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Applications of Carbon Capture and Storage in Enhanced Oil Recovery in UAE

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Abstract*— This paper aims to investigate the primary design and feasibility of the potential employment of Carbon Capture and Storage (CCS) with1 Enhanced Oil Recovery (EOR) in Zakum oilfield in the UAE. The capture system was identified to be compatible with the operating conditions of different power plants in UAE. Also the amount of CO_2 that can be captured from the major large power plants in close proximity of the field was estimated. The selected case study was modeled by COZ View software and wide range of numerical simulations was carried out to predict the oil production resulted from employing the proposed CO_2-EOR system. Economic assessment of employing CCS was also assessed by means of generating the relevant cash profiles. The obtained results showed viability of integrating CCS with CO_2-EOR in Zakum field for relatively small capacity power plant (i.e. Umm Al-Nar East) and moderate capacity one (i.e. Umm Al-Nar West) with payback periods of 3.7 and 4.6 years, respectively.

Index Terms— **Carbon Capture Storage (CCS), Enhanced Oil Recovery (EOR), COZ View Simulation.**

I. INTRODUCTION

In the recent years the rise in CO_2 emissions and other greenhouse gases, has led to increased global warming effects in the climatic conditions of the planet [1]. Fossil Fuels are the main source of fuelling the primary energy demands of the world, with around 80% of the world's energy supply being through fossil fuels. Fossil fuels will continue to be the dominant source of energy for the coming decades [2], [3]. With the continuation of the current trend of global energy related CO_2 emissions, it would result to a trajectory of emissions leading to a temperature rise of 6℃ in the long term [4]. From the total greenhouse gas emissions, 57% of it is carbon dioxide which is emitted by fossil fuel use [5]. By sector, the electricity and heat sector is the largest point source of CO_2 emissions in the world at 41%.Followed by transport sector at 22%, industry at 20% residential at 6% and others at 10% [6].

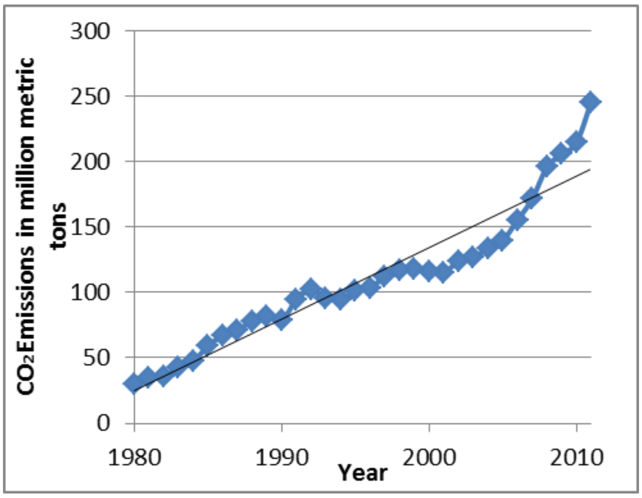

Fig.1. CO_2 emissions due to fossil fuel consumption vs. Years

The UAE has also seen a significant rise of CO_2 emissions over the years especially due to fossil fuel consumption which can be demonstrated by Fig.1.There are many options to curb these increasing levels of emissions; some of

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the most prominent are increasing the energy efficiency which leads to reductions in fossil fuel uses. On the other hand moving towards less carbon intensive fossil fuels and increasing usage of renewable energy sources is the trend today. But these methods alone would not be enough to curb emissions to a required value and hence Carbon Capture Storage (CCS) would be the most promising Carbon mitigation option for the long term. Combining CCS with EOR would result in the deploying of a possible economically viable carbon mitigation option. This would also lead to an increase in natural gas production in the UAE since it would no longer have to be used for Oil recovery. One study of CO_2 emissions [7] estimates 230,640 MMBO of CO_2 EOR Oil recoverable in the Middle East and North Africa region from the chosen 11 basins.

CCS consists of three major components which are capture (i.e. sequestration and compression), transport and storage. The three main technologies involved with CO_2 capture are Post-Combustion Capture, Pre-Combustion Capture, Oxy-fuel Combustion Capture. Post Combustion Capture employs capturing CO_2 from the flue gases generated after combustion right before they can be vented to the atmosphere. The capture process is attributed to chemical absorption using chemical solvents such as amines. This technology requires powerful solvents and large processing equipment for the process, which makes it costly to setup and energy intensive since it requires energy from the plant for regeneration of the solvent, also lowering the efficiency. But on the other hand this technology provides high capture efficiency and has a comparatively easier retrofit potential to existing power plants compared to the others [8], [9].Pre-Combustion Capture works by capturing CO_2 from the gas stream before combustion. The concentration of CO_2 being higher helps the capture process and this requires less selective solvents and works on physical solvent like Selexol. This process requires drastic changes to the power station in comparison to post-combustion capture. This process has a much lower energy requirement compared to post-combustion capture and also CO_2 is in a higher concentration. But pre-combustion capture also has an efficiency penalty due to the shift reaction and also the efficiency of hydrogen burning gas turbines is lower compared to the natural gas turbines. In the Oxy-fuel process the combustion takes place with the fuel and pure oxygen that is produced by an air separation unit. The combustion with oxygen leads to very high temperatures for today's plants and hence some flue gas must be recycled to lower the temperature to a moderate value. The flue gas contains mostly CO_2 and H_2O.The water can easily be condensed and the CO_2 can be sent for compression and storage [1]. The performance and cost of Capture technologies in Gas-fired Plants and Coal-fired Plants was estimated by the International Energy Agency [10]. It was found that the thermal efficiency for a gas fired Plant with no capture was 55.6%, compared with Post-combustion capture having 47.4%, Pre-combustion capture 41.5% and Oxy-combustion capture 44.7%.On the other hand in a Coal-fired Plant with no capture the thermal efficiency was 44%, compared with Post-combustion capture 34.8%, Pre-combustion capture 31.5%, Oxy-combustion capture 35.4%. Post combustion capture has high thermal efficiencies for conversion to electricity than pre combustion in natural gas plants and IGCC plants. The electricity costs are also lower with post combustion capture compared to pre combustion capture for natural gas plants. But on the other hand pre combustion capture is predicted to produce low carbon electricity more cheaply from coal in contrast to post combustion due to it having high capital costs and also costs of regenerating solvent.

At this stage and based on the conducted research and as the majority of the power plants are powered by natural gas as their fuel, it has been found that Post-combustion performs the best overall in NGCC plants in terms of plant efficiency, capture efficiency. Also it is the easiest Carbon capture technology to retrofit on existing power plants compared to the other technologies and therefore post-combustion was chosen.

There are three main methods of CO_2 transport: Pipelines, Ships and Trucks. Since the selected case study is based in Zakum offshore field, the most viable options are pipelines and ships. Ships are prone to accidents and have many cost elements involved which makes ships not to be the best option. The pipelines need to be constructed and would have a high initial investment but once developed it could be used for a long time with continued transport of CO_2 avoiding any delay which would in turn lead to an optimum production in the Oil field due to constant CO_2 injection. Statistical graphs published by IPCC report on total investment and operational cost of pipelines [3] were used to estimate the costs of the offshore pipeline from each power plant to the field.

There are various methods of storing CO_2 away from the atmosphere. Some of them are to store CO_2 under the ocean, in solid carbonates, underground and also in industrial products. The most viable option seems to be geological storage [9]. The geological storage may take the form of saline formation, coal seams and depleted oil

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and gas fields. Through progression of research and success of demonstration projects and commercial projects the confidence level in the technology has increased. Also there has been consensus that a varied and broad portfolio of mitigation options is needed, and also that geological storage could lead to major cuts in the CO_2 emissions to the atmosphere. The above reasons have led to geological storage being an option of limited interest to an important carbon mitigation option. For geologically storing CO_2 it has to be compressed to a fluid state with high density state called 'supercritical'. Based on the geological location and the rate at which temperature increases along with depth, the CO_2 density will also increase with depth, till around 800m or greater the CO_2 injected will be in a dense supercritical state [11]. Oil Production has three phases of recovery which are primary, secondary and tertiary recovery. The primary recovery field produces only a small amount of oil in most fields which is about 10-30% of the original oil in place. The secondary recovery which uses water flooding produces a similar amount or slightly higher than primary recovery. But this still leaves around 50% of OOIP and the prospect of recovering this with enhanced oil recovery. Enhanced oil recovery is a tertiary process of oil recovery. CO_2 is the primary miscible agent used for EOR and is pumped into the reservoir under miscible displacement conditions to improve the flow of remaining oil for EOR. The displacement of oil by CO_2 injection depends on the crude oil mixture which depends on pressure, oil composition, and reservoir pressure and also on the phase behaviour of CO_2.The mechanisms range from reduction of viscosity and oil swelling for immiscible fluids to complete miscible displacement in high pressure applications. The injected CO_2 is also produced along with the oil but some of it stays in the field and is trapped in many ways like dissolution in oil that is not produced, pore spaces not connected to the flow path of production, and irreducible saturation. Therefore as well as acting as an enhanced oil recovery agent, CO_2 is also stored in the field, making this a suitable carbon mitigation option [3], [12].

The oil produced by CO_2-EOR would be used to offset the CO_2 sequestration and transport costs, in this way employing CCS in the region would be more economic. Also another advantage of CO_2-EOR in this UAE region is that it would save natural gas from being used in enhanced oil recovery, and this would lead to having more fuel for use as natural gas has a growing demand in this region. Currently there is no existing CCS Plant in the UAE. Also due to the large point sources of CO_2 available in the region with possibility of CO_2-EOR in nearby fields makes this region very suitable for the deployment of this technology.

II. PROBLEM DESCRIPTION AND METHODOLOGY

After the secondary stage of oil recovery, a significant amount of Oil is still left back in the reservoir. The residual oil is in the form of droplets trapped in reservoir rock or around rock grains as films. EOR process of injection of CO_2 in the reservoir would mobilize the stranded oil. The CO_2 when injected in the reservoir interacts with the oil, chemically and physically creating favorable conditions to improve oil recovery. Some of these conditions are the expansion of oil and reduction in its viscosity, increasing fluidity of oil by complex phase changes. There are two methods of CO_2 -EOR which is immiscible displacement and miscible displacement. For miscible CO_2 displacement under specific favorable temperature conditions, oil composition and reservoir pressure the CO_2 can become miscible with crude oil. The miscibility of CO_2 is greatly affected by pressure and for CO_2 to become fully miscible with oil, minimum miscibility pressure (MMP) is required. To implement CO_2 miscible displacement the CO_2 injected must be at a higher pressure than MMP and in turn lower than the reservoir pressure. The immiscible CO_2 displacement method can also increase oil recovery even though MMP is not reached. In low pressure reservoirs or heavier oils, the CO_2 can still partially dissolve in oil causing swelling [13]. In this work, several power plants in the UAE were analyzed.

Table I shows the description of the main selected power plants. Based on the type of power plants and their compatibility with capture technologies, a suitable capture system was suggested. The post combustion capture was selected according to the facts presented in section I. This was followed by calculating the amount of CO_2 that can be captured. Initially CO_2 captured was calculated for ten different power plants, out of which four were then chosen based on close proximity to the field and varied power ratings. The CO_2 captured needs to be injected in oil field for EOR and hence as the case study Zakum Field which is around 80 kilometers northwest of the coast of Abu Dhabi was chosen. The exact locations of the field and selected power plants are shown in Fig.3. It is an offshore carbonate field with water depths from 20-80 ft. The structure of the field is about 45km and 28 km wide. It had initially started its production in 1967. The summarized methodology is shown by Fig.2. The Zakum Field

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was modelled in COZ View software for CO_2-EOR reservoir simulation. By modeling the field and the CO_2 injection in the software, it could be predicted how much oil is produced, and how the field performs over the specified time period.

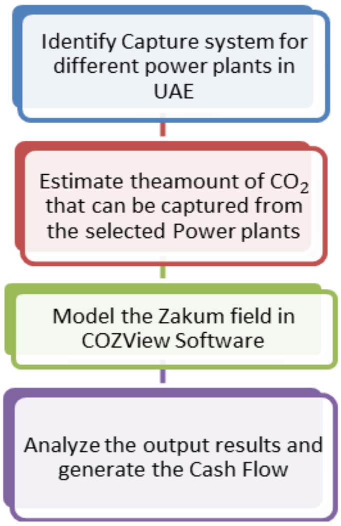

Fig.2. Methodology chart

Table I. Description of the selected power plants

Powerplant	Capacity (MW)	Output (MWh)	CO_2 (kg)
Al Taweelah A1 Power Plant (ATA1)	1502	3,008,840	975,152,000
Al Taweelah B1 Power Plant (ATB1)	1075	2,403,590	962,812,000
Umm Al-Nar West Power Plant (UANW)	790	1,581,130	743,536,000
Umm Al-Nar East Power Plant (UANE)	250	1,120,000	540,105,000

This field was chosen since it is close to the selected power plants and also due to the availability of its reservoir properties and characteristics. The Lower Cretaceous is known as the Thamama group and it is the point of interest in the field as this is the layer which was modelled via COZ View. The entire Thamama group has been modelled with the six zones as six different layers. The model layer characteristics are listed in Table II.

Table II. Model Layer Characterisation

Lower Cretaceous	Thamama Group	Zone 1	210 ft.
		Zone 2	166 ft.
		Zone 3	458 ft.
		Zone 4	250 ft.
		Zone 5	650 ft.
		Zone 6	650 ft.

Fig.3. Location of the power plants and Zakum Field. [Google Earth]

The 3D model developed of Zakum field shows the structure contour and the Well locations in the field which are illustrated by Fig.4.The reservoir properties

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that were extracted from the literature in addition to some other properties based on correlations were input into the software for modeling the Field. Table III shows some of the properties used in the simulation. The oil output estimated by the simulation was used to offset the costs of all aspects of CCS process. Cost analysis was carried out by developing a cash flow profile with estimated costs for all the four plants.

Table III. Properties input into the software.

Property	Value
Oil Gravity	37.33 API
Reservoir Tempt.	211.6 °F
Swirr	0.1617
Sorw	0.35
Sorg	0.2
Sorm	0.06
Pressure at 1/1/2008	4220 psi
Pressure at 1/1/2016	3450 psi

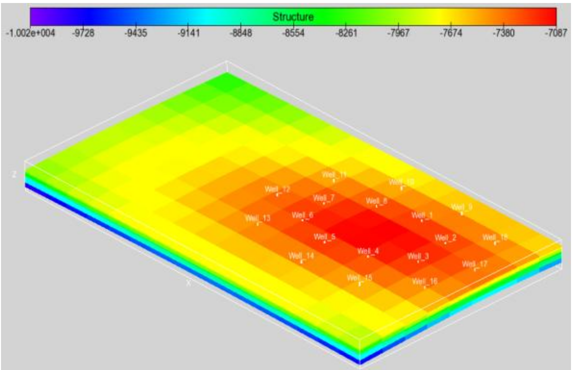

Fig.4. 3D model of Zakum field developed by COZView Software.

III. RESULTS & DISCUSSION

A. COZ View Simulation

Based on the post combustion technology of CO_2 capture and according to the emissions of CO_2 of the selected power plants provided in Table I, the amount of captured CO_2 was calculated and listed in Table IV. The CO_2 captured is about 70% of the produced CO_2 taking into account losses and mainly incomplete combustion that might take place due to the boilers being old and not performing at its maximum capability, although post combustion capture with amines can actually provide CO_2 capture efficiency up to 90%. The amounts of CO_2 injection resulted from carbon capture for the different power plants is shown by Table V. Due to losses and safety factor a slightly lower value of CO_2 is injected than what is actually captured.

A simulation was carried out for each of the plants with their captured CO_2 which represent the available amount to be injected in Zakum field wells as described in section 2. All the simulations were performed for the hypothetical duration of 9 years (i.e. 2016-2025). The generated results from the software were obtained in the form of plots for each Plant. For demonstration, Fig. 5 and Fig. 6 were provided for Al Taweelah A1 power plant. Fig.5 shows the cumulative oil, gas and water production versus the date. Also it shows the cumulative injections of gas and water. The curve of cumulative production is almost linear which represents a continual rise of total oil produced overtime which is exactly what the Oil companies aim for during production. Fig. 6 shows the rates of oil, gas and water produced per day. It shows a peak production rate of around 7300 (STB/Day) between 2018-2019.Also it is observed that there is a slight decrease of the rate of oil production as represented by downward curve towards the end of the simulation for all plants. This trend is expected since the oil production rate is supposed to drop over the

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years due to less oil remaining in the field. Also this can be explained in light of the significant pressure drops after long years of production.

Table IV. Estimation of the CO_2 Captured for the Selected Power Plants

Powerplant	CO2 Captured kg (70%)	CO2 Captured (SCF)	CO2 Captured (MSCF)	CO2 Captured (MSCF/Day)	CO2 Captured (m3)	CO2 Captured (m3/day)	Distance to Zakum Field (km)
Al Taweelah A1 Powerplant (ATA1)	682606400	13142221019.20	13142221.02	36006.08498	370578935.9	1015284.756	95
Al Taweelah B1 Powerplant (ATB1)	673968400	12975913605.20	12975913.61	35550.44823	365889468	1002436.899	95
Umm Al Nar West Powerplant (UANW)	520475200	10020709025.60	10020709.03	27453.99733	282559826.3	774136.5103	87
Umm Al Nar East Powerplant (UANE)	378073500	7279049095.50	7279049.096	19942.60026	205251628.7	562333.2292	87

Table V. Amount of injected CO_2

Plant	CO_2 injection (MSCF/Day)
Al Taweelah A1	36000
Al Taweelah B1	35000
Umm Al Nar West	27000
Umm Al Nar East	19000

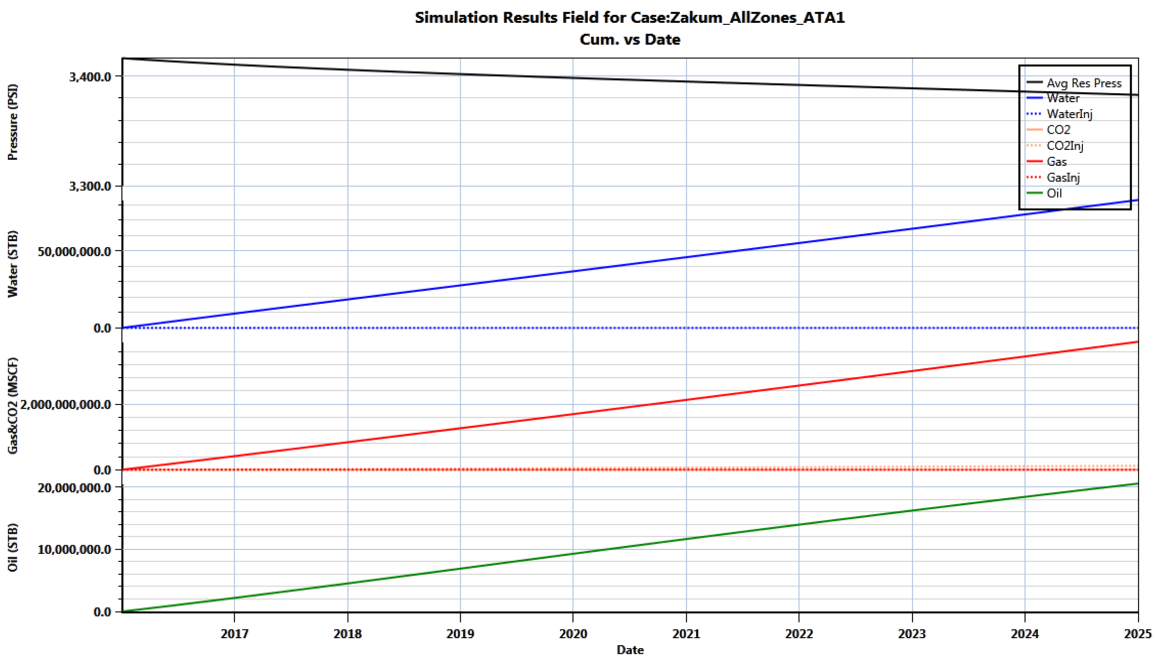

Fig.5. Cumulative Production vs. Date for Al Taweelah A1

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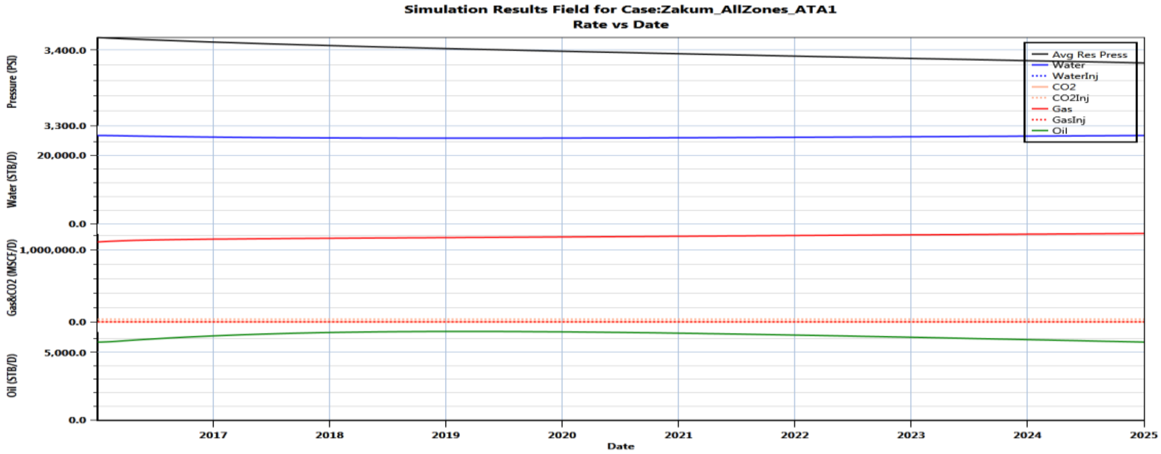

Fig.6. Production rate vs. Date for Al Taweelah A1.

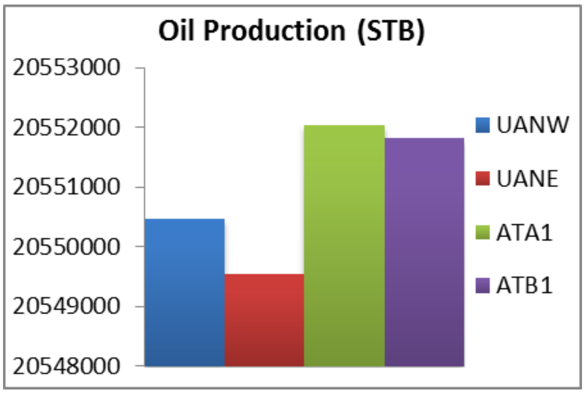

Fig.7. Total Oil Production for all selected power plants

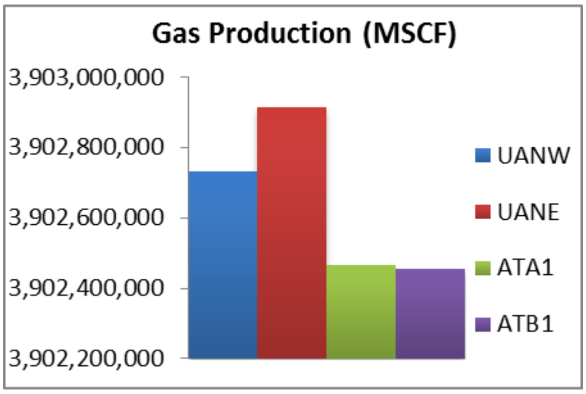

Fig.8. Total gas production for all selected power plants

Similar simulation runs were performed for other power plants. The obtained maximum oil and gas production for each plant is illustrated by Fig.7 and 8, respectively. The bar chart portrays that the plants which produce the most oil, produce the least gas and vice versa. This shows that both the amount of oil and gas corresponds to each other if a gas cap is present in the reservoir.

B. Economic Assessment

The economic assessment of the post combustion capture with Amine, transport and EOR for all the four Power plants was carried out with the help of a Cash Flow Analysis. The total capital requirement and the total operating and maintenance cost for each plant was estimated. The cost estimation was performed by following a proposed methodology for CCS costing and avoiding inconsistencies in calculation of CCS costs, which has been increasingly observed by many studies in the literature [18].

In estimating the capital costs, the bare erected costs, engineering procurement and construction cost, total plant cost, total overnight cost were taken into account to calculate the total capital requirement for each plant. To estimate the total operating and maintenance cost both fixed and variable operating cost items were considered. These costs also included capital cost pipeline and variable operating cost of the transport and storage. The capture systems cost was estimated by taking into consideration various existing plants and their performance as reported in the literature [19], [20], [3].

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Fig. 9 shows the Cumulative Cash return against the time of simulation and this graph also includes the year of 2015 as well during which only investment takes place with no production. This year is considered the year of employing the Capture technology to the plant and also time taken for construction and investment to be done. The graph shows four different curves for each plant and portrays their respective payback time. According to obtained results from this Fig.8, it was found that Umm Al Nar East power plant has a payback of 3.74 years making it the best performing plant in terms of recovering initial investment and gaining economic benefit from CO_2-EOR technology. Also it was found that Umm Al Nar West plant has a payback of 4.607 years where as Al Taweelah B1 has a payback of 6.919 years and Al Taweelah A1 has a payback of 8.486 years. It can be concluded from the graphs that as the plant size increases the payback period increases due to the increased cost of the capture processing plant. Also this is due to the fact that some of the captured gas is considered as an excess for the selected oil field without any contribution to the oil production. The payback period of large power plants can be enhanced slightly if the captured amount of CO_2 can be injected in larger oil fields.

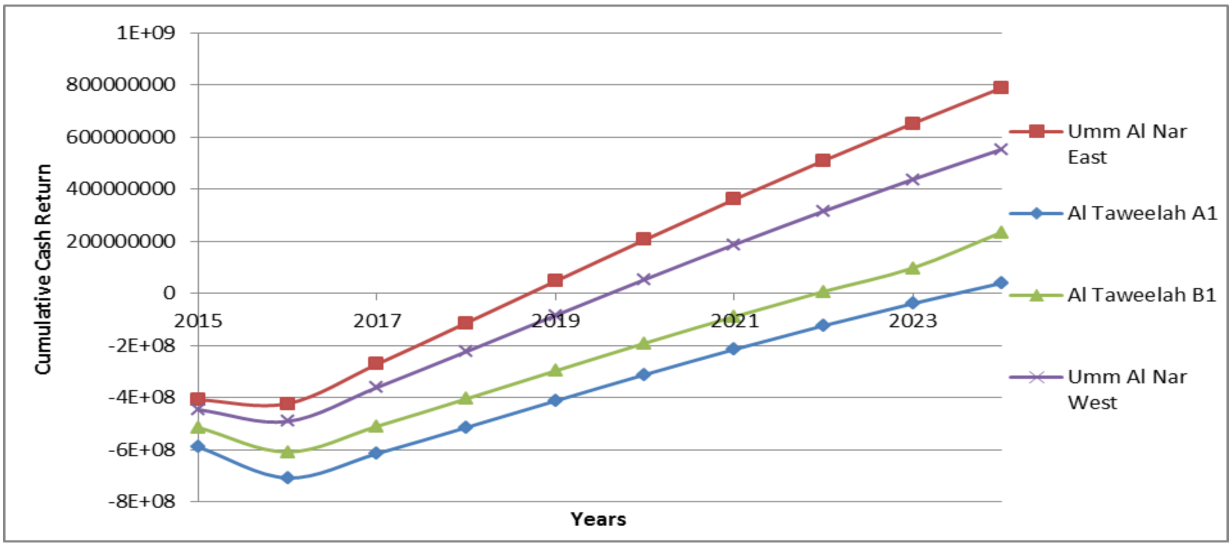

Fig.9. Cumulative Cash return Vs. Years for the selected power plants.

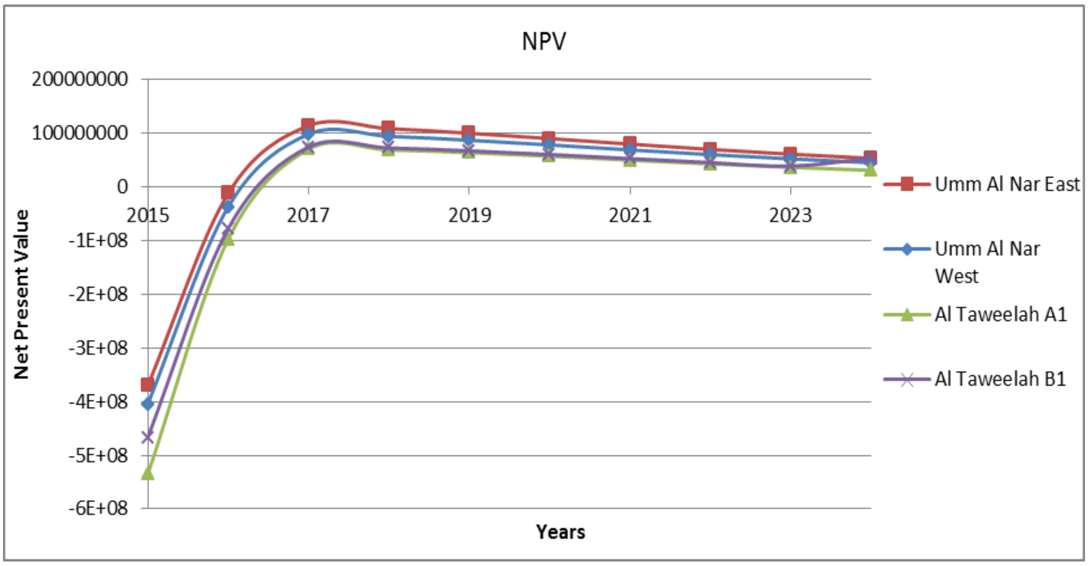

Fig.10. Net Present Value vs. Years

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Fig.10 shows the Net Present Value (NPV) graph which portrays similar curves for every plant but with different total NPV as listed in Table VI. The discount factor to calculate Net Present Value was taken to be 10% and was calculated for the 10 years from 2015-2024.

Table VI. Total NPV of each Power Plant

Power Plant	Total NPV (USD)
Umm Al Nar West	$138,566,668
Umm Al Nar East	$290,457,565
Al Taweelah B1	-$83,556,234
Al Taweelah A1	-$215,942,852

It was found that Umm Al Nar East and Umm Al-Nar West resulted in appositive NPV values during ten years investment period with possible achieved profits of about 290 and 138 Millions USD, respectively. The Al Taweelah B1 and Al Taweelah A1 have a negative NPV which implies that it would require around 15-20 years instead of 10 years for recovering the investment and having a positive NPV value. This would lead to CCS being uneconomic and it would not be viable to employ CCS in these plants. In order to make CCS viable in large capacity power plants a combined pipeline could be used for two plants or more which are in close proximity and this would make the capital cost to decrease drastically.

IV. CONCLUSION

In this paper, the applications of Carbon capture and storage in conjunction with the enhanced oil recovery were investigated. According to the conducted research on the available carbon capture methods, post combustion technology was used since it is more applicable and compatible with the power plants in UAE which have been selected due to their proximity to the oilfield (i.e. Zakum field). The CO_2 captured is about 70% of the produced CO_2 for each power plant taking into account losses incorporated with incomplete combustion. A comprehensive model of Zakum field, in particular for Thamama group was generated by Coz View software. Wide variety of simulation runs were carried out to estimate the oil and gas production resulted from injecting the amounts of CO_2 captured from each of the selected power plants. On the other hand, the total capital cost and the total operating and maintenance cost were estimated for the purpose of the economic assessment. The obtained results showed the feasibility of deploying Carbon Capture Storage in a large scale on existing Power Plants in the UAE. This was accompanied with small payback periods for the small and moderate capacity power plants (i.e.4-7 years). Also employing this technology would lead to having significant value to the region's drive to move towards a lower carbon economy.

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