Universal Journal of Petroleum Sciences 4 (2016), 40-48
www.papersciences.com

A Study on Economic Assessment of Simultaneous Use of Depleted Oil Reservoirs for Underground Natural Gas Storage and Enhanced Oil Recovery in the Niger Delta

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Abstract
The economic viability of simultaneous gas injection for underground natural gas storage and enhanced oil recovery was examined with depleted reservoir IZ-2 located South Eastern Nigeria. The geologic and engineering information on the reservoir were gathered with which the costs analyses were conducted. The storage capacity and costs of the depleted reservoir were used in conducting the profitability analyses through the expected revenue. The reservoir is suitable for underground gas storage and enhanced oil recovery with its working gas capacity and deliverability of 2.18Tcf and 46.42MMscf/d respectively. The reservoir has a positive and high net present value (NPV) of $1.96billion at 10% discount rate. The pay-out period of 0.106 year and profit per dollar invested (P/$) of 114.4 for the project indicated that it is economically viable.

Key Words and Phrases
Economics, Storage, Costs, Revenue, Profitability, Analysis, Investment, Costs, NPV, Payout, IRR, Depleted Reservoir.

1. Introduction

Natural gas is a colourless, odourless gaseous hydrocarbon. Natural gas, like most other commodities, can be stored for an indefinite period of time [1].

The exploration, production, and transportation of natural gas takes time, and the natural gas that reaches its destination is not always needed right away, so it is injected into underground storage facilities. These storage facilities can be located near market centers that do not have a ready supply of locally produced natural gas. Underground storage is generally much more cost effective than aboveground storage for larger product capacities, both in investment costs and operating costs.

Evaluating the economic viability of underground gas storage in aquifers is to determine the profitability of injecting gas into aquifers for storage purposes. Since the dream of any investor is to make profit, the target objective becomes injecting and withdrawing a considerable amount of natural gas to combat or stop flaring at the lowest possible overall costs. The gas produced and injected into the storage aquifer if continued to be flared would pose a very big loss of income, both the sales value of the gas and the flare penalty.

It involves the estimation of storage costs and the revenue realizable from the project at present and overtime. A number of operations are involved in the conversion of an aquifer to an underground gas storage system. These operations include the development of the storage facility and installation of the gas gathering systems. Developing the storage facility involves drilling and completing wells to be used for storage, observation and structural control.

The costs of carrying out these operations and many other are termed the initial investment costs and the annual storage costs are the costs of operating and maintaining the facility per year.

The revenue is the amount of money gotten from selling the working gas each year. The economic viability of underground gas storage in aquifers is analyzed by comparing and relating the costs and the revenue realizable from the project.

In the effort to understand the fundamentals of natural gas storage, and the underlying motivations of the owners, it is often asked how much does the project cost and what is the profit [2].

Natural gas storage unit cost for various storage systems are [3]:
- UGS in depleted fields: 0.70 – 1.75 dollars per m^3.
- Gas storage in water layers: 1.88 dollars per m^3.
- Gas storage in salt cavern (formation): 5.00 dollars per m^3.
- LNG storage: 4.60 dollars per m^3.
- Gas storage in propane: 1130 dollars per m^3.
- Natural gas storage in pipeline at 1600 psia: 1700 dollars per m^3.

2. Procedure

2.1 Costs Analysis: The economic flow chart for underground gas storage in depleted oil reservoir consists of the various costs at different stages: acquisition cost, development cost, cost of gathering facilities and cost of cushion gas, which are summed up to get the total cost of investment as shown in Fig 2.1 below:

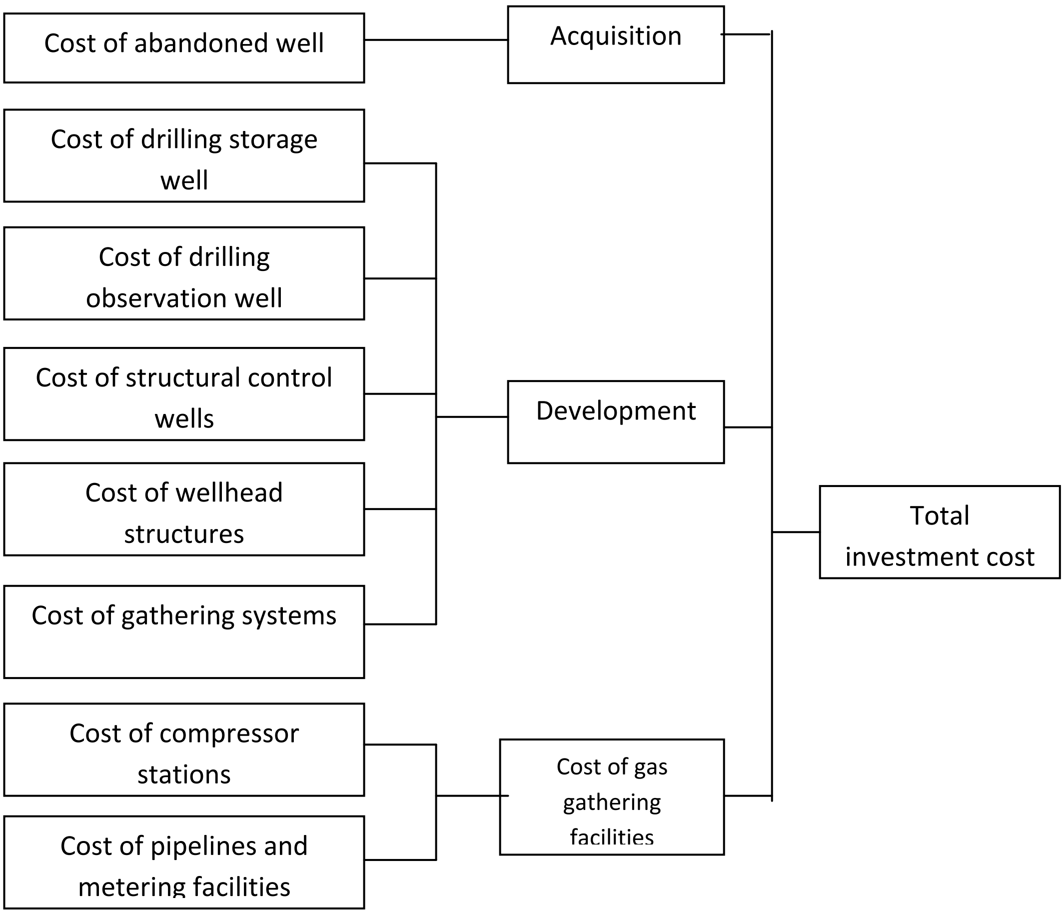

Fig. 2.1 Economic flow chart for natural gas storage in depleted reservoir.

As with all infrastructural investments in the energy sector, developing storage facilities is capital intensive. Investors usually use the return on investment as a financial measure for the viability of such projects. It has been estimated that investors require a rate of return between 12 percent to 15 percent for regulated projects, and close to 20 percent for unregulated projects. The higher expected return from unregulated projects is due to the higher perceived market risk. In addition significant expenses are accumulated during the planning and location of potential storage sites to determine its suitability, which further increases the risk [4].

The capital expenditure to build the facility mostly depends on the physical characteristics of the reservoir. First of all, the development cost of a storage facility largely depends on the type of the storage field. As a general rule of thumb, salt caverns are the most expensive to develop on a billion cubic feet (Bcf) of working gas capacity basis. However one should keep in mind that because the gas in such facilities can be cycled repeatedly, on a deliverability basis, they may be less costly. The wide price range is because of some region difference which dictates the geological requirements.

According to Anyadiegwu et al [4], these factors include the amount of comprehensive horsepower required, the type of surface and the quality of the geologic structure to name a few. A depleted reservoir costs between 800 million naira ($5million) to 1.12 billion naira ($7million) per Bcf of working gas capacity.

Finally, another major cost incurred when building new storage facilities is that of base gas. The amount of base gas in a reservoir could be as high as 50% for depleted reservoirs making them unattractive to develop when gas prices are high. The expected cash flows from such projects depend on a number of factors. These include the services the facility provides as well as the regulatory regime under which it operates. Facilities that operate primarily to take advantage of commodity arbitrage opportunities are expected to have different cash flow benefits than the ones primarily used to ensure seasonal supply reliability. Rules set by regulators can on one hand restrict the profit made by storage facility owners and on the other hand guarantee profit depending on the market model.

Several items contribute to the total investment necessary to put an underground storage field into operation, [5]. They include:

i. Cost of acquisition of the old well and/or reservoir, Acquisition cost involves the: cost of acquiring the abandoned well, cost of purchase of the remaining recoverable gas or oil in the formation, cost of acquiring the right to use the formation for storage.

ii. Cost of development of the storage facility, consisting of: cost of drilling storage wells, cost of drilling observation wells, cost of structural control wells, cost of wellhead structures, cost of gathering system.

iii. Cost of gas gathering system.

iv. Cost of base or cushion gas.

The total investment cost is given by the equation below:

Total investment cost = Acquisition cost + Development cost + Gas gathering cost (2.1)

It is represented mathematically as:

$$I = A + D + G \tag{2.2}$$

Assume oil and gas prices at average rates of $58/bbl and $2.87/Mscf respectively.

2.1.1 Acquisition cost, (A): Acquisition cost is the cost of acquiring the abandoned oil/gas well from the oil/gas producing company. It is always negotiable between the gas storage system operator and the oil producing company that produced oil from the well. The agreement is always on a lease arrangement. Acquisition cost is the sum of the cost of abandoned well and cost of the remaining gas in formation.

2.1.1.1 Cost of acquiring abandoned well, (C_{Wa}): This equals salvage value of 20% of initial well cost.

Initial cost of well = Drilling cost ($/ft) * Depth (2.3)

Salvage value of remaining oil well = 20% of Initial cost of well (2.4)

2.1.2 Development cost, (D): The development cost is the cost of drilling new wells and related activities like installation of wellhead structures required for the reconditioning of the depleted reservoir for underground storage facility. Six new wells are to be drilled in the course of developing the storage facility. One storage well would be needed: for injection withdrawal.

Five observation wells are also necessary, observation wells permit the measurements to verify that injected gas is confined to the designated area and has not migrated away. They control gas bubble evolution from the storage wells and observe leakage if gas leaks from the storage reservoir. The development cost covers: i. Drilling cost, (C_D), ii. Cost of installing wellhead structures, C_{ws}, and iii. Cost of installing gathering systems, C_{gs}. It is mathematically expressed as:

For developing one well, $D = C_D + C_{ws} + C_{gs}$ (2.5)

2.1.3 Cost of Gas Gathering System: Gathering systems are defined as the flowline network and process facilities that transport and control the flow of oil or gas from wells to a main storage facility, processing plant or shipping point.

A gathering system includes some or all of these put together: pumps, headers, separators, emulsion treaters, tanks, meters and regulators, compressors, dehydrators, valves, pipelines and other associated equipment [6].

The cost of gas gathering system in this text is the sum of the costs of compressor stations, pipelines and metering stations. It is represented mathematically as:

$C_{ggs} = C_{comp} + C_{pipeline} + C_{meter}$ (2.6)

2.1.3.1 Compressor Station: A reciprocating compressor of 200 - 1000billion hp whose daily input and output is 50 MMscf/day is chosen.

2.1.3.2 Pipelines and Metering Stations: Pipeline diameters of 12’, 14’ and 18’ and length of about 40 miles are commonly used, and 4 metering stations are installed [7].

2.2 Financial Analysis: Based on the Energy Information Administration (EIA) standards, 1031Btu of average heat content is equivalent to 1 ft^3
Average gas price = \$2.87/MMBtu
Crude oil price = \$58/bbl

1031Btu = 1scf (2.7)
Annual Operating cost = Labour costs + Maintenance costs + Management costs (2.8)
Gross Revenue = \$2.87 * Deliverability * (365/2)days/1000scf + \$58 * Marginal Oil production, stb (2.9)
Where Marginal Oil Production = N_p with Gas Storage – N_p without Gas Storage (2.10)
Net revenue for subsequent years of operation =
= Gross revenue – Annual Storage cost (2.11)

3. Results

The reservoir storage data for the depleted reservoir is as shown in Table 3.1.

Table 3.1 Storage reservoir data for Reservoir IZ-2

Pressure at Initiation of Storage, P	2260 psia
Reservoir temperature, T	140^oF
Stock tank oil in place, N	224 MMstb
Cumulative oil produced at 2260psia, N_p	48.74 MMstb
Initial oil formation volume factor, B_{oi}	1.4343
Specific gravity, SG	0.855
Porosity, Ø	0.25
Initial oil water saturation	20 %
Oil API gravity	34^0 API
Solution-gas specific gravity	0.865
Total Storage Capacity	4.35 Tcf

Working Gas Capacity	2.18 Tcf
Deliverability at Initiation of Storage	46.42 MMscf/d

The production data for the reservoir without gas storage and with gas storage are as shown in Table 3.2.

Table 3.2 Production Data for the Reservoir with and without Gas Storage

Time, year	**N_p without Gas Storage, stb**	**N_p with Gas Storage, stb**	**Marginal Oil Production, stb**
3 (Initiation of Storage)	48700000	48700000	-
4 (Ist year of Storage)	53747926	57989844	4241918
5 (2nd year of Storage)	54776866	63394487	8617621
6 (3rd year of Storage)	55365503	65445359	10079856
7 (4th year of Storage)	55581849	66686901	11105052
8 (5th year of Storage)	55581849	67560359	11978510

3.1 Storage Economics

3.1.1 Investment Costs

3.1.1.1 Acquisition cost: The present cost of drilling a well is $150/ft [8].
From eqn 2.3, Initial cost of well = $150/ft * 11 000ft = $1.65 million
From eqn 2.4, Salvage value of remaining oil well =
20% of $1.65 million = $330 000
Therefore, C_{Wa} = $330 000
Therefore, Total acquisition cost, A = $330 000

3.1.1.2 Development cost: - The cost of drilling and completing a well is $150 per foot [8].

- C_D = $150/ft * 11 000ft (Total Depth of well) = $1.65 million
- Installation of wellhead structures, C_{ws} = $10 000
- Installation of gathering systems, C_{gs} = $50 000

From eqn 2.5, Total cost of one well = $1.65 million + $10 000 +
$50 000 = $1.71 million
Therefore, Development Cost, D, for the six wells = $1.71 * 6 = $10.26 million

3.1.1.3 Cost of gas gathering system

3.1.1.3.1 Compressor station: The cost of installation of compression station is $3.2 million [8].
For two compression stations before the pipelines and before the storage facility, total cost of compression station = $6.4 million. Then including another compressor station for longer pipelines, total cost of compressor station would be $9.6 million.

3.1.3.2 Pipeline and metering stations: The installation and execution of associated civil works is at a cost of $10.4 million [7].
Total cost of gas gathering system is given as: cost of compressor stations + costs of pipelines and metering stations, which is equal to $20 million
Total investment cost = acquisition cost + development cost + cost of gas gathering system + cost of cushion gas =
$330000 + $10.26 million + $20 million = $30.59 million

3.1.2 Annual Operating Cost

- Labour costs: take the number of employees to be 100 and an average of $4 000 per month per employee. For the 100 of them, labour costs per month would be equal to 100 * $4 000 = $400 000

  Then labour costs annually = $400 000 * 12 = $4.8 million
- Maintenance costs: these include spare parts consumption in amount of $2.13 million per year; fixed assets repair in amount of $852 000/year; operating outsourced services in amount of $4.26 million/year.

  Total maintenance costs per year = $2.13 million + $852 000 + $4.26 million = $7.24 million.
- Management costs = $804 000

From (2.8), Annual Operating cost = $4.8 million + $7.24 million + $804 000 = $12.8 million

3.1.3 Profitability Analysis: The cash flows for the reservoir for 5 years is shown in Table 3.3 and in evaluating the gross revenue, a price rate of $2.87/Mscf is used.
Hence, from (2.9), the gross revenue for 46.42MMscf/d withdrawal rate of gas and marginal cumulative oil production of 4.24MMstb at the first year becomes:
Gross Revenue = $2.87 * 46.42MMscf/d * (365/2)days/1000scf + $58 * 4241918 stb
Gross revenue = $270.3 million
Net revenue, N_R, at the first year of operation is estimated from equation 2.11 as:
= $270.3 million - $12.8 million = $257.5 million

Table 3.3 Summary of the cash flows for reservoir IZ-2

Time (yr)	CAPEX ($MM)	OPEX ($MM)	GROSS REV ($MM)	NCR ($MM)	CUM NCR ($MM)	PV @ 5% ($MM)	PV @ 10% ($MM)
0	30.59	0	0	(30.59)	(30.59)	(30.59)	(30.59)
1	0	12.8	270.3	257.5449	226.95	245.28	234.13
2	0	12.8	524.1	511.3357	992.08	463.80	422.59
3	0	12.8	608.9	596.1453	1757.85	514.97	447.89
4	0	12.8	668.4	655.6067	2591.84	539.37	447.79
5	0	12.8	719.1	706.2672	3500.75	553.38	438.54

3.1.4 Calculation of Net Present Value: Net Present Value, NPV is a measure of profitability of any project. The net present value (NPV) or net present worth (NPW) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows.NPV compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account. If the NPV of a prospective project is positive, it should be accepted. However, if NPV is negative, the project should be rejected because cash flows will also be negative [9]:

$$NPV = PV \text{ at } 1yr + PV \text{ at } 2yrs + PV \text{ at } 3yrs + PV \text{ at } 4yrs + PV \text{ at } 5yrs - PV \text{ at } 0yr \quad (3.1)$$

From Table 3.3, the Net Present Value, NPV at an expected rate of return/discount rate of 10% which is the sum of all the Present Values in that column = $1.96Billion

3.1.5 Pay-out, PO: The pay-out for a project refers to the time (years) at which the initial investment on the project is just recovered. It is the time at which cumulative NCR becomes zero.
Table 3.4 shows the cumulative NCR and NCR after 5 years while Fig 3.1 represents the graph of time against cumulative NCR in billions of dollars for the gas storage project.

Table 3.4 Cumulative NCR after 5 years

Time (yr)	NCR ($MM)	CUM NCR ($MM)
0	(30.59)	(30.59)
1	257.5449	226.9549
2	511.3357	992.0813
3	596.1453	1757.846
4	655.6067	2591.837
5	706.2672	3500.746

From Table 3.4, cumulative NCR becomes zero between the 0^{th} and 1^{st} year. In this project work, 0 and 1 year were used as the initial point (IP) and final point, (FP) respectively.

Applying interpolation:
(PO – IP) / (FP – IP) = (0 – CUM NCR at IP) / (CUM NCR at FP – CUM NCR at IP) (3.2) (PO – 0yr) / (1yrs – 0yr) = (0 – (- 30.59)) / (226.95 – (- 30.59))
PO = 0.106yr which is also shown in Fig 3.1 below.

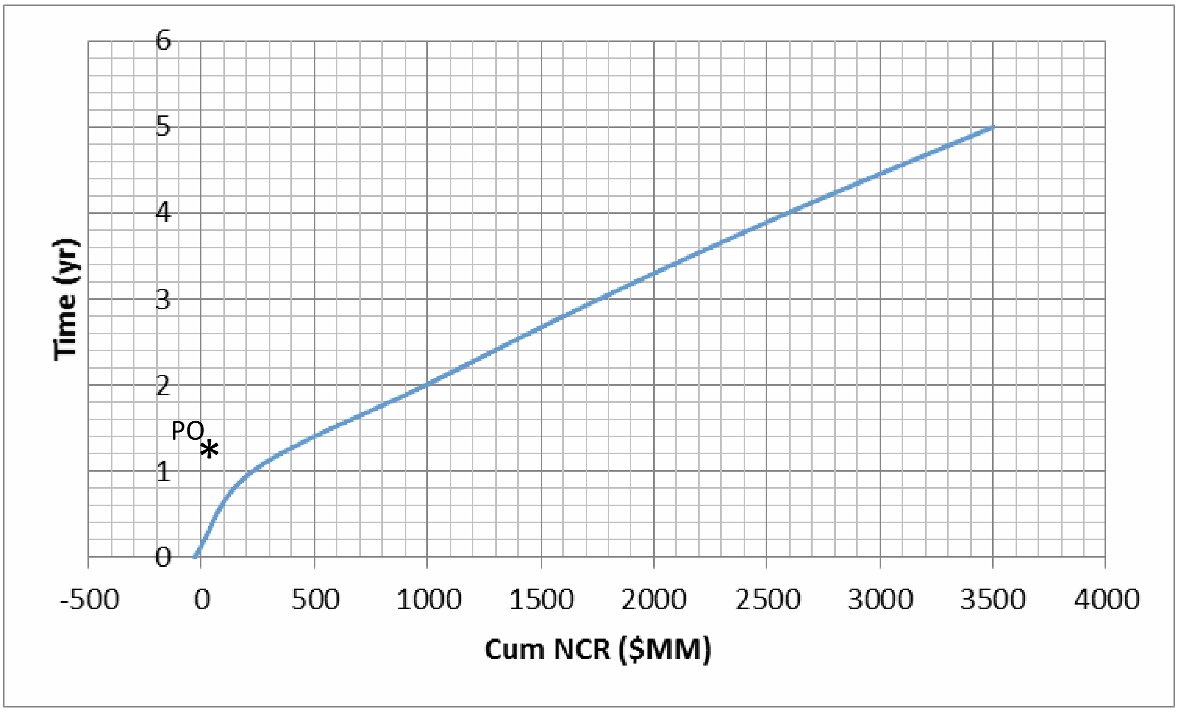

Fig 3.1 Plot of Time in Years against Cum-NCR in Millions of Dollars, Reservoir IZ-2

3.1.6 Profit per Dollar Invested on the Gas Storage Project: The profit per dollar of a project refers to the amount of profit generated by the project per unit expenditure on the project. It is an economic indicator used to predict or evaluate how economically viable the project is. A high profit per dollar (P/$) value means that the project is highly economically viable and vice versa. P/$ of a project is estimated as a function of the total net cash recovery over a period of time and the CAPEX. In this section, the P/$ after 5years is the ratio of the cumulative net cash recovery after the 5^{th} year and the CAPEX. The cumulative net cash recovery of the gas storage project after the 5^{th} year is $3500.746MM and the CAPEX is $30.59MM, so the P/$ is estimated as follows:

P/$ on the gas storage project = $3500.746MM / $30.59MM = 114.4

Table 3.5 Result of Storage Economics for IZ-2

Total Storage Capacity	4.35 Tcf
Working gas capacity	2.18 Tcf
Acquisition cost	$330000
Development cost	$10.26 million
Cost of gathering facilities	$20 million
Annual operating cost	$12.8 million
Total investment cost	$30.59 million
Gross Revenue at 1st Year	$ 270.3 million
Net Revenue at 1st Year	$ 257.5 million
Pay-out	0.106 year
Break-even point	$30.59 million
NPV @ 10% after 5 years	$1.96 billion
NPV @ 5% after 5 years	$2.286 billion
Profit per dollar invested	114.4

4. Conclusions

The result of the economic analysis in this work has shown that reservoir IZ-2 is suitable for conversion to underground storage purpose. From the economic indicators considered, the following conclusions are made:

1. The total storage capacity of reservoir IZ-2 is 4.35Tcf while the working gas capacity is 2.18Tcf.
2. The cushion or base gas required for the pressure maintenance and the working gas are got from the gas produced from the reservoir which is then not to be flared but re-injected into the reservoir for storage.
3. A potential investor in gas storage business can check the profitability of any depleted reservoir using the analyses performed in this work.
4. The Net Present Values at expected rate of return of 5% and 10% are $2.286 billion and $1.96 billion respectively which shows that the gas storage project is economically viable since they are positive.
5. The project has a very early pay-out of 0.106year which is not even up to a year of the gas storage operation.
6. The gas storage project has a very high profit per dollar invested of 114.4 which further indicates that the project is economically viable.

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NOMENCLATURE

A = Acquisition cost
B_o = Oil formation volume factor
B_g = Gas formation volume factor
B_{gi} = Initial Gas formation volume factor
B_w = Water formation volume factor
Bscf = Billion standard cubic foot
Bcf = Billion cubic foot
Btu = British thermal unit
C_{wa} = Cost of acquiring abandoned well
C_{grem} = Cost of purchasing remaining gas in formation
C_D = Drilling cost
C_{ws} = Cost of installing wellhead structures
C_{gs} = Cost of gas gathering system
C_{comp} = Cost of Compressor stations
$C_{pipeline}$ = Cost of pipelines
C_{meter} = Cost of metering facilities
Cum NCR = Cumulative Net Cash recovery
D = Development cost
EIA = Energy Information Administration
EXP = Expenses
FP = Final point
Ft^3 = Cubic foot
I = Initial Investment cost
INV = Investment
IP = Initial Point
IRR = Internal Rate of Return
MMBtu = Million British Thermal Unit
MMscf = Million standard cubic foot
N = Annual storage cost
N = Initial Oil in place
N_p = Cumulative Oil Production
NPV = Net Present Value
NPW = Net Present Worth
NCR = Net cash recovery
PO = Pay-out
PV = Present value
REV = Revenue