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RESEARCH ARTICLE

ADVANCES IN CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS): STATE OF THE ART

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ABSTRACT

Global energy demand for fossil fuel has been projected to increase into the future. As a result, dire environmental challenges are posed to our ecosystem due to increase in carbon emissions. Hence, there is an urgent need to seek clean energy solutions such as Carbon Capture and Storage (CCS) that would forestall continuous carbon emission. Therefore, this paper reviewed current global status of CCS plants, economics, policies that would support the business case of CCS and latest breakthroughs recorded in carbon conversion. Accordingly, novel adsorption-based technologies such as Metal Organic Frameworks (MOFs), Mixed Matrix Membranes (MMMs) for carbon capture and economic tools such as carbon tax, carbon credit and progressive financing critical to supporting development of a carbon market and deployment of CCS facilities in Nigeria were extensively discussed. Finally, the paper highlights segments of CCS that should be optimized to facilitate its deployment in West Africa in general and Nigeria in particular.

KEYWORDS

Carbon, Capture, Utilisation, Storage, Advances, Investment

1. INTRODUCTION

Global production and consumption of fossil fuels would continuously increase into the future, resulting in emission of carbon (IV) oxide (CO_2) into the atmosphere which cumulates in increased global warming (BP, 2017; BP, 2018; BP, 2019a; BP, 2019b; Aimikhe and Eyankware, 2019). Intergovernmental Panel on Climate Change (IPCC) projects that global warming is likely to reach 1.5^oC rise in temperature above pre-industrial era between 2030 and 2052 if anthropogenic activities that promote carbon emissions continue at its current rate (IPCC, 2018). Hence, it is imperative to cut down on global carbon emissions from process and industrial systems so as to ensure environmental sustainability. In order to limit global warming to 2^oC Scenario (2DS) by 2060 in line with the target set by Paris Agreement, International Energy Agency (IEA) predicts that a 14% cut in carbon emissions must be achieved (IEA, 2017). Also, a projection into beyond 2^oC Scenario (B2DS) era reveals that a 32% cut in carbon emissions would be needed against a backdrop of increase in carbon emissions into >2060; all reiterating an urgent need for deployment of clean energy technologies.

IPCC and IEA reports that these emission cuts can be achieved through mitigation technologies amongst which *Carbon Capture, Utilisation and Storage (CCUS)* has been identified as a ready decarbonisation technology for carbon emission reduction. For instance, it is highlighted that CCUS would be responsible for decarbonisation of the chemical sector by 38% (14 $GtCO_2$) by 2060 (IEA, 2019). Hence a rapid deployment of CCUS facilities becomes pertinent in order to achieve IPCC's decarbonisation targets; deployment of 2500 Carbon Capture and Storage (CCS) facilities (each facility with CO_2 capture capacity of 1.5 million tonnes per annum) have been predicted to be required in order to achieve Paris Agreement of below 2^oC rise by 2040 (Global CCS Institute, 2018). This is imperative as current global CCS capacity (19 commercial CCS facilities currently operate globally as shown in Figure 1 capturing CO_2 from industries such as gas processing, synfuel production, power, oil production, steel, refinery, fertiliser production and ethanol production as shown in Figure 3) plus underway projects (there are 4 CCS facilities under construction, 10 in advanced engineering development and another 18 in early development phase as shown in Figure 2) are below required capacity by a factor of 20 to meet targeted carbon emission cuts (Global CCS Institute, 2019).

Figure 1: Current CCS facilities and their respective locations, reproduced from (Global CCS Institute, 2019)

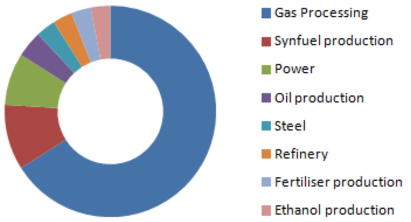

Figure 2: CO_2 capture capacity of CCUS in different industries, data from (IEA, 2019)

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Hence, capacity of existing CCUS facilities has been projected to increase by one million tonnes in the next 12 – 18 months in addition to the current global carbon capture capacity of 40 million tonnes of CO_2 per annum. An example of one of such operational CCS facilities is the Boundary Dam Project in Saskatchewan, Canada shown in Figure 3 which exceeded a storage capacity of 2 $MtCO_2$ in March, 2018 without incidences.


The first CCS project applied to coal-fired power generation commenced operation in 2014

Boundary Dam Project, Canada
Image courtesy of Saskpower

Figure 3: Boundary Dam CCS Project in Saskatchewan, Canada (IEA, 2015)

1.1 Carbon Capture, Utilization and Storage (CCUS)

In CCUS, carbon capture accounts for a significant portion of the cost of the technology. As a result, it strongly determines its commercial and industrial deployment (hence, intensive research is being targeted towards driving down cost for CO_2 capture with substantial progress made achieved). Amongst different carbon capture technologies such as oxy-combustion, pre-combustion and post-combustion carbon capture technologies, post combustion (existing at pressures of ~ 0.15 – 1 bar and high temperatures - >313K) technology depicted in Figure 4 has been identified as the most promising technology for carbon capture due to its ease of retrofitting into existing systems (Aimikhe and Eyankware, 2019; Mukherjee et al., 2019). Notably, popular amine scrubbing technology which is regarded as the most mature carbon capture technology is a post combustion carbon capture technology (Ansaloni et al., 2019). Also, a significant number of absorbent-, adsorbent- and membrane-based technologies highlighted by United States' Department of Energy (DOE) and National Energy Technology Laboratory in the Carbon Capture Program R&D report are all post combustion carbon capture technologies (US DOE/NETL, 2015).

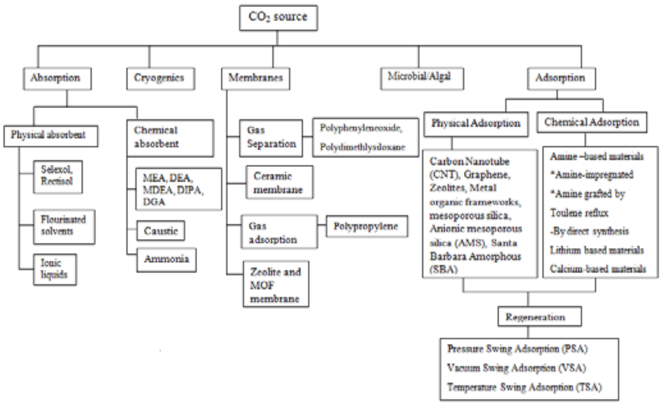


Figure 4: Post Combustion CCS technologies (Abu Ghalia and Dahman, 2017; Li et al., 2011)

These different carbon capture technologies are consequently complimented by a high confidence level CO_2 underground storage at incentives of as low as US$40 per tonne of CO_2 stored (IEA, 2019; Alcalde et al., 2018). This is due to knowledge and experience garnered over the years by the oil and gas industry in CO_2 subsurface injection through Enhanced Oil Recovery; over 260 million tonnes of CO_2 have been successfully injected underground till date, highlighting a well mature and well understood technology. Hence, various CO_2 storage sites with varying confidence level (high, medium, low and very low confidence) as shown in Fig. 5 are well suitable for projected CO_2 capture of 1200 $GtCO_2$ by 2100 as depicted by IPCC climate pathway models (Global CCS Institute, 2019). In addition, with well suited Monitoring, Measurement and Verification (MMV) programme in place, modelling studies by Alcalde et al. revealed that there is 98% certainty that CO_2 injected underground would remain safely stored for over 10, 000 years, highlighting the readiness of carbon capture and storage as a ready decarbonisation solution (Alcalde et al., 2018).

Figure 5: Global CO_2 Storage Capacity (measured in GigaTonnes), reproduced from (Global CCS Institute, 2019)

On the other hand, Carbon Capture and Utilization (CCU) which is regarded as a critical inducement of CCS has the capacity to provide economic incentives and a circular economy needed to promote industrial deployment of CCS plants at the needed rate; Global CO_2 Initiative states that market for CCU is worth 8.8 – 1.1 trillion dollars if over 10% of annual CO_2 emissions are converted to valuable products (Wang et al., 2019). Also, Life Cycle Assessment (LCA) of different conversion routes of CO_2 into useful chemicals through thermochemical, photochemical and electrochemical conversion processes shown in Fig. 6 reports that CCU consequently reduces global emissions (Thonemann and Pizzol, 2019). Unfortunately, the positive environmental impacts and economic potentials of this technology have not yet been harnessed as market for CCU is estimated to presently consume 300 Mt/CO_2 (best case scenario) (most probable market exists in chemical and oil industry) as compared to 14,000 Mt/CO_2 released (Nocito and Dibenedetto, 2019). However, this can be attributed to uncertainties associated with climate change mitigating effect of the technology (Katelhon et al., 2019). Hence, significant efforts to upscale CCU for industrial applicability is needed; this has resulted in novel research works on CCU being published frequently in recent times (Katelhon et al., 2019; Gondal and Masood, 2019; Fan et al., 2019; Sanchez et al., 2019; Guntern et al., 2019; Birdja et al., 2019; Baena-moreno et al., 2019; Arning et al., 2019; Garc et al., 2019; Dinh et al., 2018; Thengane et al., 2019; Zhang et al., 2017; Koytsoumpa et al., 2018).

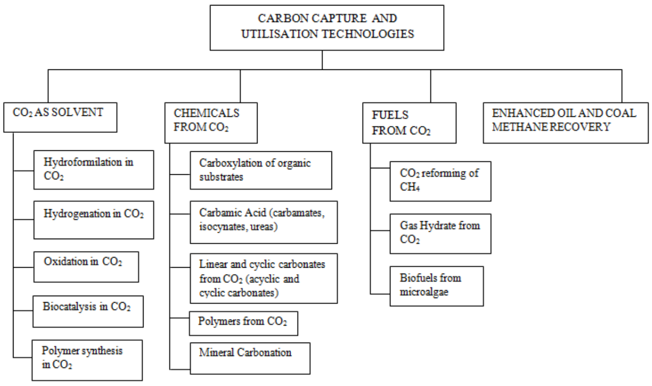


Figure 6: Carbon and Utilisation Technologies, reproduced from (Baena-moreno et al., 2019)

Over the years, knowledge and experience garnered from learning-by-doing operations of CCS facilities have increased expertise in the technology which has subsequently driven down the cost of constructing and operating CCS facilities globally; this is very instrumental for a rapid commercial deployment of CCS. For instance, SaskPower the operator of Boundary Dam CCS Project in Saskatchewan, Canada confirms this by stating that a cost reduction of 20-30% is achievable for the construction and operation of a future CCS facility. As a result, CCS technology's commercial deployment coupled with breakthroughs recorded in conversion of carbon to high valued products that can augment operational costs of running CCS plants would prove highly attractive to investors in the near future.

Due to the exigency required in the deployment of CCUS facilities globally in order to curb carbon emissions and safeguard our environment, this paper seeks to discuss latest advances recorded in carbon capture (focusing on novel post combustion carbon capture) and carbon conversion technologies so as to identify potential points of optimization that would promote deployment of cost effective and efficient CCUS facilities. Furthermore, the paper highlights critical factors that directly affect the business case of CCUS industry globally; market drivers such as economic tools and policies are herewith discussed. Finally, a strong case for industrial deployment of CCUS in West African region particularly Nigeria is made as the country remains a significant contributor to CO_2 emissions in the region.

2. ADVANCES IN CARBON CAPTURE, STORAGE AND UTILIZATION TECHNOLOGY

2.1 Post Combustion Carbon Capture and Storage

United States' DOE Fossil Fuel Program report highlighted several advances recorded in the development of technologies for post combustion CCS [16]; a significant number of these solvent, sorbent and membrane based technologies were reported to be at development/test phase with promising potential for industrial applicability (US DOE/NETL, 2015). In order to advance these technologies to commercial phase of Technological Readiness Level (TRL), and also improve system efficiency of already existing CCS facilities, intensive research is being carried out to optimize these processes for cost effective and efficient practical applicability (Bui et al., 2018).

For example, extensive research is being carried out in order to optimize popular amine scrubbing technology by synthesis of bi-solvents, tri-solvents and quad-solvents, develop and optimize novel adsorbent based technologies [such as metal organic frameworks (MOFs), polymers, activated carbon, zeolites and increase permeance and selectivity of membranes for efficient post combustion carbon capture (El Hadri et al., 2017; Kim et al., 2014; Shahraki and Sadeghi, 2016; Singto et al., 2016; Sema et al., 2012; Kim et al., 2016; Liang et al., 2016; Narku-Tetteh et al., 2017; Liang et al., 2015; Henry et al., 2015; Sodiq et al., 2018; Cuccia et al., 2018; Nwaoha et al., 2016; Wai et al., 2018; Olajire, 2018; Ye et al., 2019; Gopalsamy and Subramanian, 2018; Chen et al., 2019; Chen et al., 2018; Edubilli and Gumma, 2019; Jiang et al., 2019; Liang et al., 2019; Lv et al., 2019; Ma and Urban, 2019; Xu et al., 2019; Vinodh et al., 2019; Huang and Wang, 2019; Alahmed et al., 2019; Caskey et al., 2008; Fayemiwo et al., 2018; Wang et al., 2019; Ahmed et al., 2018; Aguilar-lugo et al., 2018; Martin et al., 2011; Li and Xiao, 2019; Das and Meikap, 2019; Chen et al., 2014; Garcia et al., 2011; Boujibar et al., 2018; Zhang et al., 2019; Rashidi and Yusup, 2016; Tan et al., 2017; Shahkarami et al., 2015; Montagnaro et al., 2015; Madzaki et al., 2018; Plaza et al., 2010; Sun et al., 2018; Zhao et al., 2018; Chen et al., 2017; Wang et al., 2019; Krishna and Van Baten, 2012; Xu et al., 2019; Ahmad et al., 2019). However, adsorbent- and membrane-based technologies which ameliorate drawbacks of amine scrubbing technology would be discussed in this section. Notably, MOFs which are regarded as benchmark adsorbents for carbon capture and novel membranes would be highlighted as follows;

2.1.1 Metal Organic Frameworks

MOFs are a novel class of Porous Coordination Networks (PCNs) composed of metal ions/clusters/secondary building blocks and organic ligands/linkers as shown in Figure 7 (Dhankhar and Nagaraja, 2019; Rosi et al., 2002; Ugale et al., 2018; Olajire, 2018; Han et al., 2015; Li et al., 2019). MOFs have been identified as a viable option that can optimize adsorbent based carbon technologies for cost-effective and efficient carbon capture, exhibiting properties such as ultra-high surface area, tunable pore sizes, ease of tunability and functionalization and low of heat of adsorption and regeneration that outperform drawbacks of popular amine scrubbing technology such as high regeneration energy, solvent degradation and high cost of operation (Wen et al., 2019; Brunetti et al., 2010; Shelly, 2009)

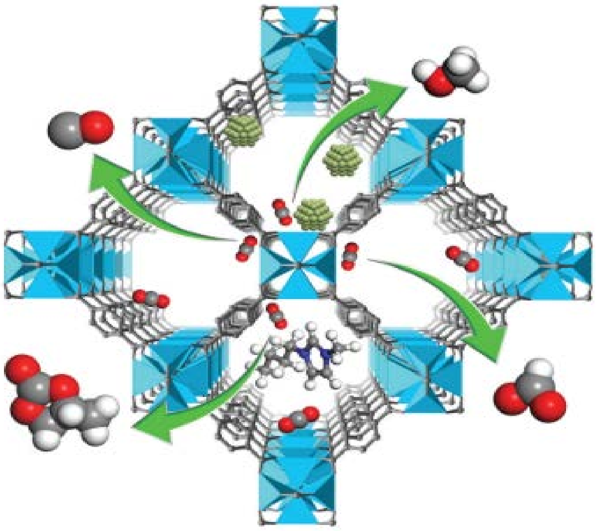


Figure 7: A generic MOF composed of tetrametallic SBUs linked by terephthalate with four channels to capture CO_2 and convert it to either CO (left), methanol using metal nanoparticles embedded in the pore (top), formate (right), or ethylene carbonate using an ionic liquid lodged in the pore (bottom), reproduced from (Ding et al., 2019)

Despite high initial cost of investment and other demerits associated MOFs highlighted in Table 1, its propensity for low overall operational energy consumption justifies its use as an adsorbent for carbon capture over a long period of time (Pal et al., 2019). Hence, intensive research for high performing MOFs for CO_2 capture at post combustion conditions have been reported in literature as shown in Table 2.

2.1.2 Membranes

Membranes show propensity for separation of CO_2 from exhaust gas fumes at post combustion conditions; this can be attributed to technical and cost-related merits that membrane technology exhibits as highlighted in Table 3 (Brunetti et al., 2010; He, 2018; Che and Lipscomb, 2019; Dai et al., 2019; Sivaniah, 2014; Fu et al., 2018; Sun et al., 2019). For membranes to be successfully, it must possess certain characteristics such as high permeability, permeance, high selectivity, low cost of production and regeneration, good chemical and thermal stability and ability to resist plasticization (Du et al., 2012). However, a membrane that exhibits these characteristics is difficult to synthesize. Hence, there continues to be serious research to improve pristine membranes or rather, synthesize new membrane compounds using novel strategies for improved performance.

Parameters such as permselectivity, permeability, selectivity, chemical and mechanical stability have been the focus of active research in synthesizing an optimum gas separation (GS) membrane resulting in the synthesis of different class of membranes such as polyimides, facilitated transport, mixed matrix, carbon molecular sieves, poly-ether-oxide, poly(vinylidine fluoride), Pebax and ceramic membranes and MOF membrane (Brunetti et al., 2010; Shah et al., 2017; George et al., 2016; Liu et al., 2018; Sabetghadam et al., 2018). These novel membranes have shown good applicability for CO_2 capture at post combustion conditions; their respective permeability and selectivity for CO_2 from flue gas stream composition are highlighted in Table 4.

Table 1: Advantages and Disadvantages of Metal Organic Frameworks (MOFs)

Advantages	Disadvantages
Large specific surface area (over 10,000 m^2/g) and regular pore distributions	Poor economic efficiency due to high production cost
Possible improvement in CO_2 selectivity according to various combinations of metal clusters and organic ligands	Complicated synthetic process
Possible improvement in the CO_2 adsorption capacity; thermal and chemical stability of the structure based on diverse choice of SBUs, organic linkers, pre- and post-synthetic modification methods	Moisture-sensitive (possible structure failure due to moisture absorption during CO_2 capture)
Ease of controllability of pore sizes	Limited regenerability/reusability cycles for commercial and industrial applications

Table 2: CO_2 adsorption capacity of selected MOFs at various conditions

MOF Types	**S_{BET} (m^2/g)**	**Pore Volume (cm^3/g)**	**CO_2 uptake**			**SCO_2/N_2**	**Q_{st} (KJ/mol)**	**Ref.**
			0.15 bar	**1 bar**	**T (K)**			
TAEA modified MIL- (Cr)	-	-	15 mmol/g 4.06 mmol/g	-	298 313	-	-	(Li et al., 2019)
Zn(BPZNH$_2$)	395	0.57	-	3.07 mmol/g	298	14	35.6	(Vismara et al., 2019)
UTSA-120	639	-	3.56 mmol/g	-	296	~600	-	(Wen et al., 2019)
1-nmen	-	-	2.92 mmol/g	3.99 mmol/g	313	164	79.9	(Lee et al., 2018)
1-een	-	-	4.04 mmol/g	5.05 mmol/g	313	293	86.4	(Lee et al., 2018)
1-ipen	-	-	3.47 mmol/g	4.05 mmol/g	313	273	86.7	(Lee et al., 2018)
Cu-Sp5	-	-	-	1.30 mmol/g 1.65 mmol/g	298 278	200	43.1	(Kochetygov et al., 2018)
IISERP-MOF24	~771	-	-	2.0 mmol/g ~3.0 mmol/g 4.8 mmol/g	298 248 273	68	23	(Maity et al., 2018)
Mg-CUK-1	586	-	-	3.37 mmol/g	303	-	-36.5	(Sanchez-Gonzalez et al., 2018)
Compound **1**	637	-	-	4.1 mmol/g 2.2 mmol/g	273 298	-	31.1	(Yuan et al., 2019)
MFM-305-CH$_3$	256	0.181	0.86 mmol/g	2.41 mmol/g	298	-	29-34	(Li et al., 2019)
MFM-305	779	0.372	1.76 mmol/g	3.02 mmol/g	298	-	29-34	(Li et al., 2019)
[MFUM-1(Cu)]		-	-	-	298	7531		(Hassanpoor et al., 2018)
NU-901-SALI-BA-3,5-NH$_2$	1793	-	-	123 cm^3/g	273	-	-	(Garibay et al., 2018)
CuBTC	1560	-	-	9.33 mmol/g	273	-	-	(Liu and Liu, 2018)
MIL-140	1282	0.50		1.90 mmol/g	313	1900	40	(Amato et al., 2019)
UTSA-120a	639	-	3.56 mmol/g	- 5.00 mmol/g	296 296	~600	-	(Wen et al., 2019)
1-dmen	-	-	-	4.34 mmol/g	313	554	75	(Lee et al., 2015)

Table 3: Advantages and Disadvantages of Membranes for CO_2 separation

Advantages	**Disadvantages**
No need for regeneration	Limitation on the operating temperature
Possible improvement in permeance and selectivity due to possibility of structural modification	Low permeation selectivity for CO_2 over other gases
Environmentally friendly	-
Low operating costs	Reduction of CO_2 permeance due to presence of water in flue gas stream
Good weight and space efficiency	Necessity to compress the gas to drive the permeation between two sides of the membrane
High separation energy efficiency comparing to equilibrium-based processes like absorption	-

Table 4: CO_2 separation capacity of Membranes at post combustion conditions

Membrane	**P (bar)**	**T (K)**	**SCO_2/N_2**	**CO_2 permeance (Barrer^a/GPU^b)**	**Ref.**
UiO-66-CN@sPIM-1	1.4	298	53.5(±4.1)	^{a}12 063.3(±106.2)	(Yu et al., 2019)
MOF-801/PEBA MMM	1	293	66	^{b}22.4	(Sun et al., 2019)
NH$_2$-CAU-1 MOF		303	-	^{b}109.4	(Zhao et al., 2019)
PVA/CNC	-	-	43.6	^{b}672	(Dai et al., 2019)
MoS$_2$-SILM	1	293	462	^{b}200	(Ying et al., 2019)
EC/ZIF-8@GO	2	298	33.4	^{a}203.3	(Yang et al., 2019)
Dual layer Cu-BDC/ Polyactive	2	298	35	^{b}129	(Sabetghadam et al., 2019)
MMM Cu-BDC/ Polyactive	2	298	77	^{b}40	(Sabetghadam et al., 2019)
COF-5/Pebax	1	303	49.3	^{a}493	(Duan et al., 2019)

Notation: ^{a} = Barrer;1 Barrer = 10^{-10}cc (STP)cm cm^{-2} s^{-1} cmHg^{-2}; ^{b} = GPU;1 GPU = 10^{-6}cc (STP)cm^{-2} s^{-1} cmHg^{-1}

2.1.3 Economics of Carbon Capture Technologies

A conservative rate of learning-by-doing of 8% per annum accompanied with growth in number of CCS facilities from tens to thousands has been projected to result in a reduction of cost of CO_2 capture by half by 2050 (IEA, 2019). This is necessary as high cost of CCS constitutes a major barrier to its commercial and industrial deployment. During SOLARIMPULSE FOUNDATION's interview with Brad Page (CEO of Global Institute of CCS), he highlighted that cost of carbon capture could range from $100 to as low as $30 per tonne of CO_2 depending on the high concentration of CO_2 in the flue gas stream and type of industry as highlighted in Table 5; emphasizing a strong tendency to achieve low cost CO_2 capture through intensive research in the near future as shown in Figure 8.

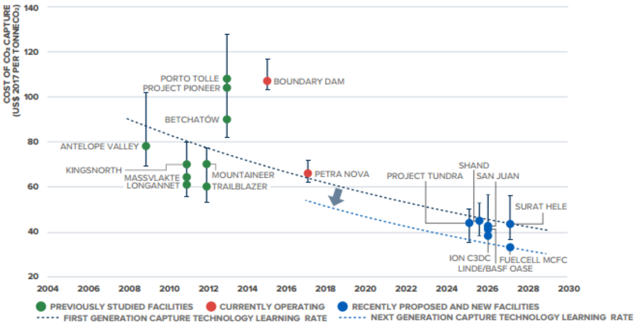


Figure 8: Projected cost of CO_2 capture from 2004 - 2030, reproduced from (Global CCS Institute, 2019)

For instance, cost of CO_2 capture in coal-fired power plants has been reduced by half from 100 USD to as low as 45 USD/tCO_2; specifically, a significant cost reduction of 65 USD/tCO_2 has been reported by Petro Nova Facility in USA as compared to Boundary Dam facility's 100 USD/tCO_2 within a period of three year. Mores so, cost of CO_2 capture by 2024-2028 has been projected to be approximately 43 USD/tCO_2 with further reduction of 33 USD/tCO_2 envisaged in new technology driven CCS plants that are currently in pilot phase. In addition, low cost of CO_2 capture of 15 USD/tCO_2 which is below target of 40 USD/tCO_2 set by US DOE for second-generation carbon technologies has been reported by membranes with selectivity >50 for CO_2/N_2 and CO_2 permeance of 4000 GPU (He, 2018; Plaza and Pevida, 2018; Yu et al., 2019).

Table 5: Cost of CO_2 capture at different CO_2 concentration

Source of CO_2	Concentration of CO_2	Cost of capture (UDS/tCO_2)
Natural Gas Processing	96 – 100	15 – 25
Coal to Chemicals	98 – 100	15 – 25
Ammonia	98 – 100	25 – 35
Bioethanol	98 – 100	25 – 35
Ethylene oxide	98 – 100	25 -35
Hydrogen	30 – 100	15 – 60
Iron and Steel	21 – 27	60 – 100
Cement	15 – 30	60 – 120

The propensity of use of multiple pathways in the operation of CCS plants to drive down cost of operations has also been reported (IEA, 2017). In this regard, optimization of CO_2 pipeline network has been identified as a significant aspect of CCS that can significant drive down the cost of operations. Factors such as cost effective and efficient design of CO_2 pipeline and storage networks, competitive advantage from key players in the industry, cost efficient technological innovation (e.g use of big data to identify and modify less cost effective pipeline networks) and reduction in cost of construction materials are potential factors that can also reduce of cost of CCS plants, improving the deployment of the technology.

2.2 Carbon Capture and Utilization (CCU)

Advances aimed at circumventing drawbacks of CCU technologies such as (i) High energy consumption as a result of the kinetically sluggish nature of multielectron transfer process during CO_2 reduction. (ii) Difficulty in the selective production of a wide range of chemicals from CO_2 reduction process. (iii) Loss of activity of catalysts used for CO_2 reduction due to instability. (iv) Absence of optimal experimental systems for CO_2 reduction studies and a fundamental theory have been reported in literature. Some of the recent works that recorded these advances would be discussed as follows (Zhang et al., 2017);

Buonsanti et al. reported the synthesis of a novel Nanocrystal/MOF hybrid electrocatalyst which impedes Hydrogen Evolution Reaction (HER), contributes to mass transfer effects, increases morphological stability of the catalyst and an overall contribution to CO_2 Reduction (CO2R) (Guntern et al., 2019). Dinh et al. reported the synthesis of a hydroxide-mediated copper catalyst that improves the faradaic efficiency by 70% during the conversion of CO_2 to ethylene while Pant et al. in their work highlighted latest trends recorded in CO2R systems such as reactor design, electrode configuration, anode reaction and membranes that ameliorate drawbacks of existing CCU technologies (Sanchez et al., 2019; Dinh et al., 2018). Sargent et al. highlighted the synthesis of an electrolyzer with 100% CO_2 conversion efficiency that converts carbonate solution to syngas through a Bipolar Membrane (BPM) instead of the conventional Membrane-Electrode Assembly (MEA) (Garc et al., 2019). Mi et al. reported the design of a novel GaN:Sn nanoarchitecture for photoelectrochemical reduction of CO_2 to HCOOH (formic acid) with a high Turn Over Frequency (TOF) of 107 min^{-1}, high Faradaic Efficiency of 76.9% and a high current density of 17.5 mA/cm^{-2} (Zhou et al., 2019).

Weireld et al. reported techno-economic investigation of an integrated CCUS system involving capture and conversion of CO_2 to Synthetic Natural Gas (SNG) (Chauvy et al., 2020). Using Aspen Tech, Aspen HYSYS and Aspen Plus™, the authors modelled an integrated CCUS system and highlighted the conversion of 1 ton of CO_2 (from 10% of cement exhaust flue gas) to 0.4 ton of SNG (with composition similar to conventional natural gas) using hydrogen as renewable in an wind-powered electrolyzer with an overall system efficiency of 72.6%. They also revealed that though cost of production of SNG is higher, prospects for cost reduction such as projected reduced cost of renewables and possible use of oxygen as co-products would reduce system cost in the future. Sinton et al. reported the design of a novel alkaline flow cell electrolyzer for conversion of CO_2 to CO (Edwards et al., 2020). Combining parameters such as minimal electrode spacing, pressurization and alkalinity, they revealed that the electrolyzer exhibits cell energy efficiency of 67% and current density of 202 mA/cm^2 (highest recorded above 150 mA/cm^2). Weireld et al. carried out a study on the conversion of industrial CO_2 to methanol using an integrated system modelled using Aspen Plus® (Meunier et al., 2020). Optimizing the integrated system using heat from exothermal methanol reaction for regeneration of MEA-based CO_2 capture system, 1546 tons of methanol per day was obtained from 2475 tons of CO_2 at 90% process efficiency at environmental cost of 50% less than conventional production of methanol from natural gas.

Furthermore, Bardow et al. carried out a review of CCU technology in the chemical industry focusing on its potential to decarbonise the sector and mitigate climate change (Katelhon et al., 2019). The authors developed a model that highlighted the technical capacity of large-scale CCU plants to reduce carbon emissions from fossil fuel utilization in the chemical industry; notably, the high-demand for low-carbon electricity of CCU technologies was also highlighted. Navarrete et al. carried out a comprehensive review of CCU technologies focusing on the different derivatives/high value chemical products obtained from CO_2 (Baena-moreno et al., 2019). They revealed that the process of carboxylation (synthesis of carbonates and carboxylates) is the most probable amongst CO_2 derivatives highlighted in their work; mineral carbonation on the other hand was revealed that as the CCU chain that has most positive effect on global warming reduction. Dibenedetto and Nocito also carried out a review on Carbon Capture, Storage and Utilization (CCUS) focusing on recent advances recorded in integrated CCUS systems (Nocito and Dibenedetto, 2019).

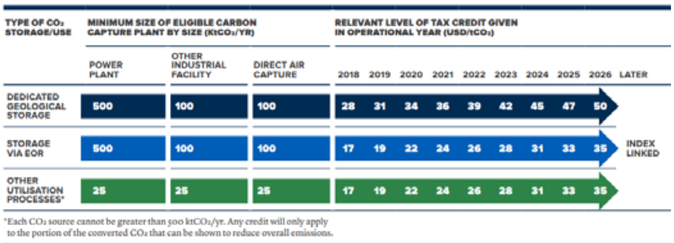
In their review, they highlighted recent materials such as membranes, polymers and porous carbon used for CO_2 capture, advances recorded in CO_2 transport and disposal and technologies such as hydrogenation, coupling catalysis and biotechnology used for CO_2 conversion. Thonemann and Pizzol reviewed CCU technologies using consequential Life Cycle Assessment (LCA) method. Comparing 12 CO_2-conversion derivatives [CO, DMC, FA, DMM, MeOH, CH4, Fischer-Tropsch (F-T) products, EtOH and polyols], the authors revealed that in a long time, only DMM, F-T products and FA produced electrochemically would have a negative impact on global warming. Also, they stated that only polyol production has the highest effect on environmental impact reduction. These selected carbon conversion advances highlights have prompted the development of different CCU projects such as CHOCHCO, enCO2re, VALCO2II, BioRE-CO2VER, Kopernikus Power-to-X, Rheticus Project etc. A group researcher coming on stream in recent times to demonstrate their feasibility for practical applicability (Sanchez et al., 2019).

3. INVESTMENT POLICIES FOR BUSINESS CASE OF CCUS: DETERMINING FACTORS

Presently, CCUS is a competitive decarbonisation strategy applicable to industrial processes such as natural gas processing, production of ammonia, production of hydrogen from fossil fuels etc. that produce high purity CO_2 stream (IEA, 2019). This highlights propensity of rapid deployment of the technology globally as the business case of CCUS becomes more attractive to potential investors. Several factors such as (i) Tax credit/emissions (ii) Carbon tax (iii) Grant support (iv) Enhanced Oil Recovery (v) Low cost of carbon capture (vi) Low cost of transport and storage (vii) Vertical Integration have been reported to drive investment and deployment of CCUS facilities globally. On a broader sense, these factors seek to put value on CO_2 so as to incentivise the industry, making it attractive to investors. However, there are still bottle necks (hard-to-reduce risks) hindering major investment by private sector in CCS; such bottle necks include cross-chain risks, policy and revenue risks, storage liability, knowledge spill overs, information failure and natural monopoly industries (Global CCS Institute, 2019). Presences of these risks have resulted in high premium lending rate or provision of insurance to private investors making funding from financial institutions difficult to access. Hence, a holistic approach involving collaborative efforts between private and public sector has been proposed so as to ensure both players bear such high risks. This translates to different policies, strategies and economic tools that make business case of CCUS attractive for investment. Some of these policies and strategies are highlighted as follows;

3.1 Tax Credit

In the US, 13 CCS projects have come on stream since 2011 and this has been attributed to favourable strategic policy framework that supports CCS deployment in industrial applications. Notably in 2018, US's Congress increased and extended tax credit through Section 45Q tax credit incentive for CO_2 storage for CCS plants that would begin construction by 2024 from 18 USD/tCO_2 to 35 USD/tCO_2 for CO_2 stored by Enhanced Oil Recovery (EOR) and from 29 USD/tCO_2 to 50 USD/tCO_2 for CO_2 stored permanently in geological formations as depicted in Fig. 9. However, only specific CCS plants with a minimum capacity of 500kt/CO_2 for power plants and EOR operations and 25kt/CO_2 for other industrial processes are eligible for 45Q tax credit. By reducing a company's tax liability and providing additional funding through sales of tax credit in tax equity markets, tax credit encourages investment in CCS technology especially in high cost CO_2 capture plants such as coal-fired plants. Consequently, 45Q Tax Credit has been estimated to encourage construction of coal and natural gas CCS plants that would capture 49 mt/yr of CO_2 by 2030 (Global CCS Institute, 2019). Considering impacts of 45Q tax credit on CCS deployment in the US, it is advisable that other countries should follow suite and enact their own market specific tax credit that would incentivise CCS plant deployment in their respective countries.



TYPE OF CO_2 STORAGE/USE	MINIMUM SIZE OF ELIGIBLE CARBON CAPTURE PLANT BY SIZE (KtCO₂/YR)			RELEVANT LEVEL OF TAX CREDIT GIVEN IN OPERATIONAL YEAR (USD/tCO₂)									
	POWER PLANT	OTHER INDUSTRIAL FACILITY	DIRECT AIR CAPTURE	2018	2019	2020	2021	2022	2023	2024	2025	2026	LATER
DEDICATED GEOLOGICAL STORAGE	500	100	100	28	31	34	36	39	42	45	47	50	
STORAGE VIA EOR	500	100	100	17	19	22	24	26	28	31	33	35	INDEX LINKED
OTHER UTILISATION PROCESSES*	25	25	25	17	19	22	24	26	28	31	33	35	

*Each CO_2 source cannot be greater than 500 ktCO_2/yr. Any credit will only apply to the portion of the converted CO_2 that can be shown to reduce overall emissions.

Figure 9: 45Q Tax Credit Incentive layout, reproduced from (Bennet and Stanley, 2018)

3.2 Emission Regulation

Regulation of emissions from industrial/process plants plays a key role in fast tracking deployment of CCS plants all over the world. The rationale behind emission regulation and its effect on investment decisions in CCS is that when restrictions and penalties for violation are placed on CO_2 emissions, industry players would seek clean energy solutions such as CCS in order to avoid penalties and possible sanctions that would hamper smooth running of their operations. For instance, compelling requirement of injecting a minimum of 80% of CO_2 emitted by Gorgon Project's natural gas processing plant (which is regarded as the world's highest CO_2 storage) underground before its approval was highly instrumental in the deployment of CCS technology in the project. Also, the raise in the cost of gas flaring from oil and gas flare stacks in Nigeria from 10 Naira/Mscf to 2 USD/Mscf provides a good start in driving its industrial sector towards use of clean energy solutions (such as CCS) for environmental sustainability.

3.3 Capital Grants

Since CCS technology is still considered to be associated with perceived risks, getting funding from financial institutions becomes difficult as a result of high lending rates. Hence, provision of capital grants by government would help to reduce cost of CCS projects and make the industry attractive to investors. It would also encourage innovations in the industry as early investments that are capital-grant funded would result in knowledge spill over making consecutive projects more cost effective and efficient. The impact of capital grant funding is evident in the construction of Alberta's CAN$1.2b Carbon Trunk Line project that was funded through capital grants of CAN$558m (Global CCS Institute, 2019). As shown in Figure 10, different CCS projects have received capital grants to support their financing. Also, Europe's Innovation Fund that hopes to make 10 billion Euros available to fund innovations low carbon innovations (CCUS inclusive) is another example of capital grant source for CCS projects (Global CCS Institute, 2019). It is highlighted that initial 40% funding would be made available to project preparation phase ("based on pre-defined milestones") while remaining 60% would be dedicated to innovation (high dependent on the outcomes of verifiable emission evaded). Notably, a call for proposals from different CCS projects has been slated to occur in 2020.

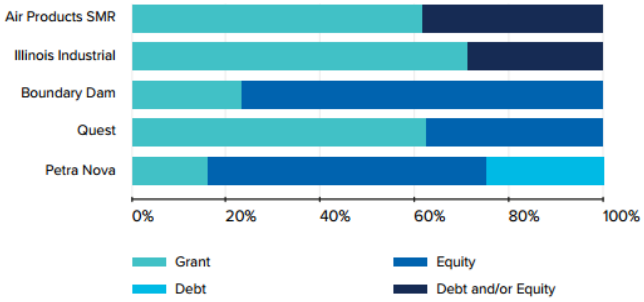


Figure 10: Funding options of selected CCS project, reproduced from (Global CCS Institute, 2019)

3.4 Carbon Pricing

Carbon pricing is regarded as a "low-hanging-fruit" policy and "best instrument for a common commitment" that can promote investment in CCS industry; it is projected that the 58 carbon pricing initiatives (either implemented or schedule) presently in operation would cover approximately 11 GtCO_2e of 20.1% of Greenhouse gases emitted globally (https://carbonpricingdashboard.worldbank.org/) (Kirchner et al., 2019; Sayegh, 2019; Brown and Li, 2018). Carbon tax, an example of carbon pricing tool has been reported to facilitate improved deployment of CCS technologies; it was highly instrumental in incentivising Sleipner and Snøhvit CCS projects in Norway due to the fact that carbon tax is higher than the cost of capturing and storing (the cost of capturing and storing CO_2 at the time was 17 USD/tCO_2 as compared to 50 USD/tCO_2 in both projects), hence making the companies capture, store or utilize CO_2 so as to abate the penalty of carbon tax (Global CCS Institute, 2019). Though the debate on the effectiveness of carbon pricing for carbon emissions continues, there is no doubting the fact that at high carbon pricing mechanisms, the instrument has the propensity to encourage rapid deployment of CCS facilities. However, it becomes important that governments should be tactical in increasing carbon prices as such steep increases would greatly affect the low-income earners.

3.5 Debt Financing

Information of funding available to CCS projects reveals that a significant proportion is provided by capital grants with minimal debt financing which consequently hinders rapid deployment of CCS plants. Hence, it is imperative that debt financing becomes accessible to private investors for construction and operation of CCS facilities globally. However, this is not the case as financiers usually demand high lending rates for CCS projects due to perceived risks associated with the projects as shown in Figure 11. Therefore, it becomes important to put actions in place that would reduce the premium rents presently being offered by financial institutions to private investors. Also, involvement of government in sharing project risks with private players would reduce the existing risk factors associated with CCS projects. Furthermore, favourable government policies on CCS have been revealed to reduce lending rates from 15% to 10% making debt financing a competitive funding option to investors. Finally, as numbers of CCS facilities increase, knowledge, experience and mastery of CCS facilities would improve which would decrease the high risks associated with CCS presently, thereby making debt financing more accessible to the private sector.

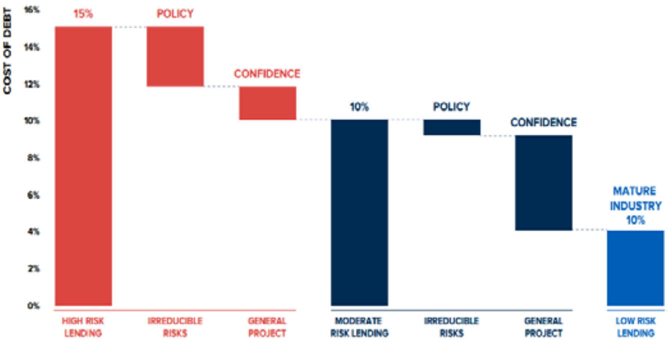


Figure 11: Lending rates of debts to private investors for CCS project financing, reproduced from (Global CCS Institute, 2019)

3.6 CCUS Clusters and Hubs

Many emission facilities are located in close proximities presenting an opportunity to utilize economies of scale to reduce unit cost of CO_2 capture in such locations referred to as "CCS Clusters and Hubs" (Global CCS Institute, 2019). Critical characteristics of CCS cluster and hubs that make them highly suitable for CCS deployment include (i) Existence of several CO_2 emitting facilities (ii) Access to large geological storage facilities (iii) Synergies between CO_2 capture and storage operators (with resultant effect on reduction of cross-chain risks) (iv) Empirical evidence of studies already carried out to ascertain the suitability of facilities for CCS operations. The advantages associated with CCS clusters and hubs have made most CCS projects planned in Europe to be situated in Clusters and Hubs; the different clusters and hubs recently developed in 2019 are shown in Figure 12. Furthermore, reduced costs and risks achievable through CCS clusters and hubs would consequently increase participation of private sector in CCS industry, prompting deployment of more CCS facilities.

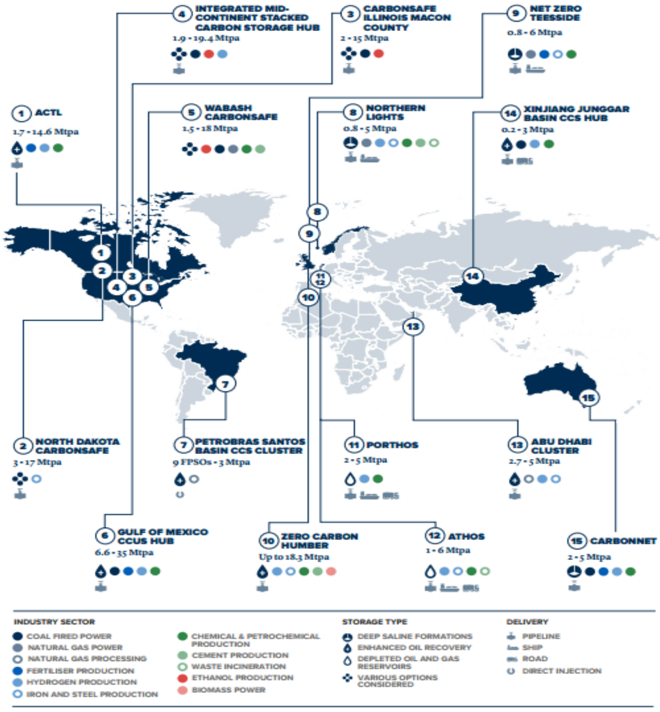


Figure 12: Capacities of different CCS Clusters and Hubs, reproduced from (Global CCS Institute, 2019)

3.7 Strengthened Partnerships

In CCS industry, the importance of collaboration and partnership cannot be overemphasized. Since the issue of carbon emission and climate change is transnational, various governments and industry players have formed alliances and consortium that harness experiences, knowledge and resources of all stakeholders to foster the rapid deployment of CCS plants globally. Different organisations such as Carbon Sequestration Leadership Forum, IEA Greenhouse Gas Technologies Programme (IEAGHG) and Global CCS Institute etc. have been created to share ideas and map out most probable ways to promote CCS industry globally. Also, partnerships between government and private sector have been achieved resulting to deployment of CCS projects in countries such as Norway, Canada and US etc. However, there are areas in public-private partnership that could be explored to identify gaps in CCS industry as highlighted by [8]. In addition, agencies or consortium that would oversee public-private partnerships by drawing a comprehensive work plan geared towards promoting activities so as to increase the deployment of CCS facilities should also be created.

4. CONCLUSION

The environmental challenges posed by carbon emissions and the solution proffered by CCUS has prompted this review paper so as to comprehensively highlight the current global status of CCUS and advances recorded by this technology in recent times. Through the study, lately trends of research advance TRL of CCUS to commercial level of application were discussed and actions that would make business case of CCS attractive to private investors were deliberated on. Hence, this paper can be considered as a "one-stop" document for recent advances in CCUS technology and market drivers that have propensity to promote commercial deployment of CCUS for environmental sustainability. Despite progresses recorded in the deployment of CCUS technologies globally, West African nations particularly Nigeria has a non-existent CCUS industry even though the country currently ranks amongst top 10 gas flare emitters in the world. Therefore, it becomes imperative that collaborative efforts between host governments of carbon emitting industries and private investors should be targeted towards optimizing CCUS technology and creating strategic policy framework critical to a rapid deployment of CCUS in West Africa in general and Nigeria in particular. As such, potential points of optimization along CCUS value chain would be highlighted below in order to prompt further research that would promote deployment of CCUS in West African region.

These potential points of optimization are highlighted as follows;

i. Adsorbents that exhibit exceptionally high CO_2 adsorption capacity and selectivity coupled with hydro-, chemical and thermal stability should be developed; cost of production of adsorbents should be driven down as to make adsorption process cost effective.

ii. Regenerability and cycles of performance of adsorbents in CCS plants should be significantly improved upon so to improve their applicability for commercial and industrial deployment.

iii. A standardized method of determining CO_2 storage capacity globally should be developed so as to have a well documented and defined global capacity for CO_2 storage with high confidence level.

iv. In carbon conversion systems, research focused on improving CO_2 conversion efficiency, Faradaic efficiency, turnover efficiency, current density and reduction of over potential should be carried out. Also, LCA of location specific high demand CO_2-derived petrochemicals should be carried out; this is necessary in order determine the best possible impact of CO_2 utilization route on the air quality.

v. Governments should devise tailored-specific policies that would discourage carbon emissions from energy intensive industries (particularly enactment of penalties for carbon emissions) thereby prompting deployment of cleaner energy policies; specifically, carbon market and appropriate carbon pricing mechanisms should be extensively encouraged.

vi. Social acceptance studies of CCUS in countries (especially West African nations, particularly Nigeria) should be carried out so as to ascertain its acceptance by the general public; also, a detailed analysis of the social cost of carbon emissions in high carbon emitting nations should be investigated as it would make go a long way to making a strong case for the need to commercially deploy cleaner energy policies and technologies.

vii. Partnerships between governments and private investors should be strongly encouraged in West Africa region in order to ensure the private sectors are shielded from hard-to-manage risks that discourage investment in the CCUS industry.

Conclusively, Nigeria as a nation has ready industries such as natural gas processing plants and ammonia production companies that emit high CO_2 concentrated flue gas stream where CCUS can be applied at competitive costs for overall air quality improvement. In 2019, Nigeria produced 49.2

billion cubic metres of natural gas, the third highest in Africa; this highlights a thriving natural gas processing industry in the country where CO_2 can be captured at a cost of 15 – 25 USD/tCO_2. Existence of fertilizer manufacturing and bioethanol production companies in-country where low cost CO_2 capture can be carried out also presents "low-hanging fruits" for CCUS deployment in Nigeria. However, high cost of carbon capture which has been reported for cement production industry, a significant contributor to carbon emissions in Nigeria acts as a barrier to commercial deployment of CCUS in the cement production sector. Hence, this emphasizes the significance of heightened research for cost competitive CCUS technologies that would encourage a kick starting of commercial and industrial deployment in Nigeria and West Africa at large.

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