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AVAILABLE TECHNOLOGICAL PROCEDURES FOR CAPTURING CO_2 IN THE INDUSTRIAL AND POWER GENERATION SECTORS

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Abstract: *Climate change is a major environmental issue caused by anthropogenic emissions of greenhouse gases. Capturing CO_2 and storing it in suitable geological formations is one of the main technological solutions that can provide mitigation of CO_2 emission into the atmosphere. Capturing CO_2 represents the first phase in process of carbon capture and storage, and includes the application of various technologies for the separation of CO_2 produced in the energy and industrial sectors. There are four main systems for capturing CO_2 that can prevent releasing CO_2 into the atmosphere, such as: capturing from industrial process stream, capturing after combustion, capturing before combustion and capturing CO_2 by oxy-fuel. In this paper is presented an overview of methods for CO_2 capture and different technological procedures for separation of CO_2 such as absorption, adsorption, cryogenic distillation, and membrane-based separation.*

Keywords: *capturing CO_2, power plants, CO_2 capture systems, CO_2 technologies*

1. INTRODUCTION

The concentration of greenhouse gases in the atmosphere is increasing rapidly. Carbon dioxide (CO_2) is the main greenhouse gas and it is primary driver of climate change. According to IEA, the global emission of CO_2 in 2020 amounted to 31.5 Gt, which is about 54% higher than in 1990 [1]. CO_2 is formed during combustion of fossil fuels mostly in industrial and power generation sectors. Carbon capture and storage (CCS) in geological formations represents very important strategy that can provide mitigation of CO_2 emission into the atmosphere. This solution includes capturing CO_2 produced in the industrial and power sectors, its compression and transportation through pipeline system and injection in different geological formations [2,3]. Capturing CO_2 is the most expensive phase in the carbon capture and storage process and it accounts for approximately 75 % of overall costs in the CCS system [4].

There are a large number of CCS projects worldwide in varius stages of development. According to the Global CCS Institute, in 2020 there were 65 commercial CCS facilities. Currently, there are 26 large-scale CCS facilities in operation, with capture capacity of 40 Mt of CO_2 per year [5]. In spite of the growing number of CCS facilities, CCS application is still small because of the high capital and operating costs for capturing CO_2 [3].

There are four main approaches for capturing CO_2 that can prevent releasing CO_2 into the atmosphere such as: capturing CO_2 from industrial process stream, capturing before combustion, capturing after combustion and oxy-fuel combustion. In addition, in this paper is presented an overview of current technological procedures for separation of CO_2 that includes adsorption, absorption, membrane-based separation and cryogenic distillation, with en emphasis on technical challenges along with advantages and disadvantages.

2. CO_2 CAPTURE SYSTEMS

There are four main systems for capturing CO_2 that can prevent releasing CO_2 into the atmosphere, such as: capturing from industrial process stream, capturing after combustion, capturing before combustion and capturing CO_2 by oxy-fuel (Figure 1).

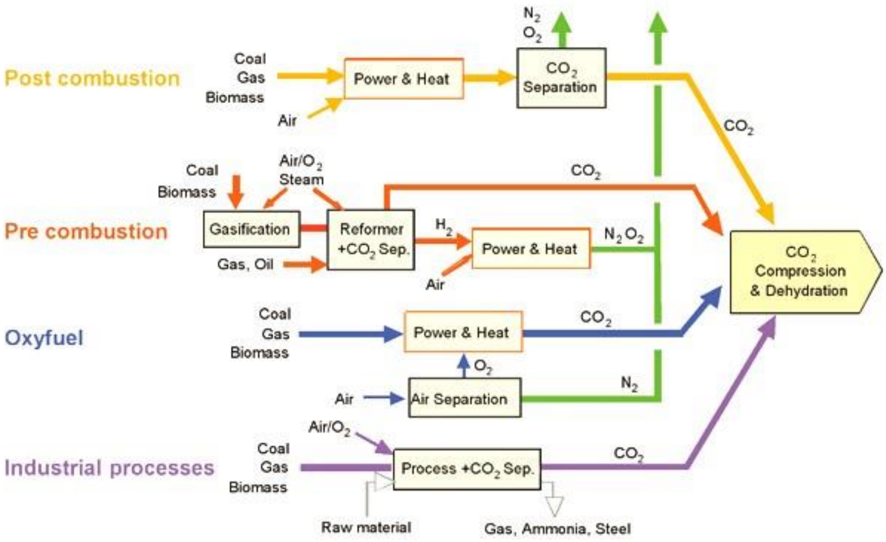

Figure 1. *Simplified illustration of the main carbon capture processes [6]*

2.1. Capturing from industrial process stream

Industrial processes are significant emmiters of CO_2, comprising about 23% of global emissions [7]. CO_2 has been captured for decades from industrial process streams that involve natural gas processing, waste incineration, fertiliser, hydrogen, ethanol, chemicals, iron, steel and cement production. There are many opportunities to reduce CO_2 emissions in industry sector such as using the natural gas instead of coal, increasing the energy efficiency, and CO_2 separation after production using CCS which is one of the leading solutions [5].

At the present time, there are 26 large scale CCS facilities in operation worlwide (Figure 2), where 12 of them include capturing CO_2 from natural gas. There are also 21 facilities under construction and in advanced development [5].

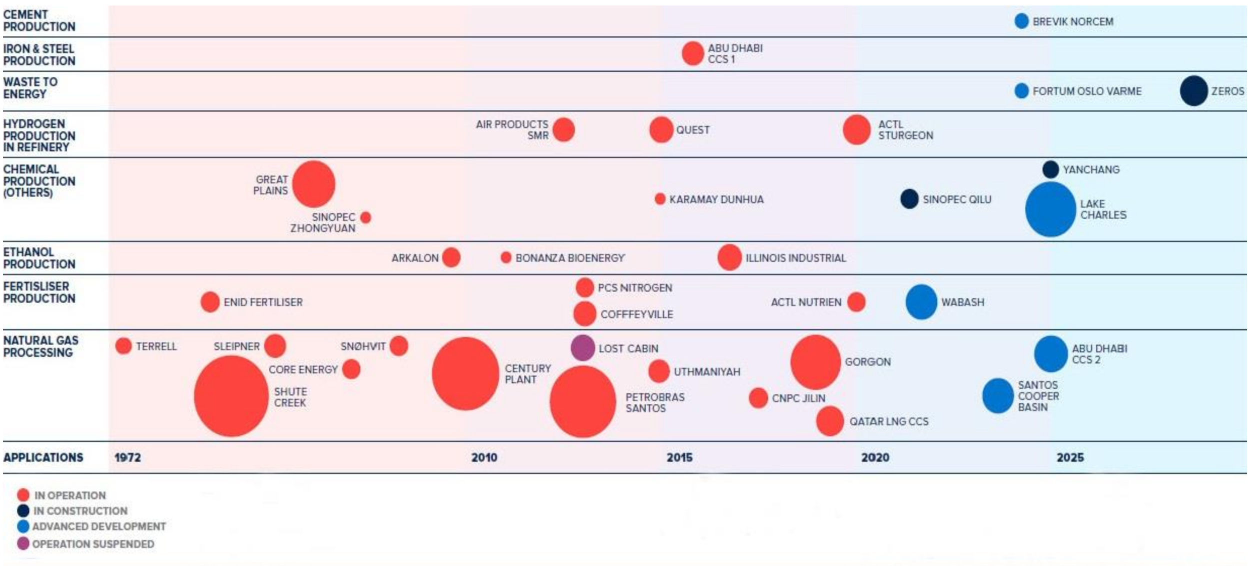

Figure 2. *CCS facilities in industrial sector in different stages of development [5]*

2.2. Capturing after combustion

In post-combustion systems, CO_2 is captured from the flue gases produced by combustion of fossil fuels and biomass in air, before they are released into the atmosphere. The fossil fuel fired power plants burn a fossil fuel, such as coal or natural gas, to generate heat energy, and provide most of the world's electricity today. There are various commercially available technological procedures that could be employed with post-combustion capture, but the preferred and the most advanced post-combustion option is chemical absorption with amine solvents [6,8].

Post-combustion CO_2 capture is advantageous because it can be integrated into existing power plants, where some components could be upgraded without altering the combustion cycle [9-11]. The main disadvantage of the post-combustion is low concentration of CO_2 (5-15%) that affects the capture efficiency [4, 12].

A simplified illustration of post combustion CO_2 capture is shown in Figure 3.

There are only two post-combustion projects in operation it the world. The world's largest post-combustion capture CO_2 facility is Petra Nova, installed at coal powered plant in Texas, which is paused in March 2020 due to the unfavorable economic situation [5]. There are also several facilities for carbon capture under construction.

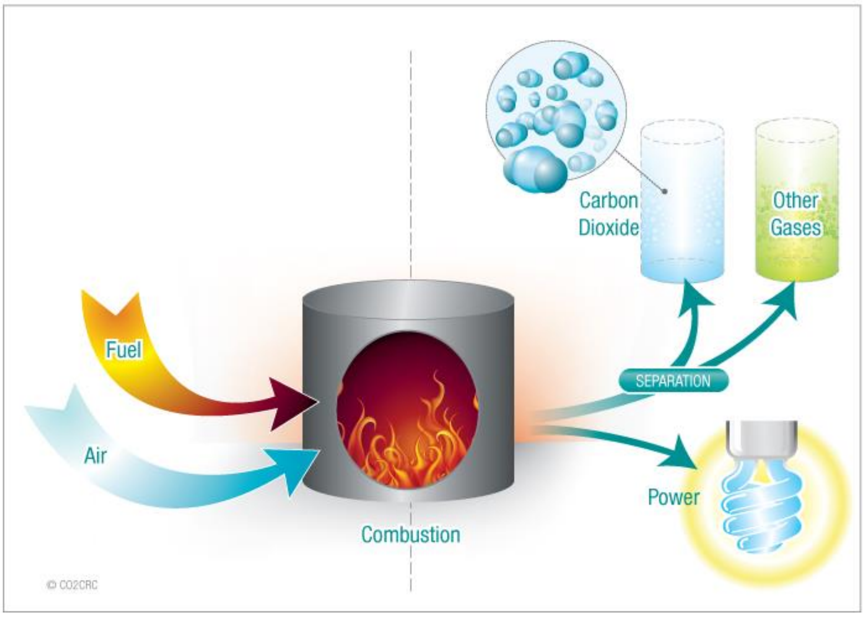

Figure 3. *Illustration of post-combustion CO_2 capture [13]*

2.3. CO_2 capturing before combustion

In pre-combustion systems, CO_2 is captured from the fossil fuels before combustion is completed. In this process, fuel is gasified to produce a gas mainly composed of carbon monoxide (CO) and hydrogen (H_2), which is known as a synthesis gas or syngas. The produced syngas is mixed with steam in a catalytic reactor, which promote reaction between CO and water, producing hydrogen and CO_2-rich gas mixture and increase mole concentration up to 40 and 55 %, respectively [14].The CO_2 is then separated from hydrogen, usually by using liquid solvents or solid adsorbents while hydrogen rich fuel is combusted to produce energy [15]. The emission of CO_2 by this technology can be reduced up to about 90-95 % [8].

Pre-combustion systems are more suitable for application in the new-build plants than in existing ones, because of the fuel conversion complexity [16-17]. This technology has found application in oil refineries but it has limited use in power plants. For power generation, pre-combustion system can be combined with an integrated gasification combined cycle power plant (IGCC) [8].

Compared to post-combustion system, the gasification process is operated at the high pressure and synthesis gas contains higher concentration of CO_2 (15-60%) [18], that makes separation easier before the H_2 is combusted [12]. Because of more concentrated CO_2, pre-combustion capture is more efficient than post-combustion, and for the same amount of captured CO_2, a much smaller volume of gas needs to be treated [12,16].

An illustration of pre-combustion CO_2 capture is shown in Figure 4.

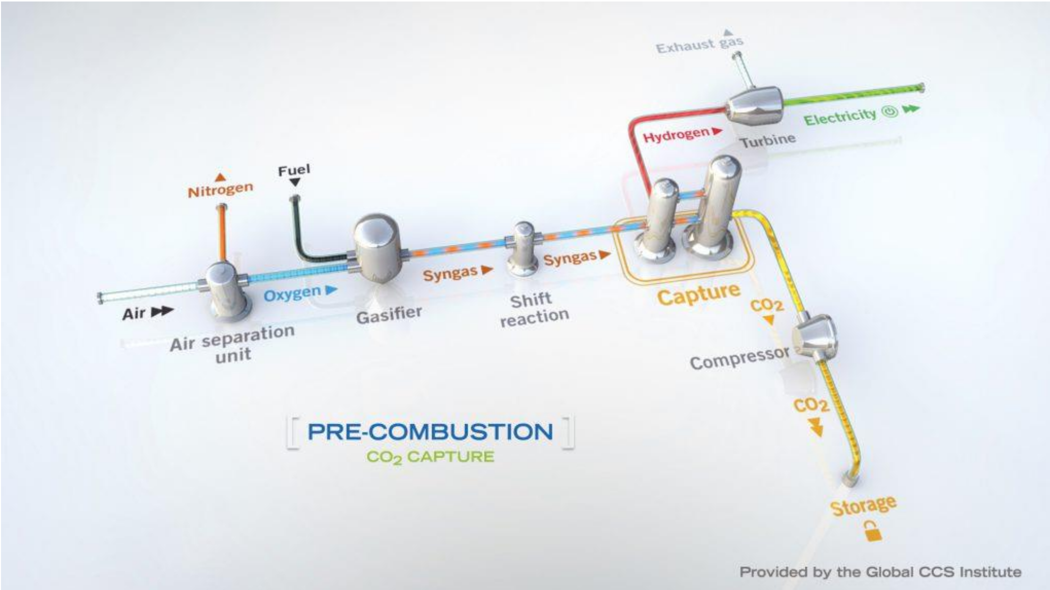

Figure 4. *Schematic description of a pre-combustion capture [17]*

2.4. Capturing CO_2 by oxy-fuel

In oxy-fuel combustion, nearly pure oxygen (95-99%) is used for combustion in power plants instead of air, resulting in reduced amount of nitrogen in the flue gas mixture [4,11]. By removing nitrogen at the start of a process, it is much easier to separate CO_2 from the flue gases, and CO_2 capture efficiency is approximately 100% [6]. The flue gases consist mainly of very high CO_2 concentration, water vapor, particulates and SO_2.

The main advantage of oxy-fuel combustion is very high concentration of CO_2 in output stream, which is about 80-98% in dependance of used fuel [4,11]. The major disadvantage of this process is very high capital cost and the energy penalty due to large amount of fuel required to separate oxygen from the air [11,18]. Also, the presence of SO_2 can cause corrosion problems [4].

Today, there is no commercial oxy-fuel combustion projects in operation worldwide [5]. This system has only been tested on pilot scale. There are few projects in construction and in early development.

An illustration of oxy-fuel combustion process is given in Figure 5.

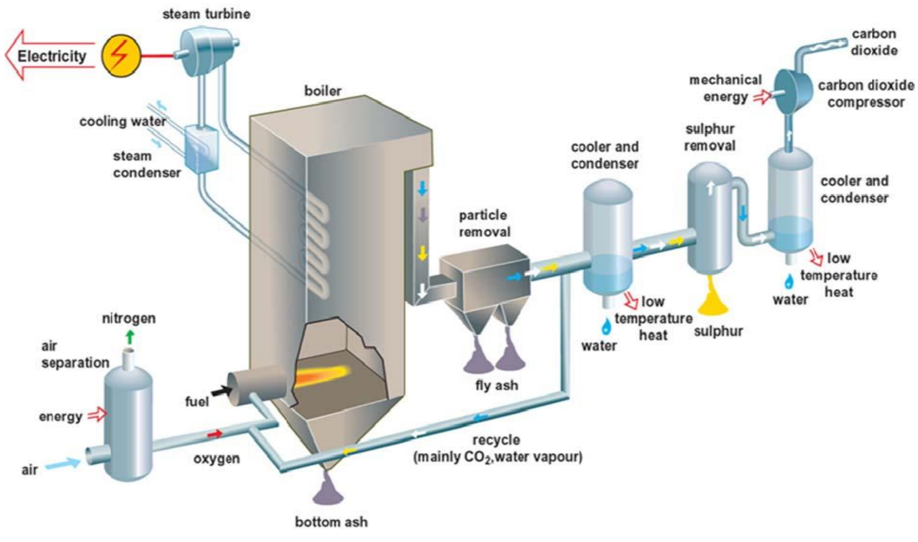

Figure 5. *An illustration of oxy-fuel combustion [19]*

3. TECHNOLOGICAL PROCEDURES FOR CAPTURING CO_2

There are various conventional technological processes for capturing CO_2 such as: absorption, adsorption, cryogenic distillation and membrane-based separation. These technologies are described and discussed below.

3.1. Absorption

In dependance on the nature of the interaction between the absorbent and CO_2, absorption as a method for capturing CO_2 can be physical or chemical.

Physical absorption is based on CO_2 solubility in a solvents, and it is mainly applied for capturing CO_2 in pre-combustion systems [20-21]. CO_2 solubility depends on presure and temperature, and it will increase with the increase of pressure and decrease of temperature. This procedure has many applications such as: in natural gas processing, in separation of CO_2 from synthesis gas which is used in the production of hydrogen, ammonia, and methanol [21-22]. There are a number of physical absorption processes with different existing commercial physical solvents: Selexol (dimethylether of polyethylene glycol), Resticol process (methanol), Fluor process (propylene carbonate), Purisol (N-methyl pyrrolidone) and Morphysorb process (morpholine) [20-22].

The most important advantage of physical absorption process is relatively low capital and operating cost, and use of non-corrosive solvents [20]. Since the physical absorption requires high pressure to achieve CO_2 capture capacity, the main disadvantage is great amount of energy needed to compress feed gas [18, 20].

Chemical absorption represents chemical reaction between CO_2 and a solvent, and it is mainly applied for capturing CO_2 in post-combustion systems [18]. Typical solvents for this technological procedure include liquid ammonia and aqueous alkanolamines such as monoethanolamine (MEA) and diethanolamine (DEA) [4,18]. MEA is the most promising solvent for capturing CO_2 with efficiency coefficient over 90% [4].

Chemical absorption is the most mature technology, and it is advantageous because it is suitable for retrofitting the existing power plants [22]. There are several disadvantages of this procedure. The potential amine degradation and evaporation can affect the solvent losses, high concentration of solvents could be corrosive to the equipment, and high energy consumption is present during the solvent regeneration [4, 18, 22].

3.2. Adsorption

In adsorption procedures, a solid sorbent is used to bind the CO_2 on its surface [4]. This is one of the promising technologies for capturing CO_2 and it can be applied for both pre- and post-combustion systems [21]. This technology procedure includes physical and chemical adsorption. The adsorption is affected by the characteristics of adsorbed particles like polarity, molecular size, and molecular weight, in addition to the characteristics of the adsorbent surface that include pore size and polarity [21]. Typical adsorbents that could be applied include zeolites (molecular sieves), activated carbon, alumina, calcium oxides, lithium zirconate and hydrotalcites [4, 23-25]. Based on adsorbent regeneration process, adsorption can be divided into temperature swing adsorption (TSA) where adsorbent is regenerated by rising its temperature; pressure swing adsorption (PSA) and vacuum pressure swing (VPA) where adsorbent is regenerated by reducing the pressure, and electric swing adsorption (ESA) where adsorbent is regenerated by rising its temperature using the Joule effect of passing electricity through a conductor [21, 26-27]. It has been determined that pressure swing adsorption is the best option due to low energy consumption, high regeneration rate, simplicity in application with wide temperature and pressure range and low investment costs [24,28].

The main drawback of this technological process is that it can be applied in the case of flue gases with low CO_2 concentration [28]. For the reason that power plants have high concentration of CO_2 in flue gases, this procedure is usually combined with other methods.

3.3. Membrane-based separation

Membrane technology for gas separation is a pressure driven process, i.e., difference of partial pressures of gas components along the membrane is a driving force of its movement through the membrane. Specially designed membrane materials allow the selective permeation [6, 11,29], and this separation works on the principle that some gases are more soluble and pass through the membrane more rapidly than others [29-30]. The parameters that influence gas separation performance are: membrane material, the share of CO_2 in the mixture and the process conditions [21,29]. Increased concentration of CO_2 in the mixture increases the separation efficiency [11]. Different types of membrane materials such as polymeric, ceramic, zeolite, carbon or metallic influence on selectivity and permeability of the membrane [21,29]. A very important characteristic is that separation of CO_2 depends on the number of membranes in the system [29], so for achieving the high degree of separation it is necessary to apply multistage separation [25]. Membrane-based separation has several advantages over other technologies due to its high CO_2 capture efficiency and small capital and operational investments which reduce costs [23,29]. This process is fully automated, easy to control and operate [29].

Membrane technology has great potential for capturing CO_2 from different gas streams such as: CO_2/H_2 separation in pre-combustion systems, CO_2/N_2 separation in post-combustion, capturing CO_2 in natural gas processing and oxygen separation from nitrogen in an oxy-fuel combustion system [21].

3.4. Cryogenic distillation

Cryogenic distillation takes place at low temperatures to provide separation, condensation and purification od CO_2 from flue gas stream [4,11]. Therefore, the gas mixture is compressed, cooled and expansed in several stages, and it enables direct production of liquid CO_2 that can be stored at high pressure through liquid pumping [11,23]. This technological procedure is applied for streams with high concentration of CO_2, approximately 90%.

The main advantages of cryogenic distillation are: technology is relatively simple, process can be carried out at atmospheric pressure, and there is no chemical solvents or other components [11,23,31]. The major disadvantage of this process is that large amount of energy is required to provide the cooling process [11]. Also, one of disadvantage is that some components, like water needs to be removed before cooling, to avoid ice formation and blockage of the evaporators in the system.

Cryogenic distillation is very effective for application in high CO_2 concentrated stream and high pressure gases such as pre-combustion systems and oxy-fuel combustion [11].

4. CONCLUSION

There are several opportunities to reduce CO_2 emissions in energy and industrial sectors such as using natural gas instead of coal, increasing the energy efficiency, and separating CO_2 after production using CCS technology which is one of the leading solutions. Capturing CO_2 is the most expensive phase in CCS process and it accounts for approximately 75% of overall costs.

The selection of CO_2 capture systems depends on more factors. Post-combustion CO_2 capture is the most mature option, and it can be integrated into existing power plants. The main disadvantage of post-combustion is low concentration of CO_2 (5-15%) that affects the capture efficiency. Pre-combustion systems are more suitable to apply in new-build plants than in existing ones, because of the complexity of fuel conversion. Compared to post-combustion system, the gasification process is operated at high pressure and synthesis gas contains higher concentration of CO_2 (15-60%), that makes separation easier. Because of more concentrated CO_2, pre-combustion capture is more efficient than post-combustion. Concentration of CO_2 in oxy-fuel combustion is 80-98% depending on used fossil fuel, but the major drawback is very high capital cost and the energy penalty for the reason that large amount of energy is needed for separating oxygen from the air.

Conventional technology procedures that could be employed for capturing CO_2 from flue gases such as absorption, adsorption, cryogenic distillation, and membrane-based separation have some drawbacks like equipment complexity, high energy consumption, and high capital and operating costs. Membrane-based separation has several advantages over other technologies due to its high CO_2 capture efficiency and small capital and operational investments, and this process is fully automated, easy to control and operate.

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