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Aplicação, investimentos necessários e custos operacionais do sequestro geológico de CO_2: um estudo de caso

The application, required investments and operational costs of geological CO_2 sequestration: a case study

La aplicación, las inversiones requeridas y los costos operativos del secuestro geológico de CO_2: un estudio de caso

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Resumo

A integridade dos sistemas naturais já está em risco por causa das mudanças climáticas causadas pelas intensas emissões de gases de efeito estufa na atmosfera. O objetivo do sequestro geológico de carbono é capturar, transportar e armazenar CO_2 em formações geológicas apropriadas. Nesta revisão, foi abordado os ambientes geológicos conducentes à aplicação de projetos de *CCS* (do inglês, *Carbon Capture and Storage*), as fases que compõem esses projetos e seus custos associados aos investimentos e operações. Além disso, são apresentados os cálculos da rentabilidade financeira estimada para diferentes tipos de projetos no Brasil. Utilizando modelos matemáticos referents à tecnologia de *Carbon Capture and Storage*, pode-se concluir que o campo de Roncador apresenta a maior receita bruta quando a quantidade de óleo extra que pode ser recuperada é de 9,3% (US$ 48,55 bilhões aproximadamente em 2018). Cálculos adicionais mostram que o aquífero salino do Paraná apresenta a maior receita bruta (US$ 6,90 trilhões em 2018) quando comparado aos aquíferos salinos de Solimões (US$ 3,76 trilhões aproximadamente em 2018) e Santos (US$ 2,21 trilhões aproximadamente em 2018), isso se um projeto de *CCS* fosse empregado nestes locais. Portanto, o método de captura e armazenamento de carbono proposto neste estudo é uma importante contribuição científica para o armazenamento confiável de CO_2 em grande escala no Brasil.

Palavras-chave: Meio Ambiente; Carbono; Armazenamento Geológico; Aquíferos; Sustentabilidade.

Abstract

The integrity of natural systems is already at risk because of climate change caused by the intense emissions of greenhouse gases in the atmosphere. The goal of geological carbon sequestration is to capture, transport and store CO_2 in appropriate geological formations. In this review, we address the geological environments conducive to the application of CCS projects (Carbon Capture and Storage), the phases that make up these projects, and their associated investment and operating costs. Furthermore it is presented the calculations of the estimated financial profitability of different types of projects in Brazil. Using mathematical models, it can be concluded that the Roncador field presents higher gross revenue when the amount of extra oil that can be retrieved is 9.3% (US$ 48.55 billions approximately in 2018). Additional calculations show that the Paraná saline aquifer has the highest gross revenue (US$ 6.90 trillions in 2018) when compared to the Solimões (US$ 3.76 trillions approximately in 2018) and Santos saline aquifers (US$ 2.21 trillions approximately in 2018) if a CCS project were to be employed. Therefore, the proposed Carbon Capture and Storage method in this study is an important scientific contribution for reliable large-scale CO_2 storage in Brazil.

Keywords: Environment; Carbon; Geological Storage; Aquifers; Sustainability.

Resumen

La integridad de los sistemas naturales ya está en riesgo debido al cambio climático causado por las intensas emisiones de gases de efecto invernadero en la atmósfera. El objetivo del

secuestro de carbono geológico es capturar, transportar y almacenar CO_2 en formaciones geológicas apropiadas. En esta revisión, abordamos los entornos geológicos propicios para la aplicación de proyectos CCS (Captura y almacenamiento de carbono), las fases que conforman estos proyectos y sus costos asociados de inversión y operación. Además, se presentan los cálculos de la rentabilidad financiera estimada de diferentes tipos de proyectos en Brasil. Usando modelos matemáticos, se puede concluir que el campo Roncador presenta mayores ingresos brutos cuando la cantidad de petróleo extra que se puede recuperar es de 9.3% (US$ 48.55 billones aproximadamente en 2018). Cálculos adicionales muestran que el acuífero salino de Paraná tiene el ingreso bruto más alto (US$ 6.90 trillones en 2018) en comparación con los Solimões (US$ 3.76 trillones aproximadamente en 2018) y los acuíferos salinos de Santos (US$ 2.21 trillones aproximadamente en 2018) si El proyecto CCS debía ser empleado. Por lo tanto, el método de captura y almacenamiento de carbono propuesto en este estudio es una contribución científica importante para el almacenamiento confiable de CO_2 a gran escala en Brasil.
Palabras clave: Medio Ambiente; Carbón; Almacenamiento Geológico; Acuíferos; Sostenibilidad.

1. Introduction

Since the Industrial Revolution in the 18th century, fossil fuels have been used as an energy source, contributing to increase the concentration of CO_2 (carbon dioxide) in the atmosphere. An increasing global concentration of CO_2 in the atmosphere (from 290 parts per million or ppm to 414 ppm) occurred during the period of 1870-2019 (note: 414.84 ppm was registered by NOAA Earth System Research Laboratory in 2019, see reference NOAA, 2019), which is marked by the Second and Third Industrial Revolution, UNEP/GRID-Arendal (1999). This period is characterized by a significant increase in the use of fossil fuels as an energy source. Due to this increase in CO_2 emissions and its consequences, the traditional concept of global development incorporated the environmental development. This incorporation resulted a broader concept referred to as Sustainable Development, which is based on the inseparability of economic, social and environmental development. The report “Our Common Future”, also known as the Brundtland Report, released in 1987, as Oxford University Press (World Commission on Environment and Development, 1987), brought to attention the need of a new type of development that is able to sustain progress across the globe and to be achievable by developing countries in the long run Markandya and Halsnaes

(2002), Hopwood, Mellor and O'Brien (2005). In this way, the concept of sustainable development, e.g., “meeting the needs of the present without compromising the ability of future generations to meet their own needs” CMMAD (1991), Kates, Parris and Leiserowitz (2005) became established.

Human actions, such as the burning of fossil fuels (coal, oil and natural gas), the use of aerosols, and biomass combustion, liberate greenhouse gases (GHG) into the atmosphere, West *et al*. (2005), Li *et al.* (2009). Such gases are also released by other basic and intense economic activities, such as rice cultivation and livestock production, Smith *et al.* (2007), Golub *et al.* (2009). The most abundantly released gases and therefore the most responsible for the greenhouse effect are nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2), Costa (2009). In particular, CO_2 has harmful effects on the environment, primarily due to the increasing speed with which it is being produced to meet the needs of today’s consumerist lifestyle. The emission of GHG, especially CO_2, causes global warming and consequently climate changes, IPCC (2005), Michael *et al.* (2010).

Carbon sequestration through the Capture, Transport and Geological Storage of CO_2 (CCS technology) is an important alternative for reducing emissions, Qiao and Li (2014), Zahid *et al.* (2011), Michael *et al.* (2010), and stabilizing the atmospheric concentration of GHGs from a sustainable development perspective. Elias *et al.* (2018) explain that CCS is an efficient technology that captures CO_2 from power plants and enables zero or near-zero emission from power plants. It is known that the occurrence of natural CO_2 accumulations (fields similar to natural gas fields) have great potential as geological formations to store gases for thousands or even millions of years, Ketzer *et al.* (2005), Ketzer (2008) and Li *et al.* (2009). With the inclusion of CCS as an activity of the Clean Development Mechanism (CDM) project, companies will invest more in projects of this nature due to the potential to generate Certified Emission Reductions (CERs), Delgado and Altheman (2007), even if this discussion has developed into a highly polarised discussion, Ketzer (2008) and De Coninck (2008).

According to Frondizi (2009) the CDM is a mechanism based on the development of projects for which the private sector is responsible. The activities of CDM projects in developing countries should present both measurable and long-term real benefits. Therefore, CDM projects may involve (i) the replacement of non-renewable energy sources with renewable energy sources, (ii) the rationalization of energy use, (iii) afforestation and reforestation activities, (iv) more efficient urban services, (v) energy efficiency policies, and (vi) other projects, including the implementation of the CCS project. The CDM seeks to achieve sustainable development in developing countries through the implementation of cleaner technologies. The CDM also facilitates the fulfillment of targets for reducing GHG emissions from developed countries, Barton *et al.* (2008), Dechezleprêtre *et al.* (2009) and Frondizi (2009).

Carbon credit is a tradable certificate which allows a country or organization to produce a certain amount of carbon emissions and which can be traded if the full allowance is not used, De Coninck (2008). Initially, the major polluting industries in a country are selected and goals are set to reduce their emissions. Companies receive negotiable bonuses in proportion to their responsibilities, where each bonus, in dollars, is equivalent to a ton of pollutants, Khalili (2003). Companies that fail to comply with the progressive reduction established by law must buy certificates from successful companies. The system has the advantage of allowing each company to establish its own pace of compliance with environmental regulation. These certificates can be traded on the Stock and Commodities, as Exchanges, as the authors Mathews (2008), Ravagnani (2009), Avila (2013), Dos Reis Junior *et al.* (2015).

Currently, the main obstacle for CCS implementation in Brazil and in the other countries is the high financial cost, MacGill *et al.* (2006), Ravagnani (2009) and Jannuzzi *et al.* (2011). However, increased knowledge derived from research studies and practical experience contributes to the minimization of the involved costs. Also, beneficial in this regard are the contributions of new technologies in the fields of capture, transport and geological storage of CO_2.

The present study consists of an exploratory and descriptive-analytical analysis of an important alternative for reducing emissions and stabilizing the atmospheric GHG concentration based on scenarios for the application of CCS projects, investments and operating costs. This article evaluates the CO_2 injection in the following scenarios: oil and gas reservoirs and saline aquifers. To achieve this objective, a literature review of the technology required for the geological storage of CO_2 was performed. Therefore, this research provides a discussion on the feasibility of CCS projects to reduce the emissions of polluting gases into the atmosphere.

2. Carbon dioxide capture and geological storage

Research and development for CCS technologies in Brazil began with the oil industry, specifically with PETROBRAS, Jannuzzi *et al.* (2011). According to Lino (2005) in May 1991 an immiscible carbon dioxide injection project began in the Sergi-C reservoir in the

Main Block of Buracica Field. The injection has been performed in seven wells located in the upper part of the reservoir. Sometime after the beginning of CO_2 injection, the reservoir pressure increases and an increase of the oil production was reached; Buracica field is located in Recôncavo Basin at a distance of about 85 km to the North of the Salvador city (Bahia state). For sustainability purposes, the State Company injects 100% of the CO_2 from natural gas streams (produced by the platform ships Cidade de Angra dos Reis and Cidade de São Paulo) into the pre-salt reservoirs, Formigli Filho (2009). According to Câmara (2012), upon completion of the COP 15 (UN Climate Change Conference - Copenhagen in 2009), a law establishing the Brazilian Policy on Climate Change (BPCC) was sanctioned. The Article 12 states: "To achieve the objectives of BPCC, the country will adopt, as a voluntary national commitment, actions to mitigate emissions of greenhouse gases to reduce projected emissions between 36.1% (thirty-six and one-tenth percent) and 38.9% (thirty-eight and nine-tenth percent) by 2020", Brazil (2009). Much was expected from Brazil, given its responsibility to preserve the Amazon. The country met all expectations by announcing the largest commitment to reduce greenhouse gas emissions – from 36.1% to 38.9% - in 10 (ten) years.

To achieve the national voluntary targets for reducing GHG emissions, the BPCC requires the development of specific mitigation plans to curb emissions in the Brazilian forestry, steel, agricultural, energy, industrial, transportation and mining sectors. Additional highlights of the BPCC include initiatives to conserve and support the recovery of national biomes, consolidate and expand protected areas (especially in the Amazon), increase energy efficiency and continue expanding the supply of renewable energy sources as Da Motta *et al.* (2011).

Brazil has already met two-thirds of its goal of reducing GHG emissions by 2020 with only reducing deforestation in the Amazon and Cerrado. The country had already reached 72.5% of its overall target (28.21% emissions reduction) in 2012. This result occurred independently of implementation of the BPCC. Deforestation rates in the Amazon have been falling since 2005, and in the Cerrado, the goal was met and exceeded before the bill was approaved. However, the actions defined by the policy that seeks to transform the Brazilian economy have not materialized, resulting in only minor progress, or even regression. Although the legal framework has been created and several metrics are being measured, there are no strategic guidelines for the mitigation plan in the government, and mitigation has disappeared from the priority scale, Greenpeace (2013).

Therefore, it is important to note that carbon capture and storage (CCS) by means of CO_2 storage in suitable geological formations is a promising endeavour that may help to reduce GHG emissions. According to Câmara (2012), 18 countries are currently operating or deploying CCS projects, for a total of 79 large-scale CCS projects (69 projects to be implemented over the next 10 years and 10 projects in operation). These projects will enable the storage of approximately 158 MtCO_2/year. Among the major contributors to these efforts are the United States, which has 31 projects and a CO_2 storage volume of 66.4 MtCO_2/year, and the UK, with 6 projects and a CO_2 storage volume of 21.25 MtCO_2/year. Some of the major CCS projects in the world are as follows: the Sleipner Project (Norway), the Weyburn Project (Canada) and the Salt Creek Project (United States). The Global CCS Institute (2017) shows that the two Sleipner fields have produced almost 2 billion barrels of oil equivalent since inception. In 2016, it has received approval according to the Environmental Protection Law and its CCS-relevant regulations

In Brazil, Petrobras began injecting CO_2 into the Miranga onshore oil and gas field in 2009. The injection rate was of the order of 370 tonnes per day. Injection was into the main reservoir, Catu-1. The Miranga field is part of the onshore portion of the Reconcavo Basin (where oil was discovered in 1939). The Miranga field itself is a mature field and was discovered in 1965. The purpose of the CO_2 injection program was to test technologies that could contribute to the then future development projects for the Santos Basin's pre-salt Cluster. The offshore pre-salt discoveries at the time indicated significant amounts of CO_2 (8-18%) in associated gas. Development options for these large offshore discoveries included utilisation of the separated CO_2 for enhanced oil recovery (by injecting the CO_2 back into the offshore reservoirs) which avoids release of the separated CO_2 into the atmosphere. This approach became operational in the giant offshore Lula field in 2013. Smaller scale CO_2 injection techniques had been pursued on the onshore portion of the Reconcavo Basin since the late 1980s. Initial efforts were implemented in the Aracas field. In 1991, CO_2 injection was deployed in the Buracica field where it is reported that injection helped support the maintenance of the field's oil production for about 20 years. It has been reported that in the case of the Buracica CO_2 injection project, studies included reservoir modelling, well integrity analysis and MMV activities, particularly with geochemistry (Global CCS Institute, 2017).

2.1 Geological environments conducive to the application of CCS projects

The geological storage of CO_2 can be safely performed in three types of reservoirs: depleted oil and gas reservoirs (e.g., reservoirs with formation pressure much lower than the

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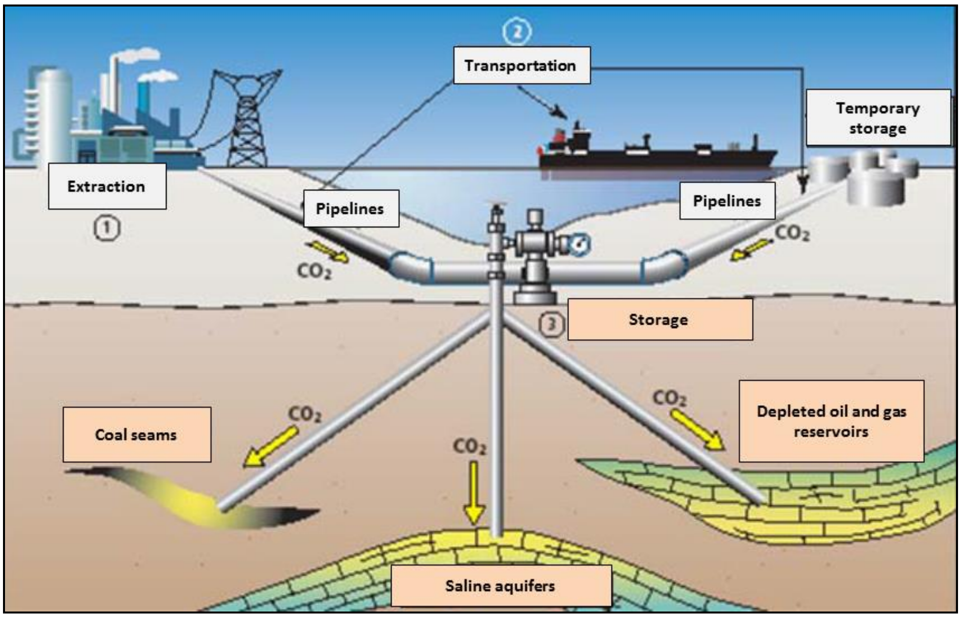
original pressure due to accumulated production), saline aquifers and coal layers (Figure 1). This paper presents the CO_2 storage in a saline aquifer and oil and gas reservoir.

Mature oil fields consist of depleted geological reservoirs that contained oil and/or natural gas for millions of years; such fields are in the final stage of exploitation (e.g., removal, extraction or acquisition of natural resources). It is estimated that approximately 103 Gt (billion tons) of CO_2 can be stored in oil fields worldwide Ketzer (2005).

Figure 1 Forms of CO_2 sequestration in geological formations.

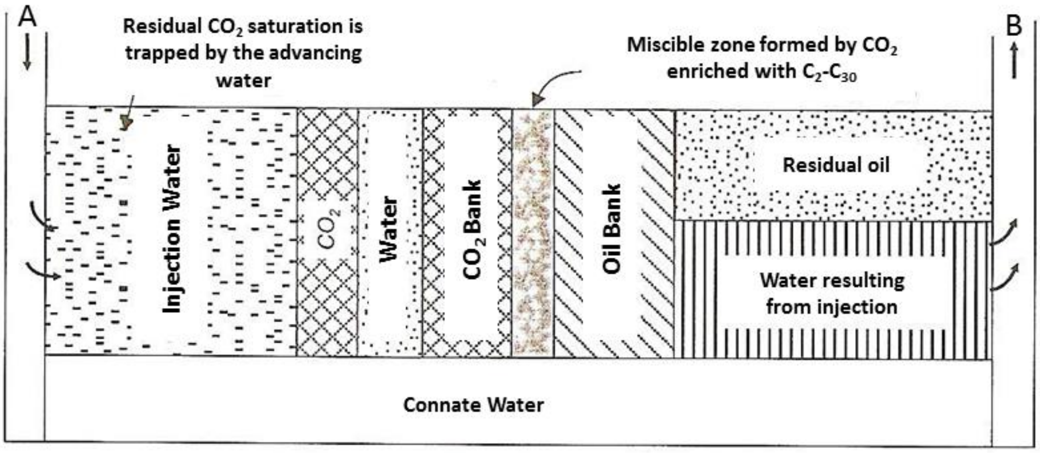


Source: Costa (2009).

According to Ravagnani (2009) the high costs of containment in oil fields can be minimized by combining CO_2 sequestration with Enhanced Oil Recovery (EOR). Specifically, the revenue generated from additional oil recovery can help offset the costs involved in the capture, separation, transport and geological storage of CO_2. Therefore, in addition to contributing to sustainable development, the injection of CO_2 promotes an efficient miscible displacement at low pressure for most reservoirs and is therefore a special method of secondary recovery.

Figure 2 illustrates how CO_2 injection can be used for secondary recovery, where “A” is the injector well and “B” is the production well.

Figure 2 Miscible injection of CO_2 representing one of the enhanced oil recovery methods.



Source: Adapted from Rosa *et al.* (2006).

The size of the initial CO_2 bank is approximately 5% of the porous volume. An alternating water and CO_2 injection follows this bank until the accumulated CO_2 is between 15% and 20% of the porous volume. Thereafter, only water is injected. When advancing through the porous medium, water traps CO_2 at residual saturation levels, with the CO_2 occupying the pores that were previously filled with residual oil. The displacement efficiency is high, and oil saturation is reduced to approximately 5% of the pore volume of the contacted region (Rosa *et al.*, 2006). Thus, after CO_2 application as a secondary recovery method, reservoirs that are considered “depleted” are used for CO_2 storage.

Saline aquifers consist of underground water reservoirs with high salinity, often similar to or greater than seawater, and therefore cannot be used for direct consumption. The injection of CO_2 into saline aquifers must occur at depths greater than 800 m, and it must be at supercritical conditions (supercritical fluid is any substance that is found at a pressure and temperature greater than its critical parameters). These reservoirs have an enormous storage capacity, with an estimated world capacity of 11 000 Gt of CO_2, only Australia appears to have abundant geological storage capacity, particularly in saline formations, Cook (2006). When CCS projects turn to saline aquifers, the high costs involved in capture, separation, transport and geological storage of CO_2 are mitigated by carbon credits of the CDM, Ketzer (2008).

Coal seams can trap CO_2 in their pore spaces, where storage is preferentially carried out in deep storage layers, e.g., layers so deep that conventional exploration is not, and will not likely become, economically feasible. It is estimated that 200 Gt of CO_2 can be stored in coal seams worldwide. As in oil fields, CO_2 injection in coal seams may result in the production of

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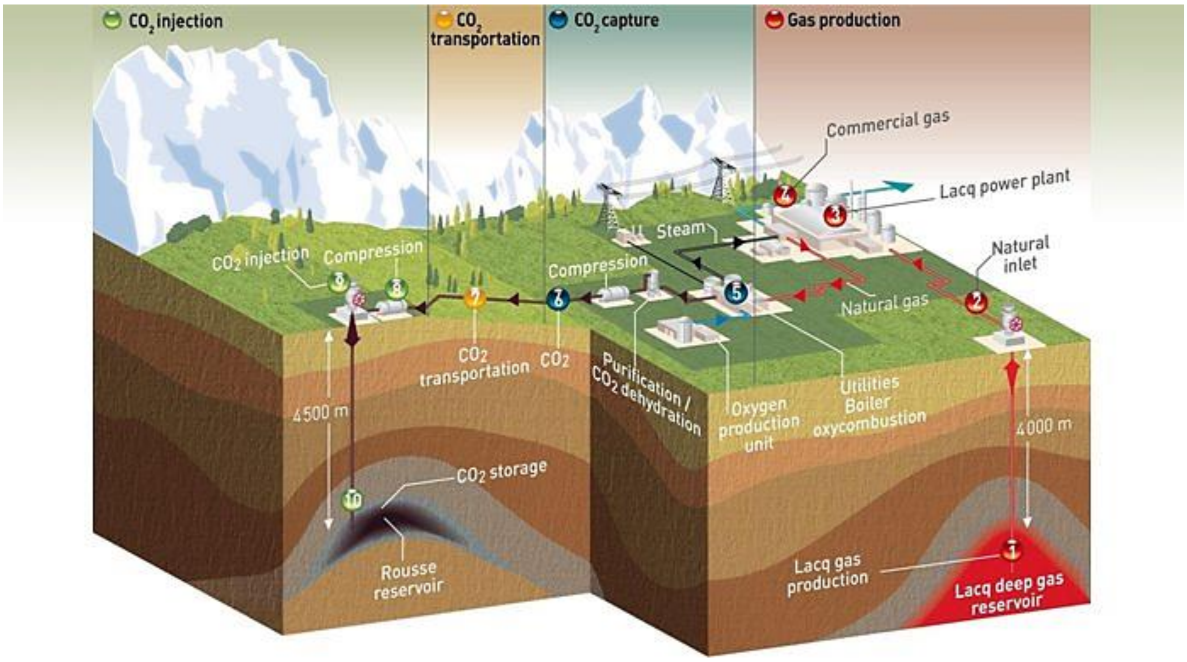
hydrocarbons by means of the technique known as ECBMR (Enhanced Coal Bed Methane Recovery). The CO_2 injected into the seam is preferentially adsorbed by the carbon matrix, resulting in the release of naturally occurring methane (CH_4), which can be produced as free gas and used to generate revenue Ketzer (2005).

2.2 The phases of a CCS project, its investments and its operating costs

The phases that make up CCS projects are as follows: capture (CO_2 capture), transportation (CO_2 transportation) and geological storage (CO_2 injection) (Figure 3), in addition to measuring, monitoring and verification.

Figure 3 Phases that make up a CCS project: Lacq CO_2 Capture & Storage demonstration pilot schematic.



Source: Government Europa and TOTAL (2018).

The first phase of a CCS project is the capture and separation of CO_2 from gas streams. This step is performed at various industrial units or plants and is followed by transportation through pipelines, trucks, or ships and subsequent geological storage. Energy from fossil fuels such as coal, oil and natural gas is released in the combustion (burning) and conversion process, which also results in the emission of CO_2 as a by-product. In systems where the coal is pulverised to a powder, which makes up the majority of coal-based power plants through

North America, Europe and China, the CO_2 must be separated at diluted concentrations from the balance of the combustion flue gases. In other systems, such as coal gasification (where coal is converted to chemicals, natural gas or liquids), the CO_2 can be more easily separated (Zucatelli, 2015 and Chan *et al*., 2016). There are three basic types of CO_2 capture: pre-combustion, post-combustion and oxyfuel with post-combustion (Araújo and Medeiros, 2017).

Regarding CO_2 emissions mitigation, an assessment of the overall life cycle environmental impacts from the resource extraction along the production chain to the final product, including off-site emissions and construction emissions, is essential. It is important to notice that the capture process discharge CO_2 as a by-product. In this sense the consideration of this amount is very important in the sequestered CO_2 calculations. The amount of CO_2 emitted by industrial units or plants depends on the size of the plant and the technology involved in the gas capture. This amount is calculated through an emission factor, and is based on concepts presented by the Environmental Protection Agency. For example, CO_2 emission factor for electricity generation in National Interconnected System (NIS) of Brazil is based on methodologies approved by the CDM advice.

2.2.1 CO_2 Capture

According to Rochedo *et al.* (2016), the selection of large industrial complexes for CO_2 capture reduces the costs of installation and operation of the capture step, e.g., it is more advantageous to capture large amounts from fewer sources than small amounts from many sources. Another financial advantage of large complexes is a reduction in the number of necessary pipelines for the transport of CO_2.

The amount of carbon to be captured varies with the technology to be applied, the units whose emissions will be captured and the CO_2 concentration present in the exhaust gas. Figure 4 shows the average quantity of total global emission per emission source, in mega tons per year ($MtCO_2$/year), according to the IPCC (2005).

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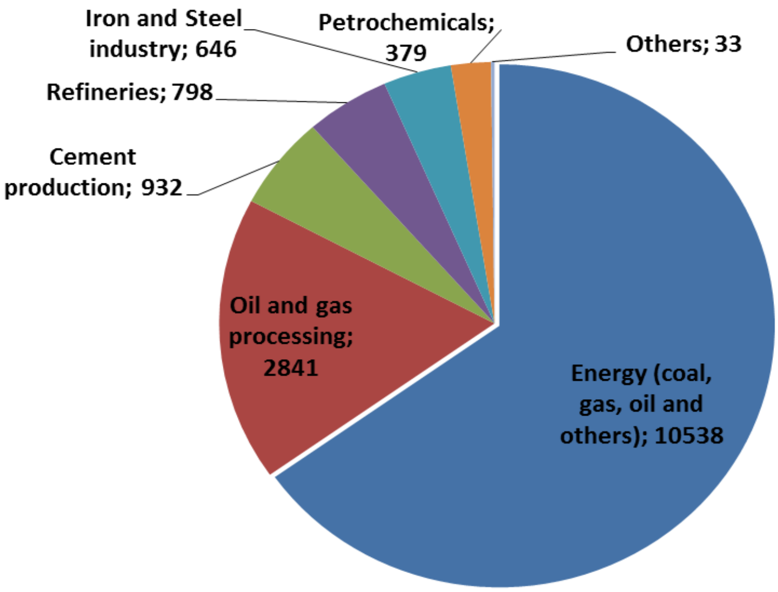
Figure 4 Average quantity of total global emissions by emission source ($MtCO_2$ per year).



Source: Adapted from IPCC (2005).

CO_2 capture is the stage of CCS that demands the greatest capital investments because it is characterized by the highest operating and maintenance costs. This is the case because large-scale gas separation technologies require significant energy expenditures. The capture cost varies significantly with the type of technology adopted for the separation of CO_2. In turn, the utilized type of technology depends directly on the pressure and CO_2 concentration in the exhaust gas. The higher the CO_2 concentration in the effluent gas, the lower the energy required for gas separation and the lower the capture cost, Rochedo *et al.* (2016).

The investments (CAPEX – Capital Expenditure) and operating costs (OPEX – Operational Expenditure) for capture and compression depend on the type of industry and the options for CO_2 separation and disposal. The main challenge with respect to CO_2 removal technology is to reduce the energy and capital costs. These costs vary substantially and depend primarily on the size of the generating plant. However, the existing infrastructure and available pipelines capacity also influence cost. The capital and operating costs of CO_2 compression, which requires cooling equipment and dehydration, are major components of the total cost of the capture system. Compression costs are based on costs related to maintenance, capital and electric power Ravagnani (2009).

To estimate compression costs, the degree of compression required and the compression unit costs must be considered. However, these two factors may vary between projects. The major cost is associated with the use of electricity. In addition, compression costs are considerably higher for smaller flows, where values range from 7.4 to 12.5 dollars per ton, Hendriks *et al.* (2004). In addition to compression costs, the high cost of CO_2 capture is a major concern. In fact, the economic demands of CO_2 sequestration are dominated by the capture cost component and are the primary consideration with current technology. Limitations on this regard have been major obstacles to the introduction of CO_2 sequestration technology.

The OPEX for capture depends on labor, maintenance, the purchase of chemical products and other factors. Capture costs depend on the amount of captured CO_2, the concentration and pressure of the CO_2 in the emission source and the nature of the capture process (e.g., chemical or physical absorption, chemical or physical adsorption, membranes, cryogenic distillation). The CAPEX for capture is associated with the equipment required, e.g., the absorption column, Freund and Davison (2002).

As mentioned above, costs can be limited if CO_2 to be recovered is from industrial process streams that contain high CO_2 concentrations. In these scenarios, less energy is required to purify the gas and costs are lower. According to Sasaki (2004), the CO_2 concentration in combustion gases influences the efficiency of separation and recovery, e.g., the costs efficiency increases as the concentration increases.

Little attention has been given to CO_2 recovery in industrial processes, although large volumes are emitted at high concentrations by certain industries, Farla (1995). According to Lysen and Peacs (2002) in an ideal scenario, only dehydration and compression are required before CO_2 transportation if the gas is nearly pure. Table 1 shows estimates of investment and operating costs for CO_2 capture from various sources.

Table 1 Investment estimates and operating costs for CO_2 capture from various sources.

Emission sources	**Capture costs (US$/t$CO_2$)***
Ammonia production	3.70
Hydrogen production (pure gas)	3.70
Cement production	32.50
Iron and Steel production	33.43
Refineries	33.43 to 49.22
Power plants	29.72 to 49.22
Petrochemicals	36.81 to 41.79

Note: (*****) The original data are presented in Euros (EUR). In this study, the values were converted to dollars (US$) using the exchange rate on August 06, 2018 (1.00 EUR = 1.16 US$).
Source: Adapted from Hendriks *et al.* (2004).

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Ravagnani (2009) explains that capture costs in the ammonia and hydrogen production industries are more competitive. In these industries, the emitted CO_2 concentration is high, and large energy and financial expenditures for purification are unnecessary.

2.2.2 CO_2 Transport

Another important stage of CCS projects is CO_2 transport between the capture/separation plants and the injection point in the strategic reservoir. The Intergovernmental Panel on Climate Change of IPCC (2005) indicates several favourable technologies.

The transport of CO_2 by pipeline is currently the most mature technology. According to Martins (2009) gaseous CO_2 is usually compressed to pressures greater than 8.0 MPa to avoid two-phase flow regimes and to increase the density of the gas, making it easier and less expensive to transport. CO_2 can also be transported by tanker ships or trucks in liquid form, requiring temperatures well below ambient conditions. Ship transport is economically more attractive, particularly when CO_2 must be transported over long distances or to offshore projects. The use of trucks is also possible, although it is not economically feasible for large-scale CO_2 injection projects when compared to ships and pipelines.

For capital costs, which are associated with construction costs, the geometry of the pipeline (internal diameter) and the characteristics of the terrain (e.g., mountainous vs. flat) must be considered. The population density is also a factor because greater safety measures are necessary for populated areas (e.g., more valves are required); this consideration can greatly increase costs Hendriks *et al.* (2004). Considering these issues, the transportation cost can significantly vary for different projects. According to Heddle *et al.* (2003), the costs for building a gas pipeline are estimated to be US$ 21,000.00/in/km. Table 2 shows average CAPEX and OPEX pipeline costs.

Table 2 CAPEX and OPEX for CO_2 transport by pipeline.

Duct	Costs	Observations	References
CAPEX	US$ 21,000.00/in/km	US$ 21,000.00 per inch in diameter per km in length	Heddle *et al.* (2003).
OPEX	US$ 3,100.00/km/year	Independent of pipeline diameter	Heddle *et al.* (2003).
OPEX	US$ 1.00 to US$ 8.00/tCO_2 for each 250 km	Dependent on pipeline size and capacity	IPCC (2005).

Source: Adapted from Heddle *et al.* (2003).

Kim and Choi (2014) shows that several factors must be considered when estimating the operating costs of CO_2 transport by pipeline. Among these factors are CO_2 flow rate, the distance from the source to the storage location and purity of the CO_2. The latter of these is an important consideration given that contamination can slightly change the optimal transport conditions. Transport costs are likely to be reduced when large-scale operations are employed.

2.2.3 CO_2 Storage

According to Nguyen and Allinson (2002) the costs of CO_2 injection at the storage location primarily include the CAPEX for the drilling of wells and costs related to the operation and maintenance of the system. The total storage cost depends on the location, injection costs, reservoir depth, average temperature, reservoir radius, monitoring and flow rate.

As there are several parameters, all of which can vary a great deal, the cost of CO_2 storage cannot be accurately estimated. Studies indicate that in most cases of storage in geological reservoirs, costs range from US$ 5.00/tCO_2 to over US$ 20.00/tCO_2, Nguyen and Allinson (2002). According ZEP (2011), costs range from US$ 1.35/tCO_2 to US$ 27.00/tCO_2. Onshore saline aquifer presents cost range from US$ 2.70/tCO_2 to US$ 16.20/tCO_2. Offshore saline aquifer ranges from US$ 8.10/tCO_2 to US$ 27.00/tCO_2. For onshore oil reservoir, the cost range is US$ 1.35/tCO_2 to US$ 9.45/tCO_2, and if reservoir is offshore, the range is US$ 2.70/tCO_2 to US$ 18.90/tCO_2.

Generally, storage in onshore basins presents lower cost than storage in offshore basins. Offshore costs must include platforms and other facilities, as well as higher operating costs. According to Hendriks *et al.* (2004) offshore drilling costs are higher when compared to onshore costs; but costs vary considerably among projects.

In some cases, storage can be low cost or even profitable. For example, carbon credits can be obtained if the CO_2 is injected into saline aquifers, or oil and/or gas production can be increased by injecting CO_2 into geological reservoirs (e.g., via EOR and/or ECBMR). Situations in which storage can be economically beneficial include the use of CO_2 for enhanced oil or coal recovery. EOR can be an economically attractive option because it can significantly reduce CO_2 sequestration costs. However, the ECBMR has a higher cost because it requires a larger number of wells when compared to EOR (Hendriks *et al.*, 2004). Furthermore, CO_2 storage in coal seams is still in the early stages of development.

According to Smith *et al.* (2002), in addition to the benefits due to EOR revenues, the cost of the construction and operation of CO_2 injection wells constitutes only a small portion of the total system cost. In addition, storage costs are generally a small fraction of the cost of CO_2 capture; for these reasons, storage costs have not received much attention. The estimated costs for geological sequestration of CO_2 depend on the specific conditions of the location, such as the required number of injection wells, the surface facilities, the requirements of monitoring and managing the reservoirs, and other factors.

As technology matures, cost uncertainties are reduced. Specifically, the investment costs for EOR include the costs of compressors, separation equipment, the drilling of wells, and the conversion/completion of wells. New wells are not required in some projects. Operating costs, in turn, include CO_2 purchase costs, field operational costs, fuel costs, etc.

2.2.4 Measurement, Monitoring and Verification

Dahowski *et al.* (2009) introduced that the goal of CCS is to ensure that CO_2 is safely and securely locked in deep geological formations, away from the atmosphere, for meaningful timeframes – perhaps thousands of years. Therefore, an adequate Measurement, Monitoring, and Verification (MMV) program is a critical component for any CCS system.

The costs of MMV activities will likely vary significantly from project to project, and there remains a lack of reliable data for a range of CCS project sizes and storage conditions. However, research published by Benson (2005), estimated an approximate MMV cost of US$ 0.08/tCO_2 for their "enhanced" monitoring suite, which was the highest-cost case presented.

2.3 Mathematical Models - Calculation of the estimated financial profitability

As previously mentioned, the injection of CO_2 into oil reservoirs increases the residual oil recovery factor (e.g., oil not produced by primary methods). The amount of recoverable oil by EOR widely varies as a function of the oil displacement mechanism (miscible or immiscible) and the characteristics of the field, including reservoir pressure, the original volume of oil in place, the remaining oil reserves and the oil's API (American Petroleum Institute) gravity. The API gravity is a hyperbolic function of density, where the smaller the value indicates a denser oil. The maximum amount of oil that can be recovered can be calculated using Equation 1, as follows Hendriks *et al.* (2004):

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$$EOR = \left(\frac{\%EXTRA}{100} \right) * VOOIP * C \qquad (1)$$

Where EOR (Enhanced Oil Recovery) is the quantity of oil that can be recovered from the reservoir (in millions of barrels); %EXTRA is the extra percentage of recoverable oil as a result of CO_2 injection; VOOIP is the Original Volume of Oil In Place of the field (in millions of barrels); C is the contact factor of CO_2 with the oil.

Hendriks *et al.* (2004) reported that the value of the contact factor C is equal to 75% (or 0.75) for all oil fields. This is a conservative estimate as it is not possible for all oil present in the reservoir to come into contact with the injected CO_2, regardless of the CO_2 displacement mechanism (miscible or immiscible).

The extra percentage of recoverable oil due to CO_2 injection (%EXTRA) is an estimated value based on the API gravity of the oil. Probabilistic studies and simulations were performed by the IEA GHG to determine %EXTRA. It was determined that for oils with API gravity values lower than 31, %EXTRA is between 0.3% and 10.3%. A simple estimate of the gross revenue that can be achieved with this extra oil production can be calculated using Equation 2:

$$\text{Gross Revenue (US\$)} = \text{EOR}*\beta \qquad (2)$$

where β is the price of a barrel of oil in dollars. With the price of the oil barrel (Brent price) on August 06, 2018 the Gross Revenue (US$) = EOR*US$ 73.90.

After the application of CO_2 as part of the EOR method, oil reservoirs considered "depleted" are used for CO_2 storage. Therefore, not all technological investment for the capture and transport stages are lost. Financial negotiations at this stage involve carbon credits, as is the case when CO_2 is stored geologically in saline aquifers, which will be discussed below.

When the geological reservoir selected for application of the CCS is a saline aquifer, before calculating the estimated gross revenue, it is necessary to estimate the volume of CO_2 that can potentially be sequestered. From Equation 3, Hendriks *et al.* (2004), the volume of CO_2 that can be captured is calculated based on the assumptions that approximately 1% (or 0.01) of the aquifer is a structural trap and only 2% (or 0.02) of the structural trap can be filled with CO_2:

$$M_{CO_2} = A * h * 0.01 * 0.02 * \left(\frac{\varphi}{100} \right) * \rho_{CO_2} * 10^{-12} \qquad (3)$$

where $\mathbf{M_{CO2}}$ is the CO_2 mass that can potentially be sequestered (g); **A** is the surface area of the sedimentary basin (m^2); **h** is the thickness of the aquifer (m); **φ** is the rock porosity (%); $\boldsymbol{\rho_{CO2}}$ is the density of CO_2 at the surface conditions (1.98 10^{-3} Mg/m^3).

Considering that 1 metric ton of CO_2 is equivalent of 1 carbon credit and that it can be commercialized through the regulated market on the stock exchange, gross revenue can be calculated using Equation 4:

$$\text{Gross Revenue (US\$)} = (M_{CO2}/10^6)*\gamma \tag{4}$$

where M_{CO2} is the CO_2 mass that can potentially be sequestered (unit: Petagram, Pg) and γ is the price of the carbon credit in dollars.

Considering that 1 carbon credit is equivalent to approximately € 13.0/tCO_2 or US$ 15.08/tCO_2 (using the August 06, 2018 exchange rate of 1.00 EUR = 1.16 US$), we have, for example: Gross Revenue (US$) = $(M_{CO2}/10^6)$*US$ 15.08.

According Silva (2012) the competitive differential between companies and even between industries will be based on providing services and manufacture of products with low carbon emissions. According to these authors, the major gain by these institutions will be through sustainability-based marketing and not through the Carbon Credit trade itself; however, this issue is a matter of debate between different groups of researchers.

Worldwide energy demand is supported by the significant role of conventional and unconventional resources of oil and gas. This huge dependency has resulted in critical environmental issues such as increased CO_2 emission known as the greenhouse gas, and for the purpose of having a clean atmosphere for next generations, CO_2 storage and sequestration has gotten a common procedure for this purpose (Boosari, 2015).

International communication has already presented the risks of climate change (Paraguassú *et al*., 2015 and Chan *et al*., 2016), and this is the perfect scenario for business opportunities. At least 70% of GHG emissions come from the production of consumer goods; therefore, products that have less impact on the environment will be more desirable in the future. These products are already competitively inserted into the market, and innovative products that reduce GHG emissions will further be highlighted. The companies that can strategically add these values will be the winning companies and will transform opportunities into tangible achievements.

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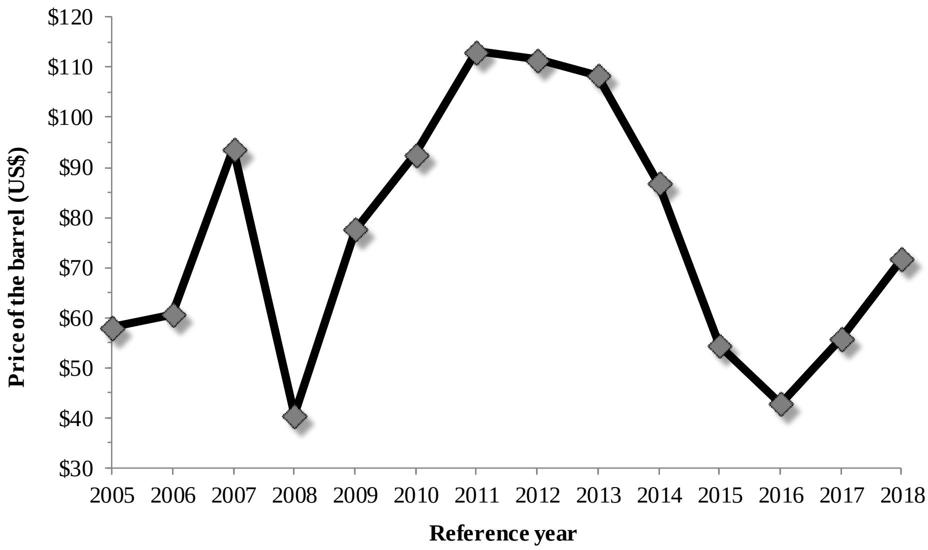
Thus, some authors state that no project involving the reduction of CO_2 emissions will offer higher returns than the actual commercial activity of a company. As reported by Silva (2012), the carbon market is accessory to the commercial activity of companies and will therefore never become their core business. Wang and Qie (2018) explain that the CCS investment threshold is affected by carbon price volatility, CO_2 capture rate, the transfer payments coefficients, and too affected by capital subsidy.

However, GHG reduction projects (CCS, for example) provide socio-political and economic benefits in a framework oriented towards sustainability. For this reason, the implementation of such projects ensures a good market position for these industries and/or companies and ensures preservation of the environment.

3. Comments and discussion

To give an example of the estimated financial profitability resulting from CCS projects applied for EOR, the historical average of the Brent oil price, Investing (2018a), was designed between the years 2005 and 2018 (Figure 5).

Figure 5 Variation of the average price of the Brent oil barrel.



The case study considers the Roncador field (Rio de Janeiro - RJ), which presents an original volume of oil in place equal to 9.7 billion barrels. For the purpose of comparison, the extra recoverable oil percentages as a result of CO_2 injection were estimated to be 1.3%, 5.3% and 9.3%. The calculated quantities of recoverable oil from the reservoir are 94.575 million, 385.575 million and 676.575 million barrels, respectively, when considering a CO_2-oil

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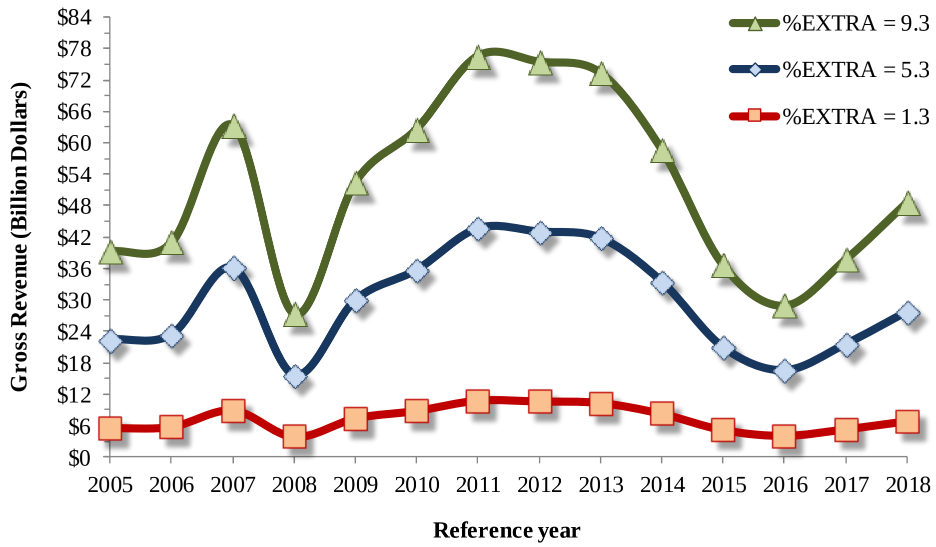
contact factor of 75%, as reported by Hendriks *et al.* (2004). The API gravity of oil in this field varies between 18º and 30º API, Benson (2005).

From the analysis presented in Figure 6, it can be observed that CCS projects, such as EOR, yield variable amounts of gross revenue. This variation is directly linked, among other factors, to variations in oil prices and recoverable oil percentages.

Figure 6 Variation of the gross revenue resulting from CCS projects, such as EOR.



The equations to calculate the volume of CO_2 that can potentially be sequestered and the CO_2 mass balance during the application of EOR technique in oil reservoir, can be seen at Zucatelli (2015). This is important because we can add the gross revenue resulting from credit carbon.

To demonstrate the estimated financial profitability resulting from CCS projects applied in saline aquifers, the historical average prices of Carbon Credit, Investing (2018b), was designed between the years 2004 and 2018 (Figure 7).

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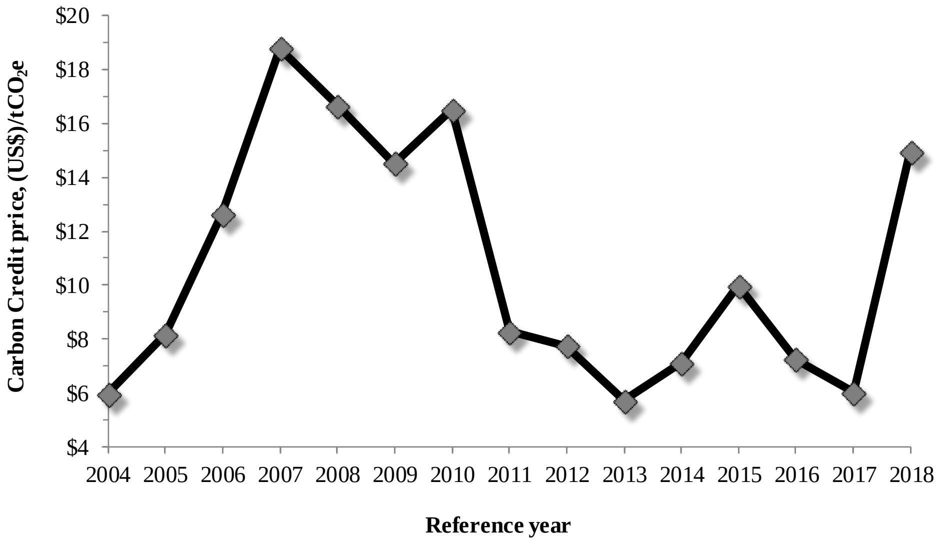
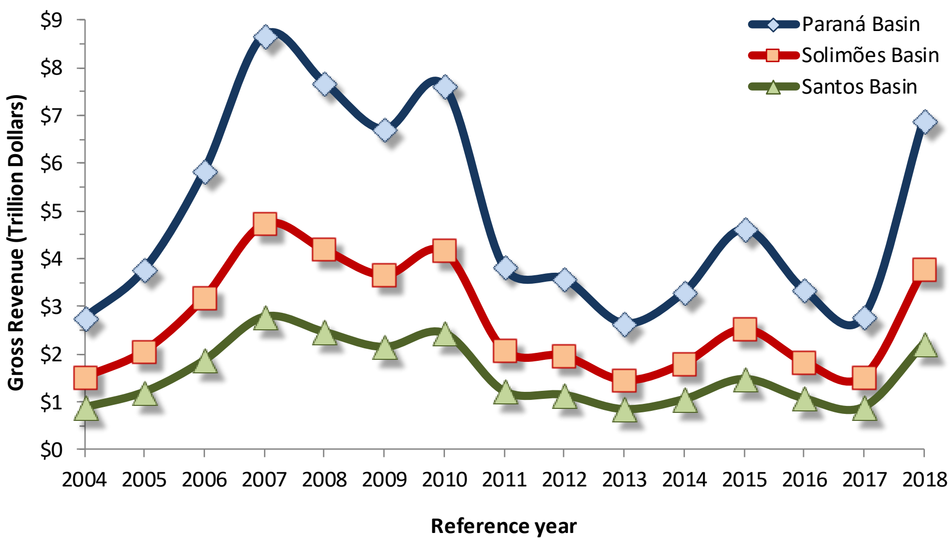
Figure 7 Variation of the average Carbon Credit price: US$/carbon dioxide equivalent tons (tCO_2e).



For this calculation, the CO_2 storage potential in saline aquifers of the following three major Brazilian basins was analysed: the Paraná Basin, Solimões Basin and the Santos Basin. These basins have, respectively, CO_2 storage potentials equal to 462 000, 252 000 and 148 000 $MtCO_2$, Costa (2009).

The Figure 8 shows the variation in gross revenue resulting from application of CCS projects in saline aquifers. This variation is directly linked, among other factors, to the basin storage capacity and the variation in Carbon Credit price.

Figure 8 Variation of gross revenue resulting from application of CCS projects in saline aquifers.



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From Figures 6 and 8, it can be observed that the gross revenues resulting from projects involving the capture, transport and geological storage of CO_2 in deep geological reservoirs, such as oil reservoirs and saline aquifers, can vary considerably. This variation results from the dependency of both project types on technical and economic factors (e.g., variation of oil price and variation of the carbon credit price).

4. Conclusions

The challenges of climate change involve totally rethinking the world's energy system. In particular, CCS technologies are still presented as a solution to reach ambitious climate targets. Using mathematical models, it can be concluded that the Roncador field presents higher gross revenue when the amount of extra oil that can be retrieved is 9.3% (US$ 48.55 billions approximately in 2018). Additional calculations show that the Paraná saline aquifer has the highest gross revenue (US$ 6.90 trillions in 2018) when compared to the Solimões (US$ 3.76 trillions approximately in 2018) and Santos saline aquifers (US$ 2.21 trillions approximately in 2018) if a CCS project were to be employed. The main obstacles to CCS project implementation are the high costs (CAPEX and OPEX). However, increased knowledge and experience, as well as the contributions of new technologies in the field of CO_2 sequestration, will reduce these costs.

An important point is that all financial costs presented here are approximations. Thus, to calculate the true cost of each project related to CCS, specific analyses must be performed. Such analyses must consider all of the specific aspects of each project, such as (i) the location and characteristics of the CO_2 source; (ii) the location, capacity and physicochemical characteristics of the chosen geological reservoir; (iii) the distance between the emitting source and the reservoir; (iv) the amount of CO_2 to be stored; the (v) feasibility of CO_2 transport; and (vi) the equipment needed for compression and injection of CO_2 into the reservoirs. Thus, when economically feasible, CCS is an option for reducing CO_2 emissions into the atmosphere, and therefore an option for mitigating climate change.

Another barrier that must be addressed is the lack of incentives and credit systems in many countries to support long-term investments by companies in CCS projects. Programs that encourage the use of carbon taxes show that this may be the most efficient method to reduce CO_2 emissions. The information in this article shows that the high cost of CCS projects can be minimized, especially by combining CO_2 sequestration with EOR projects. Specifically, in the case of storage in oil reservoirs, the costs of CO_2 sequestration can be offset by revenues from additional oil recovery. If injection occurs in coal reservoirs, the high costs are minimized via ECBMR projects. When the reservoirs are saline aquifers, the high costs involved are minimized from revenues generated by the sale of carbon credits.

Economic factors can be driven by government incentives or taxes/fees that promote the reduction of GHGs that are emitted by the private sector. In parallel, the public sector needs to be properly organized to have defined roles and responsibilities about CCS technologies. In addition, the use of instruments such as carbon credits may be a factor for reducing the deployment costs of technologies for CO_2 injection in geological reservoirs. These conclusions can provide theoretical foundation for decision-making of CCS investment and related policy-making.

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