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Progress in carbon capture technologies

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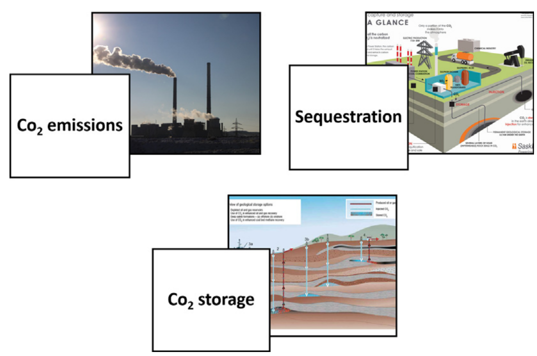
HIGHLIGHTS

- Overview of carbon capture and storage (CCS) technology is presented.
- 2 types of carbon capture and storage technologies are evaluated.
- Cost estimation of carbon capture and storage technologies are discussed.
- Prospects of CCS in CO_2 capture are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Human factors are one of the key contributors to carbon dioxide emissions into the environment. Since the industrial revolution, the atmospheric carbon dioxide levels have increased appreciably. This has been attributed to the utilization of fossil fuels for energy generation coupled with the clearing of forests and extensive manufacturing of some industrial products such as cement. The increase in atmospheric concentrations of carbon dioxide has been widely linked to climate change and the Earth's temperature.

A drastic approach is therefore needed in terms of policy formulation to address this global challenge. Carbon capture and storage are reliable tools that can be introduced to the industrial sector to address this issue. Therefore, this review presents a thorough investigation of the various technologies that can be harnessed to capture carbon dioxide. The cost associated with the capture, transport, and storage of the carbon dioxide is discussed. Socio-economic aspects of carbon capture and storage technologies are also presented in this review. Factors influencing public awareness of the technology and perceptions associated with carbon capture and storage should be a point for consideration in future research activities relating to this novel technology. This, in effect, this will ensure effective expert knowledge communication to the general public and foster social acceptance of this technology.

1. Introduction

The rapid growth in the technology and world population resulted in a significant increase in fossil fuel consumption that is available in limited quantities and has a severe environmental impact (Elsaid et al., 2020; Abdelkareem et al., 2021). Several efforts have been carried out

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to minimize the environmental impact of fossil fuel through improving the efficiency of the current processes (Malinauskaite et al., 2020; Brough et al., 2020; Olabi et al., 2020a; Jouhara and Olabi, 2018), developing innovative energy conversion devices (Olabi et al., 2021; Olabi et al., 2020b; Olabi et al., 2020c), developing cost-effective renewable energy sources (Abdelkareem et al., 2018; Mohamed et al., 2017) that have no or low environmental impacts such as solar energy (Rabaia et al., 2021; Rezk et al., 2019; Ahmad et al., 2020), biomass (Sayed et al., 2020; Inayat et al., 2019; Poškas et al., 2018), wind (Mahmoud et al., 2020), and geothermal energy (Wilberforce et al., 2019a). Carbon capture and storage (CCS) is another strategy that exhibited promising results in reducing global warming and climate change (Zhang et al., 2020; Wilberforce et al., 2019b). CCS involves the separation of carbon dioxide CO_2 produced in industrial and transportation sectors to a regulated location ideal for the storage. CCS is considered as one of the practical approaches that can be adopted to reduce global warming and its effect on the human race and other living species (Wilberforce et al., 2019b). The application of CCS directly impacts the cost of energy being generated and the pace at which the technology could easily become commercialized. Since the world continues to rely heavily on fossil energy, the need for an effective method of capturing carbon dioxide from power plants as one of the significant CO_2 sources is critical (Theo et al., 2016; Cabral and Mac Dowell, 2017). The capturing of CO_2 can be applicable in large power plants and involves compressing the CO_2 and transporting it to be stored in large storage sites like the oceans (Wang et al., 2016; Herraiz et al., 2019; Zhang et al., 2016; Ben-Mansour et al., 2016). In Scotland, the Captain Sandstone is being explored to determine its capacity and commercial viability for storing CO_2. The Scottish Government funds the project at an estimated value of £290,000. The captain sandstone is in the Moray Firth and located half a mile below the sea bed and lies 30 miles in the North Sea. It is capable of storing carbon dioxide for decades from coal-powered stations for Scotland. Fig. 1 explains a detailed outline of the project. Table 1 presents a summary of the annual global CO_2 emissions from different industrial activities, showing the domination of power generation representing almost three-quarters of the annual global emissions.

There are other options for storing CO_2 like ocean storage and industrial fixation of CO_2 into carbonates. The fraction of CO_2 captured usually determines the total reduction of emissions into the atmosphere.

Table 1
Global industrial activities and total emissions yearly (Plaza et al., 2012).

Production method	Sources	Total emissions ($MtCO_2$/yr)
Fossil products		
Power	4942	10,539
Cement production	1175	932
Refinery	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	7887	13,466

Currently, most CCS technologies available are able to absorb nearly 85–95% of CO_2 produced by a power plant. Unfortunately, most power plants with CCS systems would require more energy compared to other power plants without CCS facilities. This additional energy is needed mainly for CO_2 capture and compression that adds about 10–40% more energy on existing power plants (Ben-Mansour et al., 2016; Plaza et al., 2012). Fig. 2 shows the effect of CCS technologies on existing power plants, demonstrating the additional CO_2 emissions due to CCS, with the overall net emission reduction due to CCS as well. Once the CO_2 is adequately captured and stored, the CCS technology can support the reduction of total emissions into the atmosphere by nearly 80–90% (Bae and Su, 2013). The downside of CCS technologies being integrated with power plant systems is that more energy will be required; hence, there is an energy efficiency penalty on the power cycles.

2. Overview of carbon capture technology

The application of CCS in power plants involves three main stages. These include CO_2 separation from the power plant stream or simply carbon capture (CC), transportation of the captured CO_2, and finally, CO_2 sequestration. Several processes can be utilized for CO_2 capture, as shown in Fig. 2 (Al-Mamoori et al., 2017).

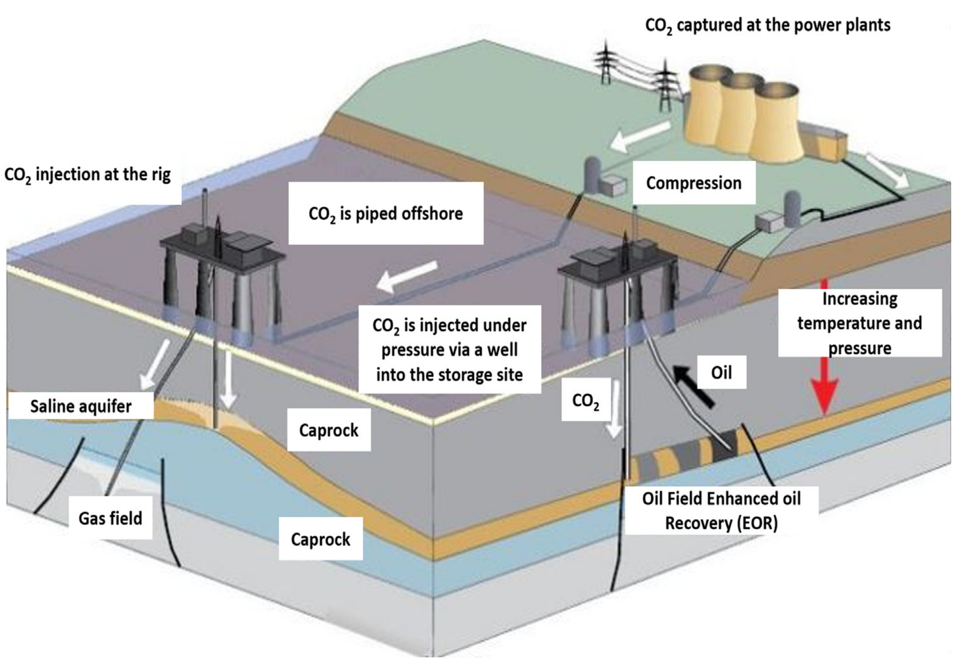

Fig. 1. Carbon capture and storage infrastructure using geological formations (Bui, 2017).

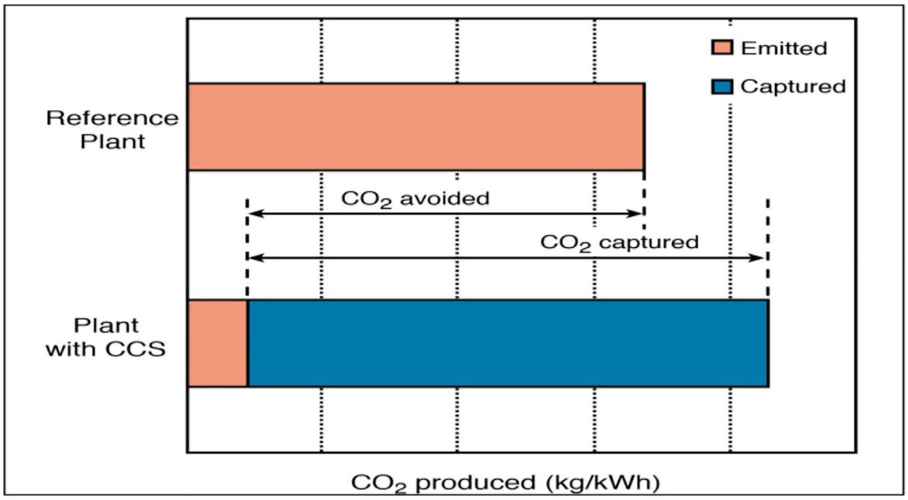

Fig. 2. Carbon dioxide capture of power plants with CCS technology (Al-Mamoori et al., 2017).

2.1. Post-combustion carbon capture

This approach involves separating CO_2 from flue gases produced from large-scale fossil fuel combustion like boilers, cement kilns, and industrial furnaces. Fig. 3 shows post-combustion CC technology in a typical layout for the absorption process. Today absorption process using chemical solvents like amine is often used in the CC from a number of power plants. The hot flue gas is cooled to temperatures between 40 and 60 °C and then introduced to the absorber, where CO_2 bonds with the chemical solvent. The CO_2 rich solvent is then pumped to a stripper where the solvent is heated for solvent regeneration between 100 and 140 °C, and CO_2 is stripped off (Bui et al., 2013; Amann and Bouallou, 2009). There are lots of energy requirements for operating the pumps, blower and compressors, and heating, which creates an efficiency penalty (Bonenfant et al., 2005; Drage et al., 2007). The fuel type determines the CO_2 content in the flue gas, and a typical CO_2 recovery of 80–90% can be realized in the CC absorption process. Removal of nitrogen oxides NO_x and sulfur oxides SO_x to prevent them from reacting with the solvent, and hence maximize CC is possible (Son et al., 2008). Use of solid sorbents like calcium oxide, pressure swing adsorption, and membrane separation have all been studied as well for CC (Di Renzo and Fajula, 2005; Dou et al., 2010).

2.2. Pre-combustion carbon capture

The pre-combustion CC involves syngas (a mixture of hydrogen H_2 and carbon monoxide CO) being produced from fuel reforming followed by CO_2 separation, as shown in Fig. 4. Fuel reforming and partial oxidation are the major processes that lead to the formation of the synthesis

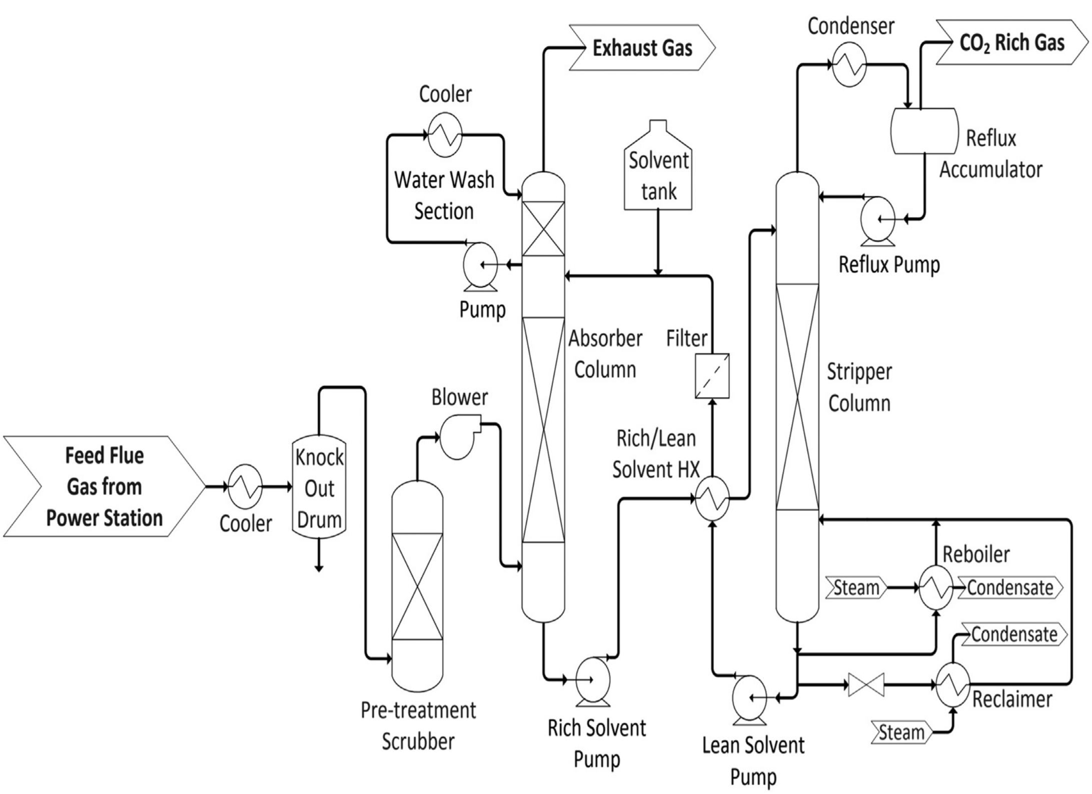

Fig. 3. Post-combustion carbon capture process layout (Bui et al., 2013).

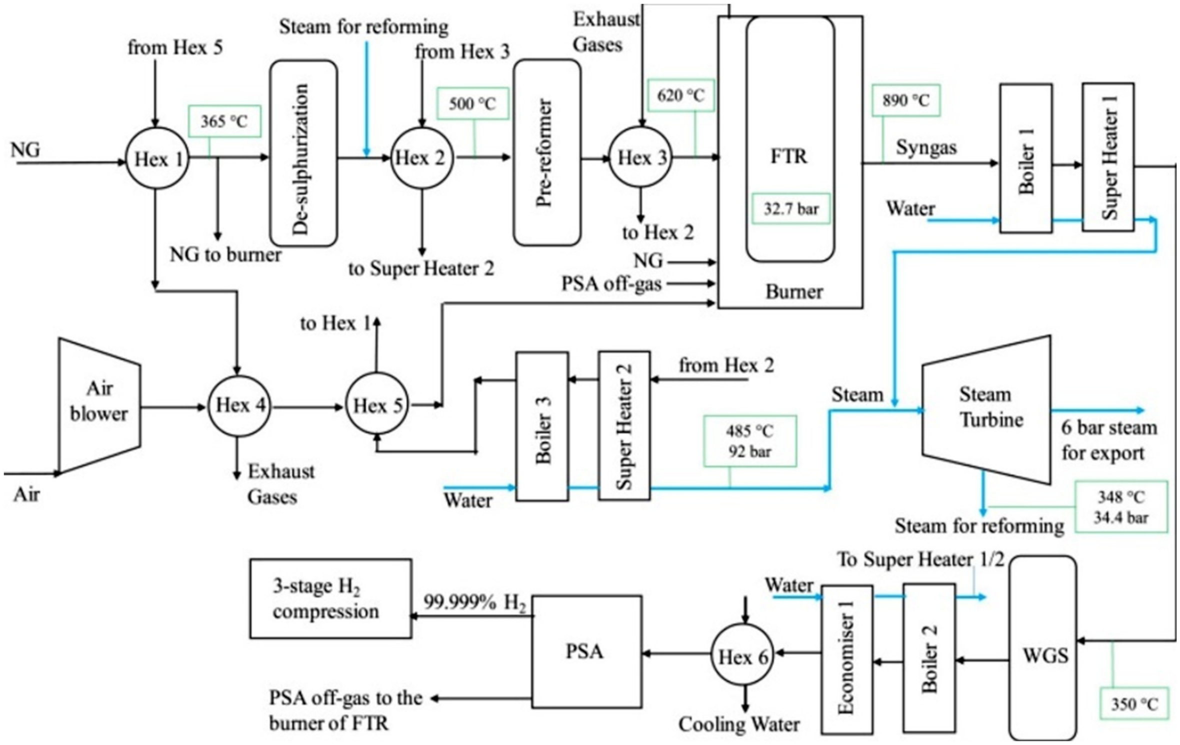

Fig. 4. Gas reforming with carbon capture (Nazir et al., 2019) (NG: natural gas, Hex: heat exchanger, FTR: fired-tubular reformer, WGS: water-gas shift, PSA: pressure swing adsorber).

gas. In steam reforming, steam reacts with fuel in a partial oxidation reaction (Nazir et al., 2019). The process also involves eliminating sulfur and particulate matter as a pretreatment to maintain catalyst operability and activity. The process net result is capturing CO_2 and hydrogen gas to be used as fuel, with water as the ultimate combustion product.

2.3. Oxy-fuel combustion carbon capture

The oxy-fuel combustion CC includes burning fossil fuel in pure oxygen, leading to nitrogen-free flue gas production with only CO_2 and H_2O. The flue gas condensation leads to a pure CO_2 stream being produced, as well as the elimination of NO_x gases. Fig. 5 explains the process of oxy-fuel combustion in a coal-fired power plant (Nazir et al., 2019).

2.4. Physical absorption technique

Carbon dioxide separation for post- and pre-combustion CC occurs in two steps; absorption and stripping process. In absorption, the gas stream is fixed physically with the solvent stream. In the stripping process, the CO_2 rich solvent is heated to regenerate the solvent and strip off CO_2 gas, as depicted in Fig. 6. The main principle in physical CO_2 absorption is Henry's law. In the absence of any form of alteration of chemical identities of CO_2 and the solvent, the breakdown of CO_2 in the liquid solvent is due to the electrostatic interaction or Van der Waals attraction forces (Nazir et al., 2019; Ban et al., 2014). Physical absorption is relatively better under higher pressure but lower temperature conditions. Lower pressure and higher temperature will be ideal for physical

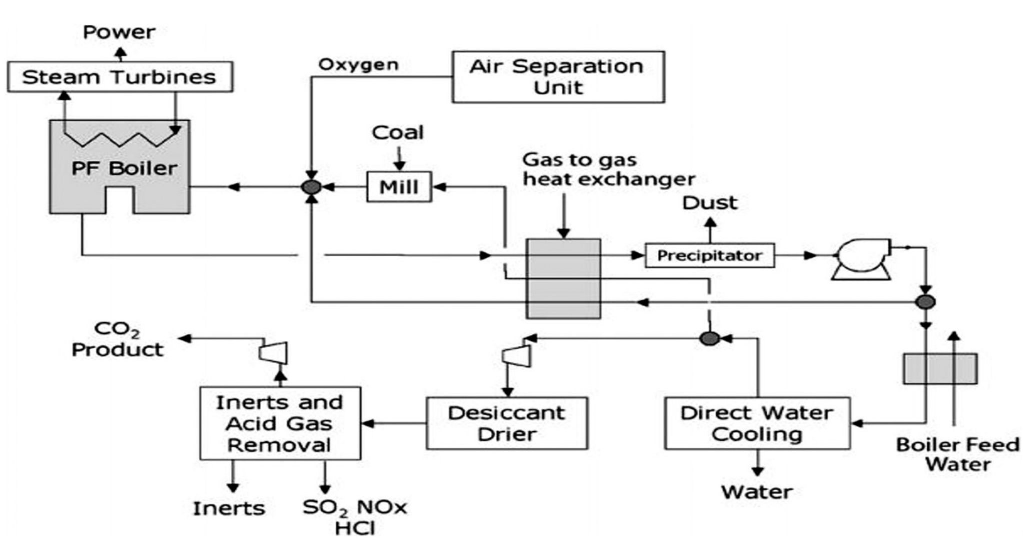

Fig. 5. Oxy-fuel carbon dioxide capturing technology (Bert Metz et al., 2005).

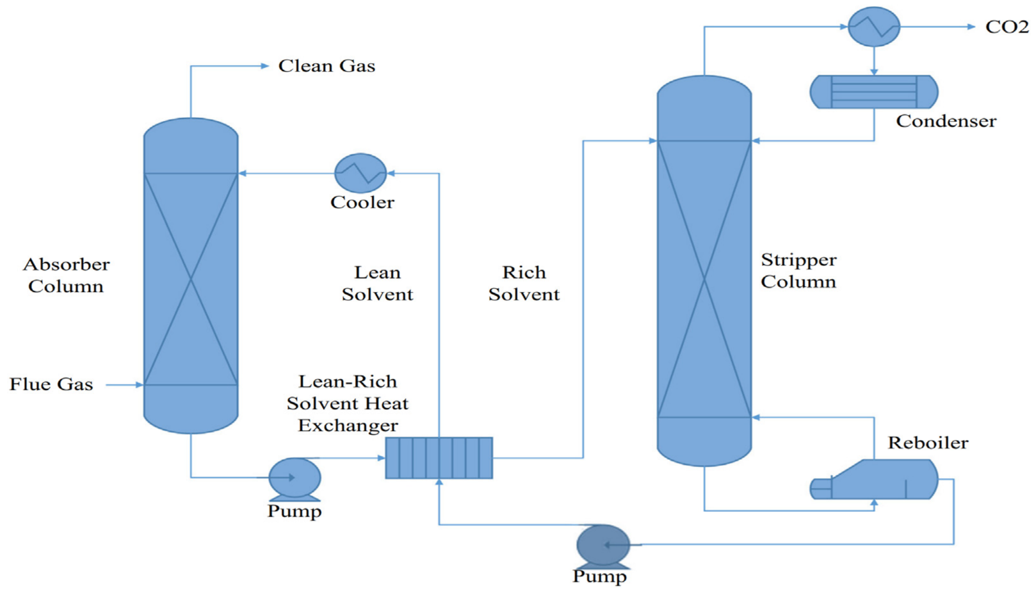

Fig. 6. Schematic of the absorption-stripping technique (Theo et al., 2016).

desorption or stripping (Yu et al., 2012). These conditions tend to make physical absorbents attain higher absorption characteristics compared to chemical absorbents (Yu et al., 2012).

2.5. Adsorption technique

The adsorption process involves forming physical or chemical interactions between the adsorbate, i.e., CO_2, and the surface of the solid adsorbent. The adsorbed CO_2 can be desorbed later either by decreasing the pressure or increasing the temperature, commonly referred to as pressure-swing or temperature-swing adsorption, respectively, in a similar approach to that of absorption. The pressure-swinging adsorption process is utilized for high CO_2 partial pressure, while temperature-swinging adsorption is often preferred when the concentration of the CO_2 being is lower. The pressure-swinging adsorption process is normally preferred because it requires a shorter time adsorbent

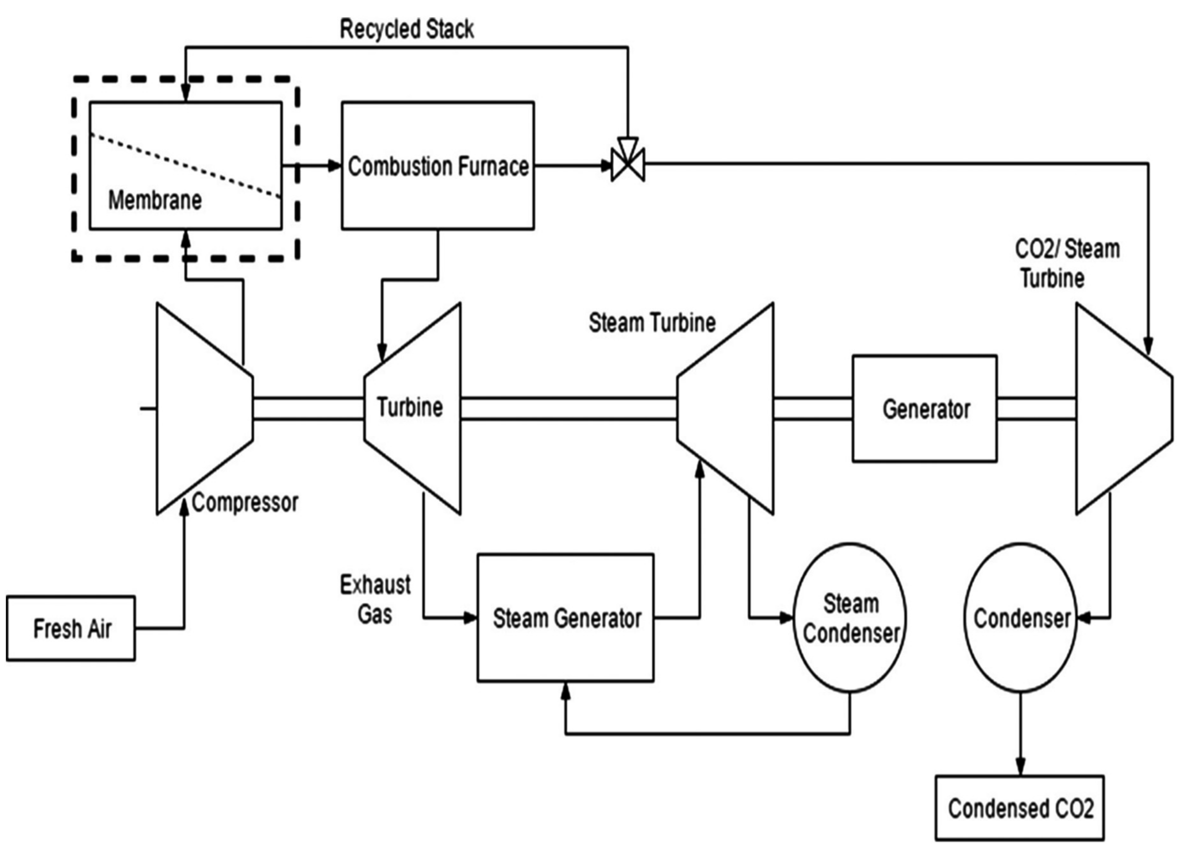

Fig. 7. Membrane process for CO_2 capture in power plants (Theo et al., 2016).

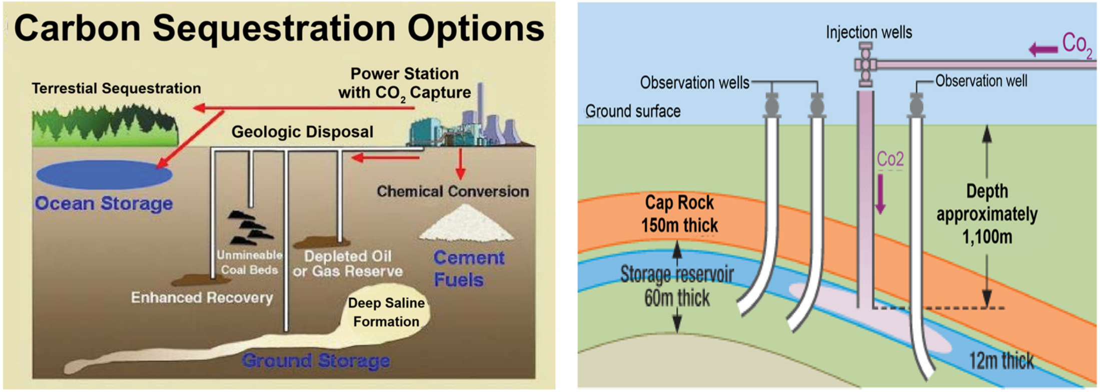

Fig. 8. Carbon dioxide sequestration methods (Shahbazi and Nasab, 2016).

regeneration. Some notable advantages of adsorption include high loading capacity at ambient conditions, lower energy demand, and economic regeneration. Other merits include good mechanical and chemical stability, high adsorption rate, simple operation, easy system maintenance, and tolerance to impurities in flue gas (Rashidi and Yusup, 2016). Some common types of physical adsorbents include activated carbon, zeolite, silica membrane, and metal-organic framework materials (MOF). The chemical adsorbents, on the other hand, are made up of calcium oxide (CaO), lithium metal-based, and solid amines sorbents (Force et al., 2009; Wahby et al., 2012).

2.6. Membrane technology

Separation with the aid of a membrane occurs via the Knudsen diffusion principle and the Fick's molecular diffusion (Khalilpour et al., 2015). The elimination of CO_2 from natural gas is best carried out using membrane separation technology, which is ideal for pre-combustion capture as well, especially for high CO_2 partial pressure (In et al., 2005). Fig. 7 depicts a power plant with zero carbon emissions. In the case of CC from low CO_2 in flue gas, a higher energy penalty is imposed (Amann and Bouallou, 2009; Bonenfant et al., 2005).

3. Carbon dioxide transportation medium

Separation of the CO_2 must be followed by transporting it to a respective location. The gas would first have to be compressed and transported in a supercritical state, with the critical point of CO_2 at 31 °C at 73.77 bar, at which its density is 500 times that of gaseous state (White et al., 2005). Pipelines are a well-known approach that can be adopted for the transportation of CO_2 (Hetland et al., 2014). The dry carbon dioxide is usually compressed to a pressure above 80 bar to avoid the two-phase flow regime. This process is also aimed at increasing the density of the CO_2 hence making the transportation process less laborious and cheaper and can be developed for onshore as well as offshore CO_2 transport in a similar approach to that used in oil and gas industry. The onshore pipelines are placed at a depth of 1 m, whiles that of the offshore is constructed in shallow waters (Ajayi et al., 2019). To protect pipelines from damages caused by fishing gear, deepwater pipelines below 400 mm diameter are developed in deep trenches. Developing pipelines also comes with the consideration of other components associated with the pipeline include valves, compressors, tanks, pumps, and block valves. The pipelines are monitored regularly, which can be carried out remotely, depending on the location of these pipes.

Today due to technological advancement, ships are being used for CO_2 transportation, as a liquid below ambient temperature but high pressure, commonly −2 °C and 20 bar, with the aid of insulated tanks, similar to those of liquefied natural gas (LNG) carriers. The liquid CO_2 is unloaded into provisional storage tanks at an onshore delivery point or unloaded to floating storage or platform in the case of an offshore delivery point. Liquid CO_2 is then transported from a provisional storage tank to a refrigerated CO_2 cargo tank. These methods are expensive compared to that of the pipeline and ships, especially for larger quantities (Fan et al., 2020; Pan et al., 2018).

3.1. Storage of carbon dioxide

Geological sequestration of CO_2 is the technique for capturing CO_2 from anthropogenic sources directly and the disposal of the captured CO_2 into geological formations for some time. Many approaches can be adopted for the capture of CO_2 in geologic formations. A low permeable geological medium is first used to capture supercritical CO_2 at the initial stage, where a reaction between CO_2 and the solid occurs. This is then followed by solubility trapping, where the CO_2 is absorbed into the water phase, with the reaction occurs directly or indirectly (Durand, 2005; Shahbazi and Nasab, 2016). The physical and geochemical techniques used for capturing the CO_2 determine the efficiency of the geological storage system, and this has a direct relation to the hot rock formations. The ideal storage site for CO_2 capture is where the gas is immobile. This means the gas is captured permanently with the aid of a low permeable seal. Temperature and pressure are key parameters that determine the physical characteristics of the CO_2 stored. Carbon dioxide exists as a gas at normal temperature and pressure, but as a liquid when the pressure reaches 64 bar at ambient temperature, or in supercritical state at temperatures and pressure exceeding critical point.

A site suitable for storing CO_2 must exhibit some characteristics, such as adequate storage capacity, injectivity, good confining unit or sealing

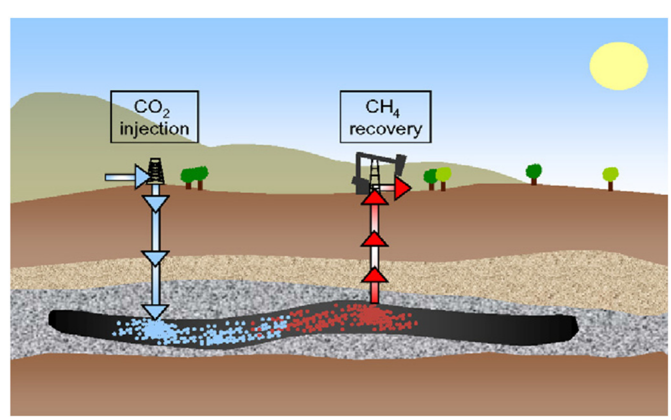

Fig. 9. Diagram of enhanced coalbed methane operation (Mazzotti et al., 2009).

caprock, and a stable geological environment to prevent compromising the site. Sequestration of CO_2, as depicted in Fig. 8, can be carried out based on three options. The first has to do with using active as well as depleted oil and gas fields for the recovery of oil and gas, in which it helps for carrying out enhanced oil or gas recovery (EOR and EOG). The next option has to do with deep unmineable coal layers capable of enhancing methane recovery called Enhanced coalbed methane (ECBM) recovery. The last option is deep saline aquifers. These storage techniques have been used in the past for storing oil and gas at a cheaper rate, which can equally be applied to CO_2 storage (Fan et al., 2020).

3.1.1. Enhance oil and enhanced gas recovery

Porous rock formations filled with physically trapped hydrocarbons are considered suitable as oil and gas reservoirs. Carbon sequestration in depleted oil and gas reservoirs can be categorized into two classes. The first can be carried out due to changes in the rock types, and this called stratigraphic traps, and the other is structural traps. These abandoned sites are considered suitable for CO_2 storage because they stored hydrocarbons for millions of years. Enhance oil recovery (EOR) and enhanced gas recovery (EGR) have lower capacity compared to other CO_2 sequestration options, but they are well-established with known characteristics and geological information, hence usually preferred (Bachu et al., 2004). Furthermore, because these abandoned sites were previously used, the infrastructure required for storage and transportation already exists (*Carbon Utilisation and Storage Atlas*, 2012). The total retention efficiency for carbon dioxide for some of these sites is up to 60% (Hadlow, 1992; Stephenson et al., 1993; Holt et al., 1995). The ideal storage site for CO_2 is specifically a location where the structural, as well as stratigraphic coupled with solubility, allows the storage of the injected CO_2 for millions of years (N. NETL, 2010). Residual and solubility trapping techniques can be exploited for this purpose; therefore, imperative that regulatory and monitoring frameworks are put in place to ensure that these methods are taking place effectively. These two techniques can effectively secure the storage of CO_2 and help to recover more hydrocarbons. Gaseous CO_2 can displace oil from porous media as well as ensure a reduction in viscosity hence enhancing the injectivity index because of its solubility in water forming carbonic acid. This technique for EOR revolves around molecular diffusion, as the mixing of the CO_2 with oil at the pore level via a rate-controlling approach that supports the oil miscibility occurs due to molecular diffusion. Dynamic miscibility occurs between the CO_2 phase and the oil, which is unswept, but bypassed at the secondary oil recovery stage via water flooding becomes mobilized. Molecular diffusion results in mobilization of waterflood residual oil via swelling of the residual oil blobs due to diffusion of CO_2 via blocking the water phase at the tertiary recovery stage (Yang and Gu, 2005; Li and Yortsos, 1995).

3.1.2. Enhanced coalbed methane recovery

Unmineable coal seams, being too deep or too thin, have the capabilities for storing CO_2, and additionally, these coal mines are close to many power plants (Mazzotti et al., 2009). Accordingly, an efficient technique for the sequestration of CO_2 in an adsorbed state is via its sequestration in coal seams as depicted in Fig. 9 in enhanced coalbed methane (ECBM). Carbon dioxide sequestration helps to recover methane gas from such layers, which can be used as a clean fuel.

Recovery of methane gas in a coal seam occurs via dewatering, depressurization, and sometimes an injection of nitrogen gas. This approach does not allow a substantial quantity of methane to be captured; hence the remaining methane gets trapped in the coal, it can be released due to the injection of CO_2. The formation of coal occurs via the gradual compaction and thermal alteration of plant matter (Thomas, 2002). Lignite, which is the first phase of coal formation, has higher moisture content and volatile matter, which decreases as the coal rank increases. There is also an increment of carbon composition from sub-bituminous, bituminous, semi-anthracite to anthracite (Speight, 2005). The Coalification process takes place to alter the organic matter, then undergoes compaction to produce 1 m thick anthracite from 30 m thick lignite (Thomas, 2002; Speight, 2005). These processes lead to the accumulation of methane in the coal seam. The methane that is trapped is then absorbed in the micropores on the coal surface and the natural fracture systems.

Coals pore structures are made up of micropores and macropores, but not mesopores. The micropores' radius is usually lower than 2 nm and occupies nearly 70% of the total porosity of the coal matrix. On the other hand, macropores have porosity more than 50 nm and usually made up of a cleat system. Coal is considered as dual porosity rock due to the existence of macropores and micropores (Flores, 2014). Movement of gas in coal seam is carried out via fractured porous network. The gas is then diffused into an organic coal matrix and stored in micropores. There is still a need to probe to the phenomena that occur when CO_2 is injected into coal seam. This is crucial because the transport characteristics of CO_2 are dependent on the chemical and physical transformation occurring during the adsorption and desorption processes. Movement of gas in coal includes the gas flow via fractured porous links and the diffusion of the gas in the organic coal matrix. Storage of the gas therefore includes adsorption as well as desorption of the gases on and from the coal matrix. Therefore, there is a need for a total comprehension of the various transformations that occurs when CO_2 is injected into a coal seam (Mosleh et al., 2018).

3.1.3. Saline formation

Saline aquifers are porous and permeable rocks saturated with saline water. These types of formations are common for onshore and offshore sedimentary basins. Carbon dioxide storage can equally be carried out on these saline formations. The technique that can be adopted for absorbing the CO_2 is via solubility trapping, reaction with fluid and minerals to form solid carbonates, or trapping the CO_2 in pore space. CO_2 density is lower than that of saline water, so CO_2 formation occurs on top of the formation layer, with caprock required to curb any possible leakage. The potential of saline formations for CO_2 storage is better as compared to the oil and gas reservoirs. Within the aquifer, water in the saline pore is displaced by the supercritical CO_2. The primary CO_2 storage approach in saline aquifers includes stratigraphic, solubility, and mineral trapping, which occur at varying timescales (Hightower, 2006; Taulis and Milke, 2013). The stratigraphic step is the dominant storage mechanism, while in the solubility approach, CO_2 is dissolved in an aqueous solution. An example of a CO_2 storage project with the aid of saline formation is the Sleipner Project in the North Sea.

3.2. Environmental impact of carbon capture and storage technologies

Despite the merits of CCS, its impact on the environment is another critical issue that must be properly addressed. CCS's goal is to reduce carbon emissions into the atmosphere, but some challenges are associated with the environmental impacts, which are summarized in the subsequent sections below.

3.2.1. Effect on water resources

The main environmental challenge with CCS is the accidental release from the pipeline and spillage when the pipelines are being constructed into the water. CC plants equally release some wastewater, which is also considered as being harmful and toxic to aquatic life. The water can also become acidic due to CO_2 leakage; when these spillages and leakages eventually get to the groundwater, they become contaminated. The groundwater can also become polluted during the operational phase due to CO_2 leakage out of wells, fault, and the caprock. The contamination of groundwater occurs due to capillary and diffusion effects. Faults from fracture networks can also lead to the groundwater becoming contaminated. The outflow water can also result in water pollution. Brine water naturally existing in the formation becomes replaced by the CO_2 when injected into the formations. For instance, in the USA, outflow water produced varies between 25 and 400 bbl/day, but these waters are not usable due to the high salinity; hence, further treatment is required (Sams et al., 2002). Other key factors like the metabolism process, aquifer recharge, and geological conditions equally play an active role in the concentration of these toxic chemicals.

3.2.2. Effect on air, land, and climate

Air quality is likely to be negatively affected during the operational as well as the construction stages of the CCS project. This is due to dust suspension, fuel utilized by the machines for the project, and the shipping. The release of CO_2 into the soil will cause an increment in the soil's pH, hence leading to the mobilization of heavy metals. Emissions from plants for capturing CO_2 can significantly affect air quality. Other factors like improper well sealing can also affect the quality of air. A solution to this challenge is to ensure the wellbore seal's quality is up to standard to curb any CO_2 leakage.

3.2.3. Induced seismicity

Literature has discussed the possibility of seismicity and geomechanical effects due to a high-volume injection of fluids into deep subsurface. The information compiled is based on knowledge obtained from the oil and gas industry. According to the Coulomb theory, a fault in the formations occurs due to changes in normal stress, pore pressure, and shear cohesion. Subsurface strata can be compromised due to injecting high-volume and pressurized fluids into them, which will influence all faults already exist due to changes in the pore pressure. Mine subsidence, oil and gas field depletion, and secondary oil recovery are all factors that can lead to induced seismicity. Other factors include deep drilling programs, disposal of wastewater, reservoir impoundments, and geothermal systems (Davies et al., 2013). It has been reported that fluid injections had been a pivotal contributor to induced seismicity. There are also issues associated with the injection of CO_2 into caprock, which can rupture, becoming a threat to the project's lives and properties (Davies et al., 2013; Verdon, 2014).

4. Socio-economic characteristics of carbon capture and storage technologies

The estimation of carbon management costs and the technologies associated with it is quite difficult to carry out. The recent CCS technologies are expensive and require extensive energy, which is a major challenge impeding the advancement of these technologies (Rubin et al., 2012). The physicochemical techniques for improving the adsorption of CO_2 are carried out with zeolites or lignite matrices (Vatalis et al., 2012). The goal of feasible cost is achievable, provided more research coupled with commercial deployment of the technology are carried out extensively. The exact cost for CCS technologies is highly unknown as several factors come to play to estimate these costs (Karayannis et al., 2014). The life cycle cost of CCS must be carried out considering the social, economic, and environmental impact assessment, which has to be carefully considered in the quest for an efficient but sustainable energy source (Hardisty et al., 2011). The usage of energy efficiently has a direct relation to climate change and its sustainability (Einsiedel et al., 2013).

To determine the ideal energy source that is environmentally friendly, investigations into CCS and their possible integration on these systems should be carried out (Viebahn et al., 2014). It is also important that CCS are taken into consideration with an emphasis on direct costs, post-operation liabilities, policy, and operational flexibility (Gupta, 2009). When the market price for carbon allowances is lower compared to the estimated cost of CCS, the commercialization of the CCS technologies might be a problem. This will mean that the Government will not be keen on formulating policies or injecting funds into projects related to CCS (Bäckstrand et al., 2011). Therefore, Governments need to develop good policies aimed at providing effective long-term incentives for CCS networks, with a clear legal framework to support this objective. The synergy impact of CCS is anticipated to accelerate realizing the technology commercialization. It has been reported that CCS will play an active role in energy-economy-climate-modeling systems (Luderer et al., 2013).

The availability of CCS, especially in developing countries, is another key issue impeding its acceptance worldwide (Román, 2011). More public awareness must be made, and the public's perception relating to CCS must be critically reviewed. Emphasis should be centered on the social factors impeding this technology's commercialization and how some of these perceptions affect local economic interests. Issues pertaining to public resistance subject to socio-environmental factors will affect the quest for decarbonization (Moran Jay et al., 2014). An investigation carried out to ascertain the general perception of the public on CCS with the aid of two research techniques, i.e., information choice questionnaires and focused group discussions, garnered key outcomes based on consistency, stability, and socio-economic indicators well as tradeoff between these energy systems. The investigations highlighted that these factors tend to affect the public's energy options in general (ter Mors et al., 2013). Other similar investigations conducted at Dresden university highlighted a neutral attitude towards CCS exhibited by the investigation participants. The majority of the participants who took part in the investigations were willing to pay more for renewable energy delivery than CCS, and this general perception was attributed to the public perception about this useful technology (Kraeusel and Möst, 2012).

To gain public support, the Government must put in measures to ensure there are some monetary compensations for using hazardous facilities (Zaal et al., 2014). It has also been reported that economic interest can play a significant role in the determination of public support for low carbon energy technologies (Cherry et al., 2014; Grimaud and Rouge, 2014). A carbon tax, subsidy to sequestered carbon, and labor in CCS could accelerate the technology commercialization. An investigation conducted in six European countries exposed the perception of CCS. This was due to socio-demographic data, lack of information on CCS technologies, and attitudinal factors relating to energy generation. The investigation further highlighted that most of the participants considered agreed that the application of CCS to systems will be very useful. Still, the majority had no clue about the practicality of integrating these technologies on energy generation systems in terms of cost (Pietzner et al., 2011). The acceptance of CCS has also been evaluated in Europe based on the options and perceptions of the public and stakeholders (Shackley et al., 2009). With the aid of an online focus group, an investigation highlighted issues pertaining to trust and challenges like to be encountered by pre-existing opinions and concerns in getting more information related to CCS (Riesch et al., 2013). Other reports concluded that diverging views from stakeholders regarding CCS technologies' commercialization are a leading contributor prospect futuristically compared to public opinions (van Os et al., 2014). They recommended that CCS policies being formulated in a framework will clear consideration for social/political/market interactions.

The public faith in CCS stakeholders is also a key factor in technology commercializing (Terwel et al., 2011). The trust for environmental non-governmental organizations and local authorities is higher than industrial stakeholders from the public point of view (Terwel et al., 2012). There were several projections made related to the commercialization of CCS in 2020. Though there has been significant improvement, there is still more work to be carried out in this field. A technique that can be adopted to evaluate the stakeholders' conceptions and the importance of extending social engagement beyond risk communication must seriously be considered, and this suggestion has been captured in literature. The investigation was carried out via interviews considering onshore and offshore conditions in Scotland (Mabon et al., 2014). Societal stakeholders' perceptions have also been reported in China in terms of the socio-economic effect, energy security, environmental concerns, and international and domestic incentives. This may likely improve the acceptance of this technology hence accelerating its

Table 2
Electricity production cost from various energy generating mediums with and without carbon capture and storage technologies (Rubin et al., 2007).

Power plant system	NGCC, US$/kWh	PC, US$/kWh	IGCC, US$/kWh
Without carbon capture (reference plant)	0.03–0.05	0.04–0.05	0.04–0.06
With carbon capture and geological storage	0.04–0.08	0.06–0.10	0.05–0.09
With carbon capture and enhanced oil recovery	0.04–0.07	0.05–0.08	0.04–0.07

NGCC: natural gas combined cycle, PC: pulverized coal, IGCC: integrated gasification combined cycle.

commercialization (Reiner and Liang, 2009). A survey conducted in the USA with the aid of interviews from focus groups perspective of CCS suggested that past encounters with the Government and existing low socio-economic status and compensations were of major concern compared to the risk associated with the technology (Bradbury et al., 2009). Political systems, government structure, economic policies, national innovation systems, and energy strategy must be critically considered to ensure this technology's public acceptance (Yuan and Lyon, 2012; Tokushige et al., 2007). Other surveys conducted on CO_2 geological storage also conclude that people were more interested in the benefit than any risk associated with this technology. An excellent public education on this technology's suitability to reduce carbon emissions into the atmosphere will significantly transform these public perceptions. All these investigations attest to the need to consider a detailed approach in communicating this useful technology to the public in general towards accepting this useful technology (Wassermann et al., 2011; Ragland et al., 2011).

5. Cost estimation of carbon capture and storage technology

The integration of CCS technologies is likely to increase electricity production cost by $0.01–0.05/kWh. This was subject to the fuel, the specific technology, location, and national factors. The integration of EOR to electricity production will also reduce the cost significantly, as depicted in Table 2. Table 3 shows the relative avoidance of carbon emissions due to the integration of CCS and EOR relative to reference power plants. It must further be noted that increasing the fuel prices for power generation is likely to increase CCS technology costs; however, the effect of oil price increment on CCS cannot be quantified. An increase in oil prices generally will cause the revenue generated from EOR to increase appreciably as well (Rubin et al., 2007).

5.1. Cost of the carbon capture components

CCS's total estimate is the highest cost component and the additional capital needs, added operating and maintenance cost. The CCS's total cost is influenced by both economic and technical factors like design and operation of both the CC system and the power plant with different cost measures, as summarized in Table 4 (Menon et al., 2007).

Table 3
Carbon dioxide avoidance costs for the complete carbon capture and storage for electricity generation for different power plant combinations (Rubin et al., 2007).

Type of power plant with CCS	NGCC reference plant US$/tCO $_2$ avoided	PC reference plant US$/tCO $_2$ avoided
Power plant with carbon capture and geological storage		
Natural gas combined cycle NGCC	40–90	20–60
Pulverized coal PC	70–270	30–70
Integrated gasification combined cycle IGCC	40–220	20–70
Power plant with carbon capture and EOR		
Natural gas combined cycle NGCC	20–70	0–30
Pulverized coal PC	50–240	10–40
Integrated gasification combined cycle IGCC	20–190	0–40

5.2. Cost of carbon dioxide transportation

The volume required to be transported is a key parameter that determines CO_2 transportation cost, coupled with the travel distance. As explained earlier, pipelines are the predominantly used medium of transport for CO_2 due to their economic viability. There are three categories of costs that contribute to CO_2 transportation: pipe construction cost, operational and maintenance cost, and finally, other miscellaneous costs. The offshore pipelines are 40–70% more costly compared to the onshore pipes of the same size. Large sea tankers are ideal for transporting the gas over long distances, with transportation fees for 6 $MtCO_2$ in a year using ship tankers would be around $10/$tCO_2$/500 km or $5/$tCO_2$/250 km. Transporting the same amount over 1250 km would cost about $15/$tCO_2$ and is close to the cost of pipeline transport (Howard Herzog et al., n.d.).

5.3. Cost of carbon dioxide storage

The concept adopted and equipment utilized for the storage of oil and gas is generally applicable for the geological storage of CO_2. There is significant variability in cost due to some specific factors like onshore or offshore, reservoir depth, and the storage formation's geological characteristics. Ocean storage cost is pegged as a function of offshore distance and injection depth (Terwel et al., 2011). Storage cost for mineral carbonation includes conventional mining and chemical processing. Table 5 provides an estimate of different CO_2 storage costs.

6. Conclusion

The increment in the Earth's temperature averagely is the largest contributor to global warming due to carbon dioxide and methane. The cause of global warming is largely due to human activities. The widespread act associated with this issue is the burning of fossil products for power plants and industries. This phenomenon is the largest contributor of CO_2 emissions into the atmosphere. These underlining factors are what lead to climate change and its harmful effects. The release of CO_2 from mining operations, natural gas production, etc. can lead to CO_2 being exposed externally to the environment. CO_2 production source is crucial, with almost 87% of CO_2 produced by human activities originating from the burning of fossil fuels. The CO_2 emissions balance comes from clearing the forests and industrial processes such as cement production. A paradigm shift in CO_2 emissions into the

Table 4
Carbon capture based on existing technology (Menon et al., 2007).

Cost measures	NGCC	PC	IGCC
Plant efficiency with lower heating value, %	48	33	55
Reduction of carbon emissions per kWh, %	86	85	86
Total capital requirement with carbon capture, US$/kW	998	2096	1825
Cost of electricity with carbon capture, US$/MWh	54	73	62
Increase in the capital cost with carbon capture, %	76	63	37
Increase in the cost of electricity with carbon capture, %	17	27	16
Cost of carbon captured, US$/$tCO_2$	44	29	20
Cost of carbon emissions avoided, US$/$tCO_2$	53	41	23

NGCC: natural gas combined cycle, PC: pulverized coal, IGCC: integrated gasification combined cycle.

Table 5
Cost of storing carbon dioxide (Howard Herzog et al., n.d.).

Options	Cost range
Geological storage	0.5–0.8
Geological monitoring	0.1–0.3
Ocean	
Pipeline	6–31
Ship	12–16
Mineral carbonation	50–500

atmosphere has become a necessity. CO_2 capture from industrial plants and storage has been crucial in reducing carbon emissions into the atmosphere. The application of carbon capture and storage (CCS) technologies to the industrial sector is likely to reduce the sector's total emissions by approximately one fifth. Therefore, this shows the importance of CCS, which is also essential in ensuring energy security. Decarbonization of the power sector can be feasible with integrating CCS, especially in regions that highly depend on fossil products for its power generation.

This review, therefore, explored various types of CCS technologies. Different geological sequestration approach was equally discussed with some challenges associated with each are highlighted. Despite the progress made, future research must also be aimed at developing novel technology to augment the existing CCS to reduce the present cost. CO_2 sequestration in depleted oil and gas reservoirs or unmineable coal seams can also significantly reduce CO_2 storage cost with enhanced hydrocarbons recovery. The readily existing infrastructure for oil and gas transportation in oil and gas reservoirs, etc. can effectively reduce the cost of CO_2 storage. CO_2 sequestration requires in through studies to ascertain the complexity of the deep subsurface conditions and environment. Development of CCS technology will also require an environmental consideration in every aspect of the capturing process from the capture to the transport and finally to the CO_2 storage.

CRediT authorship contribution statement

Conception and design of study: Tabbi Wilberforce, A.G. Olabi, Enas Taha Sayed, Mohammad Ali Abdelkareem, Khaleid Elsaid Drafting the manuscript: All Revising the manuscript critically for important intellectual content: All Approval of the version of the manuscript to be published (the names of all authors must be listed): All.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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