An overview of the methods and technologies for removal of carbon dioxide from the environment

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Abstract

According to The World Counts, about 2,400 gigatons of CO_2 were emitted by human activities between 1850 and 2019 and most climate models indicate that by 2050, there will be a need to extract billions of metric tons of CO_2 per year whilst pursuing emissions reductions. Carbon Capture and Storage (CCS) is considered as one of the most significant approaches that can reduce CO_2 emissions concentration from the atmosphere. Carbon sequestration can take many forms, ranging from emerging technologies to land management practices. This paper discusses the three main methods and the various technologies for removing CO_2 from the air and combustible gas streams. It clarifies the indistinctness in the use of technology and method in the CO_2 capture context. Also, this paper rectifies definitional uncertainty in the use of CO_2 capture and separation. Furthermore, the paper demonstrates the energy intensiveness, financial implications and reasons as to why the technologies are not commercially being deployed for CCS using the Technology Readiness Level (TRL).

Keywords: Carbon capture and storage, CO_2 removal technologies, CO_2 separation, technology costs, Technology Readiness Levels (TRLs).

1. Introduction

Greenhouse gases trap heat from the earth surface and prevent it from escaping into the atmosphere, thus making the air on the earth’s surface warmer over the years (Dahlman & Lindsey, 2020). Many independent researches confirmed this trend of energy trapped as the ocean heat content (OHC) which is in the corridor of 90-93% of the earth system since 1995. The OHC in the world for 0-700m layer of the ocean increases at the rate of 0.27 Wm^{-2} and 0.18K. Whereas OHC incremental rate for 0-2000 m layer is 0.39 Wm^{-2} with 0.09 °C (Cheng, et al., 2021). The increased emission of water vapour, melting of ice over land, and consequently rise in the sea level is informed by the OHC. This also leads to flooding (natural disaster)- a sure means of measuring climate change (Cheng, et al., 2021).

The modern economic developments and technological advancements are dependent on the energy sources obtained through burning fossil fuels. Fossil fuels are the contributors of nearly 67% of electricity produced; i.e. Coal (41%), oil (5%), natural gas (21%) (Broecks, et al., 2016). Through many international conventions such as the United Nation Framework Convention on Climate Change (UNFCCC) held over the years, many countries both developed and developing have realized the need for carbon abatement from the ambience. CCS gained popularity over the years, to effectively capture CO_2 from various point sources and store and seclude it such that it is isolated from causing adverse effects on the environment. Although CCS has attracted several types of research and investments in the prior years, energy requirement and cost constraints are an important factor that prevents its full-scale implementation. These technologies range from capturing carbon dioxide directly from the atmosphere, use of absorbent in the plant point source exhaust to remove CO_2 (K. Saravana, et al., 2018).

The trajectory of research on post-combustion CO_2 capture tends towards a full-scale development; however, the construction of CCS technologies is more complex in terms of economic, technical and social constraints. There is no real term implementation of any large-scale CCS plants to date (Cuccia, et al., 2018). In general, public acceptance and establishment of the legal framework to draw guidelines for a CCS plant are essential for significant success. Few countries that have regulations which guide the CCS deployment and geological storage have no enforcing power, while many nations do not have any law of such. Moreover, the indiscriminate use of some terminologies such as CCS methods, CCS technologies, CO_2 capture, and CO_2 separation has led to this study clarifying the vagueness in their use as detailed further in the paper. Furthermore, the advancements made and readiness of different CCS technologies are explained together with hindrances to commercial deployment of these technologies due to energy intensiveness and financial implications.

2. Clarification in the use of CO_2 methods and technologies

According to (Songolzadeh, et al., 2014), pre-combustion capture, oxyfuel process, and post-combustion capture are listed as the three methods for CCS. In the same paper, absorption, adsorption, cryogenic distillation, and membrane separation are defined as the technologies for CO_2 capture. Contrary to these, the methods that are used to separate CO_2 from other gases include membranes, electrochemical pumps, and chemical looping. Also listed as the methods for CO_2 capture include catalytic routes, electrochemical, enzymatic, membrane, photosynthesis, and chemical looping combustion for CO_2 separation or conversion. These are supposed to be classified as the CO_2 capture technologies. Cited dry regenerated sorbents, cryogenics, membrane, wet scrubbing technologies, pressure and temperature swing adsorption as the technologies. A table that compared more authors and how they use the word methods and technologies in their respective articles will be published in a subsequent article. The illustration given in this section shows that these two words; technologies and methods are sometimes used interchangeably. Whereas technologies usually supposed to be referred to as CO_2 or gas separation techniques while "methods" is pointing to the CO_2 capture systems as referred in IPCC report of 2005, see section 3.

3. Methods for capturing carbon dioxide

On the evaluation of several kinds of literature over the carbon capture and storage, three major classifications have been observed, namely: post-combustion, pre-combustion, and oxy-fuel combustion. These can sometimes be described as post-conversion, pre-conversion, and oxy-fuel combustion in choice of the type of capture method depends on the CO_2 concentration in the gas streams, fuel type (gas or solid) and the gas stream pressure (Jansen, et al., 2015; Kolster, et al., 2017; Cuéllar-Franca & Azapagic, 2015).

3.1. Post-combustion capture methods

A post-combustion method is the approach of CCS where the fuel and air undergo combustion processes leaving the product of combustion as a flue gas that contains CO_2, water, and heat. The most common separation technique in this class is through the use of chemical absorption. Here CO_2 separation from the streams of waste gasses takes place after the conversion of the carbon-source fuel (fossil). This post-combustion process can be used to remove CO_2 from numerous industrial activities that generate CO_2 gas such as fuels, production of ethylene oxide, power plants, cement, iron and steel (Shavalieva, et al., 2021).

3.2. Pre-combustion capture methods

Here, separation takes place before combustion. It is the reaction of fossil fuel with air and sometimes with steam to yield carbon monoxide and hydrogen (CO and H_2 mix) known as syngas also called fuel gas. The CO produced is made to react with shift converter which is a catalytic reactor to produce CO_2 and more hydrogen. Chemical absorption or cryogenic distillation process is then used to separate the CO_2 and consequently produce hydrogen-rich fuel that can be used in fuel cells, furnace and gas turbines. This method of CO_2 capture is complicated and costly due to higher concentration CO_2 in the gas stream and the higher pressure, which aid the separation process. Pre-combustion applies to the production of ammonia where synthesis gas (CO_2 and H combined) is produced in this process before ammonia itself. The syngas has to be removed using the absorption technology of Monoethanolamine (MEA). A pre-conversion method is also useful in an Integrated Gasification Combined

Cycle (IGCC) power generating plant where it is necessary to separate the CO_2 from hydrogen using Selexol, Rectisol and the likes as the physical solvent. The solvents used in this process are meant to be regenerated, thus attract energy penalty like the post-combustion method, though lower for the physical solvents by reducing the pressure instead of applying heat for regeneration. See (IEA, 2013) for more of pre-combustion methods.

3.2 Oxyfuel-combustion capture methods

The oxyfuel combustion is the method that removes nitrogen from the flue gas by combustion of hydrocarbon or carbonaceous fuel such as biomass in unadulterated oxygen or a mix of pure oxygen and CO_2-fortified recycled flue gas. The combustion temperature is restricted to approximately 1300- 1400°C in an ordinary gas turbine cycle and 1900°C in an oxy-fuel coal-fired boiler with the current technology. Combustion of fuel with pure oxygen has a combustion temperature of about 3500°C, which is far too high for typical power plant materials (Nemitallah, et al., 2019). The combustion temperature is controlled by the proportion of flue gas and gaseous or liquid-water recycled back to the combustion chamber (Metz, et al., 2005). This is perhaps similar to the post-combustion carbon capture, except the fact that a lot of impurities can be evaded as the oxygen is pure (21% of air is oxygen), therefore the resultant product would be a high purity CO_2 stream (M.Carpenter & A.Long, 2017).

4. Comparing the various technologies for CO_2 capture

The technologies (techniques use) for CO_2 capture adopt the basic following basic factors; fuel type (gas or solid), CO_2 concentration in the gas stream, and stream pressure.

4.1 Classification of post-combustion capture by their gas separation techniques

The three CO_2 capture methods discussed in section 3 required a unique or combination of gas separation technologies to obtain results. This section itemise some while some other technologies will be further compared in Section 6 using the TRLs model.

4.1.1 Absorption

CO_2 absorption means using a liquid solvent (e.g. amine) to absorb CO_2 from a gas. This same technique of CO_2 removal is popularly used by the direct air capture (DAC) technology where a fan blows the atmospheric air through the filters that are lined into the liquid absorbent. Caustic solution and amine-based solvent are currently in use. CO_2 reacts with sodium hydroxide to form a stable compound called sodium carbonate precipitate which is capable of regenerating a pure CO_2 when heated (American Physical Society, 2018).

4.1.2 Adsorption method

Adsorption is a physical procedure that comprises of the connexion of a gas or liquid to a solid surface. The adsorbent is regenerated by the supply of heat (temperature swing adsorption, TSA) or by reducing pressure (pressure swing adsorption, PSA). Adsorbents that can be used to capture CO_2 include activated carbon, alumina, metal oxide, and zeolite (Abdelhamid, 2020). It was also reflected that the contemporary adsorption systems are not appropriate to be used for a large-scale power generating plant because of the low adsorption power of the available adsorbents, and this may pose a serious problem. This implies that the flue gas streams intended for treatment must have high concentrations of CO_2 to match the low discrimination strength of the available absorbents, such as, Zeolites which otherwise have a great attraction for water vapour (Abdelhamid, 2020). Adsorption method includes the use of Adsorber Beds made of any of Alumina, Zeolite, and Activated Carbon; Regeneration Methods using either Pressure Swing, Temperature Swing, Washing; Membrane of different generations.

4.1.3 Cryogenics separation

In cryogenic separation, CO_2 is split using condensation. CO_2 condenses at -56.6°C and atmospheric pressure. This process is appropriate for treating flue gas with high CO_2 concentrations bearing in mind the costs of refrigeration. This can be used for CO_2 capture from the oxy-fuel process. Cryogenic distillation is a low-temperature air separation process that functions at different boiling temperatures (relative volatilities) of the feed components. Cryogenic distillation is a gas separation process using distillation at very low temperature and high pressure (Song, et al., 2017), that is related to other traditional distillation procedure only that it is used in this context for separation of gaseous components owing to their differences in their boiling points. Flue gas comprising of CO_2 is chilled to desublimation temperature of between −100 to –135 °C and the frozen CO_2 is separated from the other light gases and compressed to the high pressure of 100–200 atmospheric pressure. The amount of CO_2 recovered can reach 90–95% of the flue gas. Since the distillation is conducted at extremely low temperature and high pressure, it is an energy-intensive process estimated to be 600–660 kWh per ton of CO_2 recovered in liquid.

4.1.4 Bio-Sequestration: a natural adaptation to capture CO_2

The cheapest way to offset CO_2 emission is through planting trees. As trees absorb CO_2 available in the atmosphere freely for their various functionalities, augmenting Greenland in the world has the potential to reduce two-third of the CO_2 released in the ambience. Nevertheless, tree planting also has its failures too. Table 1 in the appendix presents the comparison of some of the CO_2 separation/sequestration technologies adopted to date.

5. Distinguish between CO_2 capture and separation in CCS

According to the IPCC special report of 2005, the word capture in the context of CCS is to contain or entrap the CO_2 present in the flue content such that it does not escape to the air. Carbon dioxide capture and storage (CCS) is a process involving the separation of CO_2 from industrial and power generation related emission sources or other industrial processes and convey it to a storage site for long-term isolation to avoid its escape to the environment. This article considers CCS to be an alternative in greenhouse gas mitigation actions. CO_2 separation is a phase in the Carbon Capture and Storage process (Songolzadeh, et al., 2014). There are many misuses of these keywords where they were used interchangeably, though maybe connected and interwoven, they do not completely connote the same thing. CO_2 are sometimes needed to be separated from the streams of large industrial plants among which are ammonia production and natural gas processing plant, and may not be necessarily captured for storage but only to meet process requirements. On the other hand, CO_2 removal is the elimination of the CO_2 that is present in a process. The removed CO_2 is either unrecoverable or captured for reuse.

6. Commercial viability of carbon capture technologies and readiness levels

The energy requirement and cost viability and readiness of innovative sustainable CCS technologies are the crucial aspects for development of stable societies with reasonable air quality and these are clarified further below:-

6.1. The energy and financial implication of the technologies

There is variation in the cost implication of CCS across the globe and this largely depends on some assumptions, which include principally the fuel cost, plant lifetime, interest rates. Other factors are the plant design and its operation, plant efficiency, fuel properties, power or energy requirement, plant size and load factor. Carbonate ion pumps separation technology requires a very high temperature of 600˚C, which is an indicator of high energy needed to raise the temperature high. See Table 2 in the appendix for energy and cost analysis of various CO_2 capture installations. The high energy required for CO_2 capture when using absorbent for continuous capturing cycle remains a major obstacle to the deployment of the technology at a commercial scale. Likewise, Molten Carbonate Fuel Cells, Advanced Supercritical Pulverized Coal plant, CO_2 permeable membranes, Integrated Gasification Combined Cycle (IGCC), High-pressure solvent absorption from high-pressure exhaust gas from pressurised combustion/power generation, Natural Gas Combined Cycle (NGCC), Supersonic flow-driven CO_2 deposition, Membrane separation, and High-pressure solvent absorption supported by exhaust gas compression discussed by (Vermaak, et al., 2021) still result to non-commercial implementation of these technologies.

6.2. Technology Readiness Levels Model for CCS technologies

Technology Readiness Levels are the technique for understanding the matureness of technology during its attainment stage. It allows the scientist, engineers and researcher to have dependable information for understanding technology progress, irrespective of their technical background. NASA invented it back in the 1970s for interplanetary exploration technologies (Mai, 2012). TRLs is a measurement parameter that is used to evaluate the maturity level of a specific technology. Each technology is assessed based on its development level criteria and then a TRL rating is determined based on the progress of the projects. There are nine levels of technological readiness; while TRL 1 which is the minimum, TRL 9 is the maximum (Mai, 2012; TWI, 2020) Technology entered TRL 1 when scientific research began at its conceptual stage and the results were translated into future research and development. TRL 2 occurs after the basic principles have been studied, and practical applications can be applied for initial discovery. TRL 2 technology is highly speculative, with little or no experimental proof of concept of TRL 2 technology. As the research and design actively begin, the technology is raised to TRL 3. This level requires both laboratory and analytical studies to be sure that the technology is viable and it can advance to the next development level. At TRL 3, a proof-of-concept model is usually built. The technology advances to TRL 4 once the proof-of-concept technology is prepared ready. Various component fragments are tried with one another at stage TRL 4. TRL 5 is an extension of TRL 4, a technology that progresses to level 5 is known as a breadboard technology, which has to go through severe testing. Simulations must be run in an environment that is close like a real-life scenario. The technology advances to TRL 6 once adequate testing is done to TRL 5 technology. A TRL 6 technology has a fully functional model or a realistic prototype. The next level is TRL 7 which requires that functional prototype be demonstrated and proved in a space environment. The technology is at TRL 8 when it has been tested, approved. It is ready to be applied to existing technology systems. The technology becomes TRL 9 when it is flight-proven at a successful task (Mai, 2012). For the application of the TRLs of the CCS technologies, see Table 3 which was adapted from (TWI, 2020; Baena-Moreno, et al., 2019).

6.3. The importance of Technology Readiness Levels to academia and industries

TRLs aid our understanding of how technology evolves from conception through to research, development and deployment. Universities and government funding sources focus on TRLs 1-4, whereas the private sector focuses on TRLs 7-9. TRLs 4 to 7 is usually termed as “Valley of Death” as it represents the developmental phase that often suffers neglect. Both the academia and the private sector bothers less to invest in this phase of development. Thus, many technologies that are promising end their maturity journey within this stage. Therefore, collaborative effort is required between the academic institutions and the industries (investors) to ensure that new and developing technologies are taking further to maturity stage.

Conclusions

This paper has established that there are only three Carbon Capture and Sequestration methods amongst which, the post-combustion method is a well-known, understood and developed to full-scale but only utilised in some commercial applications such as the power generating plants. Following the argument sustained in section 2 of this paper, the term CO_2 capture methods should not be used interchangeably with capture technologies, as often used by many authors. The research rectifies definitional uncertainty in the use of CO_2 capture and CO_2 separation, which is evident in the references (authors) shown in Table 1. It demonstrates the energy intensiveness and the reasons as to why not all has been fully deployed. The TRL model adapted from NASA technological development, shown in Table 3 clearly demonstrated the rapid innovations in the sequestration technologies and their respective levels of readiness. This is a reflection of the involving cost, energy intensity and process complexity (of initial fuel conversion) which prevent the technology from reaching TRL7. This paper argues for the adoption of CO_2 separation technologies classified under TRL9 and their likes as matured and operational in commercial-scale globally. Hence, there is need for advancement in the other technologies that can be utilised in other sectors for sustainable development that will limit the CO_2 concentration in the environment.

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Appendix

Table 1 Comparison of various separation technologies for CCS

Technology	Benefit	Shortcoming	Reference
Adsorption	▪ Adsorption efficiency is high up to 85%. ▪ The procedure is reversible for the regeneration of absorbent for recycling.	▪ Absorbent must be of high temperature. ▪ Need high energy for CO_2 desorption.	(Clausse, et al., 2011)
Cryogenic distillation	▪ Well established technology. ▪ Implemented in the industry for CO_2 recovery many years back.	▪ Possible for very high CO_2 concentration over 90% v/v only. ▪ Need a very low temperature for the process. ▪ Development is very energy demanding.	(Baena-Moreno, et al., 2019).
Chemical looping combustion	CO_2 is the main combustion product, which remains unmixed with N_2, thus avoiding energy-intensive air separation.	There is no operation on a large scale as the method is still in progress.	(Adánez, et al., 2012)
Absorption	▪ Up to 90% absorption efficiency is possible. ▪ Regeneration of sorbents is possible by reheating and/or depressurization. ▪ Most developed method for CO_2 separation.	▪ Absorption efficiency is a function of the CO_2 concentration. ▪ A substantial amount of heat is needed for absorbent regeneration. ▪ Sorbent degradation impacts the environment. ▪ The Currently available chemical solvents have low CO_2 loading capacity (implying tall expensive columns) and require significant heat energy, but technology development is improving this.	(Element Energy Ltd; Carbon Counts Ltd; PSE Ltd; Imperial College; University of Sheffield, 2014).
Hydrate-based separation	Minor energy penalty.	Innovative technology and more study and improvement are essential.	(Fan, et al., 2011)
Membrane separation	▪ This method is used for the separation of other gases. ▪ Up to 80% separation efficiency is attainable.	There are operating hitches like low fluxes and fouling. low pressure and the low concentration of CO_2 remain the main hurdles to the wide application of this technology as compared to cryogenic or adsorption technology	(Rackley, 2010)
Bio-Sequestration: Use of natural trees	▪ The cheapest way to offset CO_2 emission. ▪ Greenland in the world has the possibility of reducing two-third of the CO_2 that exist in the environment.	CO_2 released by the decay of tree fall and wood product. This can be utilised for landfill biomass fuel if properly managed with lesser or no cost.	(Bastin, et al., 2019).

Table 2 Energy and cost analysis of various CO2 capture installations

Method adapted	Vol. Of Energy used(kJkg/CO$_2$)	Conditions assumed	Associated cost (£)	Liquid Used & it's features	Achieved CO$_2$ captured kg CO$_2$/day	Limitation	References
Pre combustion through physical absorption using methanol Post-combustion capture using amines Oxy combustion CO$_2$ capture	168 for C CO$_2$ separation (14% CO$_2$ & 86%N$_2$), 358 for transport and storage, 1060 as parasitic energy i.e., 702 for the separation of	Temp- 15°C, Pressure - 1.013 bars relative humidity - 60%	**For coal:** 60 EUR/tonne + 14 EUR/tonne transportation **For natural gas:** a price of 6.29 EUR/GJ HHV + 1.19 EUR/MWh for the Internal Tax on Consumption of Natural Gas + 0.43 Euro/MWh for transport	physical absorption process using methanol post-combustion chemical adsorption using amines	Greater than 85% of CO$_2$ per kWh is captured	The study focuses on problems faced in fossil fuel power stations that are coal-fired. Thus, the experiments and the assumptions undertaken were specific and a more generic approach is required to industrially implement CO$_2$ capture technology. The variation of economic values (costs) with the varying loads for different processes is not evaluated with specificity.	(Kanniche, et al., 2010)
Post-combustion CO$_2$ capture with liquid adsorption (amine scrubbing, ammonia-based adsorption) and solid adsorption techniques, Oxy combustion CO$_2$ capture using chemical looping	17 % lower	Suboptimal operating conditions with high pressure	Carbon capture technique's transportation cost + installation cost + miscellaneous services cost > 30 to 40 % of coal consumption a coal-fired power plant	MEA Cheap, high absorption capacity, toxic, corrosive at high temp., CO$_2$ regeneration is energy-intensive. Other liquids compared: 1)Ammonia 17% lower in primary energy use than MEA, 2) Ionic liquid,	45% of the carbon dioxide emitted from various sources is assumed to remain in the ambience forever.	For ammonia, the formation of solid particles lowers the concentration to sub-optimal operating conditions. The environmental impact is worse than that of MEA.	(Smit, 2016)
Adsorption in ionic liquids - K$_2$CO$_3$aqueous solution Ionic liquid/ MOF composites – zeolites – have high adsorption selectivity Pre-synthetic modification – amines, amine functional moieties	Energy consumption is assumed to augment by 56% between 2010 and 2040.	Varies with an assumption on a different technique.	The performance of metal-organic-organic frameworks are yet to be evaluated	Review on adsorption technique and various methods of metal-organic frameworks Post synthetic materialisation of MOF, MOF as composites	Not specified	1.The high the energy required for solvent regeneration; 2. The stability of the amine system at the regeneration conditions; 3.The negative influence of impurities present in the flue gas that might significantly affect the stability and performance of the solvent	(Mohamedali, et al., 2016)

Table 3 CCS Technologies Represented in TRLs Model

Levels	Research Level			Development Level			Deployment Level		
TRL	1	2	3	4	5	6	7	8	9
Description	Basic Concept observation	Formulation of observed Concept	Lab testing to proof Concept	Validation of technology via Lab Prototype	Technology validated in a relevant environment	Technology demonstrated in a relevant environment (Pilot Plant)	Demonstration of System Prototype in an operational environment	Commercially refine & qualified the System	Commercialisation of the Technology
Illustration & Detail Explanation	Technical observations made and reported. E.g. paper-based studies of a technology's rudimentary properties	Proposed applications are theoretical at this stage. They are usually restricted investigative studies	Active research and development began. This includes investigations and laboratory measurements to authenticate analytical estimates	Technology validated by the designed investigation. This may include a breakdown of the technology parameter operational range.	Dependability of technology substantially increases. This include authentication of a semi-integrated model of technical and supportive essentials in a virtual setting	Prototype system tested. Instances may include a sample system being produced and established in a virtual environment	A key step rises in technological maturity, which may contain a prototype system being tested in a working environment.	A prototype formed and qualified vis data produced from TRL 7 to build a definite prototype, which is then qualified in a working environment. This TRL is the end of development.	A model established and equipped for full commercial deployment. An example includes the actual system/model being successfully deployed for multiple missions by end-users.
	Supersonic flow-driven CO_2 deposition, High-pressure solvent absorption supported	Ocean storage, Advanced Supercritical Pulverized Coal plant,	Post-combustion Ionic liquids	Oxy-combustion gas turbine (water cycle)	Membranes dense inorganic (H₂ Separation for reformer), Molten Carbonate Fuel Cells, CO_2 permeable membranes, Integrated Gasification Combined Cycle (IGCC), High-pressure solvent absorption from high-pressure exhaust gas from pressurised combustion/power generation, Natural Gas Combined Cycle (NGCC). EOR- Enhanced Oil Recovery; CO_2-EGR- Enhanced Gas Recovery with CO_2	Membranes Polymeric (Power Plant)	Membranes Polymeric (NG Industry)	Physical solvents, Chemical solvents	Post-combustion amines (power plants)
2			BECCS Power	Advanced amines		Post-combustion biphasic solvents	Pre-combustion IGCC+CCS		Pre-combustion NG Processing
3			Pre-combustion Low Temp Separation	Advanced mixtures		Chemical Looping Combustion	Oxy-combustion Coal power plant		Transport on-shore & off-shore pipelines
4			Membranes dense inorganic (CO_2 separation)	Potassium carbonate		Calcium Carbonate Looping	Post-combustion Adsorption		Transport Ships
5			Mineral Storage	Biomimetic-based		CO_2 Utilisation (non-EOR)	BEECCS Industry		Saline formations
6			Crystalline materials	Integrated with absorption			Direct Air Capture		CO_2- EOR
7			Supported amines	Polymeric			Depleted Oil & Gas Fields		
8			Carbon-based	Amine-doped			CO_2-EGR		
9			Sodium carbonate, Oxy-fuel combustion			Pre-combustion		Post-combustion	Industrial separation (natural gas processing, ammonia production)