other government programs designed to reduce CO_2 emissions. While largely presented in the US context here, the reverse Dutch auction could equally well be applied in other oil-rich countries seeking economically efficient policies for reducing emissions.

1. International Energy Agency. (2015). Storing CO_2 through enhanced oil recovery. http://www.iea.org/publications/insights/insightpublications/storing-co2-through-enhanced-oil-recovery.html.

2. International Energy Agency. (2014). Energy technology perspectives. http://www.iea.org/publications/freepublications/publication/energy-technology-perspectives-2014.html.

3. Kuuskraa, V., and Wallace, M. (2014). CO_2-EOR set for growth as new CO_2 supplies emerge. Oil Gas J. *112*, 92.

4. Gozalpour, F., Ren, S.R., and Tohidi1, B. (2005). CO_2 EOR and storage in oil reservoirs. Oil Gas Sci. Technol. Rev. IFP *60*, 537–546.

5. Mac Dowell, N., Fennell, P.S., Shah, N., and Maitland, G.C. (2017). The role of CO_2 capture and utilization in mitigating climate change. Nat. Clim. Change *7*, 243.

6. Ampomah, W., Balch, R.S., Rose-Coss, D., Will, R., Cather, M., Dai, Z., and Soltanian, M.R. (2017). Optimal design of CO_2 storage and oil recovery under geological uncertainty. Appl. Energy *195*, 80–92.

7. Leach, A., Mason, C.F., and van't Veld, K. (2011). Co-optimization of enhanced oil recovery and carbon sequestration. Resource Energy Econ. *33*, 893–912.

8. Ampomah, W., Balch, R.S., Grigg, R.B., McPherson, B., Will, R.A., Lee, S.Y., and Pan, F. (2017). Co-optimization of CO_2-EOR and storage processes in mature oil reservoirs. Greenhouse Gases Sci. Technol. *7*, 128–142.

9. Kamali, F., Hussain, F., and Cinar, Y. (2015). A laboratory and numerical-simulation study of co-optimizing CO_2 storage and CO_2 enhanced oil recovery. SPE J. *20*, 1–227.

10. van't Veld, K., Wang, X., and Alvarado, V. (2014). Economic co-optimization of oil recovery and CO_2 sequestration. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

11. Ampomah, W., Balch, R.S., Cathar, M., Will, R., Lee, S.Y., and Dai, Z. (2016). Performance of CO_2-EOR and storage processes under uncertainty. In SPE Europec Featured at 78th EAGE Conference and Exhibition. Society of Petroleum Engineers.

12. Kuuskraa, V., and Ferguson, R. Advanced Resources International. (2009). Storing CO_2 with enhanced oil recovery. DOE/NETL-402/1312/02-07-08. http://www.energy.ca.gov/sitingcases/hydrogen_energy/documents/08-AFC-8/applicant/Tech_Studies_CO2_EOR/NETL%20Storing%20CO2%20with%20EOR.pdf.

13. Global CCS Institute. (2011). Summary of Costs for CO2-EOR (Global CCS Institute). http://hub.globalccsinstitute.com/publications/global-technology-roadmap-ccs-industry-sectoral-assessment-co2-enhanced-oil-recovery-10.

14. Section 45Q makes available a per-ton credit for CO_2 disposed of in secure geologic storage. The program provides \$35 per metric ton for CO_2 stored through CO_2 EOR operations and \$50 per metric ton for CO_2 stored in deep saline formations. http://uscode.house.gov/view.xhtml?req=(title:26%20section:45Q%20edition:prelim).

15. Rubin, E.S., Davison, J.E., and Herzog, H.J. (2015). The cost of CO_2 capture and storage. Int. J. Greenhouse Gas Control *40*, 378–400.

[1]Department of Energy Resource Engineering, Stanford University, Stanford, CA 94305, USA

[2]Institute Professor, Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

*Correspondence: smbenson@stanford.edu

https://doi.org/10.1016/j.joule.2018.07.026