Review Article

THE FUTURE OF CARBON CAPTURE AND STORAGE (CCS) IN NIGERIA

*ANASTASSIA, M[1]., FREDRICK, O[2]., MALCOLM, W[1].

[1]University of Regina,Office of Energy and Environment
3737 Wascana Parkway, Regina, Saskatchewan, S4S 0A2 Canada.
[2]ArticCan Energy Services Inc., 2511 Broderick Road
Regina, Saskatchewan, S4V 1K6 Canada.
manuiloa@uregina.ca

ABSTRACT
Carbon Capture and Storage (CCS) is one of the techniques for greenhouse gas (GHG) emissions reduction. This article reviews the current status of CCS technology, highlights costs and discusses legal and regulatory issues of CCS. The main purpose of the article is to review CCS and CO_2-EOR experience from ongoing projects in different parts of the world and give recommendations on how this knowledge can be applied in Nigeria. A potential demonstration CO_2-EOR project in Nigeria under the Clean Development Mechanism (CDM) is discussed.

***Keywords*:** Carbon Capture and Storage; Clean Development Mechanism; CO_2-Enhanced Oil Recovery; Nigeria

INTRODUCTION
Global warming is the increase in the average temperature of the earth. This effect is caused by anthropogenic greenhouse gases (GHG) released to the atmosphere. There are six greenhouse gases covered by the Kyoto Protocol with carbon dioxide (CO_2) considered to be the principal greenhouse gas due to the very large quantities emitted.

Carbon capture and storage (CCS) is one of technological solutions for emission reduction being given serious consideration globally. It is a technique used to capture CO_2 from large stationary sources and store it in underground formations, thereby reducing the effects of global warming. Examples of large sources of CO_2 are fossil fuel power plants, major CO_2-emitting industries such as cement and steel production, etc. Geological storage options include deep saline aquifers, depleted oil and gas reservoirs, enhanced oil and gas recovery, and enhanced coal bed methane recovery (IEA, 2008). The focus in this article is on CO_2-Enhanced Oil Recovery (CO_2-EOR) and geological storage in Nigeria.

According to Hendriks *et al.,* (2004), estimates of CO_2 storage potential in Africa vary widely from 6 to 220 Gt in aquifers and 30 to 280 Gt in oil and gas fields. West Africa, and particularly Nigeria, represents the highest potential for CO_2-EOR and CO_2 storage in oil and gas fields. However, there should be public policies and legal framework in place to influence the private sector to apply CO_2-EOR techniques for tertiary recovery.

Galadima & Garba (2008) discussed potential implementation risks of CCS in Nigeria. The main barriers identified include long implementation time, inefficient technology, gas leakage from geological storage, and high capture and storage costs.

In order to overcome some of these barriers, joint projects with developed countries under the Clean Development Mechanism (CDM) could be implemented in Nigeria. CDM is an arrangement under the Kyoto Protocol allowing industrialized countries that have a greenhouse gas reduction commitment to invest in projects that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries. It allows net global greenhouse gas emissions to be reduced at a much lower global cost (UNFCCC, 2009). It is hoped that CCS will be recognized under the CDM during the course of 2009.

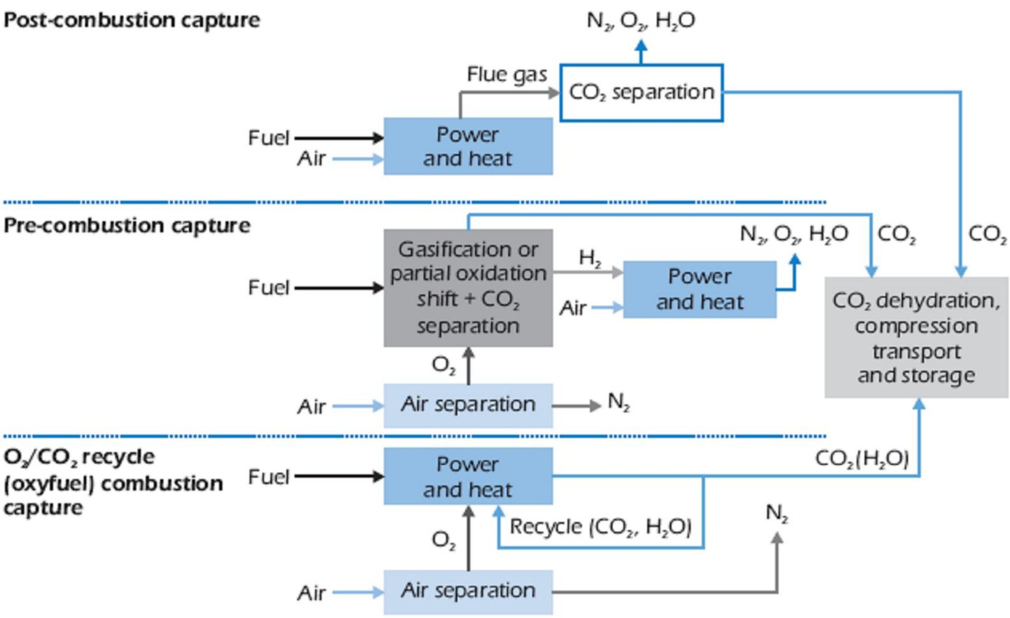
Companies have already started to identify opportunities in applying CDM in Nigeria. Recently, Abu Dhabi and Nigeria have reached an agreement to identify and develop carbon emissions reduction projects in the oil and gas sector in Nigeria under the Clean Development Mechanism (Eye of Dubai, 2009). The recognition of CCS under the Kyoto Protocol would also provide additional support for the uptake of this activity in West Africa. Also more work has to be done to evaluate the reservoir characteristics of existing oil and gas fields. An infrastructure for the transport and storage of CO_2 has to be established.

The main objective of this article is to review CCS and CO_2-EOR experience from ongoing projects in different parts of the world and give recommendations on how this knowledge can be applied in Nigeria. Other objectives include the estimation of potential for CO_2-EOR projects under the CDM. If CO_2-EOR project were to be implemented in West Africa, additional oil could be recovered as emissions are reduced. This project can generate revenues to help offset the costs of CCS.

CO_2 CAPTURE, TRANSPORT AND STORAGE
Current status of CCS technology: According to the recent IPCC report on Carbon Dioxide Capture and Storage (IPCC, 2005), the technical maturity of different components of CCS system varies greatly. For example, the interest of our research, CO_2-EOR is a feasible technology widely used worldwide. However, if this technology is “used for CO_2 storage, it is only economically feasible under specific conditions” (IPCC, 2005). This feasibility is related to oil prices, CO_2 costs and the value of CO_2 in the marketplace.

CO_2 capture: There are three main technology options to capture CO_2: post-combustion, pre-combustion and oxyfuel combustion (Fig. 1). The choice of CO_2 capture technology depends on the power plant characteristics and type of fuel used. Post-combustion capture is usually applied to coal- and gas- fired power plants.

The CO_2 is separated from flue gases produced by the combustion of the fuel in air. It is based on chemical absorption using different organic solvents, for example monoethanolamine (MEA), or ammonia. Post-combustion is the only retro-fittable technology for existing facilities.



Source: IPCC 2005

FIG. 1. CO_2 CAPTURE PROCESSES

Pre-combustion capture is the coal fired integrated gasification combined cycle (IGCC) process. This process can also be used in natural gas-based plants. In this technology, the fuel is partially reacted first with oxygen and steam to produce heat to volatilize the remainder of the coal. Then, it is further processed in a shift reactor and a mixture of hydrogen and CO_2 is produced. The CO_2 is captured, and hydrogen is used to generate electricity and heat.

Oxyfuel systems use oxygen instead of air for fuel combustion with a recirculation of an approximate 70 % flue gas stream to dilute the oxygen. The flue gas produced consists mainly of water vapour and CO_2 (IPCC, 2005, IEA 2008).

It should be noted that post-combustion and pre-combustion systems are economically feasible under specific conditions; oxyfuel combustion is still in demonstration phase (IPCC, 2005).

CO_2 capture at the power plants is the largest cost component in the whole CCS system. CO_2 capture reduces efficiency, increases resource consumption and cost of electricity. The cost of CCS ranges from 0.02 – 0.05 US$/kWh for pulverized coal (PC) power plants and 0.01 – 0.03 US$/kWh for NGCC plants (both using post-combustion capture). However, when used with CO_2-EOR, the cost of CCS can be reduced by approximately 0.01-0.02 US$/kWh due to revenues from the EOR (IPCC, 2005). With further development of CCS technology, it is believed that the cost of building and operating CCS systems will decline.

Commercial application of CO_2 capture technology is still in an early development stage. The Saskatchewan Power Corporation (SaskPower) in Canada is currently working on the development of one of the first and largest integrated clean coal/carbon capture demonstration projects in the world. The project would rebuild one of the units of Boundary Dam Power Station in Estevan, Saskatchewan with post-combustion carbon capture technology (SaskPower, 2009). This 150 MW unit is expected to be fully operational by 2014. The CO_2 capture unit would capture approximately one million tonnes of carbon dioxide annually.

The main barriers for implementation of CO_2 capture technology at power plants in developing countries such as Nigeria would be lack of technology and practical knowledge, increased cost of electricity due to CO_2 capture, and a lack of regulations and incentives from government to offset the cost of CO_2 capture.

CO_2 transport: Transport of CO_2 by pipeline is a well established technology that has excellent safety records. The CO_2 is compressed to a pressure above 8 MPa before the transportation in order to make it easier and decrease the cost (IPCC, 2005). Other options of CO_2 transport include ships, road and rail tankers where CO_2 is transported as a liquid. Transport of CO_2 by ship may be more economically attractive if CO_2 is transported over large distances. The cost of ship transport, including intermediate storage facilities, harbour fees, fuel costs, cost for liquefaction, and loading and unloading activities varies from US $15 for 1,000 km to US $30 per tonne of CO_2 for 5,000 km (IEA GHG, 2004; IPCC, 2005).

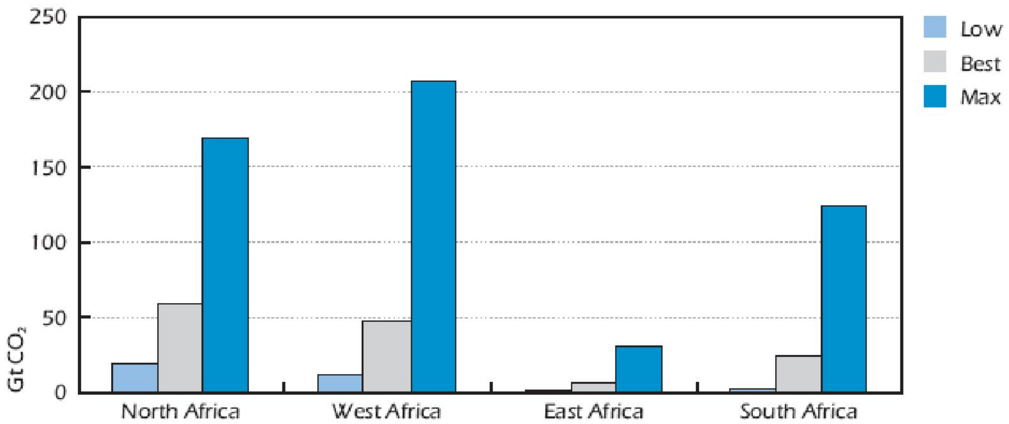
The properties of liquefied CO_2 are similar to those of liquefied petroleum gases (LPG) that are already transported by ships on a large commercial scale. This option can be feasible in case of a CDM project, when the CO_2 has to be moved from developed countries to Nigeria.

With development of CCS, the standard for CO_2 pipelines would emerge. Currently, the CO_2 pipelines are built mainly to transport CO_2 for EOR operations. The CO_2 for EOR requires low nitrogen content, a requirement that would not be important for storage applications within reason (high levels of N_2 would make compression prohibitively expensive). Other contaminants may be more problematic, for example, if the pipeline passes through a populated area, the H_2S content may be regulated (IPCC, 2005). The CO_2 leakage from pipelines is very small. In case of transport by ship, the total loss of CO_2 to the atmosphere is about 3 to 4 % per 1,000 km if boil-off and exhaust from ship engines are included.

CO_2-EOR: EOR using CO_2 injection is a mature technology that has been applied on a commercial scale in several projects around the world. This technique helps to extract an additional 5 to 20 % of the original oil in place from depleted or marginal wells (Tzimas *et al.,* 2005; Stevens *et al.,* 2001). Two processes have been developed for CO_2-EOR. These are miscible displacement and immiscible displacement (Tzimas *et al.,* 2005). Under favourable reservoir conditions (generally >22 ºAPI oil gravity and >1200 m reservoir depth), injected supercritical CO_2 becomes miscible with residual oil (Stevens *et al.,* 2001). When injected, it decreases oil viscosity and improves its mobility, thus increasing oil recovery. The conditions in some reservoirs (i.e. low pressure) and crude oil composition (i.e. heavy oil) prevent CO_2 to become fully miscible with oil. However, in the case of immiscible oil displacement, the injection of CO_2 in a reservoir can also increase oil recovery. The role of CO_2 in immiscible displacement is similar to that of water in secondary oil recovery – it helps to raise and maintain reservoir pressure (Tzimas *et al.,* 2005). Much of the CO_2 injected in reservoir is produced with oil, then separated and re-injected into the reservoir. At the end of the oil recovery, the CO_2 will be stored in the depleted oil reservoir.

Onshore miscible displacement is a commercial technology. The USA is leading in implementation of the method with 94% of the world CO_2-EOR oil production (Tzimas *et al.,* 2005). CO_2-EOR has a large potential for development in West Africa and particularly in Nigeria. The reservoir and crude oil characteristics are favourable for miscible displacement. However, reservoir geology and petrophysics need to be well studied before beginning any project. According to the latest data, with EOR, total production costs (excluding CO_2 costs) are approximately 45-90 US$/t of oil (IEA 2008). It should be noted that most of the oil reservoirs in Nigeria are offshore. It will add costs to implementation of CO_2-EOR projects compared with onshore operations.

CO_2 storage: Suitable formations for CO_2 storage can occur in both onshore and offshore sedimentary basins. IEA report on Carbon Capture and Storage (IEA, 2008) identifies that highly prospective geological basins for CO_2 storage are mainly found in the United States and Canada, Siberia, the Middle East, and North and West Africa within existing oil and gas regions. Hendriks *et al.,* (2004) indicates that in Africa the CO_2 storage capacity in aquifers varies from 6 to 220 Gt and in oil and gas fields from 30 to 280 Gt (Fig. 2). North and West Africa have the highest potential for CO_2 storage in oil and gas fields. All areas except for East Africa also have significant storage space in aquifers (15-60 Gt each). Only South Africa has ECBM potential from 8 Gt to 40 Gt (Hendriks *et al.,* 2004; IEA, 2008).



Source: IEA 2008

FIG. 2. CO_2 STORAGE POTENTIAL IN AFRICA

The injection of CO_2 in geological formations involves technologies that are already in use in the oil and gas industry, such as well-drilling and injection, computer simulation of reservoir dynamics and monitoring methods. The reservoir depth for CO_2 storage should be below 800 meters. At this depth, CO_2 is in a liquid or supercriticalstate. Under these conditions, the density of CO_2 is close to density of crude oils, reducing the buoyant forces that tend to drive CO_2 upwards. The IPCC report (IPCC, 2005) defines three main mechanisms for CO_2 storage in the subsurface and with water present as one of the fluid phases in the reservoir:

Physical trapping. These can take two main forms: static trapping where upwards movement of CO_2 is blocked by impermeable layer of shale or clay rock, also called a "cap rock", and residual-gas trapping in a porous structure provided by capillary forces.

Chemical trapping. This occurs by dissolution or by ionic trapping. Once dissolved, the CO_2 reacts chemically with minerals in the geological formation (mineral trapping) or adsorbs on the mineral surface (adsorption trapping).

Hydrodynamic trapping. The CO_2 migrates upward at a very low velocity and is being trapped in intermediate layers. Large quantities of CO_2 could be stored using this mechanism, since the migration to the surface would take millions of years.

The CO_2 storage in geological formations is expected to last for thousands of years. However, there is a small possibility that CO_2 will leak from the reservoir. Some potential leakage pathways include undetected faults and fractures in the subsurface; geological faults and new and abandoned wells intersecting the storage formation; permeable zones existing in the cap rock; fractures caused by seismic movements. Estimates of CO_2 storage costs vary from 0.5 to 8 US$/t$CO_2$ injected. Some additional costs include cost of monitoring that is estimated to be 0.1-0.3 US$/t$CO_2$ (IPCC, 2005).

Financial, legal and regulatory issues of CCS: The IEA Special report on Carbon Capture and Storage (IEA, 2005) identifies four major non-technical challenges for successful implementation of CCS. These are: Financing demonstration projects; Setting a long-term, stable price for CO_2; Establishing legal and regulatory frameworks; and Increasing public awareness and acceptance.

CCS reduces power plant efficiency, increases fuel consumption and the cost of electricity. It is unlikely that countries will proceed with commercial implementation of CCS without incentives from the government. CO_2-EOR can provide attractive opportunities for development of CCS infrastructure due to the value of additional recovered oil. However, a reasonable, long-term and stable price of CO_2 should be set to make these projects profitable and predictable.

There is also a lack of a legal and regulatory framework for CO_2 storage in geological formations. A few countries have begun to work on the development of relevant legislation. Existing laws from oil and gas, mining and industrial sectors do not provide effective regulatory mechanisms for CO_2 storage (Clifton Associates, 2004; IPCC, 2005). For the successful implementation of CCS projects, more work is needed to establish procedures for site selection, injection, abandonment and monitoring. The consultations and discussions with the public should also be conducted to expose the public to the concept of CO_2 storage and its inherent risks.

CURRENT CCS PROJECTS

Geological storage of CO_2 is ongoing in a number of projects worldwide. Three large industrial scale projects are described here: the Sleipner project in the North Sea, the Weyburn project in Saskatchewan, Canada and the In Salah project in Algeria.

Weyburn project, Saskatchewan, Canada: The IEA GHG Weyburn CO_2 monitoring and storage project is a large scale CO_2-EOR project located in Weyburn oilfield in southeastern Saskatchewan, Canada. The main goal of Weyburn project is to assess and verify the ability to safely store CO_2 in oil reservoirs. A Canadian company, EnCana, is the operator of the Weyburn oil field. The field contains approximately 1.4 billion barrels of original oil in place, and is one of the largest medium-sour crude oil reservoirs in Canada (EnCana, 2008). The project is using CO_2 from a North Dakota (USA) coal gasification facility. The CO_2 is transported via 320-kilometer pipeline and injected into the reservoir (Wilson & Monea, 2004). A significant portion of the CO_2 injected for EOR is produced with the oil, from which it is separated and then re-injected. At the end of oil recovery, the CO_2 will be stored in the geological formation (approximately 30 million tonnes).

The first phase of the research project began in 2000 and was concluded in 2004. From Phase I it was learnt "that EOR works well as a storage mechanism for CO_2" (IEA GHG Weyburn, 2009). Several technologies and techniques (i.e. 4D seismic surveying) were identified and used effectively to observe and track CO_2 movement in the reservoir. The project demonstrated that the method is safe and economically and technically feasible. The final phase of the research project is now underway, even though the oil field operations will continue until approximately 2030. More than 14 million tonnes of CO_2 have been sequestered in the oil reservoir since the beginning of CO_2-EOR operations (EnCana, 2008), making this the largest CO_2 storage project globally.

In Salah project, Algeria: The In Salah CCS project was launched in 2004. In Salah is a joint venture between Sonatrach, the Algeria national energy company, BP and StatoilHydro. It is a multi-field natural gas development in the Algerian desert. The gas fields contain from 1 to 9% CO_2 which must be removed prior to sale. Rather than venting the CO_2, it is being compressed and injected back to the reservoir. Around 1.2 million tonnes of CO_2 is injected into the reservoir every year (Riddiford *et al.,* 2006). The goal of the project is to demonstrate that secure CO_2 geological storage can be cost-effectively verified, and that short-term monitoring can provide a long-term safety assurance (Wright, 2006).

Sleipner project, Norway (North Sea): Sleipner is a gas field in the middle of the North Sea in Norway. The gas contains from 4 to 9.5 % of CO_2 that is being separated from the natural gas and re-injected into a saline formation, which lies 1,000 meter below the sea bottom (Solomon, 2007). An important driver for the project was a CO_2 emissions tax. It was more economical to store the CO_2 once captured than to vent it.

The Sleipner project is operated by the Norwegian oil and gas company Statoil. The company has been injecting one million tonnes of CO_2 per year since 1996 without leakage. The project demonstrated that CO_2 storage in deep saline aquifers is safe, and CO_2 is secure stored in such formations.

ROLE OF CDM IN DEVELOPMENT OF CCS PROJECTS IN NIGERIA

Ongoing economic reforms in the oil and gas sector in Nigeria are aimed at making the sector more vibrant and attracting more investment. Some of these reforms include the Nigerian Gas Master Plan and ongoing legislation on gas flaring (NNPC, 2009). Despite the potential economic benefit of natural gas, much is still being flared away, thereby causing huge revenue loss and environmental hazards. However, the Nigerian government is presently working on measures that will eliminate the issue of gas flaring (Malumfashi, 2007).

These ongoing reforms herald an excellent background for CCS projects under the Clean Development Mechanism (CDM). The

CDM under the Kyoto Protocol provides a mechanism to assist developed countries (Annex I Parties) to meet their GHG emissions reduction targets. CDM is a project-based mechanism that involves Annex I Parties financing the implementation of GHG emissions reduction projects in developing countries (non-Annex I Parties). CDM provides investment incentives for reducing GHG emissions beyond a business-as-usual scenario (IEA, 2008). Two projects under the CDM are currently underway in Nigeria. These are "Recovery of Associated Gas at the Kwale Oil-Gas Processing Plant" and "The Ovade Ogharefe Gas Capture and Processing" projects. Both projects capture and process associated natural gas, thus eliminating gas flaring.

Kwale project: The Kwale project is run by Nigerian National Petroleum Corporation (NNPC), Nigerian Agip Oil Company Ltd and Phillips Oil Company Nigeria Ltd. The recovery and utilization of gas started in 2006. The project utilizes a large fraction of the associated gas produced at the Kwale oil and gas field and transports it via pipeline to the Okpai combined cycle gas turbine power plant for generation of electricity. Total emissions reduction generated by the project to date is 791,325 tonnes of CO_2 eq. (NAOC, 2007).

Ovade Ogharefe project: The developer of this CDM project is Pan Ocean Oil Corporation, Nigeria. The project captures processes and sells associated natural gas from the Ovade Ogharefe oil field. The gas processing plant to treat the associated gas and the pipeline to transport the dry gas to the existing gas grid were built. The gas capture began in 2007 and expected to continue for 22 years. The estimated emission reduction for the first 10 year period is 25,315,000 tonnes of CO_2 eq. (UNFCC, 2005).

Currently, the CDM is the only mechanism that has the potential to provide incentives for development of CCS in Africa. Thus, the approval of a CCS project methodology under the CDM is an important step to help developing countries to begin mitigating their greenhouse gas emissions (IEA, 2008).

The benefits of CDM to Nigeria include attracting an increased flow of investments and capital-intensive projects; stimulating technology transfer of the most innovative technologies used in power and oil and gas sectors; promoting and creating market for its natural gas; and developing infrastructure.

A demonstration CO_2-EOR project would be a good addition to the ongoing CDM projects discussed above. Experiences learned from Weyburn CCS project in Canada can be utilized in implementation of CO_2-EOR project in Nigeria. Since CO_2 capture at the power plant in Nigeria presents number of technical and financial difficulties, the CO_2 may be sourced from Europe. The transport of CO_2 by ship overseas is a technically and economically viable solution. The ship on its way back to Europe may take liquefied or compressed natural gas (LNG/CNG). At the end of oil recovery the CO_2 may be stored in the depleted oil reservoir.

Implementation of such demonstration project in Nigeria would help to build confidence in CCS technology. It can also be a starting point for development of legal and regulatory framework to regulate CCS in the country, in addition t0 generating revenues to offset costs of CCS.

Finance for CCS project may be available through the African Development Bank (AfDB). However, the bank has not yet developed the capacity to implement climate change projects. It is currently establishing a unit that could handle issues of CDM (Bakker *et al.,* 2007).

CONCLUSIONS AND RECOMMENDATIONS

The current state of CCS technology was reviewed in this article. Three main technologies are used to capture CO_2 from power plants: pre-combustion, post-combustion and oxyfuel combustion. Pre-combustion and post-combustion systems are economically feasible under specific conditions, while oxyfuel combustion technology is still in demonstration phase. The spread of these technologies in Nigeria in the near future is unlikely. Even in developed countries large-scale commercial operations of CO_2 capture systems are still in the infancy stage. Other barriers foreseen for use of CO_2 capture techniques in Nigeria include lack of experience with modern technologies, lack of incentives and regulations from the government and increased fuel consumption due to CO_2 capture, increased cost of operations, and consequently, an increase in electricity prices.

If CCS technology is to be applied in Nigeria, the CO_2 infrastructure needs to be developed. No major problems with onshore pipeline transportation of CO_2 are anticipated. The pipeline technology is well developed and has been in use in both developed and developing countries for decades. CO_2 can also be transported as a liquid in ships. This option may be economically viable for a demonstration CO_2-EOR project under the Clean Development Mechanism, where CO_2 is to be transported from developed countries for EOR and geological storage in Nigeria. CO_2-EOR may also help to develop the CO_2 infrastructure and offset costs of CO_2 capture due to revenues from additional oil produced.

Geological storage of CO_2 is ongoing in three large industrial projects in the world: the CO_2-EOR Weyburn project in Saskatchewan, Canada; the offshore Sleipner natural gas processing project in the North Sea, Norway; and the In Salah natural gas project in central Algeria. All projects demonstrated that CO_2 can be economically and safely stored in the geological formations.

The potential demonstration CO_2-EOR project in Nigeria is proposed in this article. The project may be implemented under the CDM and will help to transfer and develop CCS technologies and expertise in Nigeria. Potential revenues may be generated from additional oil recovery and sales of natural gas. If CCS is implemented under the CDM, carbon credits may also be received.

CCS is a promising solution to reduction of greenhouse gas emissions. However, more research and demonstration projects, as well as development of legal and regulatory framework and incentives from the government are necessary for successful implementation of CCS technologies.

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