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Storage of carbon dioxide in geological reservoirs: is it a cleaner technology?

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A R T I C L E I N F O

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A B S T R A C T

Increased anthropogenic emissions and accumulation of greenhouse gases (GHGs) in the atmosphere have led to climate change, which has become a major global environmental concern. The effects of anthropogenic GHG emissions and their relationship with climate change have been extensively studied and discussed in recent decades. Carbon dioxide (CO_2) is one of the main GHGs, and several technologies have been developed to capture and dispose of it before it is released into the atmosphere. CO_2 storage in geological reservoirs to mitigate CO_2 emissions is one of the technological solutions that has attracted interest. This article primarily focuses on answering the following question: To what extent can the storage of carbon dioxide in geological reservoirs (CGS) be considered a cleaner technology? A literature review on this subject was carried out along with document analysis and expert consultation. Initially, the literature on environmental technologies, specifically that on CGS technology, was reviewed. Subsequently, the use of CGS technology as an environmental technology was investigated. We conclude that it can be considered a transitional technology.

1. Introduction

In recent years, the increasing emission of greenhouse gases (GHGs) into the atmosphere has led to climate change, which has become a major environmental concern. Strategies to overcome this problem include reducing or avoiding the use of fossil fuels as energy sources, thus reducing the resultant GHG emissions; developing new and modifying existing technologies to make them more eco-friendly; and installing large engineering projects such as solar and wind farms worldwide.

The effects of GHG emissions and their relationship with climate change have been extensively studied and discussed in scientific, political, and public circles in recent decades. Initially, environmental issues were discussed from the viewpoint of the use of fossil fuels and pollution control, with the issue of environment versus economy being the principal topic of discussion. Society has evolved to a level where there is a greater balance between the production of goods, consumption of resources, and effects on the environment. Nonetheless, human activities continue to have significant and worrying effects on the environment.

Lloyd and Subbarao (2009) suggested that it would be necessary to change the traditional fossil-fuel-based economy by developing alternative, carbon-free energy systems such as renewable energy in order to achieve an environmentally sustainable economy. This is because humans today are said to live in the information age, in which the economy cannot develop effectively by continuing to use energy-generation technologies from the industrial age. As such, the development of new and advanced technologies is essential for sustainability and for achieving a balance between production and consumption.

The issue of sustainability has attracted considerable attention in political, educational, technical, social, economic, and environmental circles. Various authors have discussed the terminology and definitions of sustainable actions. Over the years, it has been observed that these definitions have evolved with the concept of cleaner production. A widely accepted definition of cleaner production was first coined by the United Nations Environment Programme (UNEP) in Paris in 1989. Glavič and Lukman (2007) suggest that the concept of cleaner production has attracted much interest over the past decade, which they defined as follows:

> *"… a systematically organized approach to production activities, which has positive effects on the environment. These activities*

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encompass resource use minimization, improved eco-efficiency and source reduction, in order to improve the environmental protection and to reduce risks to living organisms" (Glavič and Lukman, 2007).

Subsequently, this definition has been expanded to incorporate the idea of sustainable development.

The International Centre for Environmental Technology Transfer (ICETT) (ICETT, 2012) defines cleaner technology as a manufacturing process that by its nature or intrinsically

- reduces the production of effluents and other wastes,
- maximizes product quality, and
- maximizes the use of raw materials, energy, and any other input.

According to the ICETT, a technology is usually compared to some other technology or process. Cleaner technology may be considered a subset of cleaner production activities with a focus on the actual manufacturing process itself, and it considers the integration of better production systems to minimize environmental damage and maximize production efficiency from many or all of its inputs.

Currently, cleaner technology is defined as modifications to a process that minimize or even eliminate any environmentally harmful effects. These modifications could include the introduction of modern control technology, changes in the types of raw materials, or the use of additional materials (Kuehr, 2007).

Similarly, industrial technologies and processes have also evolved. Pacala and Socolow (2004) argue that humanity already possesses the scientific, technical, and industrial expertise required to mitigate climate change and all its related problems by the second half of the 21st century. In fact, presently, the use of green technologies is being economically incentivized on a large scale through markets for carbon credits (regulated and voluntary) and funds for financing (public and private).

With the objective of achieving sustainability, the development and application of cleaner technologies in industrial processes has been prioritized. Most present technologies have been developed in the 20th century. The application of these modern technologies to industrial processes can help mitigate emissions of carbon dioxide, a major GHG. A particular advantage is that these technologies can be used with existing facilities—modifying facilities or building new ones would not be an economical solution. The availability of such technologies has encouraged the use of carbon dioxide as a raw material in the enhanced recovery of oil and gas, both of which are currently rather expensive fossil fuels. In this context, the large-scale use of technologies for the storage of carbon dioxide in geological reservoirs is also being encouraged.

This paper aims to answer the following question: To what extent can the storage of carbon dioxide in geological reservoirs be considered a cleaner technology? Toward this end, we use exploratory, descriptive, and analytical research methods that focus on qualitative and quantitative strategies and techniques. Primary data were collected through consultations with specialists such as academic researchers, industrial researchers, and stakeholders from the government, non-governmental organizations, and private sector. Indirect observations were made by participating in discussions and lectures on the subject of study and in forums with domain experts. Furthermore, direct observations were made by participating in official meetings, with the approval of the relevant authorities, and recording the results achieved. Secondary data were collected from various resources and analyzed. For example, a literature review of environmental technologies, carbon capture technologies, and technologies for the geological storage of carbon dioxide was carried out. Institutional documents such as reports, studies, and projects were also were analyzed.

2. Environmental and cleaner technologies

Jabbour (2007) defined environmental technologies as those related to the development of green products and processes and that can be used to reduce energy consumption, prevent pollution, and recycle waste. Gouldson and Murphy (1998) noted that the widespread use of environmental technologies in industry will help achieve a balance between economic growth and environmental protection.

Environmental technologies are classified in various ways in both Brazilian and international literature, giving rise to various terms that are related to the consideration of environmental aspects in technological development. Environmental technologies involve the development of hardware or software that adopts new design concepts, equipment, and operational procedures to incorporate the best practices from the viewpoint of environmental performance, mainly by using raw materials with low environmental impact and efficient processes, minimizing and promoting the reuse of industrial waste, and changing the production cycle (Jabbour, 2010). The present authors classify environmental technologies into the following categories: technologies for the control and prevention of pollution, technologies for measurement and analysis, and technologies with zero environmental impact.

This paper adopts concepts proposed in Lenzi (2006), which are similar to those in Jabbour (2010). He divides environmental technologies into control technologies that are aimed at waste treatment (end-of-pipe) and cleaner technologies that are aimed at pollution prevention.

End-of-pipe technologies involve the treatment of pollutants at the end of the production process, after all of the products and waste products have been generated, and the waste products are released through a pipe, smokestack, or other release point. This approach is designed to reduce the direct release of pollutants in order to comply with environmental regulations; however, it can occasionally result in transmitting pollutants from one medium to another. Therefore, it only delays environmental problems temporarily (Glavič and Lukman, 2007).

An alternative to cleaner technologies and end-of-pipe technologies is recycling. Recycling is used in production processes, and it combines the advantages of both the former, in that modifications are made to products and processes, and the latter, in that external recycling is carried out (Kemp et al., 2000).

Madruga and Nascimento (1999) view environmental technologies mainly from the perspective of pollution prevention, because cleaner technologies make it possible to increase the efficiency of the use of raw materials, water, and energy. This requires research into technology to eliminate, reduce, or recycle the waste that is generated in the production process. A systemic or holistic approach will be required to prevent pollution through the recycling of waste.

According to the Brazilian Business Council for Sustainable Development (CEBDS, 2004), cleaner technologies should be used during the production process rather than at the end of production in order to prevent pollution. All waste entails a certain cost, because of the purchase price of the raw materials and inputs consumed during the production process, such as water and energy. Once waste is generated, it continues to cause a monetary loss in the form of treatment and storage costs, fines, or damage to the company's image. The National Center for Clean Technologies (CNTL, 2003) stated that a change in environmental paradigms drives firms to analyze the source of their solid waste generation, atmospheric emissions, and liquid effluents; seek solutions within their production processes; and reduce the use of conventional end-of-pipe treatments, which are often expensive and do not provide definitive results.

Mello and Nascimento (2002) noted that it is important to highlight the subtle differences between the concepts of cleaner production, clean production, pollution prevention, clean technologies, cleaner technologies, and end-of-pipe technologies. The concept of cleaner production is defined by the United Nations Industrial Development Organization (UNIDO)/UNEP to encourage voluntary actions by industry without a commitment to environmental legislation. It is the continuous application of an integrated preventive environmental strategy to processes, products, and services in order to increase eco-efficiency and reduce the risks to humans and the environment. The concept of pollution prevention as defined by the Environmental Protection Agency (EPA) is similar to that of cleaner production. It refers to any practice, process, technique, or technology that aims at the reduction or elimination in volume, concentration, and/or toxicity of waste at source. Finally, the concept of clean production as defined by the non-governmental organization Greenpeace is more restrictive than that of cleaner production, because it proposes the use of non-toxic products and the use of renewable energy sources, whereas cleaner production encourages the reduction of toxicity and more efficient use of energy.

The same is the case with the concepts of cleaner technologies and clean technologies (Mello and Nascimento, 2002). Clean technologies are goals that must be pursued but are difficult to achieve in practice because there will always be some type of environmental impact. Cleaner technologies aim to prevent pollution and have a relatively lower environmental impact than other technologies. In addition, end-of-pipe technologies are technologies used to treat waste, effluents, and emissions in order to mitigate their effects on the environment.

Kiperstok (2006) considers that end-of-pipe technologies are not capable of mitigating environmental degradation and bringing about the required changes because they are applied after the generation of waste and are not aimed at pollution prevention; they are simply considered inevitable in the production process. Mello and Nascimento (2002) and Jabbour (2010) claim that pollution prevention through cleaner technologies focuses on the potential of direct gains in a given production process along with indirect gains by eliminating the costs associated with the treatment and final disposal of waste, which results in lower costs and shorter payback periods for the initial investment.

Cleaner technologies are characterized by the adoption of any action to change, reduce, or eliminate pollution at the source, with or without the use of natural resources. Therefore, we value the concept of the 3Rs—reduce, reuse, and recycle—in this order. As technologies and cleaner production practices become more effective at reducing waste generation, they will become more relevant to source reduction and the transformation matrix of the production process. In contrast, when technologies and cleaner production practices are involved in the treatment of waste from the production process, they tend toward practical end-of-pipe technologies (LaGrega et al., 1994).

This assertion can be demonstrated in Fig. 1, which shows the various positions that a corporation can adopt to reduce pollution. As the position moves toward the right-hand side of the figure, the practices tend to be end-of-pipe, whereas those toward the left-hand side focus on reducing wastes at the source, contributing to sustainable production and consumption.

With respect to source reduction, the EPA (USA and Environmental Protection Agency – EPA, 1988) showed that the initial step is to rethink the product, which could involve changes in the product, including its substitution, maintenance, or changes in its composition, with the purpose of meeting environmental requirements. Another possibility, according to Kiperstok (2002), can be to change the process by changing the inputs, using less toxic materials, and increasing the efficiency, or changing the technology, making the process more efficient in the quest for zero waste. When source reduction actions are not capable of preventing the generation of waste, internal/external recycling should be considered, through use and reuse techniques, when these recycling techniques do not require modifications in the residue. The material returns directly to the generator process itself and is used as a component or intermediate in the manufacture of a product.

3. Technologies for mitigation of carbon dioxide (CO_2) emissions

CO_2 is one of the main GHGs. It has rather specific physical properties. The UNEP (1996) defines CO_2 as a colorless, odorless, non-poisonous gas that is derived from the burning of fossil fuels

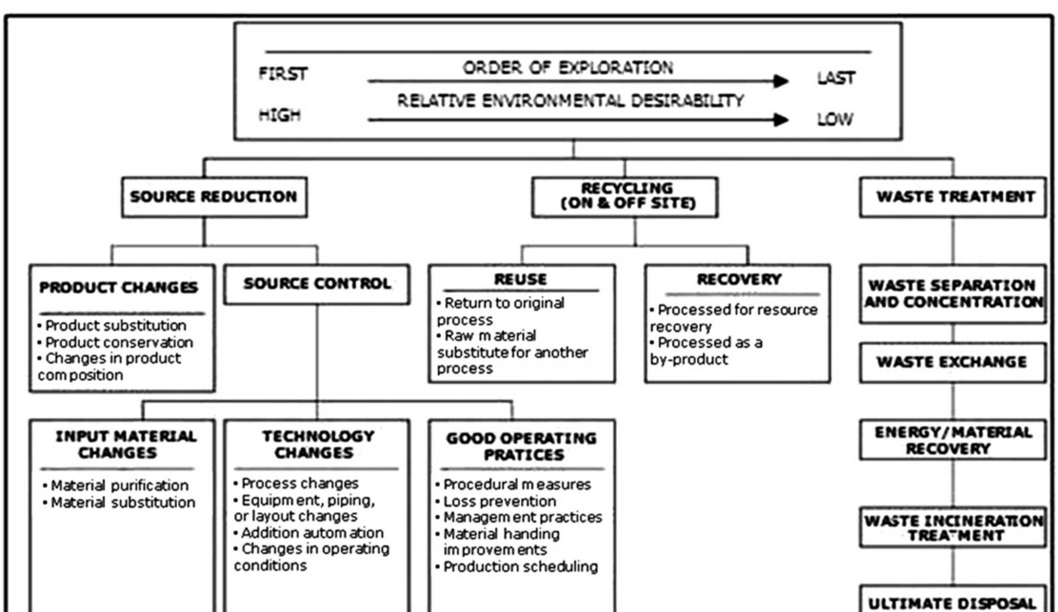


Fig. 1. Pollution reduction techniques (LaGrega et al., 1994).

and is present in the atmosphere. In the atmosphere, it mainly degrades the environment through its permanence and accumulation, which contribute significantly to the greenhouse effect and global warming. CO_2 can be found stored in natural geological reservoirs and it is also produced in industrial processes such as cement production, fertilizer production, oil extraction and refining, and power generation using fossil fuels.

Very advanced technologies exist for the separation of CO_2 in industrial processes. The use of separation technologies is not new. For example, amine-based CO_2 separation has been in practice since the 1930s for applications such as natural gas purification (Azuhata, 2011). However, technologies for CO_2 separation and capture are expensive and consume large amounts of energy. These technologies can be classified as post-combustion, pre-combustion, and oxyfuel combustion—they include absorption, adsorption, semi-permeable membrane separation, cryogenic separation, and "chemical looping" (Bello and Mustafa, 2009).

The Intergovernmental Panel on Climate Change (IPCC) discussed technological options for capturing CO_2 emissions from stationary sources in detail in its Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005). The following provides a brief description of each option, as established by the IPCC.

Post-combustion systems separate CO_2 from the flue gases produced by the combustion of the primary fuel in air. These systems normally use a liquid solvent to capture the small fraction of CO_2 (typically 3–15% by volume) present in a flue gas stream from the main constituent nitrogen (from air). Current post-combustion capture systems typically employ an organic solvent such as monoethanolamine (MEA).

Pre-combustion systems process the primary fuel in a reactor using steam and air or oxygen to produce a mixture consisting mainly of carbon monoxide and hydrogen ("synthesis gas"). Additional hydrogen, together with CO_2, is produced by reacting the carbon monoxide with steam in a second reactor (a "shift reactor"). The resulting mixture of hydrogen and CO_2 can then be separated into a CO_2 gas stream and a stream of hydrogen.

Oxyfuel combustion systems use oxygen instead of air for the combustion of the primary fuel to produce a flue gas that mainly consists of water vapor and CO_2. This results in a flue gas with a high CO_2 concentration (greater than 80% by volume). The water vapor is then removed by cooling and compressing the gas stream.

Fig. 2 shows a diagram of each type of capture technology, along with the use of these technologies in industrial processes.

The use of capture technologies for stationary sources can prevent the accumulation of CO_2 in the atmosphere. However, another issue arises: what should be done with the CO_2 after its capture? One solution is the storage of CO_2, for which potential storage methods include geological storage, ocean storage (direct release into the ocean water column or onto the deep seafloor), and industrial fixation of CO_2 into inorganic carbonates (IPCC, 2005). With regard to geological storage, the IPCC (2005) defines geological reservoirs as a subsurface body of rock with sufficient porosity and permeability to store and transmit fluids. The storage of CO_2 in geological reservoirs currently appears the most promising considering its applicability in the oil and gas industry and the availability of improved geological survey techniques and enhanced recovery techniques.

Another factor that is driving the large-scale use of carbon capture and storage (CCS) technologies is their application in the energy supply sector. According to the IPCC, in 2004, the world-wide energy sector was the main emitter of CO_2 and accounted for 25.9% of all emissions (IPCC, 2007a,b). In this sector, it is possible to analyze the technical potential and estimate the projected costs of CCS technologies compared to other technological solutions such as the use of renewable and nuclear energy. Fig. 3 shows the projected costs in 2030 for these solutions in the energy supply sector.

3.1. Technologies for storage of carbon dioxide in geological reservoirs

Meadowcroft and Langhelle (2009) noted that the idea of capturing CO_2 from fossil fuel combustion and storing it in the ocean or underground had already been proposed in the late 1970s.

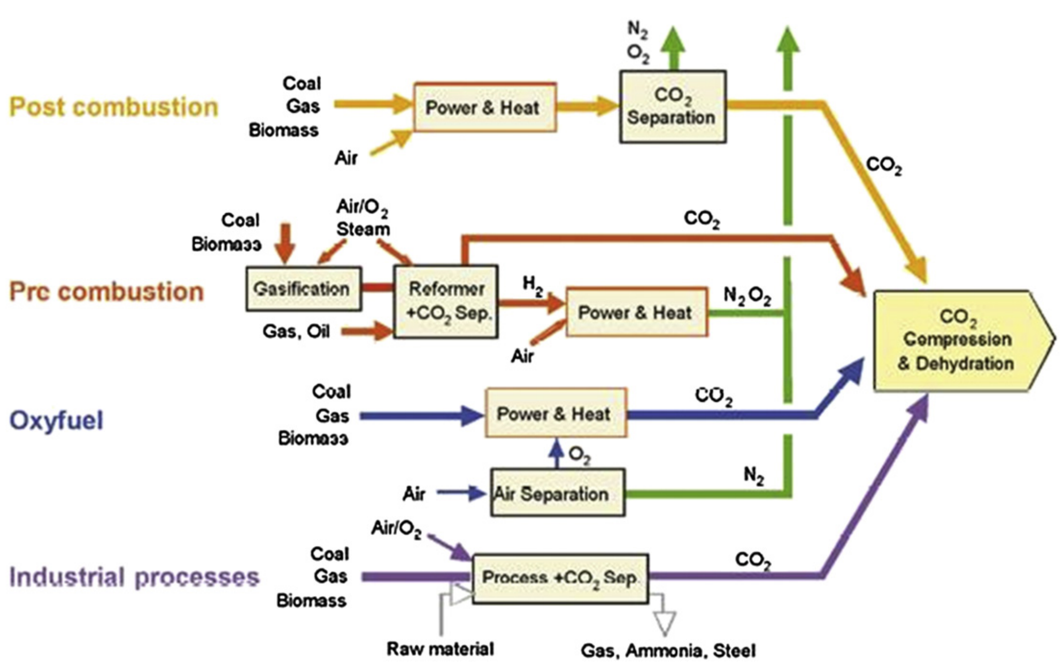
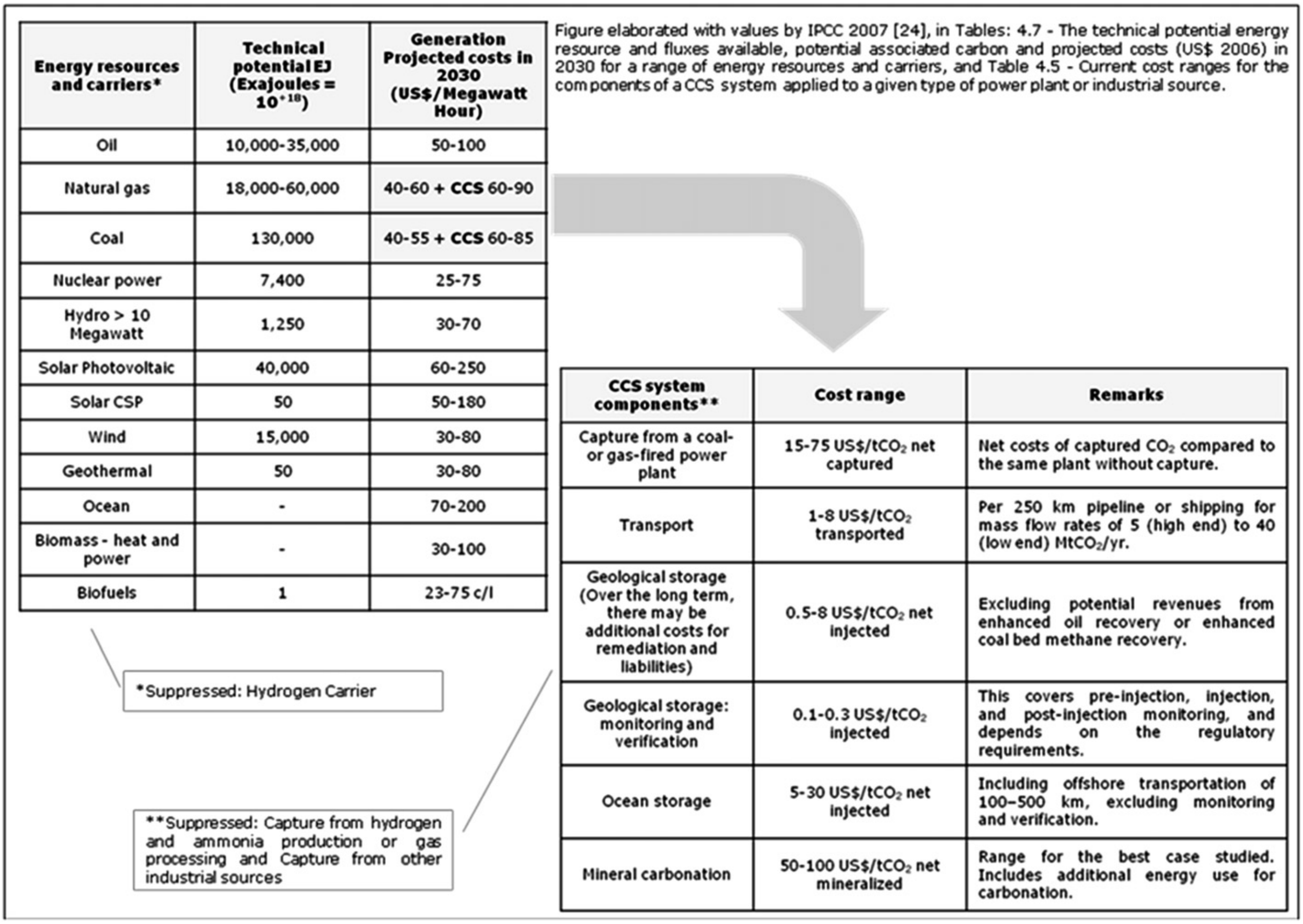


Fig. 2. Overview of CO_2 capture processes and systems (IPCC, 2005).



Energy resources and carriers*	Technical potential EJ (Exajoules = 10^{+18})	Generation Projected costs in 2030 (US$/Megawatt Hour)
Oil	10,000-35,000	50-100
Natural gas	18,000-60,000	40-60 + **CCS** 60-90
Coal	130,000	40-55 + **CCS** 60-85
Nuclear power	7,400	25-75
Hydro > 10 Megawatt	1,250	30-70
Solar Photovoltaic	40,000	60-250
Solar CSP	50	50-180
Wind	15,000	30-80
Geothermal	50	30-80
Ocean	-	70-200
Biomass - heat and power	-	30-100
Biofuels	1	23-75 c/l

*Suppressed: Hydrogen Carrier

Figure elaborated with values by IPCC 2007 [24], in Tables: 4.7 - The technical potential energy resource and fluxes available, potential associated carbon and projected costs (US$ 2006) in 2030 for a range of energy resources and carriers, and Table 4.5 - Current cost ranges for the components of a CCS system applied to a given type of power plant or industrial source.

CCS system components**	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15-75 US$/t$CO_2$ net captured	Net costs of captured CO_2 compared to the same plant without capture.
Transport	1-8 US$/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2/yr.
Geological storage (Over the long term, there may be additional costs for remediation and liabilities)	0.5-8 US$/t$CO_2$ net injected	Excluding potential revenues from enhanced oil recovery or enhanced coal bed methane recovery.
Geological storage: monitoring and verification	0.1-0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Ocean storage	5-30 US$/t$CO_2$ net injected	Including offshore transportation of 100–500 km, excluding monitoring and verification.
Mineral carbonation	50-100 US$/t$CO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

**Suppressed: Capture from hydrogen and ammonia production or gas processing and Capture from other industrial sources

Fig. 3. Projected costs for various technological solutions.

However, concerns over climate change gained footing in the scientific community and among international policy makers. It was only in the mid-1980s when work on CCS really began.

From the beginning, the International Energy Agency (IEA) has played an increasingly important role in stimulating research on CCS. Since the 1990s, the IEA has promoted discussions of CCS technologies with academia, industry, and government to promote the understanding of CCS. Fossil fuel producers and governments were the major sponsors of these investigations, which focused on capture and transport technologies, assessments of storage potential, and the modeling of costs (Meadowcroft and Langhelle, 2009).

A milestone for analyses and research on technologies to capture, transport, and store CO_2 in geological reservoirs was the publication of the Special Report on Carbon Dioxide Capture and Storage by the IPCC in 2005. The IPCC (2005) defined CCS as a process that consists of separating, collecting, and concentrating the CO_2 emitted by stationary sources; transporting it to a suitable storage site; and storing it at the site for a long period, thus isolating it from the atmosphere.

Bachu and McEwen (2011) noted that various terms are used to describe CO_2 storage: *CO_2 sequestration* is used in USA, *CO_2 storage* is used by UN agencies and in Europe, and terms such as *CO_2 removal* and *CO_2 disposal* are also used. In this paper, we use the term CGS technologies to refer specifically to CO_2 injection and storage in geological reservoirs.

The injection of CO_2 into a geological reservoir is a process that has been used in some industrial sectors. There are technologies in the oil industry for the enhanced recovery of oil or gas using chemicals for injection, including CO_2. According to the IPCC (2005), the main options for the geological storage of CO_2 include: depleted oil and gas reservoirs, the use of CO_2 in enhanced oil recovery (EOR) and enhanced gas recovery (EGR), deep unused saline water-saturated reservoir rocks, deep unmineable coal seams, the use of CO_2 in enhanced coal bed methane (ECBM) recovery, and some other options such as basalts, oil shales, and cavities.

Some technologies such as EOR, EGR, and ECBM add value to the storage of CO_2 in geological reservoirs; the injected CO_2 serves to increase the oil, gas, or methane production, respectively, in addition to simple storage. The other storage options do not add any value; storage is performed merely with the objective of storing the CO_2 and preventing its emission to the atmosphere (APEC, 2005).

As shown in a study by the IEA in 2008, the capture and storage of CO_2 using technologies that are currently available or likely to become commercially available can control emissions in the short-to medium-term. Adequate CO_2 capture and storage can contribute to a 19% worldwide reduction in total CO_2 emissions by 2050 (IEA, 2008). CCS technologies were recognized by the G8 in June 2008 when they decided to support the recommendations of the IEA and the Leadership Forum on Carbon Sequestration (CSFL) for the execution of 20 projects involving CCS on a large scale, because they believed that CCS would play a critical role in combating climate change and meeting energy security challenges (G8 2008 Summit, 2008).

To pursue these goals and present the progress made, the IEA and CSFL published the "Report to the Muskoka 2010 G8 Summit – Carbon Capture and Storage Progress and Next Steps." in 2010. They reported the following results: only 5 of the 20 projects were in operation (in Salah/Algeria, Sleipner and Snøhvit/Norway, Rangely/United States, and Weyburn-Midale/Canada and United States), and 1 was under construction (Gorgon/Australia). However, the report indicated that despite failing to achieve the expected goals, progress has been made and it would be possible for 19–43 projects to be in operation by 2020 (IEA, 2010a).

The expected resources to be allocated to CCS projects in April 2010 by public funding commitments were in the range of USD 26.6–36.1 billion (IEA, 2010a). However, because of the economic crisis in Europe, reductions are expected in these investments and the number of projects. Only 6–12 CCS projects were planned in Europe, with an expected investment of USD 4–6 billion.

In 2010, the IEA published the "Technology Roadmap – Carbon capture and storage." With regard to CGS technologies in particular, there is an urgent need to advance the state of global knowledge of prospective CO_2 storage. Whereas depleted oil and gas fields are well mapped and offer promising low-cost opportunities, deep saline formations are the most viable option in the long-term. However, the CO_2 storage potential of these formations has been adequately mapped in only a few regions (IEA, 2010b).

In spite of worldwide efforts toward the large-scale use of CGS technologies, there are important issues such as environmental risks, regulatory aspects, and public perception that directly influence their use. The risks of CO_2 leakage from geological reservoirs and the likely exposure of people and ecosystems or potable aquifers to large quantities of CO_2 and the consequences of the same are some of the main barriers to the widespread use of CGS technologies. Furthermore, regulatory aspects such as liabilities, obligations, boundaries, CO_2 classification (waste, pollutant, or industrial sub product), and CO_2 specifications for injection have not yet been resolved. Due to these issues and their impact on public perception, some CGS projects in the Netherlands (e.g. Barendrecht), Germany, and USA (e.g. Greenville, Jamestown, and Ohio) have been canceled or interrupted.

Despite the efforts of governments and the interest of the private sector, mainly in the energy industry, many environmental and regulatory issues pertaining to CGS technologies still need to be resolved. Nonetheless, in this regard, CGS technologies are still friendlier than nuclear power.

4. CGS technology versus cleaner technology

An initial conceptual analysis of CGS technology, in relation to its application only for the geological storage of CO_2 emitted from stationary sources by industrial processes, suggests that it should be considered an end-of-pipe technology, because end-of-pipe technologies conceptually prescribe control strategies to mitigate the effects of pollution generated by production processes. In this regard, CO_2 should be considered industrial waste, with its storage in geological reservoirs being a way to prevent and control its emission to the atmosphere.

On the other hand, CO_2 can be used as an input to enhance the recovery of oil or gas. In this regard, CCS technology should be reclassified, especially if the CO_2 does not originate from industrial processes but from natural sources such as geological reservoirs of CO_2 located in the United States. According to the IPCC, 30 Mt of CO_2 are injected annually for EOR, mostly in Texas, US, where EOR commenced in the early 1970s. Most of this CO_2 is obtained from natural CO_2 reservoirs found in the western regions of the US, with some coming from anthropogenic sources such as natural gas processing. Much of the CO_2 injected for EOR is produced with the oil, from which it is separated and then reinjected. At the end of the oil recovery, CO_2 can be retained for the purpose of climate change mitigation rather than being vented to the atmosphere (IPCC, 2005). The locations of EOR projects in the US are shown in Fig. 4.

Mohan et al. (2008) noted that in 2008, there were 80 CO_2 miscible flooding projects active in the US, with a total daily production of 234,000 barrels of oil. The total production potential from CO_2 EOR in the US was approximately 19 billion barrels. Many of these projects were active because the high oil prices made them economically viable, although they were limited by the availability of CO_2. The widespread use of industrial CO_2 for EOR could increase the available volume from 3 Bcf per day from natural sources alone to nearly 70 Bcf per day from both natural and industrial sources. This CO_2 would be available not only in the Permian Basin but also in all parts of the US. By providing a steady source of CO_2, at prices between \$1 and \$3 per Mcf, more than 200 CO_2 EOR projects could be carried out, with incremental production reaching 1.2 million barrels a day. At the same time, these projects would provide the opportunity to sequester nearly 5 Bcf of CO_2 each day. Over 25 years, this could result in the production of more than 5.5 billion barrels of oil and the sequestration of nearly 1 Tcf of CO_2.

In addition to the possibility of capturing CO_2 from stationary sources and natural sources, CO_2 is also found mixed with oil and gas in its natural form. In exploration and production processes for oil and gas, CO_2 is usually vented into the atmosphere, which has a large impact on the environment. As an example, the recent discoveries of oil and gas deposits off the shores of Brazil in pre-salt reservoirs should be highlighted. Almeida et al. (2010a) noted that the pre-salt reservoirs are, as is characteristic of carbonate rocks, heterogeneous, with highly variable petro-physical properties. The oil has an American Petroleum Industry (API) gravity of 28–30, a gas–oil ratio of 200–300 m^3/m^3, and a CO_2 content of 8–12% for Tupi. This percentage is considered significant in comparison with the composition of other hydrocarbons.

The guideline adopted by Petrobras for the exploration and production of oil and gas from the pre-salt cluster has been to avoid venting the CO_2 associated with the natural gas produced.[1] According to Almeida et al. (2010b), the disposal of the CO_2 expected to be produced with the hydrocarbon streams in the Santos Basin Pre-Salt Cluster is being comprehensively studied, with all options and available technologies being considered. The following options are currently being technically and economically evaluated: EOR in the pre-salt areas, CO_2 storage in saline aquifers, EOR in heavy oil fields in the Santos Basin, CO_2 storage in depleted gas fields, CO_2 storage in salt caverns to be constructed in the cluster area, and CO_2 transportation to the shore and commercialization in industrial plants (non-geological option).

Although all six alternatives are being equally appraised, some of them show more promise for the Santos Basin Pre-Salt Cluster. The preferred option for the disposal of the CO_2 rich stream to be separated from the production gas seems to be reinjection into the hydrocarbon reservoir, because this affords two benefits: enhancing oil recovery and ensuring effective storage of the produced CO_2 (NETL, 2010).

[1] The presentation made by Petrobras (Beatriz Espinosa Nassur – General Manager/Health, Safety and Environment) to the Commission on Climate Change of the Federal Senate on 11/10/2009.

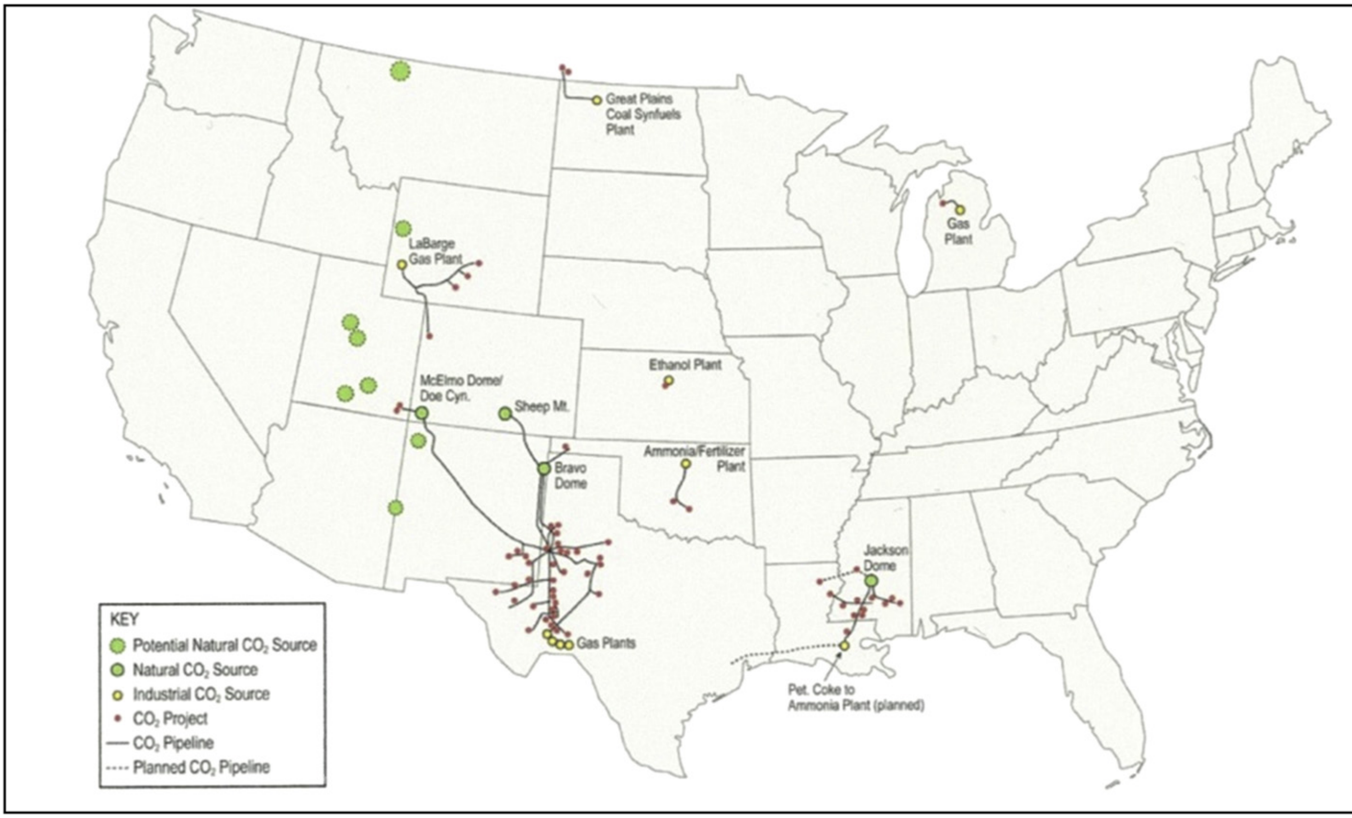


Fig. 4. Locations of EOR projects using CO_2 and pipelines in US (NETL, 2010).

Beck et al. (2011) suggested that CCS technologies could be crucial for the development of some of the "pre-salt" petroleum fields that present new challenges. Although there are no conclusive studies on the concentration of CO_2 in the region, some wells have shown concentrations of CO_2 exceeding those found in the Campos Basin, whereas others showed concentrations close to zero. Nevertheless, Petrobras has proactively committed to not releasing the CO_2 associated with the natural gas produced in the pre-salt layer into the atmosphere.

Lino (2005) noted that CO_2 injection tests have been carried out in the fields of the Reconcavo Basin in the state of Bahia by Petrobras since May 1991. The EOR Petrobras demonstration project in the Miranga field located in the Reconcavo Basin uses CO_2 from its fertilizer plant (FAFEN) located in the industrial center of Camaçari-BA. This CO_2 is a by-product of ammonia production, and it would normally be emitted into the atmosphere (200 ton of CO_2 per day). It is captured, transported by a 75-km pipeline, and used as an input for EOR. The field has an area of 12.00 km^2, and 200 ton of CO_2 is injected per day, with a storage rate of 50% and oil production of 182,500 barrels per year. The CO_2 consumption is 0.40 ton per oil barrel produced (Ravagnani and Suslick, 2008). The Petrobras Miranga Project has three different storage scenarios: EOR, depleted gas reservoir, and saline aquifer (Beck et al., 2011).

The Reconcavo Basin is the oldest petroleum basin in Brazil, and it is expected that more than 250 million m^3 of oil equivalent will be recovered from it using current recovery methods (Rocha et al., 2002). Oil production at the Reconcavo Basin in 2008 was 2,454,746 m^3, which represented 2.38% of Brazil's total oil production in 2008 (ANP, 2009). The appropriate application of EOR methods should increase production by 5–15% on average (Câmara and Reis, 2002).

Exploratory studies indicate the capacity to store 16 kton of CO_2 per day in the Reconcavo Basin. However, according to the EOR Petrobras demonstration project in the Miranga field, the rate of storage was 50% (Ravagnani and Suslick, 2008), indicating a daily storage value of 8 kton per day. This value has been calculated considering the fact that after oil and gas recovery, EOR technologies could be used for CO_2 storage projects. Rockett et al. (2011) estimated that the Reconcavo Basin has a total CO_2 storage capacity of 64.9 Mton.

In Brazil, another CGS demonstration project is being conducted by the Centre of Excellence in Research on Carbon Storage (CEPAC) with support from Petrobras and Copelmi (a Brazilian coal-producing company). The CEPAC Carbometano Porto Batista Project is being developed to investigate ECBM technology. It will inject CO_2 into the Charqueadas coal field, with the drilling phase finished and injection planned to commence in 2011 (Beck et al., 2011).

If CO_2 injection is analyzed from the perspective of its use in EOR, EGR, and ECBM technologies, with the injected CO_2 considered an input to increase the production of oil, gas, and methane, respectively, it could be captured from natural or anthropogenic sources. In these CGS technologies, value is added by the use of CO_2. However, it is important to emphasize that part of the injected CO_2 is released from the reservoir mixed with the hydrocarbons. Thus, it is necessary to create a closed process, so that the CO_2 can again be captured and reinjected into the field.

When CO_2 is injected into depleted oil and gas reservoirs, deep unused saline water-saturated reservoir rocks, deep unmineable coal seams, or other options such as basalts and cavities, the CO_2 injection has to be analyzed from the waste perspective because there is no added value from the CO_2 used in this process. In this case, CGS technologies are implemented to avoid releasing CO_2 emissions into the atmosphere, and the CO_2 should be captured from anthropogenic sources.

The current analysis departs from the premise that CO_2 is considered a waste or raw material for EOR, EGR, and ECBM. However, current research on the various uses of CO_2 may change this analysis. In addition to fuel production, according to the IPCC (2005), CO_2 can be used in mineral carbonation and the production of chemicals, with application areas including urea, refrigeration systems, inert agents for food packaging, beverages, welding systems, fire extinguishers, water treatment processes, horticulture, precipitated calcium carbonate for the paper industry, and many other small-scale applications (IPCC, 2005). Thus, in the near future, CO_2 may have significant commercial value, which will make CGS technologies important options for CO_2 storage.

CGS technologies must be analyzed separately. They can be considered a transition technology between end-of-pipe technologies and cleaner technologies. Alternatively, they can simply be considered a strictly end-of-pipe technology, adopted to perpetuate an unsustainable model of economic development that is fully dependent on fossil fuels. Thus, with reference to the classification of LaGrega et al. (1994), shown in Fig. 2, CGS technology can be classified as an internal/external recycling strategy.

Analyzing and classifying CGS technologies separately would help greatly toward clarifying regulatory frameworks in various countries. This analysis and classification would influence all regulatory stages of CGS technologies, such as the design, site selection, licenses, injection, post injection activities, obligations, and monitoring. However, where some countries such as the USA, Australia, and the European Union have clarified these frameworks, others, such as Brazil have not and should consider this in order to avoid conflicts. This should result in CGS technologies becoming more eco-friendly and safe, which in turn should contribute toward greater sustainability.

A long time will be required to change from the present development model to a sustainable one, and these changes cannot occur without a transition period. The use of technologies such as CGS represents a critical contribution to these changes. Batista (1993) suggests that before new and better environmental technologies become the norm, the market has to go through a transition period between the old modes of production using end-of-pipe technologies, and new, cleaner technologies, while seeking environmental practices that promote cleaner development.

5. Conclusions, limitations, and future directions

This paper focuses on the following question: To what extent can the storage of carbon dioxide in geological reservoirs be considered a cleaner technology? In order to answer this question, the concepts of environmental technologies and the classification of the technologies used to store carbon dioxide in geological reservoirs have been discussed. A literature review of environmental technologies and technologies for the mitigation of carbon dioxide, with an emphasis on technologies for the storage of carbon dioxide in geological reservoirs, has been presented. It was shown that it is necessary to consider the role of CO_2 in an industrial process because in some storage technologies, it can be considered waste, whereas in others, it can be considered a raw material because of the additional value that is obtained with its use.

It was observed that the classification of an environmental technology as a cleaner or end-of-pipe technology should encompass several aspects. It is important to consider not only the technology itself but also its various forms of use. It should also be considered that a concept can evolve into a cleaner technology and that the classification of a technology can change.

Based on current concepts, it is clear that CGS technology can be considered an end-of-pipe technology when it is used only to store waste and mitigate GHG emissions. On the other hand, it can be considered a cleaner technology when CO_2 is captured from an anthropogenic source and used as a raw material to increase oil, gas, or methane production as well as to mitigate GHG emissions. The use depends on the type of response required to deal with climate change and the search for more sustainable development to be adopted by companies, especially those in the energy sector, and by governments, mainly from the viewpoint of clarifying regulatory frameworks for technical solutions that reduce CO_2 emissions.

When CGS technologies are used by a company to reduce the GHG emissions, as shown through the example of Petrobras, it is possible to refer to them as cleaner technologies. This classification would be clearer if Brazil had a regulatory framework for CGS technologies based on environmental technologies that reduce the chances of unsuccessful CGS projects.

The future possibilities for the use of CO_2 in several industrial processes could change these classifications. In addition, the analysis of the technology should also consider the effects on the environment resulting from anthropogenic actions and their impacts over the years. A conceptual analysis of CGS technologies will help in this regard.

It is worth emphasizing that this is an exploratory investigation into current concepts of environmental technologies and the classifications of CGS technologies. However, CGS technologies are still in development, which implies that there is a need for future studies to enhance this research. In the near future, with the expected large-scale use of CGS technologies and new uses for CO_2, it will be necessary to reanalyze CGS technologies and their classifications. It is important to remember that CGS technologies will play a necessary role in a sustainable future.

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