An Analytic Hierarchy Process- Data Envelopment Analysis (AHP-DEA) Approach to Screening of Oil Reservoirs for Enhanced Oil Recovery (EOR) Systems

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Abstract: Enhanced oil recovery (EOR) by CO_2 injection is one of the most developed techniques for large scale deployment of carbon capture and storage systems. It involves the injection of CO_2 into the oil reservoir, enabling the recovery of the oil while storing the CO_2 into the ground. For successful operations, it is required to screen oil reservoirs for EOR based on different physical, economical and temporal characteristics. In this study, a site screening framework based on analytic hierarchy process (AHP) and data envelopment analysis (DEA) approaches is developed for oil reservoirs for EOR operations. AHP-based approach is used to aggregate qualitative criteria while DEA-based approach will be used to determine efficient sites. A case study is presented to illustrate the framework.

Key Words: Analytic Hierarchy Process; Data Envelopment Analysis; Enhanced Oil Recovery.

I. INTRODUCTION

The reduction in CO_2 emissions has been of the important means to mitigate climate change in which majority of the total global emissions comes from electricity generation (IEA, 2012). Carbon capture and storage (CCS) systems involves capturing CO_2 directly or indirectly from the flue gas and storing it to geological reservoirs such as depleted oil reservoir. It also provides additional profit through flooding of compressed CO_2 in depleted oil reservoir, thus increasing oil production (Davison et al., 2001).. This operation, commonly known as enhanced oil recovery (EOR), is one of the most developed techniques to deploy CCS in large-scale (Godec et al., 2011). However, properly selecting and screening of candidate oil reservoirs is important to avoid investing into inefficient and expensive operations and to maximize for the available CO_2 source.

For CCS, several models have been proposed to match CO_2 sources and geological reservoirs in both continuous- (Tan et al., 2012; Lee and Chen, 2012) and discrete-time (Tan et al., 2013) approaches. A unified CCS source-sink model is also proposed to address both temporal issue and power generation make-up in CCS (Lee et al., 2014). For EOR, several approaches have been proposed to optimize EOR operations especially in the economics aspects of the operations. These papers, however, requires that the sources and sinks are already qualified for large-scale deployment and selection of sources and sinks has been only addressed for CCS operations (Promentilla et al., 2013) and not for EOR. In this study, an analytic hierarchy process- data envelopment analysis- based (AHP-DEA) framework is developed for screening of oil reservoirs for both EOR operations and geological sequestration. AHP-DEA hybrid approaches has been used widely in different applications such as bridge risk assessment (Wang et al., 2008), facilities layout design (Yang and Kuo, 2003), biomass supply chains (Grigoroudis et al., 2014), logistics engineering and management facilities (Bowen, 1990), vendor selection (Krishna

Veni et al., 2012), and local government performance in china (Lin et al., 2011). These approaches make use of both qualitative and quantitative information about alternatives to be evaluated. In this study, the strength of DEA-based evaluation is maximized in quantitative data while AHP-based technique is utilized for qualitative data.

The rest of the paper is organized as follows: Section II presents the problem statement while Section III elaborates the AHP-DEA framework. Section IV presents a case study for illustration and lastly, Section V gives the conclusions and future works.

II. PROBLEM STATEMENT

In addressing the screening of oil reservoir for EOR operations, the following problem statements were addressed in this paper:

- The system consists of n candidate oil reservoirs to be evaluated.
- Each oil reservoir is defined by the following criteria:
    - Distance- the distance between the CO2 source and the oil reservoir in km of pipeline distance.
    - Minimum Flow Rate requirement- the minimum flow rate to start CO2 flooding for EOR (in Mt CO2/y).
    - Maximum Flow Rate Requirement- the maximum flow rate to maintain the structural integrity of the reservoir (in Mt CO2/y).
    - Operating Life- length of operation (in y) for a specific reservoir.
    - Oil Yield – amount of oil yield per CO2 injected (Mbbls oil/Mt CO2).
    - Oil Value- quality of oil recovered (M$/Mt/y CO2).
    - Sequestration Parameter- amount of CO2 stored per CO2 injected.
    - Reservoir Capacity- total CO2 that can be stored to the reservoir.
    - Well Security- refers to the security of CO2 from escaping in CO2 wells.
    - Structural Integrity- refers to the security of CO2 from escaping from the geological formation. This also includes risk of CO2 from escaping to a nearby groundwater source etc.
- An AHP-based pairwise comparison is used to evaluate oil reservoir for well security and structural integrity. An expert judgment will be the basis of the pairwise comparison.
- For DEA, the input criteria are those that the higher the value, the less preferred such as the distance and the minimum flow rate requirement. On the other hand, the output criteria, are those that the higher the value, the more preferred such as the rest of the criteria given.
- The qualified EOR operations for a specific oil reservoir should have efficiency equal to 1 based from the DEA approach.

III. AHP-DEA FRAMEWORK

To determine the efficient oil reservoir for EOR, the procedure for the AHP-DEA approach is shown in Fig. 1.

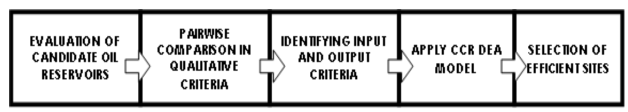

Figure 1: Framework Design for AHP-DEA approach in site screening

The quantitative data such as flow rates and operating lives should be evaluated for each reservoir. For AHP-based approach, pairwise comparison for qualitative data is made to quantify the judgments made. The pairwise comparison matrix is aggregrated using the eigenvector method to determine the weights of each alternative for both well security and structural integrity criteria.

When all data were expressed quantitatively, the Charnes-Cooper Rhodes (CCR) model for DEA in determining the efficiencies of oil reservoir is utilized. The objective is to maximize the efficiency of the reservoir relative to other reservoir. The model is executed for each reservoir to determine their efficiencies:

$$\max\ E_n = \sum_j v_{nj} y_{nj} \quad \text{(Eq. 1)}$$

Subject to:

$$\sum_j u_{nj} x_{nj} = 1 \quad \text{(Eq. 2)}$$

$$\sum_j v_{nj} y_{ij} \le \sum_j u_{nj} x_{ij} \qquad \forall i \quad \text{(Eq. 3)}$$

$v_{nj} \geq 0 \qquad \forall j \qquad$ (Eq. 4)

$u_{nj} \geq 0 \qquad \forall j \qquad$ (Eq. 5)

Eq. 2 maintains that the aggregated input of the alternative is equal to 1 while Eq. 3 ensures that the maximum efficiency of other alternatives is equal to or less than 1. This model solves the weights needed for the two constraints, Eq's 2 and 3, and will not affect directly into the decision making process. The model is then executed for each reservoir alternative and the efficiencies are calculated using MS Excel Linear solver. Each run has negligible computational time and since the model is linear, the solution is guaranteed a global optimum.

The screening process is completed by selecting the oil reservoir with efficiency equal to one. A reservoir with efficiency equal to one means that it is effectively equal or better than the other reservoir while an efficiency of less than one means that another reservoir may be better.

IV. CASE STUDY

Seven oil reservoirs were evaluated for this case study. Table 1 show the quantitative data as outputs for DEA and table 2 shows the quantitative data as inputs for DEA.

Table 1: Quantitative Output Data for DEA model

Sites	Operating Life (y)	Reservoir CO_2 Capacity (Mt)	Maximum Flow Rate Limit (Mt/y)	Oil Yield (bbls/ton CO_2)	Oil Value ($/ton)	Sequestration Parameter
1	15	190	15	9.45	100	0.9
2	10	200	20	28.47	70	0.85
3	15	260	15	46.45	90	0.8
4	20	230	25	10.56	140	0.78
5	15	200	10	17.8	75	0.86
6	15	150	15	20.53	25	0.99
7	20	300	20	6.79	120	0.75

Table 2: Quantitative Input Data for DEA model

Sites	Distance from CO_2 Source (km)	Minimum Flow Rate Limit (Mt/y)
1	300	2
2	250	5
3	200	3
4	150	1
5	200	3
6	350	6
7	400	4

A pairwise comparison is made to evaluate well security and structural integrity criteria. Tables 3 and 4 show the pairwise comparison made using the nine-point scale.

Table 3: Pairwise Comparison Matrix for Well Security Criteria

Oil Reservoir	1	2	3	4	5	6	7
1	1.00	0.33	0.20	5.00	3.00	7.00	0.20
2	3.00	1.00	0.50	9.00	7.00	9.00	0.33
3	5.00	2.00	1.00	7.00	9.00	5.00	1.00
4	0.20	0.11	0.14	1.00	0.60	3.00	0.11
5	0.33	0.14	0.11	1.67	1.00	3.00	0.14
6	0.14	0.11	0.20	0.33	0.33	1.00	0.11
7	5.00	3.00	1.00	9.00	7.00	9.00	1.00

Table 4: Pairwise Comparison Matrix for Structural Integrity Criteria

Oil Reservoir	1	2	3	4	5	6	7

1	1.00	3.00	1.00	0.33	0.14	5.00	3.00
2	0.33	1.00	0.33	0.11	0.11	1.67	1.00
3	1.00	3.00	1.00	0.33	0.33	5.00	3.00
4	3.00	9.00	3.00	1.00	0.50	9.00	9.00
5	7.00	9.00	3.00	2.00	1.00	5.00	7.00
6	0.20	0.60	0.20	0.11	0.20	1.00	0.33
7	0.33	1.00	0.33	0.11	0.14	3.00	1.00

The result of the eigenvector method is shown below in Table 5. The consistency ratio of well security is equal to 7.4% while the consistency ratio for structural integrity is equal to 4.8%

Table 5: Eigenvector Method Result for Well Security and Structural Integrity Criteria

Sites	Well Security	Structural Integrity
1	0.0955	0.1033
2	0.1989	0.0377
3	0.2872	0.1131
4	0.0321	0.2894
5	0.0396	0.3822
6	0.0232	0.0296
7	0.3236	0.0447

Based from the result above, Reservoir 3 has the highest preference weight in terms of well security while reservoir 5 has the highest in terms of structural integrity. On the other hand, reservoir 6 has the lowest well security and structural integrity preferences.

Using the data from Tables 1, 2 and 5, the efficiency were calculated and shown in Table 6.

Table 6: Eigenvector Method Result for Well Security and Structural Integrity Criteria

Oil Reservoir	1	2	3	4	5	6	7
Efficiency	0.804	0.773	1.000	1.000	1.000	0.570	0.873
Qualified for Operation?	N	N	Y	Y	Y	N	N

Three reservoirs, Reservoirs 3, 4 and 5, are selected based from a minimum efficiency of 100%. Among the seven reservoirs, Reservoir 6 has the lowest efficiency which also has the least preferred in terms of both qualitative criteria: well security and structural integrity. For a minimum efficiency of 80%, five reservoirs can be selected.

V. CONCLUSIONS AND FUTURE WORK

An analytic hierarchy process- data envelopment analysis (AHP-DEA) approach is developed to screen oil reservoir for carbon capture and storage systems with enhanced oil recovery. The framework for the screening procedure utilizes input and output criteria for measuring the efficiency of oil reservoirs relative to other oil reservoir. The screening criteria were based on physical, temporal, economic and risk aspects.

Future work includes accounting the uncertainty of the data given by extending the framework into fuzzy AHP-DEA and to account for the interdependencies of each criteria using analytic network process (ANP).

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