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GEOLOGICAL CO_2 STORAGE POTENTIAL IN THE ARAB REGION

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1. INTRODUCTION

Carbon dioxide Capture Sequestration (CCS) represents a proven solution for reducing the levels of greenhouse gas carbon dioxide (CO_2) in the atmosphere. Therefore CCS enables to pro-actively operate to face the future challenges of global climate changes.

The Arab region[1] represents one of the world's areas with very high potential forCO_2 generation. Seven countries in this region hold nearly 42% of the estimated 1.6 trillion barrels of proven global crude oil reserves, accounting for almost98% of the proven oil reserves in the region This same group of countries also accounts for over 27% of the world's proven natural gas reserves of over 187Tcm (BP statistical review 2013).The Arab countries produced in 2012 one third of the Global Oil Production and about 20% of the Global Gas Production (BP statistical review 2013).

Fossil fuels production, processing (e.g. refinery) and use (e.g. power generation) is therefore one of the main source of carbon dioxide. Often in connection with the hydrocarbon industry, industrial activities associated with iron and steel factories and cement industry represent also an important source of carbon dioxide which needs to be considered when thinking about the CCS solution.

Overall CO_2 production in the ESCWA region correspond to ca. 331 Mt of CO2 / year which are mostly associated with industrial activities in the GCC countries and three largest North African countries (Libya, Algeria and Egypt, Fig. 1).

This report provides a general overview on the geological capture and storage of carbon dioxide while offering specific insights on the ESCWA region describing the key features and characteristics of the subsurface which may represent important opportunities for implementing CCS.

2. WHAT IS CCS?

Carbon capture and storage or sequestration, also called CO_2 capture and storage (both abbreviated as CCS), is the generic term for a collection of processes with the aim to reduce the CO_2 content in the flue gases of power stations and industrial installations and store it safely to prevent it from entering the atmosphere. These technologies start in the plant by capturing CO_2 or carbon. There are three main routes you can do this. The obvious one is remove the CO_2 from the flue gas before it is vented into the atmosphere. The CO_2 can be 'washed' out of the flue gas, for instance by using a solvent that absorbs CO_2. In a subsequent regeneration step, the solvent releases the CO_2, which is dried, compressed and made ready for transport and storage. This process is called 'post-combustion' because the CO2 is removed from the power generation or industrial process at the end of the pipe, after burning fuels. An alternative is 'pre-combustion' – removing the CO_2 or the carbon from the fuels before they are combusted. This process is often based on a gas shift, where the hydrocarbons in fossil fuels such as coal, natural gas and biomass are converted into a hydrogen-rich gas and CO_2 – which is removed for storage. The third process is the 'oxyfuel' method. By using oxygen instead of air, which only contains twenty percent of oxygen, the combustion of coal or natural gas produces much lower volumes of flue gases with higher concentrations of CO_2. After drying and compressing, the CO_2-rich flue gases can then be directly transported and stored. Depending on the case, removal of some impurities might be required. CO_2 capture processes typically enable some 80-95% of the CO_2 produced to be captured. CO_2 can be transported in different ways. Because of the large volumes involved, pipes are an obvious method. Shipping and trucks are alternatives. The CO_2 can be stored underground in deep geological formations. Aquifers, i.e. geological layers containing saline water, (empty) oil and gas fields, as well as coal beds are all currently the subject of research. Also fixing CO_2 in rocks (mineralization) and industrial applications for using CO_2 are being investigated. Actual experience has been built up in storing CO_2 in oil fields. In order to recover oil more efficiently, the viscosity of the oil is reduced by pumping CO_2 into the field. There is also an equivalent to this 'Enhanced Oil Recovery' technique in gas production, both from gas fields and from coal beds.

3. CAPTURE POTENTIAL IN THE ESCWA REGION

The CO_2 capture potential in the ESCWA region is substantial. On the short and the mid-term the best opportunities are available in industrial activities (cement and steel production) and power generation (gas

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[1]In this study the MENA region includes the following Countries: Morocco, Algeria, Tunisia, Libya, Egypt, Jordan, Lebanon, Syria, Iraq, Bahrain, Qatar, Kuwait, Saudi Arabia, United Emirates Arab, Yemen and Oman.

generated power). In the longer run, CCS might also play a role in the transport sector and households, e.g. by increased use of electricity or hydrogen produced using CCS. Worldwide, electricity generation is currently responsible for about 40% of the energy-related CO_2 emissions. Without additional policies, power demand will double or triple between now and 2050. CCS is expected therefore to play a major role in the "de-carbonization process" over the next decades, allowing time for renewable to be developed and deployed in a cost-efficient way. In industry, CCS is one of the few options that are currently available to substantially reduce CO_2 emissions in sectors such as iron and steel, cement, ammonia and hydrogen production. For the ESCWA region, research conducted by independent organisms (IEA – GHG study) indicate that about 262million tons are produced annually which are relatively low levels compared with some Countries of neighboring regions such as Europe (Fig. 1). Nevertheless, the significant role played by hydrocarbon production and associated flaring practices, the possible expansion of refineries and power plant and growing cement and heavy industry activities in the region, should certainly require an early consideration for CO_2 capture processed during project feasibility stage.

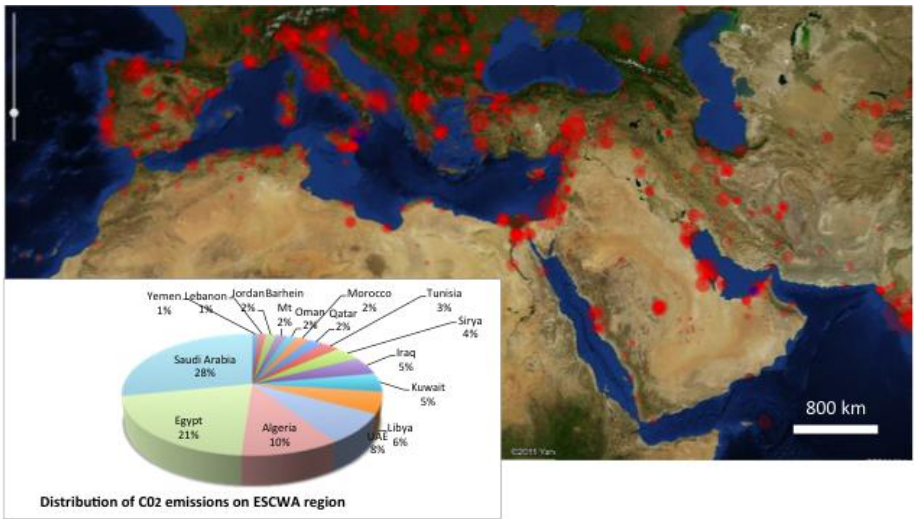

Fig. 1 Geographical outline of the ESCWA and neighbor regions with areas of CO_2 generation. Distribution of CO_2 emissions in the ESCWA region are indicated in the pie-chart (data from IAE's GHG program, modified from http://bellona.org/ccs/)

4.GEOLOGIC FRAMEWORK OF THE ESCWA REGION

The geologic evolution of Africa and the Middle East is recorded in a complex assemblage of rocks that range in age from some of the oldest found on Earth to the present (Fig. 2). They span form the Precambrian age - between 2,500 and 540 million years ago – and the Palaeozoic, Mesozoic and the Cenozoic Era. The geologic evolution of Africa and the Middle East, extending from the Archean to the present, covers much of the history of Earth (ca. 4.5 billion years old).

Rocks found in the MENA region record the conditions of their formation and subsequent evolution through time which occurred in this vast area. For instance, the accumulation of sediments in ancient oceans results in sequences of shale, limestone, and sandstone.

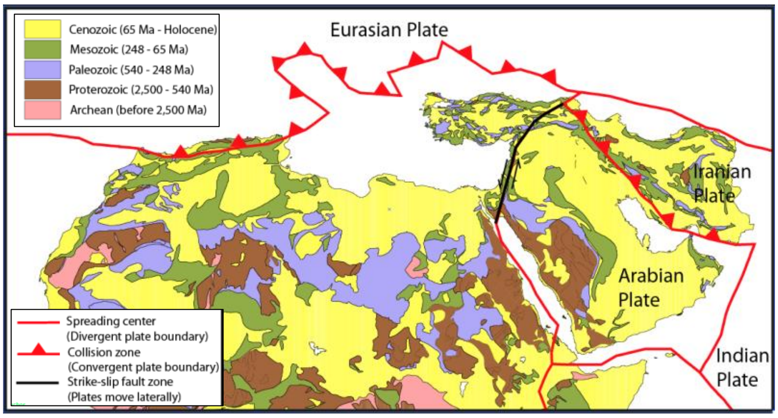

Fig. 2 Geological map of ESCWA and surrounding regions. Most of the areas younger than 248 million of years (Ma) contain large sedimentary basins with vast opportunities for CCS. Areas close to thrusts fronts and strike slip zones are the most tectonically active where CCS projects may be threatened by fault reactivation and leakage following earth quakes.

These sedimentary rocks are changed during deep burial, under conditions of high heat and pressure, into various types of metamorphic rocks such as shale into slate or limestone into marble. Metamorphism is often associated with mountain building and with the melting and intrusion (emplacement) of magma in the crust and volcanism at the surface. These processes formed the oldest rocks in the ESCWA and surrounding regions confined to the Proterozoic basement (Fig. 2). These processes lead to a new cycle of erosion and deposition of sediments in the ocean or in basins on land which filled with time younger sedimentary basins developed during the Palaeozoic and subsequent Era.

These complex phenomena of sediment accumulation and rock formation by burial and tectonic deformation ultimately led to the development of rock strata with different properties such as, for example porous sandstones, fractured carbonates and impermeable shales. It is in this context that rocks developed different properties which make them behaving differently with respect to fluid flows in the subsurface. Porous rocks, either because of intergranular space or occurrence of fracture can contain them, allowing their movement through them; on the other hand cemented rocks or very fine grained rocks such as slates and shale rich carbonates (marls) may behave as impermeable media, holding for instance high pressure fluids.
In this context several stratigraphical units in the ESCWA region spanning from the Palaeozoic to Cenozoic Era can contain reservoir and seal pairs (Fig. 3), which coupled with favourable tectonic conditions (folding or faulting) can form ideal trapping conditions for subsurface fluids.

These conditions together with extended hydrocarbon generation in several areas of the ESCWA region, resulted in accumulations of vast amount of oil and gas which have been explored and developed since the late 1930s. An estimated two-thirds of the world's ultimately recoverable oil is in the Arabian-Persian Gulf Region and in the Greater Arabian and Greater Oman Basins (Ahlbrandt et al. 2000). Most oil is generated and produced from Jurassic carbonates; however, Cretaceous, Paleozoic, and Infracambrian petroleum systems account for production in numerous giant oil fields in reservoirs of equivalent age.
Similarly, North African basins such as the northern Red Sea, Sirte, Pelagian, Illizi, Gadamesh, and Grand Erg are rich in petroleum because it comprised a really extensive depositional platform along a pre-Mesozoic passive margin of Gondwana. Subsequent development of intra-platform basins, extensive source-rock deposition within these basins, and multiple tectonic stages of compression and extension, produced large subtle structural closures coincident with peak oil generation and migration. Moreover, the large resource base was secured by efficient horizontal hydrocarbon migration into traps underlying thick, regionally extensive seals. Overall, geographically extensive source, reservoir, and seal rocks characterize each several of these prolific hydrocarbon producing systems. Relatively less prolific areas from hydrocarbon prospectivity, such as the western North Africa region do have comparable geological setting which can generate large opportunities for geological storage of CO_2.

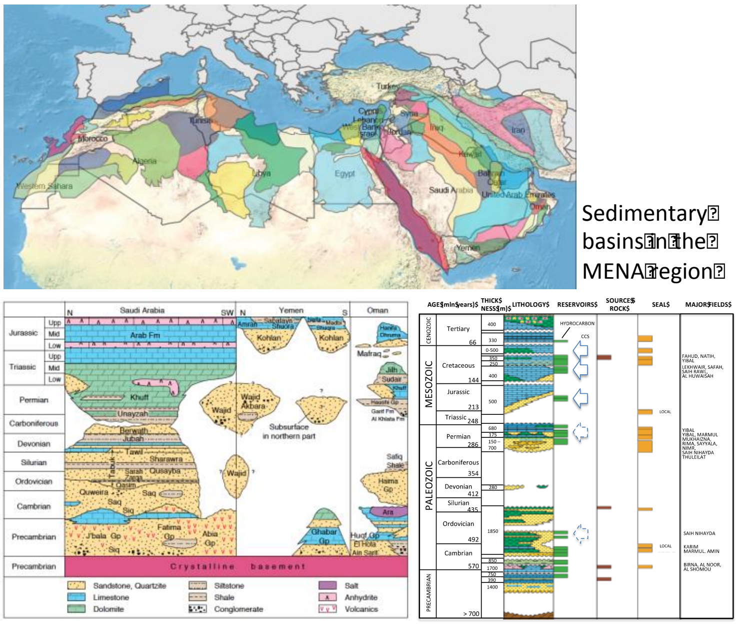

Fig. 3.Distribution of the main sedimentary basins in the ESCWA and surrounding regions with examples of chronostratigraphic charts across Saudi Arabia, Yemen and Oman highlighting the heterogeneity between different areas (white space indicate absence of rocks of a given age) and a specific stratigraphy of a basin (Oman) with reservoir and seal pairs which can be considered for CCS projects.

5. Subsurface trapping of CO_2: a review and potential applications in the ESCWA region

One of the most common CCS development techniques is to inject the captured CO_2 into saline aquifers, empty or producing gas or oil fields, or possibly coal seams (Fig. 4).

CO_2 Injection in to saline aquifers

Amongst the various possibilities of storing CO_2 in the subsurface, injection into deep saline aquifers, generally at depth of over 1 km, provides the highest storage capacity. It has been estimated that world aquifers could provide a storage capacity of up to 1 $x10^{13}$tons of CO_2 (Ormerod, 1994), which is enough to store several hundred years of the world's CO_2 emission or enough to store the CO_2 produced while generating about $2x10^{16}$ kWh electricity (current CO_2 emission rate for developed countries is about 500 g per kWh of electricity generated).

During this process CO_2 may be sequestrated through three main mechanisms (Piri et al., 2005):

1) Supercritical CO_2 can form its own phase whose plume size and the extent to which it comes in contact with the brine is controlled by relative permeability, gravity and heterogeneity of permeability field. This is the mechanism by which most of the injected CO_2 is stored and it could be in two form within the formation, either as a large continuous plume which moves while more CO_2 is injected or as a randomly distributed trapped stagnant clusters.
2) CO_2 may get dissolved in the brine lowering its pH forming an acidic solution. The dissolved CO_2 will travel away from the injection well due to dispersion, molecular diffusion and Darcy velocity of the aqueous phase. The concentration of CO_2 in the liquid phase is controlled by salinity of the brine, pressure, temperature, and geochemical reactions with primary minerals of the host rock that may also dissolve into the aqueous phase.
3) Homogeneous and heterogeneous chemical reactions of free and dissolved CO_2 with the primary minerals of the formation which are also subject to dissolution in the liquid phase may produce secondary minerals with low solubility that could precipitate resulting in indirect carbon sequestration. The reaction rates are relatively slow and consequently this mechanism of sequestration becomes important over larger time scales. The extent to which this mechanism is capable of storing CO_2 is directly affected by rock type, sedimentary structure, mineralogy and diffusion.

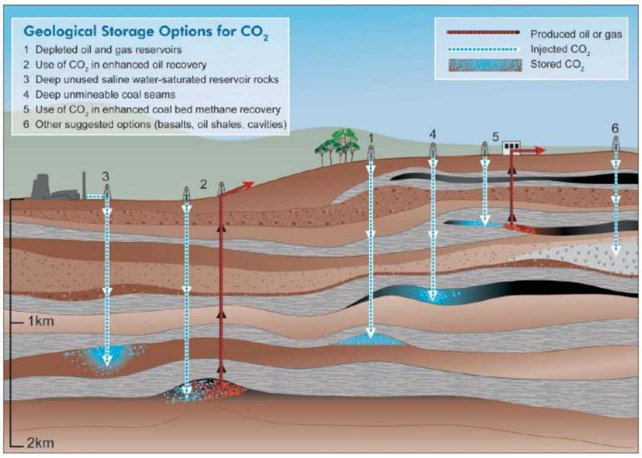

Fig. 4: Variety of options for the long-term subsurface storage of CO_2 (from www.co2crc.com.au)

Given the complex range of processes described above, in order to determine the feasibility of deep aquifer sequestration it is necessary to accurately predict the fate of CO_2 under the conditions of interest. Numerical models (Piri et al., 2005, Sato et al., 2006) have been developed in order to include variety of complex physical processes such as transport of components due to advection and dispersion, complex three-phase multicomponent phase behavior, geomechanics effects, heterogeneity in the permeability field, geochemical/ chemical reactions and hysteresis in relative permeability and capillary pressure. Experiments also indicate that CO_2 injection tends to precipitate salts that hinder injection, but that this can be solved by pre-injection of fresh water.

In the ESCWA region multiple options for saline aquifer injection exists. The relatively well established knowledge of the subsurface stratigraphy developed by hydrocarbon exploration and production activities over the last 70 years provides a very good basis to identify reservoir & seal pairs, essential for storing effectively CO_2 (Fig. 3)

<u>CO_2 Injection into depleted gas reservoirs</u>
One of the most common CCS development techniques is to inject the captured CO_2 into empty gas or oil fields, saline aquifers or possibly coal seams. Given the relatively small scale of natural gas production in the ESCWA region compared to oil, empty gas reservoirs may not offer the most promising and accessible opportunity in the short term. Such reservoirs, which typically lie at a depth of 3-6kilometers, consist of sandstone or carbonate layers covered by impermeable ‘caprocks’ that have sealed in the natural gas for tens or even hundreds of millions of years.

<u>CO_2- Enhanced Oil Recovery (EOR) practices</u>
Injection of CO_2 into oil reservoirs is a common hydrocarbon industry practice for nearly 30 years which has been successfully proven to enhance the oil recovery (EOR). This process may be performed by recycling natural CO_2 already existing in the subsurface associated with the hydrocarbons or by using captured ‘man-made’ CO_2 produced by large point sources such as industrial processes. In both cases, this practice can contribute greatly in reducing greenhouse gas emissions while allowing for maximized oil production.
The mechanisms for CO_2-EOR can be of different nature whether CO_2 will be dissolved or not within the oil (e.g. miscible or immiscible mechanisms).
Miscible CO_2-EOR is a multiple contact process, involving the injected CO_2 and the reservoir’s oil. During this multiple contact process, CO_2 will vaporize the lighter oil fractions into the injected CO_2 phase and CO_2 will condense into the reservoir’s oil phase. This leads to two reservoir fluids that become miscible (mixing in all parts), with favorable properties of low viscosity, a mobile fluid and low interfacial tension.
The primary objective of miscible CO_2-EOR is to remobilize and dramatically reduce the after water flooding residual oil saturation in the reservoir’s pore space.
Figure 5 provides a one-dimensional schematic showing the various fluid phases existing in the reservoir and the dynamics of the CO_2 miscible process.

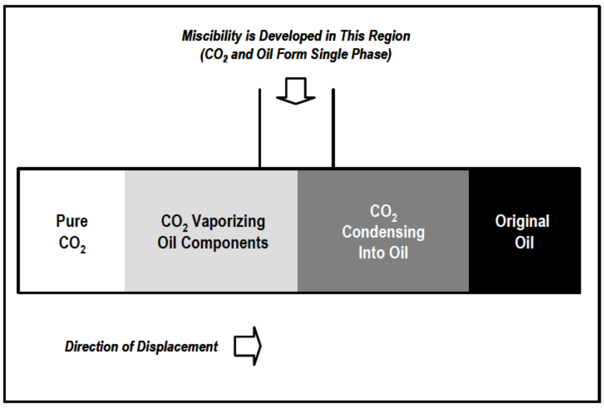

Fig. 5: One-Dimensional Schematic Showing the CO_2 Miscible Process

When insufficient reservoir pressure is available or the reservoir's oil composition is less favorable (heavier oil), the injected CO_2 is immiscible with the reservoir's oil. As such, another oil displacement mechanism, immiscible CO_2 flooding, occurs. The main mechanisms involved in immiscible CO_2 flooding include oil phase swelling and consequent viscosity reduction extraction of lighter hydrocarbon into the CO_2 phase and, fluid drive plus pressure. This combination of mechanisms enables a portion of the reservoir's remaining oil to be mobilized and produced. In general, however, immiscible CO_2-EOR is less efficient than miscible CO_2-EOR in recovering the oil remaining in the reservoir.

In the ESCWA region a number of important CO_2-EOR projects have been implemented. These are for instance the Harweel cluster in Oman (operated by PDO), the pilot study in the Rumaitha onshore field in Abu Dhabi (operated by Total) or more importantly the North-East Bab Field where back in 2009 the Abu Dhabi Company for Onshore Oil Operations (ADCO) initiated an EOR project to test the injection of CO_2 in a complex carbonate reservoir. Masdar, a subsidiary of Mubadala is supplying up to 60 tons of CO_2 per day which is injected into a series of pilot wells. In Saudi Arabia, Aramco is currently evaluating the use of CO_2 injection and plans a series of pilot programs in mature fields like Ghawar (40 mlns cf/day of CO_2). Although full-scale EOR implementation is still 20 to 30 years away, the feasibility studies form part of Aramco's carbon management road map, in which they wish to be engaged in developing EOR technology for global carbon management.

CO_2-EOR typically follows traditional improved oil recovery practices such as water injection or water flooding. CO_2–EOR is typically for the so-called "difficult reservoirs" containing "stranded oil" which become technically recoverable using CO_2 flooding technology. As usual, an economic study considering both costs for CO_2 and oil prices needs to be performed to assess the viability of these applications (e.g. cost of CO_2–EOR vs. cost of more intense infill drilling and secondary, water flooding oil recovery practices).

CO_2-Enhanced Gas Recovery (EGR) potential

Little experience exists on recycling natural CO_2 or captured industrial CO_2 emission to enhance recovery in gas reservoirs. However this has been proven technically feasible and economically viable in the K12-B gas field, located in the Dutch sector of the North Sea.

In this field currently operated by GDF Suez E&P Nederland B.V. the sandstone reservoir lies at a depth of approximately 3800 meters below sea level, and the temperature is about 127ºC. After *circa* 20 years of production the initial reservoir pressure of 400 bars dropped to 40 bars. The natural gas initially contained 13% of CO_2. Since the start of gas production, the CO_2 has been separated from the gas stream on-site and since 2004 part of the separated CO_2 was re-injected into the gas field. The sustained pressure in the reservoir through CO_2 injection might likely extend the lifetime of the producing field. However, early CO_2 breakthrough underground from depleted to almost depleted reservoir departments would make production uneconomical. This is why the flow and mixing of natural gas and CO_2 in the reservoir are being studied and closely monitored by use of tracers. The latter allow accurate assessment of the flow behavior in the reservoir and the associated sweep efficiency of the injected CO_2. Nevertheless, the most important results of the tests at K12-B have been that CO2 injection has been proved feasible and that it can be conducted safely. The

CO2 injection did not have any negative effects regarding the gas production and infrastructure under the conditions of the K12-B field.
In the ESCWA region, CO_2-EGR may be considered for those gas reservoirs rich in natural CO_2. This process may therefore both enable sequestration of carbon emissions and maintain reservoir pressure allowing overall better field performance.

Storing CO2 in coal bed seams.
Storage of CO2 in underground coal seams can also be considered as a considerable option for carbon sequestration. The so-called enhanced coal bed methane (ECBM) process stores CO2 in the coal seam, which in turn pushes out the coal gas (methane) and thus increases primary methane production. In the ESCWA region, there has been a considerable amount of coal production in Morocco, Algeria and Egypt which was generally dismissed in the early 2000. Although the coal may not be mined economically, the seams could contain considerable amounts of coal gas (methane, CH_4). This suggests the possibility of storing CO_2 in coal seams, with the spin-off of methane extraction. The combination of large sources of CO_2 and storage potential makes this an attractive option. However, the technology is not yet mature. There has so far only been one large-scale pilot programme. From 1996 to 2000, Burlington Resources injected CO_2, successfully enhancing the production of Coal Bed Methane (CBM) in New Mexico and Colorado (USA). Following this pilot, a few small ECBM pilots have been conducted worldwide, such as the Recopol project in Poland.

6. THE MAIN ISSUES RELATED TO SUBSURFACE CO_2 TRAPPING

To maximize the performance of a CCS project while minimizing the related risks, it is important to understand the fate of CO_2 injected into the subsurface and to determine how effectively it will be trapped. Four important issues here are i) the potential for enhancing gas recovery by injecting CO_2, ii) the degree of corrosion along the injection tubing, iii) the behaviour of the CO_2 and vi) the response of the reservoir (Fig. 6).
Since many natural gas reservoirs around the world also contain CO_2, storage of CO_2 in reservoirs is already proven by nature. However, in order to reduce the risk of undesired leakage through the overburden rocks, it is important to understand the fundamental physical and chemical processes controlling injection and trapping of CO_2.
In particular, the main issues are related to the physical and chemical reactions which can be induced in the subsurface by the interaction between CO_2 rich fluids and the minerals forming the hosting reservoir rocks. Modification may also affect the overlaying seal rocks therefore threatening its seal integrity and the surrounding rocks causing deformation of the neighboring area.

Subsurface mineralization:
When CO_2 is injected into an empty gas reservoir, it first fills the rock inter-granular pore space or empty fractures that were previously occupied by natural gas. It also gradually dissolves in the saline pore water or 'formation fluid' that generally occupies the lower levels of the reservoir. A major part of the stored CO_2 will therefore reside in the reservoir's pore space and in the formation fluid. However, some CO_2 will also react chemically with some of the minerals present in the reservoir rock, notably feldspars, clays and oxides that contain significant amounts of calcium, iron or magnesium. These reactions have the potential to fix CO_2 permanently in the subsurface as insoluble carbonates and clays. Injected CO_2 thus becomes converted into new minerals within the reservoir rock. This process, known as subsurface mineralization, is very attractive as it completely immobilizes stored CO2 in solid mineral form, reducing the risk of any long-term leakage. On the other hand, whether subsurface mineralization will occur to a useful extent in a given reservoir, how long it takes, and whether it might have any disadvantageous side effects are all questions that need to be addressed in developing a geological storage strategy.

Caprock and fault integrity:
Ongoing research is focusing on to the crucial issue of the effects of mechanical damage and chemical reaction on caprock integrity. For example, anhydrite formation (e.g. gypsum) often associated with rock salt sequence is highly resistant to mechanical damage and little affected by chemical interaction with CO_2 and water, retaining its integrity under a wide range of in-situ conditions. Geochemical reactions of CO_2 with the

minerals present in the seal could also improve the sealing properties in time. On the other hand, pre-existing faults in the material seem to rapidly react with CO2. The impact of this on sealing capacity is not yet clear. To ensure permanent storage of CO_2 within the reservoir rock it is imperative that faults would not behave as transmissible features to the overburden rocks. The reactions of the minerals with CO_2-loaded fluids can lead to a substantial mineral re-arrangement on the long term. Overall, an increase in volume (thus a decrease in porosity) is more likely than a decrease in volume. Fractures may be initiated and their propagation will depend on the rock property of the caprock. Physical experiments carried out in the Holland Greensand in The Netherlands for instance show that for this specific case, fractures may propagate upwards into the top seal (more than 100 meters layer of marl) only at most by 6 meters. The potential for re-activation of the faults will need to be assessed carefully to avoid artificial triggering of earthquakes.

<u>Well integrity:</u>

Well and surface facilities surveillance and management is a particularly important aspect of the CCS projects as corrosion and subsequent leakage related problems may seriously impair the efficiency of the operations.

Vintage cement plugged and abandoned wells may be sensitive to corrosive, CO_2 loaded fluids which may also corrode the well casing (in) the lower oil reservoir. However literature review shows that CO_2 corrosion rates based on diffusion processes are very low and recent experiments (CATO, 2010) indicate that Portlandite is likely to act as a buffer to protect the steel casing from corrosion although the presence of Portlandite may be limited in the long term, considering the amount of CO_2 that is intended to be injected into the reservoir.

There is also the risk of preferential pathways in the cement being present which lead the CO_2 in the formation water directly to the casing. After an initial phase of relatively fast corrosion of the steel casing, the process will slow down.

<u>Field monitoring:</u>

Once the CO_2 has been injected, the monitoring process is key to demonstrating that CO_2 remains contained in the intended storage sites. A wide range of monitoring tools are available to understand the behavior of the CO_2 plumes in the subsurface, including '3D surface seismic', 'geophysical well logging', 'down-hole fluid chemistry', 'pressure-temperature monitoring', subsurface and seabed imaging, surface deformation monitoring using satellite (e.g. InSAR, Vasco et al., 2010). The choice of the tools to be deployed depends on a number of site characteristics (location, depth, injection volume etc.), the technical information (objectives) required from the monitoring programme and, of course, the costs.

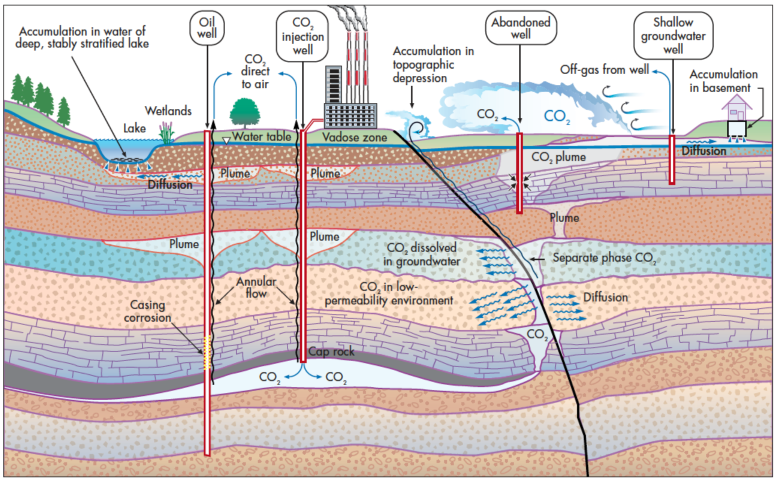

Fig. 6. Properly located, engineered, and managed geological CCS reservoirs are expected to retain stored CO2 for hundreds to thousands of years. Effective monitoring systems however, will have to consider possible underground CO2 migration paths through soils and groundwater and likely escape routes, including seismic fissures, abandoned water wells, and the injection wells themselves (from Douglas, 2003)

<u>Safety:</u>

When investigating underground CO_2, the technologies deployed are essentially the same as used for hydrocarbon exploration. However, it is crucial to show stakeholders and the general public that CO_2 can be injected safely and effectively. In particular, it must be shown that a method for risk management of CO_2 storage works and therefore a safe and effective containment of injected CO_2 is possible. With respect to safety, a great deal of attention should be paid to the integrity of the seal, faults and the wells themselves, in order to make sure that injected CO_2 cannot escape. The compatibility of CO_2 with the reservoir from chemical and physical point of view, the ground movement following the injection and related monitoring requirements need also to be investigated.

Typically production of natural hydrocarbons from both porous and fractured reservoir has left the space for injecting and storing CO_2. The extraction has therefore reduced the pressure in the reservoir, which will increase again when CO_2 is injected. As soon as the reservoir pressure approaches the initial pressure, injection should be stopped. Most of the CO_2 will then be structurally trapped in the reservoir that originally was filled with hydrocarbons. Only a small amount is expected to dissolve in the ambient formation water or to mineralize.

7. The In Salah CCS project:A success story in the ESCWA region

One of the most important industrial-scale and world-leading example of CCS process is in the ESCWA region. This is the In Salah gas storage project in Algeria in operation since 2004(Bisselet al., 2010; Vasco et al., 2010). More than three million tons of CO_2, separated during gas production, have been securely stored in a deep saline formation. BP, Sonatrach and Statoil, the project operators, aim to store a total of 17 million tons over the next 20 years. The In Salah project is of global significance, providing assurance that secure industrial-scale geological storage of CO_2 is a viable option for climate change mitigation. The project is supported by the US Department of Energy and the EU. The Carbon Sequestration Leadership Forum has identified In Salah as a key example helping to demonstrate the viability of CCS technology.

The In Salah CCS operation in fact refers to the Krechba Field. The chosen injection site, is located the down dip of the gas producing field. The CCS reservoir comprises 20 m thick Carboniferous sandstone, at a depth of 1900 m, forming the aquifer of the main gas reservoir. As the reservoir rocks have low porosity (13-20%) and permeability (10mD) the injected CO_2 is also used to enhance gas production (EGR). The reservoir is sealed by 950 m of Carboniferous mudstones, then a 900 m of Cretaceous sandstone and mudstone. Before CO2 injection commenced, the risk of leakage was assessed, a monitoring programme was designed to address the most-likely risks, and the 5 year Joint Industry Project (JIP) was set up to monitor CO2 migration and verify long term storage. The JIP is financed by BP, Sonatrach and Statoil with government co-funding from the US Department of Energy and the EU DG Research.

8. CCS geological storage selection

An extended CCS programme in the ESCWA region will require a screening exercise where both geological and geographical feasibility should be used ultimately supported by economic criteria.

<u>Geological feasibility</u>: Sedimentary basins and related reservoirs should be studied in detail in order to focus in identifying both the nature of the reservoir/seal pair and the suitability for CO_2 injection (see Chapters 5 and 6).

As far as injecting CO_2 in depleted or producing hydrocarbon reservoirs in the ESCWA region the second opportunity seems the most likely given the relative immaturity of most of the fields. For CO_2 -EOR use, five main screening criteria can be used to identify favorable reservoirs. These are: reservoir depth, oil gravity, reservoir pressure, reservoir temperature, and oil composition. As far as deep saline reservoirs, the good level of knowledge of the subsurface stratigraphy developed through the past years by the oil & gas industry, gives us already a good understanding of potential targets for injection. However, further investigations should be carried out in area far away from hydrocarbon development centers where subsurface data are more rare or inexistent. . In any case, both options assume that a comprehensive program of research, pilot tests and field demonstrations will be carried out before routine implementation.

<u>Geographical feasibility</u>: cost-effective CCS projects are typically developed in proximity of CO_2 sources which in the ESCWA region are mainly gas power plant, oil power plants, cement factories and refineries (Fig. XXX). Those activities are mostly located close to the coast of the ESCWA countries and not necessarily close to the most suitable location for injection using CO_2 –EOR process. In this case injection

into deep saline aquifers may be the most likely way forward. An accurate study of the ‘source and sink’ location should be carried out and evaluation of possible co-operations between neighboring countries. This will imply common medium to long term energy policy vision which will need to be supported by cross border operational agreements.

Economic criteria: these will have to be carefully established by considering cost of technology and their implementation. However, legislation may examines how the economic potential of CCS projects could be increased through a strategy involving state production tax reductions, state investment tax credits, royalty relief. In the case of CO_2-EOR or CO_2-EGR projects higher world oil and gas prices would add value to the price that the producer uses for making capital investment decisions.

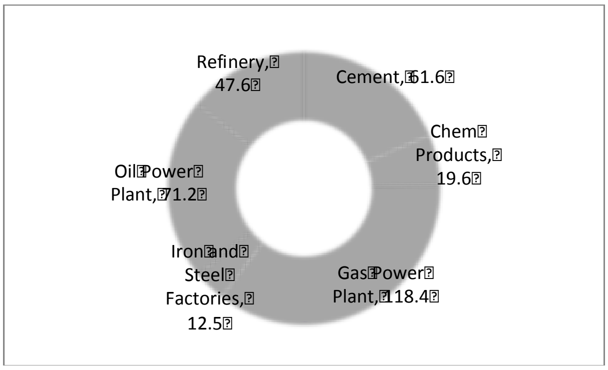

Fig. 7. Distribution of type of man-made CO_2 source in the ESCWA region (data from IEA GHG, 2008)

9.CONCLUSIONS

The overall geological characteristics of the ESCWA region support an extended CCS programme throughout all countries examined. The complexity and heterogeneity of situations (e.g. geology, location of source compared to injection location), however, make the CCS development complex and country specific. Typically CCS projects require more time than conventional hydrocarbon projects as feasibility study followed by pilot and demonstration will still be required. The practice of geological trapping of CO_2 can still be considered in fact at the juvenile stage and several technical aspects still require investigation and testing (e.g. rock-fluid interaction, caprock and fault integrity, prosecution technology, field monitoring). Both generic and site-specific studies will still be needed in future to assess any risk of leaking posed by the combined effects of mechanical stresses and chemical reactions resulting from CO_2 injection.

Good planning and understanding of all risks and opportunities of individual projects is deemed necessary. CO_2 injection in saline aquifers can be considered the most likely to be implemented and possibly the option which may offer most cost effective conditions. In the case of CO_2-EOR projects, the knowledge of the future projects and early implementation of the actual EOR phase can bring a larger amount of incremental oil production and early stage implementation will be certainly beneficial.

Given the relative rare occurrence of coal-bearing formation, ECBM in the ESCWA region may not see large scale development in near future except on those countries where coal is available (Morocco, Algeria).

10.REFERENCES

Ahlbrandt T. S., Pollastr R. M., Klett T. R., Schenk C. J., Lindquist S. J., and Fox J. E. 2000 Region 2 Assessment Summary – Middle East and North Africa. U.S. Geological Survey Digital Data Series 60

Askri H., Belmecheri A., Benrabah B., Boudjema A., Boumendjel K., Daoudi M., Drid M., Ghalem T., Docca A. M., Ghandriche H., Ghomari A., Guellati N., Khennous M., Lounici R., Naili H., Takherist D., Terkmani M. Geology of Algeria. Schlumberger WEC Sonatrach, 93 pp.

Baines SJ &Wordon RH (2004. geological storage of carbon dioxide. *Geological society, Sp. Publ. 233, 255 p.*

Bissell R.C., Vasco D. W., Atbi M., Hamdani M., Okwelegbe M., Goldwater M.H. 2010 A Full Field Simulation of the In Salah Gas Production and CO2 Storage Project Using a Coupled Geo-mechanical and Thermal Fluid Flow Simulator. Energy Procedia, 9 pp.

BP Statistical Review of World Energy June 2013,bp.com/statisticalreview

Canty D. 2012 Enhanced oil recovery leaders in the Middle East. arabian oilandgas.com June 11th, 2012.

CATO 2010: Catching carbon to clear the skies. Experiences and highlights of the Dutch R&D programme on CCS www.co2-cato.nl

Douglas J., Wilson T. and Rhudy R. 2007 Expanding Options for CO2 storage. ESPRI Journal, Spring 2007, 24-29

Fleming G. 2013 EOR and IOR in the Middle East, Manaar Energy Consulting

IEA - International Energy Agency (2008b). CO_2 capture and storage.A key carbon abatement option.Energy Technology analysis. IEA/OECD.

IPCC - Intergovernmental Panel on Climate Change (2005). B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer (eds.). Carbon capture and storage, special report, Cambridge University Press, UK. Available on line at http://www.ipcc.ch/

Macgregor, D.S., Moody, R.T.J., and Clark-Lowes, D.D., eds., Petroleum geology of North Africa: Geological Society, London, Special Publication 132.

Mathieson A., Midgley J., Dodds K., and Wright I., Ringrose P. and Saoula, 2010, CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria, The Leading Edge, February 2010, p216.

Ormerod, B. 1994 Tech. Rep. IEAGHG/SR3-229, International Energy Agency (IEA), Paris, France, greenhouse Gas R& D Programme.

Piri M., Prévost J. H. and Fuller R. 2005 Carbon Dioxide Sequestration in Saline Aquifers: Evaporation, Precipitation and Compressibility Effects Department of Civil and Environmental Engineering Princeton University, Princeton, NJ 08544, 1-19.

Ramírez A., S. Hagedoorn, L. Kramers, T. Wildenborg and C. Hendriks (2008). Screening CO2 storage options in the Netherlands, Energy Procedia.

Rodosta T. D., Litynski J. T., Plasynski S. I., Hickman S., Frailey S. Myer L. 2010. U.S. Department of Energy's Site Screening, Site Selection, and Initial Characterization for Storage of CO2 in Deep Geological Formations EnergiProceedia.

Rojey A &Torp TA. 2005. Capture et stackage géologique du CO2: état de l'art. *Oil and Gas science and technology, IFP, 60/3*

Stevens S. H., Kuuskraa V. A., Gale J., Beecy D. Article CO2 Injection and Sequestration in Depleted Oil and Gas Fields and Deep Coal Seams: Worldwide Potential and Costs Environmental Geosciences, Volume 8, Issue 3, pages 200–209

Tatsuya Sato T., White S. P. and Xue Z. 2006, Numerical modeling of CO2 injection test at Nakaoka test site in Nigata, Japan PROCEEDINGS, TOUGH Symposium 2006, Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006

UNIDO Project 2011 Global Technology roadmap for CCS in industry. Sectorial Assessment CO2 Enhanced Oil Recovery

Vasco DW, Rucci A, Ferretti A, Novali F, Bissell RC, Ringrose PS, Mathieson AS & Wright IW. Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide. Geophysical Research Letters, 2010;37:L03303

VilarrasaV.,Silva O., Carrera J., Olivella S. 2013. Liquid CO_2 injection for geological storage in deep saline aquifers International Journal of Greenhouse Gas Control Volume 14, Pages 84–96

Consulted Web sites:

http://bellona.org/ccs/
http://ieaghg.org/
http://www.insalahco2.com/
http://www.ifp.fr/IFP/fr/
http://www.clubco2.net
http://www.co2crc.com.au/
*http://www.epa.gov/climatechange/**ccs**/*
http://www.shell.com/global/environment-society/environment/climate-change/ccs
http://www.bp.com/statisticalreview