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CARBON DIOXIDE AND ENHANCED OIL RECOVERY PROJECT: ECONOMIC AND RISK BASE MODEL

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ABSTRACT: *The use of CO_2 for EOR project can either be (1) capturing flue gas, separate the CO_2, store and transport it to injection point or (2) purchase a volume of the CO_2 needed for the project. This paper examined the former, for a reservoir that requires CO_2 injection for EOR. Economics and stochastic analysis were carried out to ascertain the viability of the CO_2-EOR project. The forecast variables (NPV, IRR and PI) from the economic (deterministic) model shows that the project is viable. However, the risk (stochastic) model shows that there is less than 50.725%, 52.274% and 52.274% certainty that the project will yield $631.5MM NPV, 58% IRR and 3.51 PI, with an average of 51,76% uncertainty impacted by the input parameters (CAPEX, OPEX, oil price and discount rate). The CAPEX and discount rate are the major parameters that impact high uncertainty on the project. Therefore, mitigating them will increase the chances of obtaining the values forecast variables.*

KEYWORD: economic, stochastic, uncertainty, probability distribution function, Carbon Dioxide (CO2), Enhanced Oil Recovery (EOR).

INTRODUCTION

Human activities such as burning of combustible materials, results in the release of flue gases of which carbon dioxide (CO_2) is a component. A major effect of the release of the CO_2 is the accumulation of CO_2 in the Green House Gases (GHG). The major effect of the GHG is the increase of heat in the Earth's atmosphere via reflection of radiation from the accumulated gases in the GHG. One way to curb this accumulation, is capturing of the CO_2 and store it for utilization that enhance productivity. A better way to control the release of the CO_2 is to capture the flue gas from the emission source, processed it to obtained CO_2, store and then transport it to the point of usage.

Mohammad et al (2014), stated that fuel type determines the concentration of CO_2 in the flue gases. Coal fuel contains about 12mol% to 15mol% of CO_2, natural gas fuel contains about 3mol% to 4mol% of CO_2, oil refining releases about 8mol% to 9mol% of CO_2, cement production releases about 14mol% to 33mol% of CO_2 and iron and steel production releases about 20mol% to 44mol% of CO_2.

Post-combustion capture of CO_2 was presented in this paper, and it is assumed that the piping system, through which the flue gas is piped to the CO_2 capturing plant, is an addendum to the flue gas source design. The CO_2 is separated from the flue gas through different technologies, such as adsorption, absorption, membrane separation and cryogenic distillation. However, the choice of a technology is base on economic (low operating cost) and environmental consideration.

In their paper, Mohammad et al (2014), stated that, based on the high temperature of flue gas, low pressure and concentration of CO_2, absorption and adsorption may be suitable for CO_2 separation from flue gas streams.

The captured CO_2 is safely transported to and store at the point of utilization. However, handling of produced gas, especially storage facility is a major challenge due to its inherent unstable pressure, which might result to environmental degradation via eruption of the storage facility.

According to United Nation Climate and Technology Centre and Network report, the transportation of the captured CO_2 is efficient, when it is transported as a compressed gas at pressure and temperature above 7.4 MPa, and 31˚C, and it displays supercritical properties under these conditions, as a liquid with gas characteristics. In addition, it is normally transported at high pressures in pipelines made of carbon steel, not dissimilar to normal natural gas pipelines.

Metz et. al (2005), report that, "an abandoned oil and gas fields or deep saline formations, with an expected minimum depth of 800m, where the ambient temperature and pressures are sufficiently high to keep the CO_2 in a liquid or supercritical state, is a suitable storage location for CO_2". However, preventing migration of the CO_2 form the storage is achieved through a combination of physical and geophysical trapping mechanisms.

The utilization of captured CO_2 includes: recovery of oil and gas in reservoirs considered to be depleted and un-mineable deep coal seams.

Kechut et. al (2011), stated that, enhanced oil recovery through injection of CO_2 gives about 67.5% developments for carbonate reservoir systems and about 23.5% developments amongst sandstone reservoirs, with an estimated increase of 0.1 % annually. Injection of CO_2 for EOR in depleted reservoirs increases the mobility of the oil which enables flow into the wellbore.

However, complete analysis of CO_2 capture and utilization for EOR in depleted reservoirs, involves economic and risk analysis to enable investors make informed decision on the CO_2 capture and utilization investment portfolio. This is achieve through deterministic model (estimation of managerial indicators) and stochastic model (estimation of risk and uncertainty).

Screening of Candidate Reservoirs for CO_2-EOR Utilization

Shaw and Bachu (2002), proposed depth limit for depleted reservoir criteria; reservoir depths within 2,000ft to 9,800ft are considered for enhanced oil recovery (EOR) and for CO_2 utilization. Nonetheless, the hydrodynamic and geothermal regimes in the reservoir basin, the CO_2 supercritical conditions can be attained at different depths, ranging from very shallow depths up to very deep depths. There are possibilities of the geological space transformation from the CO_2 Pressure-Temperature space for depleted reservoir screening appropriate for CO_2 utilization, for the reason that CO_2 is subcritical at the relevant reservoir conditions.

Added to screening standard for CO_2 sequestration is that the reservoir pressure at initial CO_2 flooding starts with at least 200 psia, a measure greater than the "minimum miscibility pressure (MMP)" to realise actual miscibility of reservoir oil and CO_2 (Uti, O.S and Ubani, C.E, 2017). In addition, the fraction of oil remaining before CO_2- EOR flooding, should be greater than 0.25 which is the limiting factor to ensure an economically profitable result for CO_2-EOR project.

Rivas et al (1994), employed an algorithm to study the ranking of potential wells based on the reservoir (i), and each property (j), $P_{i,j}$, an equivalent parameter normalized i.e. ($X_{i,j}$), as defined by the equation below:

$$X_{i,j} = \frac{\left|P_{i,j} - P_{o,j}\right|}{\left|P_{w,j} - P_{o,j}\right|} \qquad 1$$

where

$P_{i,j}$ represents degree of the jth property in the ith reservoir under ranking.

$P_{o,j}$ represents degree of the jth property in an idle reservoir, referred to as the optimum reservoir

$P_{W,j}$, denotes degree of the property in a different idle reservoir, regarded as the worst reservoir, whose purpose is to present the worst response to the CO_2 sequestration amongst the rank-able reservoirs.

$X_{i,j}$, varies linearly from 0 to 1.

In extreme conditions, the value becomes 0 when the degree of a property for a particular reservoir coincidentally matches the value of same property in exact proportion in the optimum reservoir, meanwhile the value becomes 1 if there is conciseness with the poorest reservoir.

The normalized linear parameters, $X_{i,j}$ were transformed to exponential non-linear parameters, $A_{i,j}$, given as:

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$$A_{i,j} = 100 \exp\left(-4.6 X_{i,j}^{\ 2}\right) \quad 2$$

The elements matrix $A_{i,j}$, instead of $X_{i,j}$ used for actual reservoir grading, since exponential functions are generally preferred to linear functions in the comparison of elements of a set.

The comparative significance of each parameter is noted by given weighting factors w_j for each property (j), so that a final score S_i for each reservoir (i), can be computed from the equation;

$$S_i = \sum_j A_{i,j} w_j \quad 3$$

Rivas et al. (1994) compiled a summary of the weighting factors for each property with their corresponding optimum and worse values as shown in the Table 1.

Table 1: Screening Criteria for Ranking CO_2-EOR Project (Rivas et al, 1994)

Parameters	Optimum	Worse	Weighted
API Gravity (^{o}API)	37	30	0.24
Temperature (^{o}F)	160	130	0.14
Permeability (mD)	3000	18	0.07
Oil Saturation (%)	60	30	0.2
Pressure (MMP)	1.3	0.089	0.19
Porosity (%)	20	9	0.02
Sand Thickness (ft)	50	5	0.11
dip (Degree)	20	5	0.03

John et. al. (2010), stated that operators interested in utilizing CO_2 for EOR, should screen their reservoir to select a candidate reservoir. The screening should be based on the characteristics of rock and fluid properties, the behaviour of production in the past and water-flooding response and detailed geological assessments. Table 2, shows the criteria for selecting candidate reservoir for CO_2-EOR project.

Tale 2: Selection Criteria for Candidate Reservoir for CO_2-EOR Project (John et. al, 2010)

Parameters	Values
Oil Gravity (^oAPI)	> 27 to 30
Temperature (^oF)	< 250, but not critical
Permeability (mD)	> 1 to 5
Depth (ft)	< 9,800 and > 2,000
Pressure (psia)	> 1,200 to 1,500
Viscosity (cp)	≤ 10 to 12
Residual Oil Saturation after waterflood (fraction of pore space)	> 0.25 to 0.30

CO_2-EOR Utilization and Economics

CO_2-EOR project involves installation of CO_2 capture and transportation systems, drilling and preparing of storages reservoirs and injectors wells, thus, making this project capital intensive.

John et al (2010), reported that "the single largest project cost is the purchase of CO_2. As such, operators strive to optimize to reduce the cost of its purchase and injection wherever possible."

Mohammad et. al. (2014) stated that, of the three stages (separation, transportation and storage) of CO_2, separation and storage gulp the highest operating cost, which was estimated in 2008. Operating cost for CO_2 separation from exhausting gases is between $25.92 to $56.15 per ton of CO_2, transportation to storage location is between $1.08 to $6.48 per ton of CO_2 per 100 km and storage is between $30.24 to $45.36 per ton of CO_2.

The economics of CO_2-EOR project depends on the price of crude oil: high price will improve the economics. However, high oil field operating cost reduces the chances of CO_2-EOR option for oil recovery in depleted reservoir.

John et al (2010) stated that "total CO_2 costs (both purchase price and recycle costs) can amount to 25 to 50 percent of the cost per barrel of oil produced."

MATERIALS AND METHODS

The economic and risk base models involve softwares that has the capability of developing deterministic model and then estimate the managerial indicators (Net Present Value (NPV), Internal Rate of Return (IRR), Present Value Ratio (PVR), Profitability Index (PI) and Payback Time) and simulate stochastic model (Risk and Uncertainty). The capability of Excel Spreadsheet was utilized to develop the cash flow for the deterministic model, whereas, ModelRisk Software was used to simulate the stochastic model.

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Economic (Deterministic) Model

The amount of crude oil recovered from EOR project via CO_2 injection, depends on several factors (MMP, mobility, amount of CO_2 injected etc). However, based on estimation from production data of crude oil via CO_2 injection, on average, 7.867 Mcfd of CO2 injected will recover 1 bbl/d of crude oil. The case study of the reservoir located within the Niger Delta, delivers crude oil to a production facility with capacity of 20,0000bbl/d, which correspond to a peak rate of 157.34 MMcfd of CO_2.

The CAPEX for the recycling plant for CO_2-EOR project was estimated from the equation of Michael (2014), defined as:

$$CAPEX(in\ 1000\$) = 1200 * Peak\ Rate(in\ MMcfd\ of\ CO2\ throughput) \quad 4$$

The compressor capital cost was estimated from $2000/hp, based on the assessment of Joblonowski and Singh (2010). Approximately, 200 hp compressor is needed to compress 1 MMcfd of gas. Thus, Combining the peak rate and the compressor horse power, gives Equation 5, which was used to estimate the capital cost for compressor installation.

$$Capital\ Cost\ (Compressor) = \left(\frac{200hp}{MMcfd}\right) * \left(\frac{\$2000}{hp}\right) * (CO_2\ Peak\ Rate\ in\ MMcfd) \quad 5$$

Therefore, the total CAPEX was $251.744MM.
The component of the OPEX include: CO_2 production (separation, transportation and storage), energy and wellhead maintenance costs. The average value of separation, transportation and storage per Mcf are $2.13, $0.196 and $1.953. The wellhead maintenance and energy costs were $13 and $358.985/Mcf.
Other data used are oil price ($70/bbl), Discount rate (15%), income tax (30%), straight line depreciation method for 5 years and the project was forecasted for 10 years.
Equations 6 to 9 were used to estimate the managerial indicators.

For NPV;

$$NPV = \sum_{t=0}^{n} \frac{(NCF)_t}{(1+r)^t} \quad 6$$

For IRR;

$$NPV = \sum_{t=0}^{n} \frac{(NCF)_t}{(1+r)^t} = 0, (where\ r = IRR\ at\ NPV = 0) \quad 7$$

For PVR;

$$PVR = \frac{NPV}{I_o} \quad 8$$

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For PI;

$$PI = 1 + \frac{NPV^N}{I_o} \quad 9$$

Risk (Stochastic) Model

Capital expenditure, operating cost, oil price and discount rate form the input variables for the stochastic model. Site preparation, procurement, transportation and installation of facility for the CO_2-EOR project constitutes the capital expenditure, which is a one-off cost, and its probability distribution function (PDF) was modelled as uniformly distributed. In addition, the operating cost is a periodic cost starting from the period production begins. However, because of instability in the price of items that forms the operating cost, its PDF was also modelled as uniformly distributed. Thus, in the stochastic model, capital expenditure and the operating cost are defined by the uniform probability distribution function. Oil price was modelled as lognormal distribution function, since crude oil price cannot drop to zero (0) and the discount rate was modelled as triangle distribution function. Net Present value, Internal Rate of Return and profitability indicator forms the forecast variables for the stochastic model (Figure 1).

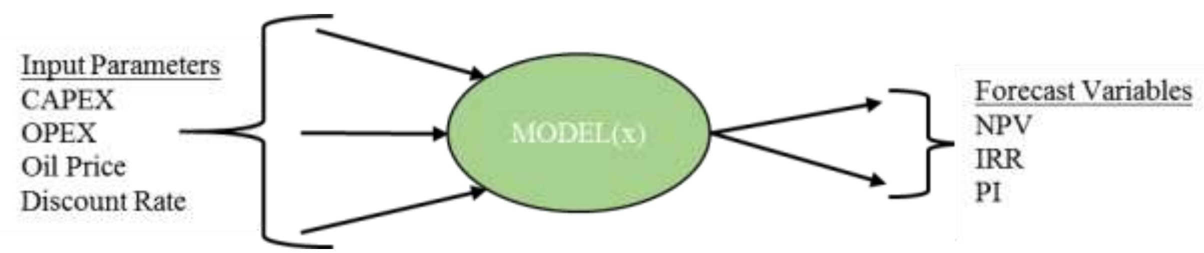

Figure 1: Input and Forecast Variables for the Stochastic Model

The stochastic model uses the Monte Carlo Simulation to estimate the probability of the response of the forecast variables to changes in the input parameters and thus, ModelRisk software was utilized to simulate the model, with 2000 simulation trials.

RESULTS AND DISCUSSION

The managerial indicators obtained from the economic model are NPV ($631.5MM), IRR (58%), PVR (2.51) and PI (3.51). The payback time for the project was 3.2 years and the maximum exposure was $251.744MM (Figure 1).

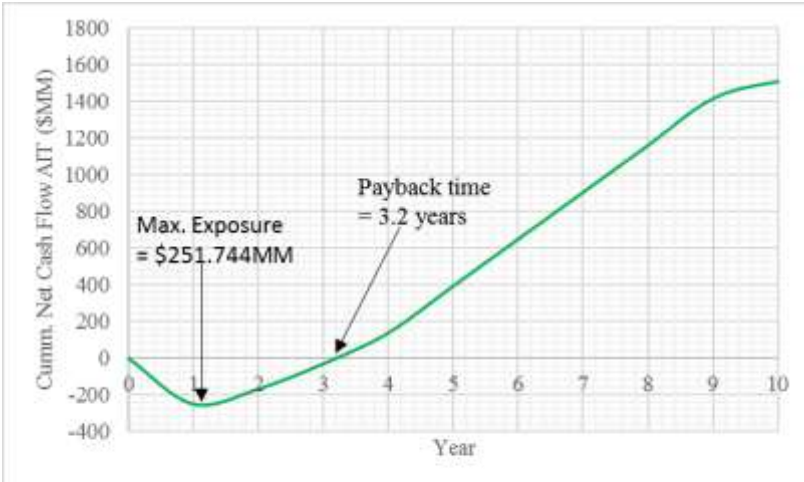

Figure 2: Plot Showing Payback time and Maximum Exposure

For a viable project, the NPV must be positive and the estimated NPV meets this criterion, indicating that for a discount factor of 15%, the present value of the project for the forecasted 10 years is $631.5MM. In addition, the IRR must be greater than the discount rate, which is also the case for the estimated IRR, indicating that the periodic rate of returns for the CO_2-EOR project is higher than the borrowing capacity of the investors.

The PVR and the PI are indication of the gain for every $1MM invested. There criteria are such that, PVR and PI must be greater than 0 and 1. Again, these criteria were met for the estimated parameters, indicating that, for every $1MM invested there is a gain of $2.52MM.

The impact of the income tax is seen in the Net Cash Flow as it dropped from $2197.72MM before Income Tax to $1538.45MM after Income Tax. Though, the estimated indicators showed that, with investment in CO_2 capturing, separation and recycling plant for CO_2-EOR project (rather than buying CO_2), is still viable, but they are deterministic (single value) which does not reveal the risk and uncertainty inherent in the project.

Oil and gas project including CO_2-EOR is bedevilled with risk and uncertainty and this is the reason for the stochastic model. The input parameters were assigned to its PDF in the ModelRisk simulation environment. Figures 3 to 5, shows the probability of certainty of the forecast variables.

The stochastic analysis shows that the CO_2-EOR project for the case study is less than 50.725% certain that it will generate $631.5MM NPV (Figure 3), indicating that the input (uncertainty) parameters impact 49.275% uncertainty on the project, which must be identify to reduce the risk associated with the project.

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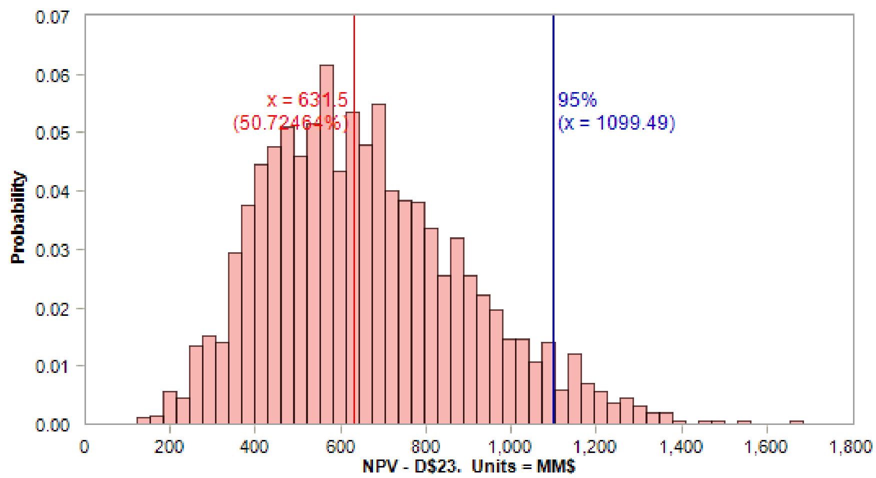

Figure 3: Stochastic Probability Plot for NPV

The probability that the IRR will be 58% was obtained from the deterministic model. However, for this project, there is less than 52.274% certainty that the IRR will be 58% (Figure 4), which exceed the investment discount rate of 15% for the project to be viable for investment. In other word, IRR between 58% and 15% (15%≤ IRR≤ 58%) is acceptable for the project, indicating that for IRR less than or equal to 15%, the project should be rejected.

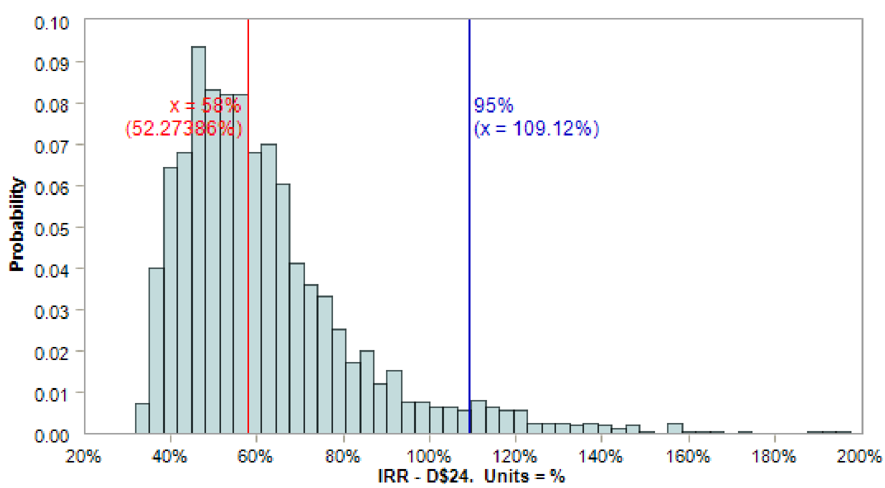

Figure 4: Stochastic Probability Plot for IRR

In addition, based on the stochastic analysis in the risk model, there is 0.05% certainty that the rate of return on investment for the CO_2-EOR project will be equal to or exceed the 15% discount rate at which the project will be funded. If the investors are not risk averse, then this should be considered as the lowest possibility of obtaining a reasonable IRR for the project to be accepted. Therefore, resources should be utilized to improve the likelihood

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of obtaining higher IRR by identifying uncertainty in the project. However, the 58% IRR for the project is significantly higher than the 15% discount rate, but the likelihood of obtaining it is affected by 47.726% uncertainty, impacted by the input parameters.
The PI which measures the returns per dollar invested, has 52.274% certainty that the project will yield a total of $3.509MM per $1MM dollar invested (Figure 5), indicating that the capital investment may have more impact on the 47.726% uncertainty of the total returns.

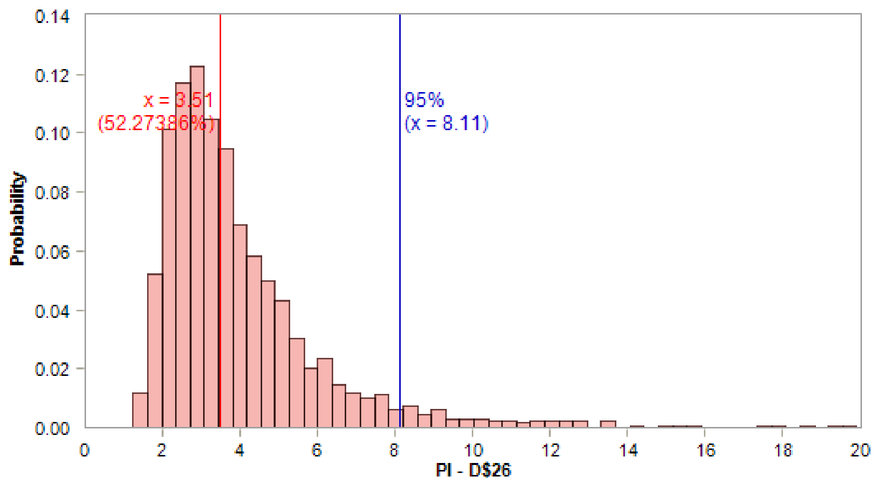

Figure 5: Stochastic Probability Plot for PI

However, identifying the uncertainty parameters that impact more on the project and mitigating their risk will increase the likelihood of obtaining the forecast variables.

Sensitivity analysis was done to identify the uncertainty parameters and the response of the forecast variables to changes in these parameters. Any one of the forecast variables can be used to decide which uncertainty parameters impact more on the project. This implies that each forecast variable may have different uncertainty parameters that have more impact on the project. Therefore, to completely capture all uncertainty for the CO_2-EOR project, all three forecast variables should be considered.

Tables 3 and 4 shows the input parameters and the forecast variables from the 2000 trials of Monte Carlo simulation. The simulation was done over a wide range, between the minimum and maximum values of the input parameters. The means are the expected values of the CAPEX, OPEX, oil price and discount rate, which are a little higher than the initial values for the deterministic model. Their residual values must be put into consideration when implementing the project, to take care of escalation of cost of procurement and installation of equipment, consumables, regular expense and drop in oil price.

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Table 3: Simulation Range for the Uncertainty Parameters

Parameters	Minimum	Mean	Maximum
CAPEX ($MM)	56.364	269.502	495.843
OPEX ($MM)	28.480	292.517	497.530
Discount Rate (%)	2.4	15.56	29.61
Oil Price ($/bbl)	63.812	70.017	77.957

The sensitive response of the forecast variables, ranges from a minimum to a maximum with their mean values (Table 4). The sensitivity analysis shows that the CAPEX and discount rate have more impact on the NPV, IRR and PI, in their order of sensitive response (Figures 7, 8 and 9), while OPEX has less impact and can be ignore, since their contribution to uncertainty is minimal. The impact of the oil price is positive, such that high price improves the economics of the project.

Table 4: Simulation Output for the Forecast Variables

Parameters	Minimum	Mean	Maximum	P50
NPV ($MM)	122.059	658.325	1653.94	628.116
IRR (%)	31.735	62.171	194.337	56.948
PI ($MM/$MM)	1.246	3.991	19.568	3.40

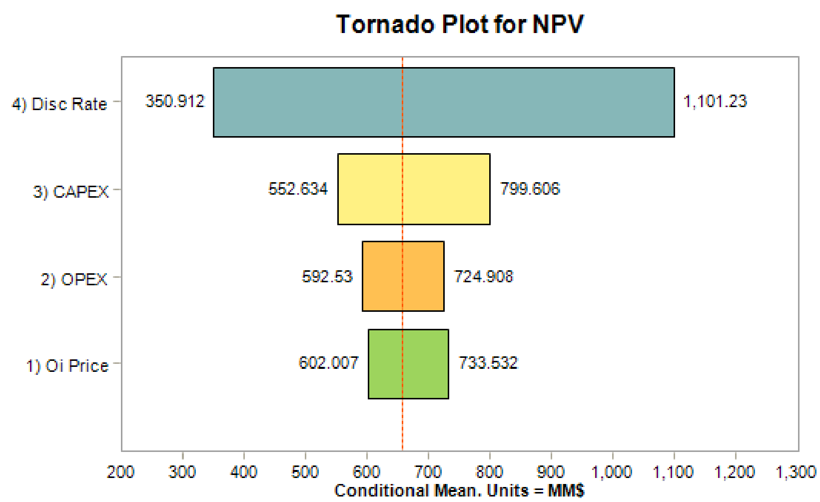

Figure 7: Tornado Sensitivity Plot for NPV

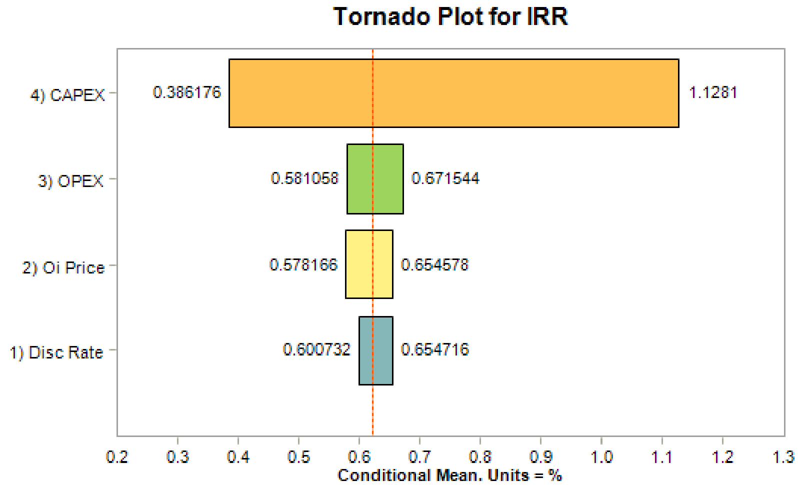

Figure 8: Tornado Sensitivity Plot for IRR

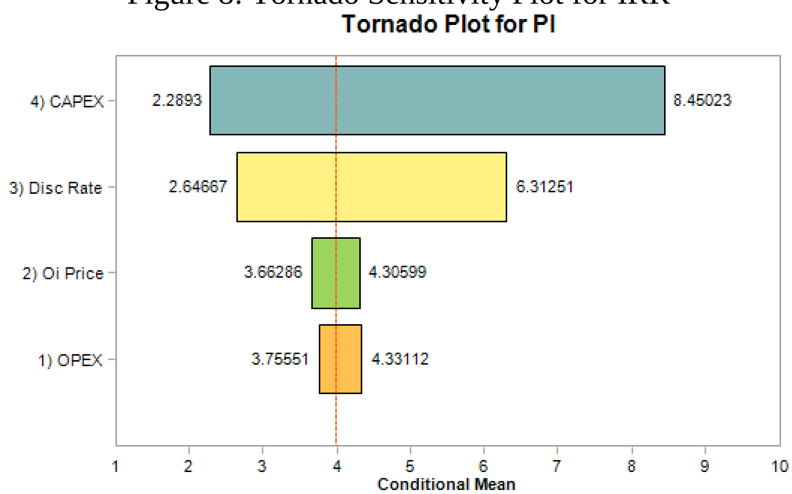

Figure 9: Tornado Sensitivity Plot for PI

The uncertainty in the CAPEX is the escalation of cost of procurement and installation of equipment, which may be caused by inflation within the period of project execution and completion. Therefore, delay in project completion will impact negatively on the project. In addition to the uncertainty of capital costs of a CO_2-EOR project, the CO_2 injection volume must be determined in advance of the onset of incremental production, otherwise the return on investment for project will tends to be low, with a gradual, long-term payback time.

Discount rate in project funding depends in the type of project and the financial institution. However, the risk in the discount rate is the uncertainty in instability of the money market and exchange rate, and inflation may also contribute to the uncertainty of the discount rate, which will escalate the capital cost for the project. In addition, the best estimate of the NPV, IRR and PI sensitivity (P50) are $628.116MM, 56.94% and 3.40, indicating that there is at least 50% probability that the values of the forecast variables generated will equal or exceed the best estimate.

CONCLUSION

CO_2 capturing and utilization in EOR project for depleted reservoir is important in recovery residual oil from the reservoir, but quantifying the parameters that drives the viability of the project is necessary for investor to make informed decision. Previous studies show that CO_2 can enhanced recovery of crude oil from depleted reservoir, especially with accurate determination of Minimum Miscibility Pressure (MMP) and good mobility. However, an economic and risk base analysis, identify the uncertainty that bedevilled the CO_2-EOR project. Though the economic model shows that the project is viable for investment, but with varying degree of uncertainty. The forecast variables (NPV, IRR and PI) are 50.725%, 52.274% and 52.274% certain that the project will yield $631.5MM NPV, 58% IRR and 3.51 PI, with 51,76% uncertainty impacted by the input parameters (CAPEX, OPEX, oil price and discount rate). The CAPEX and discount rate were identified as major contributor to uncertainty to the project. This is in agreement with John et al (2010) report, that the total CO_2 costs can amount to 25% to 50% of the cost per barrel of oil produced. Mitigating the uncertainty in these parameters, will increase the likelihood of obtaining the expected values of the forecast variables.

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