



Review: CO₂ capturing methods of the last two decades

S. Kammerer¹ · I. Borho¹ · J. Jung¹ · M. S. Schmidt¹

Received: 14 July 2022 / Revised: 14 November 2022 / Accepted: 18 November 2022
© The Author(s) 2022

Abstract

Due to the annual increase in CO₂ emissions, climate change continues to progress. In order to achieve the goals set in the Paris Climate Agreement, CO₂ capturing measures are necessary in addition to the reduction in carbon dioxide emissions. This review article describes and discusses the CO₂ capturing methods published in the last 20 years. Processes for absorption, gas–solid reaction, adsorption, cryogenic processes, membrane processes and the capture of carbon dioxide with natural inclusion were examined in more detail.

Keywords CO₂ capturing · Pre-combustion · Post-combustion · Oxy-combustion · Absorption process · Processes with gas–solid reactions · Adsorption processes · Cryogenic processes · Membrane processes · Natural inclusion · Carbon capture and utilization · Carbon capture and storage

Introduction

Since the industrial revolution in the 19th century, the level of anthropogenic greenhouse gas emissions in the atmosphere has steadily increased, especially the concentration of carbon dioxide. To prevent global warming from increasing even further, it is necessary to take action to reduce the concentration of carbon dioxide. This can be done, on the one hand, by emitting less carbon dioxide and, on the other hand, by specifically reducing CO₂ emissions. Many methods have been developed over the last 20 years and in the future more possibilities will be explored to recapture the carbon dioxide produced and make it usable.

This article focuses on the different options for CO₂ capture in industrial plants that have been developed over the last 20 years. In power plants, for example, capture can take place before combustion, after combustion or after combustion in the oxygen atmosphere. The individual CO₂ capture methods can then be divided into these three categories. Over 60 articles were reviewed for this paper.

Climate change

Climate change describes the long-term change in the Earth's global climate. This has serious consequences for precipitation and ocean currents, but also for extreme weather conditions and a significant rise in temperature. According to the Paris Climate Agreement, global warming should be limited to well below 2 °C compared to pre-industrial times. A limit of 1.5 °C would be necessary to prevent serious impacts on the global climate. To achieve this goal, a reduction in products or activities that lead to greenhouse gas emissions is necessary. In addition, greenhouse gas-intensive technologies and products should be substituted by greenhouse gas-neutral ones. A third approach is to reduce the carbon dioxide concentrations already emitted in the atmosphere. This can be achieved by specifically capturing the carbon dioxide from the exhaust gases and the air (Umweltbundesamt. 2022).

Figure 1 shows the global carbon dioxide emission by sector in 2018. The electricity and heat generation has the most emissions with 42%. Transport is responsible for a quarter of the emissions and the industry for nearly one fifth. 6% of emissions are caused by housing and 5% by other energy production. Commercial and public services cause the smallest share of emissions. These figures show that carbon capturing methods in power plants are very useful, as they produce the most carbon dioxide.

Editorial responsibility: Binbin Huang.

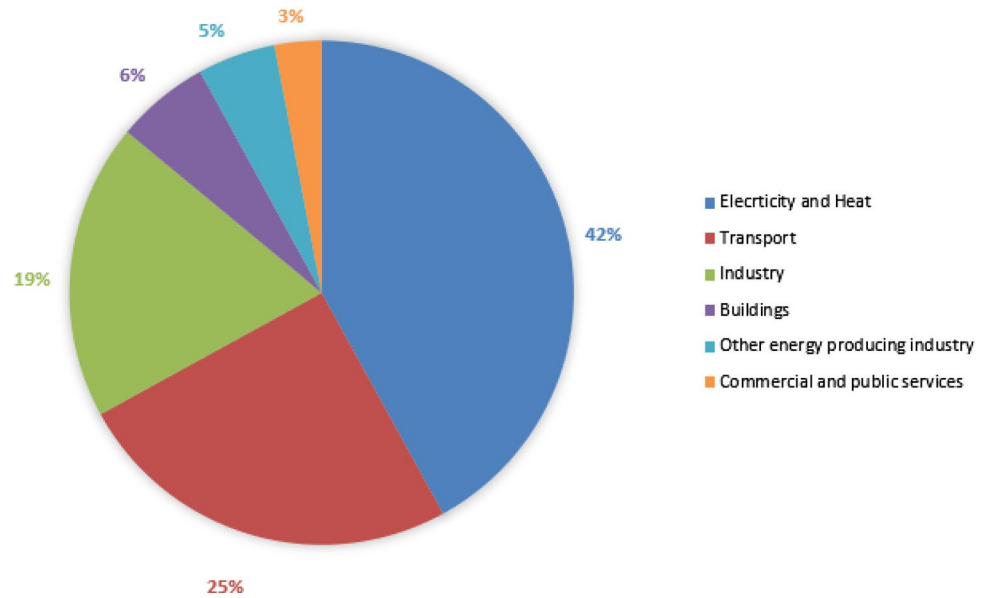
✉ M. S. Schmidt
magnus.schmidt@hs-furtwangen.de

¹ Institute of Precision Medicine, Organic and Bioorganic Chemistry Labs, Medical and Life Sciences Faculty, Furtwangen University, Jakob-Kienzle-Str. 17, 78054 VS-Schwenningen, Germany



Fig. 1 Distribution of energy-related CO₂ emissions worldwide by sector in 2018. (IEA 2018)

CO₂ EMISSIONS WORLDWIDE: SHARE OF POLLUTERS 2018



CO₂ capturing in power plants

Carbon dioxide can be separated in power plants using various methods. The separation systems can be divided into three different categories: Pre-combustion, post-combustion and oxy-combustion. These three strategies to capture the carbon dioxide emissions are described below.

Pre-combustion

In pre-combustion, carbon dioxide is separated before the combustion process.

Figure 2 shows a flow diagram of a power and heat generation process using the pre-combustion method. Carbonaceous fuel is heated to 1000–1700 °C with oxygen and hydrogen. In the gasifier reactor, synthesis gas is thus produced under elevated pressure. This consists mainly of hydrogen and carbon monoxide. With further processing steps, the synthesis gas is converted into CO₂ and hydrogen with the addition of steam. Wet gas scrubbers are then used to separate the CO₂ from the hydrogen (Madejski et al. 2022).

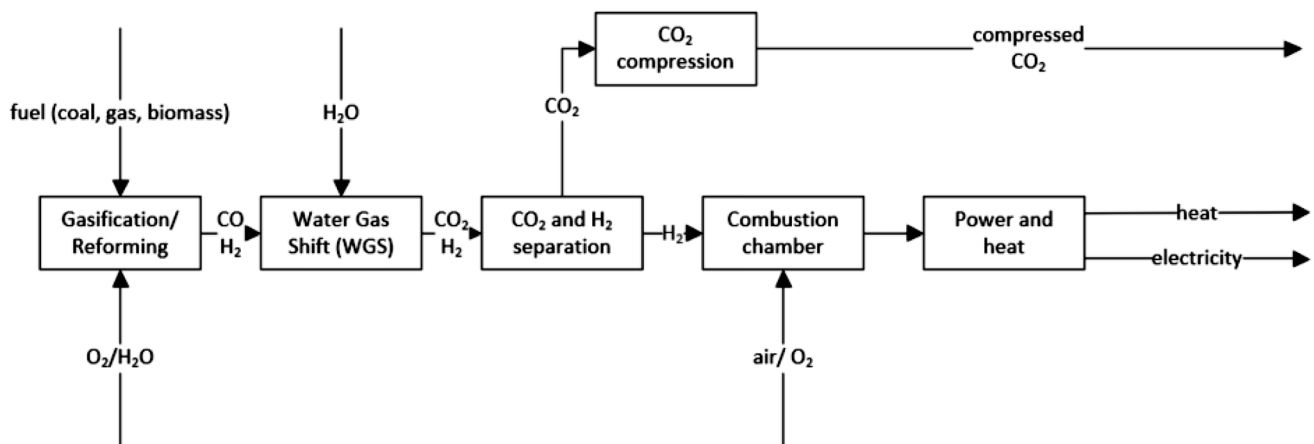


Fig. 2 Pre-combustion. (Madejski et al. 2022)



Post-combustion

In post-combustion, the carbon dioxide is separated after combustion.

Figure 3 shows a flow diagram of a power and heat generation process using the post-combustion 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 CO_2 is attached to solids. Membrane technologies can also be used for post-combustion. In this process, the gas mixture is separated by a membrane. (Fischedick et al. 2015)

Oxy-combustion

Carbon capture by oxy-combustion occurs after the combustion process in the oxygen atmosphere.

Figure 4 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 (Fischedick et al. 2015).

CO_2 capturing methods

Carbon dioxide can be separated using various methods or processes.

Figure 5 shows an overview of the different methods of CO_2 capturing. They can be subdivided into absorption process, processes with gas–solid reactions, adsorption processes, (Figs 6, 7, 8) cryogenic processes, membrane processes and natural inclusion. The individual methods are explained in detail in the following subchapters.

Absorption process

In absorption, a component of a gas phase is transferred into a liquid or a solid. The aim is to remove the component from the gas phase as selectively as possible through the absorbent. In the case of absorption, a distinction is made between chemical absorption (Chemisorption) and physical absorption (Physisorption). (Schwister and Leven 2020)

Chemical absorption

The chemical absorption (Chemisorption) is commonly used in post-combustion capture. In the process, a chemical reaction of the component to be absorbed occurs in the liquid. (Schwister and Leven 2020) The chemical absorption methods are the most frequently used CO_2 separation methods. The main advantage of chemical absorption is the

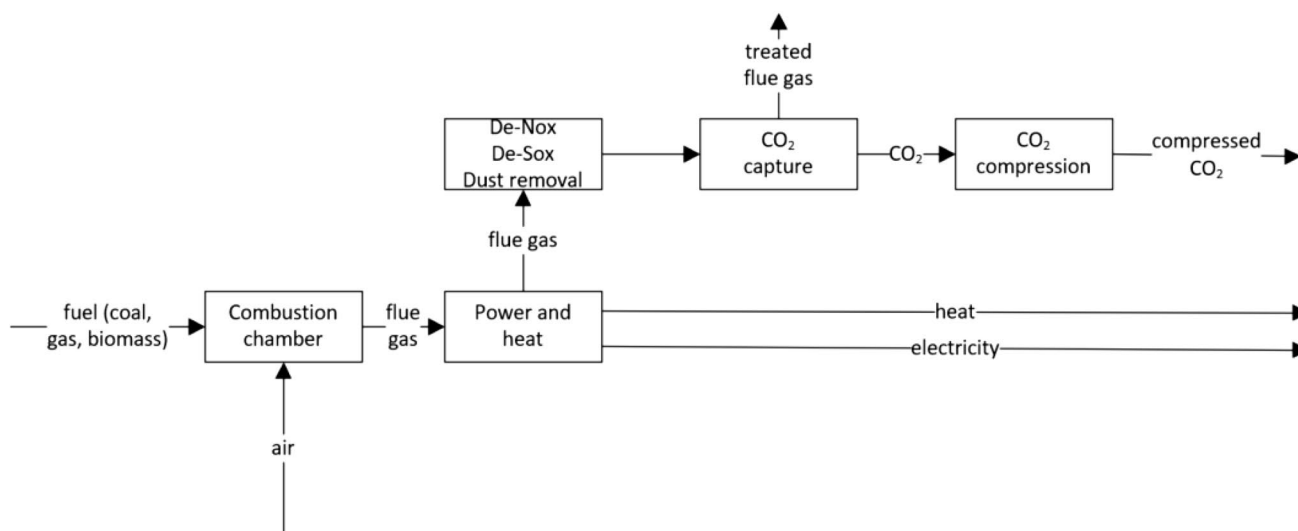


Fig. 3 Post-combustion. (Madejski et al. 2022)



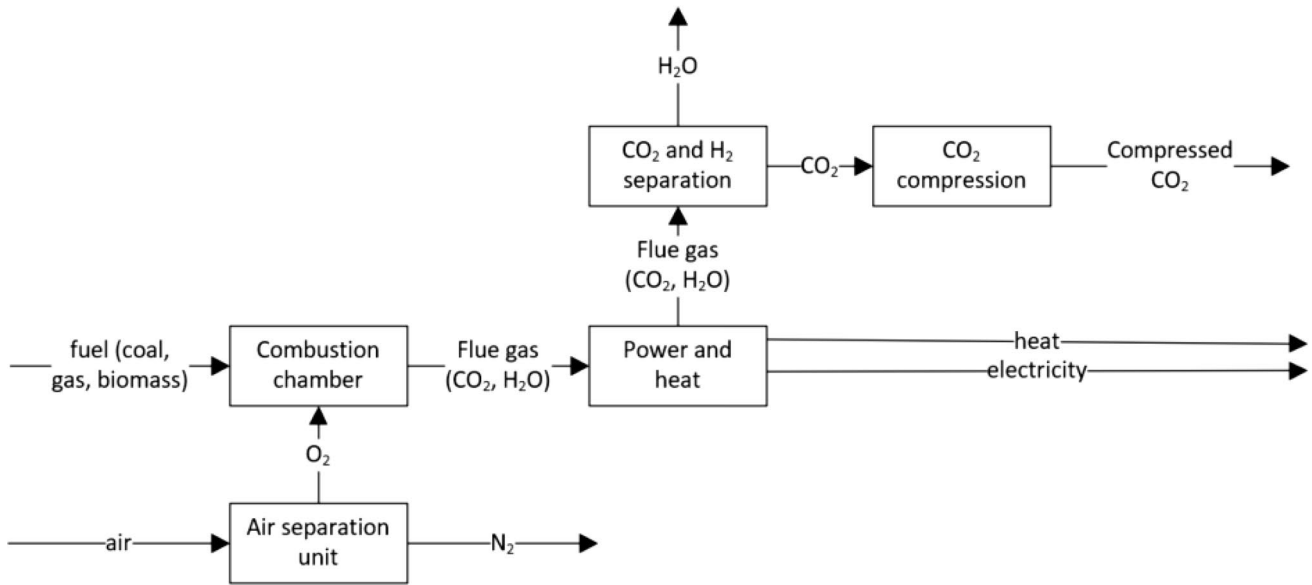


Fig. 4 Oxy-combustion. (Madejski et al. 2022)

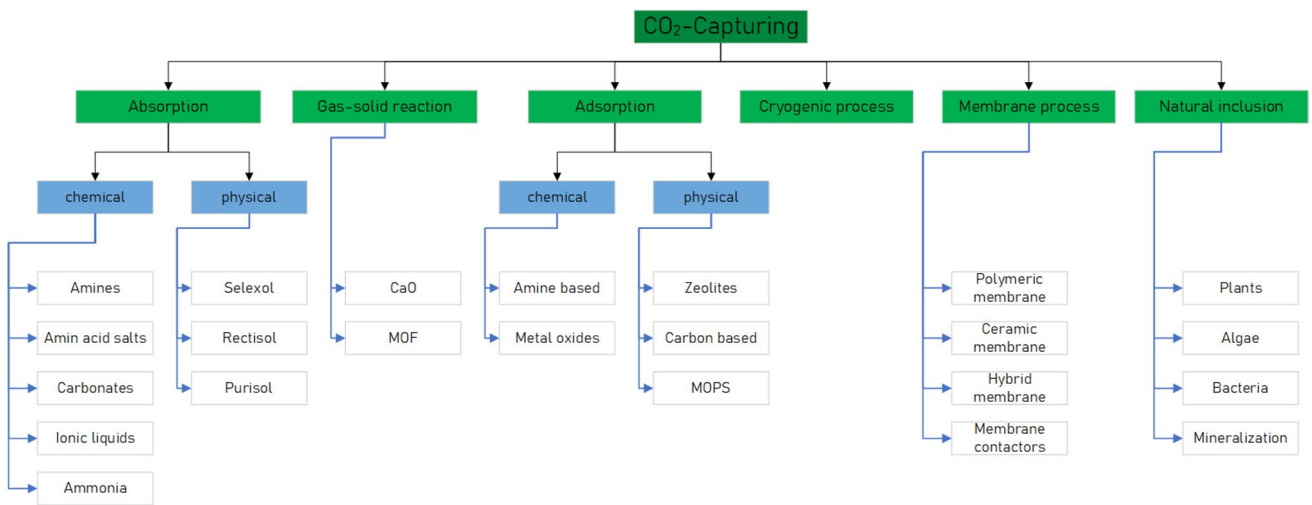


Fig. 5 Overview of CO₂ capturing methods. (Madejski et al. 2022)

high purity of the carbon dioxide product stream (more than 99% CO₂). Thus, no further purification step is necessary. However, a high energy requirement is needed for the downstream detergent regeneration step. (Fischedick et al. 2015)

Amines

Amine scrubbing is a method for CO₂ separation. Monoethanolamine (MEA) and methyldiethanolamine (MDEA) can be used for this procedure. In this process, the gas to be purified flows into a container at elevated pressure. Finely distributed droplets of the amine absorber are sprayed into it.

The carbon dioxide first dissolves in water and is then bound to monoethanolamine in a chemical reaction. The remaining gas is thus purified of CO₂. (scinexx | Das Wissensmagazin. Einfach rauswaschen. 2021)



In the following step, the amine solution loaded with CO₂ is heated and decompressed at low pressure. The counter-reaction thus promoted can now take place and the carbon dioxide is released again. The released amine can be used for another wash. (scinexx Das Wissensmagazin. Einfach rauswaschen. 2021)



Fig. 6 Principle of amine washing. (Schwister and Leven 2020)

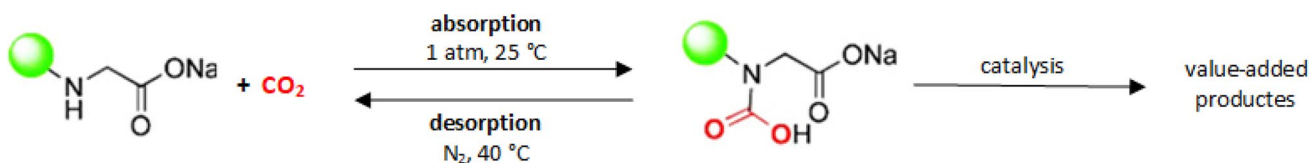
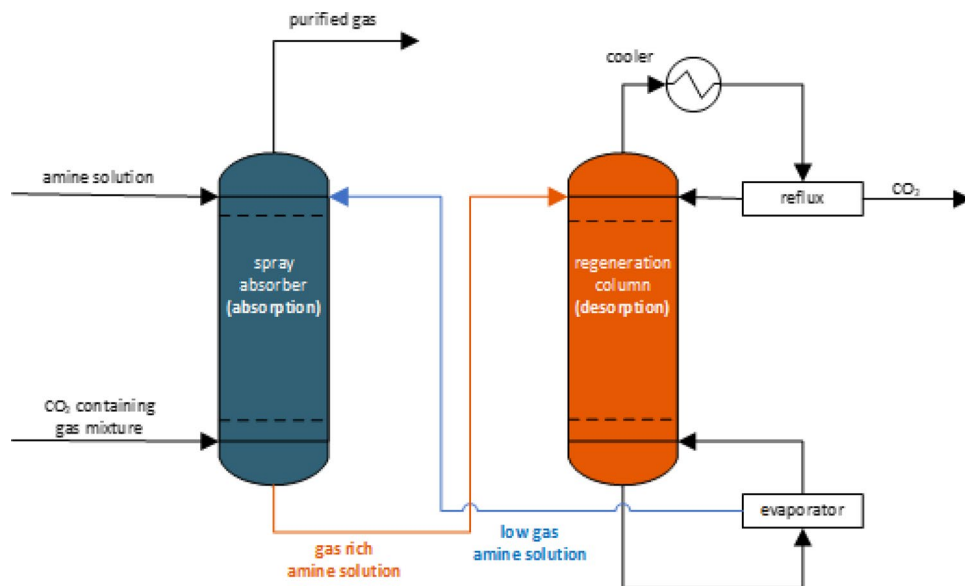
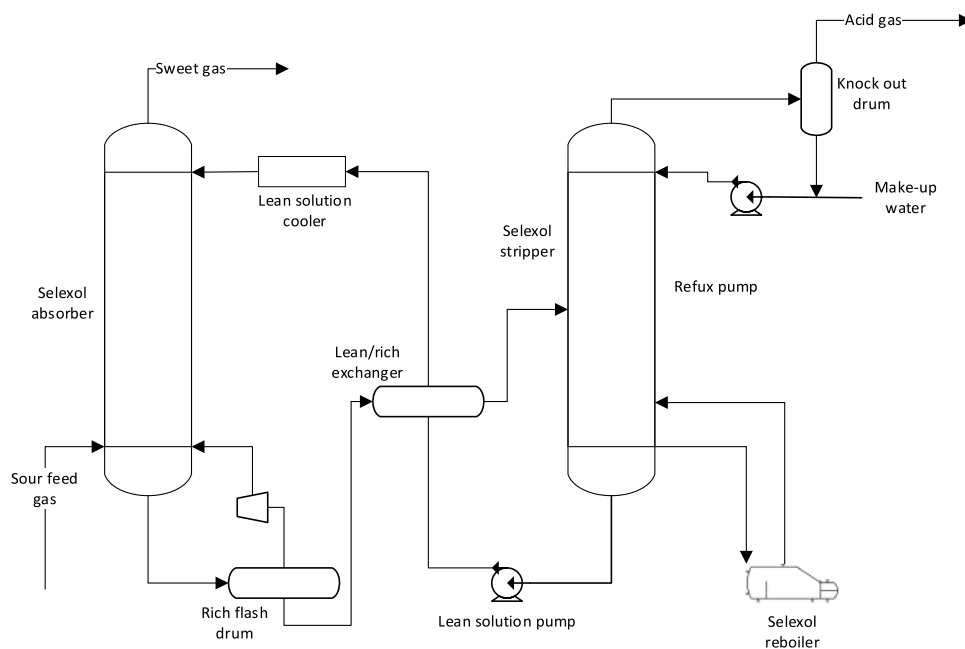


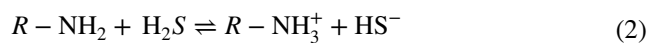
Fig. 7 Reaction of the N-substituted amino acid with carbon dioxide. (Liu et al. 2012)

Fig. 8 Schematic diagram of typical Selexol process. (Ghasem 2020)



Amine scrubbing is well suited for clean gases with high carbon dioxide content. If there are a lot of nitrogen oxides or sulphurous gases, these react with the amine and reduce the efficiency. In this case, it would be necessary to purify

the gas of nitrogen oxides and sulphur-containing gases in advance. (Schwister and Leven 2020)



The publication by Daneshvar et al. (2004) shows that the process can be optimized by using amine mixtures. For example, with MDEA + PZ (piperazine) the disadvantage of slow absorption kinetics of MDEA can be compensated by the fast reaction kinetics of the activator PZ. (Daneshvar et al. 2004)

Amino acid salts

An alternative to the amines are the amino acid salts. To increase solubility, the amino acids are neutralized with a powerful base such as sodium or potassium hydroxide. Alternatively, the salt of the amino acid can be used directly. (Fischedick et al. 2015)

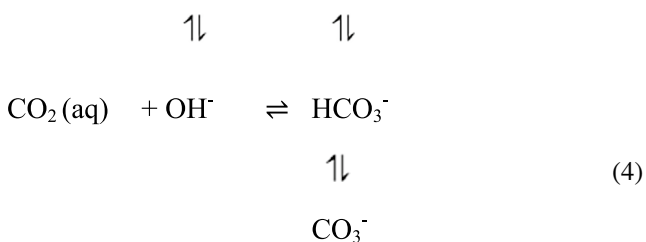
In the publication by Liu et al. N-substituted amino acid salts are used for the separation of carbon dioxide. The N-substituted amino acid salts are dissolved in polyethylene glycol. These reversibly absorb carbon dioxide in a 1:1 ratio. The absorbed carbon dioxide was converted into oxalidionones. Desorption of the CO₂ was thus circumvented. (Liu et al. 2012)

The use of amino acids has the advantage that they are stable against oxidative and thermal degradation. In addition, they have only a low toxicity. (Madejski et al. 2022)

Carbonates

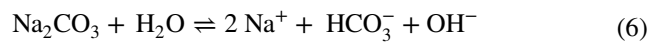
Carbonates represent another possibility for chemical absorption.

Absorption of carbon dioxide in aqueous solutions



The above reactions show the equilibrium reactions in the absorption of carbon dioxide in aqueous solutions. The reaction rate of carbon dioxide absorption is limited by the rate of hydrogen carbonate formation. (Fischedick et al. 2015)

Reactions in aqueous carbonate solutions



Alkaline salt solutions such as potassium carbonate solution and sodium carbonate solution are mainly used for the separation of CO₂ because of their basic character. (Fischedick et al. 2015)

The Benfield process (hot potash wash) uses a potassium carbonate solution.



During absorption, elevated temperatures (> 60 °C) are used for the potash solution to avoid precipitation of the salt. The process is done at an increased pressure (> 20 bar), which leads to an improved mass transfer. In addition, enhancers are added to accelerate the formation of the hydrogen carbonate ions via the formation of carbamate ions. (Erich et al. xxxx)

With the help of additives such as piperazine, an even better mass transfer can be achieved. However, this substance should be used in high dosages, which requires additional measures to reduce emissions. (Hilliard and Rochelle 2004) After absorption, regeneration follows at a temperature of approx. 130 °C (Erich et al. xxxx).

Ionic liquids

Ionic liquids (ILs) are salts in liquid state or highly concentrated aqueous salt solutions, which consist of anions and cations. (Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen INT. Ionische Flüssigkeiten - Fraunhofer INT. 2022) When using ionic liquids for CO₂ capturing, the vapour pressure can be neglected, furthermore they are minimally flammable, dissolve CO₂ very well and are thermally and chemically stable. (Pakzad et al. 2020)

Ionic liquids can be classified into three groups: Room Temperature Ionic Liquids (RTILs), Task Specific Ionic Liquids (TSILs) and Supported Ionic Liquid Membranes (SILMs). RTILs are made of organic cations and organic or inorganic anions. TSILs behave like chemical solvents at low pressures (> 1 bar) and can absorb up to three times more CO₂ than RTILs. At high temperature and pressure, a mixture of TSILs and SILMs may be a suitable alternative for carbon dioxide capture. (Pakzad et al. 2020)

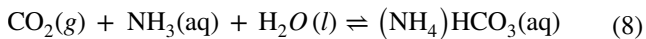
The properties of ionic liquids can be modified by various mixtures of anions and cations. (Pakzad et al. 2020) Furthermore, these substances are very well suited for the incorporation of reactive substituents. For example, the integration of an amine group can significantly improve the CO₂ absorption properties. (Fischedick et al. 2015)



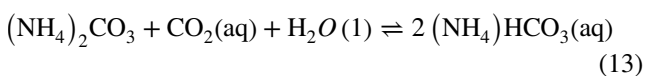
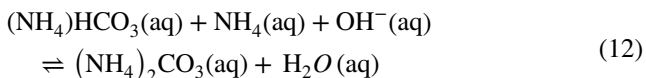
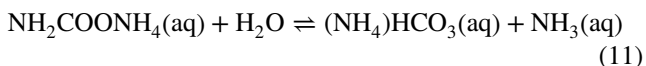
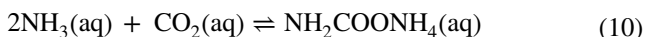
Ammonia

Ammonia scrubbing is a chemical absorption process. The carbon dioxide first passes from the gas phase into the liquid phase due to the partial pressure gradient. After hydrolysis of CO₂, it reacts with NH₃ in an aqueous environment to form an ammonium carbamate compound. (Fischedick et al. 2015)

Overall reaction



Individual reactions



The reactions in the solution are reversible. The chemical equilibrium depends on the temperature and the concentration. Therefore, a low temperature (0–10 °C) is set for absorption, because the equilibrium of reactions 3–8 is on the right side of the reaction equation. (Fischedick et al. 2015)

With a high temperature, the chemical equilibrium is on the left side. Therefore, a temperature > 120 °C is set during the subsequent regeneration. The carbon dioxide is released from the liquid phase again. The gaseous CO₂ is collected and compressed for transport. (Pieper and EnArgus.)

Compared to amine scrubbing, ammonia scrubbing requires less energy. However, low absorber temperatures are required to limit ammonia losses. (Pieper and EnArgus.)

Physical absorption

The physical absorption (Physisorption) is commonly used in pre-combustion capture. It is based on physical interactions (Van der Waals forces). Since these bonds are only very weak, the absorption process can be reversed (desorption). This requires changes in pressure and temperature. To dissolve a high amount of gas in liquid high partial pressures are necessary and low concentrations of the dissolved gas in the liquid. (Schwister and Leven 2020)

Different detergents are used for physical washing.

Table 1 shows a comparison of the process conditions and selected physical/chemical properties of three physical solvents used on a large scale. The solubility of carbon dioxide is specified at 25 °C. For methanol, the solubility was indicated at –25 °C because it is highly volatile. (Fischedick et al. 2015)

Selexol

A physical absorption method is the one used with Selexol. For this, dimethyl ether of polyethylene glycol is used as the absorbent. The carbon dioxide and sulphur compounds are removed with water and aromatic compounds. (Ghasem 2020)

Before the gas stream enters the Selexol unit, it is dehydrated. On the one hand, the gas stream is thus dried out and, on the other hand, the acid gas is removed. At the bottom of the Selexol absorber, the gas then enters the unit and rises upwards, while the solvent enters at the top and flows downwards. Via physical absorption, the carbon dioxide is thus purified and leaves the plant at the top. The spent solvent leaves the plant at the bottom of the absorber and is reintroduced at the top after recycling. (Ghasem 2020)

The advantage of the Selexol process is that little or no energy is required. The process can also be carried out with or without cooling. However, the process is not suitable for streams with high hydrocarbon content or low acid gas partial pressures. (Ghasem 2020)

The process can be used in the cement industry, for example. In the research work by Tsunatu et al. (2015), the Selexol-based CO₂ capturing method was technically evaluated. The simulation results showed that 97% of the carbon

Table 1 Comparison of detergents for physical gas washes. (Fischedick et al. 2015)

	Selexol	Rectisol	Purisol
Detergent	Polyethyleneglycol dimethylether	Methanol	N-methyl-2-pyrrolidone
absorber pressure	> 20 bar	> 20 bar	> 20 bar
absorption temperature	– 40 °C	– 70– – 10 °C	– 40–20 °C
CO ₂ solubility (m ³ CO ₂ /m ³ solvent) (25 °C, 1 bar)	3,628	13,458 (– 25 °C)	3,568



dioxide can be captured. The Selexol method was able to reduce CO₂ emissions from 4.86 to 0.13% in the simulation of the Ashaka cement plant. (Tsunatu et al. 2015)

Rectisol

In the rectisol process, the solvent methanol is used to remove carbon dioxide from the synthesis gas. It was developed independently by the two companies Linde and Lurgi. Absorption in the rectisol wash occurs at a temperature of $-50\text{ }^{\circ}\text{C}$ to limit losses of the detergent. A refrigeration system is required for the low operating temperatures. The subsequent desorption is done with nitrogen and temperature change. The detergent loaded with carbon dioxide is thus regenerated (Pieper and EnArgus.).

Figure 9 shows the process flow diagram of the simplified Rectisol Process. Because the focus of this process is on the recovery of H₂, the required purity is not achieved in

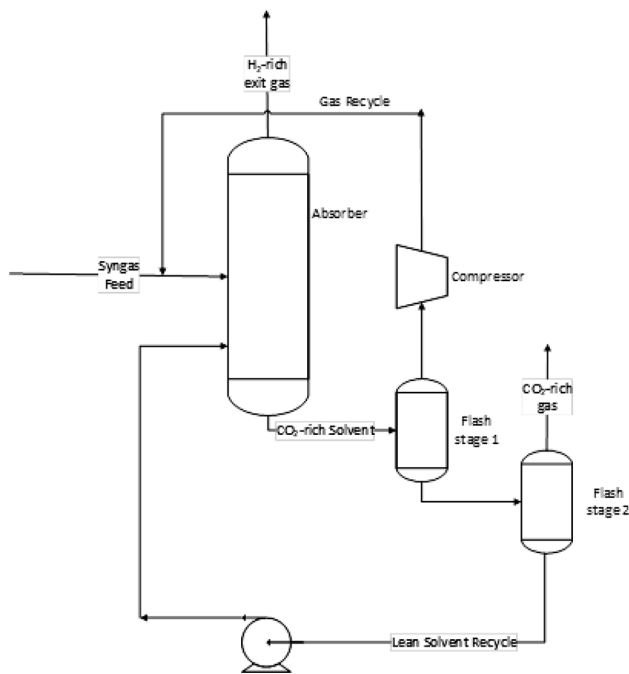
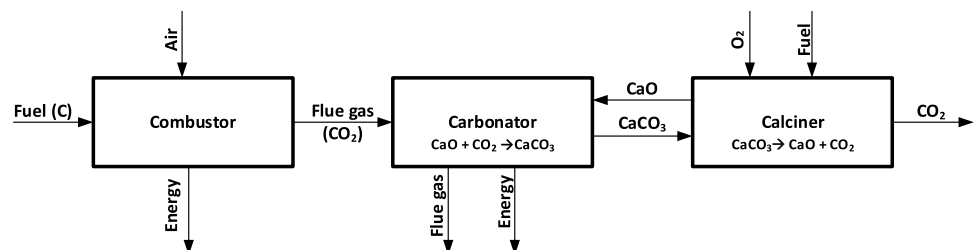


Fig. 9 Process flow diagram of the simplified Rectisol Process. (Scholes et al. 2013)

Fig. 10 Schematic representation of CaO-looping. (Manovic and Anthony 2010)



the separation of the CO₂. If a CO₂-selective membrane is used, a higher purity can be reached. (Scholes et al. 2013)

Purisol

The Purisol process was developed by the Lurgi Company and is particularly suitable for cleaning synthesis gas in gas turbines with integrated gasification (IGCC systems). A mixture of N-methyl-2-pyrrolidone (NMP) and water is used as the absorbent. (Fischedick et al. 2015)

Absorption usually proceeds at ambient temperature (although temperatures as low as $-40\text{ }^{\circ}\text{C}$ are also possible) and at a pressure of about 70 bar. Desorption is then carried out by reducing the pressure and boiling out the solvent. (Fischedick et al. 2015)

Processes with gas–solid reactions

Solids like metal oxides, zeolites or metal organic frameworks (MOF) can be used for carbon capture. MOF consists of hydrocarbon framework with embedded metal ions to achieve selectivity towards certain molecules. Solids in general are compact, have a high absorption speed and can bind more carbon dioxide per volume unit than liquid solutions.

CaO

The CaO-looping method can be also used for carbon capture. Limestones are used as a source of CaO. The sorbent circulates between two connected fluidized bed reactors. The CaO looping process is shown schematically in Fig. 10. Flue gas is fed into the carbonator which consists of a material based on CaO. The carbon dioxide reacts fast with the CaO by high temperatures around 580 to 700 °C to calcium carbonate. In the calciner the regeneration of CaO takes place and a concentrated carbon dioxide steam is produced. (Erans et al. 2016)

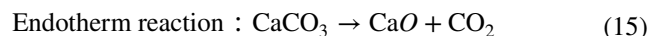
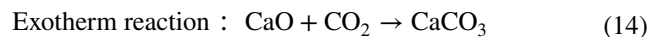
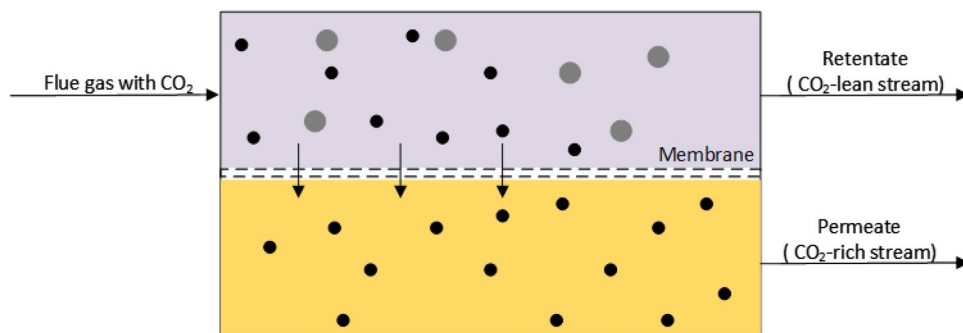


Fig. 11 Schematic of membrane-based CO₂ separation process from flue gas streams. (Khalilpour et al. 2015)



The temperature of the exothermic reaction is a limited factor. If the temperature is too high, no reaction takes place. (Erans et al. 2016)

Sulphur dioxide is also a component of flue gas and reacts irreversibly with CaO to calcium sulphate. This leads to a reduced carbon dioxide binding capacity on the surface of the CaO. Other sintering processes occur while the calcination because of high steam pressure or carbon dioxide partial pressure. (Erans et al. 2016)

Research to improve the process has been done. Limestones from different regions were used. A steam reactivation was performed in which the sorbent was hydrated by water steam. This led to a higher activity and to a better sorbent property. A thermal pre-treatment with different temperatures and time periods to stabilize the morphology of the sorbent has also been investigated. Not all limestones showed improved results. A palletization with aluminate-based cements leads to a loss of activity by high temperatures. The pellets can be formed new when reactivated with water and many cycles can be done. The palletization causes the formation of macropores and mesopores. The different methods are promising, and a combination of these methods seems to improve the performance of the sorbent. (Manovic and Anthony 2010)

MOF

MOFs are porous and crystalline. They consist of metal ions or metal group peaks which are connected by organic linkers. Selectivity, pore shape and size, capacity, kinetics and adsorbing surfaces can be easily adjusted. (Yaumi et al. 2017)

With functional groups the organic linkers can be modified to adjust the electric potential of the surface. Functional groups, organic linkers and inorganic nodes can be combined to obtain the desired properties. For carbon capture and separation by adsorption MOFs are seen as some promising possibilities. To develop efficient MOFs different strategies have been suggested. For example, the integration of amines, the addition of functional groups, the control of

the pore size and the addition of extra metal cations. (Wang et al. 2018)

MOFs can also be used in combination with water-dispersible nanocatalysts for the desorption reaction of carbon dioxide, which greatly reduces the energy required. This contributes to an energy-efficient carbon capture. Therefore, acidic Fe₃O₄ nanoclusters were used as substrates for the modulated self-assembly of various MOFs. The presence of carboxylates on the core surface promotes the formation of active mesoporosity throughout the network of assembled MOFs. The mesoporous shell created in this way simplifies the subsequent coordination of chelating sulphate groups on the metal clusters and enables a higher density of Brønsted acid sites. The water-dispersible Fe₃O₄@MOF-SO₄ nanocatalysts can actively contribute to carbon dioxide desorption reactions (Fig. 11). The energy consumption required for desorption is strongly reduced in this process. (Alivand et al. 2022)

Adsorption processes

In an adsorption process, components of a gas phase attach themselves to the solid surface. In the case of physical adsorption, the substances are bound to the surface of the solid by London dispersion forces, whereas in the case of chemical adsorption, the molecules form a chemical bond (covalent or ionogenic) at the phase interface. It is important that the adsorbents, in addition to their chemical properties, have a large surface area in relation to their mass. Furthermore, the adsorbent should have availability, CO₂ selectivity, high stability, easy regeneration, low cost and sufficient adsorption capacity (González et al. 2013). (Fischedick et al. 2015)

Chemical adsorption

In chemical adsorption, chemical bonds such as ionogenic or covalent bonds are formed between the adsorbed substance and the surface of the solid. (Schwister and Leven 2020)



Amine-based adsorbents

Amines are used to functionalize solid porous materials. A high density of amine groups on the carrier material is desired. Solid adsorbents functionalized with polymeric amines can be used for this purpose. Examples of polymeric amines being investigated are polyaniline, polyethyleneimine, polyallylamine, polypropyleneimine, amino-dendrimers or hyperbranched polyamines. (Varghese and Karanikolos 2020)

Metal oxides

For the adsorption of CO₂ with metal oxides activated aluminium oxide modified with sodium hydroxide can be used. The use in a fixed bed column adsorption system was investigated at different temperatures, time periods and sodium hydroxide concentrations (Auta et al. 2013).

Also, CO₂ capture can be performed with a mesoporous alumina produced by a sol–gel process. The mesoporous alumina has a large surface area and large pore volumes. The pores are also closely distributed. There are both chemical and physical adsorption sites for CO₂ on the surface (Chen and Ahn 2011).

Physical adsorption

Physical adsorption occurs when the substances to be adsorbed are bound to the surface of the solid by van der Waals forces (Schwister and Leven 2020).

Pressure vacuum swing adsorption (VSA) is a physical adsorption process for separating gas compounds. For this method the use of zeolite (Campo et al. 2016) or activated carbon (Shen et al. 2011; Xu et al. 2013) were investigated. When using a single VSA stage, a significantly lower vacuum is necessary to achieve the specific carbon dioxide product purity required for acceptable carbon dioxide recovery (Bui et al. 2018).

Temperature swing adsorption (TSA) is a physical adsorption process for separating gas components using thermal energy (Bui et al. 2018). Improved cycles for TSA operation have been developed with regeneration energies comparable to those of solvent-based processes. Furthermore, additional cleaning and recycling steps and reheat were used to produce CO₂ with very high purity and high recovery. The adsorbent chosen was 13 × -zeolite. This zeolite strongly adsorbs water, which reduces its CO₂ capacity. Therefore, the flue gas stream had to be dried before the TSA. This additional drying step increases the energy demand of the TSA and is therefore not well suited for large-scale CO₂ capture. Adsorbents that do not adsorb water should therefore be used (Joss et al. 2017).

Zeolites

Zeolites can be produced synthetically or naturally and are microporous and crystalline silicate framework materials. They have a uniform pore size (0.5–1.2 nm) and are connected by a channel network. Alkali and alkaline earth cations have been incorporated into chabazite zeolites studied for carbon dioxide capture. Chabazite zeolites with sodium and calcium had advantages in high temperature separations and the NaX zeolite showed good results in low temperature separation (Zhang et al. 2008). CO₂ adsorption with zeolites depends on their structure, framework composition, shape, size, purity, polarity and cationic states. The underlying mechanism of CO₂ adsorption is a linear orientation through an ion–dipole reaction (Montanari and Busca 2008). Another mechanism is the selective adsorption of molecules with large energetic dipole and quadrupole moment. CO₂ has a high quadrupole moment that can interact with the electron field generated by the structural cations of zeolites (Coriani et al. 2000). CO₂ adsorption is influenced by pressure and temperature. A pressure of over 2 bar is used. With increasing temperature, the adsorption capacity of the zeolites decreases, as does moisture in the gas to be captured (Yaumi et al. 2017).

Carbon based

Carbon-based substances can also be used as adsorption agents. For example, sustainable carbon adsorption agents were produced from biomass residues. The activation was carried out in a single step with CO₂ and was optimized to create narrow micropores, which increases the adsorption capacity. Dynamic initial experiments in a fixed-bed adsorption system demonstrated rapid adsorption and desorption kinetics and high CO₂ selectivity. The tested adsorption agents can separate a mixture of 14% CO₂ with residual N₂ at 50 °C and are easily regenerated. (González et al. 2013)

Graphene is the two-dimensional form of carbon, it has a planar hexagonal arrangement and is stable under ambient conditions (Katsnelson 2007). The adsorption capacity of graphene also decreases at higher temperatures. By using graphene-based nanocomposites, this problem can be circumvented. Iron oxide (Fe₃O₄) particles can be dispersed on the graphene surface, ensuring adsorption capacity even at high temperatures. (Mishra and Ramaprabhu 2014) Graphene can also be used to produce very thin filters with specific pore sizes for CO₂ molecules for application as membrane technology for CO₂ capture (Huang et al. 2021).



MOPS

Microporous organically pillared layered silicates (MOPS) are besides MOFs another class of microporous hybrid materials. The synthesis of MOPS is done by a one-pot ion exchange of (metal) organic cations with layered silicates (clays). The resulting pores are slot-shaped and non-spherical. The slot height and pore width are independently adjustable. Only carbon dioxide molecules can enter the pore system, all other flue gas components remaining in the flue gas flow. The separation performance of the tested a MOPS-7 (pillared with 1, 4-diammoniumbutane dictation) is based solely on physisorption, allowing regeneration with helium flushing. MOPS-7 has an increased carbon dioxide affinity under dynamic process conditions because of optimal pore properties such as size and polarity. Methane and nitrogen are excluded by the low pore height of MOPS-7. This material can be used for membrane systems. (Rieß et al. 2020)

Cryogenic processes

In the cryogenic process, the carbon dioxide is physically separated from the flue gas or exhaust gas. This can be done by condensation, sublimation or distillation. The precondition for a cryogenic process is that the sublimation temperature of the CO₂ is lower than the sublimation temperature of the other gas component. (Madejski et al. 2022)

The higher the carbon dioxide concentration (above about 70%) in the gas, the more cost-effective this method becomes. To produce liquid CO₂, the cryogenic CO₂ capture systems are also attractive because the transport by pumping of liquid CO₂ requires less energy. A hybrid process consisting of an adsorption process followed by a cryogenic process is therefore an ideal solution. (Bui et al. 2018)

The CryoCell® technology is used to remove carbon dioxide from natural gas in a liquid form. Another component of natural gas is methane. This method uses the different sublimation point of carbon dioxide and methane. A solid phase with pure carbon dioxide is generated at specific temperature and pressure conditions. A dense phase with a high percentage of carbon dioxide and a light phase with a low percentage are created. In a separator vessel the phases are subjected to physical separation. In the bottom of the vessel the solid carbon dioxide is collected and is melted there. This process can be adapted for different carbon dioxide concentrations in the natural gas. (Hart and Gnanendran 2009)

Commercially, separation using the cryogenic process takes place for waste gas streams with more than 90% CO₂, because the process is only economically efficient above this concentration. This process is also limited by the high

energy input required for cooling. They are compatible with pre-combustion or oxygen-fired combustion processes. Due to the high cooling costs, processes must be developed to reduce these costs. (Sanni et al. 2021)

For example, the cryogenic process for CO₂ capture from a flue gas has been investigated. The flue gas is generated from a liquefied natural gas (LNG)-fired power plant, which allowed the cold energy of LNG to be used. The process did not require an excessive amount of LNG to be gassed and 90% CO₂ could be recovered at temperatures of -140 °C. (Xu and Lin 2017)

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 (Madejski et al. 2022).

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 (Brunetti et al. 2010).

Membranes should have the following characteristics to capture carbon dioxide. The membranes should be resistant to ageing and plasticization. They should have a high carbon dioxide/nitrogen selectivity and a high carbon dioxide permeability. Furthermore, the membranes should be cost-efficient and also be able to be used for different membrane components (Powell and Qiao 2006).

The use of this method is efficient for selective membranes and a sufficient large concentration gradient. A low carbon dioxide partial pressure leads to a loss of energy efficiency. New materials for membranes with optimized separation characteristics and an improved process design are important. Also a combination of membrane separation with other carbon capture methods is useful (Mat and Lipscomb 2017).

Some membranes are naturally hydrophobic and therefore cannot be used for carbon dioxide capture without modifications. The performance can be increased by modifications in chemical and thermal stability, material selection, thickness, durability, permeability and surface area (Sanni et al. 2021).

Polymeric membrane

Block polymer system copolymers are made of hard and soft blocks. The hard block forms glassy segments and the



soft block rubbery segments. Good separation with no loss of permeability is ensured by a good ratio between these two components of the copolymers. The rubbery segments ensure a higher free volume which leads to a better gas permeation. One advantage of copolymers is that an effective and costly polymer can be combined with a cheaper monomer to reduce costs. Polymers like polycarbonates, polyimides and polysulfones are used for membranes. They are characterized by a good performance and offer a big range for structural variability. Polyimides are the most researched polymer class, because of their gas transport characteristics, good physical characteristics, simple production and potential structural variabilities. Besides synthetic strategies the polymer packing can affect permeabilities in a variety of manners. If the polymer chains are densely packed, the selectivity gets greater but the permeability less (Powell and Qiao 2006).

Ceramic membrane

Ceramic-carbonate double-phase membranes consist of a two-layer structure composed of a thick large-pore base and a thin small-pore ceramic top layer. The ceramic top layer is infiltrated with carbonate, making it gas tight. This thin and non-porous layer ensures the selectivity of CO₂ permeation. The permeability at high temperatures of two-phase membranes consisting of ionic or mixed conductive ceramic phase and molten carbonate phase is only given for CO₂. The CO₂ permeability can be maximized by configuring the microstructure of pores and solids of the ceramic support material (Lu and Lin 2013; Ortiz-Landeros et al. 2013).

Hybrid membrane

Mixed matrix membranes (MMMs) are produced from hybrid materials and can improve the separation performance of polymer membranes while maintaining their advantages such as low cost and ease of processing. The addition of porous nanofillers can improve the selectivity, permeability and stability of polymer membranes, and they offer great variety due to their adjustability of pore size and distribution. Porous nanofillers can be MOFs, zeolites, porous organic frameworks (POFs) and also porous carbon-silicon nanocomposite fillers (CMS). As an example, CMS can be combined with Metrimid® membranes. The CMS can be manufactured in a way that its surface chemistry and porosity are adjustable. The carbon phase provides better separation efficiency with higher CO₂ affinity and additional porosity. (Ahmadi et al. 2018; Waqas Anjum et al. 2015)

Membrane contactors

In an extended sense, membrane contactors can also be counted among the membrane processes. Contactors in general are used to achieve a direct mass transfer between non-miscible phases. The contactor increases the phase interface. Membrane contactors allow diffuse mass transfer through a porous membrane and stabilize the phase interface. In conventional membrane processes, membrane selectivities, for example, are responsible for the separation process. (Rautenbach 2007)

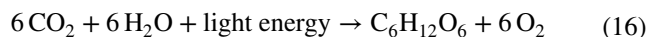
Advantages of membrane contactors are that they can be combined with other methods, such as extraction, desorption, absorption and distillation, and they are also efficient and cost-effective (Mansourizadeh et al. 2022). When using amine solutions as absorbents, hollow fibre membrane contactors (HFMC) can be used, for example. Their use in the carbon dioxide capture process reduces the size of the absorber or stripper after combustion. The materials used should be solvent and adhesive compatible, have high gas permeability and be cost effective. (Porcheron et al. 2011)

An HFMC can also be used for carbon dioxide separation from a CO₂/N₂ mixed gas. A 10% aqueous solution of glycerol was used as the absorbent. Raising the gas-liquid flow rate led to a decrease in the residence time of carbon dioxide and thus to a lower separation efficiency. The separation efficiency could be improved by lowering the absorption temperature. It was also observed that high wetting has a disadvantageous effect on the separation efficiency as a result of the increasing mass transfer resistance. (Mohammadi Saadat et al. 2022)

Natural inclusion

Plants

In photosynthesis, green plants bind the carbon dioxide in the air and convert it into glucose and water with the energy of sunlight. (Brandt et al. 2020)



Carbon dioxide fixation in the chloroplasts of the plant cells is catalyzed by the enzyme ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco). (Brandt et al. 2020)

In the publication by Morikawa et al. (2022), solar-driven CO₂ reduction is carried out using an artificial monolithic leaf. (Morikawa et al. 2022)

Similar to photosynthesis in plants, CO₂ molecules are reduced from electrons and protons obtained from water

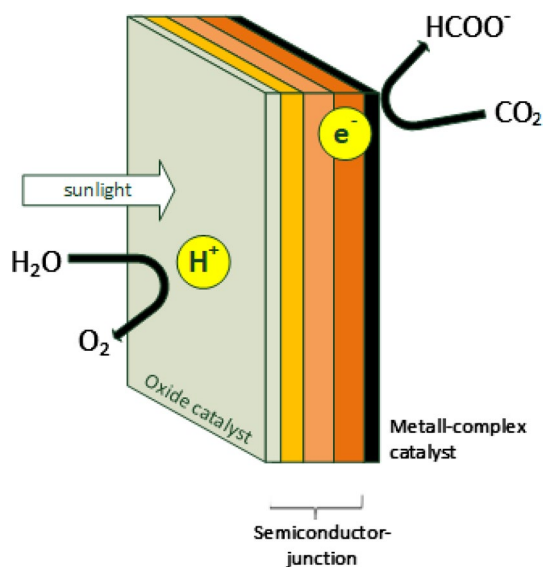
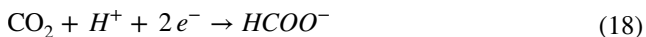


Fig. 12 Semiconductor hybrid photosystem for CO₂ reduction. (Morikawa et al. 2022)

molecules to produce oxygen. This requires sunlight as an energy source. (Morikawa et al. 2022)



In artificial photosynthesis technology (Fig. 12), a metal complex catalyst and a semiconductor capable of absorbing visible light are combined. The semiconductor-molecule hybrid system uses the low overpotential of an aqueous CO₂ reduction reaction. (Morikawa et al. 2022)



In a single-chamber reaction, formate can be produced from CO₂ and H₂O with the help of sunlight. The efficiency of 4.6% is higher than that of green plants. (Morikawa et al. 2022)

Algae

Microalgae are another way to bind CO₂ from the air. These are plant microorganisms that grow in aqueous suspensions with sunlight. In the process of photosynthesis, carbon dioxide is converted into glucose and oxygen with water and solar energy. (Fischedick et al. 2015)

Different types of algae can be used for the cultivation of algae. The performance depends on the algae species, light source, nutrients, pH, temperature and mass transfer. (Alami et al. 2021) The evaluation of the different microalgae species in the publication by Sydney et al. (2010) showed considerable differences: *Dunaliella tertiolecta* (272.4 mg/L/day), *Chlorella vulgaris* (251.64 mg/L/day),

Spirulina platensis (318.61 mg/L/day), *Botryococcus braunii* (496.98 mg/L/day), and *Chlorococcum littorale* (1,000 mg/L/day). (Sydney et al. 2010)

Microalgae have the potential to form biomass and sequester carbon dioxide 5 to 10 times faster compared to fast-growing terrestrial plants (given the same footprint and solar radiation). However, there are fluctuations in the growth of microalgae depending on the season. Thus, there can be no continuous year-round operation. (Fischedick et al. 2015)

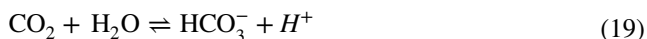
New approaches and technologies are being developed for using microalgae for CO₂ capturing. For use in the energy industry, the algae plant must be located directly at a power plant. The flue gases from the power plant are fed into reactors. The algae suspension uses the CO₂ from the flue gases to form biomass. The algae biomass is then separated from the suspension. (Fischedick et al. 2015)

Bacteria

Different types of bacteria can be utilized for the conversion of carbon dioxide into other substances.

Bacillus mucilaginosus

In the publication by Zhang et al. (2008), *Bacillus mucilaginosus* was used to capture atmospheric CO₂. This bacterium can excrete carbonic anhydrase. This reversibly catalyzes the hydration of carbon dioxide. Zhicai Z et al. 2011



When cultivated in a calcareous medium, the concentration of Ca²⁺ increased with the amount of limestone. This led to a decrease in carbonic anhydrase activity in the bacterial growth kinetics. The authors therefore suggested that *Bacillus mucilaginosus* first captures CO₂ by the enzyme carbonic anhydrase and only then fixation is carried out with bacterial metabolism. Zhicai Z et al. 2011

Acetogenic bacteria

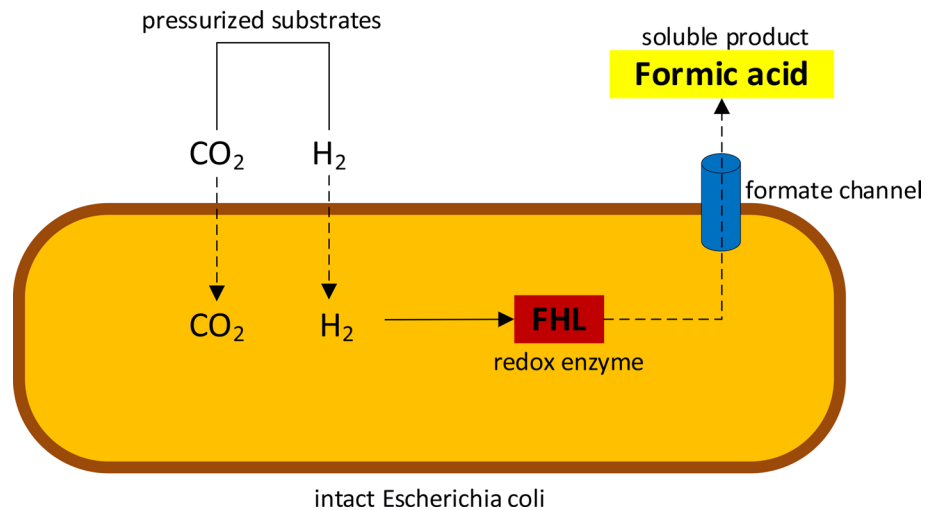
Acetogenic bacteria represent another possibility for binding CO₂ from the air. These catalyze the reaction in which the carbon dioxide reacts with hydrogen to formic acid and water. (Schwarz et al. 2021)



Biocatalysis was tested in a batch process in stirred tank bioreactors. The conversion proceeded with an efficiency of 100% and achieved a specific rate of 48.3 mmol g⁻¹ h⁻¹. The advantage of this process is that no undesired side reactions took place. (Schwarz et al. 2021)



Fig. 13 Hydrogen-dependent carbon dioxide reduction by *Escherichia coli*. (Roger et al. 2018)



Escherichia coli

In the publication by Roger et al. (2018) an efficient hydrogen-dependent carbon dioxide reduction by *Escherichia coli* was carried out. (Roger et al. 2018)

During mixed acid fermentation in *Escherichia coli*, formic acid is normally split into carbon dioxide and hydrogen by the enzyme formate hydrogen lyase (FHL). (Beyer 2014)



If the gaseous CO₂ and the H₂ are pressurized (10 bar), the enzyme can also catalyze the reverse reaction (Fig. 13). When intact cells were used, the complete conversion of the carbon dioxide could proceed. *Escherichia coli* can thus be used for carbon capture and as a cell factory for formic acid production. (Roger et al. 2018)

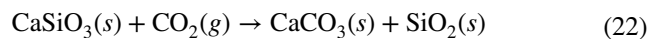
Kitasatospora setae

Carboxylases are biocatalysts that can bind CO₂ under mild conditions and atmospheric concentrations. The fastest and most efficient class is the enoyl-CoA carboxylases/reductases (ECR) found in the bacteria *Kitasatospora setae*. These enzymes contain the three amino acids asparagine, glutamine and histidine, which anchor the carbon dioxide from two sides. In addition, the amino acid phenylalanine shields the bound carbon dioxide like a protective shield against water, which would otherwise inhibit the reaction. (Stoffel et al. 2019)

Mineralization

The mineralization of carbon dioxide mimics the natural process of weathering of silicate minerals, i.e. the carbon dioxide reacts with oxides of alkali or alkaline earth metals

(calcium oxide and magnesium oxide) to form carbonates. (Meng et al. 2021)

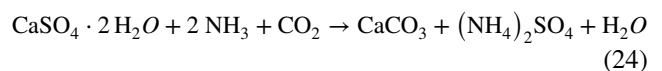


The resulting chemical reaction is exothermic, thermodynamically favourable and the carbonates formed during carbonation are stable, which offers advantages for the subsequent storage of CO₂. (Meng et al. 2021)

Various natural minerals such as serpentine, olivine, wollastonite and basalt can also be used for mineralization. (Meng et al. 2021)

Solid industrial wastes that have a high CaO or MgO content are also additional sources of alkalinity. Fly ash, steel slag, phosphogypsum and ore tailings can be used. These industrial wastes offer advantages over natural minerals because they are cheaper, have higher alkali content and have a much higher reaction rate due to the smaller particles. (Meng et al. 2021)

In the publication by Xie et al. (2015), mineralization with industrial solid waste was presented by the Sinopec Group and Sichuan University in China. In a pilot plant, phosphogypsum was used as a raw material and the ammonia was absorbed directly by CO₂ from the waste gas. (Meng et al. 2021; Xie et al. 2015)



What to do with the captured CO₂?

After the successful capture of CO₂, the question arises what can be done with it. There are currently two basic concepts for this. One deals with the storage of CO₂, for example underground. The other concept is looking for solutions to make CO₂ usable again as a resource.

Carbon capture and storage (CCS)

The aim of CCS is the removal of carbon dioxide from the atmosphere. Different project and studies have been done to get closer to this aim. The first step is the separation of carbon dioxide from flue gas to lead carbon dioxide-free flue gas into the atmosphere. The separated carbon dioxide can be transported by pipelines, ships, trucks, or railway to the storage location, which can be on- or off-shore. During transport, the carbon dioxide is liquified by high pressure above 100 bar. (Fischedick et al. 2015)

CarbFix in Iceland started as a project in 2006 and is now a separate entity. Their mission is to store one billion tons of carbon dioxide permanently. The method of choice for this is based on mineral carbonation. The carbon dioxide is dissolved in water and is then fed into the underground, which consists of basaltic rocks. These rocks are porous and have a

high permeability. Components of these rocks get dissolved in the water too and react with the carbon dioxide to carbonates (Snæbjörnsdóttir et al. 2020).

Another project is the Northern Lights project in Norway. The aim of the project is a permanent underground storage under the sea. Onshore captured carbon dioxide is transported by ships to the pipelines. From 2024 onwards, the CO₂ will be pumped out to sea via pipelines and pressed into a layer of sand at a depth of over 2500 m. This sand layer is covered by a layer of shale, which prevents the CO₂ from escaping (Stratmann 2022).

Carbon capture and utilization (CCU)

In carbon capture and utilization, carbon dioxide is re-introduced into the value chain and used physically, biologically or chemically. For physical utilization, the carbon dioxide can be used for the beverage and food industries (high purity requirements). In addition, the CO₂ can be recycled as an inert gas, insulation material, impregnating agent and to increase the methane yield in coal deposits. If the carbon dioxide is utilized for plant growth, the production of humus or bound by microorganisms or algae, it is a biological use. Chemically, the carbon dioxide can be used

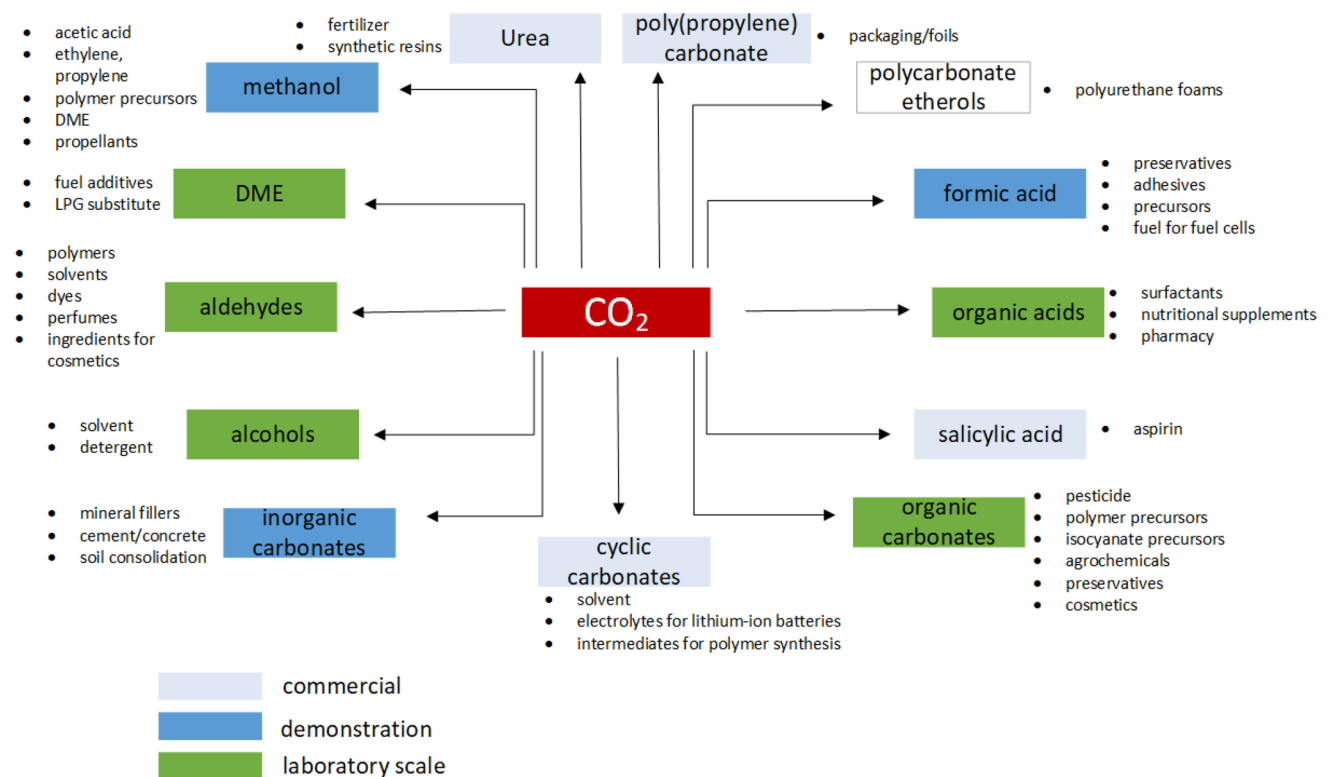
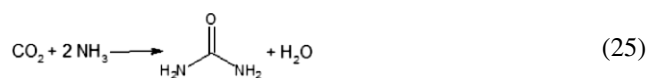


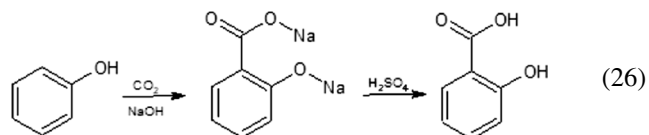
Fig. 14 Target products of CO₂-based synthesis. (Bazzanella Krämer 2017)

to synthesize different kinds of chemicals. (Fischedick et al. 2015)

Figure 14 shows an overview of which target chemicals are produced in CO₂-based syntheses. One example would be urea synthesis. In this process, the carbon dioxide reacts with the ammonia to form urea. This can be used as a nitrogen fertilizer or in the chemical industry as a starting material for further chemical syntheses. (Bazzanella Krämer 2017) (25)



Kolbe–Schmitt synthesis is also a well-known example of the chemical use of carbon dioxide. In this process sodium phenolate is reacted with CO₂ to form salicylic acid. This can be used to produce acetyl salicylic acid (aspirin) or to make dyes and perfumes. (Bazzanella Krämer 2017) (26)



Outlook and conclusion

As is so often the case, there is no ultimate and all-encompassing solution to the CO₂ problem. It would be decadent to think that you can find a simple solution to such a complex problem. Individual solutions must be found for the various areas in which too much anthropogenic CO₂ is produced.

Over the last 20 years, a variety of carbon capture methods have been researched and optimized. The goals for the future are now to develop further methods and to optimize the existing methods in terms of economy and efficiency in order to be able to apply them on a larger scale. In addition, further concepts need to be found to deal with the storage and use of captured CO₂. Nevertheless, it is necessary to save CO₂.

Acknowledgements We like to thank the Reaching program of the faculty MLS, Furtwangen University, for support.

Author contributions SK and IB performed the literature search and wrote the manuscript and produced the tables and images. The complete writing, design, and corrections of the manuscript were led and supervised by JJ and MSS. The revision work was done by JJ. All authors have read and agreed to the published version of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. No funds, grants, or other support were received.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Code availability is not applicable.

Declarations

Conflicts of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. All authors declare that they have no conflict of interest.

Consent to participate Participate consent not applicable.

Consent for publication Publication consent not applicable.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Informed consent not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ahmadi M, Janakiram S, Dai Z, Ansaloni L, Deng L (2018) Performance of mixed matrix membranes containing porous two-dimensional (2D) and three-dimensional (3D) fillers for CO₂ separation: a review. *Membranes* 8(3):50
- Alami AH, Alasad S, Ali M, Alshamsi M (2021) Investigating algae for CO₂ capture and accumulation and simultaneous production of biomass for biodiesel production. *Sci Total Environ* 759(143529):2020. <https://doi.org/10.1016/j.scitotenv.2020.143529>
- Alivand MS, Mazaheri O, Wu Y, Zavabeti A, Christofferson AJ, Mef-tahi N, Russo SP, Stevens GW, Scholes CA, Mumford KA (2022) Engineered assembly of water-dispersible nanocatalysts enables low-cost and green CO₂ capture. *Nat Commun* 13(1):1249. <https://doi.org/10.1038/s41467-022-28869-6>
- Autam M, Darbis ND, Mohd Din AT, Hameed BH (2013) Fixed-bed column adsorption of carbon dioxide by sodium hydroxide modified activated alumina. *Chem Eng J* 233:80–87. <https://doi.org/10.1016/j.cej.2013.08.012>
- Bazzanella, A.; Krämer, D., Eds. *Technologien für Nachhaltigkeit und Klimaschutz - chemische Prozesse und stoffliche Nutzung von CO₂: Ergebnisse der BMBF-Fördermaßnahme*; DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V, 2017.
- Beyer, L. Physiologische Charakterisierung des Formiat-Stoffwechsels in *Escherichia coli* 2014.

- Brandt, U.; Anderka, O.; Kerscher, S.; Kieß, S.; Ridinger, K. *Biochemie: Eine Einführung für Mediziner und Naturwissenschaftler*. <https://link.springer.com/book/https://doi.org/10.1007/978-3-662-60690-2> (accessed 2022-04-22).
- Brunetti A, Scura F, Barbieri G, Drioli E (2010) Membrane technologies for CO₂ separation. *J Membr Sci* 359(1–2):115–125. <https://doi.org/10.1016/j.memsci.2009.11.040>
- Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, Fennell PS, Fuss S, Galindo A, Hackett LA, Hallett JP, Herzog HJ, Jackson G, Kemper J, Krevor S, Maitland GC, Matuszewski M, Metcalfe IS, Petit C, Puxty G, Reimer J, Reiner DM, Rubin ES, Scott SA, Shah N, Smit B, Trusler JPM, Webley P, Wilcox J, Mac Dowell N (2018) Carbon capture and storage (CCS): the way forward. *Energy Environ Sci* 11(5):1062–1176. <https://doi.org/10.1039/C7EE02342A>
- Campo MC, Ribeiro AM, Ferreira AF, Santos JC, Lutz C, Loureiro JM, Rodrigues AE (2016) Carbon dioxide removal for methane upgrade by a VSA process using an improved 13X zeolite. *Fuel Process Technol* 143:185–194. <https://doi.org/10.1016/j.fuproc.2015.11.024>
- Chen C, Ahn W-S (2011) CO₂ capture using mesoporous alumina prepared by a sol-gel process. *Chem Eng J* 166(2):646–651. <https://doi.org/10.1016/j.cej.2010.11.038>
- Coriani S, Halkier A, Rizzo A, Ruud K (2000) On the molecular electric quadrupole moment and the electric-field-gradient-induced birefringence of CO₂ and CS₂. *Chem Phys Lett* 326(3–4):269–276. [https://doi.org/10.1016/S0009-2614\(00\)00793-4](https://doi.org/10.1016/S0009-2614(00)00793-4)
- Daneshvar N, Zaaferani Moattar M, Abedinzadegan Abdi M, Aber S (2004) Carbon dioxide equilibrium absorption in the multi-component systems of CO₂ + TIPA + MEA + H₂O, CO₂ + TIPA + Pz + H₂O and CO₂ + TIPA + H₂O at low CO₂ partial pressures: experimental solubility data, corrosion study and modeling with artificial neural network. *Sep Purif Technol* 37(2):135–147. <https://doi.org/10.1016/j.seppur.2003.09.004>
- Erans M, Manovic V, Anthony EJ (2016) Calcium looping sorbents for CO₂ capture. *Appl Energy* 180:722–742. <https://doi.org/10.1016/j.apenergy.2016.07.074>
- Erich, E.; Berry, A.; Telge Stephan. Alkalicarbonatwäsche für die Entfernung von Kohlendioxid aus Rauchgasen fossil befeuerter Kraftwerke als robuste Alternative zu Aminwäschen.
- Fischedick, M.; Görner, K.; Thomeczek, M. *CO₂: Abtrennung, Speicherung, Nutzung: Ganzheitliche Bewertung im Bereich von Energiewirtschaft und Industrie*, 2015.
- Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen INT. *Ionische Flüssigkeiten - Fraunhofer INT*. <https://www.int.fraunhofer.de/de/geschaeftsfelder/corporate-technology-foresight/Newsletter21.html>. Accessed 04 May 2022
- Ghasem, N. Chapter 21 - CO₂ removal from natural gas. In *Advances in carbon capture: Methods, technologies and applications*; Rahimpour, M. R., Farsi, M., Makarem, M. A., Eds.; Woodhead Publishing, 2020; pp 479–501. DOI: <https://doi.org/10.1016/B978-0-12-819657-1.00021-9>.
- González AS, Plaza MG, Rubiera F, Pevida C (2013) Sustainable biomass-based carbon adsorbents for post-combustion CO₂ capture. *Chem Eng J* 230:456–465. <https://doi.org/10.1016/j.cej.2013.06.118>
- Hart A, Gnanendran N (2009) Cryogenic CO₂ capture in natural gas. *Energy Procedia* 1(1):697–706. <https://doi.org/10.1016/j.egypro.2009.01.092>
- Hilliard, M. D.; Rochelle, G. T. Thermodynamics of aqueous piperazine/potassium carbonate/carbon dioxide characterized by the electrolyte non-random two-liquid model in aspen plus. In *Greenhouse gas control technologies: Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, 5–9 September 2004, Vancouver, Canada*; Rubin, E. S., Keith, D. W., Gilboy, C. F., Wilson, M., Morris, T., Gale, J., Thambimuthu, K., Eds.; Elsevier, 2005; pp 1975–1978. DOI: <https://doi.org/10.1016/B978-008044704-9/50253-6>.
- Huang, S.; Li, S.; Villalobos, L. F.; Dakhchoune, M.; Micari, M.; Babu, D. J.; Vahdat, M. T.; Mensi, M.; Oveisi, E.; Agrawal, K. V. Millisecond lattice gasification for high-density CO₂- and O₂-sieving nanopores in single-layer graphene. *Science advances* **2021**, 7 (9). DOI: <https://doi.org/10.1126/sciadv.abf0116>. Published Online: Feb. 24, 2021.
- IEA. *CO₂ Emissions From Fuel Combustion 2018*. <https://de.statista.com/statistik/daten/studie/167957/umfrage/verteilung-der-co-emissionen-weltweit-nach-bereich/>
- Joss L, Gazzani M, Mazzotti M (2017) Rational design of temperature swing adsorption cycles for post-combustion CO₂ capture. *Chem Eng Sci* 158:381–394. <https://doi.org/10.1016/j.ces.2016.10.013>
- Katsnelson MI (2007) Graphene: carbon in two dimensions. *Mater Today* 10(1–2):20–27. [https://doi.org/10.1016/S1369-7021\(06\)71788-6](https://doi.org/10.1016/S1369-7021(06)71788-6)
- Khalilpour R, Mumford K, Zhai H, Abbas A, Stevens G, Rubin ES (2015) Membrane-based carbon capture from flue gas: a review. *J Clean Prod* 103:286–300. <https://doi.org/10.1016/j.jclepro.2014.10.050>
- Liu, A.-H.; Ma, R.; Song, C.; Yang, Z.-Z.; Yu, A.; Cai, Y.; He, L.-N.; Zhao, Y.-N.; Yu, B.; Song, Q.-W. Equimolar CO₂ capture by N-substituted amino acid salts and subsequent conversion. *Angewandte Chemie International Edition* **2012**, 51 (45), 11306–11310. DOI: <https://doi.org/10.1002/anie.201205362>. Published Online: Oct. 8, 2012.
- Lu B, Lin YS (2013) Synthesis and characterization of thin ceramic-carbonate dual-phase membranes for carbon dioxide separation. *J Membr Sci* 444:402–411. <https://doi.org/10.1016/j.memsci.2013.05.046>
- Madejski P, Chmiel K, Subramanian N, Kuś T (2022) Methods and Techniques for CO₂ Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies* 15(3):887. <https://doi.org/10.3390/en15030887>
- Manovic, V.; Anthony, E. J. Lime-based sorbents for high-temperature CO₂ capture—a review of sorbent modification methods. *International journal of environmental research and public health* **2010**, 7 (8), 3129–3140. DOI: <https://doi.org/10.3390/ijerph7083129>. Published Online: Aug. 6, 2010.
- Mansourizadeh A, Rezaei I, Lau WJ, Seah MQ, Ismail AF (2022) A review on recent progress in environmental applications of membrane contactor technology. *J Environ Chem Eng* 10(3):107631. <https://doi.org/10.1016/j.jece.2022.107631>
- Mat NC, Lipscomb GG (2017) Membrane process optimization for carbon capture. *Int J Greenhouse Gas Control* 62:1–12. <https://doi.org/10.1016/j.ijggc.2017.04.002>
- Meng J, Liao W, Zhang G (2021) Emerging CO₂-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China. *Minerals* 11(3):274. <https://doi.org/10.3390/min11030274>
- Mishra AK, Ramaprabhu S (2014) Enhanced CO₂ capture in Fe₃O₄-graphene nanocomposite by physicochemical adsorption. *J Appl Phys* 116(6):64306. <https://doi.org/10.1063/1.4892458>
- Mohammadi Saadat M, Norouzbahari S, Esmaili M (2022) CO₂/N₂ separation by glycerol aqueous solution in a hollow fiber membrane contactor module: CFD simulation and experimental validation. *Fuel* 323:124370. <https://doi.org/10.1016/j.fuel.2022.124370>
- Montanari T, Busca G (2008) On the mechanism of adsorption and separation of CO₂ on LTA zeolites: An IR investigation. *Vib Spectrosc* 46(1):45–51. <https://doi.org/10.1016/j.vibspec.2007.09.001>
- Morikawa, T.; Sato, S.; Sekizawa, K.; Suzuki, T. M.; Arai, T. Solar-Driven CO₂ Reduction Using a Semiconductor/Molecule Hybrid Photosystem: From Photocatalysts to a Monolithic Artificial Leaf. *Accounts of Chemical Research* **2022**, 55 (7), 933–943. DOI:



- <https://doi.org/10.1021/acs.accounts.1c00564>. Published Online: Dec. 1, 2021.
- Ortiz-Landeros J, Norton T, Lin YS (2013) Effects of support pore structure on carbon dioxide permeation of ceramic-carbonate dual-phase membranes. *Chem Eng Sci* 104:891–898. <https://doi.org/10.1016/j.ces.2013.09.027>
- Pakzad, P.; Mofarahi, M.; Ansarpour, M.; Afkhamipour, M.; Lee, C.-H. Chapter 3 - CO₂ absorption by common solvents. In *Advances in carbon capture: Methods, technologies and applications*; Rahimpour, M. R., Farsi, M., Makarem, M. A., Eds.; Woodhead Publishing, 2020; pp 51–87. DOI: <https://doi.org/10.1016/B978-0-12-819657-1.00003-7>.
- Pieper, T. C. *EnArgus*. https://www.enargus.de/pub/bscw.cgi/d650-2/*/*Ammoniakw%3%a4sche.html?op=Wiki.getwiki. Accessed 04 May 2022
- Pieper, T. C. *EnArgus*. <https://www.enargus.de/pub/bscw.cgi/d650-2/Ammoniakw%3%a4sche.html?op=Wiki.getwiki>. Accessed 19 April 2022
- Porcheron F, Ferré D, Favre E, Nguyen PT, Lorain O, Mercier R, Rougeau L (2011) Hollow fiber membrane contactors for CO₂ capture: From lab-scale screening to pilot-plant module conception. *Energy Procedia* 4:763–770. <https://doi.org/10.1016/j.egypro.2011.01.117>
- Powell CE, Qiao GG (2006) Polymeric CO₂/N₂ gas separation membranes for the capture of carbon dioxide from power plant flue gases. *J Membr Sci* 279(1–2):1–49. <https://doi.org/10.1016/j.memsci.2005.12.062>
- Rautenbach R (2007) *Membranverfahren: Grundlagen der Modul- und Anlagenauslegung*, 3, aktualisierte und, erweiterte. VDI-Buch; Springer-Verlag, Berlin Heidelberg
- Rieß M, Siegel R, Senker J, Breu J (2020) Diammonium-Pillared MOPS with Dynamic CO₂ Selectivity. *Cell Reports Physical Science* 1(10):100210. <https://doi.org/10.1016/j.xcrp.2020.100210>
- Roger, M.; Brown, F.; Gabrielli, W.; Sargent, F. Efficient Hydrogen-Dependent Carbon Dioxide Reduction by *Escherichia coli*. *Current biology : CB* 2018, 28 (1), 140–145.e2. DOI: <https://doi.org/10.1016/j.cub.2017.11.050>. Published Online: Dec. 28, 2017.
- Sanni ES, Sadiku ER, Okoro EE (2021) Novel Systems and Membrane Technologies for Carbon Capture. *Int J Chem Eng* 2021:1–23. <https://doi.org/10.1155/2021/6642906>
- Scholes CA, Anderson CJ, Stevens GW, Kentish SE (2013) Membrane Gas Separation – Physical Solvent Absorption Combined Plant Simulations for Pre-combustion Capture. *Energy Procedia* 37:1039–1049. <https://doi.org/10.1016/j.egypro.2013.05.200>
- Schwarz FM, Oswald F, Müller V (2021) Acetogenic Conversion of H₂ and CO₂ into Formic Acid and Vice Versa in a Fed-Batch-Operated Stirred-Tank Bioreactor. *ACS Sustainable Chem Eng* 9(19):6810–6820. <https://doi.org/10.1021/acssuschemeng.1c01062>
- Schwister K, Leven V (2020) *Verfahrenstechnik für Ingenieure: Ein Lehr- und Übungsbuch (mit umfangreichem Zusatzmaterial)*, 4, aktualisierte und, erweiterte. Hanser, Carl
- scinexx | Das Wissensmagazin. *Einfach rauswaschen*. <https://www.scinexx.de/dossierartikel/einfach-rauswaschen/>. Accessed 18 April 2022
- Shen C, Yu J, Li P, Grande CA, Rodrigues AE (2011) Capture of CO₂ from flue gas by vacuum pressure swing adsorption using activated carbon beads. *Adsorption* 17(1):179–188. <https://doi.org/10.1007/s10450-010-9298-y>
- Snæbjörnsdóttir SÓ, Sigfússon B, Marieni C, Goldberg D, Gislason SR, Oelkers EH (2020) Carbon dioxide storage through mineral carbonation. *Nat Rev Earth Environ* 1(2):90–102. <https://doi.org/10.1038/s43017-019-0011-8>
- Stoffel G, Saez DA, DeMirci H, Vögeli B, Rao Y, Zarzycki J, Yoshikuni Y, Wakatsuki S, Vöhringer-Martinez E, Erb T (2019) Four amino acids define the CO₂ binding pocket of enoyl-CoA carboxylases/reductases. *Proceedings of the National Academy of Sciences* 116(28):13964–13969 <https://doi.org/10.1073/pnas.1901471116>
- Stratmann K, *Wohin mit dem CO₂? Wie Norwegen der deutschen Industrie beim Klimaschutz helfen kann. Wohin mit dem CO₂? Wie Norwegen der deutschen Industrie beim Klimaschutz helfen kann*. <https://www.handelsblatt.com/politik/deutschland/klimaschutz-wohin-mit-dem-co2-wie-norwegen-der-deutschen-industrie-beim-klimaschutz-helfen-kann/27903910.html>. Accessed 24 May 2022
- Sydney EB, Sturm W, de Carvalho JC, Thomaz-Soccol V, Larroche C, Pandey A, Soccol CR (2010) Potential carbon dioxide fixation by industrially important microalgae. *Biores Technol* 101(15):5892–5896. <https://doi.org/10.1016/j.biortech.2010.02.088>
- Tsunatu D, Mohammed-Dabo I, Waziri S (2015) Technical evaluation of selexol-based CO₂ capture process for a cement plant. *BJECC* 5(1):52–63. <https://doi.org/10.9734/BJECC/2015/12482>
- Umweltbundesamt. *Carbon Capture and Storage*. <https://www.umweltbundesamt.de/themen/wasser/gewaesser/grundwasser/nutzung-belastungen/carbon-capture-storage> (accessed 2022–03–16).
- Varghese AM, Karanikolos GN (2020) CO₂ capture adsorbents functionalized by amine – bearing polymers: a review. *Int J Greenhouse Gas Control* 96:103005. <https://doi.org/10.1016/j.ijggc.2020.103005>
- Wang B, Xie L-H, Wang X, Liu X-M, Li J, Li J-R (2018) Applications of metal–organic frameworks for green energy and environment: New advances in adsorptive gas separation, storage and removal. *Green Energy Environ* 3(3):191–228. <https://doi.org/10.1016/j.gee.2018.03.001>
- Waqas Anjum M, Clippel F, de Didden J, LaeeqKhan A, Couck S, Baron GV, Denayer JF, Sels BF, Vankelecom I (2015) Polyimide mixed matrix membranes for CO₂ separations using carbon–silica nanocomposite fillers. *J Membr Sci* 495:121–129. <https://doi.org/10.1016/j.memsci.2015.08.006>
- Xie H, Yue H, Zhu J, Liang B, Li C, Wang Y, Xie L, Zhou X (2015) Scientific and engineering progress in CO₂ mineralization using industrial waste and natural minerals. *Engineering* 1(1):150–157. <https://doi.org/10.15302/J-ENG-2015017>
- Xu J, Lin W (2017) A CO₂ cryogenic capture system for flue gas of an LNG-fired power plant. *Int J Hydrog Energy* 42(29):18674–18680. <https://doi.org/10.1016/j.ijhydene.2017.04.135>
- Xu D, Xiao P, Zhang J, Li G, Xiao G, Webley PA, Zhai Y (2013) Effects of water vapour on CO₂ capture with vacuum swing adsorption using activated carbon. *Chem Eng J* 230:64–72. <https://doi.org/10.1016/j.cej.2013.06.080>
- Yaumi AL, Bakar MA, Hameed BH (2017) Recent advances in functionalized composite solid materials for carbon dioxide capture. *Energy* 124:461–480. <https://doi.org/10.1016/j.energy.2017.02.053>
- Zhang J, Singh R, Webley PA (2008) Alkali and alkaline-earth cation exchanged chabazite zeolites for adsorption based CO₂ capture. *Microporous Mesoporous Mater* 111(1–3):478–487. <https://doi.org/10.1016/j.micromeso.2007.08.022>
- Zhikai Z, Bin L, Weiguo H, Mingxia C, Xin L, Yan L (2011) *Bacillus mucilaginosus* can capture atmospheric CO₂ by carbonic anhydrase. *Afr J Microbiol Res* 5(2):106–112. <https://doi.org/10.5897/AJMR10.690>

