Absorption principle and techno-economic analysis of CO$_2$ absorption technologies: A review

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Abstract. Since the industrial revolution, human activities have led to massive CO$_2$ emissions, and the greenhouse effect has intensified. Therefore, scientists have developed and explored various CO$_2$ capture technologies, such as absorption, adsorption, membrane separation and cryogenic technology. Among them, the absorption technology has been the most widely used. This paper reviews and summarizes the CO$_2$ absorption technologies in the past ten years, introduces the principles of the following six mainstream technologies for CO$_2$ absorption: monoethanolamine (MEA), ionic liquid, calcium looping, microalgae, ammonia, and molten carbonate fuel cells. Through comparing absorption cost, energy consumption, absorptivity as well as the advantages and disadvantages, this paper reveals that calcium looping and ammonia are the relatively suitable technologies at present. The calcium looping has low capture cost and energy consumption, but the reaction capacity of CaO adsorbent decreases rapidly during the absorption process. The absorptivity of ammonia is high and fertilizers (NH$_4$HCO$_3$) with added value can be produced, but the ammonia volatilization problem is challenging. Consequently, the two technologies have their own advantages and disadvantages and should be used considering the actual situation. The conclusions of this paper can guide industries to select CO$_2$ absorption technologies with relatively lower cost, less energy consumption and higher absorptivity.

1. Introduction
The development of global industrialization and the burning of fossil fuels have produced and emitted a large amount of carbon dioxide [8]. The increasing concentration of carbon dioxide in the atmosphere year by year leads to severe global warming [20]. It triggers extreme weather and climate, glacier melting and other phenomena [21], which do great harm to human society and the natural environment. According to the observational data, since the first industrial revolution, the average CO$_2$ concentration has increased from 277 ppm to 413 ppm in 2020, an increase of about 40%. Until the end of the 20th century, the temperature has increased by 0.74 °C compared to the pre-industrial temperature under the influence of carbon dioxide [22, 23]. From 2004 to 2013, the global average annual CO$_2$ emission from land-use change, fossil fuel combustion and cement production, are 3.3 ± 1.8 Gt and 32.7 ± 1.5 Gt, respectively. Meanwhile, the global average annual CO$_2$ absorption of land and ocean are 10.6 ± 2.9 Gt and 9.5 ± 1.8 Gt, which can offset 39.2%-75.8% of CO$_2$ generated by human activities [23, 24].

Therefore, it is urgent to solve the problem of large CO$_2$ emissions. Under the circumstance, the technology of CO$_2$ capture also arises at the historic moment. Common carbon dioxide capture technologies include absorption, adsorption, membrane separation, and cryogenic technology [25]. Among them, the most mature and most widely used technology is absorption and it captures CO$_2$ through chemical reactions [26].

At present, the main ways to capture carbon dioxide by absorption technologies around the world are
monoethanolamine, ionic liquid, calcium oxide, synthetic action of lye and microalgae, ammonia and molten carbonate fuel cells (MCFCs). By comparing the indicators of six CO₂ absorption technologies, this paper analyzes the advantages and disadvantages of each technology, and selects the relatively appropriate CO₂ absorption technology after comprehensive consideration.

2. CO₂ absorption technologies and comparison

2.1. Monoethanolamine
Monoethanolamine (MEA) uses hydroxyl groups to reduce vapor pressure and improve water solubility and alkalinity of amino groups to absorb CO₂. The characteristics of this technology are the fast carbon dioxide absorption kinetics process and strong carbon dioxide capture ability. For example, each mol MEA can capture 0.5 mol CO₂ in 30 wt% MEA solution. With these advantages, this technology has become the most widely used one in the field of CO₂ capture after combustion [20]. Nevertheless, the main disadvantages of MEA in CO₂ absorption are that MEA is volatile and prone to oxidative degradation and thermal degradation, leading to a large amount of solvent loss [4]. Rich liquid regeneration energy consumption is high, accounting for 80% of the total energy consumption cost, about 3.0-4.5 GJ/t CO₂ [27-29]. Therefore, it is necessary to explore and develop a new desorption process with low regenerative energy demand or optimize the original process to recover more waste heat in order to reduce energy consumption and capture cost [4, 30, 31].

2.2. Ionic liquids
Ionic liquids capture CO₂ by means of intermolecular forces, catalysis or introduction of functional groups. The advantages of this technology lie in the inherent properties of ionic liquids, such as involatility, high thermal stability and chemical stability. Low volatility makes ionic liquid regeneration process almost no gas loss and less energy consumption. With high thermal stability and chemical stability, it is not easy to degrade and corrode the equipment. What’s more, it has perfectly overcome the defects of MEA, such as high energy consumption and large solvent loss [6, 32], and hopefully becomes an ideal substitute for MEA [33]. However, two challenges of CO₂ absorption by ionic liquid limit its practical application in industry. The one is that ionic liquid has a high viscosity, which leads to the low CO₂ absorption rate. Although this problem can be solved by increasing the water content, it will lead to the defects that the solvent volume is too large and the absorption ability decreases. The other is that CO₂ absorption by ionic liquids is only used in laboratory scale at present due to the complex manufacturing process and high cost of production [5].

2.3. Calcium looping technology
Calcium looping (CaL) technology means that CO₂ from high-temperature flue gas is passed into the carbonation furnace and reacts with CaO at 650 °C to produce CaCO₃. Then the generated CaCO₃ is sent to the calcining furnace at 950 °C for decomposition and generation of CO₂ airflow with higher purity to achieve the purpose of CO₂ capture [8]. The biggest advantage of the calcium cycling technology is that the raw limestone is abundant and cheap [13]. Nevertheless, this technology has a serious defect, that is, wear of CaO particles, sintering, sulfation, and ash fouling during the absorption process, inevitably lead to severe degradation of the reactivity of the adsorbent [8-12]. In order to overcome this defect, many solutions have been explored, such as using Ca(OH)₂ as a precursor, conducting thermal pretreatment or chemical treatment, etc. Over the past decade, some scientists have also shifted their focus to the areas of hydration, granulation and extended carbonation time for reactivation of abandoned CaO adsorbents [7, 8].

2.4. Microalgae
CO₂ can be fixed into bicarbonate form by alkali solution such as ammonia or carbonate, and converted into biomass with added value by microalgae under light conditions [34]. Microalgae culture systems can be divided into open and closed systems [35]. Most of them are open systems with relatively low
cost but low carbon sequestration efficiency [14]. Different microalgae have different biomass production rates, carbon sequestration efficiencies, tolerance to CO₂ and different advantages and disadvantages. Thus, appropriate microalgae can be selected to fix CO₂ according to the actual demand. Microalgae technology has obvious advantages [34]. It is powered by solar energy and does not require energy consumption to regenerate rich liquid. Moreover, the biomass generated is widely used to produce biofuels such as methane and ethanol, which is in line with the principles of sustainable development goals and economic feasibility [15]. However, the use of microalgae to fix CO₂ has many limitations, such as the need for appropriate light conditions, the pH value, alkalinity and salinity of the appropriate medium and certain requirements on the temperature, CO₂ concentration and impurity content of flue gas. Otherwise, inappropriate conditions will inhibit the growth of microalgae or even kill them [14]. At present, the research of microalgae technology focuses on strain selection, domestication and optimization of photoreactor, so as to improve the efficiency of microalgae in CO₂ fixation [34].

2.5. Ammonia
Ammonia absorption technology takes advantage of the acid-base neutralization reaction between ammonia and CO₂ to absorb CO₂. The advantages of this technology are the lower regeneration energy consumption and the production of fertilizers (NH₄HCO₃) [36, 37]. Therefore, it is more economical than MEA absorption technology. Nevertheless, the problem of ammonia leakage has become a huge obstacle to the wide application of ammonia absorption technology. Due to the volatile nature of ammonia, it is necessary to cool the high-temperature flue gas and absorb volatilized ammonia gas by means of washing or pickling in order to reduce its volatilization. Furthermore, this process brings huge energy consumption and cost problems. In addition, when fertilizer products are applied to the soil, it is likely to be decomposed again and release CO₂ back into the atmosphere [16].

2.6. Molten carbonate fuel cells
Molten carbonate fuel cells (MCFCs) can also be used to absorb CO₂. The mechanism of this technology is that carbonate ions are generated during the reduction reaction of CO₂ and O₂ at the cathode. Then, carbonate ions moved to the anode for the oxidation reaction with fuel to regenerate CO₂, which is transport back to the cathode to ensure the continuous operation of the battery. Its advantage is the ability to convert the chemical energy in the fuel directly into electric energy, which is more efficient than the traditional oxidation combustion energy utilization [18]. Although MCFCs technology has been developed commercially, its main disadvantages are the high cost of battery manufacturing and power generation and the high amount of oxygen required because the anode outlet gas must be burned. Worse still, the huge energy consumption in oxygen production makes the economy and feasibility of MCFCs technology unsatisfactory [19].

3. Techno-economic analysis
From the point of view of capture cost, the cost of calcium looping and MCFCs are relatively low. Although the battery manufacturing technology has been continuously improved and manufacturing cost has been reduced in recent decades, MCFCs still cost a lot and are difficult to meet the request of industrialized application [18]. By comparison, calcium looping has a significant advantage because it can be integrated into coal-fired power plants to absorb CO₂ [8, 38].

As for energy consumption, MEA, due to its volatile nature, consumes too much energy during the liquid-rich regeneration phase [27]. The demand for oxygen and high calorific value gases significantly increases the energy consumption of molten carbonate fuel cells [18, 19]. By contrast, ionic liquid, calcium looping and ammonia have lower energy requirements, so they have certain advantages in energy consumption.

Regarding to CO₂ absorptivity, considering the tolerance of microalgae to CO₂ concentration in the flue gas and the pH value of medium suitable for microalgae growth, the solubility of CO₂ is low. Because lower CO₂ concentration in the flue gas and lower pH value of the
Table 1. Comparison of the advantages and disadvantages of CO₂ absorption technologies

| Technology     | Advantages                                                                 | Disadvantages                                                                 | References |
|----------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|------------|
| MEA            | 1. Cheap solvents                                                            | 1. High energy consumption                                                    | [1-4]      |
|                | 2. Fast absorptivity                                                         | 2. Equipment corrosion                                                         |            |
|                | 3. Strong CO₂ absorption capacity                                             | 3. Prone to oxygen degradation and thermal degradation                         |            |
| Ionic liquids  | 1. High CO₂ selectivity                                                      | 1. High viscosity and low mass transfer rate of CO₂                            | [2, 5, 6]  |
|                | 2. Recyclable and environmentally friendly                                   | 2. Only used in the laboratory                                                 |            |
|                | 4. Inherent properties (non-soluble, high thermal and chemical stability,   | 3. Accomplishing specific tasks                                                | [7-13]     |
|                | variable structure)                                                          |                                                                                |            |
|                | 5. Low regenerative energy demand                                            |                                                                                |            |
|                | 6. No equipment corrosion problem                                            |                                                                                |            |
| Calcium        | 1. Abundant and cheap absorbent                                             | 1. High energy consumption                                                    | [7-13]     |
| Looping       | 2. Recoverable high grade heat energy                                        | 2. Equipment corrosion                                                         |            |
|                | 3. Low efficiency loss, 5%-7%                                                | 3. Prone to oxygen degradation and thermal degradation                         |            |
| Microalgae     | 1. Reduce nitrogen and phosphorus content and purify waste water            | 1. Low CO₂ absorptivity                                                       | [14, 15]   |
|                | 2. Solar powered, no need to regenerate solvent                             | 2. Not suitable for flue gas with high CO₂ concentration                       |            |
|                | 3. Produce biomass with added value                                          | 3. Gas leakage because of low CO₂ solubility                                  |            |
|                | 4. Fast growth rate and CO₂ fixation ability                                 |                                                                                | [14, 15]   |
| Ammonia        | 1. No equipment corrosion problem                                            | 1. Resulting in the waste of resources and the loss of energy                  | [3, 16, 17]|
|                | 2. Low energy consumption                                                    | due to overproduction of fertilizer                                           |            |
|                | 3. Strong absorption capacity                                                 | 2. Volatile                                                                   | [18, 19]   |
| MCFCs          | 1. High CO₂ absorptivity                                                     | 1. High cost of battery manufacturing and power generation                     | [18, 19]   |
|                | 2. High efficiency of battery generation                                     | 2. Difficult to manage the battery operation under high temperature conditions |            |

Compared with the two technologies, the advantages of calcium looping lie in the low capture cost and energy consumption, but the CO₂ absorptivity is slightly lower than that of ammonia. The low cost of calcium looping capture is due to the abundant and cheap sources of limestone and dolomite [13]. The lower energy consumption is due to the low efficiency loss and high-grade heat energy recovery [8]. However, on the one hand, due to particle wear, sintering, sulfation, and other factors, the reaction capacity of the adsorbent decreases rapidly [9-12]. Therefore, pretreatment, reactivation of discarded adsorbent or artificial adsorbent based on CaO are needed to solve this problem, which increases the

Table 2. Indicators comparison of CO₂ absorption technologies

| Technology     | Cost ($/t CO₂) | Energy consumption (GJ/t CO₂) | CO₂ absorptivity (%) | References |
|----------------|----------------|-------------------------------|----------------------|------------|
| MEA            | 40-100         | 3.0-4.5                       | 86-92                | [20, 27-29, 39] |
| Ionic liquids  | /              | 1.0-3.2                       | 80-98                | [40, 41]   |
| Calcium        | 30-50          | 1.4-2.1                       | 80-90                | [7-9]      |
| Looping       | 130-140        | /                             | 10-30                | [14, 15, 34]|
| Microalgae     | 50-60          | < 2.5                         | 90-99                | [3, 16, 42, 43]|
| Ammonia        | 30-50          | 14.2-50.7                     | 75-85                | [18]       |
cost [7]. On the other hand, CO2 compression needs to consume a lot of electricity. At the same time, it will produce low-grade waste heat that is difficult to recover and use, causing efficiency loss [8].

Ammonia absorption has the advantage of high CO2 absorptivity and the production of fertilizers. However, ammonia is volatile, reducing the absorptive capacity of the solution, and likely to cause solid precipitation, equipment blockage and environmental pollution [3, 38]. Worse still, CO2 absorption produces excess fertilizer, which is much larger than the market demand and difficult to sell, resulting in the loss of resources and energy. Even when fertilizer is applied to the soil, there is a possibility that the decomposition of ammonium will produce CO2 back into the atmosphere, which goes against the original intention of ammonia absorption [16].

Therefore, the two technologies have their own advantages and disadvantages. The most appropriate technology for CO2 absorption should be selected based on the actual demand.

4. Conclusion
In this paper, based on absorption cost, energy consumption and absorptivity, combined with the advantages and challenges of six mainstream absorption technologies, two relatively suitable CO2 absorption technologies are selected: calcium looping and ammonia. Calcium looping is an energy-saving process using cheap absorbents, but the absorption capacity of adsorbent decreases rapidly in the absorption process. Ammonia has a high absorptivity of CO2. However, the ammonia volatilization problem inevitably leads to problems which are difficult to overcome. Therefore, the exploration and optimization of CO2 absorption technologies will always be the research hotspot of scientists.

References
[1] S.A. Mazari, et al., Review of modelling and simulation strategies for evaluating corrosive behavior of aqueous amine systems for CO2 capture. Int J Greenh Gas Con. 96 (2020)
[2] T. N.Borhani and M. Wang, Role of solvents in CO2 capture processes: The review of selection and design methods. Renew Sust Energ Rev. 114 (2019)
[3] F. Wang, et al., Current status and challenges of the ammonia escape inhibition technologies in ammonia-based CO2 capture process. Appl. Energy. 230: p. 734-749 (2018)
[4] P. Luis, T. Van Gerven, and B. Van Der Bruggen, Recent developments in membrane-based technologies for CO2 capture. Progr. Energy Combust. Sci. 38(3): p. 419-448 (2012)
[5] M. Aghaie, N. Rezaei, and S. Zendehboudi, A systematic review on CO2 capture with ionic liquids: Current status and future prospects. Renew Sust Energ Rev. 96: p. 502-525 (2018)
[6] A. Yethiraj, Structure of room temperature ionic liquids. J. Phys.: Condens. Matter. 28(41): p. 414020 (2016)
[7] M. Erans, V. Manovic, and E.J. Anthony, Calcium looping sorbents for CO2 capture. Appl. Energy. 180: p. 722-742 (2016)
[8] X. Zhang, P. Song, and L. Jiang, Performance evaluation of an integrated redesigned coal fired power plant with CO2 capture by calcium looping process. Appl. Therm. Eng. 170 (2020)
[9] J. Blamey, et al., The calcium looping cycle for large-scale CO2 capture. Progr. Energy Combust. Sci. 36(2): p. 260-279 (2010)
[10] H. Chen, et al., CO2 capture and attrition performance of CaO pellets with aluminate cement under pressurized carbonation. Appl. Energy. 91(1): p. 334-340 (2012)
[11] J.M. Valverde, et al., Constant rate thermal analysis for enhancing the long-term CO2 capture of CaO at Ca-looping conditions. Appl. Energy. 108: p. 108-120 (2013)
[12] F. Scala, et al., Attrition of sorbents during fluidized bed calcination and sulphation. Powder Technol. 107(1-2): p. 153-167 (2000)
[13] X. Zhang and Y. Liu, Performance assessment of CO2 capture with calcination carbonation reaction process driven by coal and concentrated solar power. Appl. Therm. Eng. 70(1): p. 13-24 (2014)
[14] N. Seyed Hosseini, H. Shang, and J.A. Scott, Biosequestration of industrial off-gas CO2 for enhanced lipid productivity in open microalgae cultivation systems. Renew Sust Energ Rev.
92: p. 458-469 (2018)

[15] W.Y. Cheah, et al., Biosequestration of atmospheric CO₂ and flue gas-containing CO₂ by microalgae. Biotechnol. 184: p. 190-201 (2015)

[16] F. Shakerian, et al., A comparative review between amines and ammonia as sorptive media for post-combustion CO₂ capture. Appl. Energy. 148: p. 10-22 (2015)

[17] K. Han, et al., Current status and challenges of the ammonia-based CO₂ capture technologies toward commercialization. Int J Greenh Gas Con. 14: p. 270-281 (2013)

[18] J.D. Slater, et al., Review and techno-economic assessment of fuel cell technologies with CO₂ capture. Int J Greenh Gas Con. 91 (2019)

[19] J.-H. Wee, Carbon dioxide emission reduction using molten carbonate fuel cell systems. Renew Sust Energ Rev. 32: p. 178-191 (2014)

[20] A. Krótki, et al., Experimental results of advanced technological modifications for a CO₂ capture process using amine scrubbing. Int J Greenh Gas Con. 96 (2020)

[21] D. Kweku, et al., Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming. Journal of Scientific Research and Reports. 17(6): p. 1-9 (2018)

[22] F. Joos and R. Spahni, Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. Proc. Natl. Acad. Sci. U. S. A. 105(5): p. 1425-1430 (2008)

[23] E. Dlugokencky and P. Tans. Trends in atmospheric carbon dioxide. 2020 August 5, 2020; Available from: https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html.

[24] F. Ozturk, M. Keles, and F. Evrendilek, Quantifying rates and drivers of change in long-term sector- and country-specific trends of carbon dioxide-equivalent greenhouse gas emissions. Renew Sust Energ Rev. 65: p. 823-831 (2016)

[25] J. David, Economic evaluation of leading technology options for sequestration of carbon dioxide. 2000, Massachusetts Institute of Technology.

[26] J. Liu, et al., The chemical CO₂ capture by carbonation-decarbonation cycles. J. Environ. Manage. 260: p. 110054 (2020)

[27] C. Song, et al., Alternative pathways for efficient CO₂ capture by hybrid processes—A review. Renew Sust Energ Rev. 82: p. 215-231 (2018)

[28] S.-Y. Oh, et al., Energy minimization of MEA-based CO₂ capture process. Appl. Energy. 169: p. 353-362 (2016)

[29] M.R.M. Abu-Zahra, et al., CO₂ capture from power plants. Int J Greenh Gas Con. 1(1): p. 37-46 (2007)

[30] A. Garcia-Abuin, D. Gómez-Diaz, and J.M. Navaza, New processes for amine regeneration. Fuel. 135: p. 191-197 (2014)

[31] Y. Le Moullec, et al., Process modifications for solvent-based post-combustion CO₂ capture. Int J Greenh Gas Con. 31: p. 96-112 (2014)

[32] D. Hospital-Benito, et al., Process analysis overview of ionic liquids on CO₂ chemical capture. Chem. Eng. J. 390 (2020)

[33] J.L. Anthony, E.J. Maginn, and J.F. Brennecke, Solubilities and thermodynamic properties of gases in the ionic liquid 1-n-butyl-3-methylimidazolium hexafluorophosphate. J. Phys. Chem. B. 106(29): p. 7315-7320 (2002)

[34] C. Song, et al., Absorption-microalgae hybrid CO₂ capture and biotransformation strategy—A review. Int J Greenh Gas Con. 88: p. 109-117 (2019)

[35] P.J. Mcginn, et al., Integration of microalgae cultivation with industrial waste remediation for biofuel and bioenergy production: opportunities and limitations. Photosynth. Res. 109(1-3): p. 231-247 (2011)

[36] H. Ishaq, et al., A solar and wind driven energy system for hydrogen and urea production with CO₂ capturing. Int. J. Hydrogen Energy, (2020)

[37] K. Li, et al., Rate-based modelling of combined SO₂ removal and NH₃ recycling integrated with an aqueous NH₃-based CO₂ capture process. Appl. Energy. 148: p. 66-77 (2015)

[38] H. Yu, et al., Results from trialling aqueous NH₃ based post-combustion capture in a pilot plant at
Munmorah power station: Absorption. Chem. Eng. Res. Des. 89(8): p. 1204-1215 (2011)

[39] T.C. Merkel, et al., Power plant post-combustion carbon dioxide capture: An opportunity for membranes. J. Membr. Sci. 359(1-2): p. 126-139 (2010)

[40] S. Lian, et al., Recent advances in ionic liquids-based hybrid processes for CO₂ capture and utilization. J Environ Sci. 99: p. 281-295 (2021)

[41] J. Haider, et al., Simultaneous capture of acid gases from natural gas adopting ionic liquids: Challenges, recent developments, and prospects. Renew Sust Energ Rev. 123 (2020)

[42] V. Darde, et al., Comparison of two electrolyte models for the carbon capture with aqueous ammonia. Int J Greenh Gas Con. 8: p. 61-72 (2012)

[43] A.C. Yeh and H. Bai, Comparison of ammonia and monoethanolamine solvents to reduce CO₂ greenhouse gas emissions. Sci. Total Environ. 228(2-3): p. 121-133 (1999)