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Selection of CO_2 Utilization Options in Carbon Capture, Utilization and Storage (CCUS) Systems using Analytic Hierarchy Process- Data Envelopment Analysis (AHP-DEA) Approach

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Carbon capture, utilization and storage (CCUS) is one of the most important technologies for reducing greenhouse gas emissions into the atmosphere. Carbon Dioxide (CO_2) utilization enables the use of CO_2 emissions as input for processes to gain additional revenue. Options for CO_2 utilization include CO_2-enhanced oil recovery (CO_2 - EOR) and CO_2-enhanced coal methane (CO_2 - ECBM) recovery. These techniques involve injection of CO_2 into a geological reservoir enabling the increased recovery of oil (CO_2 - EOR) and gas (CO_2 - ECBM and CO_2 - EGR) and storing CO_2 emissions into the ground (geological sequestration) simultaneously. Integrating these CO_2 utilization operations into a large-scale CCUS system requires selection of oil and gas reservoirs to develop an efficient CCUS infrastructure. In this study, a site screening framework based on the analytic hierarchy process (AHP) and data envelopment analysis (DEA) approaches is developed to select reservoirs for CO_2 utilization operations. AHP-based approach is used to aggregate evaluation of qualitative data (reservoir's structural integrity and injection well security) to be integrated into DEA approach in determining site efficiencies. A case study is presented to illustrate the framework.

1. Introduction

Majority of the worldwide CO_2 emissions amounting to 32.3 Gt comes from combustion of fossil fuels (IEA, 2015). Based on a business-as-usual case, it is expected that these emissions will increase by 37 % from its current level by 2040 (IEA, 2012). One of the technologies that contribute to the decrease in greenhouse gas (GHG) emissions is carbon capture and storage (CCS). It involves capturing CO_2 from flue gas and injecting it to storage reservoirs (Pires et al., 2011). CCS enables the reduction of CO_2 emission into the atmosphere and the use of fossil fuel for energy production. Despite its potential for mitigating the effects of climate change, it is expected to incur substantial additional cost for capture, transportation and injection of CO_2 (De Coninck, 2014). Thus, options for productive use of CO_2 are needed to reduce the cost associated with CO_2 emissions reduction. Such options include enhanced oil recovery (EOR), enhanced coal bed methane (ECBM) and enhanced gas recovery (EGR) from shale gas (Wei et al., 2015).These options enable the recovery of valuable product (e.g. oil and natural gas) by injecting CO_2 into the reservoirs. Moreover, some of injected CO_2 is stored into the reservoir. CCS systems can be integrated with these options to form a large carbon capture, utilization and storage (CCUS) system. However, properly selecting and screening of candidate options for CO_2 utilization is important to avoid investing into inefficient and expensive operations and to maximize for the available CO_2 source.

Mathematical models have been proposed for designing systems of CO_2 sources and storage options. Such models include a continuous-time (Tan et al., 2012) which is later improved (Lee and Chen, 2012) and discrete-time (Tan et al., 2013) scheduling approach to match CO_2 sources and sinks with different times of availability. A fuzzy mixed integer linear program (MILP) has been proposed for balancing risks due to uncertainties in

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storage reservoir capacities and injectivity limits (Tapia and Tan, 2014). On the other hand, adjusting a CCS system due to sudden availability of new information has been developed using a two - step optimization approach (Tapia and Tan, 2015). 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 developed to design EOR systems. Such studies include allocation and scheduling of EOR operations as a strip packing problem (Tapia et al., 2015). On the other hand, Mohd Nawi et al. (2015) proposed a pinch analysis approach for CCUS systems. These studies, however, requires that the sources and sinks are already qualified for the design. Selection of sources and sinks has been only addressed for CCS operations (Promentilla et al., 2013) and has been limited to geological sequestration options only.

In this study, an analytic hierarchy process - data envelopment analysis-based (AHP - DEA) framework is developed for screening of candidate options for CO_2 utilization. The presence of both qualitative expert judgment and quantitative assessment of these CO_2 utilization options needs both AHP and DEA to properly assess which options are to be selected. In this study, the strength of DEA-based evaluation is maximized in quantitative data while AHP - based technique is utilized for qualitative data. AHP - based pairwise comparison is used to make qualitative expert judgment into an output data for DEA - based approach. On the other hand, DEA - based approach determines the efficiencies of all options and screens out those which are inefficient.

The rest of the paper is organized as follows: Section 2 presents the problem statement while Section 3 elaborates the AHP - DEA framework. Section 4 presents a case study for illustration and lastly, Section 5 gives the conclusions and future works.

2. Problem Statement

In addressing the screening of option for CO_2 utilization, the formal problem statement was given below. This defines the system that needs to be solved by the AHP - DEA framework:

- The system consists of *n* different options for CO_2 utilization.
- Each options are evaluated based on the following criteria:
    - *Distance from* CO_2 *source* - in this criterion, each reservoir associated with these options is evaluated based on the nearest CO_2 source.
    - *Minimum Flow Rate Requirement* - the minimum flow rate to start CO_2 flooding (in Mt CO_2 / y).
    - *Injectivity Limit* - the maximum flow rate to maintain the structural integrity of the reservoir (in Mt CO_2 / y).
    - *Operating Life* - length of operation (in y) for a specific option
    - *Product Yield* - amount of product yield per CO_2 injected (Mtoe / Mt CO_2).
    - *Product Value* - price of commodity (e.g. oil, gas etc.) recovered (M$/ Mtoe).
    - *Sequestration Parameter*- amount of CO_2 stored per CO_2 injected.
    - *Reservoir Capacity* - total CO_2 that can be stored to the reservoir.
    - *Well Security* - refers to the security of CO_2 from escaping in CO_2 wells.
    - *Structural Integrity* - refers to the security of CO_2 from escaping from the geological formation. This also includes risk of CO_2 from escaping to a nearby groundwater source etc.
- For well security and structural integrity, an AHP - based pairwise comparison approach will be used to determine the weights of each option for these criteria. The method is best applied to measure expert judgement by pairwise comparison.
- The efficiency of each CO_2 utilization options will be evaluated using the Charnes - Cooper - Rhodes (CCR) model for DEA. The input criteria that will be considered are those preferred when the scores is higher (i.e. minimum pipeline distance and flow rate requirement). On the other hand, the rest are considered the output criteria.
- The qualified options for CO_2 utilization are those with efficiency equal to 1.

3. AHP - DEA Framework

The AHP - DEA framework that will be used for this study is illustrated in Figure 1. The quantitative data should be evaluated based on measuring tools and seismic survey. On the other hand, the qualitative criteria presented are evaluated based on a pairwise comparison approach to quantify the judgments made by experts. Quantifying expert judgment is done using a 9 - point scale proposed by Saaty (2003).The pairwise comparison matrix is aggregated 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 CO_2 utilization options were evaluated using CCR model used for DEA. This model calculates the Pareto efficiency of each decision making unit (DMU) based on an aggregated input and aggregated output. The objective of the CCR model is to maximize the efficiency of one option subject to having an aggregated input of 1 and all other options have efficiency equal to 1 or less. The model is solved based on the number of option to be evaluated and the efficiency is calculated. Note that more than one option can have efficiency equal to one. Therefore, in this study, options with efficiency equal to 1 will be selected for CCUS systems.

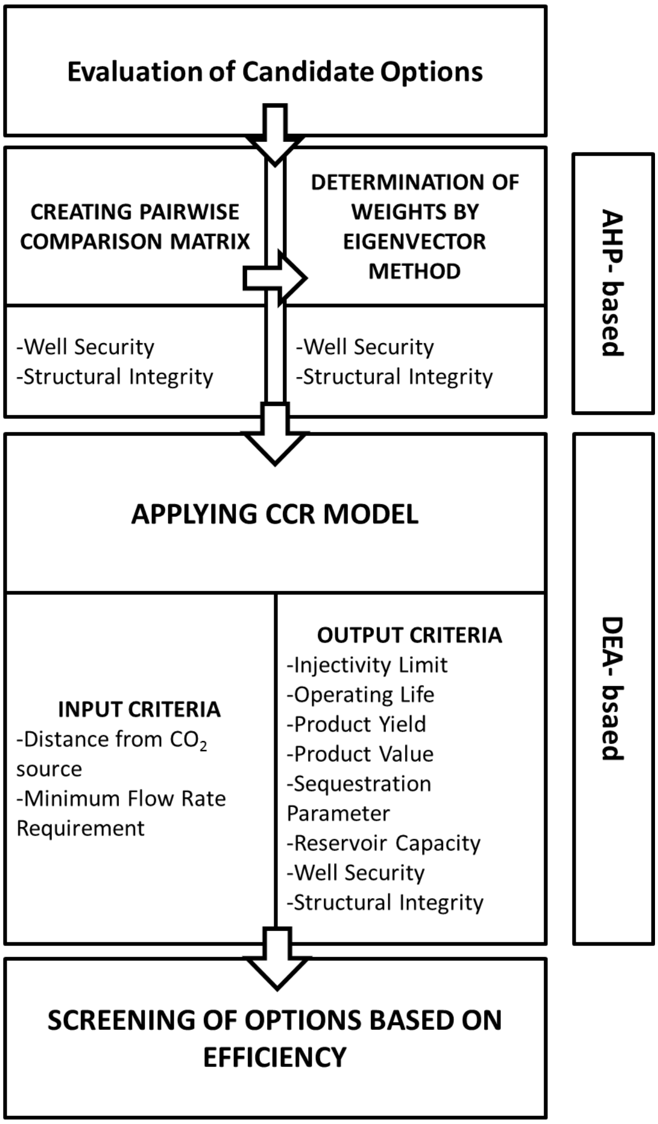

Figure 1: AHP - DEA Framework for Selection of CO_2 Utilization Options (Methodology based from Veni et al., 2012)

4. Case Study

To illustrate the methodology used, a hypothetical case study is made which consists of 9 CO_2 utilization options. These are composed of four EOR operations with depleted oil reservoir as storage medium, three ECBM operations with coal beds as storage medium and two EGR with shale reservoir as storage medium. The output data is shown in Table 1 while the input data is shown in Table 2.

The pairwise comparison matrices for both well security and structural integrity are shown in Tables 3 and 4. These were results from an expert judgment in which two options are evaluated at a time. For instance, EOR1 is 7 times better than that of EOR1 in terms of well security, thus a score of 7 is placed in the pairwise comparison matrix at row 1, column 3. The reverse is calculated by obtaining the reciprocal and placing it in row 3, column 1. This is done for both well security and structural integrity.

Table 1: Output Data for DEA Approach

DMU	Operating Life (y)	Reservoir CO_2 Capacity (Mt)	Injectivity Limit (Mt/y)	Product Yield (Mtoe/Mt CO_2)	Product Value (M$/Mtoe)	Sequestration Parameter
EOR1	25	100	10	4.5	580	0.35
EOR2	15	200	12	7.5	580	0.45
EOR3	20	150	14	8.9	580	0.67
EOR4	15	150	13	2.3	580	0.50
ECBM1	14	50	5.6	4.5	120	0.89
ECBM2	10	300	6.7	3.5	120	0.88
ECBM3	20	35	7.8	8.6	120	0.76
ShaleGas1	10	65	8.0	2.3	120	0.67
ShaleGas2	8	35	7.6	1.5	120	0.75

Table 2: Input Data for DEA Approach

DMU	Distance from CO_2 Source (km)	Flow Rate Required (Mt/y)
EOR1	150	3.4
EOR2	120	5.8
EOR3	110	3.4
EOR4	90	7.6
ECBM1	100	5.6
ECBM2	24	2.4
ECBM3	15	4.4
ShaleGas1	50	2.3
ShaleGas2	45	7.8

Table 3: Pairwise Comparison Matrix for Well Security Criteria

DMU	EOR1	EOR2	EOR3	EOR4	ECBM1	ECBM2	ECBM3	Shale Gas1	Shale Gas2
EOR1	1.000	0.333	7.000	0.111	0.143	0.167	1.000	0.111	0.333
EOR2	3.000	1.000	9.000	0.556	0.333	1.000	4.000	0.500	2.000
EOR3	0.143	0.111	1.000	0.111	0.111	0.143	0.167	0.111	0.111
EOR4	9.000	1.800	9.000	1.000	2.000	2.000	8.000	1.000	3.000
ECBM1	7.000	3.000	9.000	0.500	1.000	2.000	5.000	1.000	3.000
ECBM2	6.000	1.000	7.000	0.500	0.500	1.000	4.000	3.000	2.000
ECBM3	1.000	0.250	6.000	0.125	0.200	0.250	1.000	0.167	0.333
ShaleGas1	9.000	2.000	9.000	1.000	1.000	0.333	6.000	1.000	3.000
ShaleGas2	3.000	0.500	9.000	0.333	0.333	0.500	3.000	0.333	1.000

Table 4: Pairwise Comparison Matrix for Structural Integrity Criteria

DMU	EOR1	EOR2	EOR3	EOR4	ECBM1	ECBM2	ECBM3	Shale Gas1	Shale Gas2
EOR1	1.000	0.167	0.111	0.500	0.111	1.000	0.111	0.500	0.111
EOR2	6.000	1.000	2.000	3.000	1.000	5.000	0.333	3.000	0.333
EOR3	9.000	0.500	1.000	5.000	1.000	7.000	0.500	5.000	0.500
EOR4	2.000	0.333	0.200	1.000	0.200	2.000	0.111	1.000	0.111
ECBM1	9.000	1.000	1.000	5.000	1.000	6.000	0.333	4.500	0.500
ECBM2	1.000	0.200	0.143	0.500	0.167	1.000	0.111	7.000	0.111
ECBM3	9.000	3.000	2.000	9.000	3.000	9.000	1.000	7.000	1.000
ShaleGas1	2.000	0.333	0.200	1.000	0.222	0.143	0.143	1.000	0.111
ShaleGas2	9.000	3.000	2.000	9.000	2.000	9.000	1.000	9.000	1.000

The weights of each option for both criteria are evaluated using the eigenvector method. Table 5 shows the scores for each option in terms of both well security and structural integrity. These scores are then treated as output for the CCR model which in turn solves the efficiency of each option. Table 6 shows the solution of the CCR model. Note that each calculation for the efficiency has negligible computational time.

Table 5: Eigenvector Values for Well Security and Structural Integrity Criteria

DMU	Well Security	Structural Integrity
EOR1	0.03234	0.01948
EOR2	0.10582	0.11839
EOR3	0.01337	0.13312
EOR4	0.22269	0.03272
ECBM1	0.18811	0.12956
ECBM2	0.15877	0.03854
ECBM3	0.03381	0.25467
ShaleGas1	0.17171	0.02658
ShaleGas2	0.07339	0.24694

Table 6: Efficiency Calculations based from CCR Model

DMU	Efficiency	Efficient?
EOR1	1.000	YES
EOR2	0.872	NO
EOR3	1.000	YES
EOR4	1.000	YES
ECBM1	0.734	NO
ECBM2	1.000	YES
ECBM3	1.000	YES
ShaleGas1	1.000	YES
ShaleGas2	0.604	NO

Based from the calculations, EOR2, ECBM1 and ShaleGas2 are screened out since they have efficiencies less than one. On the other hand, options with efficiency equal to one are selected for next design stage based on the criteria given. The options with efficiency equal to one dominate the three options with efficiency less than one. For this example, an efficient CCUS system can be made using three options of EOR, two options and ECBM and one EGR operation. More detailed CCUS design can then be made from these options.

5. Conclusions

An AHP - DEA approach was developed for application in selecting CO_2 utilization options in CCUS systems. This makes use of the pairwise comparison from AHP to measure qualitative judgement such as well security and structural integrity. The basis for selecting utilizations options is the DEA efficiencies calculated from CCR model. The strength of DEA - based approach in this study is to select multiple options from the candidate alternatives without determining which criterion is better than the other. On the other hand, AHP - based pairwise comparison enables the conversion of expert qualitative judgment into DEA-usable quantitative data.
Future work includes extension of the method to address uncertainties in both expert judgment and available data. Also, the method will be extended to include CO_2 sources as one of the factors that influences the selection of CO_2 utilization and storage options,

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