Economics and Need of Carbon Capturing

Abstract

The sharp rise in the carbon di-oxide emission from just 5 billion tons per year in the mid of 20th century to touching new high record of 36.8 billion tons per year in 2022 is posing threats and resulting in severe climate change impacts like extreme droughts, heatwaves and rainfall across the globe. Although, the rate of increase in carbon dioxide emissions in 2022 over 2021 was slow mainly due to the growth of solar, wind, EVs, heat pumps and energy efficiency but it is likely to miss the target of the Paris agreement which has set the goal for limiting the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels to avoid global warming. The risks could have been reduced by accelerating the pace of implementing the carbon capturing projects as energy transition through renewable energy sources have its own limitations. However, this area needs special attention as majority of the carbon capturing technologies available today are techno-economically not attractive besides requiring large energy , which in turn provide lesser benefits on life cycle analysis (LCA) basis. Thus, the emissions still remain on an unsustainable growth trajectory and calls for urgent actions to either reduce dependency on fossil fuel, which is very unlikely or promote development & adoption of new technologies for carbon capture and utilization / storage of the same to avert climate change.

Introduction

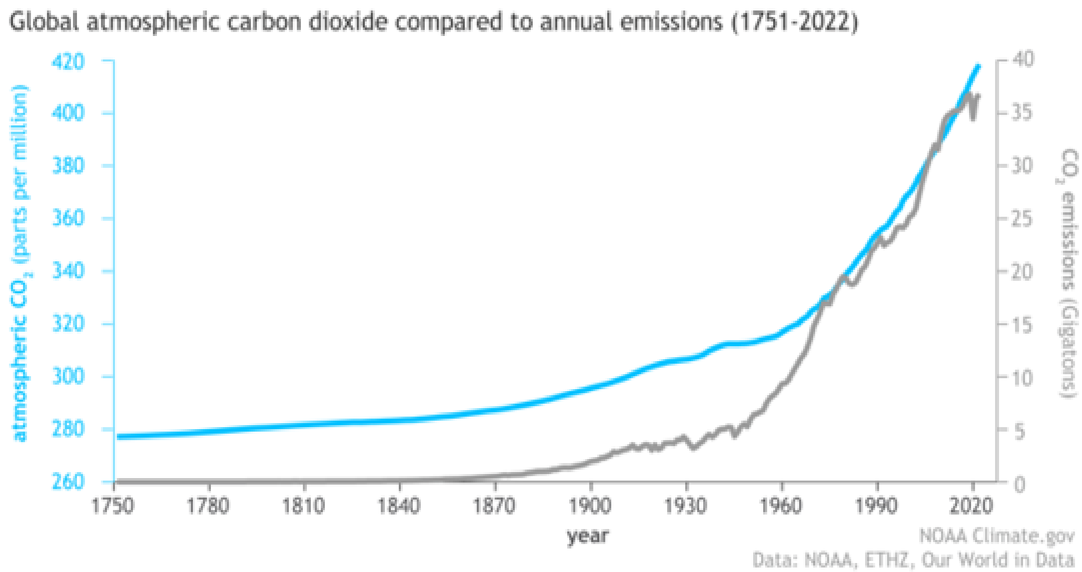
The increased urbanization and industrial revolution post 19th century has led to an increase in the anthropogenic greenhouse gas emissions of which CO_2 is the most important anthropogenic GHG and responsible for about two-thirds of the enhanced greenhouse effect . This has resulted in continuous increase in the level of CO_2 in the atmosphere, which is considered as the main cause of climate change. The impact is being seen in the form of extreme droughts, heatwaves and rainfall causing floods across the globe. To avert climate change, it is necessary to take action to reduce the concentration of carbon dioxide. This can be done either by emitting less carbon dioxide i.e. reduction in consumption of fossil fuel or removing the CO_2 emissions from the system or directly from the atmosphere. The capturing of carbon di-oxide in some of the industries like fertilizer for making urea is very common and being used for so many years but implementation of these technologies in other areas like power generation, steel making , transport etc . , which are the main sources of emissions, is still lacking due to techno-economic reasons. Many methods have been developed over the last 20 years and more possibilities are being explored to recapture the carbon dioxide produced and make it usable.

Global efforts are being made to develop cost effective technologies for capturing Carbon Di-Oxide but the high cost of capturing ranging from USD 40 to USD 100 per ton and its effective utilization to reduce the atmospheric CO_2 has not resulted much desired results. Based on the annual report from NOAA's Global Monitoring Lab, global average atmospheric carbon dioxide was 417.06 parts per million in 2022, setting a new record high. The increase between 2021 and 2022 was 2.13 ppm[1]. As the cost of capturing increases with the reduction in carbon concentration, all efforts are being directed to capture CO_2 at source instead of capturing it from the atmosphere and utilizing the same for value added products. Carbon Capture and Utilisation (CCU) is a broad term that covers processes that capture CO_2 from flue and process gases or directly from the air and convert it into a variety of products such as renewable electricity-based fuels, chemicals, and materials.

CO_2 Emission Trends

The main reason of increase of CO_2 in the atmosphere is the increase in human activities due to rise of population globally. This has resulted in large utilization of fossil fuels like coal, natural gas, oil and cutting down forests for industrialization and to meet essential needs of the society. Today, China is the world's largest contributor to CO_2 emissions — 28% with 9.9 billion metric tons followed by the United States (15% with 4.7 billion metric tons), India (7% with 2.3 billion metric tons), Russia (5% with 1.6 billion metric tons) and Japan (3% with 1.1 billion metric tons).[2]

In the 1960s, the global growth rate of atmospheric carbon dioxide was roughly 0.8± 0.1 ppm per year. Over the next half century, the annual growth rate tripled, reaching 2.4 ppm per year during the 2010s. The annual rate of increase in atmospheric carbon dioxide over the past 60 years is about 100 times faster than previous natural increases, mainly due to human activities, as can be seen from the graph shown below.[3]



The elevated level of CO_2 is now causing climate change as it traps heat, amplifying Earth's natural greenhouse effect. In line with UNFC framework for climate change, there is a need

[1] **NOAA Climate.gov National Oceanic and Atmospheric Administration ,USA**

[2] **https://www.soletairpower.fi/is-indoor-carbon-dioxide-really-harmful-to-humans/**

[3] NoAA Climate .Gov- Global Carbon Project

to remove a billion tonnes of CO_2 from the atmosphere by 2025, and more than one billion tonnes annually thereafter. It is estimated that the carbon dioxide emitted each year in the 2011-2020 decade was almost twice the natural “sinks”—processes that remove carbon from the atmosphere—on land and in the ocean absorbed . Because of this imbalance between the carbon dioxide put in into the atmosphere than natural sinks can remove, the total amount of carbon dioxide in the atmosphere is increasing every year. Although, large numbers of countries have agreed to act jointly and work in close association to limit global warming to 1.5 degrees Celsius, but even with pledges of big reductions in emissions, many scientists believe disruptive carbon dioxide removal technologies will be needed to meet the goal of averting climate change as existing technologies not only costly but majority of them cannot ensure carbon negative on LCA basis mainly due to limited options available for carbon utilization .

Carbon Capturing Technologies

Carbon capturing technology can be broadly classified into two categories viz. “direct air capture,” i.e capturing carbon from the atmospheric air and other from source i.e stack / chimney / process like steel making. The concentration of CO_2 in atmospheric air is quite low and in ppm level and thus capturing becomes highly expensive. However, industrial gases/ flue gases, mainly from coal based power plants, responsible for large CO_2 emission, are having large concentration varying from 8-9% to as high as 20-30% and thus the cost of capturing can be optimized. Despite, large concerns and efforts made for developing different carbon capturing technologies, only very few industrial operations are there for carbon capturing across the globe. International Energy Agency (IEA) observed that the main reason is lack of downstream application of the captured carbon dioxide. Carbon capture, utilisation and storage (CCUS) technologies are critical for putting energy systems around the world on a sustainable path. Despite the importance of CCUS for achieving clean energy transitions, deployment has been slow to take off. But momentum is building[4] and carbon removal is

Depending upon the source and stage of capturing, carbon capturing technologies can be classified into three types viz. pre-combustion carbon capture, post-combustion carbon capture, and the oxy-combustion carbon capture method.

- **Pre-combustion carbon capture**: In pre-combustion, carbon dioxide is separated before the combustion process. In this process, carbonaceous fuel is heated to 1000–1700 °C with oxygen and hydrogen and the process is known as Gasification. In the gasifier reactor, the gas produced is called as producer gas and mainly consist of CO, H_2, CO_2, CH_4 and traces of others. The gas is cleaned to remove mainly CO2 consists mainly of hydrogen and carbon monoxide (called Syn Gas) and used for chemicals, fertilizer, Iron making or generating power. The simplified flow diagram is shown in figure-1 below:[5]

[4] IEA: Is carbon capture too expensive?

[5] Review: CO2 capturing methods of the last two decades, International Journal of Environmental Science and Technology (2023) 20:8087–8104 , https://doi.org/10.1007/s13762-022-04680-0

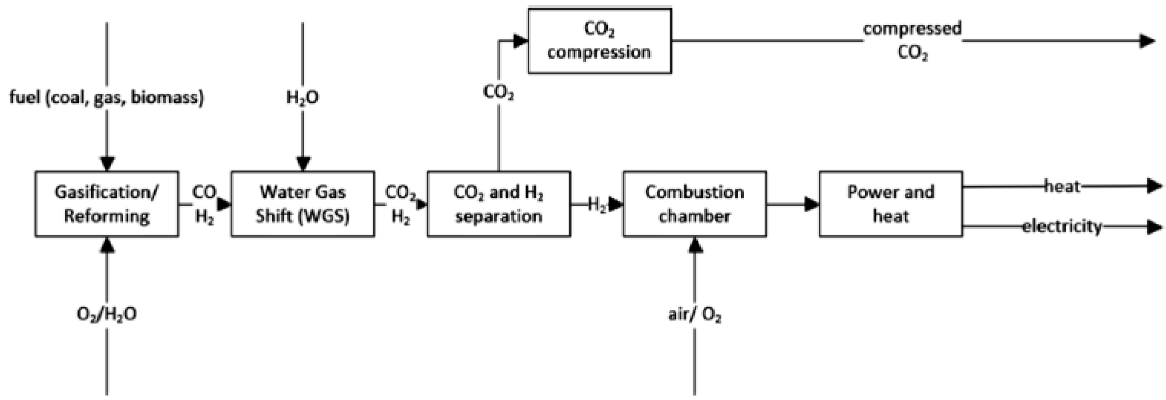


Figure-1: Block diagram of electricity generation and heat production with the use of the pre-combustion CO_2 capture method

- **Post-combustion carbon capture**: In this process capture occurs after the combustion process (capturing CO_2 from flue gas, e.g., capturing CO_2 from flue gases of power plant, Steel making furnaces etc). The capture unit is placed after the purification systems, such as desulphurization, denitrogenation, and dedusting installations. Figure 2 shows a general block diagram of the post-combustion capture technique.

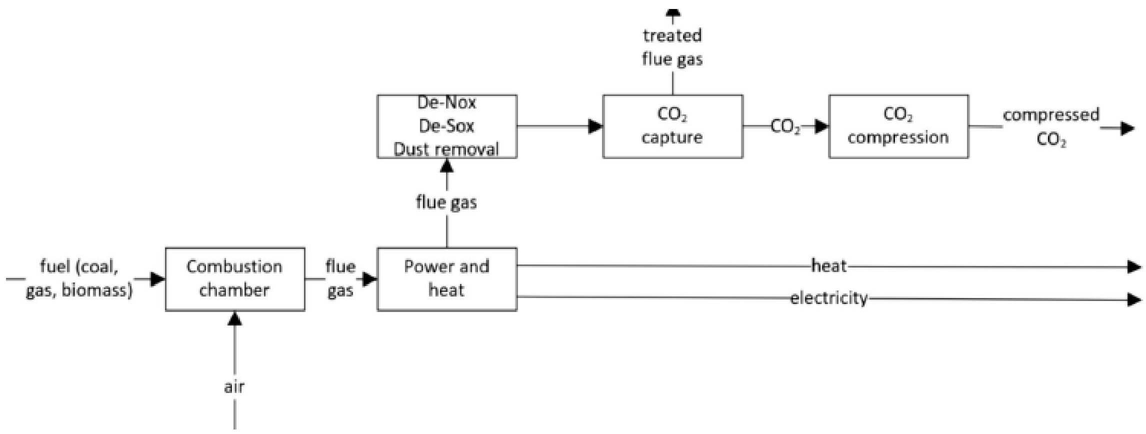


Figure 2: Block diagram of electricity generation and heat production through the use of the post-combustion CO_2 capture method.

In this process, after the overall process in the power plant, another cleaning step is added afterwards. In most cases, cleaning is carried out wet-chemically by means of gas scrubbing with solvents. The carbon dioxide from the exhaust gas is bound to the scrubbing agent. By heating the scrubbing liquid, the carbon dioxide can be released again. Thus, a regeneration of the scrubbing agent takes place. Another process would be dry adsorption, in which the CO2 is attached to solids. Membrane technologies can also be used for post-combustion. In this process, the gas mixture is separated by a membrane

- **Oxy-combustion carbon** capture occurs after the combustion process in an oxygen atmosphere by separating CO2 generated during the oxy-combustion process, e.g., using an oxygen gas turbine. Oxygen atmosphere can be obtained by removing nitrogen from the air before the combustion process. Figure 3 shows a flow diagram of a power and heat generation process using the oxy-combustion method. In a coal-fired power plant, the coal is not burned in the air but with pure oxygen. The exhaust gas consists mainly of CO_2 and water vapour. When the water vapour is cooled, it condenses and can be separated. Through further cleaning steps, the remaining waste gas can be freed from accompanying substances such as SO_2. The advantages of the oxy-combustion process are that the carbon dioxide is thus completely retained. The disadvantage, however, is that the extraction of pure oxygen from the air is very energy intensive.

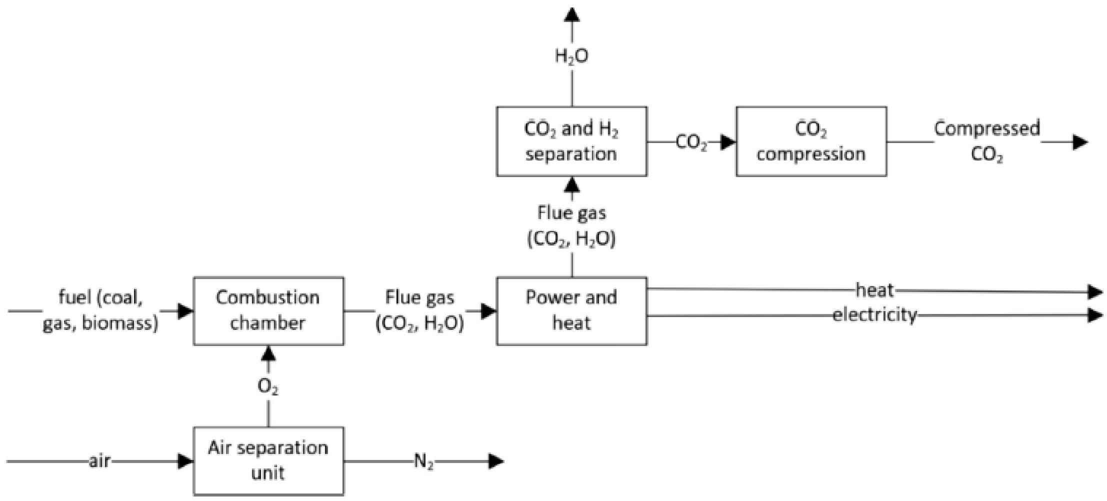


Figure 3. Block diagram of electricity generation heat production with the oxy-combustion CO_2 capture method

The strengths of oxy-combustion are nitrogen oxide (NO_x) reduction, boiler dimension reductions, a simplified CO_2 capture method compared to other technologies, the possibility of applying in existing technologies, and less mass flow rate of exhaust gases (about 75% less compared to combustion in air). The weaknesses of oxy-combustion are the high material requirements because of the high temperatures, an efficiency decrease (oxygen production process is energy-consuming), and a high capital cost.

Different technologies developed under these three categories and their present status are shown in shown in figure 4 below, and it is expected that ongoing research in each areas shall make these technologies more cost effective and energy efficient in future[6]. These technologies can be subdivided into absorption process, processes with gas–solid reactions, adsorption processes, cryogenic processes, membrane processes and natural inclusion processes.

[6] US Department of Energy, National Energy Technology Laboratory (NETL)

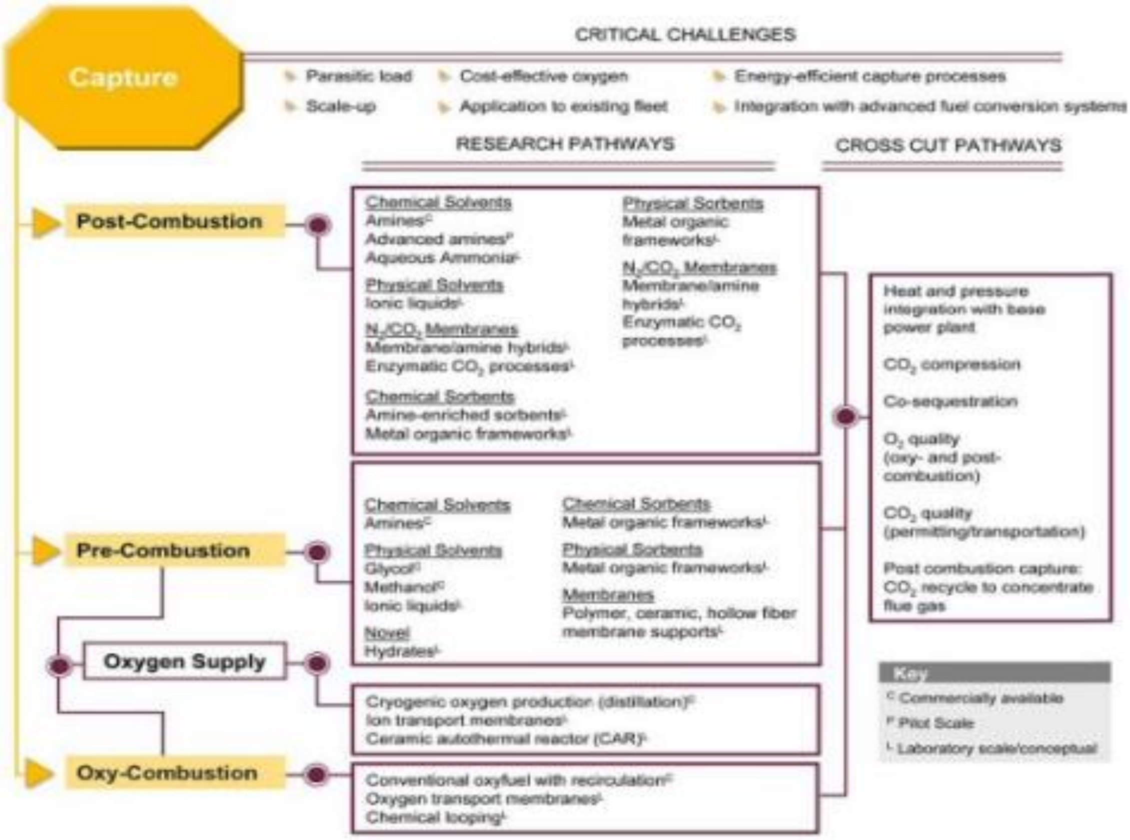


Figure-4: Present status of Carbon Capturing Technologies

There are different categories and types of commercial-scale carbon capture technologies and their suitability or appropriateness for different applications/sectors depends on the typical CO_2 gas stream composition:[7]

1. **Solvent-based CO_2 capture technologies:**

The solvent-based CO_2 capture technologies are distinguished based on whether CO_2 reacts with the Solvent chemically (chemical absorption) or dissolved physically (physical absorption). The Chemical solvent technologies are preferred when dealing with gas streams that are lean in CO_2 and have relatively lower pressures, such as flue gas streams from power plants, Blast Furnace (BF) gases in steel plants, gas streams in refineries or chemicals plants. Physical solvent technologies work well on gas streams with relatively higher CO_2 concentration and pressure, such as pre-combustion capture in the case of gasification projects

The fundamental principle on which solvent-based CO_2 capture technologies work is 'selective absorption' of CO_2 over the other gaseous constituents. The cost and availability of steam is also a key factor as regenerating the solvent requires large quantities of steam. A simplified diagram of such system is shown below in Figure-5.

[7] **Carbon Capture Utilization and Storage (CCUS) –** Policy Framework and Deployment Mechanism in India, NITI Aayog

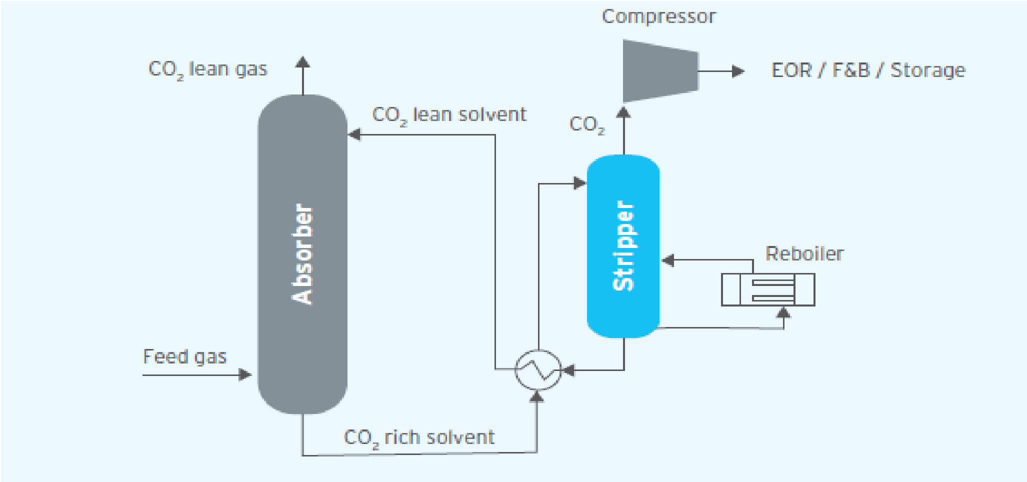


Figure-5: Chemical Solvent based CO2 Capturing System

While the CO_2 present in the feed/process gas is first selectively absorbed in an absorber using a solvent (physical or chemical), the CO_2 lean gas exits the absorber. Next, the CO_2 rich solvent is sent to a stripper-type configuration where the CO_2 is released from the solvent and the lean solvent is regenerated for reuse. The CO_2 rich stream needs to be purified, dehydrated, and compressed to raise the pressure to the required level.

The purity of captured carbon dioxide in such system is high and close to 98% and the same can be utilized in Food and Beverages, manufacturing chemicals like methanol & ethanol, in hydrocarbon sector for increasing the oil production from well having low pressure and not economical to extract oil, called "Enhanced Oil Recovery" or just simply storing it underground i.e. sequestration. New technologies are being developed where it is proposed to convert CO_2 into carbon mono oxide o in a gas mixture of carbon mono oxide and hydrogen (called syn gas) with the use of electrolysis. It is expected that in time to come, these technologies may gain momentum and system of carbon recycling may be evolved which will minimize consumption of fresh fossil fuel and thus mitigation carbon emission.

The chemical reaction between CO_2 and the chemical solvent is an exothermic reaction and hence favoured at lower temperatures. Hence it is necessary to pre-cool the feed gas. On the other hand, the stripper requires heat (100-140°C) to regenerate the solvent by breaking the chemical bonds between CO_2 and the chemical solvent. The heat required for the regeneration of the solvent is provided by a reboiler, supplied with steam. Such a heat and strip operation for the regeneration of the solvent leads to a high thermal energy consumption making process expensive.

A multitude of chemical solvents have shown varying degrees of success, including amine-based (primary/ secondary/tertiary/hindered), non-aqueous solvent (NAS), carbonate-based and phase change. While primary and secondary amines (such as MEA, DGA, AEE, DEA) have higher reaction rates and lower CO_2 carrying capacities, tertiary, and polyamines (such as Methyl Di-Ethanolamine (MDEA) and piper zine) have lower reaction kinetics and higher CO_2 carrying capacities. Due to competing characteristics, often blends of varying solvent compositions are used to exploit high reaction rates and CO_2 carrying capacity along with lower regeneration loads.

In Physical absorption system, there is no chemical reaction involved in the capture process as it is guided purely by physisorption. Since no chemical bonds need to be broken for solvent regeneration, the thermal energy requirement is much lower. The regeneration of the physical solvent is achieved by reducing pressure. However, the operating temperatures of physical solvent-based capture processes are much lower (ranging from -70°C to +20°C) compared to chemisorption-based capture, thus necessitating higher power consumption.

Such system are very common in Coal Gasification process where coal is used to produce Syn Gas i.e a mixture of carbon mono oxide and hydrogen or simply hydrogen using water gas shift reaction in which carbon mono oxide reacts with steam and produce CO_2 and hydrogen (also known as CO shift reaction) . Physical solvent process is used for separating hydrogen and Carbon monoxide as shown in the simplified flow diagram figure-6(figure is of one of such process known as Rectisol process):

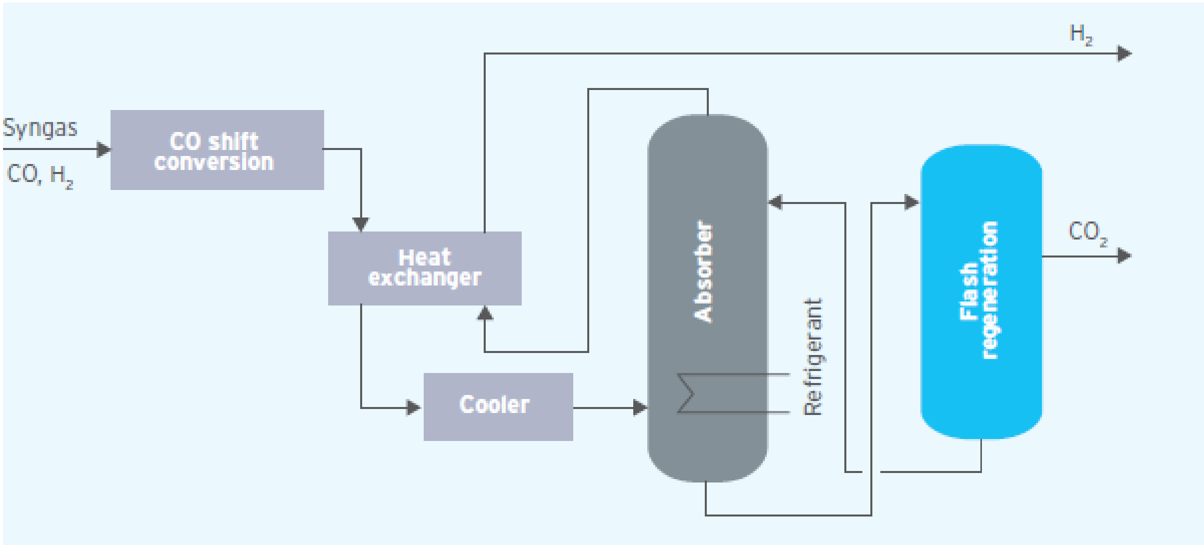


Figure-6: Physical Solvent Absorption Process (Rectisol)

2. **Adsorption-based CO_2 capture:**

These technologies are suitable for gas streams with moderate to high pressure and moderate CO_2 concentration such as Steam Methane Reforming (SMR) flue gas or Blast Furnace (BF) gas. In the adsorption-based CO_2 capture process, the CO_2 molecules selectively adhere to the surface of the adsorbent material and form a film.

3. **Cryogenic CO_2 capture:**

These technologies are preferred in cases where the cost of power is low. Cryogenic separation for CO_2 capture is similar to the conventional distillation process, except that it involves the separation of components from a gaseous mixture (instead of liquid) based on the difference in their boiling points. The feed gas stream is cooled to sub-zero temperatures (lower than -50°C) to separate CO_2 from the other components. Due to the extreme operating conditions of high pressure and low temperature, it is an energy intensive process. The energy consumption can range from 600-660 kWh/t CO_2 recovered in liquid form.

4. Microalgae Based Carbon Capture

The basic philosophy behind the process of carbon capture by microalgae is the use of CO2 as a nutrient for the cultivation of microalgae. The selected strains of microalgae can be cultivated in ponds or vertical/horizontal photo-bioreactors. The flue gas stream after removal of traces of heavy metals and other harmful components can be mixed in the ponds/photo-bioreactors, cultivating selected strains of microalgae. The CO_2 will be absorbed by the microalgae and the resulting gas will leave the cultivation system. Selection of appropriate strain of algae and maintaining its growth condition is critical to this process of carbon capture. The technology is in its nascent stages, with a majority of tests being performed at lab and pilot scales.

5. Membrane processes

Membrane processes separate atoms and molecules according to their size. The large particles cannot pass through the membrane and are retained. The separation characteristics of the membrane are determined by permeability and selectivity. Only the concentration gradient is the driving force of this separation. Therefore, these methods are energetically favourable because they do not require any additional energy. Membranes are often mentioned as possible methods in post-combustion separation. The low carbon dioxide concentration and the low pressure in the flue gas is a major problem in the use of membranes. A high selectivity of the membrane is necessary. The performance can be increased by modifications in chemical and thermal stability, material selection, thickness, durability, permeability and surface area.

Conclusion

Fossil fuel-fired power plants, Cement Plants and Iron and Steel sector generate a larger percentage of CO_2 emissions than any other industry. Therefore, applying carbon capture technology to these sector – whether on new or existing plants – has the potential for the greatest reduction of CO_2 emissions compared to other sectors. CO_2 capture technologies can be installed into all types of new coal and gas-based plants but unless it is clubbed with cost effective utilization technologies, wider application shall remain low.

The development of cost effective carbon capturing technologies are very important to mitigate carbon emission and avert climate change. As on date, Solvent based capturing technologies (chemical/physical) have been commercialized and are being used on a very small scale. The development of other technologies and end use of CO_2 can only accelerate the process so that carbon is recycled back in the system as a resource and is not treated as an evil.