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Research Article

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Cost Effective Strategies to Reduce CO_2 Emissions in the UAE: A Literature Review

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Abstract

The objective of this literature review is to propose cost-effective strategies to reduce CO_2 emissions in the UAE. First, fuel gas is the most suitable combustible to avoid corrosion and other technical problems in a future Carbon Capture Storage (CCS) plant. The resulting low concentration of CO_2 in the absorption column could be increased by recycling part of the flue gas or using oxygen for combustion. To capture CO_2, a blend of a Task Specific Ionic Liquid containing amine moiety mixed with an ionic liquid in polymer form is a potential candidate to replace the existing amine mixture. For the compression of CO_2, the combined process of reciprocating compressors with inter-cooling, liquefaction and pumping with a diaphragm pump could offer a higher overall efficiency than using compressors alone. For the sequestration of CO_2, the "New Generation" miscible CO_2-EOR technique optimizes both oil production and CO_2 storage but immiscible CO_2-EOR is the recommended strategy for wells that fail the asphaltene precipitation test. Finally, if the 76 million tons of CO_2 presently emitted in Abu Dhabi and nearby could be stored using the "New-Generation" and the "Second-Generation" CO_2-EOR technologies, 152 billion AED could be annually added to the UAE's economy.

Keywords: Carbon capture; Ionic liquids; Compression of CO_2; CO_2-EOR

Introduction

Global climate change is arguably the most challenging environmental problem the world will face in the coming decades and centuries. To curb the dramatic growth of greenhouse gases and its related consequences, a broad set of CO_2-limiting policies will be needed. The strictness and extent of such policies will play a significant role in decision process regarding future investments in different energy technologies.

The Carbon Capture/Storage (CCS) is included as an integral part of all climate change mitigation strategies proposed by the Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA).CCS is a good and viable option for reducing CO_2 emissions because it can be implemented on a large scale. If CCS is fully implemented, there is a potential of capturing and storing 236 billion tons of CO_2 globally by 2050. This corresponds to a 33% reduction in global CO_2 emissions in 2050 compared to today's emission levels [1].

While there are multiple challenges in launching CCS demonstration projects around the world, the high capital cost of CO_2 capture technologies is often cited as a key barrier by the potential CCS developers and investors. According to some published data, 70 to 80% of the operating cost of a CCS plant is due to the large amount of energy needed during the capture of CO_2 using available technologies [2].

The objective of this literature review is to explore the different technologies actually available or under investigation for capturing, compressing, transporting and storing CO_2 and propose them as cost effective strategies to reduce the CO_2 emissions and extend the production life of the crude oil wells in the UAE.

The different available technologies for capturing CO_2

The goal of the capture part of any CCS project is to reduce pollution by isolating and concentrating carbon dioxide from its many sources in a form which is suitable for transport and sequestration. As shown in Table 1, three major technologies are presented in the literature as potential candidates for CO_2 trapping from its different sources [3,4].

Oxy fuel and Pre-combustion strategies are still under investigation in laboratories or pilot plants in different research centers. On the other hand, technologies for the Post-combustion capture are already commercialized or near commercialization. The other advantage of Post-combustion CO_2 capture is its flexibility to use any type of fuel for the combustion. However, flue gas coming from the combustion of heavy liquid fuel could contain impurities such as SOx, NOx, HCl, HF, mercury, other metals and other trace organic and inorganic contaminants. These contaminants are a very important factor for the design of a CCS plant and could increase its cost considerably.

Post combustion CO_2 management options

Post combustion CO_2capture involves the removal of CO_2 from the flue gas produced by the combustion of fossil fuel. The different technologies investigated for this process are presented in Table 2 [3-6].

The three first strategies (Biological, Membrane and Adsorption) are still in the developmental stage. All these technologies need to be evaluated when choosing the best one to incorporate in a power plant to be built in the future. The only immediately realizable and mature CO_2 capture technology appears to be chemical absorption [5,6].

Post combustion CO_2 capture by absorption

In a typical Absorption/Stripping unit, carbon dioxide is first separated from the other flue gases in the absorber and pure CO_2 is obtained in the stripper where the solvent is regenerated and recycled to the absorber (Figure 1).

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The potential solvents for the absorption of CO_2 should have high CO_2 capacity and low energy requirements for regeneration. Solvents should also be resistant to thermal degradation and less corrosive. For the actual absorption processes using amine solutions, a typical solvent is a blend of low concentration of primary or secondary amine mixed with relatively high concentration of a tertiary amine or the hindered amine 2-amino-2-methyl-1 propanol (AMP). The primary or secondary amine (MEA or DEA) is selected for its higher reactivity with carbon dioxide. On the other hand, the tertiary amine MDEA or the hindered amine AMP needs lower heat during its regeneration [6].

In order to reduce the global cost of a CCS plant by avoiding corrosion and other technical problems in the facilities and reservoirs due to the impurities (H2S, SOx, NOx, HCl…) in the captured CO_2, it is recommended to use only fuel gas as combustible in all industrial plants emitting flue gas including the CO_2 capture units. When recovering CO_2 from flue gas by an absorption process (amine scrubbing), it is advantageous to have a high concentration of CO_2, in order to maintain the driving force for mass transfer at a high level and to keep the gas volumes to be handled at a minimum level. However, power generation plants using fuel gas have a typical overall excess air ratio in the range 3-3.5, which results in flue gas CO_2 concentrations of typically 3-3.5%. This is a very low flue gas concentration of CO_2 compared to other combustibles. There are two possible options for increasing the flue gas concentration of CO_2 from plants using fuel gas as combustible: (1) Recirculation of part of the flue gas and mixing with air; (2) Using oxygen instead of air for the combustion. For the second strategy, an air separation plant is needed and should be added to the total cost of the CCS plant [7].

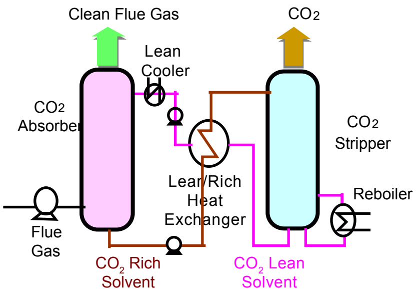

Figure 1: A Typical Absorption/ Stripping Unit for CO_2 Capture.

Finally, to avoid oxidative degradation of amines, the approach currently practiced is the use of chemical inhibitors. For example, the processes licensed by Kerr-McGee/ABB Lummus Global Inc. and by Fluor Daniel use inhibited monoethanolamine solutions [6]. However, corrosion inhibitors could also act as a catalyst towards the solvent degradation. Praxair has recently been granted two patents for improved oxygen tolerant absorption processes. The key aspect of Praxair's successful approach is handling the dissolved oxygen in amine mixture through process modifications instead of the introduction of additional chemicals. In Praxair's process, oxygen is removed using a vacuum pump in a flash tank before the Lean-Rich heat exchanger (Figure 1) [6].

The use of ionic liquids for the absorption of CO_2

Since 80% of the total energy consumption of a "CO_2 capture" unit using amine solutions is due to the heat duty of the reboiler at the bottom of the stripping column, scientific research aims to investigate a suitable solvent that could be regenerated at the lowest temperature possible in

Technology	Short Description	Advantages	disadvantages
Oxy-fuel	Nearly pure oxygen is used for combustion instead of air. The flue gas that is mainly CO_2 and H_2O.	Very high CO_2 concentration in flue gas	Large cryogenic O_2 production requirement may be cost prohibitive
Pre-combustion	Involves reaction of a fuel with air and/or steam to givemainly a gas composed of carbon monoxide and hydrogen. The carbon monoxide reacts with steam to give CO_2 and more hydrogen.	Concentrated in CO_2, high pressure and potential for reducing the cost of compression for sequestration	Applicable mainly to new plants, Cost of equipment and extensive supporting systems requirements
Post-combustion	Involves the removal of CO_2 from the flue gas produced bycombustion of fossil fuel.	Applied to any kind of fuel. Has the greatest near-term potential for reducing CO_2 emissions,	Dilute in CO_2, Ambient pressure and low pressure compared to sequestration requirements

Table 1: Technologies for CO_2 capture [3,4].

Technology	Short description	Advantages	Disadvantages
Biological	Biologically based capture systems are a potential avenue for improvement in CO_2 capture technology. These systems are based upon naturally occurring reactions of CO_2 in living organisms (enzymes).	The potential for 90% CO_2 capture followed by regeneration at ambient conditions. This is a significant technical improvement over the MEA temperature swing absorption process.	Slow reaction, loss of enzyme activity, long-term operation and scale-up.
Membrane	Flue gas would be passed through a bundle of membrane tubes, while an amine solution flowed through the shell side of the bundle. CO_2 would pass through the membrane and be absorbed in the amine, while impurities would be blocked.	Solvent assisted membranes are being developed to combine the best features of membranes and solvent scrubbing.	Low degrees of separation, multiple stages and/or recycling. This leads to increased complexity, energy consumption and costs.
Adsorption	A number of solid adsorbents, such as zeolites and activated carbon are used to react with CO_2 to form stable compounds at some operating conditions and then, at another set of conditions, be regenerated by liberating the absorbed CO_2.	Research Triangle Institute Laboratory and pilot plant tests using Sodium Carbonate (Na_2CO_3) have achieved over 90% CO_2 removal from simulated flue gas. The process economic evaluation shows lower capital costs and energy requirements than conventional MEA Absorption.	CO_2selectivity of available adsorbents is lower than liquid solvent.
Absorption	The cooled flue gas is brought into contact with the liquid solvent in the absorber. The "rich solvent", which contains the chemically bound CO_2 is then regenerated in the stripper,	Established over 60 years ago in the oil and chemical industries. Commercially, it is the most established technique for CO_2 capture.	Requires a large amount of energy for the regeneration of the solvent.

Table 2: Different Technologies for Post Combustion CO_2 capture[3-6].

order to minimize energy consumption and, by consequence, the cost of CO_2 capture. Innovative off-the-shelf CO_2 capture approaches are burgeoning in the literature, among which, Ionic Liquids (ILs) seem to have been omitted in the recent Intergovernmental Panel on Climate Change (IPCC) survey [8]. Since no chemical reaction is taking place during the absorption of CO_2 in some ionic liquids (physical absorption), the amount of energy needed for the regeneration of these solvents is expected to be small compared to the present process using amine solutions (chemical absorption). This property has a great potential to lower the cost of CO_2 capture and CCS in general. Another advantage of ILs is that the properties can be selected on the basis of the choice of anion, cation or other substituents [9]. This flexibility leads to innumerable different structures and variation possibilities. Anderson et al. [10] suggest that there are about 10^{18} possible structures for ionic liquids.

Because of their tunable properties, wide liquid range, reasonable thermal stability, and negligible vapor pressure, many researchers are focusing on the use of ionic liquids as suitable solvents for post-combustion CO_2 capture by absorption [11-14]. Examples are Room Temperature Ionic Liquids (RTILs) and Task Specific Ionic Liquids (TSILs). For the TSILs, an amine moiety is introduced in the structure to enhance CO_2 absorption [15]. Published data show that the CO_2 absorption ability of TSILs can reach up to threefold of the corresponding RTILs [14,15]. However, these functionalized species exhibit much higher viscosities as compared to the corresponding RTILs or other commercially available CO_2 scrubbing solutions, posing too serious complications to be applicable on industrial scale [16,17].

A number of studies have also been performed to explore the prospects of Supported Ionic-Liquid Membranes (SILMs) involving RTILs or TSILs or both in CO_2 capture [18,19]. To take advantage of thermal/chemical stability and essentially no volatility; and to deal with the limitations due to viscosity and also to increase the contact area between gas and ionic liquid, SILMs could be a better choice in CO_2 separation. For example RTIL, [bmim] [Tf2N], supported on porous alumina membrane revealed very optimistic results in favor of CO_2 capture ability [16]. One of the negative aspects of SILMs is the leaching of the liquid through membrane pores as the pressure drop surpasses the liquid stabilizing forces within the matrix. Therefore, membranes made up of polymerizable ionic liquids may be a better option for CO_2 separation [18-20]. Comparing the performance of certain ionic liquids during the absorption-desorption process, Riisagera et al. [19] concluded that functionalized ionic liquids (TSILs) containing an amine group are preferred because the CO_2 absorption capacity for these ILs is much higher. However, for ease of operation and reducing energy consumption, ionic liquids in polymer form, and ionic liquids supported on solid sorbents, such as silica gel will be more and more popular.

Shifleet et al. [13] compared the energy requirement and economic investment of a commercial MEA Post Combustion CO_2 capture facility with a new process designed to use the Room Temperature Ionic Liquid 1-Butyl-3-methylimidazolium Acetate. Their simulation using Aspen Plus showed that, in both cases, greater than 90% of CO_2 can be removed from the flue gas at high CO_2 purity (>95%) and modeling results for the MEA process were in agreement with a commercial process. ASPEN Icarus was used to estimate the engineered equipment costs based on the equipment size, materials of construction, and temperature and pressure ratings. The IL process reduced the energy consumption by 16% compared to the MEA process. Moreover, engineering design estimates indicate that the investment for the IL process was 11% lower than the MEA-based process and provided a 12% reduction in equipment footprint. The authors added that the Ionic liquid was not optimized. The lack of availability of inexpensive and diverse ionic liquids nowadays represents the major cause of hesitation in employing ionic liquid systems for CO_2 capture on large scales.

Compression and transport of CO_2

The compression of CO_2 represents an important process step for any CCS project. It requires significant power to boost the pressure of CO_2 from the atmospheric pressure of the stripping column up to a pressure suitable for injection. Current R&D activities are focused on developing and improving the energy- and cost-intensive sub processes of compression. In low pressure (<15 MPa) applications, the compression can be performed by multi-stage reciprocating or turbo compressors. However, for high pressure applications depending on the specific characteristics of the injection process, it can be reasonable to utilize new concepts with part compression followed by liquefaction and pumping. Significant power savings in the compression step can be achieved with this tandem approach [21]. In this perspective, a compressor could be used to compress CO_2until its critical pressure of 7.38 MPa, while a pump is used from 7.38 MPa to the final pressure when CO_2 is in the dense or liquid phase. The critical pressure of CO_2 is often cited as the “cut-off” pressure for switching from a compressor to a pump. For example, for a compression of 30 ton/hr. of CO_2 from 0.2 MPa to 20 MPa, Dübi et al. [21] compared the combination of a reciprocating compressor and a high pressure pump to the conventional way of CO_2 compression by compressors only. The first process consisted of a reciprocating compressor with three stages and intercooling, liquefaction of CO_2 and a triplex diaphragm pump where the CO_2 is compressed to 7 MPa in the compressor, subcooled to 25°C and boosted to the final pressure of 20 MPa by the pump in a single step. The results indicate that this process consumed 17% less energy than the traditional process using a five stages compressor with intercooling. Additionally, the combination of reciprocating compressors and pumps for CO_2 compression also reduces corrosion issues for processes with discharge pressures above 100 bars. McCollum and Ogden [22] estimated the power requirements of compressing CO_2 as a function of the flow-rate. Compression of gaseous CO_2 from 0.1 MPa to 7.38 MPa was performed using a five stages compressor with inter-cooling and a pump was added to boost the liquid CO_2 from 7.38 to 15 MPa. A linear relationship was found between the power requirement and the flow-rate for both the compressor and the pump when the flow-rate changes from 1,000 to 25,000 tons CO_2 per day. The authors added that, if the total compression power requirement is greater than 40,000 kW, the CO_2 flow rate and total power requirement must be split into N parallel compressor trains, each operating at 100/N of the power/flow.

Existing R&D projects in the CO_2 transportation field have been exclusively focused on the CO_2 emitted by the major emitting industries, in particular power generation stations. These major industrial facilities can be fitted with their own CO_2 capture and transport installations. However, this does not apply to industries that emit less CO_2 (from a few 10,000 to 100,000 metric tons/year). For these small industries, compressing the flue gases from the different sources and sending them to one particular CO_2 capture unit could be more economic than building a CO_2 capture unit in each individual industry [23].

For the transportation of CO_2, many strategies including transport by pipelines are presented in the literature [24-27]. According to Coy and Rubin [26], efficient transport of captured CO_2 via pipeline requires that CO_2 be compressed and cooled to the liquid state. Transport at lower densities (i.e., gaseous CO_2) is inefficient because of the low density of the CO_2 and relatively high pressure drop per unit length. Booster pumping stations may be required for long pipeline distances but investing in booster pumps will also have the benefit of decreasing the cost of transportation by reducing the required diameter of the pipeline. To reduce difficulties in design and operation, Farris [27] has recommended that a CO_2 pipeline operates at pressures greater than 8.6 MPa where the sharp changes in compressibility of CO_2 can be avoided across a range of temperatures that may be encountered in the pipeline system. On the other hand, by operating the pipeline at pressures greater than the CO_2 critical pressure of 7.38 MPa, temperature fluctuations along the pipeline will not result in the formation of gaseous CO_2 and the difficulties encountered with two-phase flow [28].The operating conditions of compression and transport of CO_2 will then be dictated by the temperature of the surrounding soil.

For the design and cost of CO_2 compression and transportation, many mathematical models are presented in the literature [25-30]. According to M. Coy [26], both the pumping station size and the pipeline diameter are estimated on the basis of the design mass flow rate of CO_2 but the pumping station power is calculated on the basis of a nominal mass flow rate of CO_2 (which is the product of the power plant capacity factor and the design mass flow rate of CO_2). The pumping station size is required to determine the capital cost of the pump while the pumping station annual power requirement is required to calculate the variable operating and maintenance cost. In addition, the cost of CO_2 transports increases with distance and decreases with pipeline capacities, resulting in economies of scale that are reached at high design capacities.

Besides the efficiency improvement, the corrosion behavior of CO_2 has to be considered at a pressure level around and above the critical point. To prevent liquid building during decompression (e.g., sealing elements and packing of the compressor) the temperature level shall be above 90°C [21]. Moreover, water vapor in the injection gas may precipitate to a liquid or solid phase, when the compressed gas is cooled during transport in the pipeline. Liquid water accelerates corrosion, and ice or solid hydrates can plug valves, fittings, and even the pipeline. CO_2 corrosion is very aggressive when free water is present. CO_2 gas should then be treated at the source in order to avoid these technical problems [28] and the higher cost of a CCS plant.

A major surface facility characteristic that would appear to dominate oil reservoir sequestration is the distance of the source of CO_2 from an oil reservoir. The cost of very long pipelines appears to be prohibitive. Recht. [29] has proposed that 500 km might be the maximum distance to move CO_2 from its source to a sequestration site. According to the economic comparative analysis of three ways of transporting CO_2conducted by Norisor et al. [30], the CO_2 pipeline transport way could be rentable for a plant's life more than 23 years. Otherwise, road and the rail transport are preferred strategies for transporting carbon dioxide.

Enhanced Oil Recovery (EOR) as a technique for CO_2 sequestration

Oil reservoir sequestration is the storage of carbon dioxide in mature and/or partially depleted oil reservoirs, which have held crude oil reserves, and thus have geologic conditions suitable for CO_2 storage. CO_2 injection into oil reservoirs has been widely accepted as an effective technique for Enhanced Oil Recovery (EOR), and has been used by the oil industry for over 40 years. Concerns over CO_2 emissions are leading to the investigation and realization of its potential as a carbon storage method in recent years. With the right reservoir conditions, the CO_2-EOR technique can result in incremental oil recovery and permanent storage of CO_2 in geological formation.

Screening criteria are useful for the cursory examination of many candidate reservoirs before expensive reservoir descriptions and economic evaluations. In this perspective, Jelmert et al. [31] used ECLIPSE Simulation to compare different EOR methods including chemical, CO_2- miscible displacement and thermal Processes. Their final results indicate that CO_2 flooding is particularly effective in reservoirs deeper than 2,000 ft., where CO_2 will be in a supercritical state, with API oil gravity greater than 22° and remaining oil saturations greater than 20%. They also noted that CO_2 flooding is not affected by the lithology of the reservoir area but simply by the reservoir characteristics. The authors concluded that, for both economical and oil recovery reasons, CO_2 flooding should be applied.

CO_2-EOR projects around the world are 124 in total in 2010 and 114 projects are located in the USA [32]. The US experience indicates that approximately 40% of the originally injected CO_2 is being produced in producer wells and can be reinjected. This suggests a "gross" CO_2-retention efficiency of approximately 60% at CO_2 breakthrough if separation and reinjection is not considered [33]. According to Tabber et al. [34], if only depth of the well and oil gravity are considered, about 80% of the world's reservoirs could qualify for some type of CO_2 injection. Compared to other tertiary recovery methods, CO_2 has the potential, in its supercritical status, to enter into zones not previously invaded by water and thus releasing the trapped oil not extracted by traditional methods. Some screening criteria of miscible CO_2 flood technique are presented in Table 3.

Miscibility of CO_2 in the crude oil is an important factor for any CO_2-EOR technique. Depending on reservoir pressure, temperature and oil characteristics, CO_2 flooding can be either miscible or immiscible. The parameter summarizing this combination of phase behavior and flow is the Minimum Miscibility Pressure (MMP). Practically, MMP is the pressure necessary to assure the mutual solubility of oil and CO_2 and thereby achieve significant recovery. MMP varies with oil composition and density and generally increases as oil becomes denser. At pressures above the MMP, flooding will be miscible and CO_2 forms a single phase solution with the hydrocarbon reservoir, decreasing the interfacial tension between the two substances to almost zero to form a low viscosity fluid that can be easily displaced and produced. On the other hand, immiscible flooding occurs when the pressure is below the Minimum Miscible Pressure (MMP) where CO_2 does not form a single phase solution with the hydrocarbons in the reservoir but can still cause the swelling of the oil, reducing its density, improving mobility and, consequently, increasing the oil recovery. However, in

	Recommended	Range of current projects
Crude Oil		
Gravity (^{0}API)	>22	27-44
Viscosity (cp)	<10	0.3 to 6
Composition	High percentage of C_5 to C_{12}	
Reservoir		
Oil saturation (% PV)	> 20	15 to 70
Type of formation	Sandstone or carbonate and relatively thin unless dipping.	
Average permeability ,md	Not critical if sufficient injection rates can be maintained	
Depth and temperature	Depth should be enough to allow injection pressures greater than MMP which increases with temperature and for heavier oils.	

Table 3: Screening criteria of miscible CO_2 flood[34].

heavy and extra heavy oil reservoirs CO_2 and the oil form two distinct fluid phases, maintaining a separation interface all along the process [32].Considering the depth of the well and crude oil density only, some screening criteria for CO_2 miscible and immiscible flooding are presented in Table 4.

To summarize Table 3 and 4, CO_2 flooding can be performed in geological formations such as sandstone and carbonate. Miscible flooding is recommended for the density of oil higher than 22^0 API if the depth of the reservoir is at least 4000 ft. On the other hand, immiscible flooding is required if the density of oil is between 13 and 22^0 API and the depth of the well is more than 1800 ft. For some current projects using miscible CO_2-EOR, the crude oil density and viscosity are in the range 28- 45° API and 0.35 -6 cP. For projects using immiscible CO_2-EOR, the ranges are respectively 11-35° API and 0.6-6 cP. For both miscible and immiscible flooding, the percentage of intermediate hydrocarbons (C5-C12) in the crude oil is high [32].

Miscible CO_2 injections generally have excellent microscopic displacement efficiency but they often result in poor sweep efficiency. In order to address sweep problems and maximize recoveries, other schemes of gas injection have been developed. Two such processes are Water-Alternating-Gas (WAG) and Simultaneous Water-And-Gas (SWAG) injection. WAG and SWAG have been successfully used to minimize poor sweep [35,36]. However, these techniques have the tendency to optimize oil production efficiency, often by limiting the volume of CO_2 stored [37]. This is in contrast with the objective of a CCS project, which is maximizing sequestration of CO_2 per unit volume of reservoir rock. Therefore, if miscible flooding is the most common in active CO_2-EOR projects (117 out of 124); immiscible flooding will become more important in the future because of their higher efficiency in CO_2 sequestration [32]. Besides, some concerns for CO_2-miscible flooding are associated with the possibility of asphaltene precipitation, if a sufficient amount of CO_2 is dissolved into the crude, lighter de-asphalted oil can be produced but the precipitated asphaltenes may cause reservoir plugging, reducing the oil recovery. The characteristics of some projects using these two CO_2-EOR techniques are compared in Table 5.

Type of CO_2 flooding	Oil Gravity (^{0}API)	Depth must be greater than (ft.)
Miscible	>40	2500
	32-39.9	2800
	28-31.9	3300
	22 to 27.9	4000
	<22	Fails for miscibility
Immiscible	13 to 21.9	1800
	<13	All reservoirs fail at any depth
At <1800 ft., all reservoirs fail screening for either miscible or immiscible flooding with supercritical CO_2		

Table 4: Screening criteria for miscible and immiscible CO_2 flooding[35].

According to Table 5, projects using immiscible flooding seem to achieve not only higher CO_2 storage but also higher oil recovery. Since miscible flooding has a higher potential for oil recovery, the contradictory data could suggest that the asphaltene precipitation had reduced the oil recovery for miscible flooding during the last years of the project. Finally, the comparison between the two oil productions confirms that immiscible flooding is a slow process compared to miscible flooding.

As CO_2 sequestration in geologic media is in its infancy, it is not clear that MMP alone will be a useful indicator of successful CO_2-EOR projects where the primary concern is to store effectively CO_2 [38]. Three broad areas of characteristics appear to be relevant: reservoir properties, oil properties, and surface-facilities properties. Some of these screening criteria are shown in Table 6.

The conclusion that emerges from Table 6 is that the density of CO_2 at reservoir depth and pressure needs to be considered in concert with reservoir characteristics. Adequate porosity and thickness (for storage capacity) and permeability (for injectivity) are critical. For example, the specific sequestration capacity C is proposed to be higher than 10. Other parameters such as $S_0\o$ and kh should also be higher than 0.05 and 10^{-14} respectively.

As defined in Table 7, State of the Art, New Generation and Second Generation CO_2-EOR technologies are presented in the literature as the newest approaches to the traditional CO_2-EOR [37].

A case study involving a large Gulf Coast oil reservoir (USA) with about 340 million barrels of OOIP in the MPZ pursued using the gravity stable CO_2-EOR flood design. This reservoir is assumed to hold another 100 million barrels in 130 feet of a ROZ, and has an underlying saline aquifer 195 feet thick within the spill point of the anticline structure of the reservoir. The reservoir properties of the main pay zone are assumed to be as follows:

1) Depth–14,000 feet
2) Oil gravity–33 degrees API
3) Porosity–29%
4) Net pay–325 feet
5) Initial reservoir pressure–6,620 psi
6) Miscibility pressure–3,250 psi.

The primary/secondary oil recovery in this oil reservoir is favorable at 153 million barrels, equal to 45% of OOIP in the main

	CO_2 Miscible	CO_2 Immiscible
Project start	Before or after Water flooding	After Water flooding
Project duration	Short (<20 years)	Long (>10 years)
Project Scale	Small	Large
Oil Production	Early (1-3 years)	Late (5-8 years)
Oil Recovery Potential	**4-12% of OOIP (Original Oil In Place)**	**Up to 18% OOIP**
Recovery Mechanism	Complex	Simple
Recycling of CO2 injected	Unavoidable	Voidable
CO2 Storage Potential	**Low (0.3 ton. /bbl.)**	**High (up to 1 ton. /bbl.)**
Experience	Significant	Limited

Table 5: Comparison of projects using miscible or immiscible flooding[32].

Criteria	Positive indicators	Cautionary indicators
Reservoir Properties		
S_0ø(average oil saturation x porosity)	≥0.05	<0.05 (Consider filling reservoir voidage if capacity is large)
kh (Average permeability x thickness of oil-bearing zone in m^3)	$\geq 10^{-14}$	$<10^{-14}$ (Consider whether injectivity will be sufficient)
Capacity (kg/m^3)	>10	< 10
Pore Pressure gradient	≤ 17.4	>17.4
Location	Divergent basin	Convergent basin
Seals	Adequate characterization of caprock, minimal formation damage	Areas prone to fault slippage
Oil properties		
Density (^{0}API)	>22	<22Consider immiscible CO2EOR, fill reservoir voidage if sequestration capacity per volume of rock is large
Viscosity (mPa.s)	<5	>5 Consider Immiscible flooding
Composition	High concentration C_5-C_{12} and few aromatics	
Surface facilities		
Corrosion	CO_2 can be separated to 90% in a cost effective manner	H_2O and H_2S concentrations above 500ppm each.

Table 6: Screening Criteria for CO_2 Sequestration [39].

Technology Case	Definition
"State of the Art" CO_2-EOR	"State of the Art" CO_2-EOR represents best practices used by operators today, which are much improved over traditional CO_2-EOR practices. Assumes injection of much larger volumes of CO_2, and rigorous CO_2-EOR monitoring, management and remediation activities that help assure that the larger volumes of injected CO_2 contact more of the reservoir's residual oil, appropriate well spacing (including the drilling of new infill wells), the use of a tapered WAG process, the maintenance of minimum miscibility pressure (MMP) throughout the reservoir, and the reinjection of CO_2 produced with oil.
"New Generation" CO_2-EOR	After using the "State of the Art" CO_2-EOR, the "New Generation" miscible CO_2-EOR technique will optimize both oil production and CO_2 storage[40]. The following strategies are needed to implement the "New Generation" miscible CO_2-EOR : 1) Increasing the volume of CO_2 injected into the oil reservoir from 1.0 to 1.5 HCPV (Hydrocarbon Pore Volume); 2) Optimizing well design and placement, including adding infill wells to achieve increased contact between the injected CO_2 and the oil reservoir; 3) Improving the mobility ratio between the injected CO_2/water and the residual oil; and 4) Extending the miscibility range, thus helping more reservoirs achieve higher oil recovery efficiency. According to C. Nichols[40], these practices could store 14% to 18% more CO_2 and produce 47% to 50% more incremental oil than "state-of-the-art" CO_2-EOR technology**.**
"Second Generation" CO_2-EOR	Assuming a reservoir is developed with one or more "next generation" technologies, the "Second Generation" technology will target both the main pay zone plus the underlying residual oil zones (ROZs), with continued CO_2 injection into and storage in an underlying saline aquifer, including injecting continuous CO_2 after completion of oil recovery operations.

Table 7: Definitions of Alternative CO_2-EOR Technologies[38]

	"Next generation" CO_2-EOR	"Second generation" (CO_2-EOR and CO_2 storage)
CO_2 Storage (million metric tons)	32	109 76 (CO_2-EOR) + 103 (Storage)
Storage Capacity Utilization	22%	76% 53% (CO_2-EOR) + 23% (Storage)
Oil Recovery (million barrels)	92	180

Table 8: Case Study: Integration of "Next Generation" CO_2 Storage with EOR.

pay zone. Even with this favorable oil recovery using conventional practices, 181 million barrels is left behind ("stranded"). This reservoir was assumed to be developed using "state-of-the-art" CO_2-EOR technology, including vertical wells, one HCPV of CO_2 injected (including both purchased and recycled CO_2) and one-to-one WAG ratio. Next, this was compared to "next generation" CO_2-EOR and CO_2 storage, including gravity stable, vertical CO_2 injection with horizontal production wells targeting the main pay zone, plus the ROZ and the underlying saline aquifer, along with injecting continuous CO_2 (no water) and continuing to inject CO_2 after completion of oil recovery.

Based on the above considerations, the theoretical CO_2 storage capacity of this oil reservoir and associated structural closure is 143 million metric tons. Assuming there is value to storing CO_2 with gravity stable CO_2-EOR and sequestration technology, much more CO_2 can be stored relative to "next generation" technology and more oil becomes potentially recoverable (Table 8) [37].

Finally, it is noted that the cost of CO_2 storage increases exponentially when permeability decreases and the cost of both transport and storage decreases with increasing capacities [26].

Final proposal for future CCS projects in the UAE

According to the World Environment Agency, 31.5 billion metric tons of CO_2 were globally emitted during the year 2008 [39]. If there is one area in the world where carbon capture linked to EOR has the potential to be optimized and implemented on a large scale, it is likely to be the Middle East, and in particular the Gulf Region [40]. The Gulf region is of special interest in that numerous suitable anthropogenic CO_2 sources exist in close proximity to candidate EOR reservoirs. In order to serve the many potential CO_2-EOR projects in the Gulf region, large volumes of CO_2 will be required for injection. It is estimated that some 300–400 million tons of CO_2 will be required for every billion barrels of incremental oil to be recovered by this method [40].Options to provide large volumes of CO_2 to serve EOR projects in the region's giant oil fields are either to ship it in from distant sources, or to produce it locally by capture from the region's industrial facilities such as power and desalination plants, oil refineries, gas processing facilities and/or petrochemical complexes.

The amount of carbon dioxide emissions per capita for some countries is shown in Table 9.

From the published data, the UAE is among the highest in the world in carbon dioxide emissions per capita. For example, Abu Dhabi and nearby emitted about 76 million tons of CO_2 for the year 2008. Forty-three percent (43%) of these emissions are from power-generation plants. These facts underline the need to look toward a more sustainable future for the UAE. The government of the UAE aspires to reduce CO_2 emissions by capturing carbon dioxide from industrial emitters and transporting the CO_2 to oilfields for Enhanced Oil Recovery (EOR). In order to demonstrate and test this concept, Abu Dhabi Company for Onshore Oil Operations (ADCO) recently implemented a pilot-scale CO_2 Enhanced Oil Recovery scheme in one of its onshore oil fields. This is the first ever CO_2-EOR flood to be implemented in the Middle East [40]. In this perspective, Masdar is planning to capture the CO_2 from several industrial sources in Abu Dhabi and nearby. The captured CO_2 will be compressed and transported in a pipeline system to ADCO oil field.

According to Table 9, the major source of CO_2 in the Abu Dhabi is the power-generation plants (43%). Because of the changing weather, the flow rate of the flue gas from these plants is not constant; there is a peak in summer, a minimal value in winter and a mean value during the mid-season. For the plants emitting less than 100,000 metric tons of CO_2, it is recommended to pool the flue gas from different sources and connect them to a single CO_2 capture unit. Assuming that future CO_2 capturing plants will have a production rate of 2 million tons CO_2/year, Masdar might have to build about thirty seven "CO_2 capture" units. To reduce the cost of CO_2 capture in these absorption plants, a blend of low concentration of a Task Specific Ionic Liquid (TSIL) containing amine moiety and a relatively high concentration of an ionic liquid in polymer form is proposed in this paper as a potential solvent for capturing carbon dioxide. In order to avoid corrosion and other technical problems in the facilities and reservoirs due to some contaminants of the flue gas, it is recommended to use only fuel gas as combustible in all industrial plants including the future CO_2 capture units. To increase the resulting low concentration of CO_2 from plants using fuel gas as combustible, part of the flue gas could be recirculated and mixed with fresh air or an air separation plant could be built in order to use oxygen instead of air for the combustion. The cost of the new plant should be added to the total cost of the CCS pant.

Country	CO_2 Emissions (million metric tons)
Qatar	53.5
UAE	**34.6**
USA	17.5
Germany	9.6
Japan	9.5
China	5.3

Table 9: Data from World Environment (2008) [41].

Industry	Millions Tons of CO_2
Power generation plants	33 (43%)
Gas processing & refineries	25 (33%)
Metal industries	15.8 (21%)
Petrochemical plants	2.2(3%)
Total	76

Table 10: Estimated amount of CO_2 by industry in Abu Dhabi and nearby for the year 2008 [43].

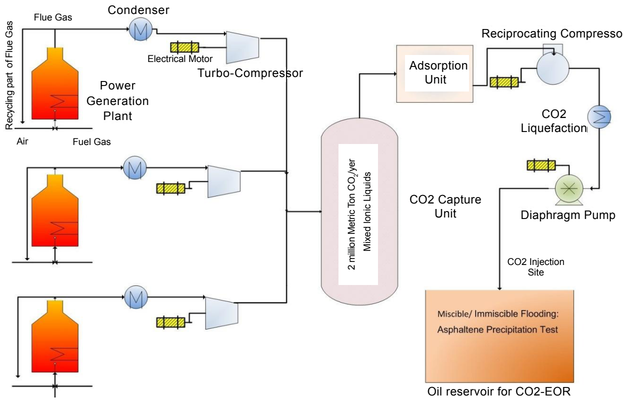

Figure 2: Process Flow Diagram of the proposal.

Compression and transport of CO_2 are major elements in the cost of CO_2 supply. However, in the UAE, numerous suitable CO_2 sources exist in close proximity to candidate EOR reservoirs [41].Therefore, the total cost is mainly due to the compression of flue gas to the absorption units and the compression of CO_2 from the low pressure stripping column to the EOR injection sites. Reciprocating or turbo compressors using electrical energy could be used for the compression of flue gases and a combination of semi-isothermal compression with reciprocating multi-stage compressors with inter-cooling, liquefaction and pumping with diaphragm pumps offering high overall efficiency for CO_2 compression.

Information from ADCO indicate that most of the Abu Dhabi reservoirs fall in the potential CO_2-EOR category because of the high API gravities (31- 42° API) and resident depths between 3500-9500 feet. According to the literature, CO_2 floods are normally carried out in reservoirs that are more than 2,500 ft. deep and oil gravity exceeds 30°API [39]. Therefore Abu Dhabi oil reservoirs satisfy the criteria of CO_2 flooding. Oil reservoirs in Abu Dhabi are also potential candidates for miscible CO_2 flooding because they have a depth higher than the minimum depth for miscibility (4000 ft.) and crude oils have an API density much higher than 22°.

ADCO CO_2-EOR pilot plant is using miscible CO_2 flooding because it is located in an area where the carbonate reservoir is above Minimum Miscibility Pressure (MMP) of CO_2 [42]. Since the objective of any CCS project is to decrease the total amount of CO_2 emitted in the UAE, immiscible CO_2 flooding could be a better option. However, miscible CO_2 flooding is needed because it provides a higher commercial value to help cover the cost of CCS development. To avoid reservoir plugging, it is proposed in this paper to perform an asphaltene precipitation test for all the reservoirs and perform immiscible flooding only for the reservoirs which fail the test. For the other wells, the "New Generation" followed by the "Second Generation" miscible CO_2-EOR techniques will maximize both the oil recovery and the storage of carbon dioxide.

For safety, the possible integrity of reservoir seals must be gauged. The reservoir storage sites should be chosen only if the initial pore pressure gradient is less than about 17.4 kPa/m (Table 10). The effect of oil production on reservoir properties, especially fault movement and induced fractures must also be gauged and included in assessments [38].

A schematic flow diagram, Figure 2, shows the principal steps and equipments of the proposed CCS plant. The significant dependence of compression, transport and storage cost on transport distances, reservoir parameters and capacity factors suggest using a mathematical model in combination with performance and cost of CO_2 capture, compression, transport, and storage technologies to optimize the overall cost of an integrated CCS project.

Finally, if the 76 million metric tons of CO_2 presently emitted by Abu Dhabi and nearby could be stored using the "Next Generation" CO_2-EOR, about 329 million barrels of crude oil could be recovered. Moreover, if the "Next Generation" and "Second Generation" technologies are used simultaneously, about 415 million barrels of crude oil could be recovered [43]. By consequence, CO_2-EOR strategy has the potential to add about 152 billion AED per year to the economy of the UAE. It is then crucial to optimize between CO_2 sequestration and oil recovery by defining the minimum acceptable amount of CO_2 to be stored every year.

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