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Review of Carbon Capture and Storage (CCS) and the Way Forward in Developing Country – Nigeria

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***Abstract**: Carbon Capture and Storage (CCS) is an emerging method aimed at reducing greenhouse gas (GHG) emissions. This paper examines the current landscape of CCS technology, explores related economic implications, and addresses regulatory and legal frameworks. It focuses particularly on data drawn from global CCS and CO_2-Enhanced Oil Recovery (EOR) initiatives, including recommendations for their adaptation in Nigeria. The study also considers the feasibility of a pilot CO_2-EOR project under the Clean Development Mechanism (CDM) within the Nigerian context. CCS involves separating carbon dioxide from industrial sources, transporting and storing it in suitable geological formations. This review is projected to significantly aid in both oil recovery and climate mitigation by 2030. Though it scientific, technical, and environmental aspects remain largely unfamiliar in many oil-dependent African nations, including Nigeria. The paper examines the principles of CCS and evaluates the risks tied to its prospective application in the country. A detailed review of Nigeria's petroleum sector with its economic and political landscape suggests potential barriers to successful CCS deployment, including implementation timelines, technological inefficiencies, risks of CO_2 leakage, high operational costs, and complex decision-making processes.*

***Keywords**: CO_2 capture, CO_2 mechanism; implementation challenges, EOR, reservoirs and geological formations*

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1.0 Introduction

Global warming refers to the gradual rise in the Earth's average surface temperature, primarily driven by human-induced emissions of greenhouse gases (GHGs). Among the six GHGs identified by the Kyoto Protocol, carbon dioxide (CO_2) stands out as the most significant due to the vast quantities emitted by human activities to the air. One of the key strategies gaining global attention for reducing CO_2 emissions is CCS. This method captures carbon dioxide from large, fixed sources and stores it underground to prevent its release into the atmosphere. Major sources of CO_2 emissions include fossil fuel-based power plants and heavy industrial sectors such as cement and steel production. Once captured, CO_2 may be injected and contained underground in areas such as deep saline aquifers, depleted oil and gas fields, or utilized in processes like enhanced oil recovery and coal bed methane extraction (IEA, 2008). This article focuses on the use of CO_2-Enhanced Oil Recovery (CO_2-EOR) and underground containment in Nigeria. As noted by Hendriks et al. (2004), Africa's estimated capacity for CO_2 storage ranges from 6 to 220 gigatonnes (Gt) in saline formations and between 30 to 280 Gt in oil and gas fields.

West Africa, and Nigeria in particular, is recognized as having considerable capacity for both CO_2-EOR and underground storage. However, realizing this potential will require supportive policy frameworks and legal instruments to encourage private sector investment in EOR technologies for tertiary oil recovery. Galadima and Garba (2008) identified several challenges to CCS deployment in Nigeria, including extended implementation periods, inadequate technological capacity, risks of CO_2 leakage, and substantial financial costs associated with both capture and storage processes. One approach to mitigating these challenges involves collaboration with industrialized nations through Clean Development Mechanism (CDM) established under the Kyoto Protocol. CDM enables global north people with emission reduction commitments to support emission-reduction projects in lower-income or emerging economies, offering a cost-effective alternative to domestic reductions (UNFCCC, 2009). Efforts are already underway to explore CDM opportunities in Nigeria. For example, Abu Dhabi and Nigeria recently agreed to pursue carbon reduction initiatives in Nigeria's oil and gas sector under the CDM framework (Anastassia et al., 2009). Including CCS under international mechanisms like the Kyoto Protocol would further facilitate its adoption across West Africa. To advance CCS and CO_2-EOR in Nigeria, more detailed assessments of existing oil and gas reservoirs are essential. Moreover, establishing the required systems for CO_2 transportation and storage is critical. The review aimed to evaluate global CCS and CO_2-EOR practices and offer guidance on how these can be implemented in Nigeria. A secondary objective is to estimate the feasibility of CO_2-EOR under the CDM. If successful, these initiatives could boost oil output and cut emissions at the same time, providing financial motivation to manage the significant expenses of implementing CCS

2.0 CO_2 capture, transport and storage

Based on the current status of CCS technology (Fig.1), the Intergovernmental Panel on Climate Change (IPCC, 2005; Sanchez and Kammen, 2016) highlights that the technological readiness of various components within the CCS framework differs significantly. Specifically, CO_2-EOR, which is central to this study, is a well-established and widely implemented method across the globe. However, its application as a long-term CO_2 storage solution tends to be viable under certain factors (Anastassia et al., 2009). The economic practicability of CO_2-EOR largely depends on factors such as market oil prices, the cost associated with capturing and transporting CO_2, and the overall market value assigned to CO_2.

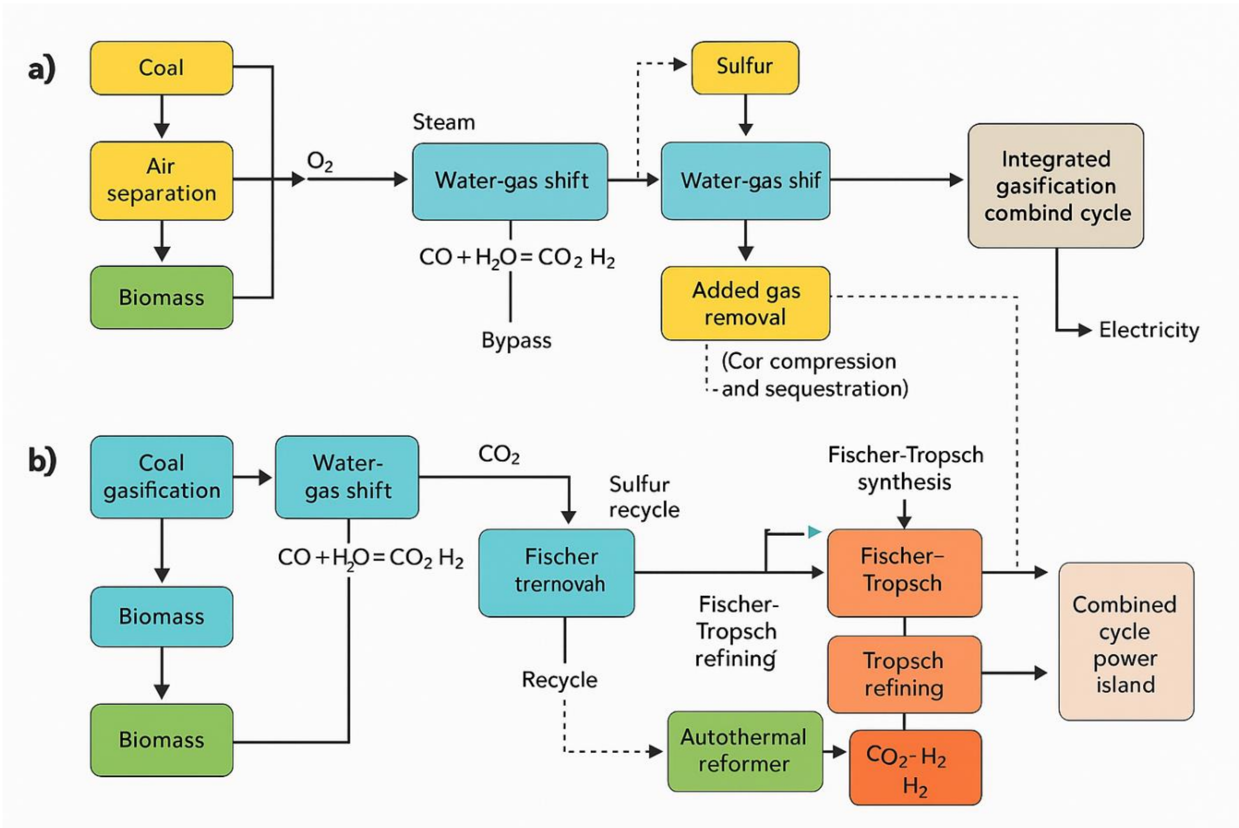

Fig. 1: Diagrams depicting the processes involved in CCS (Ogbo et al., 2024)

2.1 Mechanisms of ammonia-based Co₂ capture

The ammonia-based methods for capturing carbon dioxide have attracted growing interest due to their potential benefits over traditional amine-based systems, especially in terms of lower energy consumption and cost efficiency (Peu et al., 2023). This approach operates through a chemical interaction between carbon dioxide and ammonia (NH_3), resulting in the formation of ammonium bicarbonate (NH_4HCO_3). The reactions can be expressed as:

$$CO_2 + 2NH_3 + H_2O \rightarrow (NH_4)_2CO_3CO_2$$
$$(NH_4)_2CO_3CO_2 + 2NH_3 + H_2O \rightarrow 2(NH_4)_2HCO_3$$

These reactions are more favorable under cooler conditions, typically below 30°C, which enables effective CO_2 absorption from exhaust streams (Darde et al., 2017). The process is reversible, allowing for CO_2 recovery by decomposing the ammonium bicarbonate at elevated temperatures to release pure CO_2. The absorption efficiency is influenced by variables such as temperature, ammonia level, and the partial pressure of CO_2, with the reaction kinetics governing the overall performance (Vadillo et al., 2021). However, a challenge in the process is ammonia loss through volatilization, which becomes more pronounced at higher ammonia concentrations unless the system is properly managed (Rahimpour et al., 2024).

2.2 CO_2 capture methods

CO_2 capture in industrial applications is commonly achieved through three main approaches: post-combustion, pre-combustion, and oxyfuel combustion (Figure 2). The choice of method largely depends on the type of fuel used and the design of the power plant. Post-combustion capture, often utilized in coal and natural gas power stations, involves extracting CO_2 from the flue gas produced after combustion in air. This is typically done using chemical absorbents like monoethanolamine (MEA) or ammonia. One of the key benefits of this method is its compatibility with existing power infrastructure, making it a viable solution for reducing emissions in already-operational facilities.

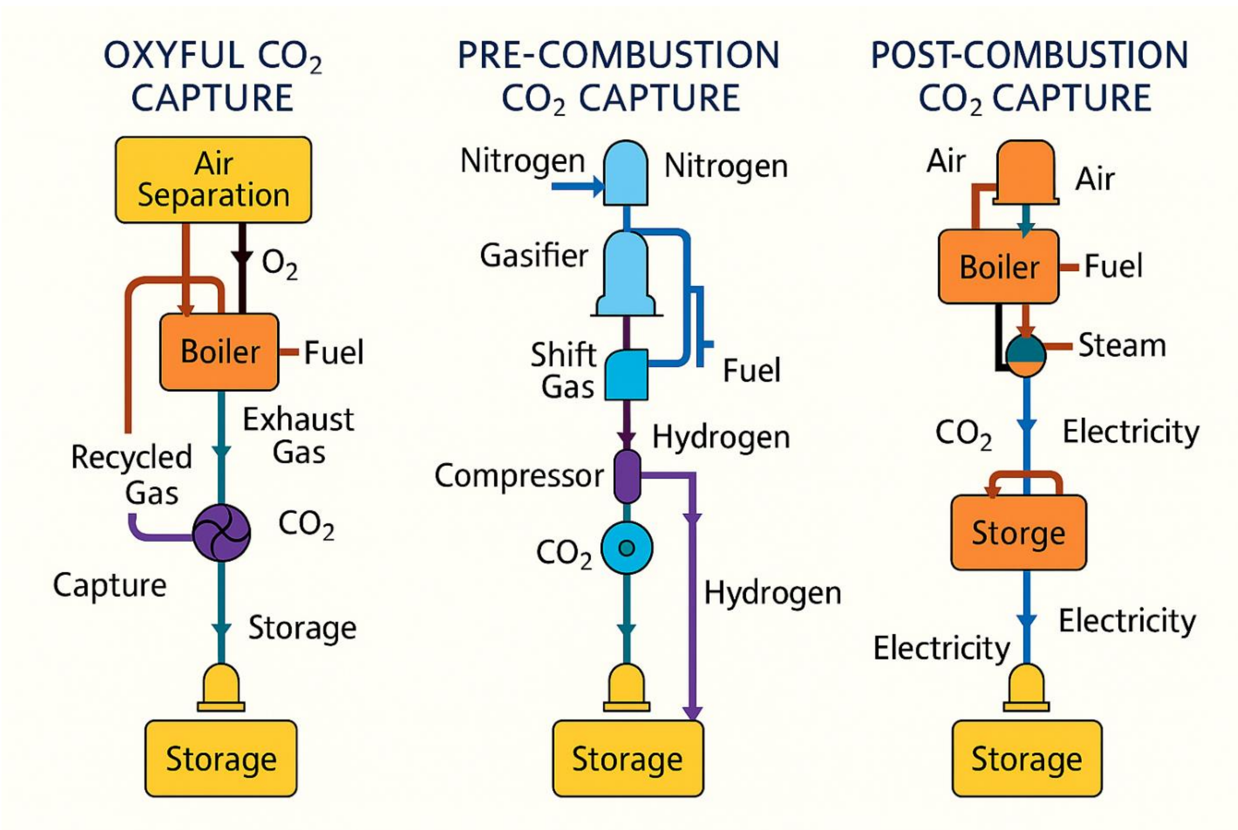

Fig. 2: The three primary technological approaches for capturing CO_2 (GCCSI, 2024)

2.3 Pre-Combustion and Oxyfuel Combustion

Pre-combustion carbon capture is mainly associated with Integrated Gasification Combined Cycle (IGCC) technology, which is commonly used in coal-powered plants but is also adaptable to natural gas systems. This technique involves partially oxidizing the fuel with a combination of oxygen and steam, producing a synthetic gas. This gas is then processed in a shift reactor to convert carbon monoxide into carbon dioxide and hydrogen. The CO_2 is captured for storage, while the hydrogen serves as a clean fuel for generating electricity and heat (IPCC, 2005). In contrast, oxyfuel combustion burns fuel in a highly oxygen-rich environment, often mixed with recycled flue gas to manage combustion temperatures. This process generates exhaust that mainly consists of water vapor and CO_2, making it easier to isolate and store the carbon dioxide (IEA, 2008). Although post-combustion and pre-combustion capture techniques have reached commercial application in certain scenarios, oxyfuel combustion is still largely limited to pilot-scale testing (IPCC, 2005).

CO_2 capture remains the most expensive element of CCS systems, as it lowers plant efficiency and raises both resource demand and electricity costs. For post-combustion applications, the cost of CCS varying from \$0.02–\$0.05/kWh for coal plants and \$0.01–\$0.03/kWh for natural gas combined cycle (NGCC) plants. However, integrating CO_2-EOR can offset these costs by approximately \$0.01–\$0.02/kWh through revenue generation (IPCC, 2005). Despite its potential, widespread CCS deployment faces challenges, especially in developing countries like Nigeria, where technological gaps, increased energy costs, and insufficient regulatory support are significant barriers. A notable advancement is SaskPower's project in Canada, which retrofitted a 150 MW unit at Boundary Dam with post-combustion CCS. Expected to capture about one million tonnes of CO_2 annually, it represents one of the first large-scale clean coal initiatives (SaskPower, 2009).

2.4 CO_2 transport

Once CO_2 is captured using available methods, it must be transported to suitable storage locations. This stage demands both significant investment and robust facilities due to the high volume of gas involved (Svensson et al., 2004). A common and established method involves compressing CO_2 to high pressure and transporting it via pipelines to geological storage sites. This approach has been applied for decades in places like the Permian Basin in Texas, USA, where CO_2 is pumped into low-yield oil reservoirs to EOR.

Pipeline transport is considered one of the safest and most efficient methods, with a strong safety record over the years (IPCC, 2005). The gas is typically compressed to pressures above 8 MPa to facilitate movement and minimize cost. CO_2 may also be conveyed as a liquid using ships, road tankers, or railcars. In such cases, the gas must be cooled and kept under pressure (around -20°C and 2 MPa) in insulated containers, making this method more suitable for smaller volumes or specialized applications (GF, 2008). Ship-based CO_2 transport can be economically attractive for long-distance transfer, especially between countries, such as in Clean Development Mechanism (CDM) projects. The estimated cost for shipping, including liquefaction and handling, ranges from \$15 per tonne over 1,000 km to \$30 per tonne over five thousand kilometers (IPCC, 2005). The properties of liquefied CO_2 are comparable to LPG, which is routinely transported by ship, indicating technical feasibility for large-scale deployment. The current CO_2 pipeline networks are mainly designed for Enhanced Oil Recovery (EOR), where purity is critical. High nitrogen levels, though acceptable for storage, are costly to compress, and contaminants like hydrogen sulfide may pose safety concerns in populated areas (IPCC, 2005). Leakage from pipelines is minimal, while ship-based transport may lead to 3–4% CO_2 loss per 1,000 km due to boil-off and engine emissions.

2.5 CO_2-EOR and its potential

CO_2-EOR is a commercially mature technique used in many oil-producing regions. It can regain an additional 5-20% of the original oil in place (Tzimas et al., 2004; Stevens et al., 2001). There are two main methods: miscible and immiscible displacement. In miscible EOR, CO_2 fully mixes with residual oil under favorable conditions (typically oil gravity above 22°API and reservoir depths exceeding 1,200 m), lowering the oil's viscosity and improving flow (Stevens et al., 2001). In less favorable reservoirs, CO_2 may not be fully miscible with oil but can still boost recovery by maintaining reservoir pressure, similar to water injection. The injected CO_2 is cycled back, separated from produced oil, and reinjected. After oil recovery ends, the CO_2 can remain in the reservoir as permanent storage. The United States leads in the use of CO_2-EOR, accounting for about 94% of global production using this method (Tzimas et al., 2005). In Nigeria, conditions are favorable for miscible CO_2-EOR due to reservoir depth and oil characteristics. However, most oil fields are offshore, which could increase implementation costs. Reservoir geology and rock properties must be carefully studied before launching such projects. Production costs for CO_2-EOR, excluding the cost of CO_2, range from \$45 to \$90 per tonne of oil (IEA, 2008).

2.6 CO_2 storage potential and technologies

Potential CO_2 storage sites exist in sedimentary basins located both inland and offshore. As reported by the IEA (2008), significant geological storage opportunities are available in regions such as North America, the Middle East, and various parts of Africa most notably in the northern and western areas. Based on the works of Hendriks et al. (2004), Africa estimated CO_2 storage ranges between 6 and 220 gigatonnes (Gt) in deep saline aquifers, and 30 to 280 Gt in depleted oil and gas fields. Although storage capacity in East Africa is relatively limited, all areas excluding South Africa—exhibit potential for both aquifer- and reservoir-based storage. South Africa, on the other hand, holds promise for Enhanced Coal Bed Methane (ECBM) recovery, with an estimated potential of 8 to 40 Gt (Hendriks et al., 2004; IEA, 2008; Fig. 2). The methods used for CO_2 storage are largely adapted from established oil and gas sector practices, including techniques like well drilling, injection infrastructure, reservoir simulation, and monitoring technologies. CO_2 is typically stored at depths beyond 800 meters, where it exists in a dense supercritical or liquid state. Under these conditions, its density becomes comparable to crude oil, reducing the tendency of the gas to migrate upwards. The IPCC (2005) outlines three main mechanisms for subsurface CO_2 trapping when water is present in the formation, offering long-term containment solutions.

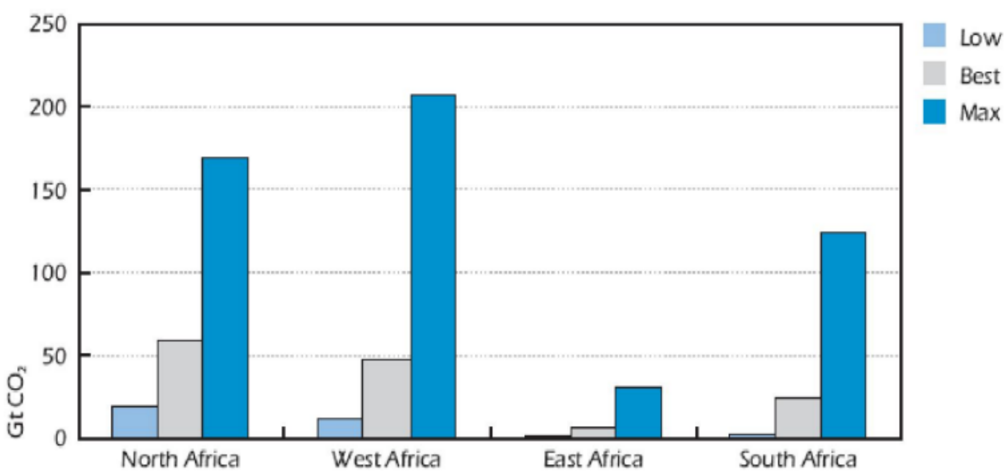

Fig. 2: Data showing CO_2 storage potential in Africa (IEA, 2008)

2.7 Physical trapping

Physical trapping involves two primary mechanisms:

Static trapping: This occurs when an impermeable layer, such as shale or clay (commonly referred to as a "cap rock"), prevents the upward movement of CO_2. Residual gas trapping: In this process, CO_2 is immobilised within the pore spaces of the geological formation due to capillary forces, effectively trapping it in place.

2.8 Chemical trapping

Chemical trapping encompasses dissolution and ionic trapping:
(i) Dissolution trapping: CO_2 dissolves in the formation water, increasing the water's density and promoting downward movement. (ii) Mineral trapping: Dissolved CO_2 reacts with minerals in the formation to form stable carbonate minerals, thereby permanently storing the CO_2.

2.9 Hydrodynamic trapping

Hydrodynamic trapping takes place when CO_2 slowly ascends through subsurface layers and becomes confined within intermediate geological strata. This process enables the containment of substantial volumes of CO_2, as its upward movement toward the surface could take millions of years. Long-term containment within underground formations is anticipated to be effective over several millennia. However, there remains a minor risk of leakage through unrecognized fractures, faults, or abandoned and active wells that intersect the containment zone. Additional risks include porous sections in the sealing rock or fissures resulting from seismic activity. The design of deep subsurface CO_2 containment systems aims to ensure stability for thousands of years. Nonetheless, minor risks of leakage still exist. Potential escape routes include undetected faults, cracks in the rock layers, old or poorly sealed wells, permeable zones in cap rocks, or fractures caused by seismic activity. Storage costs range from \$0.5 to \$8 per tonne of CO_2 injected, with monitoring costs adding an estimated \$0.1 to \$0.3 per tonne (IPCC, 2005). The International Energy Agency (IEA, 2005) outlines four key non-technical barriers to widespread deployment of CCS: funding for pilot projects, establishing a reliable carbon pricing system, creating suitable legal and regulatory policies, and building public trust and understanding. CCS implementation tends to reduce the efficiency of power plants, increase fuel usage, and raise electricity costs, making government support essential. Using CO_2 for Enhanced Oil Recovery (CO_2-EOR) can make CCS infrastructure more viable by generating revenue from extra oil production. However, the absence of clear regulatory frameworks for underground CO_2 storage is a major obstacle. To advance CCS, there is a need for policies on site selection, injection procedures, long-term monitoring, and abandonment, along with proactive public engagement to build awareness and support.

2.10 CO_2 storage

For effective and permanent isolation of captured CO_2 from the atmosphere, several key factors are crucial: long-term storage (ideally over 1000 years), minimized transport and storage costs, identified and eliminated potential risks, consideration of environmental impacts, and compliance with national and international regulations (Herzog, 2001; Herzog and Golomb, 2004). Geological storage options vary in their suitability. The USGS (2000) categorized global basins based on their potential. Major depleted geological storage options include hydrocarbon reservoirs, EOR sites, deep saline formations, unmineable coal seams, CO_2-driven enhanced coal bed methane recovery, and deep saline basalt formations. Currently, depleted oil and gas reservoirs are considered the most appropriate land-based option due to their proven capacity to absorb pressurized fluids over extended time frame (Herzog et al., 1997). While EOR applications utilize CO_2, their storage capacity is limited compared to overall emissions. Enhanced methane recovery from coal beds, with substantial global reserves, presents a promising future option. Deep saline formations, though heterogeneous, offer long-term potential, especially if CO_2 reacts to form stable carbonate rocks, mitigating leakage risks (Flett et al., 2004).

3.0 Current CCS projects

Several large-scale industrial projects worldwide are actively engaged in the storage project of CO_2. Notable examples include the Sleipner project in the North Sea, the Weyburn project in Saskatchewan, Canada, and the in Salah project in Algeria.

The GHG Weyburn CO_2 Monitoring and Storage Project in southeastern Saskatchewan, Canada, aims to evaluate the safety of CO_2 storage in oil fields. Managed by EnCana, this CO_2-EOR initiative focuses on the Weyburn oilfield, which originally contained around 1.4 billion barrels of oil (EnCana, 2008). CO_2 from a coal gasification plant in North Dakota (USA) is transported through a 320-kilometer pipeline and injected into the reservoir (Wilson & Monea, 2004). A substantial portion of the injected CO_2 is recovered with the oil, separated, and reinjected into the field. Ultimately, the project plans to store millions of tonnes of CO_2 in the underground formation following oil extraction. Initial research conducted between 2000 and 2004 demonstrated the effectiveness of EOR for CO_2 storage (IEA GHG Weyburn, 2009). Advanced technologies, including 4D seismic surveys, were utilized to monitor CO_2 movement, confirming the safety, technical feasibility, and economic potential of this approach. Although operations are expected to continue until around 2030, the final phase of research is currently ongoing. Over 13 million tonnes of CO_2 have been captured since the commencement of CO_2-EOR activities (EnCana, 2008), making this one of the largest CO_2 storage projects worldwide.

In Algeria, the In Salah CCS project, a joint venture between Sonatrach, BP, and Statoil Hydro, began in 2004. This project involves removing a small percentage of CO_2 from natural gas before it is sold. Rather than releasing the CO_2, it is compressed and re-injected into the reservoir, with about 1.0 million tonnes of CO_2 injected annually (Riddiford et al., 2006). The goal of the project is to demonstrate cost-effective verification of secure CO_2 storage and to explore short-term monitoring methods to ensure the ongoing safety of the storage process (Wright, 2006).

In the Norwegian North Sea, the Sleipner project, which has been operational since 1996, deals with a gas field containing 4-9.5% CO_2. Statoil has been separating this CO_2 and injecting around one million tonnes annually into a deep saline aquifer located 1,000 meters beneath the seabed, with no leakage reported (Solomon, 2007). A CO_2 emissions tax has provided a strong economic incentive to store the CO_2 instead of releasing it. The Sleipner project has successfully demonstrated the safety and effectiveness of CO_2 storage in deep saline aquifers.

3.1 Potential risks of implementing CCS in Nigeria

Nigeria faces increasing greenhouse gas emissions due to population growth, rising incomes, and energy consumption. With substantial reserves of oil, gas, and coal, and growing energy use (EIA, 2007), emissions are projected to remain high. While CCS will likely be important for Nigeria, as for other developing nations, potential challenges need proactive identification and management. These risks are influenced by Nigeria's specific economic, environmental, and political context.

3.2 Technological challenges

Despite global interest in low-carbon energy like biofuels, fossil fuels are expected to remain significant over the coming years (Watson et al., 2007). For effective CO_2 capture from fossil fuel combustion, efficient technologies are essential. Achieving clean coal technology alone necessitates advanced technologies currently limited in Nigeria, covering coal preparation, combustion, and flue gas cleanup (Watson et al., 2007). The entire CCS process involves sophisticated technologies, many still in early adoption in industrialized nations. Inefficient technology could severely hinder CCS implementation in Nigeria, a country already struggling in energy such as power supply challenges leading to company closures). Furthermore, potential offshore geological formations for CO_2 storage in Nigeria lack practical offshore CO_2 transportation technology. Existing pipeline transport experience, like in the Permian Basin (Gozal et al., 2005), is primarily onshore.

3.3 Leakage risks

While geological formations can potentially store CO_2 long-term (Ha-Doung and Keith, 2003), the interaction of acidic CO_2 with formations and stored resources poses environmental risks. Nigeria's storage options might be susceptible to leakage due to formations with low storage capacity, unsuitable geological traps, or low-density seals. Increased atmospheric CO2 from leaks can acidify groundwater and soils, harming plant and animal life and reducing soil fertility. In a country heavily reliant on agriculture, this could severely impact food production, outweighing the benefits of CCS.

3.4 Economic aspects of carbon capture and storage

The costs of CO2 capture, transport, and storage vary based on country, technology, and fuel type (Kallbekken and Torvanger, 2004). Capture from coal power plants, likely relevant for Nigeria's coal reserves, is generally more expensive than from gas-fired plants. Transportation costs also depend on the chosen method. In Nigeria, ship and pipeline transport are potential options. Cost estimates vary, with Anderson & Newell (2003) suggesting $7-$19 per 1000 kg of CO_2 and Hendriks et al. (2000) reporting $13-$44 per 1000 kg (assuming 1000 km transport). Longer distances, especially offshore, increase both transportation costs and corrosion risks. Nigeria's metocean conditions could further elevate costs due to the need for advanced pipeline technology and potentially longer transport distances. High costs could impede implementation unless oil and gas companies utilize CO_2 for EOR or are mandated by the government, potentially leading to increased consumer costs in a country with significant poverty.

3.5 Regulatory approaches and decision-making

Successful CCS implementation in Nigeria requires major emitters (oil and gas companies) and other relevant stakeholders to adopt effective strategies, learning from international experiences (Mandil, 2005). This includes developing a robust government regulatory framework ensuring strong engagement/contract and national support. Current Nigerian environmental policies do not adequately address CCS, potentially hindering its progress without new or modified regulations that assign capture and storage responsibilities to the emitters. Ideally, environmental policy should encourage oil companies to pursue CCS alongside biofuel initiatives discussed in the 2007 National Biofuels Policy.

3.5.1 Operational time frame

Establishing a CCS system capable of capturing significant greenhouse gas quantities demands considerable time and planning. Each oil/gas formation and power generation facility requires tailored methods for efficient CO_2 isolation and capture (Amey, 2008). Transport infrastructure (pipelines or ships) and fully operational capture facilities must be in place, contingent on finalized cost-sharing agreements. Beyond the lack of suitable technology and potential cost issues, poor planning, weak implementation policies, insecurity in the oil industry, and corruption could further prolong project timelines. Early compliance from major emitters is crucial for timely success. While addressing these challenges could enable short-term positive results, it presents a significant hurdle.

3.6 The Contribution of the CDM to Advancing CCS Initiatives in Nigeria

Ongoing changes in Nigeria's petroleum industry are designed to encourage foreign and local investment (NNPC, 2009), alongside initiatives aimed at minimizing the routine burning of excess natural gas (Malumfashi, 2007). These developments create a supportive environment for implementing Carbon Capture and Storage (CCS) projects within the framework of the Clean Development Mechanism (CDM). Established under the Kyoto Protocol, the CDM promotes greenhouse gas reduction efforts in developing nations, supported by industrialized countries (IEA, 2008). Two notable Nigerian CDM initiatives "Utilization of Associated Gas at the Kwale Oil-Gas Processing Facility" (NAOC, 2007) and the Ovade Ogharefe Gas Utilization and Treatment Project (UNFCC, 2005) highlight how gas utilization can help reduce flaring activities. At present, the CDM remains the key international platform supporting CCS project development in Africa (IEA, 2008), and gaining formal endorsement for a CCS methodology within this framework marks a significant milestone. Benefits for Nigeria include increased investment, technology transfer, natural gas market development, and infrastructure development. A CO2-EOR demonstration project, potentially learning from the Weyburn project in Canada, could be a valuable addition. Given technical and financial challenges of CO2 capture at Nigerian power plants, CO2 could potentially be sourced from Europe via ship transport, with return journeys carrying LNG/CNG. Storing the CO2 in depleted oil reservoirs post-EOR could build confidence in CCS and initiate the development of a legal and regulatory framework, while also generating revenue. Funding might be available through the African Development Bank (AfDB), which is currently developing its capacity for climate change projects (Bakker et al., 2007).

4.0 Conclusion

Carbon Capture and Storage (CCS) is gaining global attention as a promising solution for reducing greenhouse gas emissions while allowing continued use of fossil fuels like coal and natural gas. It offers an opportunity to enhance energy security and recover additional oil from low-producing or depleted reservoirs through Enhanced Oil Recovery (EOR). Despite its potential, CCS is currently not considered economically viable in many regions, including Nigeria. However, it is expected to play a crucial role in future emission reduction strategies for developing countries. This review covered three major CO_2 capture methods: pre-combustion, post-combustion, and oxyfuel combustion. While the first two is feasible under certain conditions, oxyfuel remains largely at the demonstration stage. Nigeria faces several challenges in adopting CCS technologies, including limited technical expertise, absence of strong regulatory frameworks, and increased operational costs.

To implement CCS successfully in Nigeria, there must be proactive plan with collaboration between government and the oil industry. Policies should be informed by local research and international experience. Transporting CO_2 via pipelines or ships is technologically mature and may be economically viable, particularly for EOR projects under the Clean Development Mechanism (CDM). Existing international projects Weyburn (Canada), Sleipner (Norway), and In Salah (Algeria) demonstrate that geological CO_2 storage can be safe and effective. To realize CCS potential, Nigeria must invest in infrastructure, establish legal frameworks, and provide incentives. Pilot projects, mainly CO_2-EOR under CDM, could catalyze technology transfer, build local expertise, and generate economic and environmental benefits to Nigeria when adopted.

5.0 References

Bakker, S. J., de Coninck, H. C., Ba, L., & Zhou, P. P. (2007). *Advancing CCS and CDM in Africa: Outcomes of two workshops in Africa*. Energy Research Centre of the Netherlands. ECN-E--07-079.

Clifton Associates. (2004). *The long term storage of CO_2: A regulatory requirements project* (Final report). Clifton Associates Ltd.

EIA. (2005). *Nigeria country analysis brief*. Energy Information Administration. http://www.eia.doe.gov/emeu/cabs/nigeria.html1

EIA. (2007). *Nigeria energy data: EIA international short term energy outlook, Tables 3a and 3b*. http://www.eia.doe.gov/

EnCana. (2008). *Operations profile: Weyburn*. http://www.encana.com/operations/canada/weyburn/pdfs/p006504.pdf

Eye of Dubai. (2009, January 21). *Masdar to pursue carbon reduction projects in Nigeria*. http://www.eyeofdubai.com/v1/news/newsdetail-27634.htm

Flett, M. A., Gurton, R. M., & Taggart, I. J. (2004). Heterogeneous saline formations: Long-term benefits for geo-sequestration of greenhouse gases. In *GHGT7: Proceedings of the 7th International Conference on Greenhouse Gas Technologies* (pp. 5–9). Vancouver, Canada.

Galadima, A., & Garba, Z. N. (2008). Carbon capture and storage (CCS) in Nigeria: Fundamental science and potential implementation risks. *Science World Journal*, 3(2), 95–99.

GCCSI. (2024). *Carbon capture and storage images*. Global CCS Institute. https://www.globalccsinstitute.com/resources/ccs-image-library/

GreenFacts. (2008). *How can CO_2 be transported once it is captured?* http://www.greenfacts.org/en/CO2_capture_storage/

Gozalpour, F., Ren, S. R., & Tohidi, B. (2005). CO_2 EOR and storage in oil reservoirs. *Oil and Gas Science and Technology*, 60(3), 537–546.

Ha-Doung, M., & Keith, D. W. (2003). Carbon storage: The economic efficiency of storing CO_2 in leaking reservoirs. *Clean Technology Environmental Policy*, 5, 181–189. https://doi.org/10.1007/SI0098-003-0213-Z

Hedriks, C. A., Wildenborg, A. F. B., Blok, K., Floris, F., & Vanwees, J. D. (2000). Cost of carbon removal by underground storage. In *Proceedings of the 5th International Conference on Greenhouse Gases Control Technology* (GHGT-5). Cairns, Australia.

Heller, J. P., & Taber, J. J. (1986). Influence of reservoir depth on enhanced oil recovery by CO_2 flooding. In *Permian Basin Oil and Gas Recovery Conference of SPE*. Midland, Texas.

Hendriks, C., Graus, W., & van Bergen, F. (2004). *Global carbon dioxide storage potential and costs* (ECOFYS Report EEP-02001).

Herzog, H. J. (2001). What future for carbon capture and sequestration? *Environmental Science and Technology*, 35(7), 148A–153A.

Herzog, H., Drake, E., & Adams, E. (1997). *CO_2 capture, reuse, and storage technologies for mitigating global climate change* (Final report, DOE No. DE-AF22-96PC01257).

Herzog, H., & Golomb, D. (2004). Carbon capture and storage from fossil fuels use. In *Encyclopedia of Energy* (Vol. 1, pp. 1–11). Academic Press.

IEA. (2006). *World energy outlook 2006*. OECD/International Energy Agency. http://www.eia.org

IEA. (2008). *CO_2 capture and storage: A key carbon abatement option*. OECD/IEA.

IEA GHG. (2004). *Ship transport of CO_2* (Report No. PH4/30). United Kingdom.

IEA GHG Weyburn. (2009). *IEA GHG Weyburn CO_2 monitoring and storage project*. IEA Greenhouse Gas R&D Programme. http://www.ieagreen.org.uk/glossies/weyburn.pdf

Ikeme, J. (2008). Assessing the future of Nigeria's economy: Ignored threats from global climate change debate. *Africa Economic Analysis*. http://www.afbis.com/analysis/climate_change.htm

IPCC. (2005). *IPCC special report on carbon dioxide capture and storage*. Cambridge University Press.

IPCC. (2007). *Climate change 2007: Summary for policymakers*. IPCC Fourth Assessment Report. Valencia, Spain.

Irons, R., Sekkappan, G., Panesar, R., Gibbins, J., & Lucquiaud, M. (2007). *CO_2 capture ready plants* (IEA Technical Study Report No. 2007/4).

Kallbekker, S., & Torvanger, A. (2004). *Can geological carbon storage be competitive?* CICERO Working Paper 2004:05. http://www.cicero.uio.no/media/2735.pdf

Lewis, C. (2007). *Capturing CO_2*. IEA Greenhouse Gas R&D Program.

Malumfashi, G. I. (2007). *Phase-out of gas flaring in Nigeria by 2008: The prospect of a multi-win project*. Swiss National Centre for Competence in Research. http://www.nccr.trade.org/

Mandil, C. (2005). *Legal aspects of storing CO_2*. International Energy Agency Publication Services.

NAOC. (2007). *First monitoring report on recovery of associated gas that would otherwise be flared at Kwale Oil-Gas Processing Plant, Nigeria*. Nigerian Agip Oil Company Ltd.

NNPC. (2009). *Gas investment opportunities*. Nigerian National Petroleum Corporation. http://www.nnpcgroup.com/nigeriagas.htm

Ogbo, U., Okon, A., & Chukwuemeka, R. (2024). Carbon capture and storage (CCS) in Nigeria: A review of challenges and opportunities. *British Journal of Multidisciplinary and Advanced Studies (Environmental Sciences)*, 5(4), 1–18. https://bjmas.org/index.php/bjmas/index

Riddiford, F., Wright, I., Bishop, C., Espie, T., & Tourqui, A. (2004). Monitoring geological storage: The In Salah gas CO_2 storage project. In *7th International Conference on Greenhouse Gas Control Technologies*. Vancouver, Canada. http://uregina.ca/ghgt7/PDF/papers/nonpeer/529.pdf

Rosenzweig, C., & Casassa, G. (2007). Assessment of observed changes and responses in natural and managed systems. In *IPCC Fourth Assessment Report (AR4), Chapter 1*.

SaskPower. (2009). *SaskPower's CLEAN CO_2ALTM Project*. http://www.saskpower.com/cleancoal/

Solomon, S. (2007). Security of CO_2 storage in Norway. *The Bellona Foundation Fact Sheet*. http://www.bellona.org/filearchive/fil_Factsheet_Security_of_CO2_storage_in_Norway_-_english_-_rev_16aug07.pdf

Stevens, S. H., Kuuskraa, V. A., Gale, J., & Beecy, D. (2001). CO_2 injection and sequestration in depleted oil and gas fields and deep coal seams: Worldwide potential and costs. *Environmental Geosciences*, 8(3), 200–209.

Swiss National Centre for Competence in Research (NCCR). (2008). http://www.nccr.trade.org/

Svensson, R., Odenberger, M., Johnsson, F., & Stromberg, L. (2004). Transportation system for CO_2: Application to carbon capture and storage. *Energy Conversion and Management*, 45, 2343–2353.

UNFCCC. (2005). *The Ovade Ogharefe gas capture and processing project: Clean Development Mechanism Project Design Document Form*. http://cdm.unfccc.int/index.html

USGS. (2000). *A survey of geological options for CO_2*. United States Geological Survey. http://www.usgs.gov/

Watson, J., Mackerron, G., Ockwell, D., & Wang, T. (2007). Technology and carbon mitigation in developing countries: Are cleaner coal technologies available options? In *UNDP Human Development Report* (May 2007/16).

Williams, R. H., Larson, E. D., & Jin, H. (2006). Synthetic fuels in a world with high oil and carbon prices. In *8th International Conference on Greenhouse Gases Control Technologies*. Trondheim, Norway.

Wilson, M., & Monea, M. (Eds.). (2004). *IEA GHG Weyburn CO_2 monitoring and storage project summary report 2000–2004*. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, Vancouver, Canada.

Wright, I. (2006). CO_2 geological storage: Lessons learned from In Salah (Algeria). *Presentation at SBSTA Meeting, Bonn, May 20th 2006*. http://unfccc.int/files/meetings/sb24/insession/application/pdf/sbsta_may_20th_in_salah_wright.pdf

http://unfccc.int/files/meetings/sb24/insession/application/pdf/sbsta_may_20th_in_salah_wright.pdf. Accessed 9 March, 2009

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