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Carbon Capture and Storage: *What Role in Nigeria's Energy Future?*

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Abstract
This work aims to study the potential for carbon capture and storage (CCS) in Nigeria. The study begins with an extensive investigation of the strategic framework for CCS in Nigeria. The study then reviews the development of CCS in Nigeria comprising investigative studies, CO_2 emission sources and CO_2 storage potential. In the final analysis, the study explores stakeholder's attitudes on the potential of CCS in Nigeria, using a survey administered to professionals in the in Nigeria's Department of Petroleum Resources (DPR). The DPR is Nigeria's government agency concerned with confirming the compliance to petroleum laws, guidelines and regulations in the oil and gas industry. The stakeholders surveyed have shown a common agreement that CCS is one of the significant options for the effective management of carbon emissions. The stakeholders believe that regulatory frameworks and high capital costs are primary impediments to CCS demonstration and the risks related to CCS is generally not considered as predominant. Majority of stakeholders approve that the financing for a CCS project in Nigeria should be subsidised by contributions from bilateral and multilateral banks and/or organisations, followed by support from foreign and national governments. There is also a support from stakeholders on the need for providing same or even more incentives for CCS as is the case for renewables. There is a substantial support in favour of merging CCS with enhanced oil recovery (EOR) in Nigeria.

Keywords: *Nigeria; Carbon Capture and Storage; Enhanced Oil Recovery; Stakeholders.*

Introduction

The industrial scale emissions of anthropogenic carbon dioxide (CO_2) and other greenhouse gases (GHGs) is one of the main contributors to global warming and subsequently climate change (IPCC, 2005). Between the mid-1800s to 2016, the concentration of CO_2 in the atmosphere has increased from 280 ppm to about 404 ppm, causing almost a 1^0C increase in the earth's mean temperature (IEA, 2016; NASA, 2017). As a consequence of global warming, between 1901 to 2010, there was a 20cm increase in mean sea level across the globe (IPCC, 2005; MET Office, 2016). To mitigate the severity of climate change, there is a need for the mean temperature of the earth to be kept well below 2 ^{0}C by 2100 (IPCC, 2005). Thus, using the 1990 baseline, the European Union and the G8 states have set a goal to cut down GHG emissions by no less than 80% in 2050 (ECF, 2010).

The major CO_2 emitters are mainly power plants, refineries, cement, steel and lime industries; thus, it is critical that these manufacturers drastically cut down their emissions in order for the world to meet its GHG emissions reduction targets (Aminu, 2018a; Aminu *et al.*, 2017; IPCC, 2005). About 42% of the global electricity supply is attributed to coal-fired power plants which are highly carbon intensive (Hanak *et al.*, 2015). Moreover, the emergence of technologies for shale gas in North America increases coal exports to other parts of the world. This has caused a significant reduction in the market value of coal, which means there would be higher inclination toward coal-based electricity production (Hanak *et al.*, 2015).

Carbon capture and storage (CCS) is an important technology that has been considered for decarbonisation of the industrial sector (IPCC, 2005). Through CCS, virtually 20% reduction of emissions is possible by 2050, while barring the technology can increase the worldwide cost of emission reduction targets by up to 70% (DECC, 2012). When CO_2 is captured from industrial point sources, it is transported via pipelines, tankers or ships and stored in suitable geologic media such as saline aquifers, depleted oil and gas reservoirs, unmineable coal seams and other appropriate geologic formations. To ensure feasible and effective CO_2 storage, several factors are considered such as huge storage capacity, possibility for long term seclusion of stored CO_2, reasonable cost of technology implementation and minimum environmental impact (Yamasaki, 2003). It is important to note that CCS can be employed in combination with enhanced oil recovery (EOR), which creates a win-win prospect by storing CO_2 as well as increasing hydrocarbon production (Liu *et al.*, 2012).

Although the less industrialised countries of the world contribute not as much GHG emissions relative to the more technologically advanced ones, being one of the biggest economies in Africa, Nigeria's GHG releases are about 2 tCO_2e per capita representing around 1% global emissions (Lin *et al.*, 2015; Roche *et al.*, 2020). The Climate Change Vulnerability Index has constantly ranked Nigeria amongst the top ten most climate susceptible countries, while Lagos is the tenth most susceptible city in the world (Verisk Maplecroft, 2021). Although not much studies were conducted on the financial costs of climate change in Nigeria, nevertheless, there has been pointers to losses in Gross Domestic Product (GDP) of about 2-11% in 2020 if measures for adaptation are not met (Spurgeon *et al.*, 2009). However, the GDP loss figures are considered as conservative given the economic losses from prevailing developments such as receding of the Lake Chad, the floods of 2012 and 2018, with costs related with the 2012 floods amounting to approximately 2% of the yearly GDP (Roche *et al.*, 2020). In Nigeria's nationally determined contribution (NDC) in line with the Paris Agreement, about 60% of GHG reductions are foreseen from industrial emissions especially in the power and oil and gas sectors (Roche *et al.*, 2020). Accordingly, Nigeria has vowed to target a 20% unconditional decrease of its Business-as-Usual (BAU) GHG emissions by 2030, and another 45% decrease which is conditional based on financial, technical and capacity building support for implementation (Roche *et al.*, 2020). It is therefore expected that developing economies including Nigeria should achieve inclusive economic developments while ensuring environmental sustainability (Lin *et al.*, 2015) with a critical part to play in CCS.

One of the fundamental elements for CCS advancement is understanding the stakeholder perceptions and effective communication as regards risks and benefits of technology deployment (Aminu, 2018a; Aminu *et al.*, 2017; Liu *et al.*, 2012). With regards to the size of Nigeria's economy in Africa as well as its position in international oil production and marketing, there are several reasons that make the region uniquely suitable for CCS implementation. Some of these reasons are the presence of enormous hydrocarbon reserves; significant possibility for CO_2-EOR; other prospects for CO_2 development at low cost in hydrocarbon production; and possible potential for a better awareness of CO_2 storage operations in hydrocarbon fields. Therefore, this paper explores stakeholder's attitudes toward CCS implementation in Nigeria. In the paper, we designed our study in line with a similar investigation conducted to establish the potential for CO_2 capture and storage in Saudi Arabia's future (Liu *et al.*, 2012). The paper is arranged as follows. Section 2 analyses the planned context for CCS in Nigeria. Section 3 reviews the potential for CCS advancement in Nigeria. Section 4 considers the attitudes of stakeholders concerning CCS in Nigeria. Section 5 draws deductions from the study.

The Context for Carbon Capture and Storage in Nigeria

Oil exploration in Nigeria was initiated in 1956 while production commenced several years later (Enemo *et al.*, 2019). Some years later, the Nigerian government opened exploration to foreign companies and multinationals, thereby nurturing the industry into a global one. The government founded the Nigerian National Petroleum Corporation (NNPC) in 1977 as a state-owned establishment to partake in and regulate the country's oil activities. Today, Nigeria is one of Africa's main oil producers having 18 operating pipelines and regular daily production of nearly 2 million barrels per day in 2019 (Varrella, 2020). Globally, Nigeria is the eleventh major oil producer and the petroleum industry contributes about 9% of the GDP and 90% of total export worth (Varrella, 2020). Between January and March 2020, the typical oil production in Nigeria was about 1.81 million barrels per day (Varrella, 2020). In 2020, there was a decrease in production due to the coronavirus (COVID-19) pandemic and the consequent lessened demand for oil. From estimates in April 2020, oil production would have reached 2.1 million barrels per day in a situation without the pandemic (Tagliapietra, 2020; Varrella, 2020). The most significant drop in petroleum value was noted in April 2020 when the typical price decreased by 10% in comparison to the previous month. Nonetheless, petroleum prices increased again in July 2020, reaching about 144 Naira per litre, which was about \$0.37 (Alo, 2020; Varrella, 2020).

Nigeria has been a member of the Organisation of

Petroleum Exporting Countries (OPEC) since the early 1970s. The main purpose of OPEC is to unite and organize the oil market. OPEC's membership is drawn largely from Africa and the Middle East, with Venezuela as the only member country from South America. Europe is the main destination of Nigeria's oil followed by Asia and Africa (Sayne and Hruby, 2016; U.S. Energy Information Administration, 2016). Between January and March 2020, oil exports to Europe were valued at $3.3 billion, while exports of other oil products excluding crude oil had the highest worth in the Asian market with about $655 million (Varrella, 2020). The major oil companies operating in Nigeria are originally from Europe and the United States. For example, ExxonMobil, which is a United States company, produced 191,000 barrels of oil per day in 2019, and in the same year, another United States company, Chevron, produced 173,000 barrels (Varrella, 2020). Similarly, in the same year, Royal Dutch Shell, of the Netherlands, produced almost 57,000,000 barrels in Nigeria (Varrella, 2020). Thus, the value produced by external corporations is a significant source of revenue for Nigeria. In 2019 alone, Equinor paid $427,000,000 to Nigeria mainly as taxes which accrued from exploration activities (Equinor, 2019).

Nigeria has about 12,500 MW of installed electricity generation capacity, which is mostly derived from hydropower and fossil fuels (gas) or thermal power (GET Invest, 2020). Of the total installed generation capacity, 12.5% and 87.5% are derived from hydropower and gas thermal power sources respectively (GET Invest, 2020). At present, about 3,500 MW to 5,000 MW is obtainable for transmission to end users. Thus, based on this situation and given Nigeria's population, the energy sector could be said to be in crisis mainly because there are widespread losses traceable to technical and non-technical issues within the electricity supply value chain (Wolde-Rufael, 2006, 2005). After generation and transmission, electricity is delivered to consumers connected to the national grid although there are extensive power outages in Nigeria which results in the annual electricity consumption per capita to be amongst the lowest in Africa (Ibitoye and Adenikinju, 2007; Wolde-Rufael, 2009). Thus, a significant number of small-, medium- and large-scale businesses in Nigeria are sustained by standby generators. In response to the energy crisis, in 2013, the Nigerian government completed an extensive procedure for power sector reforms which resulted in privatisation of the key assets for generation and distribution (Aminu, 2019). Additionally, to confront the energy crisis, a total of 15 state owned generation and distribution establishments were privatised in 2015 (Aminu, 2019; Gatugel Usman *et al.*, 2015). Nigeria's electrification rate as at 2020 was about 45% (GET Invest, 2020) and notwithstanding the fairly low figure in comparison with the noteworthy problems hampering power supply in the country, the demand for energy is growing. The power supply in Nigeria was in the region of 3.1 GW in 2015 (GET Invest, 2020), which was appraised to be only a third of the least demand, compelling customers to depend on privately owned generating sets. Consistent with estimations by foreign observers, the grid electricity demand in Nigeria is anticipated to rise at a continuous rate from 2018 (GET Invest, 2020). The grid demand is expected to be improved by off-grid source to meet consumer needs especially in rural areas.

In October 2020, the Doha Amendment came into force when Nigeria became the 144th nation in the world to endorse the climate agreement in a final scramble which secured the loose ends of the 1997 Kyoto Protocol (Farand, 2020). The Kyoto Protocol set obligatory climate goals for industrialised nations while its amendment contracted in Doha in 2012 stretched the obligations by creating a second pledge period for 37 nations to reduce their emissions from 2013 to 2020 (Farand, 2020). The Doha Amendment's admission into force also establishes a positive step toward the implementation of the Paris Agreement which necessitates all nations to contribute to climate goals. Thus far, the lessons learned from the Kyoto Protocol, involving driving origination, raising responsiveness, promoting climate action, including measuring, reporting, and reviewing emissions reductions ought to remain to the Paris Agreement implementation. Consequently, as energy is central to Nigeria's climate change mitigation efforts, the country's attention is growing and should be focused on advancing energy efficiency while encouraging renewable and sustainable energy.

The Potential for Carbon Capture and Storage in Nigeria

The works in the open literature describing studies on carbon capture and storage in relation to Nigeria are quite limited (**Table 1**). The main highlights of these studies are regional and field assessments; techno-economic analysis; cost analysis; carbon capture process; and storage capacity estimation.

Carbon Dioxide Storage Options

The storage of CO_2 can be conducted by a variety of options such as storage in saline aquifers; oil and gas reservoirs; coal seams; basalt formations; hydrate storage within the subsurface; and CO_2-based enhanced geothermal systems (Aminu *et al.*, 2017). However, of all the options available, storage of CO_2 in saline aquifers and oil and gas reservoirs are considered amongst the most viable for technology deployment. This is probably because it can be argued that storage of CO_2 in saline aquifers offers the largest possible storage capacity and the majority of saline aquifers are not appropriate for further uses (Aminu *et al.*, 2018, 2017). Moreover, from an economic perspective, storage of CO_2 in saline aquifers is less desirable because there is usually little or no essential infrastructure such as surface equipment, injection wells and the associated expenses for infrastructure development (Aminu *et al.*, 2018, 2017; Aminu and Manovic, 2020). Consequently, storage of CO_2 in oil and gas reservoirs is one of the most effective options due to numerous benefits. These benefits include (i) depleted oil and gas reservoirs have been thoroughly investigated during exploration and production activities and as such adequate subsurface information is available, including storage volume; (ii) the existing underground and surface infrastructure can be utilised for storage operations probably with minor modifications; (iii) the injection of CO_2 as an EOR technique which has been deployed in the industry elicits knowledge that can be utilised for technology deployment. Additionally, oil and gas reservoirs are treasured natural analogues that could demonstrate the caprock or sealing efficiency within a potential storage site, drawing from the knowledge that if that were not the case, the fluids in the reservoirs would not have been effectively contained over geological timescales (Aminu *et al.*, 2017). It must be noted however, that storage of CO_2 in oil and gas reservoirs can be likened to that in saline aquifers since elements of the storage medium such as the rock lithologies are similar (Li *et al.*, 2006) and brine is contained in both instances.

Table 1: Summary of research on carbon capture and storage in relation to Nigeria.

Source	Scope of study
(Umar et al., 2020)	A study on field and regional assessments of possibilities for geological carbon dioxide storage using the Niger Delta basin as a case study.
(Ugwuanyi et al., 2020)	A study on techno-economic investigation of transportation of sequestered carbon dioxide from the Afam IV power plant.
(Ugwuishiwu et al., 2019)	A study on cost investigation of carbon capture and storage for existing gas-fired power plants.
(Olajire, 2013)	A study on carbon dioxide capture by aqueous ammonia method in the clean development mechanism for the oil industry.
(Lawal, 2011)	A study on an enhanced assessment of the storage volume of possible carbon sequestration sites.

To store CO_2 effectively, it is important to evaluate the feasibility of storage in a particular site using several evaluation standards. These standards were developed to assess whether technology deployment is dependable, safe, environmentally friendly and economically feasible (Aminu *et al.*, 2017; Bachu, 2000). Some of the key standards to be considered are geological, geothermal, geohazards, hydrodynamic, hydrocarbon potential and basin maturity, and economic, societal and environmental issues (Aminu *et al.*, 2017; Bachu, 2002, 2000; Birkholzer and Tsang, 2008; Grataloup *et al.*, 2009; Kim *et al.*, 2014; Meyer *et al.*, 2008; Wei *et al.*, 2013). In addition to the technical feasibility, these key evaluation criteria would provide clear concepts for risks, costs, and investment choices.

The most suitable sites for CO_2 storage deployment have been ascribed to sedimentary basins, where suitable rocks provide appropriate porosity and permeability. Within the sedimentary basins, the key geological parameters to be evaluated for storage feasibility, aside from the porosity and permeability, should typically include reservoir size, temperature and pressure of formation, sweep efficiency as a function of reservoir heterogeneity, seal or caprock permeability, entry and fracture pressures at injection depth, extents of reactive minerals, thickness of formation at injection depth, solubility of CO_2 in water, possibility for faults reactivation, etc.

There are six sedimentary basins in Nigeria **(Figure 1)**. These are the Benue Trough; the Bornu basin (Nigerian segment of the Chad basin); the Sokoto basin (Nigerian segment of the Iullemmeden basin); the Mid-Niger (Bida) basin; the Niger Delta basin and the Dahomey basin. Of all the aforementioned basins, a detailed assessment of the Niger Delta suggest that it is potentially the most suitable for geological CO_2 storage (Umar *et al.*, 2020). The Niger Delta basin has one of the largest natural gas reserves in Africa, availing Nigeria the opportunity to claim having the ninth largest natural gas reserve globally (Oni and Oyewo, 2011; Umar *et al.*, 2020). Oil exploration and production in the Niger Delta has caused the emission of significant amounts of CO_2 into the atmosphere. Thus, CCS implementation would utilise the gas being flared continually such as through CO_2-EOR to maintain reservoir pressure and enhance hydrocarbon production or for permanent storage in geological media (Umar *et al.*, 2020).

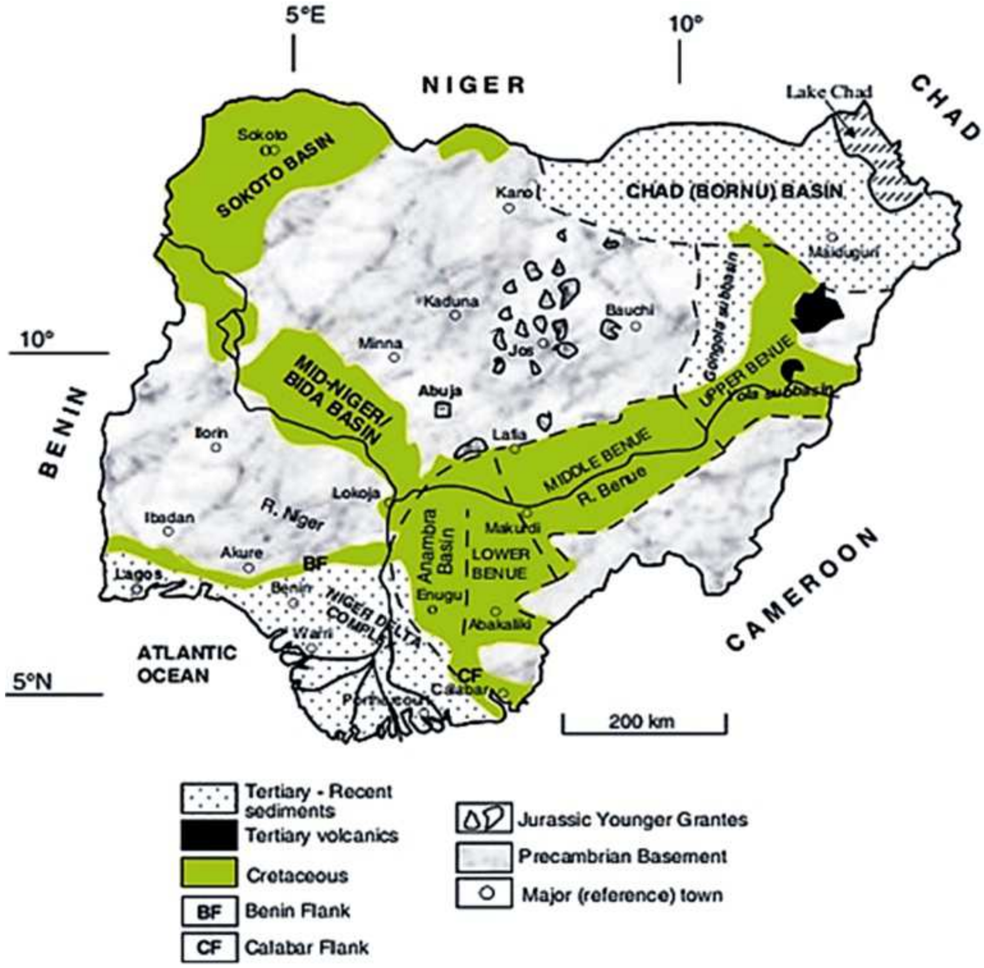

Fig. 1: Geological map of Nigeria showing the basement rocks, sedimentary basins and younger granites (Obaje, 2009).

Geology of the Niger Delta Basin

The Cenozoic Niger Delta basin is set at the juncture of the Benue Trough and the South Atlantic Ocean where a triple junction rift system formed through the parting of African and South American plates in the late Jurassic (Obaje, 2009; Whiteman, 1982). This parting was followed by subsidence of the African continental margin and cooling of the lately formed oceanic lithosphere in the early Cretaceous (Obaje, 2009). The evolution of the Niger Delta basin began in the early Tertiary when the input of river sediments of clastic nature increased (Doust and Omatsola, 1990). In general, the basin prograded over the subsidising continent-ocean lithospheric transition zone and later spreading against the oceanic crust of the Gulf of Guinea in the Oligocene (Adesida *et al.*, 1997). The sediment thickness in the basin averages 12 km covering an extent of approximately 140,000 km^2. The early Niger Delta is taken as river-dominated while the post-Oligocene delta is understood as typically wave-dominated with mature shoreface sands, tidal channels, beach ridges, freshwater and mangrove swamps (Obaje, 2009). The Niger Delta is one of the vast deltas in the world and displays a general upward stratigraphic change from the marine shales of the Akata Formation through a sand-shale paralic interval known as the Agbada Formation, to the continental sands of the Benin Formation (Deng *et al.*, 2008; Fränkl and Cordry, 1967; Reijers, 2011; Reijers *et al.*, 1997).

The Akata Formation is typically marine shale with infrequent turbidite sandstone and siltstone (Short and Stäuble, 1967). Its thickness ranges from 600 – >6000m (Omoboriowo *et al.*, 2012) and regarded as the foremost source rock for hydrocarbons. The Agbada Formation overlies the Akata Formation **(Figure 2)** and comprises alternating deltaic sandstones and shale (Weber, 1987), and is considered as the foremost reservoir unit for hydrocarbons. The rock thickness in the formation varies reaching a maximum of 3940m (Avbovbo, 1978). The texture of the formation comprises coarse to fine-grained, poorly to very sorted and unconsolidated to slightly consolidated sandstones (Omoboriowo *et al.*, 2012). The porosity varies with depth and values of 40% have been noted (Doust and Omatsola, 1990; Umar *et al.*, 2020). The Benin Formation is a fluvial sand-rich deposit (Maloney *et al.*, 2010; Omoboriowo *et al.*, 2012; Owoyemi and Willis, 2006). It is interpreted as having coastal plain sands that outcropped at Owerri, Onitsha, Benin, all in the Delta area (Reyment, 1965). It consists mostly of continental, high porosity, freshwater-bearing sandstones with slight shale intercalations which intensifies toward the bottom of the formation (Umar *et al.*, 2020). Dependent on changes in sea level, sediment supply and local subsidence, the Niger Delta underwent stages of transgressions plus regressions and as such, the stratigraphic outline and comprehensive Tertiary stratigraphy of the basin are founded on correlations of foraminiferal zones and palynomorphs (Obaje, 2009).

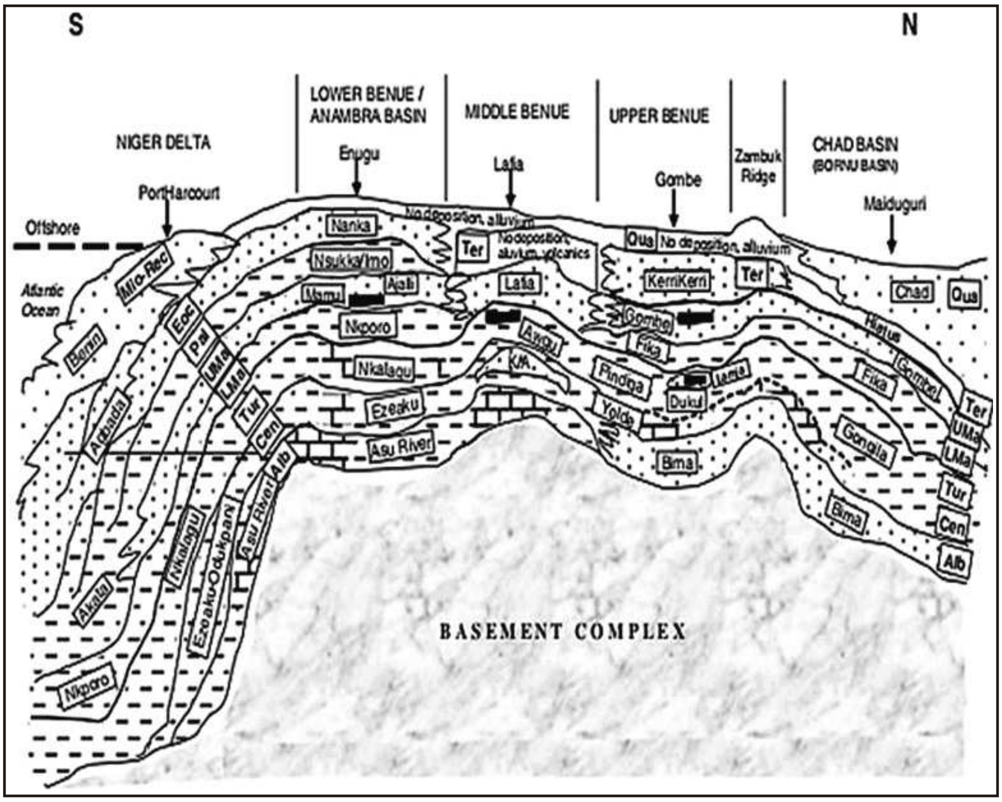

Fig. 2: Idealised N-S stratigraphic cross-section across the Niger Delta Basin and the relationship to the Benue Trough and Chad Basin (Obaje, 2009).

Field Scale Assessment

The potential for CO_2 storage in the Niger Delta was studied in detail in terms of field scale assessment (Umar *et al.*, 2020). The assessment conducted on two fields within the Niger Delta emphasised on well correlation; possible reservoir and seals; intensity of faults; likely traps; and fault stability or geomechanical analyses.

As regards well correlation analysis, gamma ray logs from four wells were used to disclose the existence of a reservoir at a depth of between 2900 – 3200 m, which satisfies the requirement for CO_2 storage (Bachu, 2003). The reservoir extends laterally through the study area and has thickness of about 50 – 55 m and is placed amid thick layers of shale which has thickness of about 100 – 110m (Umar *et al.*, 2020). The shale layers may well be possible seal for the reservoir. Additionally, a main fault of about 1.3 km trending at 84° cutting through the reservoir in the western part of the field might offer the possible structural closure needed to seal injected CO_2 (Umar *et al.*, 2020).

It has been reported that the Niger Delta reservoirs are generally found within depths of 2000 – 6500 m, having geothermal gradient of about 27 °C/km (Tuttle *et al.*, 1999), suggesting ideal conditions for storage of CO_2. The reservoirs are mainly unconsolidated sands and sandstone of the Agbada Formation (Umar *et al.*, 2020). The typically stacked sequence has thickness of less than 15 m and extends up to about 45 m in some areas (Evamy *et al.*, 1978). These irregular shale and sand sequence within the reservoirs may perhaps offer numerous CO_2 storage opportunities (Umar *et al.*, 2020). The reservoir sandstones have porosity of 40%, permeability of 2 Darcy and thickness of 100 m (Edwards and Santogrossi, 1990). The porosity, permeability and thickness values suggest that the reservoirs are potentially good for CO_2 storage.

The intensity of faults in the Niger Delta basin is largely considered as moderate, with growth faults reported as the most abundant structural style (Doust and Omatsola, 1990). It is well known that faults can serve as barriers to fluid flow and can also aid fluid migration (Bryant *et al.*, 1997), nevertheless, highly fractured, and faulted areas may not be favourable for CO_2 storage due to concerns for possible leakage (Bachu, 2003). Through 3D seismic dataset interpretation, it was revealed that complex fault geometries exist in the Niger Delta basin which means that likely sites must be carefully evaluated to determine their structural integrity (Umar *et al.*, 2020). Nonetheless, despite the relatively intricate structural settings, the stratigraphic section analysis for the basin revealed some potential locations for CO_2 storage deployment (Umar *et al.*, 2020). It was concluded that generally, in terms of fault setting and stratigraphy, the onshore Niger Delta basin offers a more ideal environment for CO_2 storage due to its shale sequence and interbedded sand characterisation which could favour multiple storage locations (Umar *et al.*, 2020).

Previous works in the open literature have shown that one of the key factors that assures the security of stored CO_2 in geological media is understanding the type of trapping mechanisms that exist within a storage formation (Bachu, 2008; Kaldi and Gibson-Poole, 2008; Raza *et al.*, 2017). It has been reported that structural and stratigraphic traps dominate the Niger Delta basin (Doust and Omatsola, 1990; Evamy *et al.*, 1978). It is thought that traps such as simple rollover anticlines, clay filled channels, collapsed crests, etc., in the basin had resulted from syn-sedimentary deformations (Doust and Omatsola, 1990; Umar *et al.*, 2020).

Geomechanical or fault stability is critical for CO_2 storage in geological media since elevated pressures are needed for fluid injection into the reservoir to move existing reservoir fluids. These pressures could possibly cause fault instability which might result in the reactivation of pre-existing structures and resultant CO_2 leakage (Rogers *et al.*, 2008; Streit and Hillis, 2004; Zoback, 2010). To analyse fault stability, it is important to study slip tendency and fracture stability and the slip tendency of a fault surface is defined as the ratio of shear to effective normal stress (Meixner *et al.*, 2018; Umar *et al.*, 2020). For possible CO_2 storage site evaluation, the slip tendency analysis detects fault surfaces that are oriented to slip in a current stress field (Streit and Hillis, 2004). Thus, the fault surfaces that are oriented in the current-day stress field are at risk to slip (van Ruth *et al.*, 2006). This could lead the stored CO_2 to migrate vertically or upward and out of the reservoir along fault sections (Umar *et al.*, 2020). In the Niger Delta basin, the slip tendency analysis conducted on faults show that generally, there is low tendency for potential fault slips (Umar *et al.*, 2020). The faults were reported to be steeply oriented at 87° in the path of the maximum principal stress, indicating a region of mechanical stability (Umar *et al.*, 2020). The fracture stability is the measure of the amount of pore pressure a fault can withstand prior to fracture (Baouche *et al.*, 2020; Miocic *et al.*, 2014). The fracture stability analysis conducted for the Niger Delta basin show that the probability for fault failure by reactivation or fracturing is low (Umar *et al.*, 2020).

Carbon Dioxide Capture Techniques

There are three main stages in CCS technology: capture, transportation, and storage. There are equally three ways to capture CO_2: pre-combustion capture, post-combustion capture and oxy-fuel combustion technologies, respectively. It has been reported that the separation stage of CO_2 capture incurs about 75 – 80 % of the overall cost of CCS (Dooley *et al.*, n.d.). Studies on relevant CCS technologies propose that post-combustion capture is advantageous over other technologies due zero NOx emission (Kather and Scheffknecht, 2009) and the high cost related to oxy-fuel capture is associated with the separation of N_2 and O_2 which entail energy amounts (Burdyny and Struchtrup, 2010). Due to the potential ease in retrofitting the currently operating power plants in Nigeria, the post-combustion capture technology could be more viable because of its reduced energy penalty (IPCC, 2005; Zhai and Rubin, 2013). In the Niger Delta basin, there are a the total 606 oilfields, 355 are onshore while 251 are offshore (Ugwuishiwu *et al.*, 2019). However, only 193 oilfields are in operation while 23 are abandoned (Ugwuishiwu *et al.*, 2019) probably due to poor prospecting or total depletion of the wells (Ambituuni *et al.*, 2014). The availability of these non-producing wells further suggests the potentiality for storage of CO_2 in the Niger Delta basin in line with global recommendations, while estimating storage volume in depleted oil and gas reservoirs at around 675 – 900 $GtCO_2$ (IPCC, 2005).

The Clean Development Mechanism in Carbon Capture and Storage Development in Nigeria

The Clean Development Mechanism (CDM) relates to activities conducted in non-industrialised, developing nations (Möller, 2010). The CDM allows the setting up of a project to reduce CO_2 emissions and the 'saved' carbon can be 'credited' by issuing certificates on per tonne carbon base (Aminu, 2018b; Jotzo and Michaelowa, 2002). The developed nations are legally bound to cut down their emissions and might also buy carbon credits from the CDM projects and offset it against their own obligations which creates market for carbon credits (Olajire, 2013). The CDM is well-defined in Article 12 of the Kyoto Protocol (United Nations, 1998) to achieve two key objectives: (i) to assist states not included in Annex 1 nations (especially developing countries) in contributing to the sustainable development which is to avert climate change; and (ii) to assist Annex 1 nations in achieving compliance with their greenhouse gas reduction obligation. In addition, the CDM can positively support the sustainability objectives of developing countries (Böhringer, 2003; Olajire, 2013) by: (i) transferring technology and financial resources and instruments; (ii) developing sustainable energy production methods; (iii) increasing consciousness on energy efficiency and environmental matters; (iv) lessening poverty through employment and income generation; and (v) helping to outline investment priorities in sustainability projects. The Nigerian Gas Master Plan and legislations related to gas flaring, which are amongst some of the current reforms in the oil sector, are intended to make the sector more vibrant and investor friendly (Olajire, 2013; Olujobi, 2020). The reforms would also provide workable backgrounds for CCS projects implementation under the CDM in Nigeria (Aminu, 2015; Olajire, 2013). To this extent, there have been some emerging green projects under the CDM aimed at capturing and processing associated natural gas and eradicating gas flaring. These projects are (Aminu, 2015; Olajire, 2013): (i) Kwale oil and gas processing plant for the recovery of associated gas; (ii) Ovade-Ogharefe gas capture and processing projects; (iii) Obodugwa and Umusadege oilfields for the recovery and utilisation of associated gas; and (iv) Lafarge WAPCO (West African Portland Cement company) for the partial substitution of alternative fuels in cement companies in Nigeria.

Stakeholder Attitudes Toward CCS in Nigeria

Methodology

In this paper, we based our study on a questionnaire examination administered from April 13 to May 12, 2021, to prompt the opinion of stakeholders as regards the potential for CCS in Nigeria. The main objective of the study was to survey stakeholders that would be involved directly in the advancement of CCS technologies, including other plans such as climate change, energy policy and allied decisions in Nigeria. The survey questionnaire was designed in line with a similar study conducted in Saudi Arabia (Liu *et al.*, 2012). As with the previous study (Liu *et al.*, 2012), the questionnaire was made in such a way to confirm that all enquiries were entirely understood by the respondents to the extent that information collected addressed the purpose of this study. The survey was done online via a devoted website.

Since CCS is still an emerging technology around the world, there could be indications that the public may be unacquainted with it. To lessen uninformed opinions from limitations on expertise and experience, the survey focused on discernments of environmental and energy experts rather than being open to the public. The survey was sent to the technical staff of Nigeria's Department of Petroleum Resources (DPR). The DPR is so far the only agency with the legal duty of confirming compliance to petroleum laws, regulations, and guidelines in the oil industry. These duties involve supervising all activities at drilling sites, producing wells, producing platforms and flow stations, crude oil export terminals, refineries, storage depots, pump stations, retail outlets and any other places where petroleum is sold or stored, including all pipelines carrying crude oil, pipelines and petroleum products (DPR (Department of Petroleum Resources), 2021). More specifically, DPR conducts the following roles, amongst others: overseeing all petroleum industry procedures being conducted under licenses and leases in Nigeria; monitoring the petroleum industry to confirm that operations are consistent with countrywide aims and objectives including those related to flare down and domestic gas supply obligations; ensuring that health, safety and environment (HSE) regulations follow international best practices in the oil industry; keeping records on petroleum industry operations, especially on matters concerning petroleum reserves, production, exports, licenses and leases; advising government and appropriate agencies on technical matters and public policies related to petroleum activities; processing industry applications for licenses, leases and permits; ensuring timely and accurate payments of rents, royalties and other proceeds due to the government; and upholding and administering the National Data Repository (NDR) (DPR (Department of Petroleum Resources), 2021).

We received 150 valid responses from the participants who were spread across four technical departments of DPR. These departments are engineering and standards; upstream monitoring and regulation; downstream monitoring and regulation; and HSE. The technical departments were chosen for survey as majority of the staff are acquainted with energy and environmental issues. However, it is important to state that the study has several limitations since the number of respondents in dissimilar sections are disproportionately spread.

Results, Analysis and Discussion

As shown in **Figure 3**, CCS is seen as one of the major answers to climate change in Nigeria. The most prevalent options are energy efficiency and CO_2-EOR, with each having about 60% of the respondents. These are closely followed by concentrated solar power (CSP), wind (onshore) and wind (offshore), each with 40% of the respondents. A considerable amount of the respondents also reveals optimistic attitudes toward solar photovoltaic (solar PV) and biofuels, each with 33.3% of the respondents. The next in order of prominence are oil and gas to electricity (single cycle) and CCS (26.7%), oil and gas to electricity (combined cycle) and CCS (20%) and electric vehicles (20%). Other technologies with weak support are fuel cells, geothermal, high purity CO_2 sources and CCS, nuclear power, smart grid, and gas to hydrogen and CCS. The responses confirm that there is no definite approach to lessen climate change (IPCC, 2005; Liu *et al.*, 2012), necessitating that countries should tailor their approach in relation to the uniqueness of their economies.

As shown in **Figure 4**, there are positive supports for

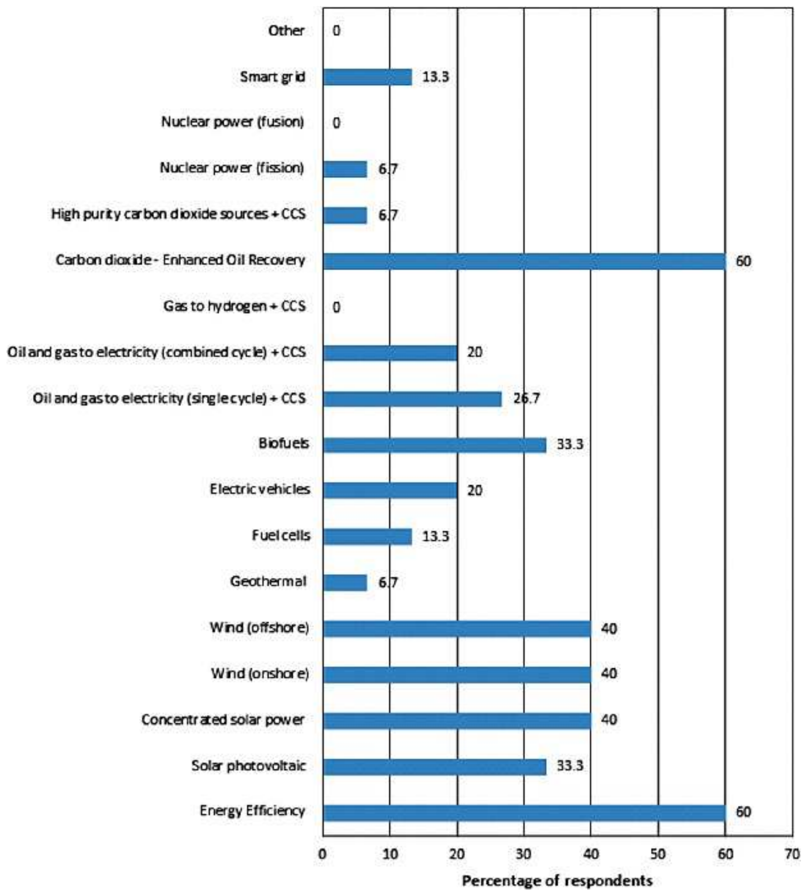

Fig. 3: Stakeholder's views on solutions to climate change. Question: What in your opinion are the most practical options to address carbon management in Nigeria? Multiple answers allowed.

CO_2-EOR, CSP and wind. A significant majority of the respondents consider CO_2-EOR (66.7%), CSP (60%) and wind (53.3%) as potential game changing technologies. This is followed by CCS and solar PV, with each being equally favoured by 40% of the respondents.

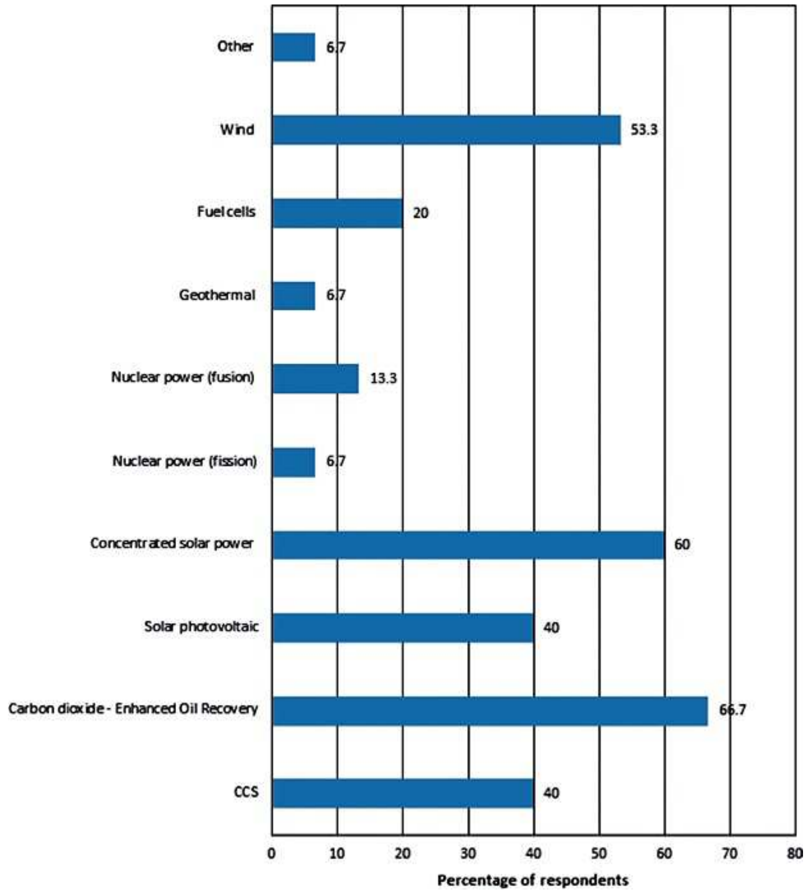

Fig. 4: Stakeholder's views on game-changing technology. Question: What are the potential game-changing technologies for Nigeria? Multiple answers allowed.

Figure 5 shows key challenges for cohesive large-scale CCS demonstration in Nigeria. Regulatory frameworks are perceived by significant number of the respondents (66.7%) as the greatest challenging factor for large scale CCS demonstration in Nigeria. High capital costs are considered as the second challenge (60%). The responses imply that although the challenges listed are not considered new by the respondents, however, there is still little confidence on an integrated CCS project. To boost stakeholder confidence, it is necessary to embark on a public awareness campaigns (Aminu *et al.*, 2017) while physically demonstrating that the full CCS chain is viable and effective at both pilot and commercial deployments. Additionally, other respondents have perceived technical uncertainty (53.3%), absence of a price on carbon (46.7%) and financial mechanism (46.7%) as important challenges for large-scale cohesive CCS demonstration in Nigeria. The responses speak to the effect that firms would not be willing to accept the added costs of CCS projects except CO_2 emissions has monetary costs connected to it (Liu *et al.*, 2012). As shown from the respondents, it is also important to address challenges of CO_2 leakage from sequestration (33.3%) and public acceptance of the technology (33.3%). A few other respondents perceive pipeline infrastructure (26.7%) and climate negotiation uncertainty (13.3%) as challenges.

Figure 6 compares the perception of stakeholders of the main HSE risks arising from CCS. The respondents in total do not consider CCS related risks as particularly huge. The predominant response was "No" risk for all HSE related questions. These responses are in line with stakeholder surveys undertaken in Europe (Shackley *et al.*, 2007) and Saudi Arabia (Liu *et al.*, 2012). Probably, the only areas of concern could be risks related to leakage from CO_2 geological storage (**Figure 6c**) and environmental damage from CO_2 capture (**Figure 6d**), each of which is perceived as having appreciable adverse effects by 46.7% of the respondents. The

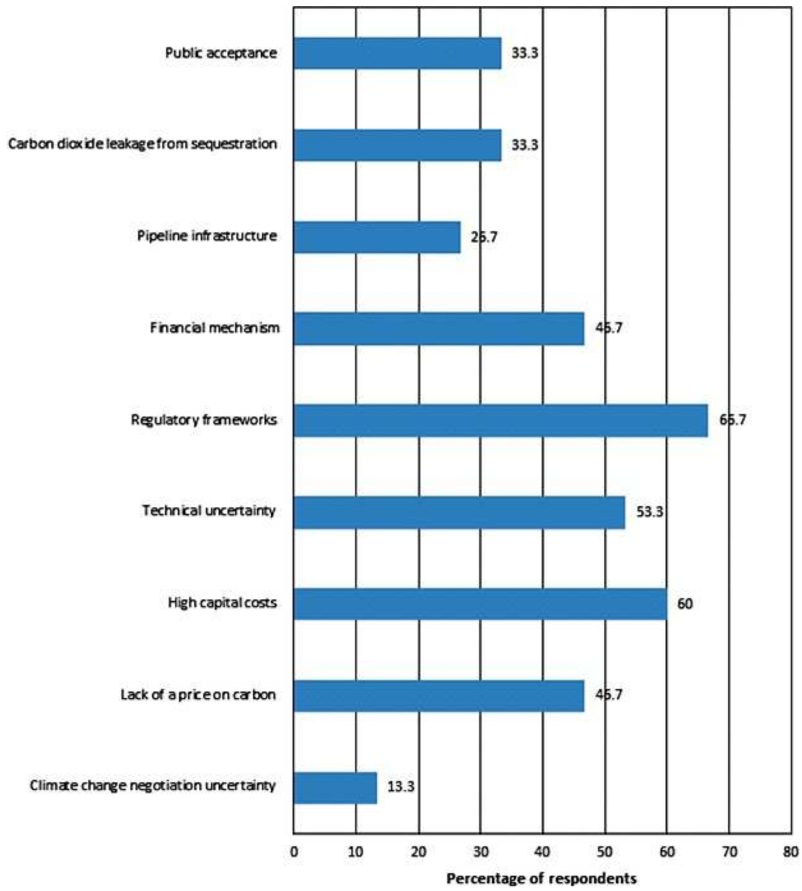

Fig. 5: Stakeholder's views on challenges for CCS. Question: What are the major challenges for integrated large scale CCS demonstration in Nigeria? Multiple answers allowed.

responses on HSE related risks may be attributed to the awareness and knowledge of CCS in the oil industry (Liu *et al.*, 2012).

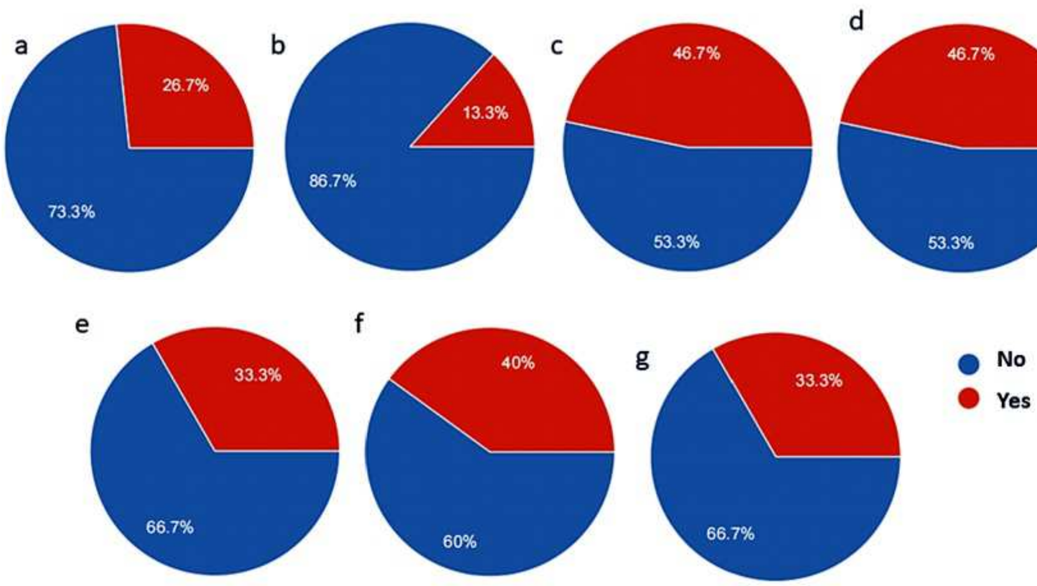

Fig. 6: Stakeholder's views on risks for CCS (a – Leakage from CO_2 capture; b – Leakage from CO_2 pipeline; c – Leakage from Co_2 geological storage; d – Environmental damage from CO_2 capture; e – Environmental damage from CO_2 pipeline transportation; f – Contamination of underground water resources from CO_2 storage; g – Impact of CO_2 geological storage on microorganisms. Question: Please indicate your opinion to each of the following potential risks to health, safety and environment arising from CCS. Only one answer per risk is allowed

It was previously reported that one of the main impediments for CCS implementation at the commercial scale lies in financial mechanisms and investment risks (IPCC, 2005; Liu *et al.*, 2012; Parker and Folger, 2011). **Figure 7** shows that the majority of respondents (73.3%) consider the financing for CCS to be subsidised by contributions from bilateral banks and/or organisations. The respondents similarly suggest that grants from foreign governments (66.7%) and Nigerian government subsidy (53.3%) should constitute CCS financing options.

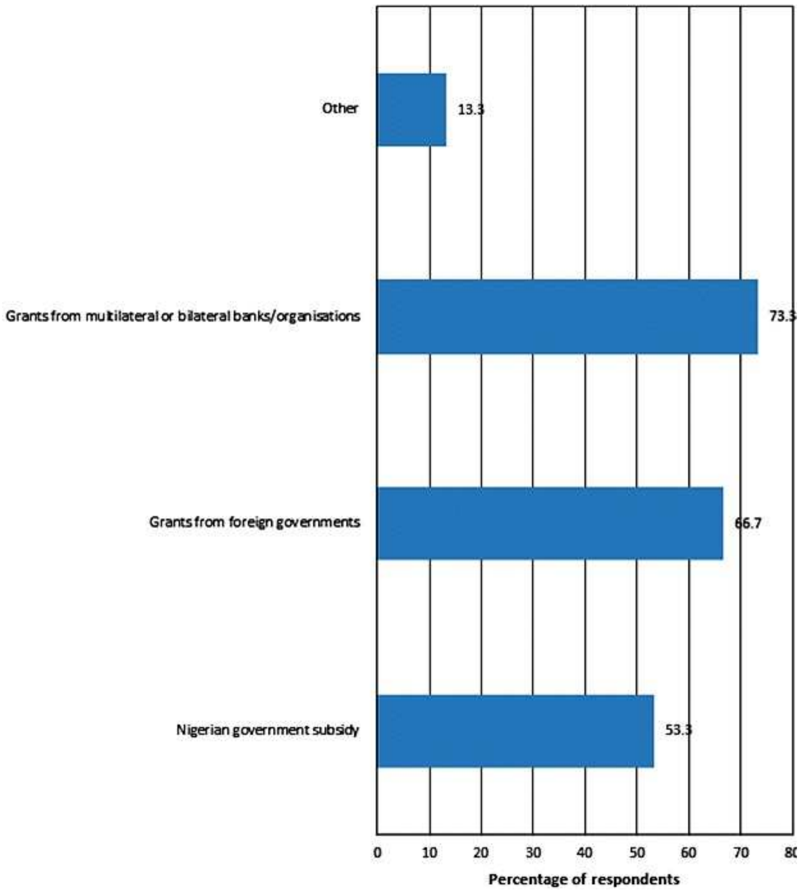

Fig. 7: Stakeholder's views on financial mechanisms. Question: For the first large scale CCS demonstration in Nigeria, what are the most appropriate financing options? Multiple answers allowed.

The incentive policies that lead to CCS demonstration at the pilot scale (e.g., the Otway Project Facilities in Australia) are important for overcoming technological and economic impediments and supporting learning-by-doing (Aminu *et al.*, 2017; Liu *et al.*, 2012). **Figure 8** illustrates the most suitable motivations for CCS demonstration in Nigeria. The most important motivations are mandate emission targets for major emitters (80%), launch national CCS roadmap (73.3%) and carbon tax (66.7%). The other incentives that are worthy of note are government subsidy (46.7%) and performance standards (33.3%). These responses suggest the need to have a wide-ranging strategy that emphasises both market-orientated instruments and command-and-control methods to form motivations for CCS deployment (Liu *et al.*, 2012).

To reduce global CO_2 emissions, it is important to have far-reaching approaches that combines several efforts toward energy producing technologies. These efforts would typically involve a blend of greater energy efficiency, increased production of renewable energy and CCS deployment (Liu *et al.*, 2012). As shown in **Figure 9**, the respondents concur that the incentives for CCS deployment should be placed at the same- or greater level as renewables, each with 33.3% of the respondents. In comparison, an equal number of respondents (each with 13.3%) are either unsure of the level of incentives or in agreement that a lower level be set as those for renewables. As CCS is a link technology between fossil fuels and renewables, often there are concerns on whether CCS will contest with renewables for capital and resources toward research and development, which could curtail the swift progress in

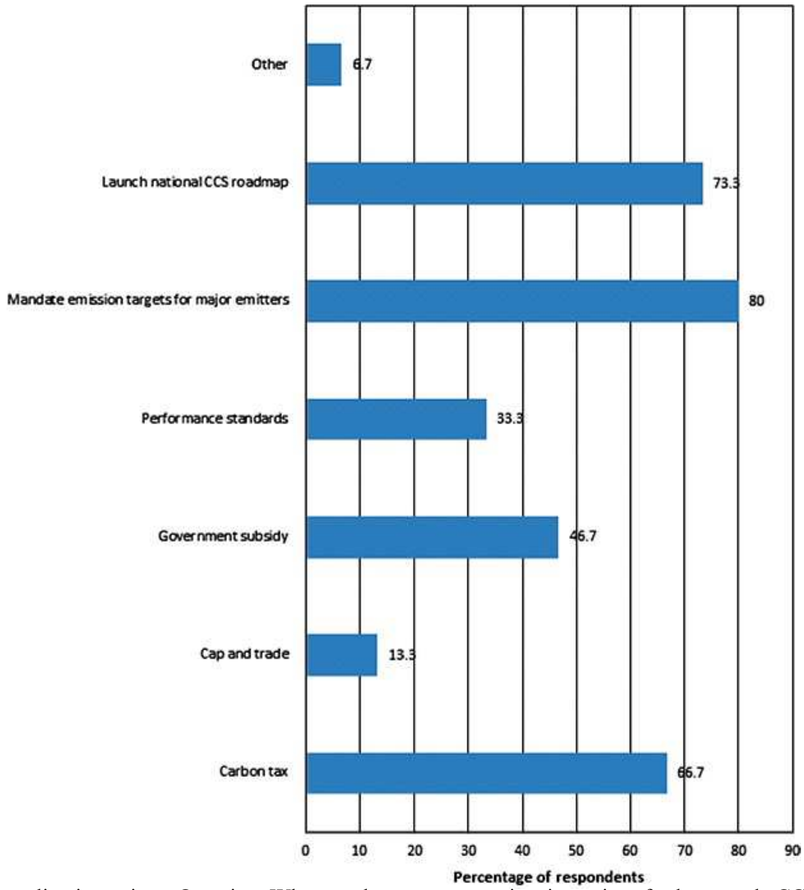

Fig. 8: Stakeholder's views on policy incentives. Question: What are the most appropriate incentives for large scale CCS? Multiple answers allowed.

renewable energy (Liu *et al.*, 2012). As shown in **Figure 10**, the respondents believe that the effect of investing in CCS on renewables will be equally very positive and slightly positive (each with 33.3%). However, an appreciable number of respondents (20%) believe the effect of investing in CCS on renewables should remain neutral while a minority (13.3%) are unsure.

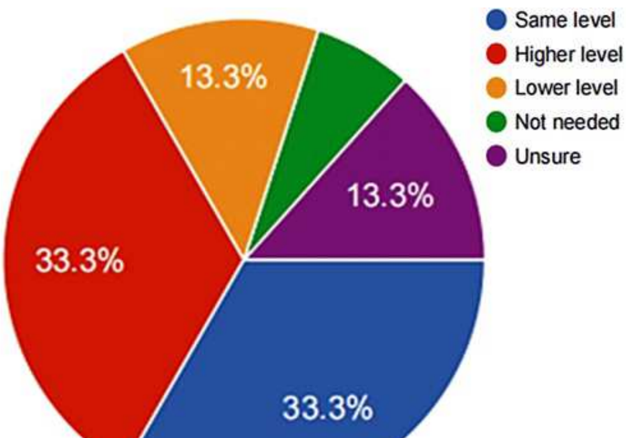

Fig. 9: Stakeholder's views on incentives of CCS vs. renewables. Question: Should CCS receive similar subsidies to those used in renewables development? Only one answered is allowed.

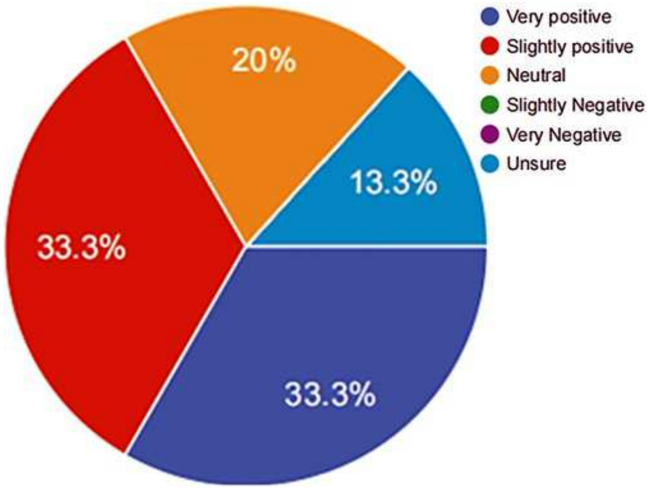

Fig. 10: Stakeholder's views on impact of CCS investment on renewables. Question: The impact of investment in CCS on renewables would be? Only one answer is allowed.

Conclusions

The hydrocarbon industry is always affected by the geopolitics of oil and Nigeria, being a major oil exporting country, is a stakeholder. As the world moves toward decarbonisation, CCS would become an important technology for mitigating climate change through cleaner energy production. For hydrocarbon producing countries like Nigeria, CCS implementation can combine with EOR as a favourable answer to the challenges of rising energy need and climate change policies through boosting oil production and lowering CO_2 emissions (Aminu *et al.*, 2017; Liu *et al.*, 2012). At present, energy efficiency and renewable energy are gaining interest from the Nigerian government, which has been part of several initiatives in these areas. On the other hand, the potential for CCS demonstration in Nigeria is mainly discussed by stakeholders within government and the energy industry. While there are not any intends in place to advance an integrated commercial scale CCS project, there have been some emerging research interests mainly focussing on the viability of technology deployment across all parts of the CCS value chain. When CCS technology is implemented, it would normally progress in a series of scaled-up stages, which would essentially involve pilot, demonstration, and commercial scales, respectively. However, given the positive outcomes of pilot CCS facilities around the world, the experience to be gained from the operation of demonstration projects in Nigeria would assist in improving the country's CO_2 management plan. The majority of CO_2 sources in Nigeria are located around the Niger Delta, which is the most potentially suitable basin for CCS technology deployment. As policies and regulatory frameworks for CCS are currently emerging at local and global levels, it is important for Nigeria to set realistic policies and efforts to demonstrate the viability of demonstration and commercial scale integrated CCS technology.

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