

Pen-Chi Chiang · Shu-Yuan Pan

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# Preface

Carbon dioxide (CO<sub>2</sub>) mineralization and utilization is an important technology wherein CO<sub>2</sub> is captured and stored for utilization instead of being released into the atmosphere. CO<sub>2</sub> mineralization and utilization demonstrated in the waste-to-resource supply chain can “reduce carbon dependency, promote resource and energy efficiency, and lessen environmental quality degradation,” thereby reducing the environmental risks and increasing the economic benefits towards sustainable development goals. This book provides comprehensive information on CO<sub>2</sub> mineralization and utilization using alkaline wastes via accelerated carbonation technology from theoretical and practical considerations, presented in 20 chapters. Engineers, scientists, government officers, and project managers will consider this book as an essential reference on CO<sub>2</sub> mineralization and utilization.

In this book, the concept of carbon cycle from the thermodynamic point of view was first introduced. The principles, applications, and environmental impact assessment of carbon capture and storage technologies also are illustrated in Part I. Among the carbon capture and utilization processes, CO<sub>2</sub> mineralization via accelerated carbonation technology is especially focused in Part II. Throughout the carbonation process, huge amounts of CO<sub>2</sub> and alkaline wastes generated from industries can be reclaimed and reused. From the theoretical consideration, the process chemistry, reaction kinetics, mass transfer, and system analysis for accelerated carbonation are systematically presented. On the other hand, from the practical consideration, the analytical methods and the application of accelerated carbonation are introduced as well. In Part III, it then explores the utilization of carbonated products as green materials such as supplementary cementitious materials and high value-added chemicals. Key performance indicators for evaluating the function and properties of carbonated products are developed. Lastly, an integral approach for waste treatment and resource recovery is proposed to establish a waste-to-resource supply chain towards a circular economy system. It discusses the challenges, barriers, and strategies of integrated air pollution control at industry in detail, and then illustrates the importance and significance of establishing waste-to-resource green supply chain. Furthermore, the carbonation system is

critically assessed and optimized from aspects of engineering, environmental, and economic analysis.

Reduction in CO<sub>2</sub> emission in industries and/or power plants should be a portfolio option. Integrated alkaline waste treatment with CO<sub>2</sub> mineralization and utilization is an attractive approach to achieving direct and indirect reduction in greenhouse gas (GHG) emissions in industries. The accelerated carbonation can not only stabilize alkaline wastes but also fix CO<sub>2</sub> in flue gas from industries as a safe and stable carbonate precipitate. On the other hand, the amount of CO<sub>2</sub> reduction by carbonation could be certified as emission reduction credits, in conjunction with the joint implementation (JI), emission trading scheme (ETS), and clean development mechanism (CDM) issued by the Kyoto Protocol. Therefore, it suggests that the establishment of a waste-to-resource supply chain should provide a method of overcoming the barriers of energy demand, waste management, and GHG emissions to achieve a circular economy system, under which the “win-win” philosophy demonstrating green economy and healthy environment can be coexisted.

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Furthermore, we would like to express our gratitude to Mark Goedkoop, who kindly granted permission to use their photographs and valuable information in this book. Over the years, Ministry of Science and Technology (Taiwan), along with several industrial partners including China Steel Corp., Tung-Ho Steel Enterprise Corp., Formosa Petrochemical Corp., and Cheng Loong Corp., provided funding in support of our research grants for the development and deployment of carbon mineralization and utilization technologies. Much of the results reported in this book are based on the aforementioned efforts. Our thanks also go to Xiao-Li Pei for her assistance in the preproduction of this book.

Taipei, Taiwan

Pen-Chi Chiang  
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# Chapter 1

## Introduction

**Abstract** Since the industrial revolution in 1750, human activities have resulted in a 40% increase in the atmospheric concentration of CO<sub>2</sub>, thereby leading to rapid global warming. To mitigate the global warming and climate change caused by huge anthropogenic CO<sub>2</sub> emissions, different strategies, action plans, and economic instruments have been proposed and implemented around the world. In this chapter, the significance and importance of climate change and global warming are illustrated. An overview of several important formal meetings of the United Nations Framework Convention on Climate Change (UNFCCC) Parties, i.e., Conferences of the Parties (COP), is provided to reveal key milestones in dealing with global greenhouse gas emissions. One such method uses accelerated carbonation of alkaline wastes to capture and utilize CO<sub>2</sub>, the theoretical and practical considerations of which are presented in 19 Chapters in this book.

### 1.1 Climate Change and Global Warming: Significance and Importance

Greenhouse gases (GHGs) are gases in the atmosphere that can absorb and emit radiation within the thermal infrared range, thereby leading to the greenhouse effect. Without GHG, the average temperature of Earth's surface would be approximately 0 °F (−18 °C), rather than present average of 59 °F (15 °C) [1, 2]. Of the gases affecting the ambient temperature of the Earth, the following are most interesting because they are known as long-lived greenhouse gases (LLGHGs):

- Carbon dioxide (CO<sub>2</sub>)
- Methane (CH<sub>4</sub>)
- Nitrous oxide (N<sub>2</sub>O)
- Chlorofluorocarbons (CFCs)
- Hydrochlorofluorocarbons (HCFCs)
- Hydrofluorocarbons (HFCs)
- Perfluorocarbons (PFCs)
- Sulfur hexafluoride (SF<sub>6</sub>)

The most abundant GHGs in the atmosphere of the Earth are water vapor ( $\text{H}_2\text{O}$ ),  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{O}_3$ , and CFCs. These gases can be discharged into the atmosphere by natural and anthropogenic sources. However, since the beginning of the industrial revolution, human activities have produced a 40% increase in the atmospheric concentration of  $\text{CO}_2$ , from 280 ppm in 1750 to 400 ppm in 2015. The rapid increase of  $\text{CO}_2$  concentration in the atmosphere has spurred worldwide concerns of global climate change from government, industrial, and academic groups. Anthropogenic emissions of  $\text{CO}_2$  mainly come from combustion of carbon-based fossil fuels (such as coal, oil, and natural gas), along with deforestation, soil erosion, and animal agriculture. It is noted that the major anthropogenic GHGs are  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ,  $\text{SF}_6$ , HFCs, and PFCs, which are regulated under the international Kyoto Protocol treaty. The global warming potential (GWP) depends on both the efficiency of the molecule as a GHG and its atmospheric lifetime.  $\text{CO}_2$  is defined to have a GWP of one over all time period. For instance, methane has an atmospheric lifetime of  $12 \pm 3$  years, resulting in a GWP value of 72 over a timescale of 20 years [3].

### ***1.1.1 Kyoto Protocol in 1997***

The Kyoto Protocol is an international treaty signed in 1997, which extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol was adopted in Kyoto (Japan), and originally aimed to attain, by 2012, a reduction of global GHG emissions at least 5% less than the observed levels in 1990. A total of six GHGs, including  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , HFCs, PFCs, and  $\text{SF}_6$ , were regulated in the Kyoto Protocol, which came into effect in 2005. As a result of the Kyoto Protocol, the European Union (EU) issued a global reduction aim of GHG levels by 8%. The Protocol defines three flexibility mechanisms to meet the emission limitation commitment for the Annex I Parties, which include international emissions trading (IET), the clean development mechanism (CDM), and joint implementation (JI). The economic basis for providing this flexibility is that the marginal cost of reducing emissions differs among countries [4].

To negotiate the Kyoto Protocol for establishing legally binding obligations of reducing GHG emissions for developed countries, the United Nations Climate Change Conferences (UNCCC) are held annually in the framework of the UNFCCC. They serve as the formal meeting of the UNFCCC Parties, i.e., Conferences of the Parties (COP), which assess the progress in dealing with climate change. The first UNCCC (COP 1) was held at Berlin, Germany, in 1995. From 2011, the COP meetings have also been used to negotiate the Paris Agreement, as part of the Durban platform activities (adopted at COP 17 in 2011), until its conclusion in 2015.

### ***1.1.2 Cancún Agreement (COP 16) in 2010***

The 2010 UNFCCC, officially referred as the 16th session of the Conference of the Parties (COP 16), was held at Cancún, Mexico, in 2010. The agreement includes voluntary pledges made by 76 countries to control GHG emissions. At the time of the agreement, these countries were collectively responsible for 85% of annual global CO<sub>2</sub> emission. The most significant outcome was the agreement for a “Green Climate Fund (GCF)” and a “Climate Technology Centre,” adopted by the states’ parties. The GCF aimed to distribute US\$100 billion per year by 2020 to assist poorer countries in financing emission reductions and adapting to climate change. It also asked rich countries to reduce their GHG emissions as pledged in the Copenhagen Accord and planed to reduce the emissions for developing countries. However, at that time, the funding of the GCF was not agreed upon.

### ***1.1.3 Durban Agreement (COP 17) in 2011***

COP 17 meeting was held at Durban, South Africa, in 2011. In this meeting, the implementation of carbon capture and storage (CCS) technologies was regarded as eligible for clean development mechanism (CDM) projects and activities. However, the geological storage of CO<sub>2</sub> demonstrated around the world still faces many uncertainties and risks, such as accidental leakage of CO<sub>2</sub>, environmental impacts, and public acceptance. On the other hand, carbon capture, utilization, and storage (CCUS) have recently received global attention as a viable option for reducing CO<sub>2</sub> emissions from industries and/or power plants [5–8]. In this meeting, the creation of the GCF was also discussed.

### ***1.1.4 Paris Agreement (COP 21) in 2015***

The COP 21 meeting was held at Paris (France) in 2015. Negotiations resulted in the adoption of the Paris Agreement, which represented a consensus of the representatives of the 196 parties, to govern climate change reduction measures starting from 2020. The agreement will become legally binding only if at least 55 countries, which together produce at least 55% of the global GHG emissions, ratify the agreement [9]. The agreement ended the work of the Durban platform which was established during COP 17. The expected key result of COP 21 was highlighted by the below statement:

Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

The agreement also called for “zero net anthropogenic GHG emissions” to be reached by 2050. Prior to the conference, a total of 146 national climate panels each publicly presented draft national climate contributions, called intended nationally determined contributions (INDCs), which was estimated to limit global warming to 2.7 °C by 2100. For instance, the EU suggested the INDC should set a binding target for at least a 40% domestic reduction in GHG emissions by 2030, compared to 1990 [10]. It also suggested that the regulated GHGs by EU members should include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, SF<sub>6</sub>, and NF<sub>3</sub>.

## 1.2 Mitigation and Adaptation

The ocean is the major short-term sink in nature because of the imbalance between CO<sub>2</sub> concentrations in the ocean and the atmosphere. Although the natural sink is very important, offering −0.5 °C of temperature reduction following an overshoot [11], the major application of anthropogenic sinks, such as carbon capture utilization and storage (CCUS) and rapid reforestation, is also required to achieve a plateau at 2 °C. Without technologies that remove CO<sub>2</sub> from the atmosphere, the 350 CO<sub>2</sub> ppm target is out of reach in the twenty-first century [11].

To mitigate rapid global warming and adapt to the climate change caused by huge anthropogenic CO<sub>2</sub> emissions, different strategies and tools from various aspects have been proposed and implemented. Action plans and practical technologies have been executed to pursue scientific solutions for overcoming the challenges of global warming [12, 13]. According to the international energy agency (IEA) report, the strategies for reducing CO<sub>2</sub> emissions include the following: (1) improving overall energy efficiency, (2) implementing carbon capture and storage (CCS) technologies, and (3) utilizing renewable energy and material recycling [14]. Among the above strategies, the CCS technologies could reduce CO<sub>2</sub> emissions by 9–50% in industrial sectors, compared to the present level, by 2050 and could mitigate cumulative global climate change by 15–55% in 2100 [15].

Putting a price on carbon emission can also help shift the burden of the environmental damage back to those who can reduce it. There are two types of carbon pricing instruments that can be utilized to accelerate the CO<sub>2</sub> emission reduction: (1) emissions trading systems (ETS) and (2) carbon taxes. The choice of carbon pricing tools depends on national and economic circumstances. The ETS is sometimes referred to as a cap-and-trade system. It caps the total level of greenhouse gas emissions and allows industries with low emissions to sell their extra allowances to larger emitters. By creating a platform of supply and demand for emission allowances, an ETS can effectively establish a market price for GHG emissions, ensuring that the emitters will be kept within their pre-allocated carbon budget. Conversely, a carbon tax directly sets a price on carbon by defining a tax rate on the GHG emissions (or the carbon content) of fossil fuels. It is different from an ETS because the emission reduction outcome of a carbon tax is not predefined but the carbon price is.

## 1.3 Structure and Contents of This Book

This book provides comprehensive information on CO<sub>2</sub> capture and utilization using alkaline wastes via accelerated carbonation technology from theoretical and practical considerations, presented in the following 19 chapters. This book should be beneficial to readers who take scientific and practical interests in the current and future *accelerated carbonation technology* for CO<sub>2</sub> mineralization and utilization. Engineers, scientists, government officers, and project managers will find this book an essential reference on CO<sub>2</sub> mineralization and utilization.

In Part I, a broad review on challenges and opportunities for global warming issues is provided, including post-combustion carbon capture, storage and utilization (Chap. 2), CO<sub>2</sub> mineralization and utilization via accelerated carbonation (Chap. 3), and environmental impact assessment (EIA) and carbon capture and storage (CCS) guidance (Chap. 4).

In Part II, the integrated waste treatment via ex situ accelerated carbonation is systematically presented, in terms of theories and principles (Chap. 5), analytical methods for carbonation material (Chap. 6), mechanisms and modelling (Chap. 7), practices and applications (Chap. 8). Chapter 9 covers the system analysis methodology, including response surface methodology (RSM), life cycle assessment (LCA), cost–benefit analysis (CBA), and 3E (Engineering, Environmental, and Economic) triangle model.

In Part III, various types of feedstock for CO<sub>2</sub> mineralization are illustrated, including natural silicate and carbonate minerals (Chap. 10), iron and steel slags (Chap. 11), fly ash, bottom ash, and dust (Chap. 12) and paper industry, construction, and mining process wastes (Chap. 13).

In Part IV, the valorization of carbonization product as green materials is discussed, including utilization of carbonation product as green materials (Chap. 14), supplementary cementitious materials (SCMs) in cement mortar (Chap. 15), and aggregates and other high-value products (Chap. 16).

In Part V, the concepts of integral approach for waste treatment and resource recovery are illustrated. First, the carbon capture with flue gas purification (e.g., SO<sub>x</sub>, NO<sub>x</sub>, and particulate matter) via process integration and intensification is provided in Chap. 17. After that, the importance and significance of waste-to-resource (WTR) supply chain are discussed, in terms of barriers, challenges, strategies, and action plans (Chap. 18). Following that the principles of system optimization, such as (1) mathematical programming approach, (2) graphical presentation for optimization, and (3) comprehensive performance evaluation, are introduced to demonstrate the best available technology (Chap. 19). Moreover, several demonstration and action plans around the world are reviewed. Finally, the prospective and perspective on the strategies toward zero waste for sustainability are provided in Chap. 20.

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**Part I**  
**Global Warming Issues: Challenges and Opportunities**

## Chapter 2

# Post-combustion Carbon Capture, Storage, and Utilization

**Abstract** Deployment of carbon capture, storage, and utilization technologies worldwide from the CO<sub>2</sub> emission point source is a strategy that has been proposed to address the challenge of climate change and global warming. As a viable option for reducing CO<sub>2</sub> emissions, moving carbon capture and storage technology to incorporate “utilization” (carbon capture and utilization) has received dramatically global attention. This chapter provides an overview of various types of carbon capture, storage, and utilization technologies. After that, one of the carbon capture and utilization technologies, i.e., microalgae pond systems, is illustrated in detail. The principles of microalgae open pond systems, key parameters affecting productivity, and economic considerations of operating open ponds are systematically illustrated.

### 2.1 Significance and Importance

Human activities resulted in emissions of four long-lived greenhouse gases (GHGs): CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and halocarbons, of which CO<sub>2</sub> is the most important anthropogenic GHG due to its solitary responsibility for about two-thirds of the enhanced greenhouse effect [1]. Meanwhile, rapid economic growth in developing countries such as China and India is driving worldwide energy demand and usage day by day. At the same time, it has been predicted that fossil fuels will remain the dominant energy source around the world for at least another 20 years to fulfill such energy demands [2]. As CO<sub>2</sub> keeps accumulating in the atmosphere after generating from power plant, concerns about serious and irreversible damage, such as rising water level and species extinction, are being raised regarding its influence on climate change. Consequently, it is clear that effective control of CO<sub>2</sub> emissions is required to achieve the goal of global CO<sub>2</sub> concentration below 550 ppm over next the 100 years [3].



### ***2.1.1 Strategies on Global CO<sub>2</sub> Mitigation***

It is noted that the increased global average CO<sub>2</sub> concentration in the atmosphere is likely to cause further warming and induce many changes in the global climate system. To reduce CO<sub>2</sub> in the atmosphere, five strategies can be considerable [4]:

- Strategy 1: Reducing the amount of CO<sub>2</sub> producer sources (reducing energy intensity)
- Strategy 2: Using CO<sub>2</sub> (or reducing carbon intensity)
- Strategy 3: Capturing and storing of CO<sub>2</sub>
- Strategy 4: Switching to less carbon-intensive fuels from conventional fuels
- Strategy 5: Increasing the use of renewable energies.

The third strategy involves the development of innovative, available, and cost-effective carbon capture and storage (CCS) technologies because of a 50-year estimate for the continued widespread burning of fossil fuels, the goal of reaching a 500 ppm atmospheric CO<sub>2</sub> concentration plateau, and the lag time needed for the development and implementation of new carbonless sources of energy [4, 5]. In general, the carbon capture technologies can be classified into three categories:

- Precombustion capture
- Post-combustion capture
- Oxy-fuel combustion

### ***2.1.2 Transition from Storage to Utilization***

As a viable option for reducing CO<sub>2</sub> emissions, moving CCS technology to incorporate “utilization” [i.e., carbon capture and utilization (CCU)] has received dramatically global attention. Europe (in particular Germany), the USA, and Australia are well advanced in research and development of carbon capture, utilization, and storage (CCUS) technologies [6, 7]. The utilization routes of the captured CO<sub>2</sub> include enhanced fuel recovery (i.e., enhanced oil recovery and enhanced gas recovery), biological conversion (i.e., algae), food industry, chemicals (i.e., fertilizer and liquid fuel), refrigerant, inerting agents, fire suppression, plastics, and even mineralization as carbonates (i.e., precipitated calcium carbonates (PCC) and construction materials). The benefits of CCU technologies include the following: [6, 8].

- Potentially reduce annual CO<sub>2</sub> emissions by at least 3.7 Gt, equivalent to about 10% of the world’s current annual emissions
- Value-added products that create green jobs and economic benefits and help offset the abatement cost.

As a result, CCUS technologies are key strategies to attenuate the impacts of global warming during the transition period for developing sustainable energy technologies. CCUS is considered to be a critical strategy in the pathway to a sustainable energy system, contributing ~14% of reductions in global CO<sub>2</sub> emissions by 2050 [9, 10]. However, none of the CCUS technologies alone can provide a short—to medium-term solution to reduce CO<sub>2</sub> emissions at a level necessary to stabilize current concentrations. Rather, a portfolio solution must be identified to achieve the most effective CO<sub>2</sub> reduction while minimizing social and economic costs.

### 2.1.3 Concept of Carbon Capture, Utilization, and Storage (CCUS)

Figure 2.1 shows the major CCUS technologies, including CO<sub>2</sub> capture, storage (sequestration), utilization (direct use), and conversion into chemicals and/or fuels.

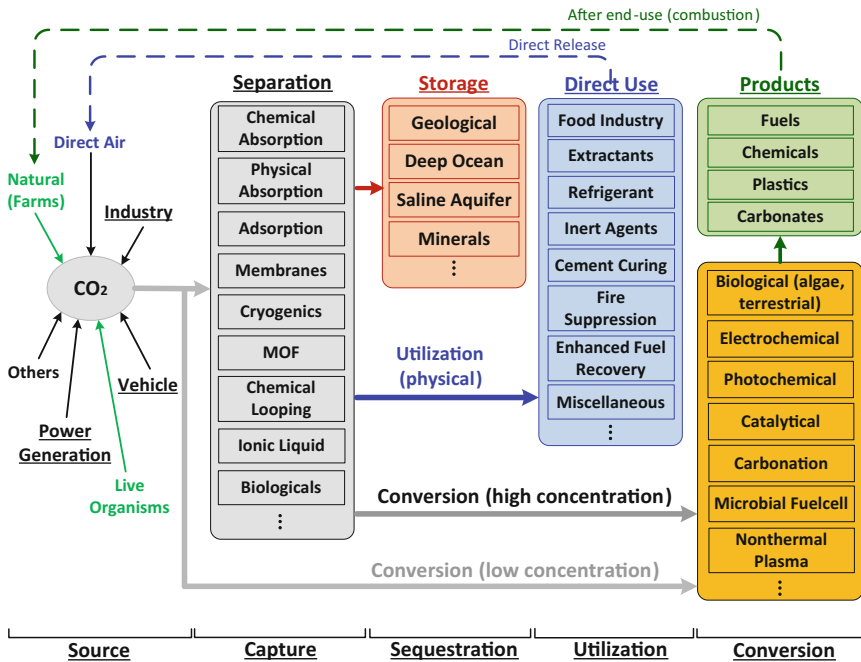


Fig. 2.1 Concepts of post-combustion carbon capture, utilization, and storage (CCUS) technologies

For example, the CCS technologies can effectively capture CO<sub>2</sub> from emission sources, transport it, and then store it at suitable and permanent geological sites.

## 2.2 Post-combustion Carbon Capture and Storage

As the first step for CO<sub>2</sub> capture, dilute CO<sub>2</sub> in flue gas from industries and/or conventional power plants should be separated and concentrated to a high purity in a cost-effective manner with low energy consumptions. After capture, the CO<sub>2</sub> can be stored into geological or saline formations to ensure long-term sequestration. Also, the concentrated CO<sub>2</sub> stream can be directly utilized or converted into carbon-based materials, such as fuels and chemicals.

### 2.2.1 Post-combustion CO<sub>2</sub> Capture Technologies

Figure 2.2 shows various approaches to post-combustion CO<sub>2</sub> capture from flue gas or air. Although various CO<sub>2</sub> capture technologies are available, only a few processes have been deployed on a large scale due to significant mass transfer limitations in the processes and the need to treat a significant amount of flue gas [11]. Therefore, successful development and deployment of CO<sub>2</sub> capture processes have been required for obtaining the breakthroughs in innovative reactor concepts and process schemes as well as advancement for new materials.

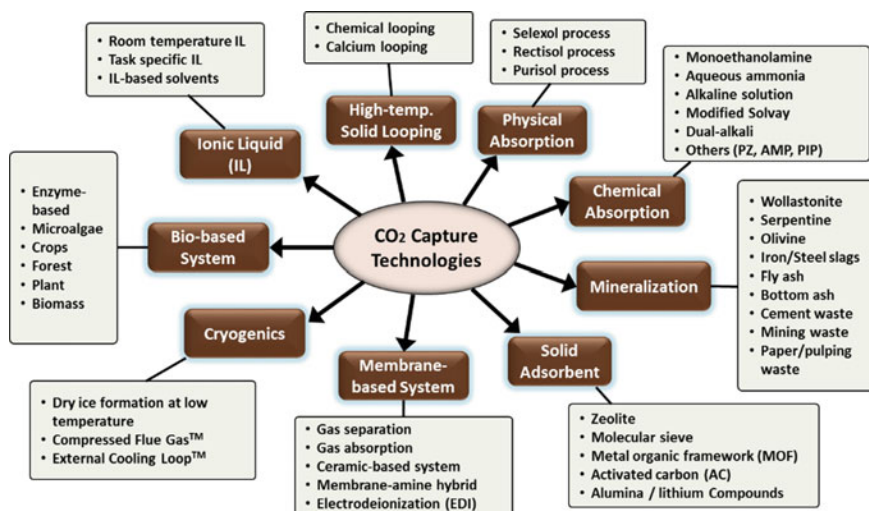


Fig. 2.2 Different approaches to CO<sub>2</sub> capture technologies

In order to achieve the above goals, the dilute CO<sub>2</sub> in flue gas (or air) can be concentrated via various technologies:

- Chemical absorption: alkaline solutions such as NaCl, ammonium solution, and monoethanolamine [11, 12]
- Physical adsorption: zeolite [13], activated carbon [14], and metal-organic frameworks [15]
- Selective membrane separation [16, 17]
- Cryogenic techniques [18]
- Ionic liquid absorption process [19]
- High-temperature solid looping processes: calcium looping [20] and chemical looping [21].

The aforementioned capture technologies can concentrate the dilute CO<sub>2</sub> in flue gas to nearly pure CO<sub>2</sub>. After that, it should take the sequential storage or utilization into consideration. Other approaches of post-combustion capture are integrated with CO<sub>2</sub> utilization including the following:

- Mineral carbonation: natural ores and/or solid wastes [22]
- Biological method: microalgae and enzyme-based processes [23].

Some of the CO<sub>2</sub> capture technologies, such as biological method and mineral carbonation, are related to direct conversion and utilization of CO<sub>2</sub> because the physico-chemical property of CO<sub>2</sub> is changed after capture process. Therefore, no additional CO<sub>2</sub> storage site is required with the capture plant. These two approaches, i.e., biological method and mineral carbonation, are illustrated in detail in the following Sect. 2.4 and Chap. 3, respectively.

### 2.2.1.1 Absorption and Adsorption Processes

Table 2.1 presents the comparison of the post-combustion CO<sub>2</sub> capture technologies by absorption process, such as using aqueous absorbents and ionic liquid (IL). Meanwhile, chemical absorption via aqueous alkanolamine solutions is regarded as the most applicable technology for CO<sub>2</sub> capture by 2030 [24]. It can be accomplished in two stages: (1) CO<sub>2</sub> absorption using an absorbent or solvent, and followed by (2) desorption using pressure, temperature, or electric swing. However, several technological issues, including equipment corrosion, energy consumption in regeneration, and absorber volume, should be critically assessed in using alkanolamine aqueous solutions as absorbents. Thus, a modification and intensification of the absorption process should be considered to enhance the mass transfer between CO<sub>2</sub> gas and solution, for example, a high-gravity rotating packed-bed reactor [25, 26]. In addition, appropriate absorbent genomes, such as using piperazine with diethylenetriamine [27], piperazine with diethylene glycol [28], and NaOH solution [12], are needed to achieve high CO<sub>2</sub> capture efficiency and low regeneration energy.

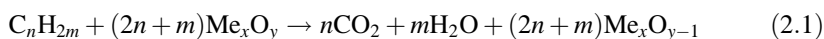
**Table 2.1** Merits and demerits of various physical and chemical absorption processes for post-combustion CO<sub>2</sub> capture

Process description/chemical components	Advantages	Disadvantages
Physical <ul style="list-style-type: none"> <li>• Selexol process</li> <li>• Rectisol process</li> <li>• Purisol process</li> </ul>	<ul style="list-style-type: none"> <li>• Low vapor pressure and toxicity (Selexol)</li> <li>• Low corrosion (Rectisol)</li> <li>• Low energy consumption (Purisol)</li> </ul>	<ul style="list-style-type: none"> <li>• Low absorption capacity</li> <li>• Limited refractory life (Selexol)</li> <li>• High capital and operating costs (Rectisol)</li> </ul>
Chemical <ul style="list-style-type: none"> <li>• Alkanolamine solution (MEA, DEA, and MDEA)</li> <li>• Sterically hindered amine (AMP)</li> <li>• Promoter (PZ, PIP)</li> </ul>	<ul style="list-style-type: none"> <li>• High absorption capacity</li> <li>• Low operating pressure and temperature</li> <li>• Suitable for retrofitting of the existing power plant</li> </ul>	<ul style="list-style-type: none"> <li>• Severe equipment corrosion rate</li> <li>• High energy consumption in regeneration</li> <li>• Large absorber volume required</li> <li>• Amine degradation by SO<sub>2</sub>, NO<sub>2</sub>, and O<sub>2</sub></li> </ul>
<ul style="list-style-type: none"> <li>• Ionic liquid (IL)</li> </ul>	<ul style="list-style-type: none"> <li>• Low vapor pressure</li> <li>• Non-toxicity</li> <li>• Good thermal stability</li> <li>• High polarity</li> </ul>	<ul style="list-style-type: none"> <li>• High viscosity</li> <li>• High energy requirement for regeneration</li> <li>• High unit costs</li> </ul>

Table 2.2 presents the post-combustion CO<sub>2</sub> capture technologies by adsorption process using solid adsorbent and metal-organic frameworks (MOFs). The adsorption processes exhibit a lower CO<sub>2</sub> adsorption capacity, compared to chemical absorption processes.

### 2.2.1.2 Chemical Looping Process

Chemical looping process (CLP) is an advanced combustion process, where CO<sub>2</sub> is inherently separated from the other flue gas components. Oxygen-carrier materials, such as Fe-, Cu-, Ni-, Mn-, and Co-based metal oxides, are frequently used in the transfer of oxygen from combustion air to the fuel. In this case, direct contact between fuel and air can be avoided, thereby resulting in near 100% CO<sub>2</sub> in flue gas. Figure 2.3 shows the schematic diagram of CLP for power generation. Oxygen-carrier material (Me<sub>x</sub>O<sub>y</sub>) is reduced by carbonaceous fuel, such as coal and CH<sub>4</sub>, to generate H<sub>2</sub>O and CO<sub>2</sub> in the fuel reactor, as described in Eq. (2.1).



**Table 2.2** Post-combustion CO<sub>2</sub> capture processes via physical and chemical adsorption

Process description		Advantages	Disadvantages
Physical	<ul style="list-style-type: none"> <li>Activated carbon (AC)</li> <li>Zeolite</li> <li>Mesoporous silica (MS)</li> <li>Metal-organic frameworks (MOFs)</li> </ul>	<ul style="list-style-type: none"> <li>Wide availability and low cost</li> <li>High thermal stability (AC)</li> <li>Low sensitivity to moisture (AC)</li> <li>High pore size and tunable pore size (MS and MOFs)</li> </ul>	<ul style="list-style-type: none"> <li>Low CO<sub>2</sub> adsorption capacity</li> <li>Low CO<sub>2</sub> selectivity</li> <li>Slow adsorption kinetics</li> <li>Thermal, chemical, and mechanical stability in cycling</li> </ul>
Chemical	<ul style="list-style-type: none"> <li>Amine-based adsorbent</li> <li>Alkali earth metal adsorbent</li> <li>Lithium-based adsorbent</li> </ul>	<ul style="list-style-type: none"> <li>Exothermic reaction</li> <li>High adsorption capacity</li> <li>Low cost in natural minerals</li> </ul>	<ul style="list-style-type: none"> <li>Deactivation of synthesis adsorbent</li> <li>Low CO<sub>2</sub> selectivity</li> <li>Serious diffusion resistance</li> </ul>
	<ul style="list-style-type: none"> <li>Alkaline solid waste (steelmaking slag, ashes, etc)</li> </ul>	<ul style="list-style-type: none"> <li>Thermodynamically stable product</li> <li>High availability of wastes</li> <li>Reuse product in a variety of application</li> <li>Decreased leaching of heavy metal trace elements from the wastes</li> </ul>	<ul style="list-style-type: none"> <li>Low CO<sub>2</sub> adsorption capacity</li> <li>Slow adsorption kinetics and mass transfer</li> <li>High energy consumption in crushing</li> </ul>

**Fig. 2.3** Schematic diagram of chemical looping process (CLP) for power generation with high-purity CO<sub>2</sub> production

