Review Paper

Recent developments and challenges ahead in carbon capture and sequestration technologies

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Abstract

Rapid industrialization and increasing trend of energy utilization resulted into exploitation of natural resources, i.e., fossil fuels, for power generation. This is resulting into addition of huge amount of carbon dioxide (CO_2) as greenhouse gas into the environment. By year 2030, the primary production of energy from coal will reach to 3976 Mtoe and CO_2 discharge of 38749 $MtCO_2$ per year. In this review paper numerous aspects on carbon capture and sequestration (CCS) technologies have been compiled and discussed. The CO_2 can be captured during fuel processing itself or after fuel combustion and transported to the sequestration site for long-term storage. A wide variety of the carbon separation and capture techniques including absorption into liquid, gas phase separation, and adsorption on solid and hybrid processes such as adsorption-membrane systems are discussed. In addition to this, the regulations for CCS, economic analysis and policy issues are addressed.

Keywords Clean energy · Carbon capture and sequestration · CO_2 mitigation · Hydrogen · Saline aquifer · Membrane separation

1 Introduction

Energy has been need of flourishing civilization, but utilization of conventional energy resources based on fossil fuels are creating environmental problems such as emissions of greenhouse gases, particulate matter, smoke, etc. About 82% of energy required all over in the world is generated from fossil fuels [1] through various modes. This is resulting into production of carbon dioxide (CO_2) and being released into the environment. The CO_2 is a greenhouse gas (GHG) and primarily responsible for global warming as per [2].

Rapid industrialization and changing life style with increasing energy consumption pattern resulted into intense demand of power, which demanded into more electricity generation. On another side the growing fleet of automobiles in use resulted into more fuel consumption. Most of the power generation units (e.g., thermal power plants and diesel generator sets) and transportation vehicles (e.g., automobiles, trains, ships, aeroplanes, etc.) are based on fossil fuels. The combustion of fossil fuels (e.g., coal, diesel, gasoline and natural gas) produces lots of CO_2, which is emitted into the environment. Apart from these chemical process and industries also produce CO_2. Figure 1, shows the world energy generation trend from different resources, where coal, oil and natural gas are the major sources of energy and their use is increasing continuously [2]. By year 2030, the primary production of energy from coal will reach to 3976 Mtoe and discharge of CO_2 into environment about 38749 $MtCO_2$ per year.

The consumption of fossil fuels is resulting into CO_2 discharge, where the electricity generation sectors are discharging highest CO_2 followed by industries and transportation vehicles, as shown in Fig. 2 [2]. The concern over environmental protection resulted into start of CO_2 sequestration, which is increasing with energy generation,

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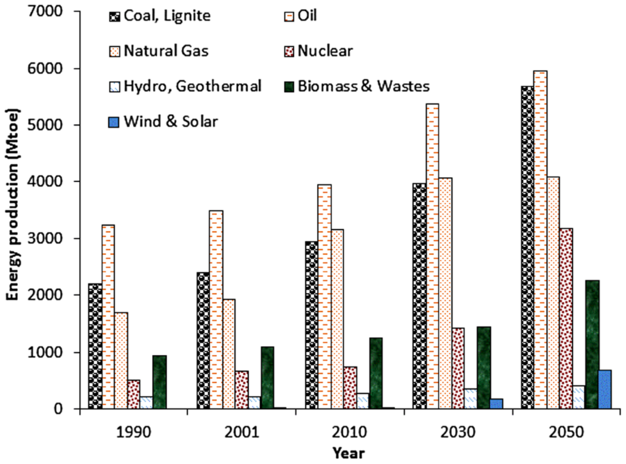

Fig. 1 World Energy generation from different resources (*Data source*: World Energy Technology Outlook–2050 [2])

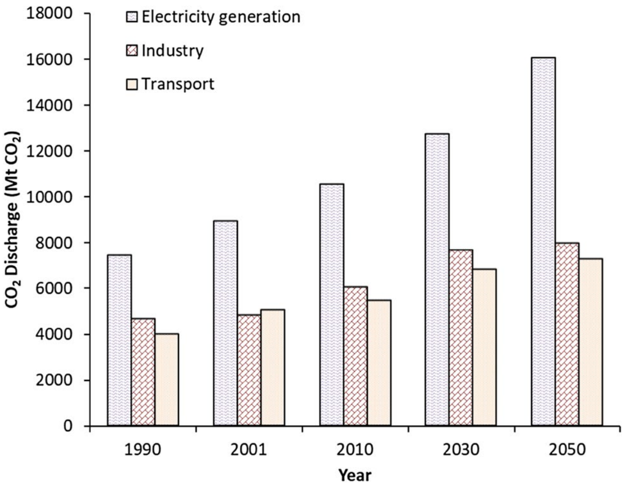

Fig. 2 Carbon dioxide discharge from various sectors (*Data source*: World Energy Technology Outlook–2050, 2006 [2])

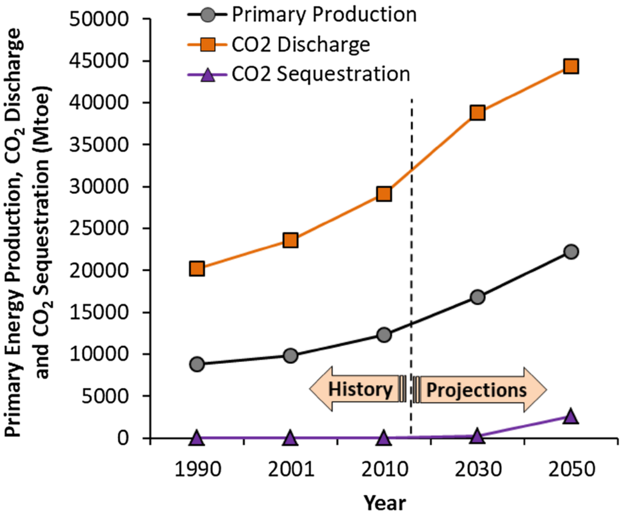

Fig. 3 Energy generation, CO_2 emissions and sequestration (*Data source*: World Energy Technology Outlook–2050 [2])

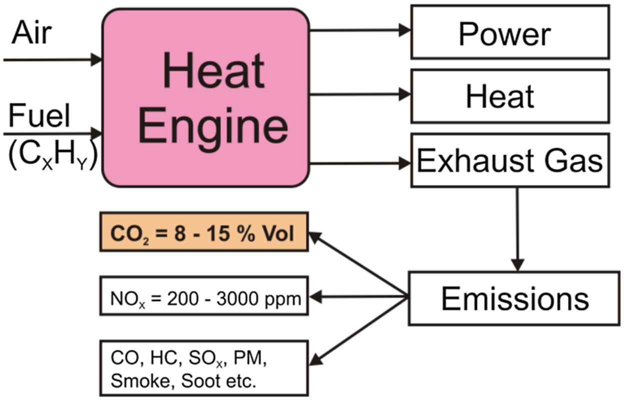

Fig. 4 Power generation using hydrocarbon fuels and pollutants emission (*Source*: Salvi and Subramanian [3])

as shown in Fig. 3 [2]. By year 2050, fossil fuels and petroleum consumption will be dominating in the market, leading to more environmental pollution. During power generation the direct combustion of hydrocarbon based fuels, i.e., fossil fuels, in heat engines (i.e., external combustion and internal combustion engines) produce exhaust emissions such as NO_x, CO, HC, SO_x, PM, smoke and soot as well as CO_2 as unregulated emission, as shown in Fig. 4.

Long back, a theory of life expectancy for the Industrial Civilization was proposed by Olduvai, which reported the expected life of industrial civilization between the years 1930–2030 [4]. After discovery of fossil fuels, the human civilization entered into the Industrial Civilization and the energy generation per capita increased. Muda and Pin [5] carried out a numerical study on depreciation time of fossil fuels and reported that petroleum will deplete faster due to its massive consumption and subsequently the natural gas and coal will be major sources of energy. In United States, the power plants for electricity generation alone contributes over 40% of U.S. CO_2 emissions from fossil fuels [6].

The fossil fuel based energy generation is resulting into huge amount of CO_2 discharge into the environment. Thus, increasing demand of energy is leading to greater concentration of GHG into the atmosphere and creating a threat to the very existence of civilization on the globe. Therefore, it is need of time to reduce CO_2 generation and addition into the environment.

This review work is aimed for thorough compilation of literature for generation of clean energy and CO_2 mitigation with carbon capture and sequestration (CCS) technologies. Different methods of carbon separation and capture techniques including absorption into liquid, gas phase separation, adsorption on solid and hybrid processes such as adsorption-membrane systems are discussed. In addition to this, the regulations for CCS, economic analysis and policy issues are addressed.

2 Clean energy generation

Growing need of energy is leading to more consumption of fossil fuels, which is resulting into further addition of anthropogenic emissions, especially CO_2 emission, to the environment. Instead of direct use of fossil fuels, it can be processed to produce the hydrogen along with carbon capture and storage of captured carbon at suitable storage site.

The energy generation from hydrogen fuel is one of the suitable options, as utilization of hydrogen energy is CO_2 free. Hydrogen has many unmatched properties including higher flammability limit (4–75) % by volume, lower ignition energy (0.02 mJ), low density (0.083 kg/m^3) at NTP [3, 7] and no carbon contents as compared to the conventional fuels, like gasoline, methane, biogas, etc. The National Hydrogen Energy Board of India has prepared the hydrogen road map of India and targeted about one million hydrogen fuelled vehicles on Indian roads by year 2020. It was aimed to develop a useful bridge for future pure-hydrogen and fuel cell vehicles, particularly through the cost effective introduction of a hydrogen infrastructure [8]. The hydrogen supply for short term and immediate needs can be accomplished by steam reforming, partial oxidation of heavy hydrocarbons and gasification or partial oxidation of coal. The hydrogen can be produced from primary sources of energy (e.g., coal, natural gas and biomass) as well as renewable energy sources (e.g., solar, hydro and wind power). For the immediate supply and mid-term supply, it can be produced from the primary energy sources such as fossil fuels, i.e., Natural gas, Coal, etc. [7, 9]. Wang and Cao [10] carried out a combined theoretical and experimental study for generation of hydrogen and reported that NiO could convert C_2H_5OH to H_2, CO, CO_2 CH_4 and H_2O almost completely. The hydrogen concentration increases with increasing NiO/C_2H_5OH molar ratio in the range from 1 to 3 at temperatures below 800 K.

The major challenge in moving towards a futuristic hydrogen energy system is the production of sufficient quantity of hydrogen in an efficient and environmentally benevolent manner. The production of hydrogen through all above methods, by using carbon fuels, produces the CO_2 as by-product. Thus, generated CO_2 has to be captured and sequestered, so that the total process becomes nearly clean from CO_2 emission into the environment. In order to avoid the economic and human consequences of severe climate change, the CO_2 emission must significantly be reduced. Any approach to develop eco-friendly energy system will inevitably involve certain methods including improvement in energy efficiency, reduction of CO_2 emissions, and substitution of high carbon-emitting fuels with low carbon fuels, such as gas, etc. As long as fossil fuels (i.e., gas, oil and coal) continue to provide utmost of the world's total energy; there is a need to capture and sequester the CO_2. A pathway for sustainable energy supply system is shown in Fig. 5. Variety of feed-stocks including fossil coal, natural gas and biomass can be used for clean hydrogen production with CO_2 capture technology. The produced hydrogen can be used as fuel for existing transportation systems with small modification and in fuel cells for electricity generation.

3 Carbon capturing and sequestration

Carbon capture and sequestration, known as CCS, is one of the technological steps toward the clean energy generation. Any technique that prevent or reverse the release of CO_2 into the atmosphere and divert the carbon to a viable carbon sink can be considered as carbon capture and sequestration (CCS). The CCS refers to process of capturing CO_2 at its source and storing it before its release to the atmosphere. The worldwide efforts on CCS were started in March 1992 at Amsterdam where many scientists and engineers from various countries gathered in the First International Conference and discussed about Carbon Dioxide Removal. It is established that the clean energy can be produced by either removal of carbon from the fuel itself or removal from post-combustion exhaust gases [3]. The CCS methodology can reduce or even eliminate the

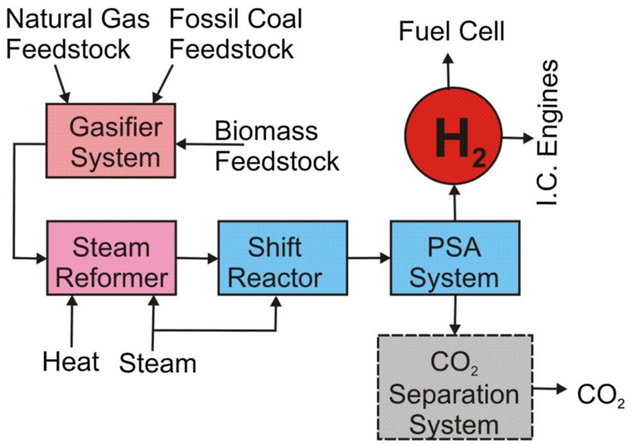

Fig. 5 A pathway for sustainable energy supply system (*Source*: Salvi and Subramanian [3])

CO_2 emission to the atmosphere and clean energy can be produced [9] and it may be a long-term solution to curb carbon emissions [11]. Taiwan has recognized that before arrival of new energy era, the carbon capture and storage (CCS) technologies are to be practiced to permit the continuing use of fossil fuels for energy security and economic development while reducing the emission of CO_2 into the atmosphere [12]. In Nigeria, also attention is being given on CCS activities for continuing utilization of fossil fuels for power generation [13]. The CCS is mid-term solution for utilization of fossil fuels and adoption to use of renewable sources of energy for long term sustainability [14].

The amounts of CO_2 generation and addition in environment are very large. Typically, a coal-fired power plant with a capacity of 1000 MWe generates approximately 30,000 tonnes of CO_2 per day [15, 16]. The CO_2 released by power plants can be mitigated by CCS techniques, but the cost is quit high [17]. An integrated CCS system will include the three main steps: (1) Capturing and separating the CO_2, (2) Compression and transportation of the captured CO_2 to the sequestration site and (3) sequestration of CO_2 in geological reservoirs or the oceans. The main options for sequestration include (a) use of deep saline reservoirs, (b) injection of CO_2 into hydrocarbon deposits to enhance oil recovery (EOR) or production of coal-bed methane (CBM), and (c) injection into the deep ocean [7]. The deep saline formations (100–1000 GtC) and Oceans (1000 GtC) are having highest world sink capabilities of CO_2 disposal options [10].

The CCS can be implemented in two ways: (1) pre-combustion CCS process, where carbon is captured during fuel processing itself, before combustion of fuel for generation of energy and (2) post-combustion CCS process, where separation of CO_2 from combustion products, i.e., flue gases, is done after combustion of the fuel. Removing CO_2 from the atmosphere by enhancing its uptake in soils and vegetation (e.g., afforestation) or in the ocean (e.g. iron fertilization) is yet another form of sequestration.

3.1 Pre-combustion CCS

In pre-combustion CCS process, the fuel (generally coal, crude oil or natural gas) is pre-treated before combustion. In case of coal, the pre-treatment involves a gasification of coal in a gasifier under low oxygen level forming a syngas, which consists mainly of CO and H_2, as shown by Eq. (1). The syngas then undergo water–gas shift reaction with steam forming more H_2 while the CO gas will be converted to CO_2, as shown in Eq. (2). The steam-methane reforming also produces CO and then CO_2, as shown in Eq. (3).

$$Coal \xrightarrow{Gasification} CO + H_2 \tag{1}$$

$$CO + H_2O \xrightarrow{Water-gas\ shift} H_2 + CO_2 \tag{2}$$

$$CH_4 + H_2O \xrightarrow{Reform} CO + H_2 \tag{3}$$

The high concentration of CO_2 in the H_2/CO_2 fuel gas mixture necessitates the CO_2 separation [10]. Subsequent burning of H_2 in air produces mainly products of N_2 and water vapour, eliminating the CO_2 emission to the atmosphere.

3.2 Post-combustion CCS

The capturing and sequestration of CO_2 from the flue gases, before being emitted into the atmosphere is termed as post-combustion CCS. The post-combustion technologies are preferred options for retrofitting the existing power plants [18]. The post-combustion CCS technology has been proven at small-scale; however, the major challenges in it are its large parasitic load because of low concentration of CO_2 in combustion flue gas and related costs for the capture unit to increase the concentration of CO_2 (above 95.5%) needed for transport and storage. The post-combustion approaches in use today require clean-up of products of N_2, NOx and SO_2 before CO_2 separation [19].

4 Development of CCS technologies for CO_2 capture

The emerging technologies comprise a combination of products and processes that have demonstrated, either in the laboratory or in the field, significant improvements in efficiency and cost over the current level of knowledge and development achieved in technologies. There are numerous methods for CO_2 separation and capture including absorption, adsorption, cryogenics, membrane separation and microbial/algal system [18, 20], as shown in Fig. 6. The emerging technologies involved in carbon capture range from major improvements in existing processes to highly novel approaches.

4.1 Membrane separation process

The membrane separation process contains a specially designed membrane sieve that separates molecules based on their molecular size. Several demonstrations of CO_2 separation have been performed, notably the separation of CO_2 from CH_4, CO_2 from air and CO_2, CO, H_2S and H_2O from a mixture of gases [21, 22]. Use of membranes for removing CO_2 provides versatility, adaptability, environmentally

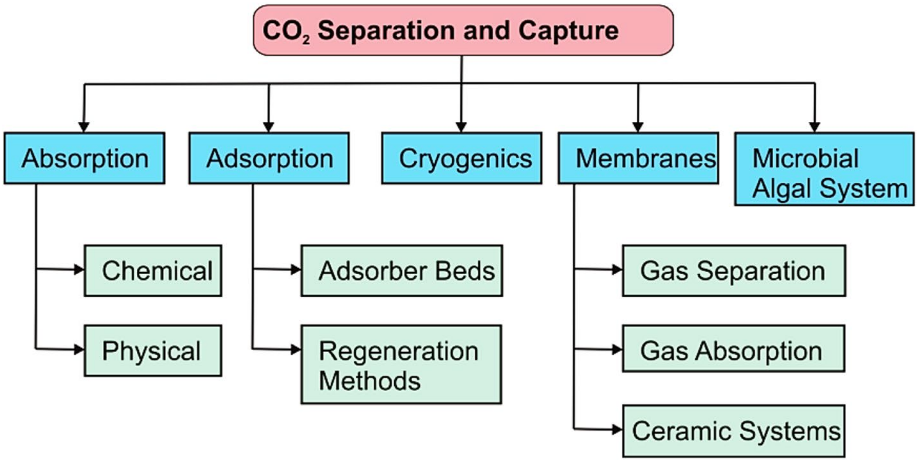

Fig. 6 Technical options for CO_2 separation and capture (Prepared by authors based on information from sources: Rubin et al. [18], Rao and Rubin [20])

friendly, easy to operate, requires less space and light in weight.

Membranes in application are polymeric gas permeation membranes (PGPM), facilitated transport membranes (FTM), hollow fibre gas–liquid membrane contactors, inorganic membranes and mixed matrix membranes (MMM). Low manufacturing cost of polymeric membranes is of great interest for industrial applications, but they generally exhibit selectivity about 5–10 fold lower than those of inorganic membranes. The inorganic membranes are useful for CO_2 separation processes at high temperatures due to their robust thermal, chemical and mechanical stability; however, more R&D is required to improve the reproducibility, reliability and to reduce cost [22]. Polymer membranes with better plasticization suppression properties are useful for CO_2 separation, but aging and conditioning of polymer membranes need to be investigated [21]. Hasebe et al. [23] fabricated high gas permeable separation membranes containing silica nano-particles, a type of MMM. They reported that gas transport channel formed by the nano-particles can enhance the gas permeability without significant decrease in gas selectivity and the syntheses of silica nano-particles are cost-effective.

A two-stage membrane based process with boiler air feed as a sweep stream to increase the CO_2 concentration for CO_2 capture was studied and optimised by Mat and Lipscomb [24]. They reported slightly higher operating pressure, but achieved the target for less than a 35% increase in electricity cost for CO_2 capture. However, boiler air feed sweep stream leads to a detrimental reduction in the O_2 concentration of the feed air to the boiler [24]. With use of the facilitated transport membrane the CO_2 separation is feasible, even for low CO_2 concentration about 10% in flue gas and it is possible to achieve more than 90% CO_2 recovery and with a purity in the permeate above 90% CO_2 [25].

The membrane-based technologies are under development targeting for advancement towards sustainable systems that minimizes CO_2 emissions. Research work is on the way for membrane separation technologies including non-dispersive absorption using porous membranes, gas permeation and supported liquid membranes [26]. With currently available membranes having selectivity up to 50, it is difficult to get simultaneously, desired CO_2 recovery and purity (80% CO_2 in permeate stream) [27]. The arguments in favour of membrane separation technology are that it is cost effective (once developed on a commercial level), produce minimal waste and can be adapted to a variety of carbon sequestration schemes.

4.2 Adsorbent based systems

An adsorbent is a substance, usually porous in nature and with high surface area that can adsorb substances onto its surface by intermolecular forces. It is capable of holding other molecules on its surface by physical or chemical means. The adsorbate is the substance, which is adsorbed on the surface. The adsorbent beds are regenerated, i.e., release of adsorbate, by pressure swing, temperature swing and washing methods [18]. The solid adsorbents are classified into amine-based and alkali (earth) metal-based adsorbent. The various adsorbents with adsorption environment and CO_2 capturing capacity are shown in Table 1 [28].

The carbonate systems are based on the ability of a soluble carbonate to react with CO_2 to form a bi-carbonate, which when heated releases CO_2 and reverts to a carbonate. In a research it was reported that K_2CO_3 based system with catalyst of pipe razine (PZ), the K_2CO_3/PZ system (5 molar K; 2.5 molar PZ) has shown an absorption rate 10–30% faster than a 30% solution of mono-ethanolamine (MEA) [29, 30]. The mineral carbon sequestration has the potential to capture and store CO_2 in a single step. Bobicki et al. [31] carried out an overview of the types of industrial wastes that can be used for mineral carbon sequestration

Table 1 Solid adsorbents with environmental requirement and functionality [28]

Adsorbent	Examples	Adsorption environmental condition	CO_2 capturing capacity up to (mmol/g)
Amine-based solid sorbent	silica gels, activated carbon, tetraethylene pentamine	At – 20 °C to 75 °C in absence of water vapour and pressure 1 bar	4.3
Alkali earth metal-based solid sorbents	CaO, MgO/ZrO_2, MgO/Al_2O_3	Absence of water vapour and high temperature between 600 °C and 650 °C	1.39
Alkali metal carbonate solid sorbents	Na_2CO_3 and K_2CO_3, MgO, ZrO_2, SiO_2, Al_2O_3, TiO_2, CaO, and zeolites	Low temperatures with water vapour	2.49

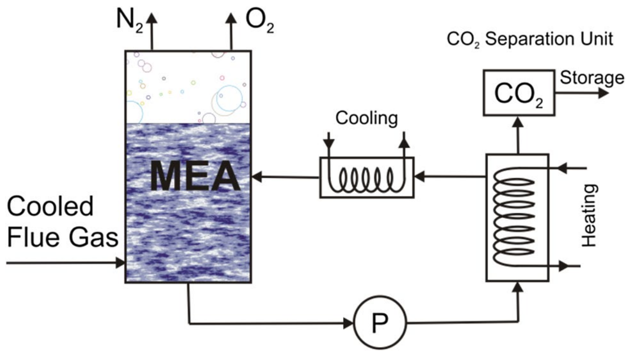

Fig. 7 Mono-ethanolamine scrubbing process (prepared by Authors based on information from sources: Figueroa et al. [34], Veawab et al. [35], Leung et al. [36])

and the process routes available. The varieties of industrial wastes are difficult to be converted from one to another, and each waste has its own unique characteristics. The abandon wastes generated from cement contain a large fraction of CaO, which can be used as CO_2 adsorbent. In a review of the underground coal gasification (UCG) technologies, it was reported that UCG is a suitable technique for production of low carbon fuel by capturing CO_2 generated at gasification site itself [32, 33].

4.3 Amine based scrubbing process

Amine based systems are able to recover CO_2 from flue gases as the amine react with CO_2 to form water soluble compounds [34]. In mono-ethanolamine scrubbing process, a chemical absorption process is used with a mono-ethanolamine (MEA) solvent whereby CO_2 is scrubbed from the flue gases of the combustion process. The process allows the MEA solution to come into contact with the flue gases and mix in the absorber. The absorption takes place at temperatures around 38 °C. The CO_2 rich MEA solution is then passed to a stripper, where it is reheated to a temperature of 150 °C to release almost pure CO_2. The MEA solution is then recycled to the absorber, as shown in Fig. 7.

Other amine compounds such as di-glycolamine (DGA), di-ethanol amine (DEA), tri-ethanol amine (TEA) and methyl diethanol amine (MDEA) can also be used for scrubbing, but the MEA is the most efficient for CO_2 absorption with efficiency over 90% [35, 36]. The separated CO_2 can be utilized for any industrial application or can be sequestrated. This process is generally deemed uneconomical as it results in large equipment sizes and high regeneration energy requirements (about 30% of the energy produced) to release the CO_2 from MEA. The regeneration heat energy may be received from the solar heating system. Apart from this, the additives can help to improve the system performance and the design modifications are possible to drop capital costs and increase energy integration (Figueroa et al., 2008) [34]. The carbon capture through solvent process should be oriented to produce CO_2-based products with economic value that can be reintegrated in a closed carbon loop, which will reduce the use of fresh materials and decreasing the production cost [37].

The energy consumption required to regenerate the solvent can be reduced by using ejector technology into post-combustion carbon capture. A numerical simulation study was targeted for 85% capture rate for the simulated 400 MW coal-fired power plant flue gases, using 20% wt MEA as the reference solvent. There was valuable energy savings of 14% and 23% when the ejector secondary steam was produced from the stripping column condensate and the lean solvent, respectively [38], while in similar study the energy savings of 10% and 14% was reported by Reddick et al. [39].

In order to overcome the limitations of energy intensive process MEA scrubbing, another technique called reactive hydrothermal liquid phase densification (rHLPD), is used to solidify monolithic material without using high temperature kilns. The integration of MEA based CCS processing and mineral carbonation by using rHLPD technology results into formation of a mineral (wollastonite $CaSiO_3$), which has high compressive strength of ~ 121 MPa. The produced material, similar to Portland cement, can be used as value added binding material for construction and infrastructure development [40]. Mineral carbonation is an alternative method for CCS where value added product is produced [41].

4.4 Aqueous ammonia scrubbing of CO_2

The ammonia-based carbon capture technology can be divided into the normal temperature method (15–30 °C) and the low temperature method (2–10 °C). In ammonia-based wet scrubbing of CO_2, the flue gas is passed through aqueous ammonia. The ammonia and its derivatives react with CO_2 via various mechanisms, one of which is the reaction of ammonium bicarbonate. In this mechanism the lower heat of reaction for amine-based systems, results in energy savings. Aqueous ammonia scrubbing of CO_2 and ammonium bicarbonate production process is shown in Fig. 8. The ammonia-based absorption has a number of other advantages such as the potential for high CO_2 capacity, lack of degradation during absorption/regeneration, tolerance to oxygen in the flue gas and low cost [34]. Based on thermodynamic analysis and process simulation it was found that the equilibrium regeneration energy can be reduced to 1285 kJ/kg CO_2 and the energy consumption for the NH_3 abatement system is 1703 kJ/kg CO_2. As this process is operated at room temperature, the additional energy consumption for the cooling of the flue gas and the absorbent can be avoided [42]. The ammonium bicarbonate is used by plants as fertilizer and converts into biomass. The gasification of biomass again would give fuel for energy generation. Therefore, CCS by CO_2 conversion into fertilizer is most convenient and sustainable process as CO_2 is recycled in the environment and the environment remains carbon neutral.

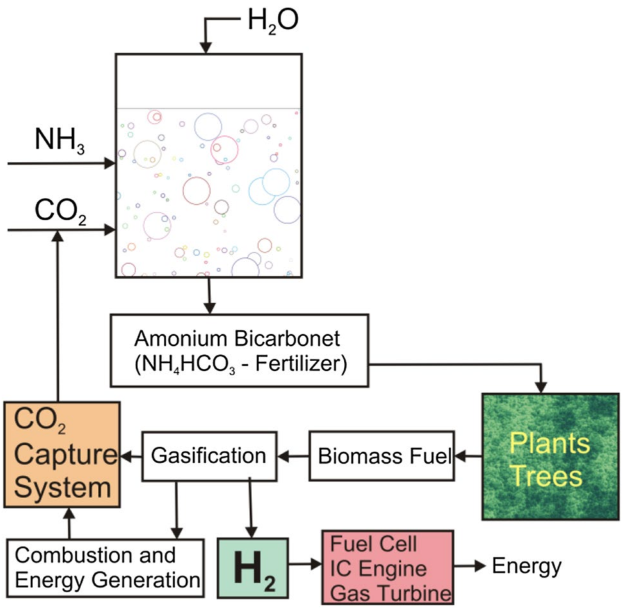

Fig. 8 Aqueous ammonia scrubbing of CO_2 and ammonium bicarbonate production (prepared by Authors based on information from sources: Figueroa et al. [34], Niu et al. [42])

Post-combustion CO_2 capture (PCC) with solar assisted chilled-ammonia-based CO_2 capture system in a coal-fired power plant was undertaken for study under different meteorology conditions. It was found from the economic viewpoint that prices of the solar thermal collector and the equipment of the phase change materials (PCM) have clear impacts on the levelized costs of electricity (LCOE) and the cost of CO_2 removed (CCR). The prices of solar thermal collectors vary from location-to-location resulting into varying cost of PCC system. Typically, in order to achieve lower LCOE and COR than that of the reference PCC system, the price of the vacuum tube (VT) has to be reduced to 131.02 $/m^2, 91.76 $/m^2 and 57.10 $/m^2 for the location of M1 (Lhasa), M2 (Tianjin) and M3 (Xi'an), respectively [37].

4.5 Cryogenic separation process

Cryogenic separation is a CO_2 removal process using distillation at very low temperature and high pressure. In this technique flue gas is passed through cooling media. The flue gas containing CO_2 is cooled to de-sublimation temperature (– 100 to – 135 °C), where the solidified CO_2 is separated from other gases. The amount of CO_2 recovered can reach 90–95% of the flue gas [36]. There are two cryogenic systems: flash separation with internal cooling and separation with distillation column. Since the distillation is accompanied at extremely low temperature and high pressure, it is an energy intensive process estimated to be (600–660) kWh per tonne of CO_2 recovered [36, 43]. Numerous patented processes have been developed and research has mainly been focused on cost optimization [44].

There are various technologies for carbon separation and capture. A comparative study on the emerging technologies for CCS along with advantages, limitations and cost complications is shown in Table 2. Every technology has its own merits and accordingly it should be selected as per suitability.

5 Transportation of captured CO_2

Captured CO_2 is required to be transported up to suitable location. The CO_2 can be transported by pipelines, trucks and ships. The mode of CO_2 transportation can be selected based on separation and capturing site, and sequestration site. Morbee et al. [45] carried out numerical study

Table 2 Comparative study on emerging technologies for CCS

S.No.	Technology/method	Technological advancement	Advantages and limitations	Cost implications	Refernces
1	Membrane separation process	Membrane sieve that separates molecules based on their molecular size	Adaptability, environmentally friendly, compact in size and light in weight. Difficult to get simultaneously, desired CO_2 recovery and purity (80% CO_2 in permeate stream)	Low production cost of polymeric membranes. Two stage membrane required high operating pressure and cost of electricity increased	[21, 22, 24, 27]
2	Adsorbent based systems	A porous material in nature and with high surface area that can adsorb substances onto its surface by intermolecular forces	Single step absorption of CO_2, adsorbents are available as wastes generated from cement	Cost effective at underground coal gasification (UCG) technologies	[18, 28, 31–33]
3	Amine based scrubbing process	A chemical absorption process is used with a mono-ethanolamine, di-glycolamine, di-ethanol amine, tri-ethanol amine and methyl diethanol amine solvent	Absorbs CO_2 from flue gases and useful in post-combustion CCS but, purity of released CO_2 is poor. Ejector secondary steam technology with lean solvent could save energy by 23%	CO_2 release from amine require heating up to 150 °C, which can be attained from solar heating system	[34–37]
4	Aqueous ammonia scrubbing of CO_2	Scrubbing of CO_2 by aqueous ammonia and production of ammonium bicarbonate	Lack of degradation during absorption and regeneration, tolerance to oxygen in the flue gas	Low cost and ammonium bicarbonate is used as fertilizer for plants	[34, 42]
5	Cryogenic separation process	Distillation of CO_2 at very low temperature and high pressure	Up to 95% CO_2 can be removed from flue gases	Energy intensive process about 660 kWh per tonne of CO_2 recovered, hence, very costly	[36, 43, 44]

to determine the optimal EU-wide CO_2 transport network for 2015–2050 and EU CO_2 pipeline network would reach 17,000 km. Hasan et al. [46] carried out study on multi-scale framework for the optimal design of CO_2 capture, utilization, and sequestration supply chain network for cost minimization. They reported optimized cost of US $35.63 per ton of CO_2 captured and managed.

According to IPCC-2005 report [47], at present pipeline transportation is much more mature technology, but shipping of captured CO_2 is economically viable under specific conditions. The transportation cost ranges 1–8 US $/t CO_2 transported for per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) Mt CO_2/y. In a study the overall costs for a European carbon capture, transport and storage supply chain was estimated in the range of 27–38 €/ton of CO_2 [48].

6 CO_2 sequestration methods

In all cases where fossil fuels are the source of energy, CO_2 is inevitably produced and released into the environment. The carbon capture and sequestration (CCS) becomes essential to prevent the generated CO_2 reaching into the atmosphere. Annually about 3Gt carbon dioxide, which is around one-eighth of current global CO_2 production, needs to be sequestrated [49]. In the US, the Southeast Regional Carbon Sequestration Partnership has identified more than 900 large stationary sources of CO_2 that contributes 31% of the country's CO_2 stationary source emissions. The work is going on to identify the role of regional partnerships in conducting integrated field tests, carbon sequestration locations within the Gulf Coast Basin, infrastructural integrity of wells, long-term storage formations and impact of captured CO_2 from power plants on the geochemistry of the saline water [50]. So far the two locations viz. deep ocean and geological structure beneath the earth have been identified as CO_2 sequestration site. Generally, CO_2 is stored at depths between 800 and 1000 m [47, 51]. The CO_2 sequestration can be done in geological formations, deep oceans, saline aquifers, tar-sands and by CO_2 fixation methods as shown in Fig. 9.

6.1 Geological sequestration of CO_2

The injection and storage of captured CO_2 into the used oil wells and mined coal mines beneath the earth, is termed as geological sequestration. The geologic injection that could be considered is the use of abandoned, uneconomic coal seams. The CO_2 injections in geological formations are usually performed for enhanced hydrocarbon recovery in oil and gas reservoirs, and storage and sequestration in saline aquifers. Once, CO_2 is injected into the formation, it diffuses through the pore structure of coal and is physically adsorbed, thus retention on a permanent basis is possible. The chemical reactions between brine ions and CO_2 molecules and consequent reactions with mineral grains are also important processes [52]. The CO_2 geo-storage efficiency in oil wells is strongly affected by the wettability of CO_2-brine-mineral system at storage conditions. Water-wetness decreases with increase in CO_2-wetness, which results in reducing both structural and residual trapping capacities. Use of nano-fluid, e.g., silicon dioxide (SiO_2) nano particles, renders CO_2-wet calcite to water-wet, which enhances CO_2 geo-storage potentials [53].

The geologic sequestration of CO_2 has higher expected retention rate and expected residence times are at least thousands of years. The consideration of carbon credits should be made on the retention ability of the geologic reservoir. The amount of CO_2 that leaks into the atmosphere should be considered as the difference of the amount sequestered in the geologic formation versus the actual quantity remaining [54, 55]. Coal beds often contain large amounts of methane. The extraction of this methane could represent a value added process. Currently, Burlington Resources is injecting 70,000 tonne of CO_2 per year into a deep coal formation located in the San Juan Basin [55, 56]. A similar small scale project was undertaken by the Alberta Research Council in Canada and reported that by using CO_2 instead of water to flood the bed, there exists a higher potential to recover the methane efficiently and also sequester the CO_2. While this sounds ideal, much further research is needed in this area to understand and optimize the process. Worldwide storage capabilities for CO_2 within deep coal beds are estimated to be up to 150 Gt [16].

6.2 Deep ocean and saline aquifers CO_2 sequestration

The direct injection of CO_2 into the ocean can reduce the peak atmospheric CO_2 concentrations and their rate of increase. However, using this method, it is estimated that around 15–20% of the CO_2 injected into the ocean will leak back into the atmosphere over hundreds of year [55].

The geologic injection may be superior to oceanic injection because of its higher expected retention period, at least thousands of years compared to that of oceanic injection of only hundreds of years [55]. Even longer residence times could be achieved if the CO_2 reacted underground to form carbonate minerals, thus reducing the possibility of escape into the atmosphere [52].

Large deep formation of porous rocks is known as saline aquifers. These are basically porous sand stones and lime stones, which contain large amount of brine water in their pore space. Disposal of CO_2 from stationary sources (e.g., fossil-fuelled power plants) into brackish (saline) aquifers has been suggested as a possible means for reducing emissions of greenhouse gases into the atmosphere. The CO_2 at first compressed at very high pressure, about 95 bar or higher [57], and then injected into the saline aquifers, where aquifer water is replaced by the CO_2 which occupies the porous space, as shown in Fig. 10.

The reactions among CO_2, brine and formation minerals play an important role in formations with a large number of proton sinks, such as feldspar and clay minerals. The CO_2 dissolves in formation brine. First, it simply dissolves, then equilibrium is established between the dissolved CO_2 and carbonic acid H_2CO_3, which dissociates into HCO_3^- and CO_3^{2-}. About 1% of the dissolved CO_2 exists as carbonic acid H_2CO_3 [58]. The reaction mechanism is shown in Eq. (4) and Eq. (5).

$$CO_2(g) \rightarrow CO_2(aq) \tag{4}$$

$$CO_2(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq) \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-} \tag{5}$$

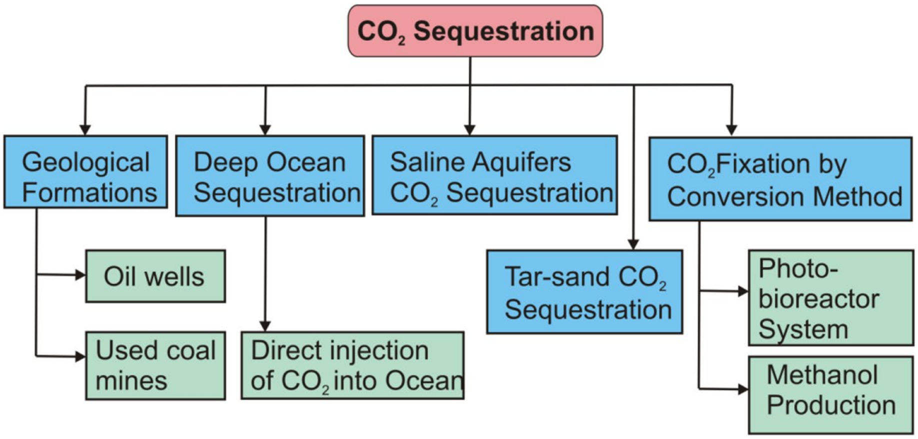

Fig. 9 Technical options for CO_2 sequestration (prepared by Authors based on information from sources: Metz et al. [47], Cuellar-Franca and Azapagic [51])

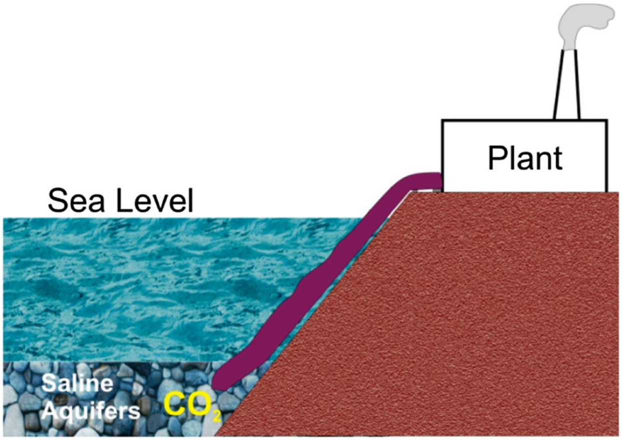

Fig. 10 Saline aquifer CO_2 sequestration (prepared by Authors based on information from sources: Stewart and Hessami [55], Soong et al. [57])

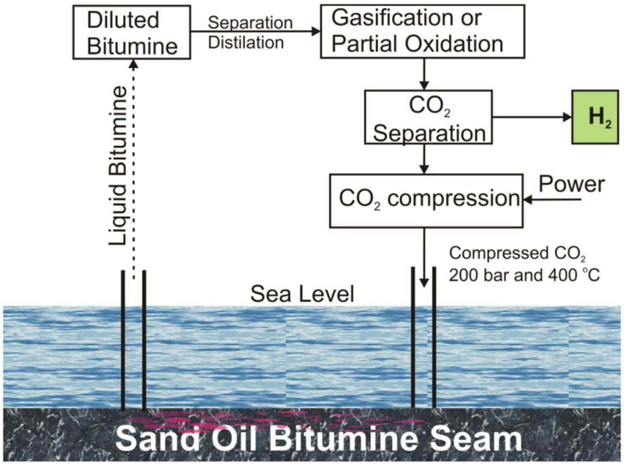

Fig. 11 Tar-sand bitumine CO_2 sequestration (prepared by Authors based on information from source: Holloway [61])

Next, the carbonate anion CO_3^{2-} interacts with cations in formation water such as Ca^{2+} and Mg^{2+} to precipitate carbonate minerals. Extensive deposits of lime stone and dolomite have been formed in this way [58]. The mutual solubility of CO_2 and brine affects the injection process and flow properties. First, CO_2 dissolves in brine and reacts with water, forming an acid. Then, H_2O dissolves into CO_2 increasing the salinity of brine [59]. The solubility of CO_2 in brine depends essentially on pressure, temperature, total salinity, density difference between CO_2 and brine, critical CO_2 saturations, etc.

The effects of contaminants such as SO_2 on CO_2 sequestration in saline aquifers were studied and it was reported that SO_2 reaction with water would form sulphuric acid, which would lead to substantial reduction in brine pH due to the formation of bassanite (major) and anhydrites [57]. Currently CO_2 injection into the deep geological formation is about 15 megatons of CO_2 underground annually [60].

6.3 Tar-sand CO_2 sequestration

Compressed CO_2 at 200 bar and 400 °C is injected into the deep sea oil-bitumine sand bed. At the depth about 600–1000 m the CO_2 will exist as a supercritical fluid [61] with specific gravity of somewhere between 0.6 and 0.8. The supercritical CO_2 is buoyant in the saline formation water and will rise until it encounter a seal. Bitumine is soluble in CO_2 and becomes liquid, which can be extracted easily from unminable bitumine seams, as shown in Fig. 11.

6.4 CO_2 fixation by conversion methods

Carbon dioxide fixation can be done by conversion methods such as photosynthetic conversion and methanol production by using renewable hydrogen. The photosynthetic conversion of CO_2 into carbohydrate is done in a photo-bioreactor in presence of bacteria or micro-algae under a controlled environment. A photo-bioreactor system makes use of the natural process known as photosynthesis to convert light, heat and carbon dioxide to useful products, such as carbohydrates, hydrogen and oxygen [55], is shown in Eq. (6).

$$6CO_2(aq) + 6H_2O(l) + Light + Heat \rightarrow C_6H_{12}O_6(aq) + 6O_2(g) \tag{6}$$

The type of product produced in photosynthesis reaction Eq. (6), in this case glucose, depends highly on the biological strain used in the photo-bioreactor. A photo-bioreactor requires use of the 'flashing light effect' with light–dark cycle of 1 Hz frequency with a light versus dark residence time of 1:10 [55, 62].

Production of liquid hydrocarbon fuels from CO_2 and water by using a concentrated solar energy source is an established technology. A life cycle assessment (LCA) analysis of the environmental impacts of sunshine-to-petrol (S2P)-derived and petroleum-derived gasoline was carried out by Kim et al. [63]. Based on the LCA results, it was reported that S2P gasoline shows lower impact scores for global warming potential (GWP) than the conventional gasoline and provides external cost savings.

Another method of CO_2 fixation is production of methanol from CO_2 by using renewable hydrogen as shown in Eq. (7). The methanol as transportation fuel is certainly much better than the hydrogen, much easier and safer to store and distribute, and can be used in internal combustion engines [64].

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{7}$$

Taking advantage of CO_2-derived chemical commodities, known as carbon capture and conversion (CCC), is another methodology which may be a mile stone in the way of sustainable reduction of CO_2 emission. Advances in CO_2 chemical transformation with the emphasis on the energy constraints, materials, and process design are leading to promote the environmentally benign use of carbonaceous fuels and derived hydrocarbon products. But, the surface chemistry of CO_2 reduction is a major challenge due to large energy barriers and requiring noticeable catalysis [65].

7 Characterization and monitoring of CO_2 storage-site

Storage of CO_2 securely in geological formations depends on number of physical and chemical mechanisms. For storage of CO_2 securely and long term duration proper location of plants, infrastructure and pipelines is essential for optimum use of capital invested and subsurface capacity. Fang et al. [58] reviewed about phase behaviour of CO_2 and reported that supercritical CO_2 injection can avoid the prior separation of CO_2 into liquid and gas phase, and also provide longer residence time than gaseous CO_2 injection. The CO_2 will exist as a supercritical fluid at depths about 600–1000 m [61]. Supercritical CO_2 is preferred, because it is much denser and takes up much less volume than gaseous CO_2; but for remaining CO_2 in supercritical phase, such storage conditions are required.

7.1 Numerical models and analysis

Numerical modelling permits time saving and less utilization of resources for quantitative analysis of thermodynamic and geo-mechanical formation for various CCS practices. Numerous numerical models have been developed and put forward for analysis of geochemical evaluation of the CO_2 injection. A prompt screening analysis for selection of suitable geological formations for CO_2 injection may be obtained by using the steady-state and one-dimensional Eulerian convection–diffusion–depletion equation governing the transport and temporal evolution of an averaged or mean macro scale CO_2 concentration (C), as shown in Eq. (8).

$$\frac{\partial C}{\partial t} + \bar{U}^{*} \cdot \bar{\nabla} C - \bar{D}^{*} \cdot \bar{\nabla}\bar{\nabla} C + \bar{K}^{*} C = 0 \tag{8}$$

where, $\bar{\nabla} = \partial/\partial\bar{\mathrm{R}}$, represents the gradient with respect to the continuum scale position vector, $\bar{\mathrm{R}}$ [45]. Continuity of the CO_2 flux across the porous bed inlet requires imposing the boundary condition: $C = C_{in}$ at $x = 0$ and $\frac{\partial C}{\partial x} = 0$ at $x = L$. The efficiency of a CO_2 storage/sequestration process is given by Eq. (9) [45].

$$\eta_{CO_2} = \frac{\textit{Total number of } CO_2 \textit{ molecules stored or sequestrated in the bed}}{\textit{Total number of } CO_2 \textit{ molecules entred into the bed}} \tag{9}$$

A comparative study on experimental and numerical simulation was carried out by Izgec et al. [66], which reported that amount of dissolved particles and the total amount of particles that are blocking the throat increases with respect to increase in the reaction frequency of forward reaction (dissolution). This leads to decrease in permeability. They reported that because of several uncertainties and approximations such as chemical complexity of injection induced water–CO_2–rock interaction processes, the present state-of-the-art numerical models are not able to give a complete quantitative prediction of geochemical evolution of CO_2 injection.

Rutqvist and Tsang [67] carried out a numerical study of hydro-mechanical changes during a deep underground injection of supercritical CO_2 in a hypothetical brine aquifer/caprock system and reported that hydro-mechanical changes were induced in the lower part of the caprock near its contact with the injection zone. The flow dynamics study during CO_2 disposal in saline aquifers has shown the CO_2 flow pattern in aquifers, but stressed on to carry out quantitatively realistic studies with detailed representation of aquifer heterogeneities and comprehensive description of coupled processes [16].

Mathias et al. [68] worked on governing equations for CO_2 injection into a slightly compressible brine aquifer with a vertical pressure equilibrium assumption and carried out a new similarity solution by using the method of matched asymptotic expansions and prepared a dimensionless parameter equation. A large time approximation of the solution was then extended to account for inertial effects using the Forchheimer equation and allowed the slight compressibility in the fluids and formation. The validation of both solutions was explored by comparison with equivalent finite difference solutions and revealed that the new method can provide robust and mathematically rigorous solutions for screening level analysis, where numerical simulations may not be justified or cost effective.

Javadpour [52] worked on an advanced up-scaling theory to relate the tiny pore scale events to the macroscopic properties of interest. The dispersion effects of impulse and CO_2 injection in field disturbance was studies by using macro transport theory, which is the extension of the celebrated Taylor-Aris dispersion theory [69, 70] and reported that dispersion process for the impulse and CO_2 injection in field disturbances was the same [71, 72]. Hongjun et al. [73] carried out sensitivity analysis of CO_2 sequestration in saline aquifers and

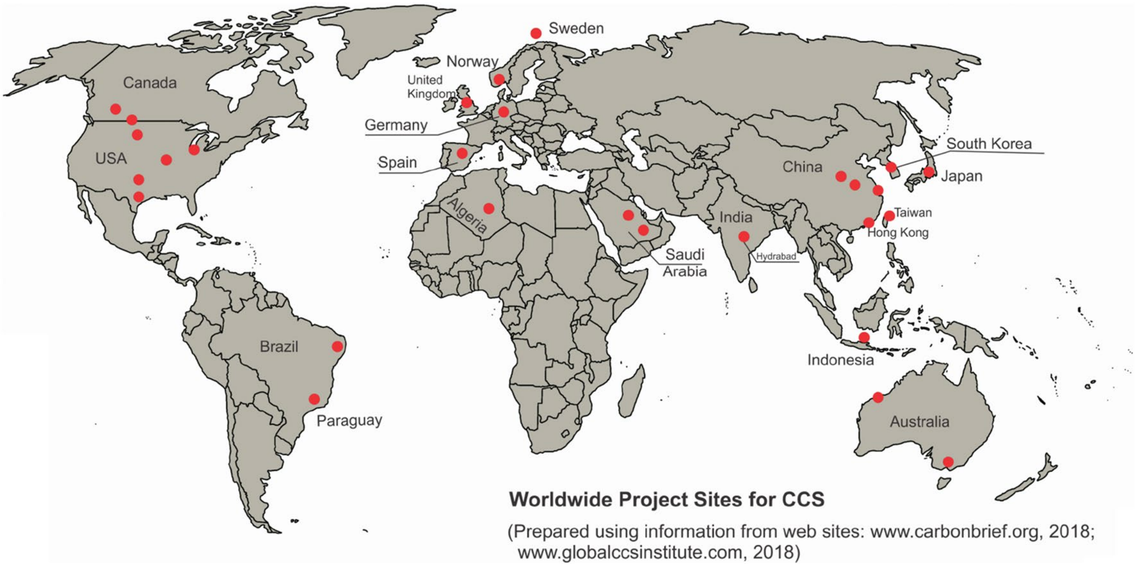

Fig. 12 Worldwide sites for CCS at pilot stage (prepared by Authors based on information from sources: [86, 87])

reported that during injection phase only about 5–10% CO_2 dissolves in the brine and rest of the CO_2 migrates in the gas phase. After termination of injection the CO_2 continues to dissolve mainly due to the contact of gas with brine and the efficiency of dissolution depends on many factors including brine salinity, vertical to horizontal permeability ratio and residual phase saturations; but, hysteresis and mineral trapping should be investigated further.

A numerical simulation was carried out by Beni et al. [74] to provide an insight into flow and transport processes to quantify the CO_2 storage potential of selected sites in North Rhine Westphalia (NRW) in Germany. A numerical code TOUGHREACT [75, 76] was used to study three trapping mechanisms: hydrodynamic trapping, dissolution trapping and mineral trapping, for CO_2 injected into the Bunter sandstone formations. The injected CO_2 plume initially migrated towards the top of the reservoir due to buoyancy until it reached the confining layer. Then, it spread laterally and dissolved partially in the formation water. This dissolution of CO_2 resulted in an increase of brine density causing the CO_2 enriched water to migrate downward [74]. A retrofit of a CO_2 capture pilot plant using superstructure and rate-based model was developed. It was optimized and found that thermal energy and total energy consumption in the optimal retrofit process were reduced by about 59% and 27%, respectively [77]. The optimum CO_2 injection pressure depends on the aquifer depth, while the effects of salinity and temperature are negligible. An increment in aquifer depth from 0.8 to 1.4 km causes the optimum injection pressure increment from 19.55 to 42 MPa [78].

Azin et al. [79] carried out numerical analysis for injection of CO_2 into saline aquifer by using finite element method and reported that instability occurs earlier and grows faster with increase in Rayleigh number, which affect the wave number. But, number of assumptions imposes the limitations to the numerical analysis. The numerical models are good for optimal prediction of parameters, but uncertainty associated with sequestration methods is a major hindrance to practical application of developed models. The CCS technologies in action are still new and it is not known exactly the full consequences of such abatement technologies, in terms of environmental consequences or in terms of efficiency, once the leakage problem is considered [10].

Once the CO_2 injection starts, a site monitoring and verification program of CO_2 distribution is required in order to observe key features and risk assessment, manage the injection process, describe and identify leakage risk and surface escapes, provide early warnings of failure near the reservoir and verify the storage for accounting and crediting. For CO_2 storage to succeed, a site must have sufficient injection storage capacity to sequester point-source volumes, sufficient capacity to store the total emissions of an injection project over its lifetime and effective storage.

8 Economic analysis of CCS methods

Storage cost of CO_2 depends on many factors including the type of storage options, location, depth and characteristics of the storage reservoir formations. The CO_2

Table 3 Summary of worldwide pilot projects for CCS

Name of project	Type of industry	Technology used	CO_2 capturing capacity	Sequestration method	Start year	Country or region	References
Capitol SkyMine, Skyonic Corp, San Antonio, Texas	Cement plant, acid gases and heavy metals	Transform CO_2 discharge from exhaust streams into solids	83,000 t/y	Mineralization of CO_2 as Sodium bicarbonate	2013	USA	[87]
Taiwan Cement Corp	Cement plant and power plant	Calcium looping process	8,760 t/y	Pumping to underground to enhance the production of natural gas	2013	Taiwan	[87]
Norcem Cement Company, Norway	Cement Plant	Chemical absorption, adsorption and membrane technologies	NA	Capture the CO_2 and release it into the atmosphere afterwards	2013	Norway	[87]
Pond Biofuels, Canada	St. Marys Cement in Southwestern Ontario	Photo-bioreactor of 1,500 square foot facility	NA	Production of Algae	NA	Canada	[87]
Mantra Energy, Canada	Lafarge Cement, Richmond, Canada	Electro-reduction of carbon dioxide	36,500 t/y	CO_2 is transferred to formic acid and O_2 as by-product	NA	Canada	[87]
Kemper County IGCC	Mississippi Power, Southern Energy, KBR	Pre-combustion IGCC plant using TRIG™ technology (65% capture)	3.0 Mt/y	Pipeline for onshore EOR	2010	USA	[89]
Petra Nova W.A. Parish, USA	NRG Energy and JX Nippon Oil & Gas Exploration Corp., Texas, USA	Post-combustion: KM-CDR amine scrubbing CO_2 developed by MHI and KEPCO	1.4 Mt/y	Pipeline for onshore EOR in Hilcorp's West Ranch Oil Field in Jackson County, Texas	2016	USA	[89]
Texas Clean Energy Project (TCEP), USA	Summit Power Group Inc, and Texas Bureau of Economic Geology	Pre-Combustion: Siemens IGCC technology and Linde Rectisol acid-gas capture technology (90% CO_2 capture)	2.0 Mt/y	EOR in the Permian Basin	2019	USA	[89]
Peterhead Project	Scottish and Southern Energy (SSE) and Shell	Post-combustion retrofit	1.0 Mt/y	Onshore to offshore 102 km pipeline to offshore depleted Goldeneye gas reservoirs at a depth of 2 km	2015	UK	[89]
Don Valley Power Project, Stainforth, South Yorkshire, UK	Sargas Power (sold in 2014 by 2 Co Energy Ltd)	IGCC: Pre-combustion	4.5 Mt/y	175 km onshore to offshore pipeline for sequestration in offshore deep saline formations	2020	UK	[89]
Captain Clean Energy Project	Captain Clean Energy Limited, Grangemouth, Scotland, UK	Siemens Pre-Combustion Gasification	3.8 Mt/y	351–400 km pipeline to offshore deep saline formations	2022	UK	[89]
Dongguan, China	Dongguan Taiyangzhou Power Corporation, Xinxing Group, Nanjing Harbin Turbine Co	Pre-combustion capture (KBR and Southern Company Technology)	1.0 Mt/y	Transported 51–100 km via pipeline for use in EOR in the Shangdong Province	2015	China	[89]
Shengli Oil Field EOR	Sinopec, Shengli power plant, Dongying, Shangdong Province, China	Post-combustion- Retrofit	40,000 t/y	Transported 80 km via pipeline for use in EOR at 3 km depth in the Shangdong Province	2007	China	[89]

Table 3 (continued)

Name of project	Type of industry	Technology used	CO_2 capturing capacity	Sequestration method	Start year	Country or region	References
Taweelah Project	Abu Dhabi Future Energy Company and Taweelah Asia Power Company	Post Combustion absorption	2.0 Mt/y	EOR	2018	UAE	[89]

mitigation costs for electricity generation with CCS [8] can be calculated by using Eq. (10).

$$CO_2\ mitigation\ costs = \frac{COE_{CCS} - COE_{ref}}{m_{CO_2,ref} - m_{CO_2,CCS}} \tag{10}$$

where COE is the cost of electricity ($/kWh) and *m* is the CO_2 emission factor (kg/kWh) with the CCS and reference or without CCS. The Eq. (10) is applicable when hydrogen produced with CO_2 capture replaces conventionally produced hydrogen.

In an economic analysis it was reported that the carbonates over amine-based systems has benefits of significantly lower energy requirement for regeneration [29, 34]. In a power plant for the capture and sequestration up to 90% of the CO_2 generated, an additional cost of US $2/kWh would be added to the production costs [54, 55]. Studies suggested that CCS would increase the hydrogen supply costs at filling stations by 25–30%; some studies indicate even higher costs. The cost of the fuel is the principal component in this extra cost when hydrogen is produced from natural gas while the capital cost is the most important component when hydrogen is produced from coal [2]. The capture of CO_2 would add about 25–30% of the cost of production to the cost of producing hydrogen [9].

According to IPCC [47] the estimated total cost for saline aquifer storage ranges from US $ 0.2–12.0/ton CO_2. Kuramochi et al. [80] carried out a comprehensive review study to assess CO_2 capture options for various industrial processes in details. They reported that standardized key performance data could be a useful input to various energy-economic models that wants to incorporate CO_2 capture from industries. An engineering-economic analysis of pre-combustion gas-turbine combined cycles (IGCC and IRCC) with CO_2 capture was carried out by Lorenzo et al. [81] and their economic performance was evaluated in terms of the break-even electricity selling price. The results indicate that the proposed pre-combustion power plant efficiency values (37% and 43.7% for the IGCC and the IRCC, respectively) were significantly lower compared to a conventional plant value (55.3%). Flexible CCS as compared to normal CCS provides more system benefits, generator's net efficiency and capacity, which could make flexible CCS an economic CO_2 emission reduction strategy [82].

Accomplishing the significant cost reduction will require not only a strong and sustained level of research and development, but also a substantial level of commercial deployment, which, in turn, demands a significant market for CO_2 capture technologies [18]. In order to place the risks into perspective, the comparison risks involved in CO_2 transport and storage activities can be

Table 4 The earth and atmospheric hazards due to risk elements related to CCS (prepared by Authors based on information from sources: Koornneef et al. [83], Selvadurai [92], Song and Zhang [93]

Source of leakage	Expected hazard level		
	Crustal deformation	Ground water degradation	Atmospheric release
Well leakage	High	Highest	Highest
Fault leakage	Highest	High	High
Caprock leakage	Moderate	Moderate	Moderate
Pipeline leakage	High	NA	High

done; however it is not judicious to use the results of such a comparison to provide any argument for the acceptance/rejection of these risks. The systematic comparison between the risks of CO_2 pipelines and CO_2 storage is rather difficult and could not be done within limited study [83]. Deployment of hydrogen vehicles on road will lead to abatement of CO_2, but it is strongly dependent not only on vehicle cost, but also on global marginal abatement cost [84]. Various incentive programs can accelerate the development and deployment of improved CO_2 capture systems. The Government actions that significantly limit CO_2 emission to the atmosphere ultimately are needed to realize considerable and continual reductions in the future cost of CO_2 capture [18].

9 Opportunities and challenges ahead in CCS

The carbon sequestration beneath the ocean and saline aquifers has great potential and can save millions of tonnes of CO_2 emission to the atmospheres. Over the period, the stored carbon again may convert into fuel, which may be explored in future. On the contrary, there are challenges and problems related to the stored carbon. Injection of CO_2 into saline aquifers will give rise to a variety of coupled physical and chemical processes, including pressurization of reservoir fluids, immiscible displacement of an aqueous phase by the CO_2 phase, partial dissolution of CO_2 into the aqueous phase, chemical interactions between aqueous CO_2 and primary aquifer minerals, and changes in effective stress which may alter aquifer permeability and porosity, and may give rise to increase in seismic sensitivity as well.

Non-isothermal effects may arise from phase partitioning, chemical reactions, and compression/decompression effects. Many of the important processes involve non-linear effects and dependencies on pressure, temperature, and fluid composition. If geo-sequestration of CO_2 is to be employed as a key emission reduction method in the global efforts to mitigate against climate change, simple yet robust screening of the risks of disposal in brine aquifers will be needed [68]. The CCS technologies require water and huge amount of waste water in generated; therefore cost-effective water treatment technologies are also required for site-specific cases [85].

9.1 CCS technologies as opportunities and worldwide projects

Efforts have been started long back for CCS technologies and numbers of projects are under way for CCS worldwide. Many countries including USA, Canada, Brazil, United Kingdom, Germany, Spain, Norway, Sweden, Algeria, Saudi Arabia, India, Australia, China, Indonesia, China, Taiwan, Hong Kong, Japan, South Korea, etc. are working on CCS. Most of the CCS sites are concentrated around the coal fields, oil fields and fuel processing plants, where low carbon fuel is produced along with CCS. Worldwide projects and sites for CCS are shown in Fig. 12 [86, 87]. Germany started it's CCS program on 24th August 2012 with an act on the demonstration and use of the technology for the capture, transport and permanent storage of CO_2 [87].

The cement industries and power plants are the most significant industrial sectors with high CO_2 discharge. Pilot and demonstration projects are essential to develop carbon capture for this major CO_2 discharging sector. A comprehensive review on worldwide pilot projects for CCS along with technologies used, CO_2 capturing capacity, sequestration method and start of year is shown in Table 3 [87–89].

9.2 CO_2 leakage hazards

After storage of CO_2 into different formations, there is risk of leakage. A number of circumstances, such as leakage through existing or induced faults and fractures, leakage along a spill point, caprock failure or permeability increase and leakage along a well and wellhead failure, are possible for the leakage of CO_2 from the target reservoirs [83]. Injection of captured carbon at depth of sea may contaminate ground water through leakage. This leads to understanding for design and implementation of appropriate monitoring and control system, both for serving the purpose

Table 5 Comparison of CCS with other clean technologies for energy generation (compiled by authors based on information sought from various sources referred in this paper)

Comparison parameters	Energy generation with CCS technology	Renewable sources of energy			
		Biomass	Solar Energy	Wind energy	Hydro energy
Primary source of energy	Fossil fuels	Forest and agriculture wastes	Sun light	Wind	Water falls or stored rain water
Fuel/energy processing	Carbon capturing is required	Carbon neutral	Solar panels	Wind mills	Hydropower stations
Transportation mode	Yes, fuel and captured carbon	Yes, onsite fuel delivery	Electricity	Electricity	Electricity
Availability of fuel/energy	Abundant any time depending on the availability of primary sources, but gradually depleting	Forestation and rainfall, transportation of fuel to the demand site	Day time only, subjected to availability of sunlight, extra measures to match demand	Weather and location dependent, extra measures to match demand	Rainfall, water catchment area and storage, extra measures to match demand
Safety issues	Leakage of stored captured carbon and geological disturbance	Local storage and fire	Storms, heavy wind flow	Storms, heavy wind flow	Rain storms, earthquake, etc.
Economic	High capital cost of fuel processing and CCS	Medium capital cost and local employment generation	Low running cost while high capital and energy storage cost	High capital cost and acquire more space	High capital cost and low running cost
Overall comments	Suitable for short-term and fast energy need, present infrastructures can be used effectively	Suitable for medium and long term energy need, but less energy intensive	Depends on the duration of sun light and energy storage is still a challenge	Perennial winds at comparatively smoother flow rate are required throughout year	High rainfall and water storage site is required, it may disturb the ecological system

and assurance of environmental safety [90]. In the storage of supercritical CO_2, if there is any leakage of stored CO_2, then it will rise in saline water until it encounters a seal as the supercritical CO_2 floats in the saline formation water. Therefore, determination of the effectiveness of such seals will be a necessary part for the appraisal of suitable sites for CO_2 storage. The seal integrity of shattered oil and gas wells will be relatively well known, but the deep saline aquifers will be less well-understood. So, considering such formations for secure CO_2 storage will represent significant challenges. The uncertainties in quantifying leakage rates and expected cost of leakage risk is unlikely to significantly hinder global CCS deployment or the effectiveness of policy for mitigating climate change [91].

Table 4 shows the earth and atmospheric hazards because of various risk elements [83, 92, 93]. The well leakage has highest risk for ground water and atmosphere. The leakage of CO_2 in geological formations may dissolve the rocks/saline aquifers leading to the land sliding and CO_2 concentrating near leakage area. The increase in pH value of saline water due to dissolving of CO_2 into water may affect the life-cycle of sea creatures.

9.3 Development in cost effective technologies

The CCS technologies today are well understood and effective, and can probably provide what is expected. However, there are some outstanding technical concerns including development of indigenous and lower-cost CCS technologies, integration and deployment of CCS technologies, regulations and protocols for sequestration site characterization, characterization of sequestration site leakage and mitigation, and technical basis for monitoring, verification, operational protocols and risk characterization. There are multiple hurdles including cost-effective and viable technologies for implementing CCS technologies [36].

There are many issues, which are not technical; but related to technical readiness and maximizing early investment in CCS. The developed countries such as USA, Japan, Germany, UK, etc. should take lead in the field of CCS. This in turn will promote potential CCS users in making key investment decisions. A global assessment framework should be prepared as a policy priority. The developing countries may be given carbon credit to develop and deploy the CCS system in their power plants and industrial organisations. The infrastructure to transport CO_2 (e.g. trucks, pipelines) is a key enabler for commercial deployment of CCS system [48]. Initially, some incentives and Government actions for this infrastructure are needed to build networks sufficient for large-scale commercial CCS deployment.

9.4 Regulatory and policy issues for CCS

The CCS technologies are striving to gain traction in the set of options for dealing with climate change, but growth is very slow due to absence or low intervention of government action on climate change, public scepticism, increasing costs, and advances in other options including renewables and shale gas [60]. A comprehensive evaluation of various technologies or methods is necessary for reducing or avoiding CO_2 emission to the environment. There is need for formulating and implementing overall policy that should be successful not only in reducing CO_2, but also in saving energy and generating jobs in the economy of the twenty-first century [49].

The R&D activities are underway to conquer the technological hurdles to the effective implementation of CCS; however, the legislative framework is required for proper implementation of technologies and monitoring of the substantial role in the mitigation of carbon emission. The CCS regulations should be liable for the regulatory treatment of CO_2 and other gases in the CO_2 stream, monitoring, verification and remedial strategies to ensure whether the CCS can effectively mitigate carbon emissions and provide avenue to future hydrocarbon supplies.

Moreover, the coordination between central and state governments about their roles in deployment of CCS is required. The authority and responsibilities should be fixed for granting permission and monitoring the various processes. The proper regulation policies certainly will help to attract commercial players into the CCS market. The CCS will help in mitigation of extra CO_2 liberation associated with heavy oil, coal-to-liquids (CTL) and gas-to-liquids (GTL) technologies and, thereby, help render these resources more readily usable even under carbon constraint world.

Based on literature review, the authors have tried to summarise the energy receiving from different sources and there comparative merits and demerits. Comparison of CCS with other clean technologies for energy generation is shown in Table 5 (compiled by authors based on information sought from various sources referred in this paper). The renewable sources of power generation are carbon free and sustainable in nature, but their availability at all time and portability is one of the challenges. The limitation and energy supply gap between conventional sources and renewable sources of energy can be bridged by use of fossil fuels with CCS technology. Instead of using individual system or energy generation methodology, the hybrid system is suggested for wider acceptability and sustainable power generation. The renewable sources of energy should be used as major power generation sources and fossil fuels with CCS technology can be used as supplementary sources for peak power generation and standby mode.

10 Conclusions

Most of the energy requirements for industrial application and transportation activities are fulfilled from fossil fuels (e.g., diesel, gasoline, natural gas and coal), which is resulting into addition of CO_2 as greenhouse gas into the environment. By year 2030, the primary production of energy from coal will reach to 3976 Mtoe and discharge of CO_2 into environment about 38749 $MtCO_2$ per year. The compilation work is summarised as follow:

- The CO_2 capture techniques, such as membrane separation process can separate about 90% of CO_2, amine scrubbing can separate above 85% of CO_2 from flue gases emitted from fossil fuel based electrical generators, membrane, molecular sieve and desiccant adsorption technologies are in use.
- Geological and oceanic injection techniques are having good potential for CO_2 sequestration and worldwide capacity of about 2200 GtC, but its leakage and monitoring aspects are yet to be finalized.
- More than 50 projects on CCS are going on worldwide, but the uncertainty around global climate change negotiation may somehow affect large-scale demonstration projects on CCS.
- The sequestration of CO_2 was found to be a challenging problem and require the economic viability. Decrease in associated costs and practical solutions may be found as mix of technologies and the local circumstances where CCS is to be adopted.
- The research community should have coordination between the policy makers and the environmental community. The common public should be brought into confidence and be educated on the possibilities and limitations of the CCS approaches.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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