Economical Co-optimization of CO_2 Sequestration and Enhanced Oil Recovery

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Abstract

Injecting carbon dioxide into oil reservoirs for both enhanced oil recovery (EOR) and sequestration are of current interest and have gained increasing attention due to both high crude oil prices and the concern about greenhouse gases on the global climate. The use of carbon dioxide for EOR is a commercial process with wide spread field experience in the U.S., but there is relatively little field experience with maximizing the geological storage of CO_2, and most of the storage is outside the U.S. and has involved injecting the CO_2 into aquifers. With EOR, the goal is to make a profit by minimizing the use of CO_2 and reusing it once it has been produced for the reservoir undergoing the CO_2 flood. With sequestration, the goal is to maximize the storage of the CO_2. To a large extent, these appear to be competing goals. Therefore, we have done an exploratory economic analysis based upon systematic compositional simulations of CO_2 EOR to establish how much and what type of economic incentive might be needed to encourage oil companies in the U.S. to store more of the CO_2 in oil reservoirs. The economic analysis took into account factors such as capture and transportation costs. Experimental design and the method of response surfaces along with Monte Carlo-based simulations were utilized to perform this study in a systematic, efficient and accurate manner. Combination of reservoir parameters and economic factors were studied to achieve comprehensive understanding of the financial performance of coupled CO_2 sequestration and EOR projects. Possible CO_2 credits were also quantified in a probability based distribution for various uncertain economical and geological characteristics in different projects.

Objectives

- Construct mathematical relationships between CO_2 credit incentives and projects' economical and flood characteristics
- Investigate effect of wide range uncertainties in different economical and reservoir characteristics on possible CO_2 credit incentives for coupled EOR and sequestration projects

Methodology

- Extensive information on CO_2 EOR floods was compiled and used in the analysis
- A compositional reservoir simulator (CMG's GEM) was used to model CO_2 performance in oil reservoirs
- Comprehensive 3D reservoir studies were performed to investigate flood performance in carbonate and sandstone reservoirs with their corresponding typical characteristics
- Sensitivity analysis was preformed to study the effect of uncertainties in the economic parameters and construct mathematical relationships
- Statistical methods was applied to quantify the effect of all economic factors and with their range of uncertainties

Summary of Important Data for Simulation Models

	Carbonates	Sandstones
Permeability Distribution	Layered	Stochastic
Vertical to horizontal Perm. Ratio	0.01	0.1
Average porosity, frac.	0.11	0.23
Reservoir temperature, °F	110	150
Remaining oil saturation before flood, frac.	0.58	0.33
Remaining oil saturation after flood, frac.	0.32	0.18

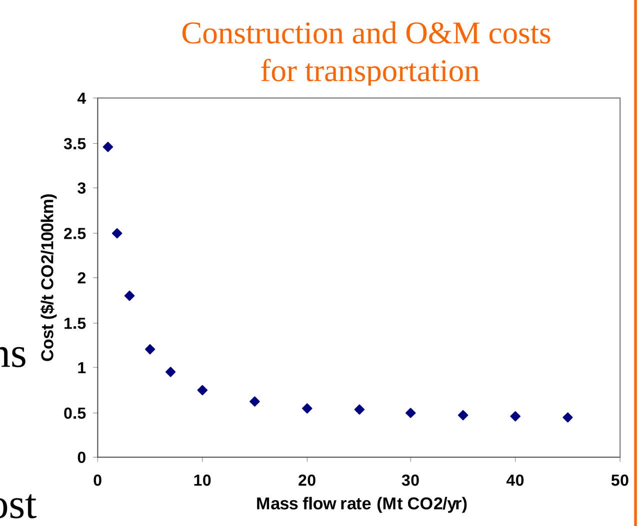
CO_2 Costs Associated with Sequestration

- Capture and Compression Costs[1]

  Assumptions
  - CO_2 source is nominal 500 MW_e conventional coal-fired power plant with emission level of 7390 tCO_2/day or 141 mmscf/day and it corresponds to annual total injection of 51.4 TSCF/yr
  - Capture using Monoethanolamine as solvent
  - Compression to 152 bars delivered on injection site
  - Total capture and compression costs is calculated as 45 $/t (or 2.6 $/mscf)

- Transportation Costs[2]

  Assumptions
  - CO_2 is transported from sources at 200-400 miles far from reservoirs (e.g., from Houston vicinity to oil fields along gulf coast)
  - Based on these assumptions and considering costs for CO_2 transportation in this plot, CO_2 transportation cost will vary 0.5-1.2 $/mscf of CO_2

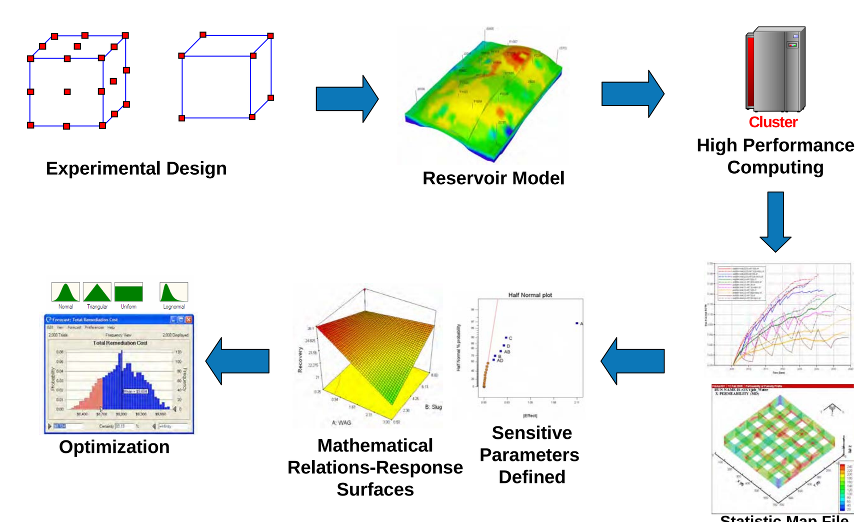


Discounted Cash Flow Analysis

- Experimental design was used to evaluate effect of uncertain economical parameters on possible CO_2 credit incentives. The goal was to establish mathematical relationship for CO_2 credit as a function of uncertain economic and reservoir parameters
  - D-optimal design method was used to perform the sensitivity
  - Uncertain factors in DCF analysis:

Symbol	Factor		Low (-1)	Median (0)	High (1)
A	Oil price, $/bbl		15	35	55
B	CO_2 price, $/mscf		1	2.5	4
C	Flood performance, mscf/bbl		7	12	20
D	Drilling cost, $mm/well		0.75	0.9	1.05
E	Discount rate, %		0.1	0.15	0.2
F	Operational costs	Fixed op. costs, $mm/month	0.0192	0.024	0.029
		Recycle costs, $/mscf	0.56	0.7	0.84
		Lift costs, $/bbl	0.32	0.4	0.48

Methodology to perform experimental design analysis



Response Surfaces for CO_2 Credit

Mathematical relation between CO_2 credit and economic factors for **CO_2-WAG flooding** in **carbonate reservoirs**:

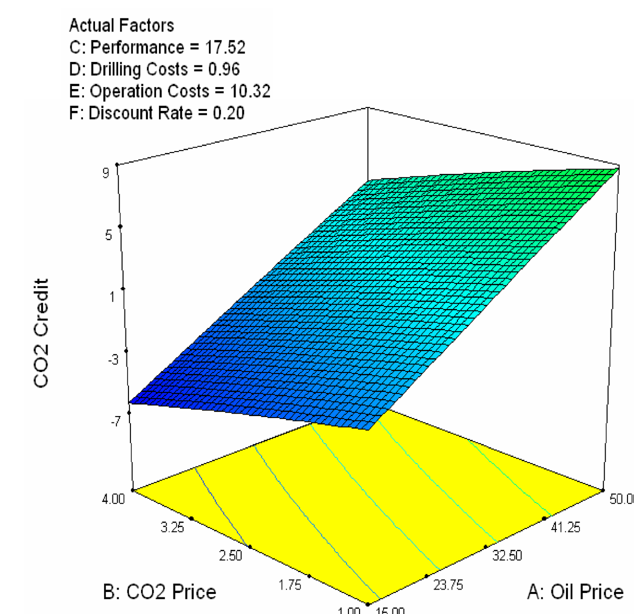
CO_2 Credit ($/mscf)$=1.08+0.36\times A+1.33\times B-1.11\times C-15.09\times D-0.04\times E+151.59\times F+0.01\times A\times B-0.02\times A\times C-0.13\times A\times D-0.001\times A\times E+1.08\times A\times F+0.02\times B\times C-1.83\times B\times D+0.02\times B\times E-12.66\times B\times F-0.18\times C\times D+0.001\times C\times E-2.95\times C\times F-0.02\times D\times E-41.58\times D\times F+0.0002\times A^2-0.09\times B^2+0.06\times C^2+15.37\times D^2-0.0003\times E^2-427.62\times F^2$

Response Surfaces for CO_2 Credit

- Same mathematical models were obtained for projects' profit with and without accounting for constant CO_2 storage credit (assumed 2.5 $/mscf) for all cases-12 equations in total
- Ranking effect of uncertain economical factors on CO_2 credit in different reservoirs and flooding types

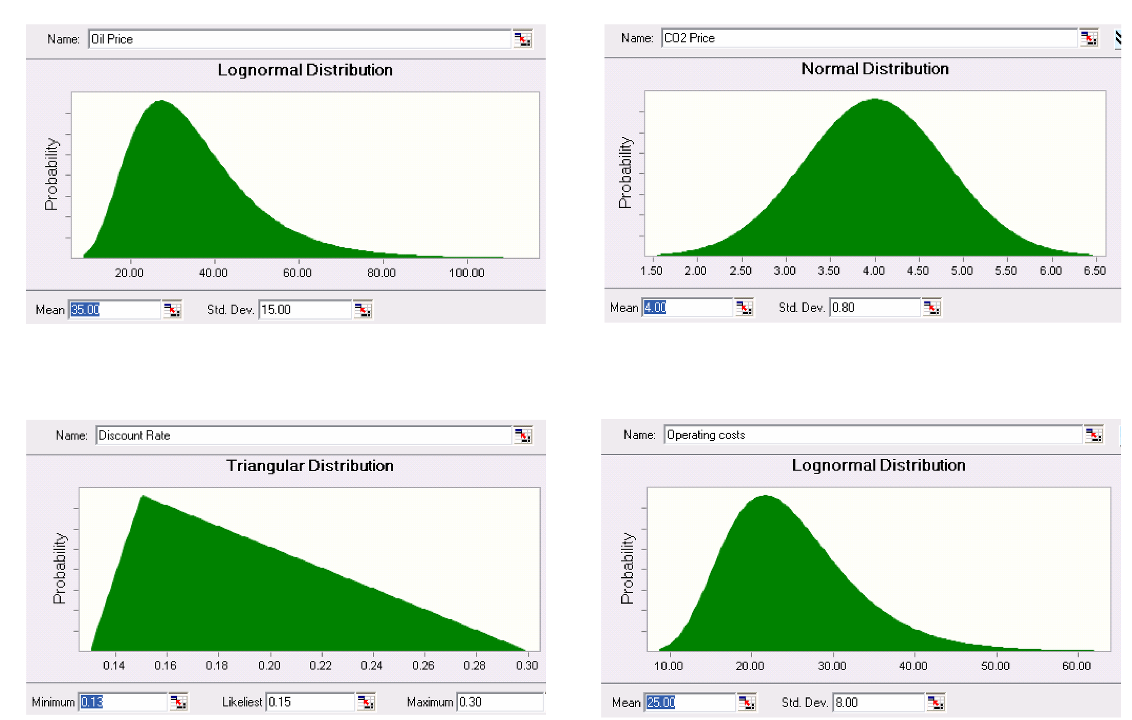
Rank	Carbonates		Sandstones	
	WAG	CO_2	WAG	CO_2
1	A	A	A	A
2	C	C	C	C
3	F	C^2	C^2	C^2
4	B	AC	B	AC
5	C^2	B	AC	B
6	AC	AF	AF	AF
7	F^2	CF	CF	CF
8	CF	E	F	F
9	BF	F	BF	E
10	AF	EF	E	EF
11	D	BE	EF	DE
12	BE	DE	DE	BE
13	BD	DF	F^2	BF
14	AD	BF	BE	F^2
15	D^2	D	BD	DF

- Sample response surface for CO_2 Credit

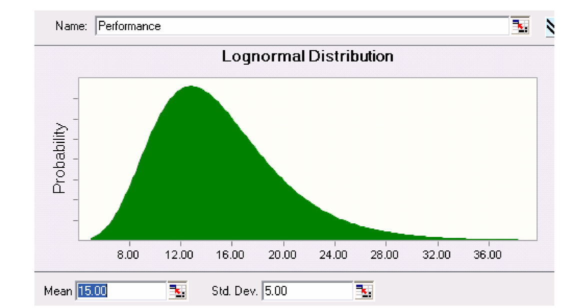


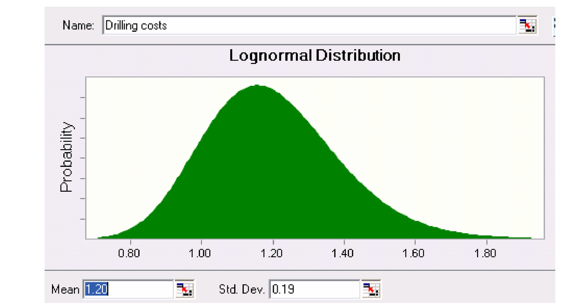
Uncertainty Analysis of Variables

- Monte-Carlo type simulations were performed in order to account for uncertainty in the economical variables by considering their probabilistic distribution.
- Probability distribution functions assumed for each economical variable



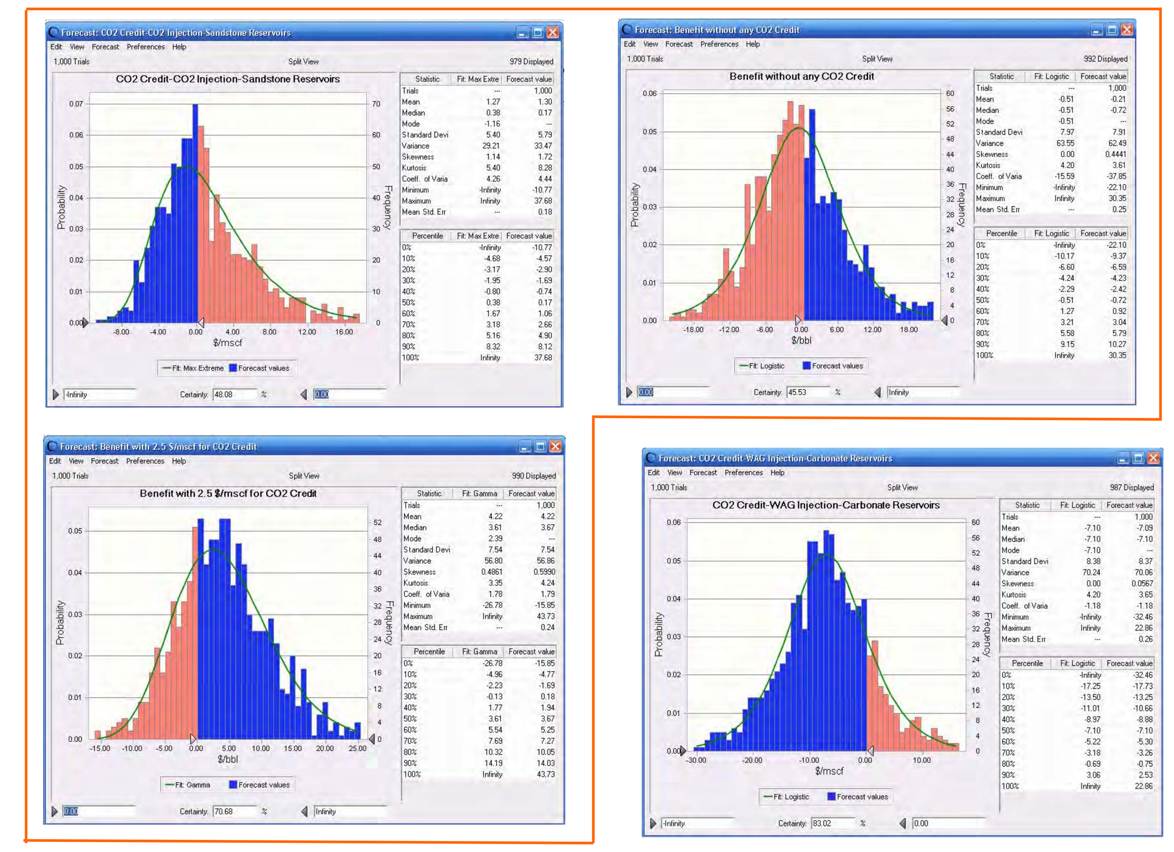
Uncertainty Analysis-Assumptions





CO_2 Credit-Is It Necessity for Sequestration?

- Probability distribution functions for CO_2 credit ($/mscf) needed for a positive net present value, as well as project's profit, and project's profit considering fixed CO_2 credit of 2.5 $/mscf



- Summary of the final probability distribution functions

	Carbonates		Sandstones	
	WAG	CO_2	WAG	CO_2
Probability of need for CO_2 credit,%	83.0	35.8	72.4	48.0
Profit, $/bbl	-2.0	0.9	-5.8	-0.5
Profit with 2.5 $/mscf as credit, $/bbl	0.5	2.4	-1.5	4.2

Summary and Conclusions

- The need for CO_2 credits to encourage CO_2 storage in the oil reservoirs with different properties was quantified using a compositional numerical reservoir simulator and decision analysis
- Oil price dominates the economics of CO_2 EOR and storage
- In all of the cases, oil price, flood performance, CO_2 cost, and operational costs are the most important variables
- The largest CO_2 costs are due to capture and transportation
- A higher CO_2 credit is needed for CO_2 WAG floods
- A higher CO_2 credit is needed for sandstone reservoirs compared to carbonate reservoirs

References

[1] Rochelle, G., Jassim, M., "Integrating MEA Regeneration with CO_2 Compression and Peaking to Reduce CO_2 Capture Costs," Report NO. DE-FG02-04ER84111, NETL, U.S. Department of Energy, 2005

[2] Heddle, G., Herzog, H., Klett, M., "The Economics of CO_2 Storage," Report NO. MIT LFEE 2003-003, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, 2003

[3] Benson, S. M., "Monitoring Carbon Dioxide sequestration in Deep Geological Formations for Inventory Verification and Carbon Credits," paper SPE 102833, presented at the 2006 ATCE held in San Antonio, TX