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Technologies for carbon dioxide capture: A review applied to energy sectors

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ABSTRACT

Carbon dioxide (CO_2) is a gas generated by both natural and man-made sources, such as the burning of fossil fuels for power generation and from agriculture. Currently, it is seen as the main contributor to the increase in the greenhouse effect, leading to global warming. Therefore, the development of technologies for the capture and use of this gas are of great importance for the mitigation of greenhouse gases (GHG) and the reduction of their negative environmental effects. The objective of this review is to survey the main carbon dioxide capture technologies under development for the energy sectors, especially for thermoelectric and bioenergy (ethanol plant). Pre-combustion, oxy-fuel and post-combustion technologies were depicted, among them: adsorption, absorption, membrane separation and chemical capture. By means the compiled information, it was possible to identify the main advances as well as the main difficulties of carbon dioxide capture & use technologies. Moreover, aspects of the carbon market were discussed also.

1. Introduction

Carbon dioxide (CO_2) is a gas originated from natural processes - produced during breathing by all animals, fungi and microorganisms that depend directly or indirectly on living or decomposing plants for food - and anthropic activities, mainly from combustion processes using fossil fuels. Carbon dioxide is considered a gas with potential to be used as a raw material (Poliakoff and LeitnerStreng, 2015). As its commercial applications, it can be highlighted: use as a solvent for extraction by supercritical fluid, vasodilating agent, anesthetic, antagonist, gas for food packaging, food propellant, gas for soda; in addition, it is a metabolite of the yeast *Saccharomyces cerevisiae*, used in the production of ethanol.

For a better understanding of the potential use of this gas, promoting the decarbonization of industrial and agro-industrial processes, especially those of power generation, several aspects must be considered, with thermodynamics and kinetics, the technical and economic viability of projects and technologies, process integration, sustainability and green chemistry & engineering principles.

It is known that the emission of greenhouse gases (GHG) occurs through natural sources, but that a significant portion of these emissions are of anthropic origin - for which carbon dioxide is considered the main contributor. Such gases produce climate change on a global scale, with adverse environmental effects. Events such as global warming due to the greenhouse effect, present themselves as a valuable justification for the search for technologies that mitigate the consequences of air pollution.

The objective of this review is to position the main technological developments in each R&D&I theme, such as carbon dioxide capture for usage purposes. For this case, its scope is delimited in order to substantiate the composition and concentration of gaseous residues from chimneys of thermochemical plants and ethanol plants (bioenergy) and to present the main capture technologies available on the market. The literature review survey is justified by the need for new technologies that mitigate the uncontrolled emissions of carbon dioxide, contributing to the decarbonization of the various sectors that make up the global economy.

2. The environmental context of carbon dioxide emission

It is paramount to establish the impact of carbon dioxide on global warming to justify the application of technological approaches.

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2.1. Global warming

With industrial growth, emissions of gaseous pollutants have gained strength. According to the Intergovernmental Panel On Climate Change et al. (2018), approximately 41 billion tons of carbon dioxide are emitted annually that contribute to an increase in the temperature of the planet. Because of this, global warming, caused by uncontrolled emissions of gases that promote the greenhouse effect (e.g., carbon dioxide, methane and nitrous oxide), is the object of scientific research, environmental policies and awareness of modern society.

The greenhouse effect is a phenomenon that occurs naturally in the Earth's atmosphere. It is a fundamental phenomenon for the existence of life on the planet, as it acts as a blanket receiving solar energy to maintain the average global temperature (Kweku et al., 2017). The greenhouse effect prevents the heat that returns to the atmosphere from being lost to space. Without this condition, the earth would have a temperature so low that there are no suitable conditions for terrestrial life (United Kingdom, 2011). In turn, global warming occurs due to the massive presence of gases in the atmosphere that retain heat beyond what is necessary for the maintenance of the earth (Kweku et al., 2017).

Greenhouse gases (GHG), mostly carbon dioxide, nitrous oxide and methane, have a molecular structure capable of absorbing a certain amount of heat and this capacity configures the effect of global warming. If the concentration of molecules in these gases is high, the earth's protective blanket is overloaded with heat, causing global warming. The percentage contribution to the greenhouse effect is as follows (Falci, 2019):

- Carbon dioxide: 53%
- Methane: 17%
- CFCs (chlorofluorocarbons): 12%
- Nitrous oxide: 6%
- Others: 12%

The large amount of GHG emitted to the atmosphere through industrial and agro-industrial activities - such as the burning of fossil fuels for the generation of energy in thermoelectric plants and the fermentation of sucrose to produce ethanol in sugarcane plants -, they can promote the greenhouse effect by allowing greater absorption of infrared radiation from the electromagnetic spectrum. Thus, anthropic processes are those that are intensifying global warming (Kumar, 2018). Since global warming is a matter of great economic, social and environmental interest, most countries have directed major actions towards mitigating GHG (Lin and Xu, 2018).

It is worth highlighting the importance of understanding, monitoring and controlling climate change, especially global warming, which can be reflected in the organization of major world conventions on the subject, such as the Paris Agreement,[1] Rio +20[2] and Convention-United Nations Framework on Climate Change,[3] which aim to join efforts and establish international actions and policies to reduce GHG emissions.

2.1.1. The Paris Agreement as an incentive for GHG reductions

Vigorously accepted in the 1990s, world conventions add great prominence to discussions on climate change, especially for establishing goals and agreements that guide the tools for reducing GHG. The Paris Agreement corresponds to one of the most important treaties on the subject. It was from this point onwards that the United Nations Framework Convention on Climate Change established 1.5 °C as the limit for the increase in Earth's temperature (Intergovernmental Panel On Climate Change et al., 2018).

For the 1.5 °C limit to be met, the countries involved in the agreement pledged to reduce disorderly GHG emissions and stressed that by the year 2050, net CO_2 emissions must be zero.

Aiming at the most punctual sources of GHG emissions worldwide, the tools sought by the countries mainly serve the following sectors: energy, land change and use, and traffic and transport, as according to the Intergovernmental Panel On Climate Change et al. (2018), they are the sectors that contribute the most to emissions.

For the energy sector, great efforts have been directed towards clean energy. Based on the Paris Agreement, the International Energy Agency (2021), defines as a priority action for the 2020s the expansion of clean energy sources worldwide. García-Freites et al. (2021), studies bioenergy with integrated CO2 capture as a technology to achieve zero net emissions targets by 2050, Hafner et al. (2021) addresses the main economic impacts involved in GHG reduction targets in the energy sector through scenarios of electricity system costs of different low-carbon electricity transitions.

As for land use, many studies are focused on the issue of deforestation and suggest that reforestation, sustainable agriculture and forestry can be responsible for a 30% reduction in emissions by 2050 (Roe et al., 2019). Tanneberger et al. (2021) proposes an emission reduction scenario for organic soils in Germany with panoramas up to the year 2050, the Intergovernmental Panel On Climate Change et al. (2018) produced a report on land use changes and presents data on the relationship between population density in 2050 and the impacts that are linked to this factor and explore scenarios, since the trend is to intensify the search for areas of cultivation.

For the traffic and transport sector, the research is aimed at formulating alternatives that range from social factors to financial factors, such as the massive purchase of combustion cars. The International Energy Agency (2021) discusses the policies imposed by governments in order to boost the switch from combustion cars to electric cars, fuel cells, public transport, bicycles, etc. Becattini et al. (2021) proposed scenarios for air transport, since the sector directly demands fuel and faces challenges to collaborate with GHG mitigation, Yan et al. (2021) explored decarbonization in cargo transport, proposing traffic and emissions scenarios until the year 2050.

Actions aimed at combating global warming are predominantly based on the Paris Agreement. These are carried out in the scientific community through research on new GHG mitigation technologies, as well as the optimization of existing technologies, environmental and social policies and the monitoring and establishment of new GHG reduction tools.

Currently, there is a great contribution from the scientific community in proposing scenarios, priority actions and sectors that require a detailed look and that will in fact contribute to making net emissions zero in 2050.

2.2. Sources of GHG emissions

According to van Heek et al. (2017), the main GHG emission activities are:

- The generation of energy in plants that use fossil fuels such as mineral coal, natural gas and oil.
- Traffic and transportation.
- Agriculture.
- Manufacturing industries.
- Construction.

Tajudin et al. (2019) point out that the notable increase in industries and automobiles in urban areas characterizes the main cause of the uncontrolled emission of pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2) and carbon dioxide (CO_2). Antony et al. (2018), observed that the chemical industry is the sector that most contributes to the generation of gaseous pollutants, being desirable the development of sustainable transformation processes.

[1] https://news.un.org/en/tags/acordo-de-paris.
[2] http://www.rio20.gov.br/sobre_a_rio_mais_20.html.
[3] https://unfccc.int/.

The GHG emission had its global growth accelerated from the first industrial revolution, in the middle of the 19th century. The need to burn fossil fuels to obtain energy, for example, is responsible for ¾ of the emission of carbon dioxide into the atmosphere (Khapre, 2020), this being the sector that most contributes to the release of gas. Then there is a change in land use, with uncontrolled deforestation and misuse of wood and the like. Knowing that the thermoelectric plants are included in the sector that contributes the most with the emissions of gaseous pollutants, it is pertinent to add efforts for the development of GHG mitigating technologies for this sector. In the agroindustry sector, more specifically in the production of ethanol, Paulo (2019) highlights as the main gaseous emissions of this activity carbon dioxide, water vapor, particulate matter and nitrogen dioxide.

Carbon dioxide comes mainly from activities such as combustion and changing forest use (Sistema de Estimativa de Emissão de Gases, 2017) and it is used as a reference medium for other gases when considering their potentials for influencing global warming; for example: the nitrogen oxide (N_2O) resulting mainly from combustion has a global warming power 310 times greater than carbon dioxide (Braga et al., 2007). Methane, which is produced by activities such as the decomposition of organic matter, being issued generally in landfills and landfills, has global warming power 21 times greater than carbon dioxide (Brasil, 2018).

As previously observed, carbon dioxide is considered the GHG that contributes the most to global warming, mainly due to a 35% increase in its emission after the beginning of the industrial era. For instance, in the case of Brazilian emissions in the year 2019 was 2.17 billion gross tonnes of carbon dioxide equivalent (CO_2e) (Brasil, 2022). This is 3.2% of the world total, which keeps Brazil as the sixth largest emitter of this gas on the planet (Sistema de Estimativa de Emissão de Gases, 2020).

According to GWP100 (100-year Global Warming Potential), as per the document of the Intergovernmental Panel On Climate Change et al. (2014a), reference used in decarbonization calculations, the relative impacts of different gases on global temperature are:

- $CO_2 = 1$
- CH_4 fossil = 30
- CH_4 biogenic = 28
- $N_2O = 265$

2.2.1. *Thermoelectric and ethanol plants as sources of carbon dioxide*

The generation of fossil electricity is the economic activity that most contributes to air pollution, accounting for 17% of this contribution (Intergovernmental Panel On Climate Change, 2014b). A thermochemical plant (Fig. 1) generates energy by burning non-renewable fossil fuels - such as coal and diesel.

Due to the environmental impacts caused by this non-renewable generation of energy, alternatives for substitution with natural gas, nuclear energy, hydroelectric plants and technologies that minimize the impacts are the fully studied (World Health Organization, 2016). However, many of these alternatives depend on technical and economic viability, which varies according to the country and its natural conditions. This impasse requires technologies that reduce gaseous emissions from existing plants, despite the concentration of carbon dioxide emitted being approximately 8% v/v.[4]

Ethanol production presents itself as a mitigation alternative in relation to other agro-industrial processes, since the gas emitted could, in theory, be fully absorbed by cultivated plants (e.g., sugarcane) through photosynthesis. As by-products of sucrose fermentation to produce ethanol, there is heat and carbon dioxide (Fig. 2). In addition to yet another alternative to reduce GHG emissions through use as a biofuel, ethanol production generates 99% v/v carbon dioxide (Zhang et al., 2017), very desirable purity for the use of the second as an industrial raw material. Due to the high purity content of the gas, the feasibility of capturing it becomes more significant as it allows for lower cost capture technologies (Silva et al., 2018).

[4] Value determined by the Agricarbono project (Eletrobras CGTEE-Embrapa-ANEEL R&D Program) in 2019.

3. Carbon dioxide capture technologies

Considered the main cause of global warming, carbon dioxide is a topic of great academic and industrial interest. Mikayilov et al. (2018) claim that the number of activities emitting this gas tends to grow in the future and they emphasize that not only countries with large economies should adopt reduction measures, but every country should employ environmental policies aimed at mitigating them.

To address the control of carbon dioxide emissions, several R&D&I efforts are conducted in order to mitigate this gas emission. Ghanbaralizadeh (2016) point out that its use can be divided into four categories:

i. Chemical production (e.g., raw material for polymers and carbonates).
ii. Fuel production (e.g., raw material for gasoline and diesel).
iii. Biological exploitation (e.g., source of C for microalgae growth).
iv. Conventional use (e.g., solvent).

Moreover, Souza (2016) cites as carbon dioxide mitigation processes: more efficient use of energy, replacement of fossil fuels with others with less carbon content, use of energy solutions that use renewable energy sources and storage of carbon dioxide in geological formations.

Among the alternatives for mitigating carbon dioxide, its use as a raw material represents an option of great economic and environmental appeal, as it allows its use as an input in industrial processes and can collaborate in the formation of innovative products and materials (van Heek et al., 2017). Characteristics such as abundance, low toxicity and low cost, make carbon dioxide an excellent raw material (Antony et al., 2018).

Aiming its capture for industrial usages, the technologies are directed to capture this gas in the purest, economical and environmentally viable way. The carbon dioxide capture can be carried out during three stages (Intergovernmental Panel On Climate Change, 2005):

- Pre-combustion
- Combustion
- Post-combustion

Pre-combustion is based on a gasification process through which the fuel passes and is intended to produce a synthesis gas, mainly composed of hydrogen and carbon monoxide. Subsequently, hydrogen and carbon monoxide are converted into carbon dioxide and then this goes through the gas separation process (Mohammad et al., 2020).

The capture of gases that occurs during combustion is called oxy-combustion and its principle is the burning of fuel in an oxygen-enriched environment (Wilcox, 2021; Mohammad et al., 2020).

Post-combustion is the capture in the final phase of release of the combustion gases. It is ideal for capturing CO_2 from energy generation sources, such as thermoelectric plants and other plants that use waste to generate energy (Mohammad et al., 2020). After the combustion gases exit, they go through the process of separating CO_2 from the other gases using the appropriate technology.

Defining the stage at which gas capture will occur is essential for defining separation technologies. Since these two factors are directly related, it is possible to provide the best technology that meets the criteria of cost, deployment, time, purity and abundance of CO_2. In the next session we will discuss the main categories of carbon dioxide separation technology.

To determine the quantity of carbon dioxide captured, Kemache et al. (2017) proposed to use Equations (1) and (2).

Fig. 1. A thermoelectric plant for energy generation. This plant is located in Candiota, Rio Grande do Sul, Brazil. Credit: Eletrobras.

Fig. 2. An ethanol plant (A) with its chimney of carbon dioxide emission from fermentation vessels (B). This plant is located in Araraquara region, São Paulo State, Brazil. Credit: Sílvio Vaz Jr.

$$CO_{2(captured)}\ (g) = CO_{2(inlet)}\ (g) - CO_{2(output)}\ (g) \quad (1)$$

$$CO_{2(captured)}\ (\%) = CO_{2(captured)}\ (g)/CO_{2(inlet)}\ (g) \times 100 \quad (2)$$

3.1. Adsorption

In the adsorption process, the gas meets porous particles capable of adsorbing the gas due to its surface affinity (e.g., similar chemical groups), separating it from the gas mixture. Table 1 shows examples of technologies in development to promote adsorption.

The adsorption processes are considered complex separation processes. Research that aims to minimize the costs of these processes has, today, some limitations, among them the low efficiency in the gas separation process (Karimi et al., 2018). Another limiting factor in the development of adsorption technologies is the need for large amounts of energy to operate the process - that is, the energy balance is unfavorable. Table 2 shows the main advantages, disadvantages and research trends of surveys in this category.

3.2. Absorption

In absorption processes, they must occur in such a way that the carbon dioxide is capable of later separation, post-capture. This is possible, as this technology has materials capable of absorbing the gas and transporting it from one phase to another, in this case the carbon dioxide is solubilized by passing to the liquid phase of the mixture, making it possible to separate it from the other components.

In thermoelectric plants, for instance, the mixture of process gases is directed to a system in which the gases come into contact with amine solutions. This phase is intended to separate the CO_2 from the other components of the mixture by increasing the temperature (Silva et al., 2018).

Absorption is among the most promising technologies for its efficiency and economic viability. However, and as already mentioned, the energy expenditure during the process is also high (Silva et al., 2018). Because of this, research is aimed at optimizing the energy needed for the operation. Table 3 shows examples of technologies under development to promote absorption.

Absorption technologies are highly chosen by researchers for their advantages. These, in turn, occur, mainly because absorption has been a reason for research for over 70 years (Silva et al., 2018). This condition makes absorption the most mature technology and capable of large-scale

Table 1
R&D&I examples for adsorption.

Title of the work	Author	Summary
In-situ capture and conversion of atmospheric CO_2 into nano-$CaCO_3$ using a novel pathway based on deep eutectic calcium chloride	Karimi et al. (2018)	In this study, CO_2 capture is carried out from a solvent solution based on eutectic choline chloride and has the purpose of making CO_2 a useful precursor for the production of calcite nanoparticles with added value. The results show feasibility for the precursor to be applied on a large scale, reducing CO_2 emissions and demonstrating the efficiency of the solution for the adsorption process.
Enhancement of CO_2 capture by using synthesized nano-zeolite	Pham et al. (2016)	This research deals with the application of nano-zeolite in the process of CO_2 capture by adsorption, based on the temperature employed. Simulations were performed that varied parameters such as percentage of adsorbent, CO_2 captured and temperature. Keeping the CO_2 capture above 88% v/v, resulting in: high efficiency of the nano-zeolite, in addition to the savings produced by the adsorbent.
Development of carbon-based vacuum, temperature and concentration swing adsorption post-combustion CO_2 capture processes	Plaza and Rubiera (2019)	This work deals with vacuum, temperature and concentration adsorption in a coal thermoelectric plant. Energy expenditure is considered the main impediment of this technology. In order to be able to evaluate the parameters used during the research, two scenarios were established, and the main result referred to the specific heat rate that presented itself as an advantage in relation to the use of conventional amines.

Table 2
Advantages, disadvantages and research trends aimed at adsorption technologies.

Advantages	Disadvantages	Research trends
Simple operation process compared to others and does not produce liquid waste, (Ochedi et al., 2021); lower energy cost for regeneration, operates at different temperatures and has no problems related to corrosion (Silva et al., 2018).	Low efficiency in the gas separation process (Karimi et al., 2018) and, therefore, in gas capture; not suitable for high volume flue gas sources (Ochedi et al., 2021); unfavorable energy balance; low selectivity of adsorbents (Liu et al., 2021).	Studies: aimed at optimizing energy expenditure; the parameters of the adsorption process (temperature, percentage of adsorbent); feasibility of large-scale application of solid adsorbents, as they facilitate the regeneration process compared to chemicals (Abd et al., 2020); which aim at the adsorption capacity of the adsorbent and, consequently, its selectivity (Liu et al., 2021).

application (Freeman and Bhown, 2011). Table 4 presents the advantages and disadvantages of chemical absorption and research trends in this category.

Table 3
R&D&I examples for absorption.

Title of the work	Author	Summary
Results from a pilot plant using un-promoted potassium carbonate for carbon capture	Quyn et al. (2013)	This work aimed to study the capture of CO_2 by absorption using potassium carbonate as a solvent. The specificities of the process were analyzed from the incorporation of the chosen solvent. To trace the simulation parameters, the Aspen® software was used and percentages of the solvent were established to evaluate scenarios. The authors considered the results as promising to predict the performance of potassium carbonate in the absorption process.
Use of frothers to improve the absorption efficiency of dilute sodium carbonate slurry for post combustion CO_2 capture	Valluri and Kawatra (2020)	In this work, a pilot scale study was carried out of 4 types of solvent for the capture of CO_2 by absorption. During the tests, the authors incorporated a surfactant in order to evaluate it and sparkling material. The main result of the tests, referred to the efficiency of absorption by the solvents that had the sparkling water incorporated in the process. The capture efficiency in the scenario in question increased from 55 to 99%. The feasibility of this optimization was low cost, in addition to being environmentally appropriate.
Experimental investigation on absorption performance of nanofluids for CO_2 capture	Devakki and Thomas (2020)	In this research, nanofluids were studied as CO_2 absorbers. The nanofluids used were those of TiO_2 and Al_2O_3. The main objectives of this research were to observe the types of nanoparticles and the influence of their concentrations on the absorption process. The result showed that increasing the concentration of these nanofluids decreased the relative CO_2 absorption index. To perform the comparison, a base fluid was used. Saline-based nanofluids were also tested, where it was found that this combination decreased the stability of the nanoparticles, reducing the efficiency of absorption.
CO_2 absorption rate and capacity of semi-aqueous piperazine for CO_2 capture	Yuan and Rochelle (2019)	This research studied one of the most used solvents in CO_2 absorption technologies, piperazine. Combinations with water and another solvent, were carried out to evaluate the piperazine for its precipitation. The precipitation of this compound influences the efficiency of the gas absorption and, therefore, interest in its properties is considered. The results showed that due to the incorporation of new compounds, the CO_2 capture capacity and the absorbent recycling capacity were increased.

Table 4
Advantages, disadvantages and research trends aimed at absorption technologies.

Advantage	Disadvantages	Research trends
More effective from an economic and operational point of view; large processing capacity on an industrial scale; better return and better long-term performance, (Castro et al., 2021)	High solvent consumption; tendency to corrosion of equipment; low carbon dioxide load justified by general solvent stoichiometry (Castro et al., 2021); environmental issues related to the composition of solvents; low solvent regeneration (Ochedi et al., 2021; Baltar et al., 2019)	Studies: of solutions, as they are more effective than isolated solvents; the capture capacity and selectivity of solvents; solvents that reduce energy expenditure and have regeneration capacity; the potential for atmospheric pollution of solvents, as they are highly released; (Ochedi et al., 2021);

3.3. Separation by membranes

The capture by membranes is based on the selectivity of the material constituting them in relation to the gas. Carbon dioxide permeates through membranes, separating itself from other compounds. Due to their function, membranes depend on parameters such as medium permeability, particle size, selectivity and pore volume (Nocito and Dibenedetto, 2020). Table 5 shows the main directions of research on this technology, according to the literature.

Research aimed at capturing carbon dioxide by membranes has as a major challenge the development of systems that optimize the parameters necessary for the capture process. However, according to Wilcox (2021), this technology is considered the most effective technology among the existing ones. Table 6 presents the advantages, disadvantages and main research trends of this capture category.

Defining the capture technology - as well as all the unit operations involved in the process - is of fundamental importance and will dictate its application feasibility. Then gas separation methods involving membranes highlights to show better results.

The main discussion raised by the capture processes is related to the economic factors involved - CAPEX (*CAPital EXpenditure*) and OPEX (*OPerational EXpenditure*). It is known that green technologies require a high level of improvement and are generally linked to high investments (KalatjariHaghtalab et al., 2019).

3.4. Chemical capture

Among the carbon dioxide capture technologies currently under development, there is also the chemical capture for the generation of carbonates as one that can promote added value to industrial and agro-industrial chains, in addition to leading to more sustainable production systems. This capture makes use of chemical reactions with carbon dioxide to obtain final products - these can be inorganic or organic – mainly carbonates. Table 7 shows works involving the capture of carbon dioxide to produce carbonates.

The great interest in this class of technology is because the carbonates obtained have a high boiling point, low toxicity and are biodegradable (North et al., 2010). Table 8 presents the main advantages, disadvantages and research trends of this category in the scientific community.

Regarding this category of technologies to capture of CO_2, we highlight its application in cement production plants as a possibility to transfer technology to other industry sectors with a considerable GHG emission. Cement sector is responsible for high amount of CO_2 emissions, thus requiring capture technologies to mitigate them.

Gupta et al. (2021) and Gupta (2021) investigated the application of biochar as an additive in cement matrix aiming at carbon sequestration in carbonate mineralization. Gupta et al. (2021) combined biochar with

Table 5
R&D&I examples for membrane separation.

Title of the work	Author	Summary
Hybrid membrane process for post-combustion CO_2 capture from coal-fired power plant	Ren et al. (2020)	This research is aimed at evaluating the selectivity of hybrid membranes that act in the process of capturing CO_2 and N_2 (which is also a greenhouse gas) in thermoelectric plants. In this work, Aspen® software was used to simulate a UT, and economic parameters of the membrane technology, permeability and useful life were optimized. The result showed causality factors between the design of the UT and the properties of the membranes, in addition to identifying the selectivity of the membrane and cost variables.
CO_2 capture by modified hollow fiber membrane contactor: Numerical study on membrane structure and membrane wettability	Abdolahi-Mansoorkhani and Seddighi (2020)	In this work, the authors researched characteristics of membranes to be used to capture CO_2 from a natural gas source. A mathematical model was used to study elements such as membrane wettability, structure, type of absorbent used in the capture process, porosity and fiber size. The simulations were carried out with four types of absorbents, varying fiber sizes; percentages were defined to estimate the most efficient values, in order to define the ideal membrane. The results presented showed that absorbent concentration, density and porosity directly influenced the separation of CO_2.
Mass transfer characteristics of a continuously operated hollow-fiber membrane contactor and stripper unit for CO_2 capture	Nieminen (2020)	The focus of this work was to evaluate the mass transfer of a hollow fiber membrane contactor. The parameters that directly influenced the mass transfer coefficient were explored in order to make the efficiency of the contactor visible when connected to the membrane. From the tests it was possible to observe the workability of the contactor used. It had many limitations regarding desorption. Therefore, it was suggested that vacuum tests were inefficient,

(*continued on next page*)

Table 5 (*continued*)

Title of the work	Author	Summary
		requiring the moistening of the membranes, in order to facilitate the transfer of mass through them.
Membrane gas-solvent contactor pilot plant trials for post-combustion CO_2 capture	Scholes et al. (2020)	This research involved an absorption test carried out in a pilot plant for the generation of energy from mineral coal. Here, the authors used gas-solvent contactors in order to promote greater efficiency and compactness in the CO_2 capture process through hybrid membrane capture technology. The contactors were able to assist the solvents in the gas absorption process. As a result, the contactors proved to be efficient when applied on an industrial scale.

Table 6
Advantages, disadvantages and research trends aimed at membrane separation technologies.

Advantages	Disadvantages	Research trends
Easy operation and ecological process (Castro et al., 2021); low energy consumption (Liu et al., 2021); no need for additives, relatively low costs (Czarnota et al., 2019); the percentage of separation of CO2 from other gases can reach 80% (Mohammad et al., 2020); separation properties and ease of fabrication (Scholes, 2020).	Low processing capacity and low stability (Ochedi et al., 2021); as it is a new capture category, many parameters are still unknown to researchers (Norahim et al., 2018);	Studies: aimed at optimizing the selectivity, permeability and energy of material regeneration (Silva et al., 2018); of hybrid membranes; materials that optimize the permeability of the membrane, aiming mainly at reducing the membrane areas and, consequently, the capital cost (Singh et al., 2021); of the partial pressure of gases (Scholes, 2020)

fly ash to improve CO_2 absorption and carbonate mineralization in cement mortars. As a main result, the research showed that the use of 3% biochar contributes to greater carbon sequestration and shows better yields in parameters such as durability and mechanical strength when compared to plain mortar. And in his study, Gupta (2021) evaluates the insertion of biochar in cementitious composites, stressing that its application has potential in the production of low-carbon cements and highlights its use as a “green mixture".

Then both examples show the potential of use of the chemical capture technologies, based on mineralization, for CCU.

3.5. Technological readiness level (TRL) of CO_2 capture technologies

The search for green technologies gained proportion due to the worldwide concern with the environmental impacts arising from industrial processes, such as chemical processes. Since the beginning of the 21st century, this problem has driven the great increase in research and new technologies for the most diverse areas. The energy generation, chemical and agricultural sectors stand out quantitatively in the emergence of green technologies, as they are the main responsible for the high GHG emissions. Monitoring the development of new technologies and the optimization of existing technologies is important as it enables future projections for a particular branch of R&D&I.

Technological maturity analysis is a tool developed by NASA in 1990 and was adapted by The Electric Power Research Institute (EPRI) such as the Technology Readiness Level (TRL) system, which can level existing technologies, pointing out the status in which they are found (Freeman and Bhown, 2011). TRL has a simple nomenclature (TRL1, TRL2, TRL3, …) and allows analyzing the development of technologies through stages. These stages progress gradually and each one of them is a

Table 7
R&D&I examples for chemical capture.

Title of the work	Author	Summary
Experimental investigation of the carbonation reactor in a tail-end calcium looping configuration for CO_2 capture from cement plants	Hornberger (2021)	In this work, CO_2 capture through calcium looping technology was investigated. The research was conducted on a semi-industrial scale in thermoelectric plants burning fossil fuels. The results showed that higher concentrations of sorbent increase the transport of gas. The tests validated the technology used to capture CO_2, with the same being shown for application in cement manufacturing plants.
Captura de CO_2 utilizando o processo* Ca-Looping *com CaO e Al_2O_3	Silva and Santos (2018)	In order to optimize the Ca-Looping technology, this work investigated the use of additives in order to reduce the deactivation of CaO during the CO_2 capture process. The results obtained showed that the combinations of carbonates withAl_2O_3, additive used in this experiment, were effective in capturing CO_2, since prevented the closure of pores and the growth of CaO crystals.
***Captura de dióxido de carbono utilizando óxidos a base de cálcio* [Carbon dioxide capture using calcium oxides]**	Bisinoti et al. (2017)	This work aimed to evaluate the incorporation of calcium oxide to the CO_2 capture process by carbonation. Two carbonation combinations were made: one with pure calcium and the other with calcium mixed with alumina. It was found that carbonation with pure calcium promoted greater CO_2 capture than the mixture with alumina, which proved to be inefficient in the process of capturing CO_2 as carbonate.
Single-step, low temperature and integrated CO_2 capture and conversion using sodium glycinate to produce calcium carbonate	Liu and Gadikota (2020)	This work studied the capture and conversion of CO_2 to produce calcium carbonate with CaO and $CaSiO_3$ as precursors. Calcium glycinate was used to promote CO_2 capture and parameters such as temperature, concentration of the additive and reaction time were investigated. The results obtained suggested that glycinate undergoes multiple cycles of capture and regeneration, favoring the precipitation of carbonates.

Table 8
Advantages, disadvantages and trends of research aimed at chemical capture technologies.

Advantages	Disadvantages	Research trends
Products from this category have a high boiling point, low toxicity and are biodegradable (North et al., 2010); favor sectors such as energy, agriculture and the polymer industry (Liu et al., 2020);	Cost for solvent regeneration and degradation by oxidation that generate corrosive compounds that reduce the efficiency of the process (Aquino et al., 2016); generally, the substances used in carbonation lose their capture capacity due to the closing of their pores, with the need for additives (Silva and Santos, 2018).	Studies: focused on chemical cycles of carbonation/ decarbonation, of solvents involved in chemical reactions and their kinetics (Liu et al., 2020); on ionic liquids, mainly aiming at economic factors (Hospital-Benito et al., 2021); of additives that favor the capture of CO_2 (Silva and Santos, 2018).

prerequisite for the next, as shown in Table 9.

The analysis through TRL allows projections of time, cost and environmental impacts, quantifies existing technologies and helps decision making. Currently, it is a tool used worldwide by political leaders and entrepreneurs in various fields, especially in R&D&I.

As they are generally high-cost technologies, the use of technological maturity analysis is extremely important for carbon capture, storage and use (CCSU) technologies, as it identifies promising technologies capable of guiding investments in R&D&I by analyzing the TRL levels the technology can achieve (Roh et al., 2020).

The International Energy Agency (2020) carried out a survey of perspectives on CO_2 capture technologies according TRL levels. From this review, data from the four categories of technologies discussed so far (adsorption, absorption, membrane separation and chemical capture) is presented in Table 10.

TRL surveys are conducted using data from technology providers. For comparison purposes, data from Kearns et al. (2021) were considered.

Freeman and Bhown (2011) also point out that the main limitation of the TRL scale is the lack of requirements at each stage of development to advance to the next stage, that is, the level of effort required to advance from TRL-1 is unknown for the TRL-2 and so on.

4. Carbon market

With the negative impacts rising from climate change, pollution

Table 9
TRL development stages according to EPRI. Source: adapted from Freeman and Bhown (2011).

	TRL Level	Technology maturity level
	9	Normal trade service
Demonstration	8	Commercial demonstration, large-scale deployment in final form
	7	Subscale demonstration, full functional prototype
	6	Fully integrated pilot testing in a relevant environment
Development	5	Subsystem validation in an environment
	4	System validation in a laboratory environment
	3	Proof of concept tests, component level
Research	2	Application formulation
	1	Observation of basic principles, initial concept

Table 10
TRL analysis for adsorption, absorption, membrane separation and chemical capture technologies carried out by the International Energy Agency (2020).

Technology category	TRL Level	Considerations
Adsorption	9	Mainly applied in natural gas and ethanol processes, this technology is responsible for CO_2 capturing in large plants and has great application perspectives. Its advances are mainly due to the simple operation attributed to it.
Absorption	9	It is the most advanced technology. This is due to the research time and consequently its application in small and large power generation, fuel transformation and industrial production plants.
Membrane separation	6–7	Relatively new but promising technology and considered to be the most effective separation technology among the existing ones. Its advances depend on the type of gas emission source and its application. Currently, part of its applications is in the demonstration phase, and another part in the development phase, few are commercially available.
Chemical capture	4–6	The capture involving chemical reactions, are presented in that TRL for its time and research intensity. As it is relatively new, its level is justified by the need for large pilot scale tests.

control mechanisms are even more focused on mitigating GHG emissions. Kim and Park (2018) argue that the mechanisms created in world conventions such as the Kyoto Protocol,[5] are essentially due to the increase in GHG emissions, especially carbon dioxide. Thus, the global concern with the emissions of this gas goes beyond global warming, gaining an economic and social focus.

The carbon market comprises agreements made at world conventions by several countries with the objective of promoting and boosting searches for mitigating processes and to provide the union of them aiming at raising awareness of GHG reductions (Godoy, 2013).

As a way of encouraging the reduction of GHGs, this market allows carbon transactions between countries that have not reached their reduction quota and those that have exceeded it, with these transactions generating revenues for those who have carbon credits (Anand et al., 2021), making them of great economic and social interest.

Understanding the economic viability of the carbon dioxide market will help to estimate, more accurately, the anthropogenic emissions of this gas. Over the years, climate change will promote more aggressive effects, with the carbon market being a stimulus for countries to comply with the agreements made in international conventions (World Health Organization, 2018), in addition to promoting research on the reduction and/or use of GHGs.

Currently, carbon pricing systems mainly cover industrial, energy and land use change sectors. Examples of international pricing efforts:

- The Partnership for Market Readiness (PMR)[6]
- The Carbon Pricing Leadership Coalition (CPLC)[7]
- The Mitigation Action Assessment Protocol (MAAP)[8]

In Brazil, the thermoelectric and ethanol sectors are objects of research because they are major generators of carbon dioxide. It is worth mentioning the purity of this gas produced by the ethanol production, which makes it more easily *monetizable*, when compared to that coming from the thermoelectric sector, whose purity is considerably reduced. As an example of carbon pricing, the sale of carbon credits on the stock exchange can be mentioned: B3 - Bolsa Brasil Balcão - records the

[5] https://ipam.org.br/entenda/o-que-eo-protocolo-de-quioto/.
[6] https://www.thepmr.org/.
[7] https://www.carbonpricingleadership.org/.
[8] https://maap.worldbank.org/#/homepage.

emissions made by producers and importers of biofuels, negotiates and requests the retirement of the decarbonization credits (CBIO) in Brazil (Brasil, 2022).

5. Conclusion

Due to the environmental impacts caused by the non-renewable generation of energy, alternatives for substitution depend on technical and economic viability, which varies according to the country and its natural conditions. This impasse requires technologies that reduce gaseous emissions from existing plants as those dedicated to energy from coal. On the other hand, ethanol production presents itself as a mitigation alternative in relation to other agro-industrial processes, since the gas emitted could, in theory, be fully absorbed by cultivated plants (e.g., sugarcane) through photosynthesis. In addition, ethanol production generates a high-purity carbon dioxide, very desirable for use as an industrial raw material.

Regarding the capture and use processes for carbon dioxide, the adsorption processes are considered complex separation processes and research aims to minimize the costs of these processes and technical limitations, among them the low efficiency in the gas separation process. Another limiting factor in the development of adsorption technologies is the need for large amounts of energy to operate the process with an unfavorable energy balance.

In absorption processes, they must occur in such a way that the carbon dioxide is capable of later separation, post-capture. This is possible, as this technology has materials capable of absorbing the gas and transporting it from one phase to another, in this case the carbon dioxide is solubilized by passing to the liquid phase of the mixture, making it possible to separate it from the other components. Absorption is among the most promising technologies for its efficiency and economic viability and the most mature technology capable of large-scale application. However, the high-energy expenditure is a limitation.

The capture by separation membranes is based on the selectivity of the material constituting them in relation to the gas. Carbon dioxide permeates through membranes, separating itself from other compounds. Due to their function, membranes depend on parameters such as medium permeability, particle size, selectivity and pore volume. Research aimed at capturing carbon dioxide by membranes has as a major challenge the development of systems that optimize the parameters necessary for the capture process. However, this technology is considered the most effective technology among the existing ones.

Among the carbon dioxide capture technologies currently under development, there is also the chemical capture for the generation of carbonates as one that can promote added value to industrial and agro-industrial chains, in addition to leading to more sustainable production systems. This capture makes use of chemical reactions with carbon dioxide to obtain final products - these can be inorganic or organic – mainly carbonates. The great interest in this class of technology is because the carbonates obtained have a high boiling point, low toxicity and are biodegradable. Furthermore, its application in cement production plants is a possibility to transfer technology to other industry sectors with a considerable GHG emission.

Monitoring the development of new technologies and the optimization of existing technologies is important as it enables future projections for a particular branch of R&D&I. The analysis through TRL (technology readiness level) allows projections of time, cost and environmental impacts, quantifies existing technologies and helps decision making.

To finalize, the carbon market is highly promisor to develop a new sustainable value chain. The understanding the economic viability of the carbon dioxide market will help to estimate, more accurately, the anthropogenic emissions of this gas.

Declaration of competing interest

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

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