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Potential research of carbon (iv) oxide enhanced oil recovery (CO_2-EOR) in Middle East

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Anthropological carbon (iv) oxide (CO_2) emissions to the atmosphere are identified as a major driver for the global warming effect. Major CO_2 emissions sources are located within power and industrial sectors where fossil fuels are consumed to generate energy. With the anticipated escalation of global energy demand, CO_2 emissions are also expected to grow. Therefore, reducing CO_2 emissions to atmosphere is a fatal issue worldwide. Capturing CO_2 from emissions sources and injected into safe geological places for storage shows a practical mitigation strategy through CO_2 capture and storage (CCS) practices. In CCS projects, several options are available for CO_2 storage such as subsurface aquifers, coalbed bed methane formations, or depleted oil and gas reservoirs. Alternatively to these storage places, CO_2 can be utilized to enhance oil production from mature oil reservoirs. Utilization of CO_2 in enhanced oil recovery techniques (EOR) is a well known practice in oil industry. Therefore, synchronizing between the objectives of storing CO_2 and enhancing oil production to meet global demand can be achieved through CO_2-EOR projects. The giant oil reservoirs in the Middle East represent potential places for CO_2-EOR projects. In this paper, oil reservoirs located in the Middle East are selected to evaluate the potential of CO_2-EOR projects in the region. These reservoirs were subjected to CO_2-EOR screening where the fluid and rock properties are compared with a well known criteria. Furthermore, an analytical model is used to predict the performance of CO_2-EOR in these reservoirs. The results showed that implementing CO_2-EOR practices would enhance the oil recovery while storing a considerable amount of CO_2 in these reservoirs.

Key words: Carbon (iv) oxide enhanced oil recovery (CO_2-EOR), capture and storage (CCS), green house gases (GHG), Middle East.

INTRODUCTION

The challenges facing offshore CO_2 enhanced oil recovery (EOR) and carbon capture and storage (CCS) projects are presented in this paper along with potential solutions based on the oil and gas (O&G) industry's CO_2 EOR and CCS experience and technology as applied in a few offshore locations. Prospects for future offshore projects are also discussed based on the O&G industry's experience, technology, and best practices. These achievements are the result of a safe and successful 58-year history of well construction and operations in land-based, commercial CO_2 EOR projects.

Achieving CCS by injecting CO_2 into saline formations

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or for EOR in mature oil reservoirs is a safe and effective method to reduce GHG (greenhouse gas) emissions. The Intergovernmental Panel on Climate Change (IPCC) has defined enhanced oil and gas recovery via CO_2 injection as a recognized form of CCS. Using existing industry experience and technology developed over the past 58 years, CO_2 injection into oil reservoirs for EOR has been safely and effectively applied in 18,077 active wells worldwide (17,112 in USA) according to the latest EOR survey (O&GJ, 2010). Production from natural gas reservoirs has also benefitted from CO_2 injection in enhanced gas recovery (EGR) applications.

Records of earth surface temperature show an increasing trend in the recent years. Figure 1 shows a history of the annual average of the earth surface temperature during 1880 to 2008 (Goddard Institute for Space Studies). During the last century, the annual average of earth surface temperature increased by 0.74°C. Many researchers define this growing trend as Global Warming Effect which is a result of an increase in the concentrations of some gasses. These gases, which are known as Green House Gases (GHG), include mainly Carbon (iv) oxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O). According to the global warming theory, GHG allow sunlight to enter the atmosphere freely; however, they absorb the heat from the reflected sunlight. The annual average of earth surface temperature would be about (-19°C) rather than the present average of 14°C without GHG effect (Treut et al., 2007). However, increasing GHG concentrations in the atmosphere allows for more heat absorption and ultimately a rise in earth surface temperature.

Table 1 shows the concentrations of the main GHG in the atmosphere (Carbon Dioxide Information Analysis Center) with CO_2 representing more than 99%. The role of each gas in the global warming phenomenon is based on gas heat retention capacity, therefore; the contributions of GHG to the global warming effect is defined by the Global Warming Potentials (GWP) which represent the ratio of heat retention capacity of a specific GHG to that of CO_2 (United State Greenhouse Gas Inventory Program). Table 1 shows the concentrations and contributions of each GHG. CO_2 contributes to more than 73% of the global warming effect followed by N_2O (18.96%) and CH_4 (7.09%).

SOURCES OF CARBON (IV) OXIDE (CO_2) EMISSIONS

Carbon (iv) oxide (CO_2) emissions sources are classified as natural or anthropological sources. The natural sources include animal and plant respiration, ocean-atmosphere exchange, and volcanic eruptions; whereas, the anthropological sources include burning of fossil fuels to generate energy and as products of some industrial processes United Nation Environment Programme (UNEP) estimated that emissions of CO_2 from natural sources are 20 times greater than those from anthropological sources (United Nations Environmental Programme). However over a long period of time, the natural emissions sources are closely balanced by natural CO_2 sinks. As a result of this balance, CO_2 concentrations remained between 260 and 280 ppm for the last 10,000 years (Denman et al., 2007). Human activity increased CO_2 emissions to the atmosphere starting from year 1750, when the industrial era started (IPCC, 2001), and continue to increase strongly in the current years. Figure 2 shows the development of CO_2 concentration in the atmosphere for the period 1980 to 2008 (Environmental Protection Agency). CO_2 concentration ascended from 338 ppm in 1980 to 385 ppm at the beginning of 2008. This represents an annual increase rate of 1.6 ppm, and accordingly if this rate is persisted, CO_2 concentration might reach 400 ppm in the next decade. This increase is driven by the growth of anthropological CO_2 emissions to the atmosphere. Figure 3 shows the global CO_2 emissions from petroleum, natural gas and coal consumption for the period 1980 to 2005 (Energy Information Administration). Annual CO_2 emissions rose rapidly from 18 billion tones in 1980 to 28 billion tones in 2005. This represents an annual rate of increase of 400 million tones. The main rationale behind this trend is due to the development in global energy demand.

The development of Arab World share to the worldwide CO_2 emissions is shown in Figure 4. In 1980, the Arab world contributed 2.8% to the global CO_2 emissions which rose to 4.7% in 2005 representing 1316.8 million tones. Figure 5 shows the CO_2 emissions for the Arab world countries at the end of 2005 where Saudi Arabia, Egypt, and UAE accounted for more than 50%.

CARBON (IV) OXIDE (CO_2) CAPTURE AND STORAGE (CCS)

The first patent for CO_2 EOR was granted in 1952 (Whorton). The Texas Railroad Commission (TRRC report) proposed CCS rule states that “the first three projects (immiscible) were in Osage County, Oklahoma from 1958 to 1962.” Another early CO_2 EOR project was in Jones County, near Abilene, Texas in the Mead Strawn field in 1964 (Holm). The first large-scale, commercial CO_2 EOR project (Langston) began operations in 1972 at the SACROC field in West Texas, which continues in operation today. Many more CO_2 “flood” EOR projects have started since then. By 2010, CO_2 EOR projects had reached a global total of 127 (112 in USA) with 12 more

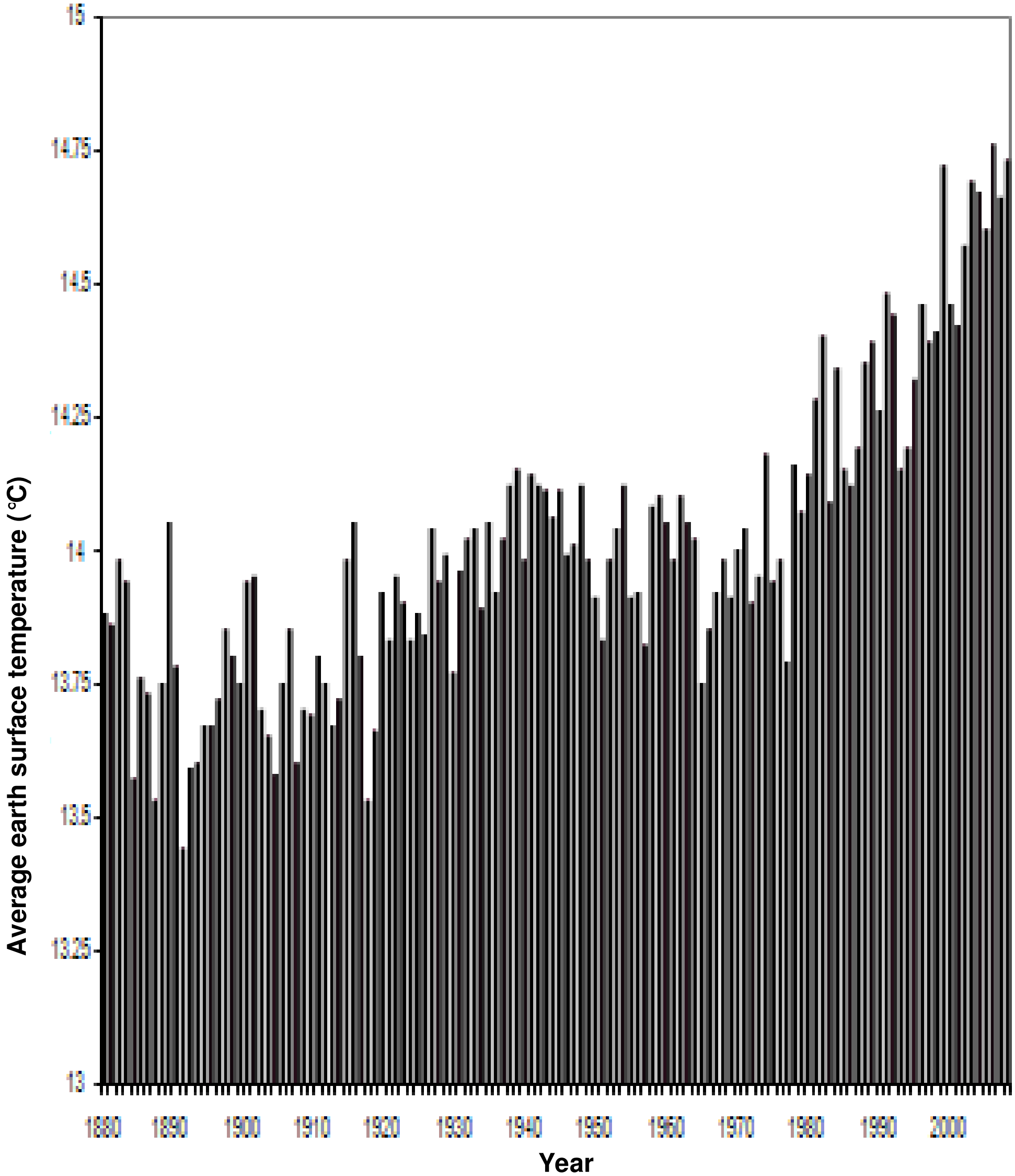

Figure 1. Development of the annual average of the earth surface temperature (1880-2008).

Table 1. Recent GHG concentrations in the atmosphere.

GHG	Concentration (ppm)	Percentage of total (%)	Multiplier (GWP)	Relative contribution	Percentage of total (%)
Carbon (iv) oxide (CO_2)	385.69	99.464	1	385.69	73.95
Methane (CH4)	1.76	0.454	21	36.96	7.09
Nitrous Oxide (N_2O)	0.319	0.082	310	98.89	18.96
Total	387.769	100		521.54	100

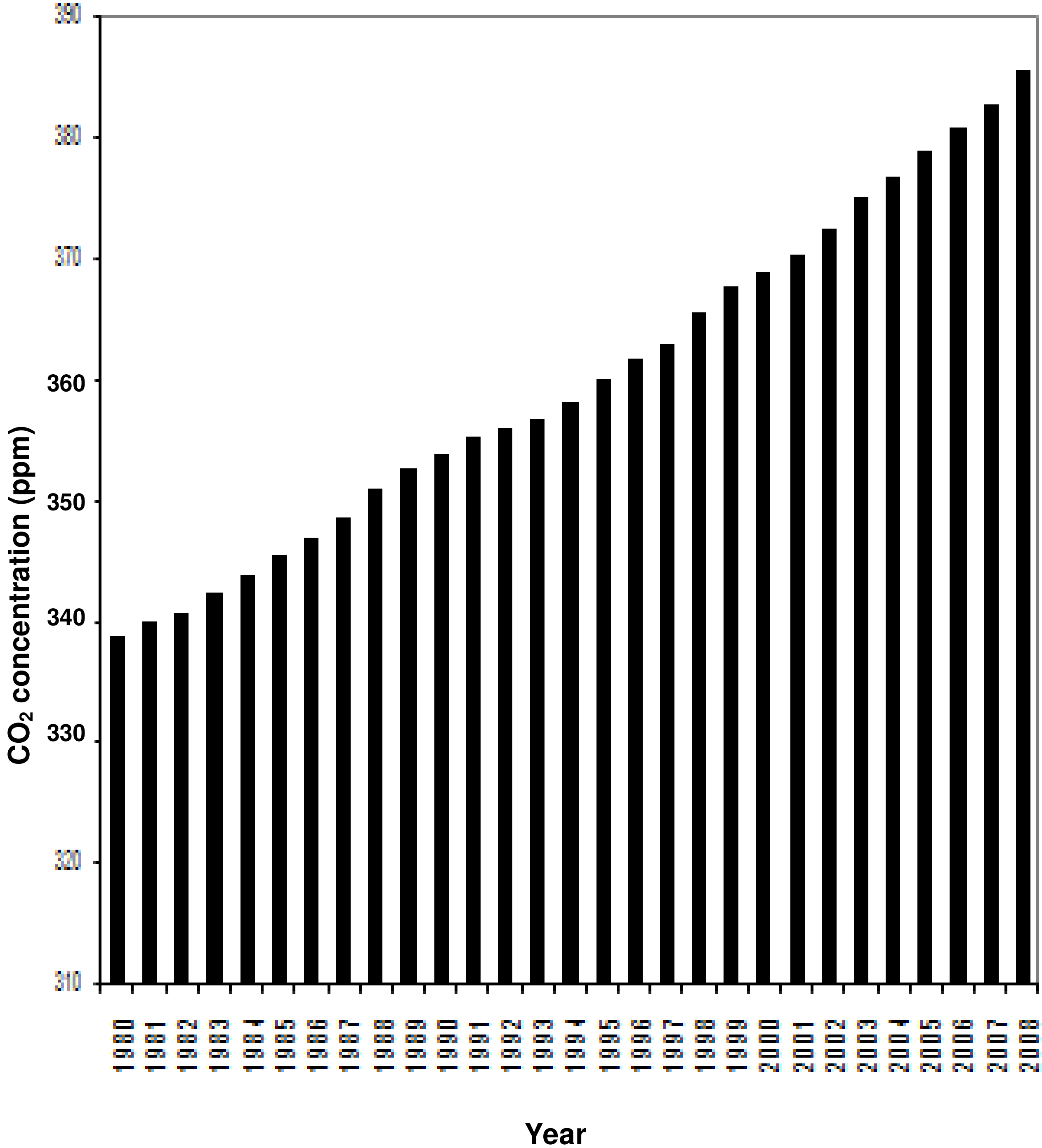

Figure 2. Development of CO_2 concentration in the atmosphere (1980-2008).

planned for the USA, as reported in the EOR survey by the Oil and Gas Journal (O&GJ, 2010). Rising oil prices, low cost sources of high purity CO_2, and access to miscible fields with large amounts of unrecovered oil have supported growth in CO_2 based EOR in the U.S., which now accounts for 272 mbd (O&GJ, 2010) or over 8% of total Lower 48 crude production of 3.22 mmbd in the 2nd quarter 2010, as reported by the U.S. Energy Information Administration.

Due to the expected growing energy demand, the

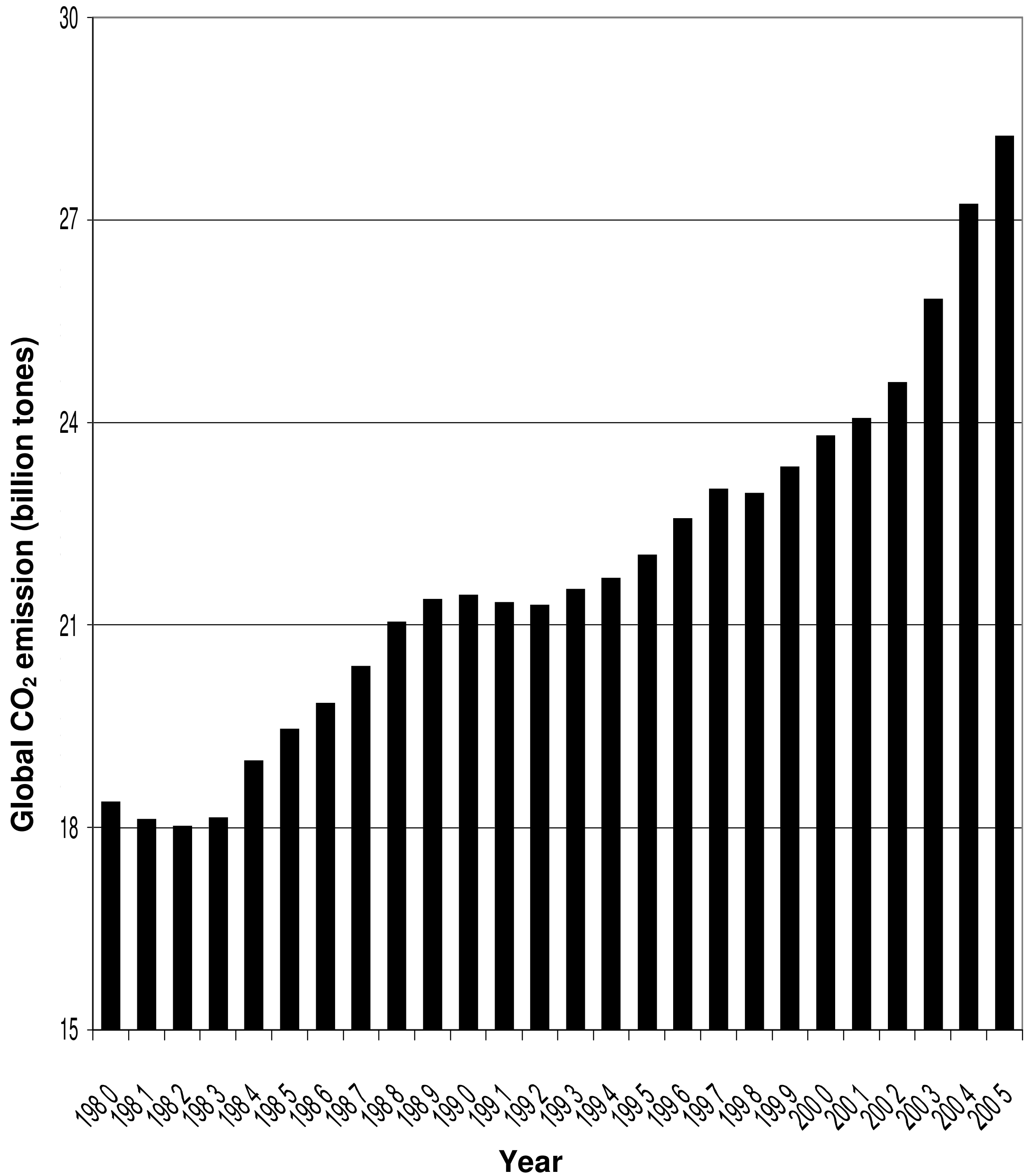

Figure 3. Development of worldwide CO_2 emissions (1980-2005).

emissions of CO_2 will grow in the future. Figure 6 shows the future energy demand as predicted by EIA (Rajesh et al., 2004). Energy consumption in industrial and transportation sectors represent over 80% of the future energy demand. These sectors are anticipated to emit large quantities of CO_2. In order to minimize the global warming effect; efforts are currently focused on ways and techniques to capture CO_2 from large emissions sources

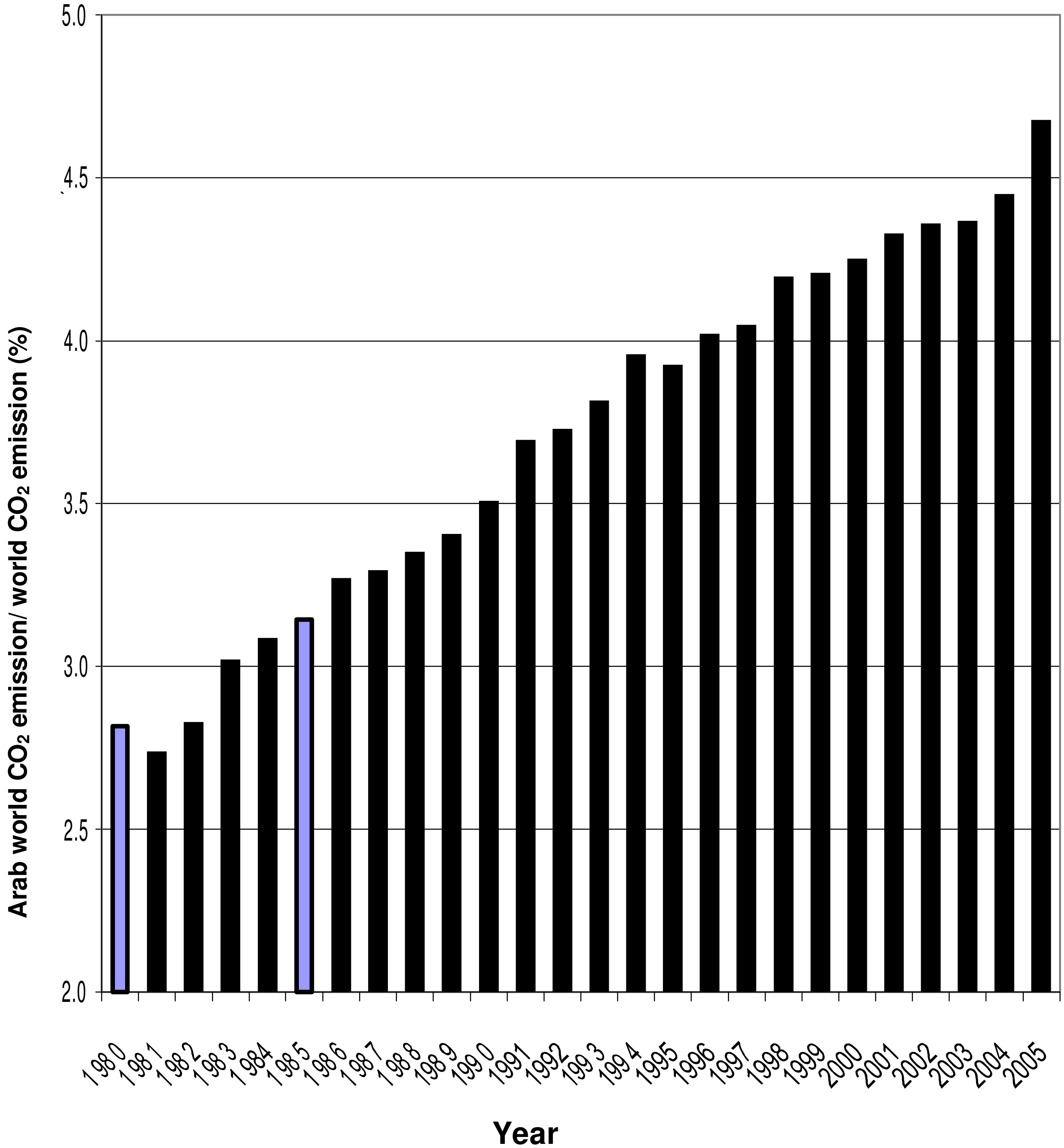

Figure 4. CO_2 emissions from Arab World (1980-2005).

and store them in safe geological formations. Recently, CO_2 Capture and Storage (CCS) practice shows a practical mitigation strategy in order to reduce CO_2 emissions to the atmosphere. In CCS projects, CO_2 is captured from emissions sources and injected into safe places for storage. The possible geological venues to store CO_2 are: depleted oil or gas reservoirs [(10)], saline aquifers, coal bed methane formations (Wong et al., 2000), and in mature hydrocarbon reservoirs to enhance oil production (Picha, 2007; Feng,, 2010; IPCC, 2005).

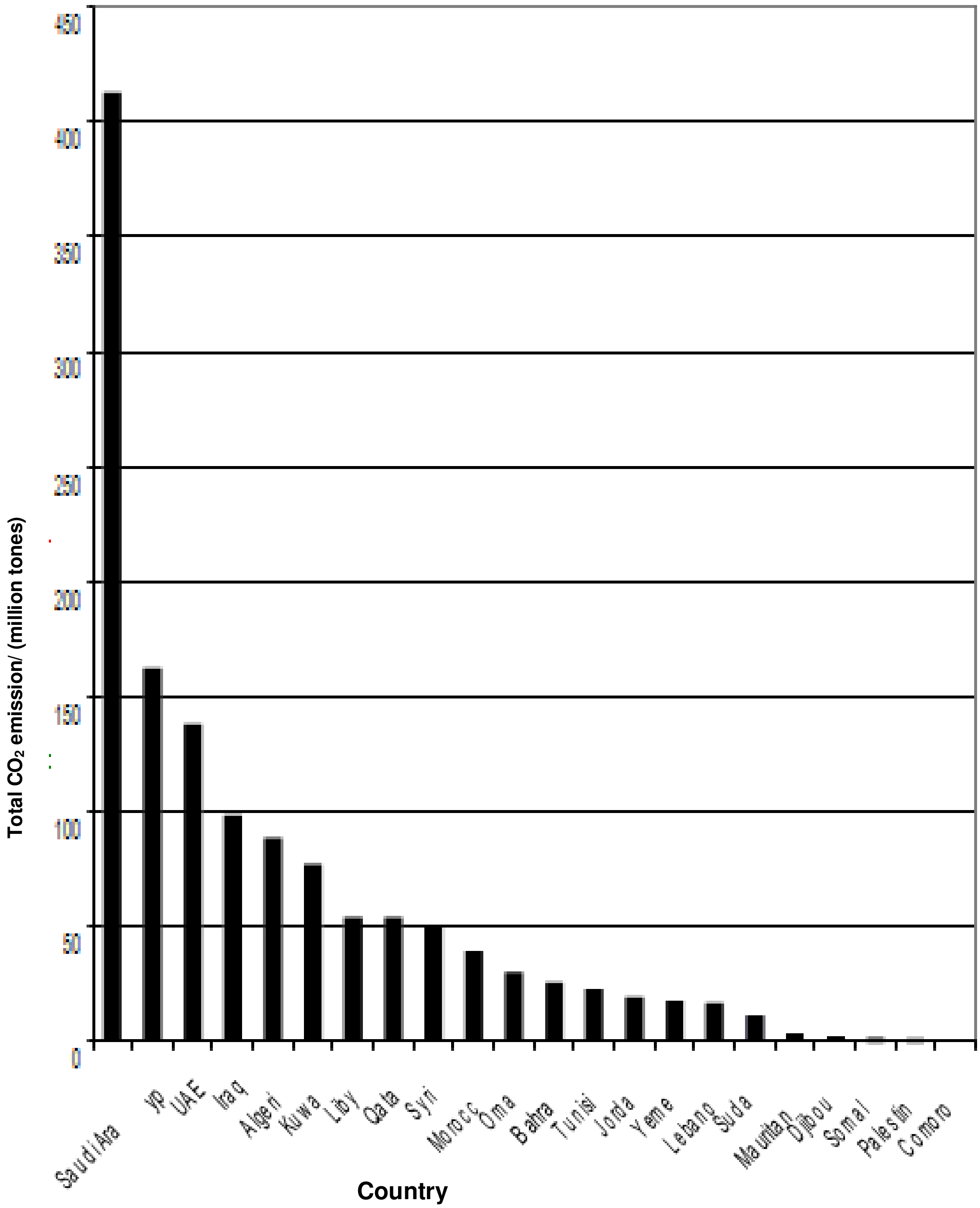

Figure 5. CO_2 emissions from Arab World countries in 2005.

Currently, there are a number of CCS projects around the world in which CO_2 is being captured and stored into geological formations. Table 2 shows a listing of some CCS projects with their corresponding CO_2 storage venues (Zhao et al., 2011; Herzoq, 1999) Most of these projects utilize CO_2 in EOR activities or

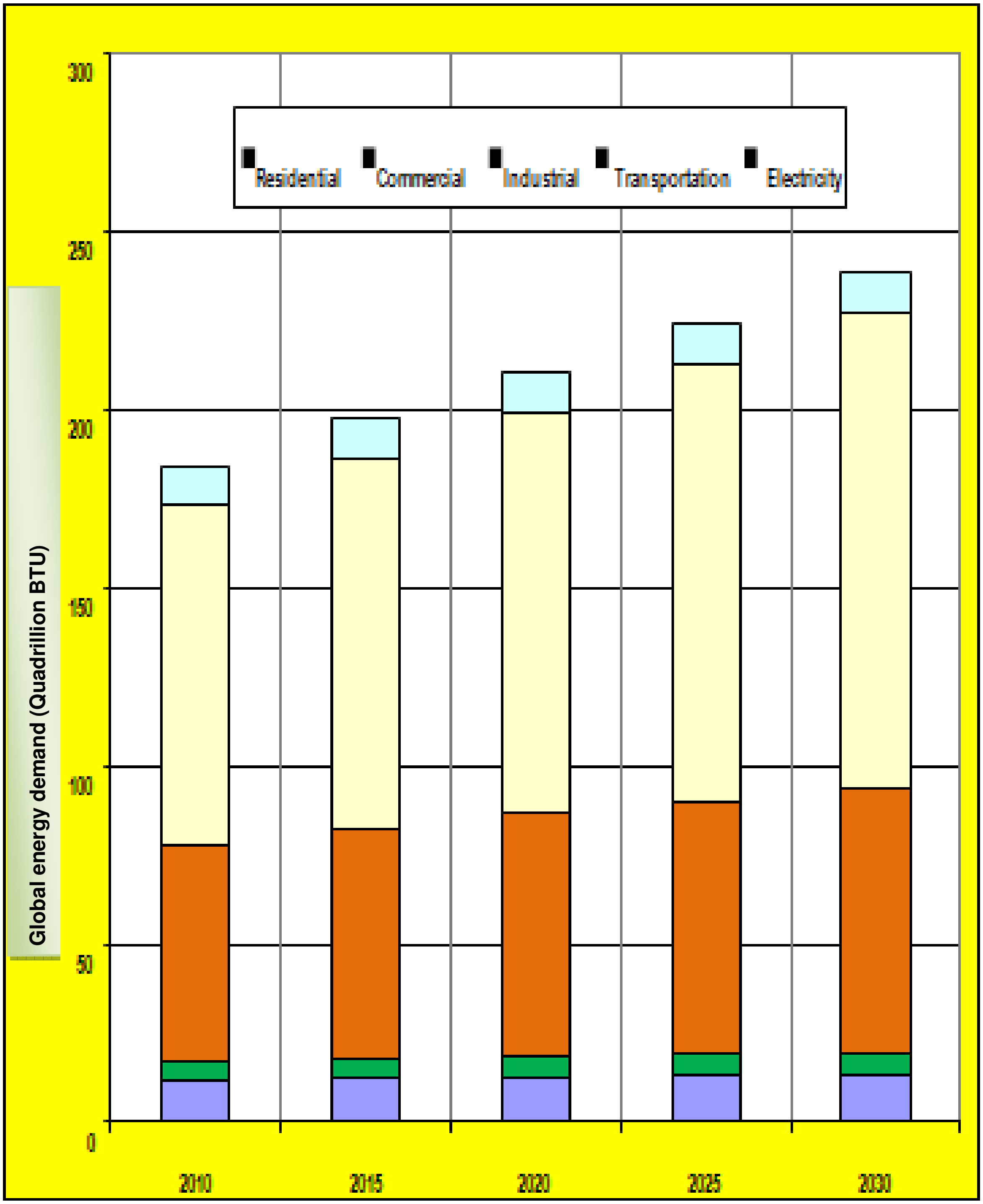

Figure 6. Future energy demand

saline aquifers storage. Four of the reported projects are in the operational phase: GdF K12B, BP in Salah, Statoil SLEIPNER, and N-ReN Southwest; whereas the remaining are either in research or planning phases.

THE FUTURE OF CO_2-EOR PROJECTS IN THE ARAB WORLD

The current utilizations of CO_2 in the Arab World are

Table 2. Worldwide CCS projects.

No.	Project name	Year	Status	CO_2 storage venue
1	GdF K12B	2004	Operational	Depleted Reservoir
2	CO_2 GeoNet	2009	Research phase	EOR
3	CO2 Remove	2009	Research phase	EOR
4	BP in Salah	2004	Operational	Deep saline aquifer
5	Statoil SLEIPNER	1996	Operational	Deep saline aquifer
6	CO_2SINK	2009	Research phase	Deep saline aquifer
7	STATOIL/Shell HALTEN CO2	2011	Planned	EOR
8	Statoil Mongstad Ph1	2010	Planned	Deep saline aquifer
9	Statoil Mogstad Ph2	2014	Planned	EOR
10	Naturkraft Karsto	2009	Planned	Deep saline aquifer
11	CASTOR	2008	Research phase	Deep saline aquifer
12	BP-CARSON	2011	Planned	EOR
13	BP-MILLER	2010	Planned	EOR
14	HYPOGEN	2012	Planned	EOR
15	DYNAMIS	2009	Research phase	EOR
16	EON IGCC	2011	Planned	Deep saline aquifer
17	RWE ZEIGCC	2014	Planned	Deep saline aquifer
18	Carbon (iv) oxide Technology	NA	Shut	EOR
19	Mitchell Energy	NA	Shut	EOR
20	TOTAL LACQ	2009	Planned	Depleted reservoir
21	VATTENFALL OXYFUEL	2015	Planned	Deep saline aquifer
22	VATTENFALL SP	2008	Planned	Deep saline aquifer
23	N-ReN Southwest	1985	Operational	EOR

limited mainly to industrial purposes. For example, CO_2 is being used in chemical, pharmaceuticals, food processing, and beverages industries. Currently, a joint venture between Sonatrach, BP and Statoil, operates a CCS project to capture 1.2 million tones of CO_2 annually from a natural gas stream in Algeria and inject it back into water aquifer (Wright, 2007). This is the only known CCS practice in the Arab World; however, great efforts are now initiated regionally to improve the contribution of Arab World in reducing CO_2 emissions. Saudi Arabia, for instance, has recently contributed $300 million to research and development programs related to climate change activities (The Guardian, 2007).

Moreover, Kuwait, Qatar and UAE pledged an additional $150 million each for similar purposes.

The promised utilization of CO_2 in the Arab World is in the field of Enhanced Oil Recovery (EOR). Abu Dhabi, for example, announced the initiation of a strategic project to capture CO_2 from major existing and future emission sources and delivers it to oil fields for enhanced oil recovery purposes (Abu Dhabi Future Energy Company). The estimated $2 billion project would limit greenhouse gas emissions by capturing around 90% of the CO_2 generated, and permanently storing up to 1.7 million tones of CO_2 per year into geological formations. This is believed to be equivalent to decarbonizing Abu Dhabi's entire domestic transport sector. The project is planned for commercial operation in 2012.

The employment of CO_2 in EOR is a well known practice in the oil industry, in which CO_2 is injected into hydrocarbon strata to reduce oil viscosity and expands oil volume. Generally, it takes about 6 to15 thousand cubic feet of CO_2 to produce one barrel of oil (Pariani et al., 1992; Masoner et al., 1996). Currently, more than 38% of the daily EOR oil production in USA is due to CO_2- EOR techniques (Moritis, 2008). Figure 7 shows the development of oil production due to CO_2-EOR in USA for the period 1986-2008. The daily oil production rate exhibits a continuous growth with time. Figure 8, on the other side, shows the number of active CO_2-EOR projects in USA for the same period. Currently, there are more than 100 CO_2-EOR active projects which represent more than 57% of the total EOR projects in the USA.

Recently, many oil reservoirs in the Middle East approach their technical limit of primary oil production which necessitates the introduction of new energy to further exploit these reservoirs. Algharaib conducted an EOR screening study over 107 Middle Eastern oil

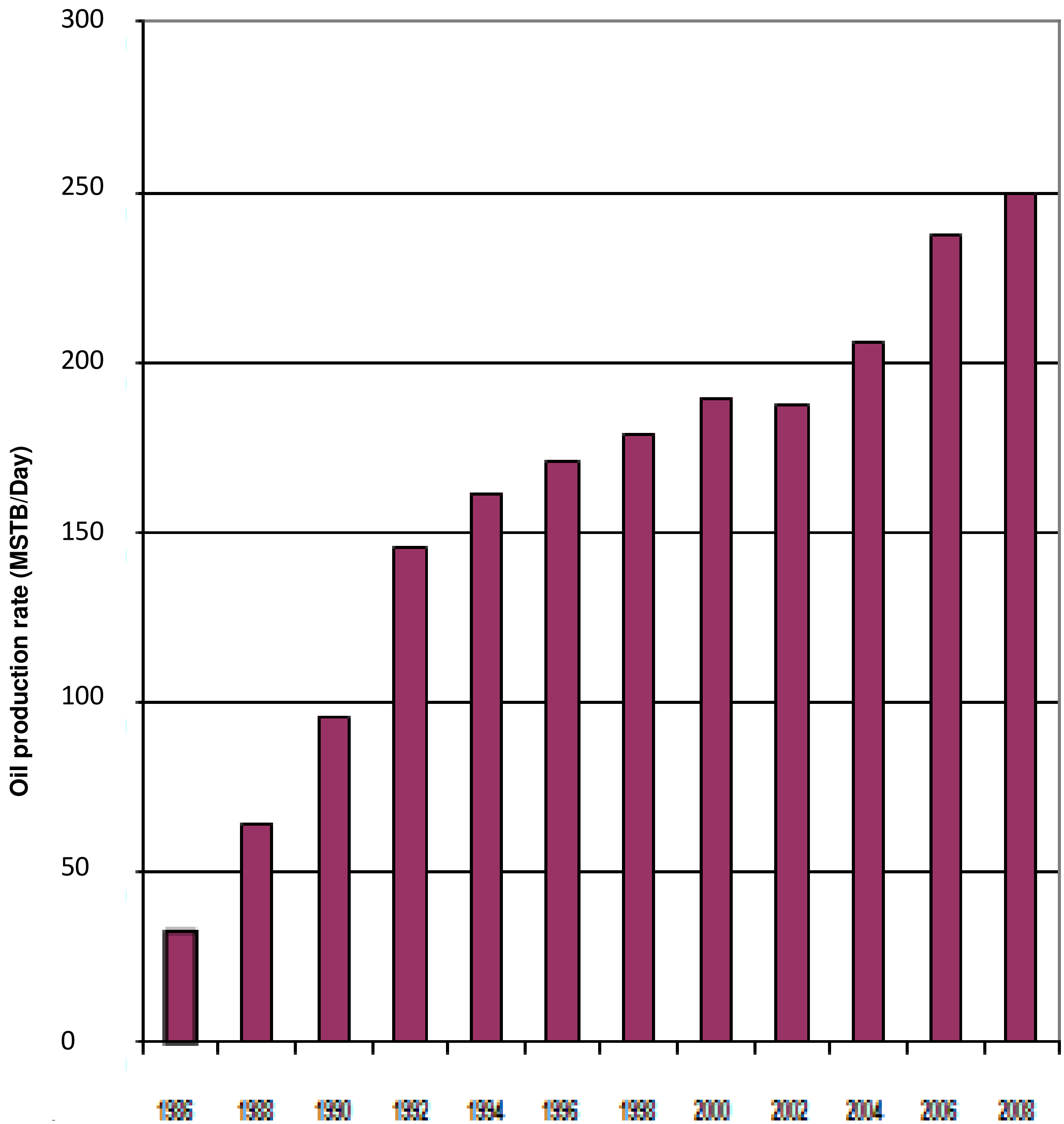

Figure 7. Daily oil production from CO_2-EOR in USA (1986-2008).

reservoirs to evaluate the applicability of CO_2-EOR projects (Algharaib, 2008). The reservoirs' properties were subjected to CO_2-EOR screening where the suitability of these reservoirs to CO_2-EOR applications was checked against a well known criteria. Since these criteria are based on a worldwide experience, CO_2-EOR screening task is expected to highlight the anticipated challenges for field applications. Table 3 shows the geographical distribution of the selected reservoirs and the results of the screening test. The results show that 64 reservoirs, out of 107, passed the screening criteria for CO_2-EOR applications and are recommended as potential places for CO_2-EOR projects. Furthermore, Table 4 shows the recommended ranges of reservoir fluid and rock properties to pass the screening criteria (Li et al., 2012) and the failure frequency of each screening parameters in the selected reservoirs. All reservoirs met temperature, density, saturation, and fracture

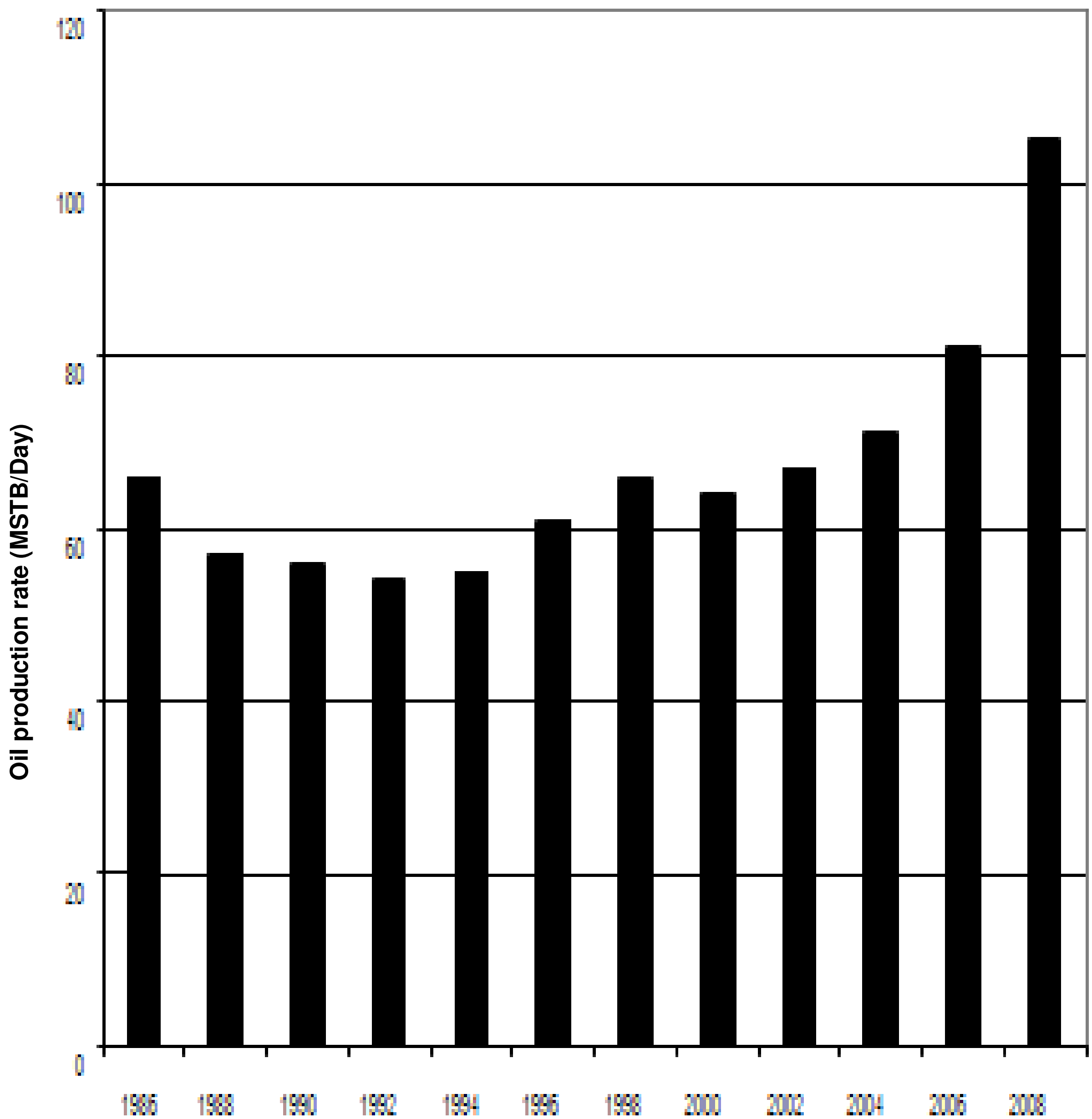

Figure 8. Development in the Number of CO_2-EOR Projects (1986-2008)

pressure criteria, while, failing to meet the minimum miscibility pressure and the presence of gas cap criteria represent more than 75% of the screening failures.

The reservoirs passing the EOR screening test were subjected to further investigations to determine the expected performance of CO_2-EOR applications. An analytical predictive tool, which is developed by DOE and known as "CO_2 Miscible Flood Predictive Model", was used for this purpose (Department of Energy, 1986). During the performance prediction task, the incremental oil produced due to CO_2-EOR, the amount of CO_2 stored, and CO_2 effectiveness ratio were determined. The performance predictions runs were based on implementing a CO_2-EOR project on a 40-acres spacing with a five-spot well arrangement. The overall assessment of CO_2-EOR applications shows promising results.

The Figure 9 show the incremental oil produced due to CO_2-EOR applications. Incremental oil produced ranges from 2,700 to 42,800 barrel of oil per acre-foot.

Table 3. Geographical distribution of the selected reservoirs.

Country	No. of reservoirs	No. of reservoirs met screening criteria	No. of reservoirs failed screening criteria
Algeria	2	2	0
Bahrain	2	0	2
Egypt	29	14	15
Iraq	7	3	4
Kuwait	5	4	1
Natural Zone	4	2	2
Libya	9	8	1
Mauritania	1	0	1
Oman	11	4	7
Qatar	10	6	4
Saudi Arabia	9	8	1
Sudan	1	0	1
Syria	2	0	2
Tunisia	4	3	1
UAE	11	10	1
Total	107	64	43

Table 4. CO_2-EOR screening criteria.

Screening criterion	Value	No. of failed reservoirs
Reservoir depth (ft)	> 1968	2
Reservoir temperature (°F)	> 86	0
Initial pressure > Minimum miscibility pressure	yes	16
Oil density (lbm/ft^3)	< 57	0
Oil viscosity (cp)	< 10	8
Minimal presence of gas cap	yes	17
CO_2 Miscibility pressure < Fracture pressure	yes	0
Current oil saturation, fraction	> 0.25	0

Figure 10, on the other hand, shows the cumulative mass of CO_2 stored in these reservoirs in terms of tones per acre-foot, at the end of CO_2-EOR. The variation in reservoirs storegability is a function of reservoir properties. The amount of CO_2 stored ranges from 300 to 8,500 tonnes per acre-foot. Figure 11 shows CO_2 effectiveness ratio, which represents the volume of injected CO_2 to produce one barrel of oil. As mentioned previously, this ratio generally ranges from 6 to 15. Lower effectiveness ratios represent an effective CO_2-EOR project where smaller amount of CO_2 are required to produce on barrel of oil. In this study, the resulted effectiveness ratios range from 2 to 23.

Although the current implementation of CO_2-EOR projects is driven by oil prices and the global energy demand, CO_2 capture and storage in geological formations is technologically feasible and could play an important role as a climate change mitigation approach. The possible inclusion of CCS projects under Clean Development Mechanisms (CDM) raises a number of issues such as CO_2 leakages from pipelines and through formations and identifying the appropriate CO_2-EOR project boundaries (Algharaib and Abu, 2007). The individual components of CO_2-EOR projects are well developed, but they need to be integrated into a full scale project for further economical and technical assessments (International Energy Agency). For example, implementation of a full scale CO_2-EOR project where CO_2 is captured from a power station and injected into a hydrocarbon reservoir would increase the

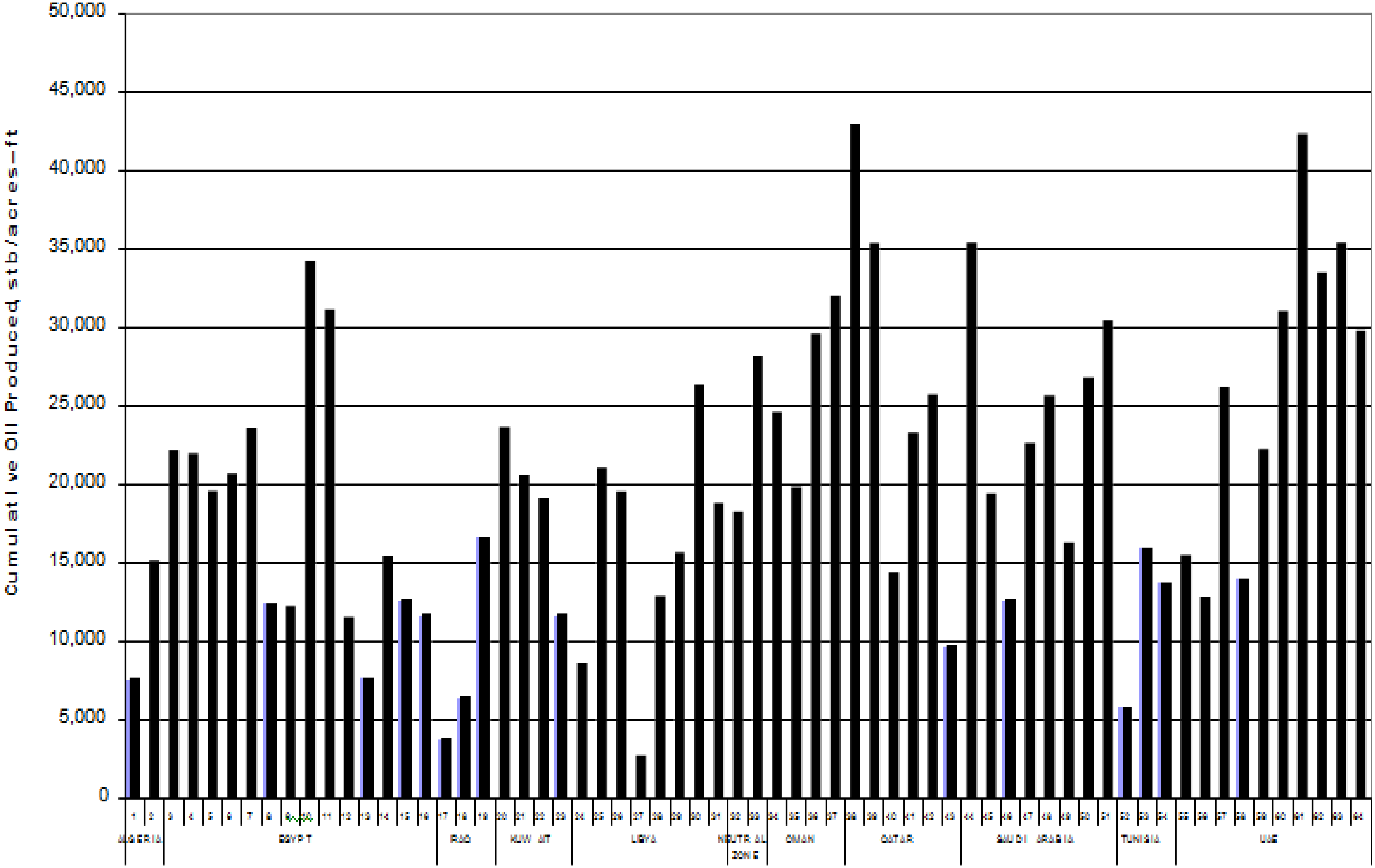

Figure 9. Cumulative oil produced per acre foot due to CO_2-EOR.

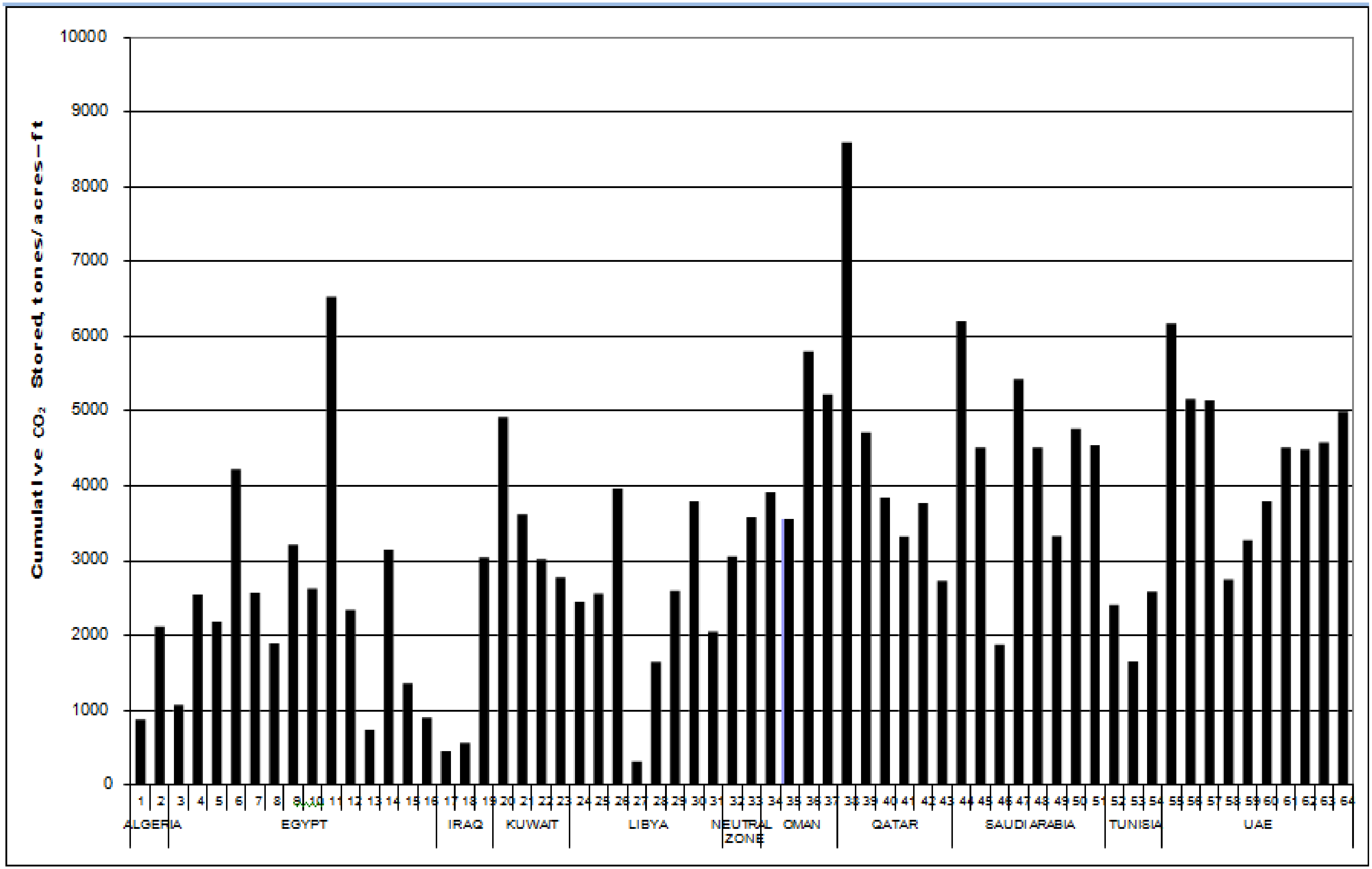

Figure 10. Cumulative CO_2 Stored per acre foot at the End of CO_2-EOR.

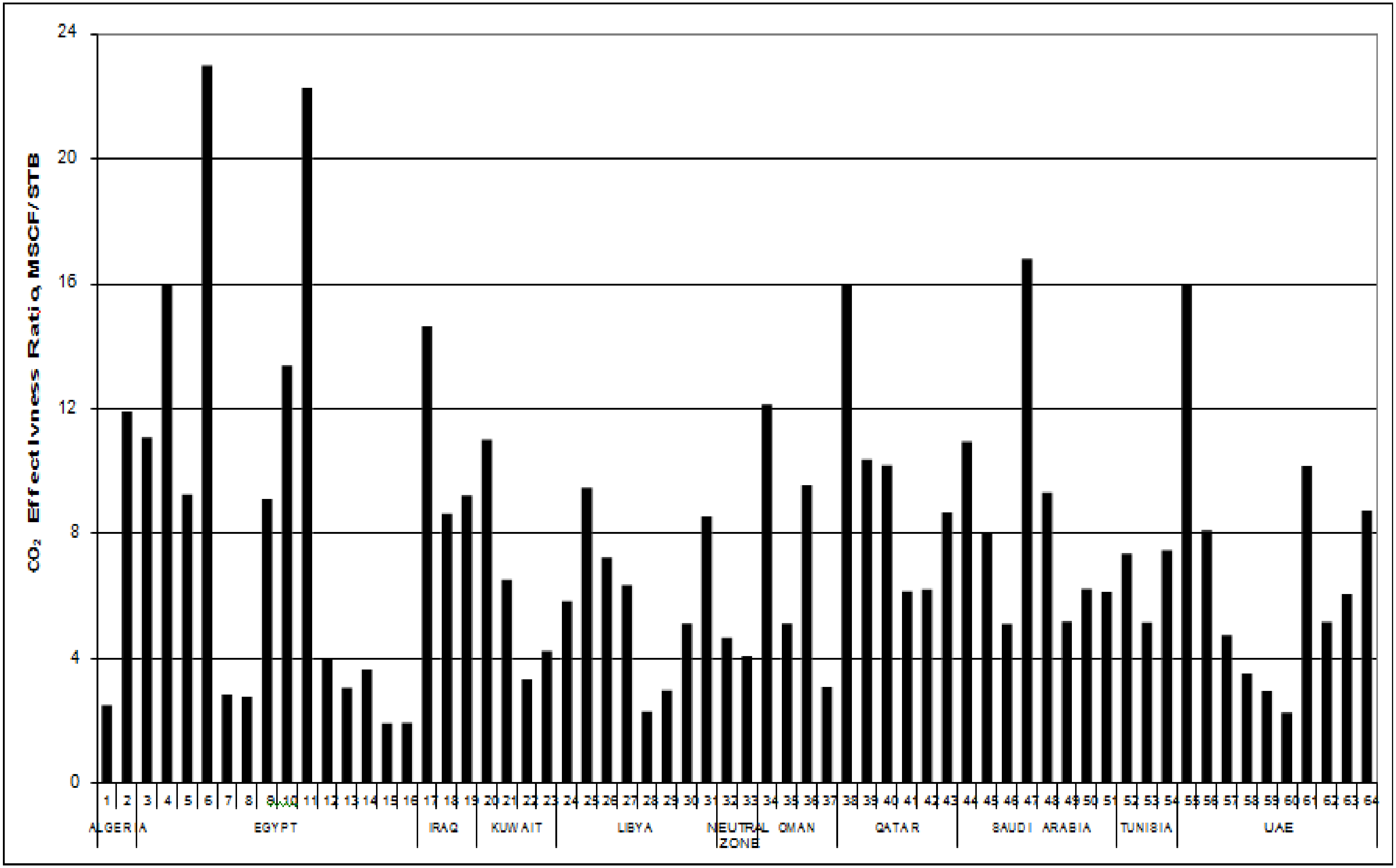

Figure 11. CO_2 effectiveness ratio at the end of CO_2-EOR.

knowledge and experience needed for commercial evaluation. If the geological formation is properly chosen, CO_2 can be retained for very long periods. During CO_2-EOR projects, the risk of CO_2 leakages is higher during the injection period, when reservoir pressure is high. Therefore, CO_2 leakages are more likely to happen during the early time of CO_2-EOR project. The total amount of CO_2 stored and emitted during CO_2-EOR projects is then can be estimated at the end of the project. However, there is still a need to provide site monitoring and proper remediation, in case any leaks occur. Currently, there is a commercial demonstration of CCS project where CO_2 is being captured from an industrial facility and injected back in a hydrocarbon reservoir to enhance oil production. Such demonstration is expected to provide more data and information about the storageability of geological formation (Malik and Islam, 2000).

CONCLUSIONS

In light of the previous discussions, the following conclusions are drawn:

1. Tremendous amount of CO_2 can be stored in the Arab world as indicated by performance prediction phase. Therefore, CO_2 capturing researches and technologies should be promoted especially in the power sector.
2. Inclusion of CCS projects in CDM is very beneficial for Arab World.
3. Despite the current small contribution of Arab World countries to the global CO_2 emissions, the role of Arab World shows a continuous increase with time. Therefore, environmental policies of the Arab World countries should be evaluated in order to ease this trend.
4. CO_2-EOR screening shows a potential for utilizing a number of oil reservoirs in the Arab World in CCS projects. Hence, the Arab World countries are encouraged to invest in full scale CCS projects in order to gain the required experience and knowledge.
5. Analytically, the performances of CCS projects in Arab World show encouraging results. Therefore, these results should be supported by numerical simulations and laboratory experiments.

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