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A Review on Emerging, Promising, and Future CCUS Technology

Futao YANG[1], Sheng GE[2], Guoqiang CHEN[3*]

1 Sinopec Shengli Oilfield

2 Suzhou Tonglian Environmental

3* Genting Energy (gqchen@hotmail.com)

ABSTRACT

The concentration of CO_2 in the atmosphere has risen to 415 ppm from 280 ppm since the industrial revolution in the 1760s, and now it is going up at 2.5 ppm yearly. It is imperative to tackle CO_2 emission and to decrease CO_2 level in the atmosphere by use of proven CO_2 capture, utilization, and storage (CCUS) technology.

CCUS technology has been around for decades, and is used to strip CO_2 from industry emissions as well as remove CO_2 that's already in the atmosphere. But CCUS technology was not funded and studied for climate mitigation efforts until the 1980s. Utilization of embodied CO_2 from hard-to-abate industrial sectors such as steel, cement, glass, and aluminum is promising and emerging. Capturing and utilizing embodied CO_2 in these sectors would reduce global carbon emissions significantly as they account for 25% of total emission globally, and 40% as in China.

CO_2 enhanced oil recovery (EOR), one of the mature and proven CCUS technologies, only consumes a very small portion of annual total carbon emissions. Some promising and emerging CCUS technologies- includes locking up embodied CO_2 in concrete permanently with higher early compressive strength, carbon-neutral fuels for jets, CO_2-based plastics, green polyurethane for textiles and flooring, and CO_2-derived super-strong and superlight carbon fiber etc.. By 2030, it is estimated that those emerging CCUS technologies can dispose 360 million tons CO_2 per year, merely 1% of total global equivalent CO_2 emission in 2021. So more practical and solid CCUS technologies must be studied and developed, which will be critical to scaling the CCUS industry for humans to win the battle against excessive CO_2 concentration in the atmosphere.

The fight against global warming is a continuous effort and it never stops. This review concludes with a discussion that more research and studies should be funded to develop emerging, promising, and future CCUS technology for CO_2 reduction in cost-effective, environment-friendly, and sustainable ways.

Keywords: CCUS, climate mitigation, global warming, embodied CO_2, CO_2 reduction

NONMENCLATURE

Abbreviations	
CCUS	Carbon Dioxide Capture, Utilization and Storage
EOR	Enhanced Oil Recovery
CO_2	Carbon Dioxide
ppm	Particles per million
MOFs	Metal-organic Frameworks
Symbols	
n	Year

1. INTRODUCTION

This paper gives a thorough review of current, promising, and future CCUS technology given CO_2 concentration in the atmosphere, global CO_2 emission, and global warming goal.

Firstly, the paper reviews CO_2 concentration upward trend in the atmosphere from 1750s to 2021 and its important role in regulating earth temperature and briefs the necessity of CCUS in the aid of achieving global warming goal set out in Paris Climate Agreement. Then take a look at worldwide annual CO_2 emission by country and different sectors.

Secondly, eight types of emerging, promising, and future capture, utilization, and storage technology such

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as CO_2 EOR, allam cycle capture, carbon farming, carbon to fuel and fibres, and various frameworks and membranes to capture CO_2 are elaborated and/or evaluated for different applications by discussing their scalability, permanence, cleanness, and economics.

Finally, the fight against the global warming in terms of reducing CO_2 emission is a continuous effort and it never ends for the sake of humans' increasing need for better daily life. Cost-effective and environment-friendly, and promising CCUS technology must be funded, researched, and studied to develop fit-for-purpose, robust, and solid CO_2 reduction equipment and facilities. Human will win the battle by achieving the paris climate agreement of global warming limit within 1.5 degree Celsius.

2. WHY CCUS?

2.1 CO_2 in the atmosphere

Nitrogen and oxygen accounts for 78% and 21%, respectively, of the Earth's atmosphere composition, 0.9% is argon, and the remaining 1% is composed of different types of chemicals such as CO_2 and methane. Fig. 1 gives the composition of air.

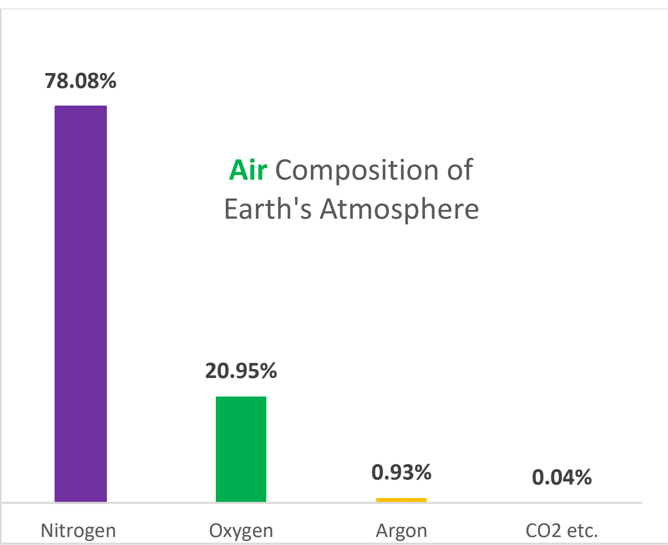

Fig. 1 Composition of Earth's Atmosphere

Although CO_2 is only 0.04% of the atmosphere, it plays a critical role in regulating the earth's temperature. The earth's temperature would sink to minus 20 degree Celsius compared to average surface temperature of 14 degree Celsius if there was no CO_2 and other greenhouse gases. On the other hand, the earth would be too hot for human and most creatures to live as they are living now.

2.2 Changes of CO_2 concentration and annual emission

The CO_2 concentration in the air has risen from 280ppm to 415ppm since industrial revolution in the 1760s. Currently it grows at 2.5ppm per year as a result of global annual CO_2 emission of 35 billion tons in recent years and total CO_2 emission is about 1.9 trillion tons by the end of 2022.

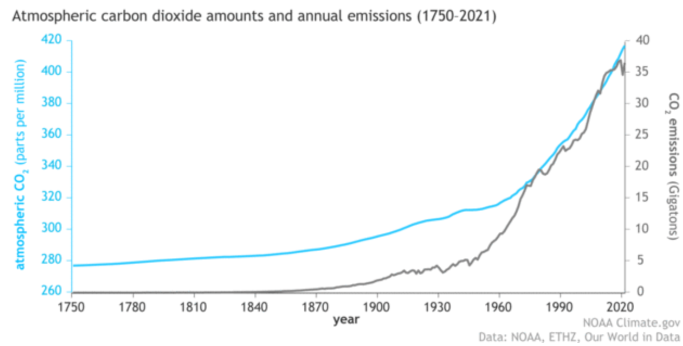

Fig. 2 CO_2 Concentration and Annual Emission

2.3 Global CO_2 emission

Fig. 3 gives the CO_2 emission by each country, It is not a surprise that China's annual CO_2 emission accounts for nearly one third of the global emission as a result of China's second to none manufacturing capability and massive infrastructure investment in high-speed railways, express highways, airports, ports, power plants and so on.

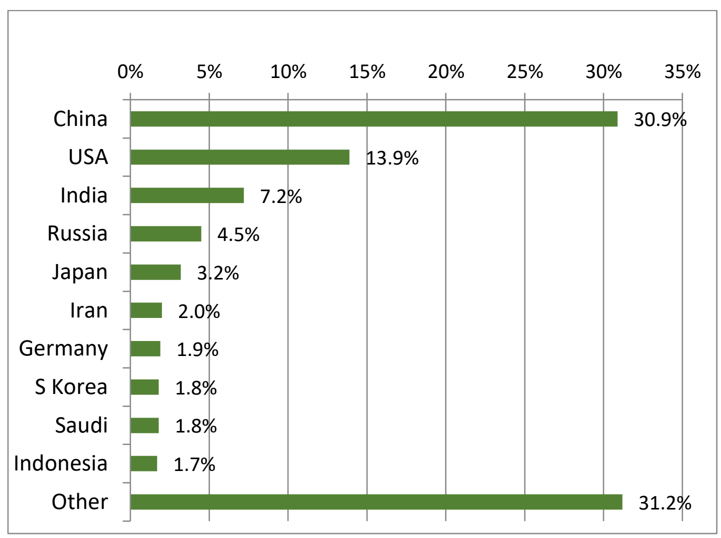

Fig. 3 Global CO_2 Emission by Country

Fig. 4 shows the global CO_2 emission by sectors, coal power plants, hard-to-abate industry such as cementing, chemical, and steel, and transportation make up 75% of the total emission.

China's primary CO_2 emission contributors are different from the global because coal accounts for its 60% energy consumption. Coal plants and hard-to-abate industry emit 85% of China's CO_2 emission. Refer to Fig. 5 for details for different sectors.

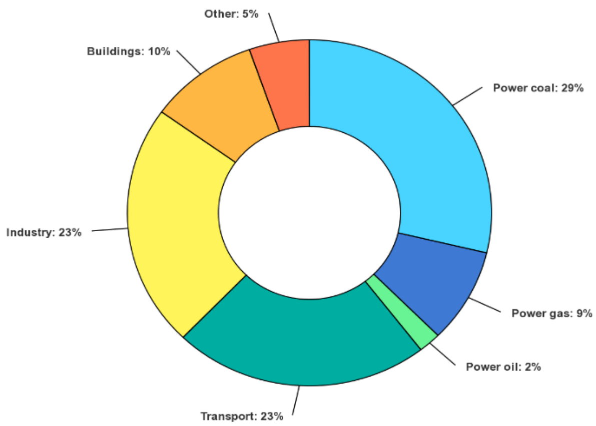

Fig. 4 Global CO_2 Emission by Sector

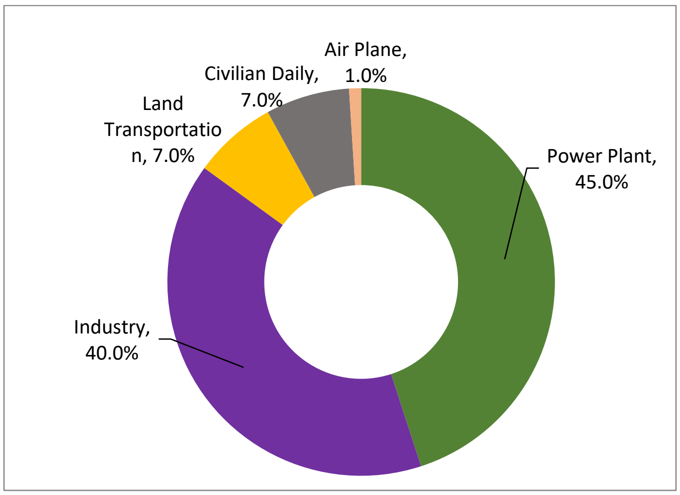

Fig. 5 China CO_2 Emission by Sector

2.4 Paris Climate Agreement goal and China's goal

The goal set out at Paris Climate Agreement are carbon emission peak by 2025 and carbon emission net-zero by 2050 in order to achieve no greater than 1.5 degree Celsius warming while China's goal is carbon peak by 2030 and net-zero by 2060. In order to accomplish the mission of carbon emission peak and net-zero, significant amount of CO_2 must be removed from the atmosphere as quite some CO_2 emission is unavoidable from hard-to-abate industry.

3. CCUS TECHNOLOGY

Practical, robust, and cost-effective CCUS technology is very essential and becomes increasingly significant to meet the goal set out at Paris Climate Agreement. Although CCUS technology has been around for tens of years, it is not employed for climate mitigation ecnomical until late 1980s and it is also not economical unless the price of CO_2 emission rises sharply, otherwise the willingness to use CCUS is limited. Below is a summary of promising and future CCUS technology.

3.1 CO_2 EOR (Enhanced Oil Recovery)

CO_2 EOR is the earliest CCUS technology and it has been used to boost crude production in petroleum industry since 1970s. Sinopec's model CCUS project, a joint project between Shengli Oilfield and Qilu Refinery, injects 1.0 million tons of CO_2 captured from Qilu Refinery to produce more oil, about 350,000 bbls more oil produced in one year period.

Fig. 6 Shengli EOR Well Site

3.2 Allam cycle CO_2 Capture

The Allam cycle, patented in 2013 by Rodney Allam, utilizes oxyfuel combustion and supercritical CO_2 stream as the working fluid to produce high-purity liquid CO_2 and energy. This technology can capture 100% CO_2 emission in gas power plant in a reliable and cost-effective manner.

3.3 Curing concrete with CO_2

The ready-mix concrete can be set and hardened by CO_2 instead of hydration with several benefits: acdceleration of curing process, improved early compressive strength, and similar or better concrete properties. Each cubic meter concrete absorbs 3.5 kilograms CO_2.

Fig. 6 CO_2 Cured Concrete

3.4 CO_2 farming

There are some benefits for sequestering CO_2 into the soil: improved soil health, reduced fertilizer use, and approximately 10% more yield of crops. It has a potential of sequestering 2.0 billion tons of CO_2 into the soil for sustainable and organic farming.

3.5 Metal-organic frameworks to capture CO_2

A group of very absorbent, nanoporous materials called metal-organic frameworks (MOFs) have the potential as hopeful material to capture CO_2 in power plants. MOFs have significantly high surface areas with their nanoscopic pores. Very large volume of gas can be stored in MOFs' vast internal surface area. An MOF capable of sorting CO_2 and NOx gases has been designed, this type of MOF is ideal for China's coal-power plants not only to capture CO_2, but also to ease pollutants from coal.

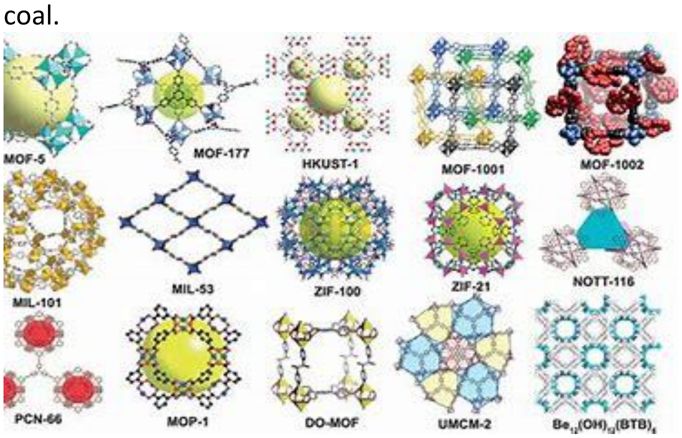

Fig. 7 Metal-Organic Frameworks

3.6 Future CO_2 capture: hybrid membranes

Hybrid membranes, part of polymer and part of MOFs and composite of inorganic and polymeric membranes, could lead to more efficient ways to separate CO_2 from power plant exhaust. CO_2 molecules can pass through via two distinct channels, laboratory tests shows this dual-route approach makes the hybrid membrance 8 folds more CO_2 permeable than polymer membranes only.

3.7 Future and promising utilization: CO_2 to fuel

This chemical reaction $3H_2 + CO_2 \rightarrow CH_3OH + H_2O$ can convert nearly 80% CO_2 into methanol in an aqueous solution of pentaethylenehexamine with catalyst. Methanol is clean-burning fuel for internal combustion engines and a widely used raw chemical material for many petrochemical products.

3.8 Future and promising utilization: CO_2 into fibres

A future and promising technology is underway to transform CO_2 in the atmospheric into high-yield carbon nanofibers. Superlight and superstrong carbon fiber is used to make airplane wings, high-end sports equipment, wind turbine blades, and other products.

4. DISCUSSIONS

Some CCUS technology has strived through the economic threshold and has been gradually used for CO_2 reduction. For most future and promising CCUS technology, there are large uncertainties over scalability, the cleanness of the energy CCUS methods, and the permanence of the capture and storage. Such uncertainties need to be addressed and resolved quick enough for human win the battle against global warming caused by excessive CO_2 emission.

5. CONCLUSIONS

By 2030, it is estimated that those emerging CCUS technologies can dispose 360 million tons CO_2 per year, merely 1% of total global equivalent CO_2 emission in 2021. So more practical and solid CCUS technologies must be studied and developed, which will be critical to scaling the CCUS industry for humans to win the battle against excessive CO_2 concentration in the atmosphere.

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DECLARATION OF INTEREST STATEMENT

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

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