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CO$_2$ Allocation for Scheduling Enhanced Oil Recovery (EOR) Operations with Geological Sequestration using Discrete-Time Optimization

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Abstract

Carbon capture and storage (CCS) can be carried out in conjunction with enhanced oil recovery (EOR) to yield complementary environmental and economic gains. Thus, CCS in combination with EOR will provide economical value from incremental oil recovery besides providing source for CO$_2$ sequestration. Given a fixed CO$_2$ supply to be distributed to different reservoirs, it is necessary to develop an allocation model to maximize profit from EOR operations. In this study, a discrete-time optimization model is developed subject to scheduling, capacity and flow rate constraints. A case study is presented to illustrate the model.

*Keywords:*CO$_2$ capture and storage; enhanced oil recovery; optimization.

1. Introduction

CO$_2$ injection in depleted reservoirs can be coupled with enhanced oil recovery (EOR) operations to gain additional profit from incremental oil production. Planning for efficient utilization of captured CO$_2$ is necessary for viable EOR operations. Hence, CO$_2$ supply should be allocated to different reservoirs to achieve optimum results in terms of increasing revenues from existing reservoirs. Optimization models have been proposed for such problems [1]. Various models have also been developed for CCS source-sink matching for sequestration purposes [2-4]. These models addressed problems with the economics of CCS alone and CCS in combination with EOR, but lack consideration of the optimal scheduling of

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commencement of EOR for each oil reservoir. In the context of this study, optimal scheduling for oil reservoirs is defined as a trade-off between of reservoir life against decision to invest in EOR application which is a capital-intensive. In this study, a mixed integer linear program (MILP) is developed for allocating available captured CO_2 to different EOR operations subject to fixed operation. In reality, the operation duration or availability of continuous CO_2 supply is subjected to the operating life of the power plant (assuming captured CO_2 soure) or field life for natural CO_2 supply from underground deposits. The rest of the paper is organized as follows. Section 2 gives the formal problem statement while Section 3 shows the model. Section 4 shows a case study and Section 5 gives conclusions and future works.

Nomenclature	
Parameters	
F_T	Total CO_2 Flow Rate Available (Mt/y)
T	Total Source Operating Life (y)
Y_i	Oil Yield (Mbbls/Mt)
V_i	Oil value (M\$/Mbbls)
I_k	Present worth Factor at time k
S_i	Sequestration parameter: total amount of CO_2 stored per total CO_2 sequestered
C_i	Capacity of sink j
$(F_i)^{min}$	Minimum flow rate for sink i (Mt/y)
$(F_i)^{max}$	Maximum flow rate for sink i (Mt/y)
C^*	Carbon Credits (M\$/Mt)
ΔT_i	Duration of EOR operation
$(T_i)^{early}$	Earliest time at which the operation can start (y)
$(T_i)^{late}$	Latest time at which the operation can start (y)
D_i	Distance for the source to the reservoir
$(C_o)^{pp}$	Fixed cost for CO_2 transportation (million \$)
$(C)^{pp}$	Variable cost proportionality constant for CO_2 transportation (M\$/ km-Mt CO_2)
ΔK	Length of one time period
Variables	
f_{ik}	CO_2 flow rate to sink i at time k.
f_i	CO_2 flow rate to sink i.
b_{ik}	Binary variable indicating the existence of an EOR operation at time k
a_{ik}	Binary variable indicating a time period on or after the start of the EOR operation in sink i.
c_{ik}	Binary variable indicating a time period on or before the end of the EOR operation in sink i.
$(T_i)^{start}$	Time at which the operation starts (y)

2. Problem Statement

The problem statement is as follows. The system consists of m depleted oil reservoirs and one CO_2 source. In this study, the CO_2 source operates for T years and has a fixed total flow rate of F_T. On the other hand, each reservoir is characterized by a capacity, C_i and yields a fixed amount of oil per CO_2 injected, Y_i with a value, V_i. The injection to each reservoir should be within the bounds, $(F_i)^{min}$ to $(F_i)^{max}$ and a portion, defined as S_i, of the CO_2 injected is sequestered. The amount of CO_2 stored gets credits amounting to C^*. The operations corresponding to these reservoirs have fixed durations ΔT_i and can start between $(T_i)^{early}$ and $(T_i)^{late}$. The cost of transporting and injecting CO_2 to the reservoir is estimated using a linear cost function with a fixed component of $(C_o)^{pp}$ and variable component of $(C)^{pp}$. The latter is proportional to the flow rate to the reservoir and the distance of the reservoir to the source.

3. Optimization Model

The objective function is to maximize the total profit from all EOR operations:

$$\max Z = \Sigma_i \Sigma_k (f_{ik})(Y_i V_i)(I_k) + \Sigma_i \Sigma_k (f_{ik})(S_i)(C^*) - \Sigma_i [(C_o)^{pp} + (C)^{pp}(f_i D_i)] \qquad \text{(Eq. 1)}$$

Subject to:

$$a_{ik} + c_{ik} - 1 = b_{ik} \qquad\qquad \forall i,k \qquad \text{(Eq. 2)}$$

$$c_{ik} \leq c_{i(k-1)} \qquad\qquad \forall i,k \qquad \text{(Eq. 3)}$$

$$a_{ik} \geq a_{i(k-1)} \qquad\qquad \forall i,k \qquad \text{(Eq. 4)}$$

$$(T_i)^{start} = T - \Sigma_k a_{ik} \qquad\qquad \forall i \qquad \text{(Eq. 5)}$$

$$(T_i)^{early} \leq (T_i)^{start} \leq (T_i)^{late} \qquad\qquad \forall i \qquad \text{(Eq. 6)}$$

$$\Sigma_k (f_{ik})(S_i) \leq C_i \qquad\qquad \forall i \qquad \text{(Eq. 7)}$$

$$\Sigma_i (f_{ik}) \leq F_T \qquad\qquad \forall k \qquad \text{(Eq. 8)}$$

$$(F_i)^{min} \leq f_i \leq (F_i)^{max} \qquad\qquad \forall i \qquad \text{(Eq. 9)}$$

$$f_{ik} \leq f_i \qquad\qquad \forall i,k \qquad \text{(Eq. 10)}$$

$$f_{ik} \leq F_T b_{ik} \qquad\qquad \forall i,k \qquad \text{(Eq. 11)}$$

$$f_{ik} \geq f_i - F_T(1 - b_{ik}) \qquad\qquad \forall i,k \qquad \text{(Eq. 12)}$$

$$\Sigma_k b_{ik} = \Delta T_i \qquad\qquad \forall i \qquad \text{(Eq. 13)}$$

$$I_k = (1+r)^{-k} \qquad\qquad \forall i,k \qquad \text{(Eq. 14)}$$

The objective function has three components: the revenue for recovered oil, the credits for CO_2 sequestered and the cost of facilities for transporting CO_2 to each reservoir. Equations 2, 3 and 4 show the relationship of three binary variables used for scheduling the EOR operations. Equations 5 and 6 are used for obtaining the time at which the operation is carried out. Equation 7 ensures that the total CO_2 stored during the operation is less than the capacity. Equation 8 is the flow rate balance and expresses the distribution of available CO_2 to each reservoir. Equation 9 to 12 ensures that the flow rate is within the bounds and fixed at all time periods. Equation 13 links the span of EOR operations to binary decision variables. The time of value of money is calculated by Equation 14.

4. Case Study

The model is tested using a case study solved with Lingo 12.0 on a PC of 2.00 GHz and 4.00 Gb RAM. Data for the case study are given in Table 1. The source is operating for 25 years in which the total capturable CO_2 is 8.5 Mt/y. An 8% interest rate is assumed for the entire time horizon. Transporting CO_2 to the reservoirs has a fixed cost of $20 million and a variable cost of $20,000/Mt/km. The optimal solution is shown in Figure 1 About 10% of the total revenue is from the oil recovered. According to the results, 53% of the total flow rate is allocated to Sink A, accounting for 27% of the total $124 million oil revenue. From this case study, it is shown that no operations are performed after 16 years. Over the entire planning horizon, 92 out of 117.5 Mt CO_2 injected (78%) were stored in these sink. The optimization model solves the problem of both the allocation of available CO_2 and scheduling of the three EOR operations in this case study.
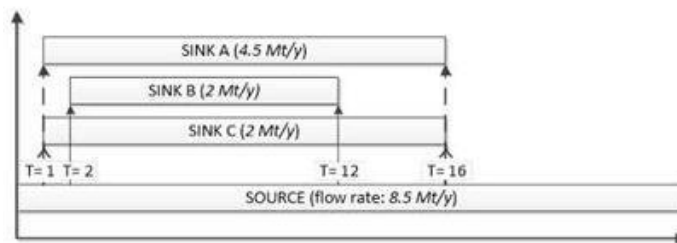

Figure 1 Optimal Solution for Case Study

Table 1. Case Study Data.

	Sink A	Sink B	Sink C
Earliest Start of Operation, O_i^{early}, y	1	2	1
Latest Start of Operation, O_i^{late}, y	15?	10	15?
Capacity, C_i, Mt	100	100	100
Minimum Flow Rate, F_i^{min}, Mt/y	2	2	2
Maximum Flow Rate, F_i^{max}, Mt/y	15	15	15
Oil Yield, Y_i, million bbls/Mt	0.009490	0.02847	0.04745
Oil Value, V_i, \$/bbl	100	70	90
Sequestration Parameter, S_i	0.95	0.85	0.35
Operating Life for EOR, ΔT, y	15	10	15
Distance from the source (km)	100	300	600

5. Conclusion and Future Works

A discrete time mixed integer linear program (MILP) for scheduling enhanced oil recovery (EOR) operations with geological CO_2 sequestration has been developed. The model allows the allocation of CO_2 from a single source to different reservoirs that corresponds to different EOR projects of fixed durations. Future work includes extending the model to multiple sources of CO_2 supply as well as considering other aspects such as uncertainties in oil prices, reservoir storage capacity and oil yield.

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Biography

J.F.D. Tapia is a Master of Science (MS) in Chemical Engineering graduate in De La Salle University-Manila, Philippines. His work includes developing optimization models such as linear program applied to carbon capture and storage (CCS) system source-sink matching.