BRAZILIAN ATLAS OF CO_2 CAPTURE AND GEOLOGICAL STORAGE

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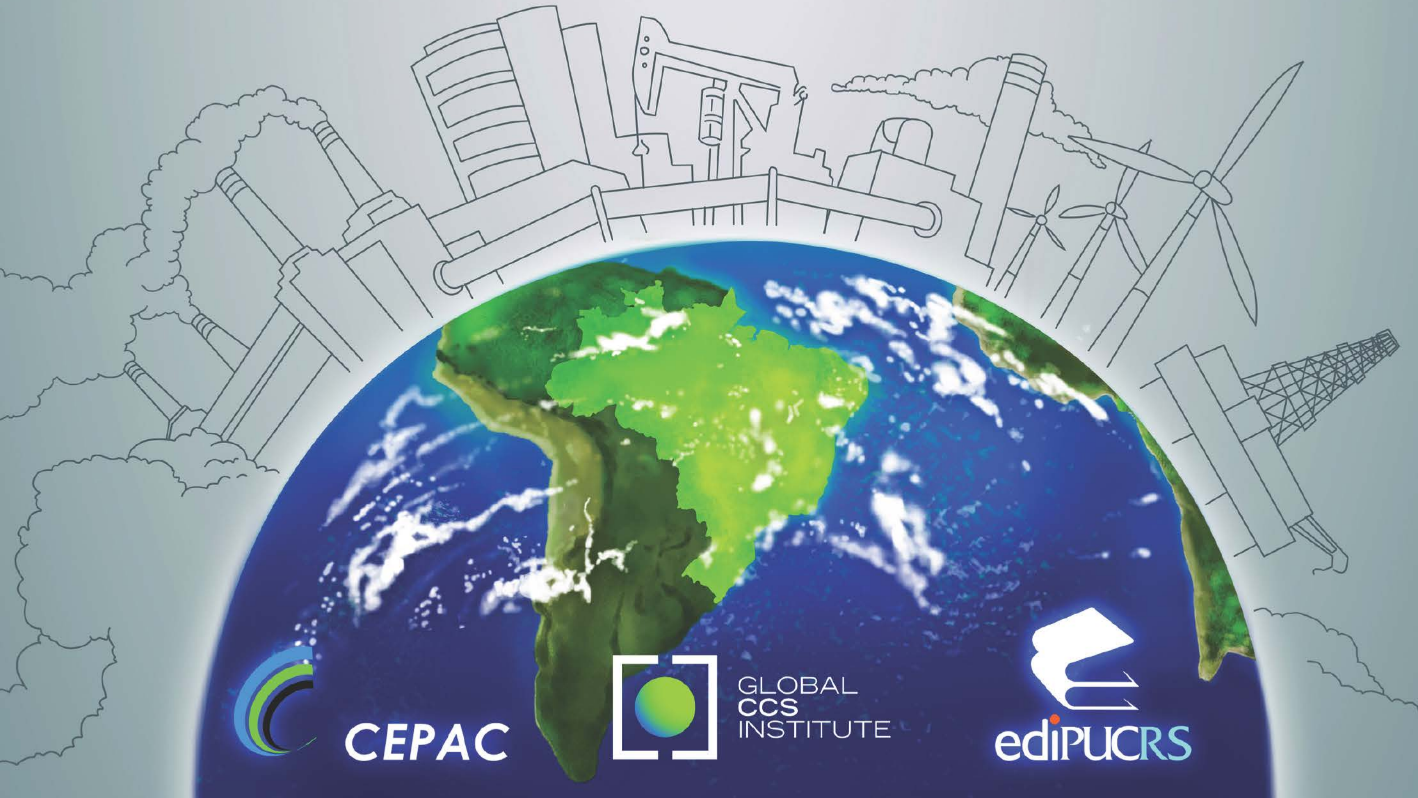

Brazilian Atlas of CO_2 Capture and Geological Storage

Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage

Pontifícia Universidade Católica
do Rio Grande do Sul

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Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage

edipucrs
October/2014

Published in April 2015

COVER DESIGN Shaiani Duarte

LAYOUT DESIGN Dani Editorial

FINAL EDITING Neil Wildgust, Meade Goodwin and Diane Teigiser

CEPAC
Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage

SUPPORTED BY
GLOBAL CCS INSTITUTE

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International Data Cataloguing in Publication (CIP)

B827 Brazilian atlas of CO2 capture and geological storage [recurso eletrônico] / org. João Marcelo Medina Ketzer ... [et al.]. – Dados eletrônicos. – Porto Alegre : EDIPUCRS, 2014.
66 p.

Sistema requerido: Adobe Acrobat Reader
Modo de acesso: <http:www.pucrs.br/edipucrs>
ISBN 978-85-397-0577-1

1. Engenharia. 2. Captura de Carbono – Atlas. 3. Carbono – Armazenamento – Atlas. I. Ketzer, João Marcelo Medina.

CDD 665.89

Cataloguing prepared by the Department of Information Processing – PUCRS Central Library.

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ACKNOWLEDGEMENTS

Agência Nacional de Energia Elétrica (ANEEL)
Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP)
Carbon Sequestration Leadership Forum (CSLF)
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)
Global CCS Institute (GCCSI)
Instituto Brasileiro de Geografia e Estatística (IBGE)
International Energy Agency (IEA)
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Ministério de Ciência, Tecnologia e Inovação (MCTI)
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Foreword

The Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) and the Pontifical Catholic University of Rio Grande do Sul (PUCRS) are proud to present the first Brazilian Atlas of CO_2 Capture and Geological Storage. This Atlas represents the outcome of a large research effort by CEPAC since its foundation, in 2007, dedicated to comprehension, development, and dissemination of the technologies involved in the CO_2 capture and storage (CCS) in Brazil, a recognized solution for the reduction of greenhouse gas emissions worldwide.

For the development of CCS technologies, an international effort in the mapping of CO_2 sources and evaluation of potential target reservoirs for geological storage is necessary, and the release of this Atlas positions Brazil among the countries that are on the way to accomplish this task.

CEPAC and PUCRS firmly believe that the publication of this Atlas will represent a substantial step in the development of CCS in Brazil and the dissemination of knowledge of these technologies, contributing to actions leading to mitigation of climate change.

The Organizers

The Global CCS Institute (the Institute) is pleased to sponsor the Brazilian CO_2 Storage Atlas. The Atlas is a welcome addition to the growing body of knowledge advancing carbon capture and storage (CCS) globally and particularly in Latin America. Identifying viable geologic storage sites is an essential part of CCS deployment and one that can take several years. The completion of Brazil's Atlas represents a significant step forward.

The Institute acknowledges and commends the major contribution made by the Centre of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) to produce this work. We look forward to an ongoing collaborative relationship with CEPAC and other Brazilian stakeholders to progress CCS knowledge and expertise. We also thank the many other colleagues who provided technical and logistical support to produce the Atlas and who provided reviews. The Atlas is an important milestone in the Institute's collaboration with CEPAC and other Brazilian stakeholders who are dedicated to progressing CCS knowledge.

The Global CCS Institute accelerates CCS, a vital technology to tackle climate change and provide energy security. We advocate for CCS as one of the options required to reduce greenhouse gas emissions from power generation and industrial sources.

The Institute shares information from our international membership while building capacity and bringing together projects, policymakers and researchers to overcome challenges and ensure that CCS can become a widely-used technology as quickly as possible. We collaborate with international organizations involved in advancing CCS, driving progress by integrating expertise with government decision making and international policy agreements.

Elizabeth Burton
Global CCS Institute, General Manager Americas

Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage

Headquartered in the Central Campus of the Pontifical Catholic University of Rio Grande do Sul (PUCRS), the Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) is the result of a joint initiative of PETROBRAS and PUCRS, through the University's Environment and Natural Resources Institute. CEPAC is an interdisciplinary center dedicated to research, development, innovation, demonstration and technology transfer in carbon dioxide (CO_2) storage and unconventional sources of energy related to fossil fuels such as gas hydrates, shale gas, methane in coal seams and hydrogen. Through this research CEPAC aims to contribute toward the mitigation of climate change and production of cleaner energy sources (Figure 1).

Figure 1: CEPAC facilities.
Source: CEPAC.

CO_2 Storage Research

When its activities started in 2007, CEPAC became the first Brazilian research center dedicated exclusively to research on CO_2 storage. Among the projects and research areas developed, are the following:

- Geological and mineralogical characterization of storage reservoirs and reservoir interaction with CO_2
- Investigation of the integrity and reliability of different materials and procedures applied to the injection of CO_2 through injection wells, in order to maximize the safety and feasibility of geological carbon storage.
- Studies of the geochemical interactions and flow mechanisms in the CO_2-water-rock system with focus on Brazil's pre-salt reservoirs.
- Development of a Geographic Information System (GIS) containing data on CO_2 emissions resulting from stationary sources, transport infrastructure, and potential geological reservoirs.

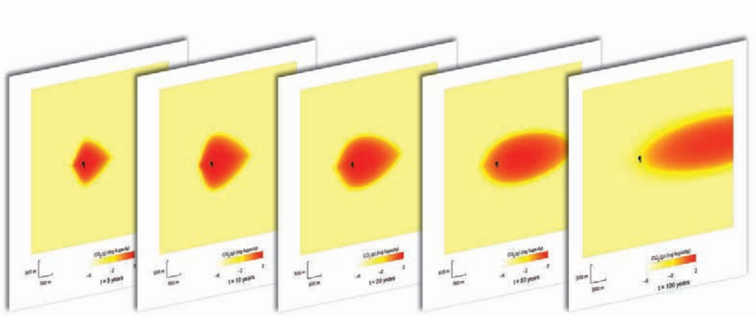

Figure 2: Numerical model showing displacement of CO_2 in a reservation over time.
Source: CEPAC.

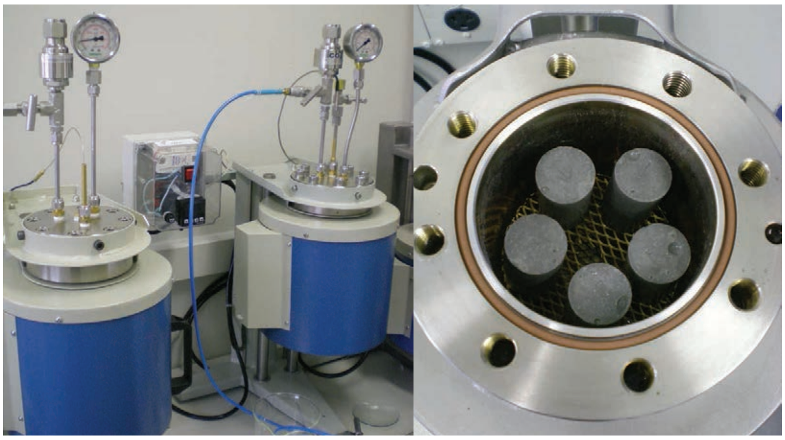

Figure 3: Stainless steel vessels used in laboratory experiments for simulation of reservoir conditions (left). Configuration of an experiment to evaluate CO_2-cement interaction (right).
Source: CEPAC.

Unconventional energy sources research

Ongoing projects focused on the development of knowledge and technology for unconventional energy sources include:

- Evaluation of the potential for enhanced coal bed methane recovery through implementation of a pilot project for methane production tests in Porto Batista, Rio Grande do Sul. These tests included perforation of two wells for production of methane, injection and monitoring of CO_2 (Figure 4).
- Stratigraphic characterization, petrophysics, petrography, geochemistry, adsorption/desorption of gases involved in hydraulic fracturing and selection of potential areas for exploration of shale gas.
- Study of the origin and geological evolution of the Rio Grande Cone (Pelotas Basin), focusing on gas hydrate deposits (Figure 5).

Figure 4: Pilot project for coal bed methane potential evaluation (Porto Batista/RS, Brazil)
Source: CEPAC.

Figure 5: Oceanographic mission in the Southern Atlantic for research on gas hydrates
Source: CEPAC.

Carbon Capture and Storage (CCS) Technology Overview

The steep increase in atmospheric concentration of CO_2 and other greenhouse gases during the past two centuries has been widely recognized as the cause of global temperature rises of at least 0.8ºC in the same period. Considering the current trend in the world's economic and population growth, this concentration will continue to rise. This could potentially lead to a further increase in temperature and severe climatic change. Therefore, reducing emissions of CO_2 and controlling its atmospheric concentration are challenges that need to be addressed.

One of several existing measures for reducing greenhouse gas emissions to mitigate climate change is the capture and storage of carbon dioxide in geological reservoirs (CCS)(Figure 6). This technology consists in the integrated process of the capture and separation of CO_2 from stationary sources (industries, power plants, etc.), transport to an adequate storage site, and injection into the porous space of deep underground rock formations.

CCS is one of the most important technologies available to reduce CO_2 emissions. CCS stands out due to its enormous potential in terms of CO_2 volumes that can be stored in geological media for millions of years.

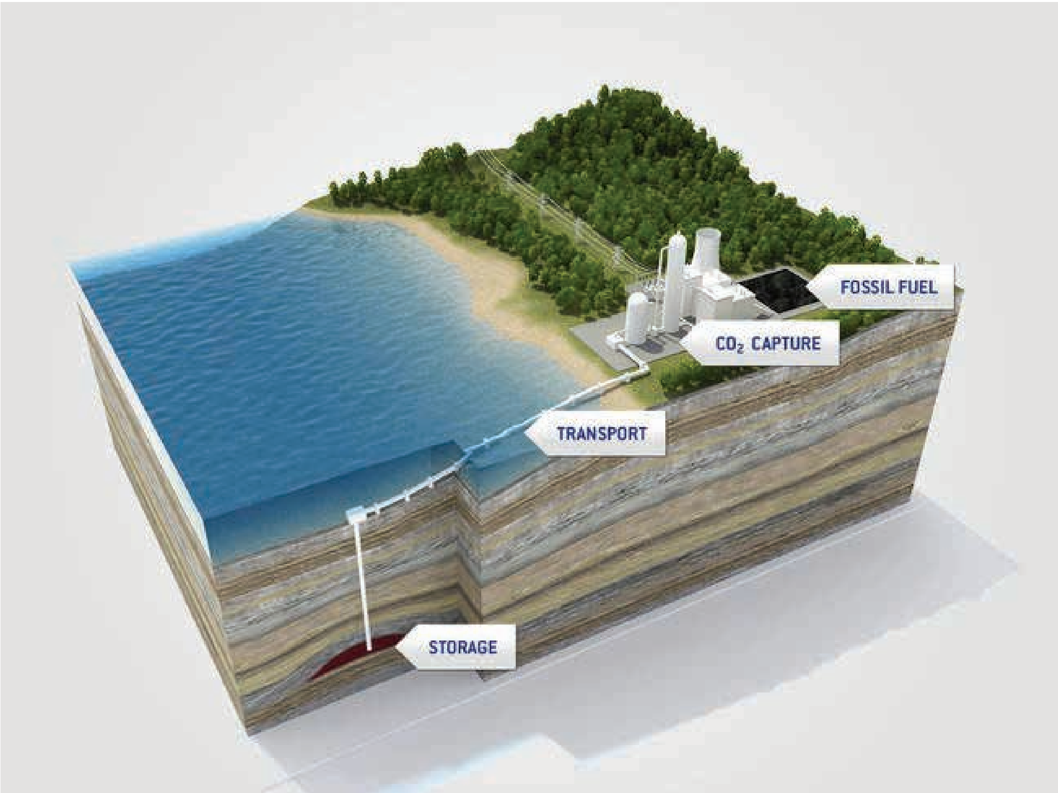

Figure 6: Carbon capture and geological storage.
Source: Bellona.

CO_2 capture and geological storage includes four basic stages:

- CO_2 capture and separation from other gases from the stationary emitting source, to achieve a high purity stream (typically greater than 90%);
- CO_2 transportation from emitting source to the storage location, which can be done through pipelines, trucks or tankers;
- CO_2 storage in different geological formations, each with specific advantages and disadvantages, and
- CO_2 measurement, monitoring and verification during and after injection phase into a geological formation.

There are different technologies available for each stage, however the feasibility and performance of each technology can vary according to the specific characteristics of the project.

CO_2 Capture and Separation

CO_2 capture can be carried out through four main processes: post-combustion, pre-combustion, oxy-combustion and industrial processes separation (Figure 7).

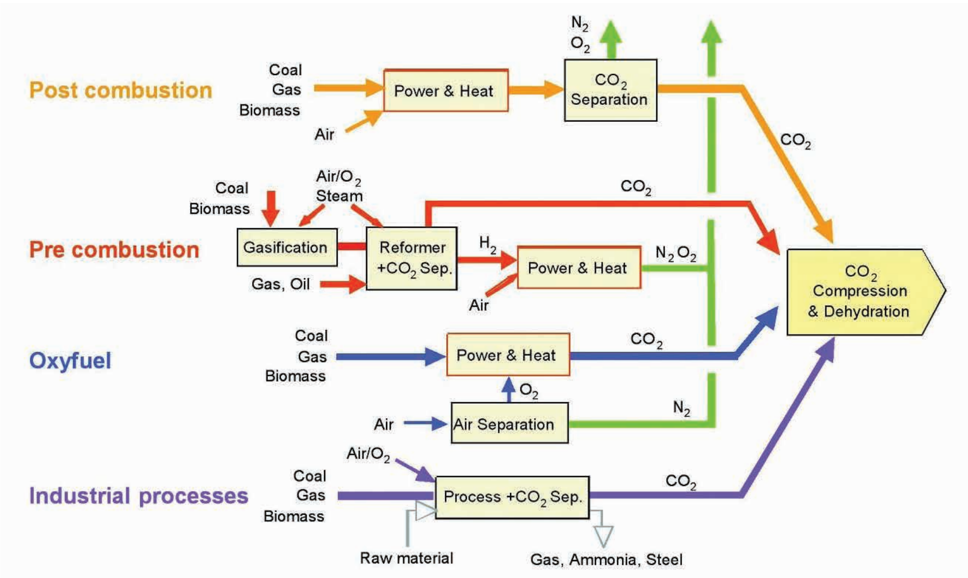

Figure 7: Overview of CO2 capture processes.
Source: IPCC.

Figure 8: Post-combustion CO_2 capture plant
Source: GCCSI.

During post-combustion capture the CO_2 is separated from the flue gas after burning fossil fuels or biomass in the presence of air (oxygen and nitrogen). The main products of this combustion are nitrogen (N_2) and carbon dioxide (CO_2), in which the latter is in low concentration (3-15% vol.). Currently, post-combustion processes are among the most used in CO_2 capture from stationary sources (Figure 8).

Pre-combustion capture is a three-stage process. First, the fuel (coal or biomass) is gasified, i.e., converted to hydrogen (H_2) and carbon monoxide (CO), a mixture called syngas. Next, a steam reforming (shift reaction) converts CO in CO_2, to yield more hydrogen. After these processes, the CO_2 must be separated from the hydrogen. The latter can then be used in several applications such as fuels or energy generation.

Figure 9: Air separation unit.
Source: Wikipedia.

In the oxygen combustion technology (or oxy-combustion), the fuel is burnt with pure oxygen. In this way, CO_2 (in high concentration, > 80%) and water vapor are produced, which can be easily separated by condensation. A critical part of this technology is the previous requirement for oxygen separation from air, which is usually carried out through a cryogenic process (an energy-intensive technique) (Figure 9).

Several types of industrial processes may be important large-scale sources of CO_2. In industries such as steel, cement and fertilizer plants, and natural gas processing, significant amounts of CO_2 may be produced and captured through different methods.

Depending on the capture process, a technology is necessary to separate CO_2 from other gases. Several methods may be used in this stage. The most common ones are based on selective absorption of CO_2 (chemical or physical), using solvents such as amines. Solid adsorption with membranes or zeolites is also employed. Other technologies are being investigated to optimize this separation step, such as ionic liquids - room temperature liquid salts with a highly selective CO_2 dissolution capacity.

CO_2 Transport

Captured CO_2 must be transported from the emitting source to the storage site. The pipeline system, similar to those used to transport natural gas, is a frequently utilized CO_2 transport option. Other options for transport include trucking and shipping.

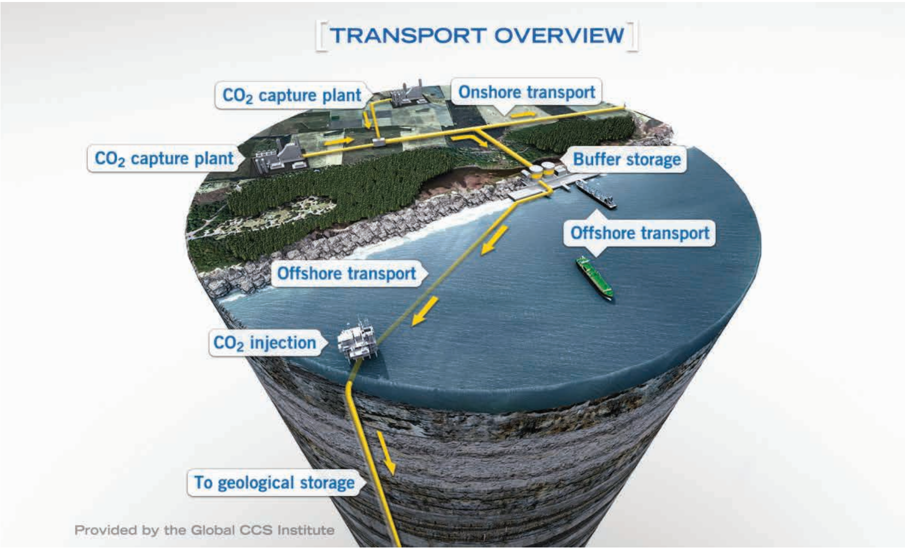

Figure 10: CO_2 transport options.
Source: GCCSI.

Usually CO_2 is compressed to a supercritical state (or a 'dense phase') for transport and injection. Depending on how long the pipeline is, the CO_2 may need to be 'recompressed' along various points of the pipeline to keep it in this 'dense phase' (Figure 10).

There are still some technological challenges associated with pipeline transport of CO_2. Several factors need to be considered in long-distance pipeline projects, such as terrain characteristics, moisture content of the gas, accidental entry of wet gas into the pipeline and corrosion resistance of the pipeline material.

CO_2 Geological Storage

The main geological options than can safely store large amounts of CO_2 and keep it from reaching the atmosphere are oil and gas fields and deep saline formations:

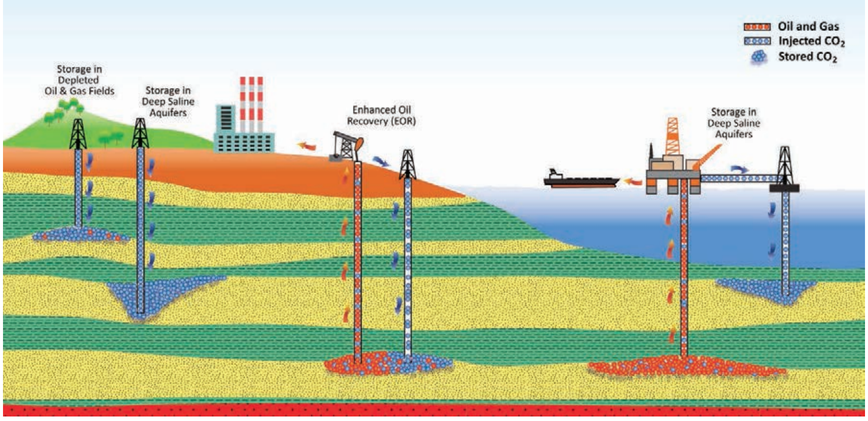

Figure 11: CO_2 geological storage options.
Source: CEPAC.

In most cases, and due to the increase in temperature and pressure with depth, injected CO_2 will be in a supercritical (or dense phase) state (pressure > 7.38 megapascal (MPa) and temperature > 31.1º C). In this condition, CO_2 acquires a liquid-like density, between 600 and 800 kilogram per cubic meter (kg/m³) therefore occupying a smaller pore volume, leading to more efficient storage (Figure 12). To ensure storage in a supercritical state, the minimum depth estimated for a reservoir is around 800 meters (m).

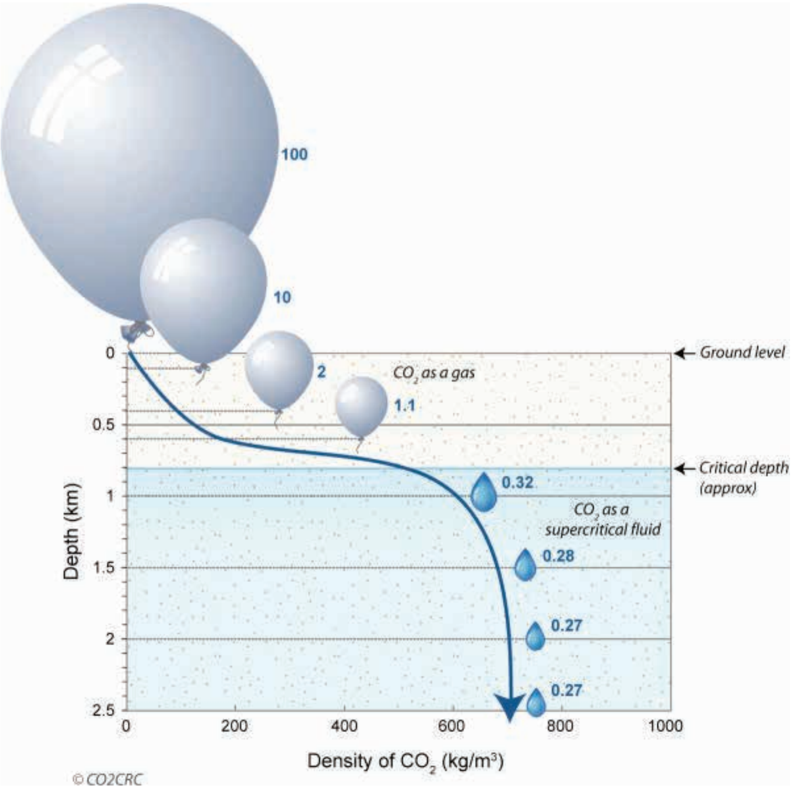

Figure 12: CO_2 density and state changes with depth.
Source: CO2CRC.

A reservoir rock is usually well suited for CO_2 storage according to the following properties:

- Porosity: refers to the volume of fluid that can be contained within the rock between the rock 'pore spaces', i.e. the minute spaces existing between rock grains. Porosity often decreased with depth, due to rock compaction and cementation, i.e. these 'pore spaces' become even smaller, so less fluid can be stored there (Figure 13).

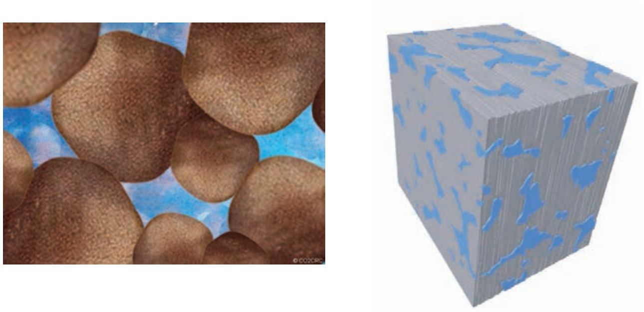

Figure 13: Rock porosity (in blue).
Source: CO2CRC/CEPAC.

- Permeability: refers to the connectivity between the rock pore spaces, i.e. the space or channels linking the pore spaces that fluid can flow through, from one pore space to the next. A minimum permeability is necessary and especially important in the early stages of a storage project to avoid CO_2 injectivity issues (Figure 14).

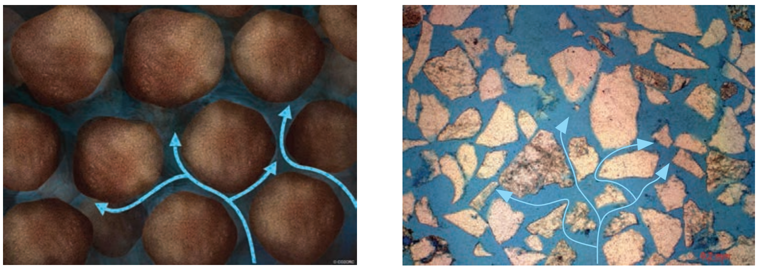

Figure 14: Permeability (flow paths).
Source: CO2CRC/CEPAC.

Physical and chemical trapping mechanisms are responsible for preventing the injected CO_2 from migrating back to the surface (Figure 15). A requirement for a physical trapping mechanism is the existence of an impermeable cap-rock formation, overlying the storage reservoir. This cap-rock acts as an obstacle and stops the vertical migration of the CO_2 to the upper parts of the sedimentary basin and the atmosphere (Figure 16).

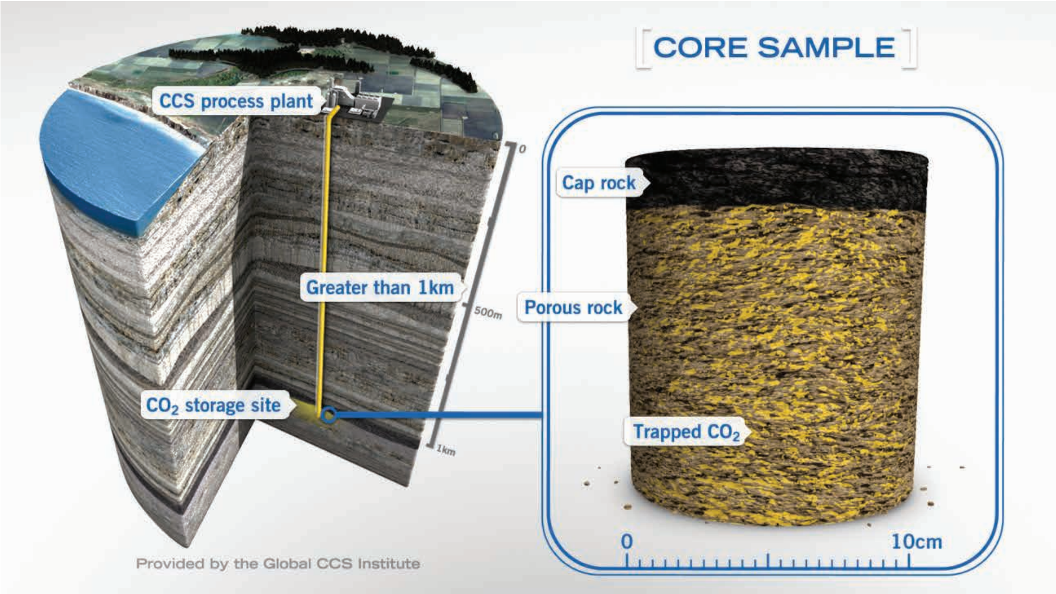

Figure 15: Typical geological reservoir and caprock setting.
Source: GCCSI.

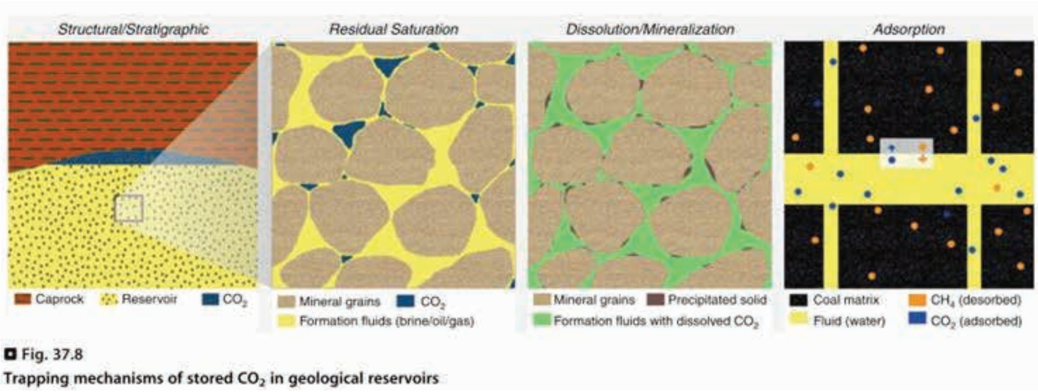

Figure 16: CO_2 trapping mechanisms in geological reservoirs.
Source: CEPAC.

Physical trapping of fluids (like CO_2 in its dense phase) in the sub-surface is achieved by means of a caprock and 'traps', which can be structural or stratigraphic (or even a combination of both).

CO_2 injected into storage reservoirs, especially deep saline formations, will over time partially dissolve into the saline groundwater (brine) present in these reservoirs. The rate at which this dissolution occurs will vary according to a number of factors, including reservoir geology, pressure and temperature conditions, and brine composition. This mechanism is referred to as ionic or solubility trapping and can serve as a further means to immobilize CO_2 in the reservoir and reduce risks associated with any potential leakage. In the ionic or solubility trapping mechanism, CO_2 dissolved in the aqueous phase of the geologic formation is retained as dissolved carbonate and bicarbonate (CO_3^{2-} and HCO_3^-, respectively) species.

Dissolved CO_2 may also chemically react with reservoir rocks and fluids, causing precipitation of carbonates. This process is referred to as mineral trapping, and has the potential to immobilize injected CO_2 in a solid phase. Mineral trapping occurs when the dissolved CO_2 reacts with selected cations (such as Ca^{2+} or Mg^{2+}), present in the aqueous phase or originated from mineral dissolution. Once in a solid phase, CO_2 will likely remain immobilized for thousands or millions of years, and therefore is considered the safest trapping mechanism.

Adsorption trapping occurs in coal seams, where the CO_2 displaces the methane contained in the seam, and then remains adsorbed in the coal matrix.

Storage in oil and gas fields

Injection of CO_2 can be carried out in particularly, but not exclusively, in mature or depleted oil and gas fields. Mature oil fields are those where hydrocarbon production is in its final stages, while depleted fields are those where only residual oil (trapped in the pores of the reservoir rock) remains. This operation can increase production of hydrocarbons from these fields, resulting in economic benefits. Furthermore, these projects take advantage of the geological data acquired in their exploration and development.

For several decades, CO_2 has been used as injection fluid for additional recovery of oil and gas. In over 100 projects worldwide, injected CO_2 has been used to successfully recover additional oil, given that significant reserves can remain in reservoirs after conventional recovery. This technique is known as Enhanced Oil Recovery (EOR) (Figure 17). Most of these projects are located in the United States, and a large proportion of the CO_2 used has been obtained from natural accumulations, with a smaller part coming from anthropogenic sources. Brazil has EOR projects developed in the Recôncavo Basin, which will be discussed further on in this Atlas.

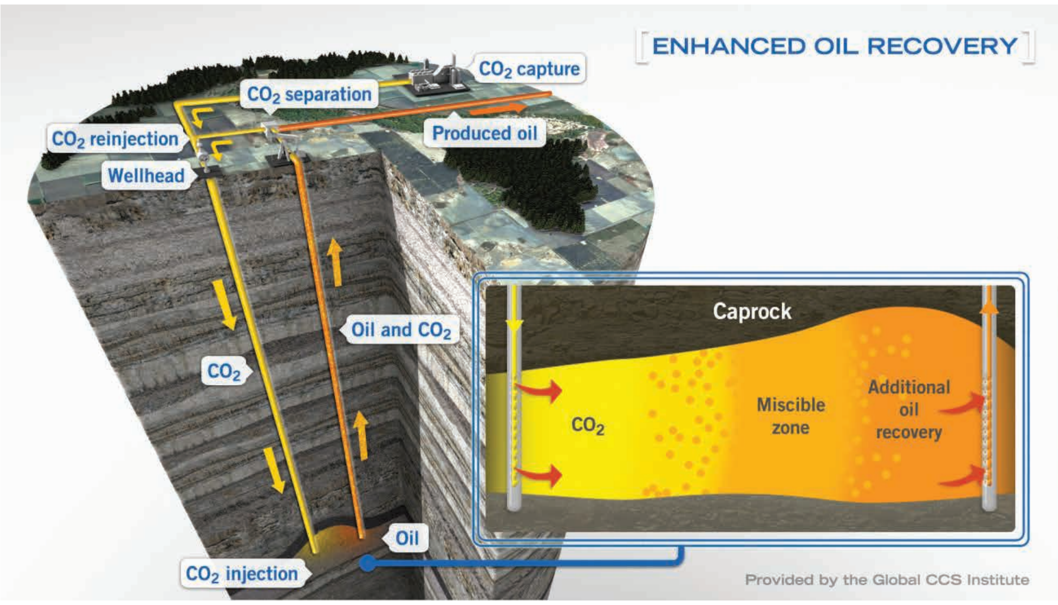

Figure 17: CO_2 Enhanced Oil Recovery

CO_2-EOR operations have the potential to extend the economic life of individual fields by a decade or more, as proven by a number of projects where several tens of percent of additional oil reserves have been produced. Typically, a proportion of the injected CO_2 is stored in the reservoir by trapping mechanisms as described above, whilst some injected CO_2 is produced from the reservoir with oil. The proportion of this 'recycled' CO_2 increases with time, and it should be stripped from the oil and re-injected into the reservoir with 'new' CO_2 in a closed loop system.

The ultimate storage capacity provided by any CO_2-EOR project will depend on a number of technical and economic factors. At the end of economic oil production, an operator may choose to use the closed loop system to ensure all CO_2 is stored in the reservoir before sealing and abandoning wells. Alternatively, a significant portion of the CO_2 could be produced for further utilization in other oil fields. Storage capacity could be increased with injection into residual oil zones beneath the main field, or into the reservoir for storage only.

Storage in Deep Saline Formations

Deep Saline Formations (DSF) are rock formations with pore spaces filled with highly saline (salty) groundwater, also commonly referred to as brine. An arbitrary limit of 10,000 milligrams per litre (mg/l) of dissolved solids is usually considered the lower limit of salinity of DSF suitable for CO_2 geological storage. For comparison, potable water in Brazil has a maximum limit of 500mg/l, whereas seawater has an average salinity of 34,600mg/l. In some DSF, brine salinity can reach up to 300,000mg/l. These considerations of salinity are less relevant in offshore storage scenarios, where groundwater is unlikely to be utilized (Figure 18).

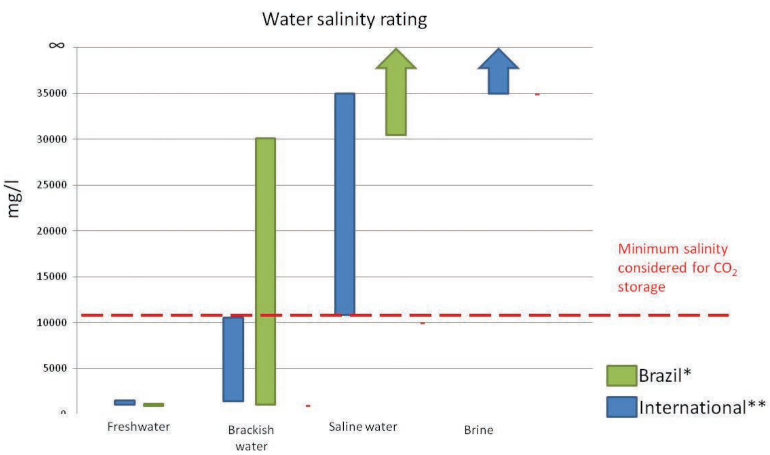

Figure 18: Water salinity grades

Deep saline aquifers are more common than oil and gas fields and coal deposits, and have an enormous potential for CO_2 storage in terms of capacity. However, there tends to be much less information available on these reservoirs, compared to the data available on hydrocarbon reservoirs and coal deposits.

LARGE-SCALE COMMERCIAL PROJECTS

Currently, there are 12 large-scale projects (i.e. injecting more than 400 ktonnes/year) where CO_2 is stored in geological reservoirs. In total, these projects store more than 20 million tonnes of CO_2 in geological formations each year. The operational projects that have storage in deep saline aquifers are all associated with CO_2 captured from produced natural gas, such as the case of the Sleipner Project in the North Sea, and the Snøhvit, in the Barents Sea, both operated by the Norwegian oil company StatoilHydro. In Sleipner, the natural gas produced has a CO_2 content of approximately 9%, which is separated, purified and injected in the Utsira Formation, 800 m below the sea bed of the North Sea, at a rate of 1Mt/year. In the Snøhvit field, CO_2 is also separated from natural gas (ca. 5-8% content), and injected 2300 m below the sea bed in the Stø formation.

Coal is a combustible sedimentary rock with high carbon content, formed by decomposition and alteration of organic matter from vegetable sources (Figure 19).

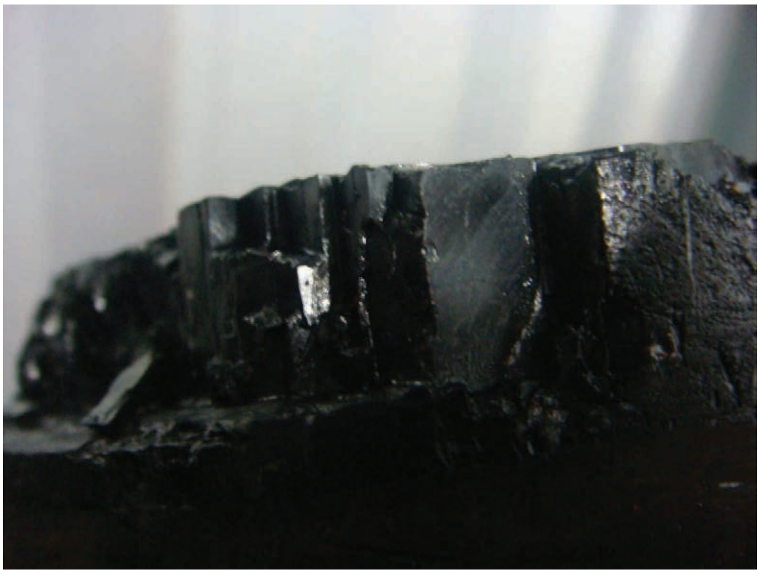

Figure 19: Coal sample.
Source: CEPAC.

Coal beds have a natural affinity for adsorbing CO_2 in its microporus matrix. Coal can trap approximately twice as much CO_2 as methane, which is commonly found trapped in the coal beds for millions of years. Methane in coal beds is exploited as an energy resource in countries such as Australia, China and the U.S. This activity is termed Coal-bed Methane recovery (CBM). Currently, there are several projects for CBM exploitation worldwide. In the U.S., approximately 10% of the domestic natural gas is originated from CBM projects.

Due to the difference in coal's adsorption capacity between carbon dioxide and methane, CO_2 molecules are adsorbed while CH_4 molecules are released, in a process called enhanced coal-bed methane recovery (ECBM). Once injected, CO_2 will be adsorbed preferentially in the coal matrix, displacing the methane to the coal's fracture system, which can be produced as a free gas. The depth window for storing CO_2 in coals is between 300 and 900 meters.

According to global estimates, storage capacity associated with coal is between 15 to 200 billion tonnes of CO_2.

Other reservoir options

Coal beds have also been considered as a potential reservoir for CO_2 storage although they have yet to be demonstrated to be an effective and secure option. CO_2 storage in mafic rocks (i.e. rocks rich in iron and magnesium minerals) has also been investigated in several studies. Storage in mafic rocks is of interest due to the considerable volume and distribution of these rocks. The composition of these rocks, rich in magnesium, iron and calcium, could facilitate chemical reactions with CO_2, potentially leading to mineral trapping. Studies investigating the possibility of CO_2 injection in volcanic rocks are ongoing in India and the U.S. However, storage in these rock types still needs to be validated with pilot projects.

Site selection criteria

Potential geological reservoirs for CO_2 storage must meet certain requirements that ensure the integrity of the storage site and the efficiency of the activity, such as:

- Adequate capacity and adequate injectivity rates (permeability in the vicinity of injection wells);
- Cap-rock containment capacity for preventing upward migration of CO_2;
- Stable geological environment (geochemically and geomechanically).

The implementation of a storage project will depend upon a combination of favorable factors, which includes:

- Basin characteristics (adequate stratigraphy and reservoir depth, favorable geothermal and hydrodynamic regimes, low seismic activity);
- Basin resources (occurrence of oil and gas for EOR, coal for ECBM, safe distance from freshwater aquifers, availability of deep saline formations);
- Oil industry maturity and infrastructure (existing rigs, pipelines, wells and geological data);
- Social and economic issues (appropriate development levels, funding opportunity, public acceptance).

Safety of geological storage

Storage safety is an essential consideration for CCS projects. Although CO_2 is a non-combustible low-toxicity gas, in high concentrations it can be dangerous to human health and the environment. Therefore, safety and risk assessments are always necessary to evaluate potential sources of CO_2 leakages or seepages away from the storage complex, in order to plan remediation options.

Experience with natural gas and CO_2 reservoirs, and the oil and gas industry expertise in transporting and injecting carbon dioxide in geological reservoirs provide good examples where the transport and storage of CO_2 has already been demonstrated.

The safety of subsurface storage can be supported by the several known natural accumulations of CO_2, and can be used to gather further knowledge on containment conditions. These natural fields range from shallow (100's meters) to deep (up to 5 km) reservoirs, with high-purity (> 90%) CO_2 accumulations around the world that can be used as analogs for the study of geological storage long-term effects.

Monitoring, measuring and verification of CO_2

CO_2 is likely to remain stored for millions of years, however, in any given project, the safety of storage must be ensured by monitoring the CO_2 in the subsurface. Atmospheric, soil and shallow groundwater monitoring is also essential to ensure that in the unlikely event of any leakage to the shallow subsurface or above surface, any associated impacts could be rapidly mitigated.

Monitoring operations must be carried out before, during and after the injection phase (always in comparison to baseline measurements), and usually rely on proven technologies employed in the oil and gas industry. Geophysical methods are predominantly used, such as seismics and electric resistivity. Geochemical methods can also be used to evaluate the movement of CO_2 in the subsurface through fluid analyses (Figure 20). Some of these tools can be used to understand or characterize the local geology before injection, and models can be made to predict the behavior of the injected CO_2. Rigorous characterization is needed to select appropriate storage sites with adequate capacity, injectivity and containment, and to design safe operational parameters, for example maximum injection rates. Thorough characterization is also required to inform a comprehensive risk assessment process, to demonstrate that the probability of any potential leakage event is very low and that any associated impacts could be identified, monitored and mitigated appropriately. It is usually considered that a leakage of 1% of stored CO_2 in a hundred years would be an acceptable value.

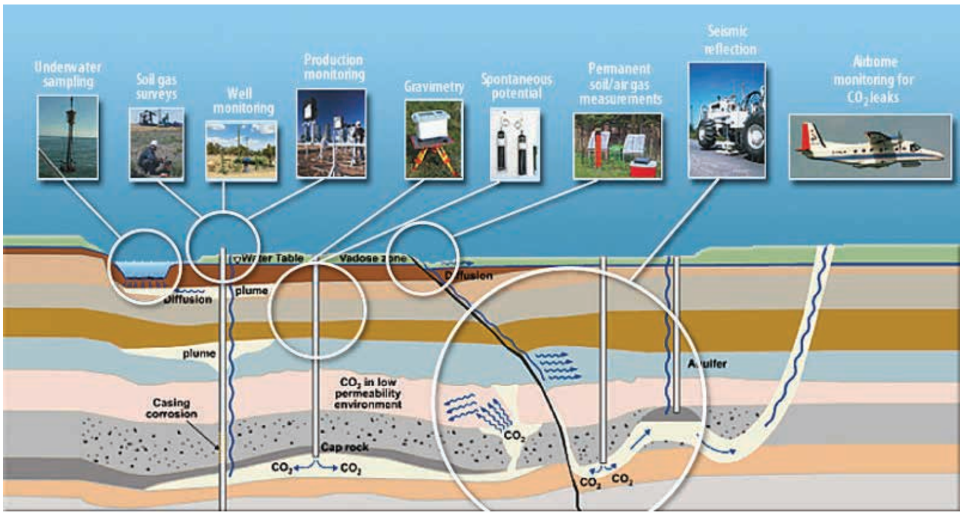

Figure 20: CO_2 Monitoring Techniques.
Source: CO_2 Capture Project.

Flow of injected CO_2 in the sub-surface can be modelled prior to injection by simulating CO_2 interactions with the reservoir and cap-rock in laboratory experiments. These experiments simulate the subsurface conditions using real rock and fluid samples. Simulations can also be carried out using numerical modeling tools to predict flow and chemical interactions in the storage site in geological timescales. The observed flow of the injected gas in the subsurface can be compared with the predicted paths, allowing calibration of both experimental and numerical models.

Monitoring of shallow or surface environmental compartments also needs to be undertaken prior to injection to provide baseline data, and during/after injection to detect any changes or impacts that might arise in the unlikely event of leakage. These compartments include: (1) freshwater aquifers and groundwater resources; (2) the shallow subsurface including the soil profile; (3) surface water bodies; and (4) the atmosphere. A variety of methods can be employed for shallow and surface environmental monitoring, such as chemical and biological analyses, tracers and remote sensing, among others.

CO_2 MONITORING FIELD LABORATORY

In December 2011, the Ressacada project, the first Brazilian CO_2 monitoring, measuring and verification (MMV) field lab was initiated, as a joint R&D project between PETROBRAS and academic institutions focus on testing and validation of CO_2 monitoring techniques and methodologies. Field experiments consist of CO_2 injection and controlled releases over a specified time to simulate shallow subsurface leakages reaching both saturated and unsaturated sediments and soil, and ultimately the atmosphere. Time-lapse monitoring was carried out following the releases, focusing the investigation on several areas such as atmospheric fluxes and concentration, groundwater studies, CO_2 tracer studies, geophysical surveys (electrical imaging techniques), soil CO_2 flux measurements and evaluation of botanic stress using remote sensing.

The experimental area is located in the Ressacada Farm, a rural region close to the city of Florianópolis, Southern Brazil. Two injection campaigns were conducted in the site, both using vertical wells for CO_2 injection.

Hence, monitoring, measuring and verification of CO_2 in CCS projects is not limited to the geological reservoir target of injection, or the confining cap-rock. it must consider all the areas where CO_2 can migrate, including soil, water bodies and atmosphere.

CO_2 storage capacity

The maximum theoretical CO_2 storage capacity in any rock formation can be estimated as a function of effective porosity (i.e the amount of connected pore spaces in the rock) and the volume of the formation. The capacity for storing CO_2 depends ultimately on the effective porosity (i.e. how much pore space is available) and volume of the reservoir rock. Also, capacity estimation at both regional and local scales depends on a number of other factors including geological structure, fluid flow characteristics injection rates, reservoir conditions, etc.

According to the concept of the techno-economic resource-reserve pyramid proposed by the Carbon Sequestration Leadership Forum (CSLF) for CO_2 storage capacity estimation methodology, four different types of capacities can be estimated, as outlined below.

Theoretical capacity: represents the physical-geological limit for fluid storage, assuming that CO_2 will ocupy all porous space of the reservoir.

Effective storage capacity will be smaller than the theoretical capacity, and is obtained by applying a number of technical parameters (geological or engineering), which will limit the capacity that can be utilized.

Practical capacity will be smaller than the effective capacity, and can be calculated by considering technical, legal and regulatory barriers, infrastructure, and economic issues.

Source-sink matched capacity: corresponds to a fraction of the practical capacity that is associated with CO_2 sources that can be captured, obtained by matching those sources against mapped storage formations with practical capacity estimates.

In oil and gas fields, through specific analyses of each reservoir, the storage capacity of carbon dioxide can be estimated from reserves and production databases. In hydrocarbon reservoirs under production or already depleted, the injected CO_2 may occupy the pore volume previously occupied by the hydrocarbons.

Estimating storage capacity for DSF may be challenging, due to the often limited amount of pre-existing characterization data and corresponding uncertainties over local and regional pressure and fluid flow conditions (hydrodynamics) that can influence injectivity and capacity. Moreover, the possible absence of trapped, buoyant fluids such as hydrocarbons require characterization efforts for DSF to demonstrate the presence of suitable sealing or cap-rock layer(s) above the intended reservoir. These factors may require greater investments of time and money to prove geological storage sites in DSF.

Brazilian Context

Brazil has an overall favorable situation regarding the potential for CO_2 geological storage. The country has a large area covered with sedimentary basins, both onshore and offshore. Most of the stationary emitting sources, especially in the Southeast region, are located in proximity to these basins (Figure 21).

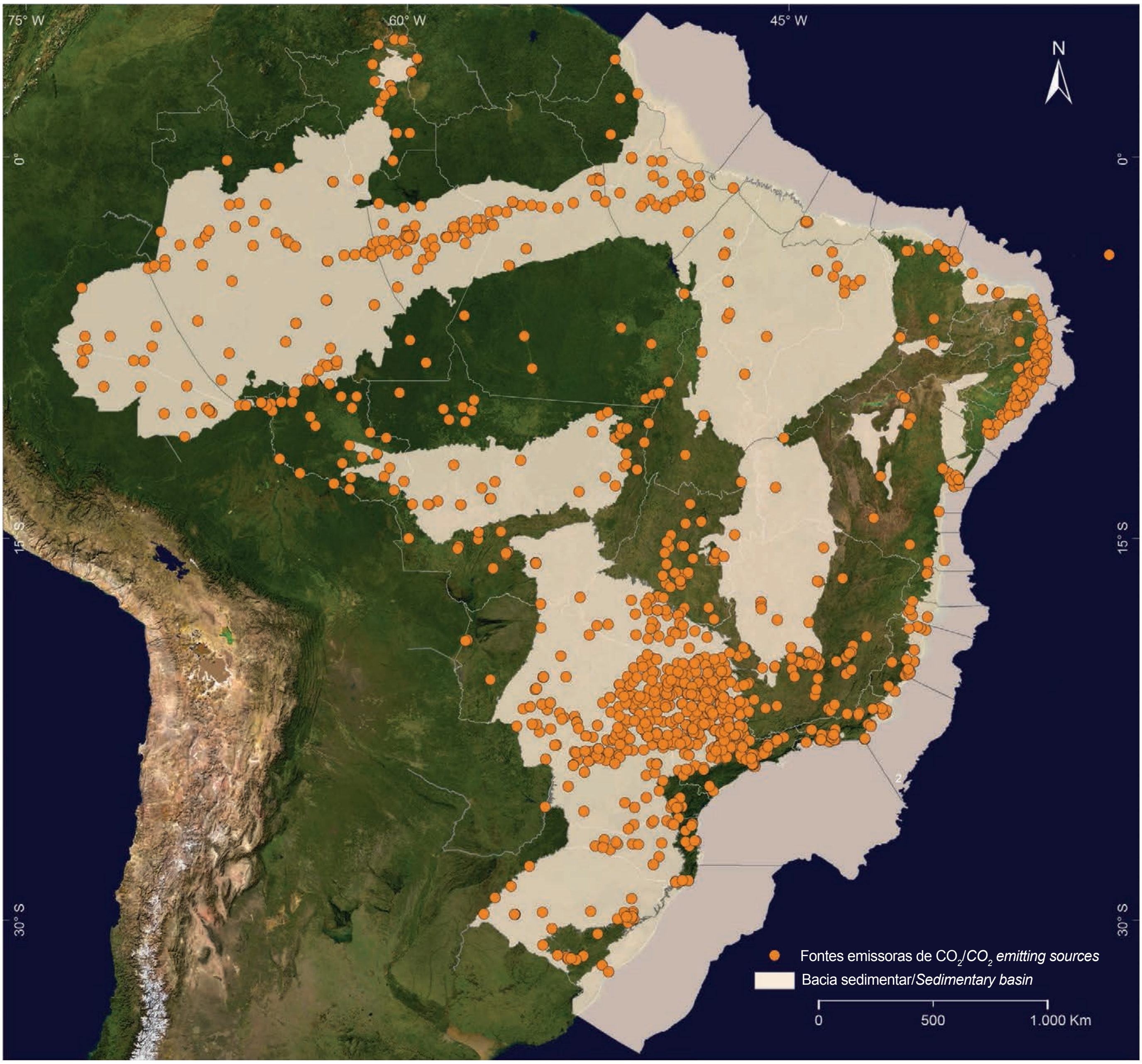

Figure 21: Sedimentary basins and CO_2 emitting sources in Brazil.

CO_2 Stationary Sources

Source: João Marcelo Ketzer.

The large CO_2-emitting stationary sources in Brazil are those related to power plant, biomass, cement, steel, oil refining, ethanol, ethylene and ammonia sectors and the majority are concentrated in the country's Southeast region. That is especially the case for biomass and ethanol, for example, which are concentrated in the Southeast and Central regions. In total, all sources are responsible for the emission of 395 MtCO_2/year (in 2006). The energy generation sector is distributed all over the national territory, with some concentration in the Southeast, Northeast and North. Cement plants occur in smaller numbers and are dispersed throughout the country (Figure 22; Figure 23).

In addition to onshore stationary sources, Brazil has several offshore sources – mostly petroleum platforms. Despite their significant emissions, the location of these facilities are not available from official records, therefore are not represented in this Atlas.

Data for emitting sources was obtained from the National Electric Energy Agency (for power plants) and the International Energy Agency.

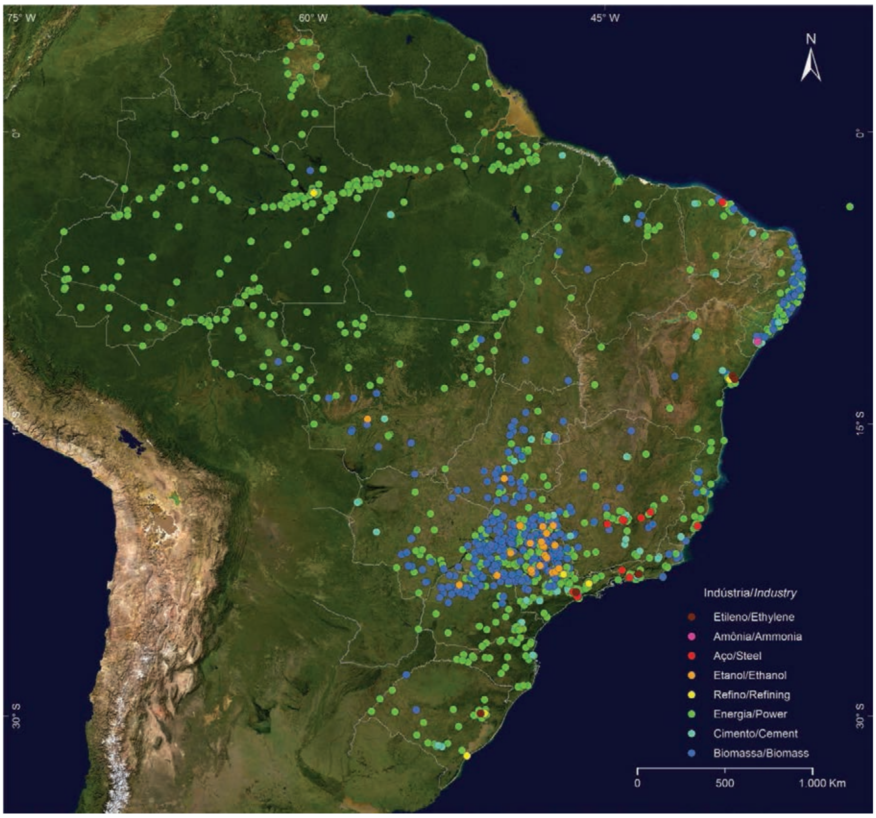

Figure 22: CO_2 stationary sources per type.

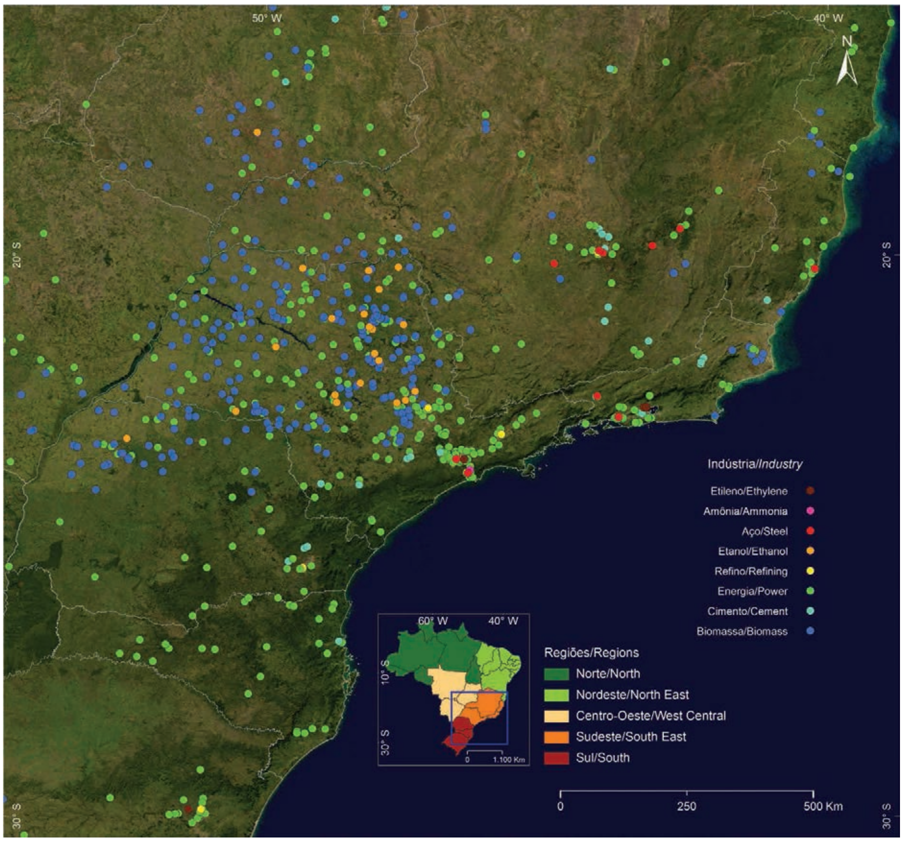

Figure 23: CO_2 stationary sources per type: Southeast region.

Energy generation is the largest source of CO_2 emissions, with over 1100 facilities in operation (Figure 24). This sector is responsible for 43.6% of Brazil's CO_2 emissions from stationary sources and produces over 170,000 kilotones (kt) of carbon dioxide per year (Figure 25). Following power generation, the second largest emitter is biomass, which emits approximately 136Mt of CO_2 annually through more than 568 plants. Cement, steel and refining facilities also stand out for the amount of emitted CO_2, together accounting for 18% of Brazilian emissions, or a total of 71.5Mt per year.

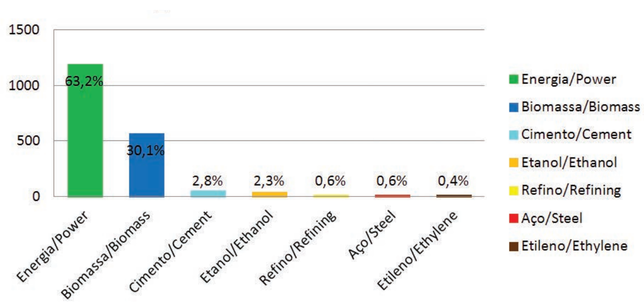

Figure 24: CO_2 stationary sources per sector

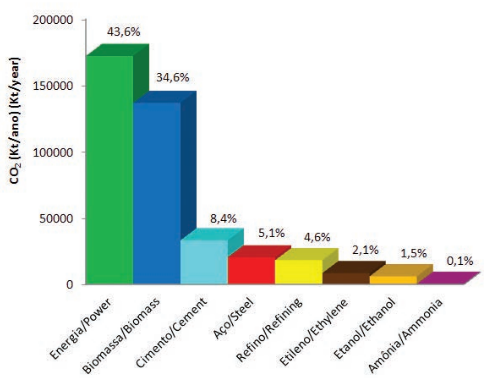

Figure 25: CO_2 emissions per industry

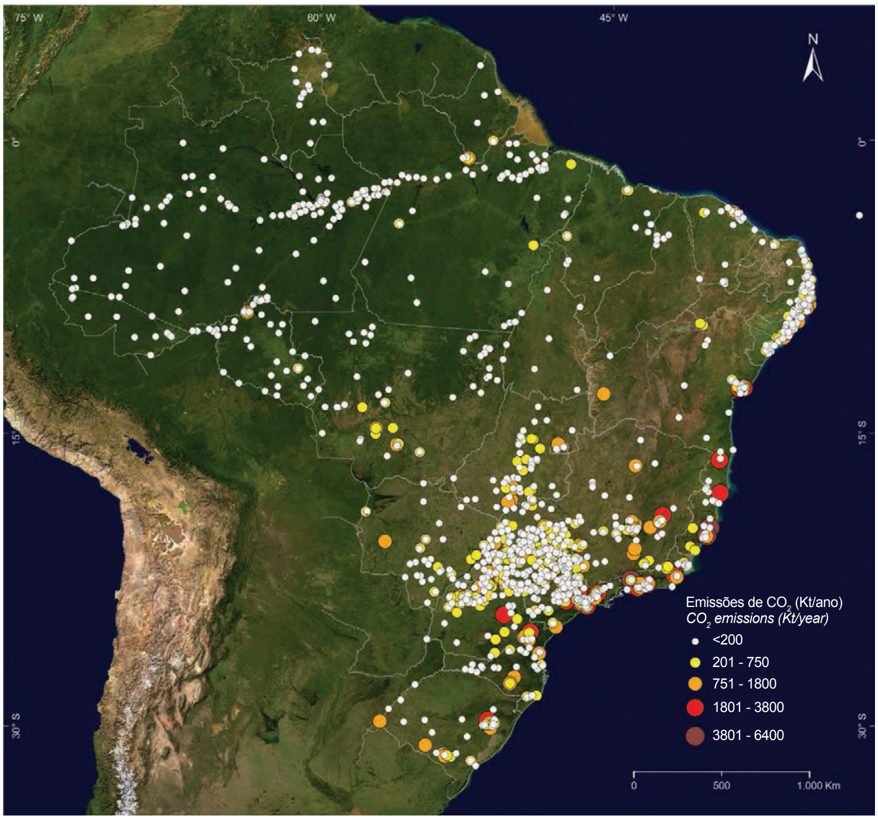

Figure 26: CO_2 emissions from stationary sources per mass emitted annually.

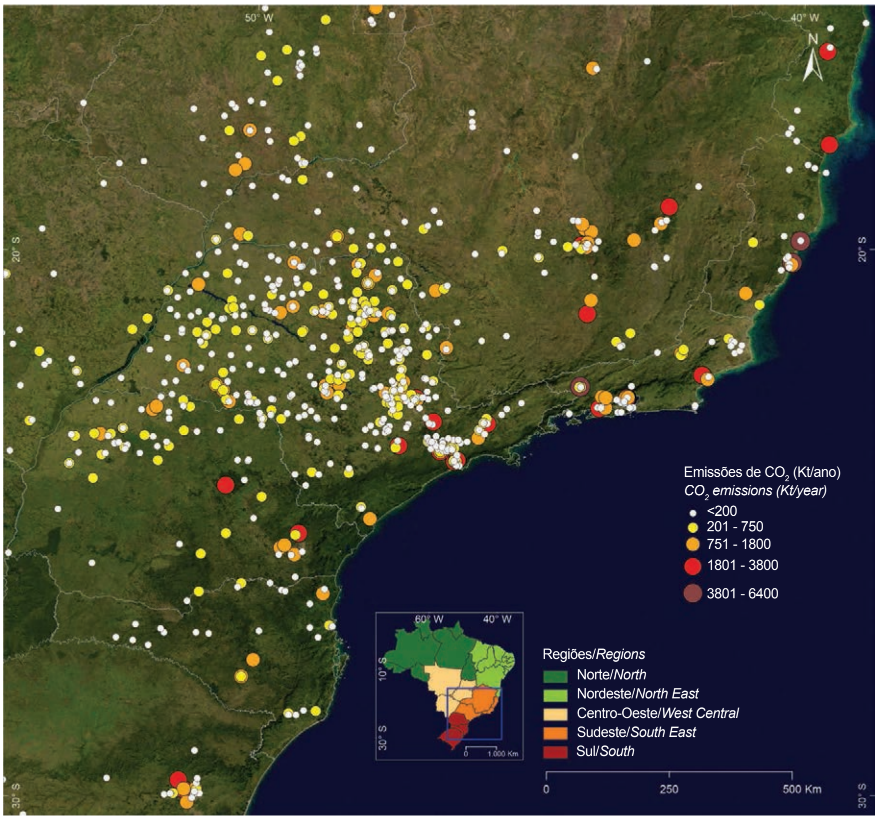

Figure 27: CO_2 emissions from stationary sources per mass emitted annually: Southeast region.

It should be noted that, for energy facilities where CO_2 emission data was not available, the estimation was based on the assumption that the facilities operate 152 days per year, 24 hours a day, at maximum efficiency. For each type of industry, a CO_2 emission factor was applied based on the nature of the fuel used for energy generation.

The most emission intensive geographical areas are located in the central-southeast portion of the country, with some clusters in the coastal areas, where many state capitals and industrial cities are located (Figure 26; Figure 27).

CO_2 Capture

Based on the fuel source for energy generation in Brazilian energy and industrial facilities, the most likely CO_2 capture process to be used in each source was assigned. It should be noted that the suggested process is not based on an analysis undertaken for each specific plant, but was based on existing literature regarding maturity of technology and its usual application in different industrial/energy sectors. From this information, a map was generated with the potential capture method for each source. In this map, only CO_2 sources with emissions over 0.1 Mt/year were considered. When more than one process is possible, the most viable (economically and technologically) was considered (Figure 28; Figure 29). It was concluded that the process most likely to be applied, associated with the existing sources, would be post-combustion. This process could potentially be applied on 78% of the sources, capturing over 243 Mt/year. In many sources (ca. 9%), CO_2 is produced in a nearly pure stream (such as the case of ethanol production plants); therefore simple separation processes such as dehydration of the steam are applicable (Figure 30).

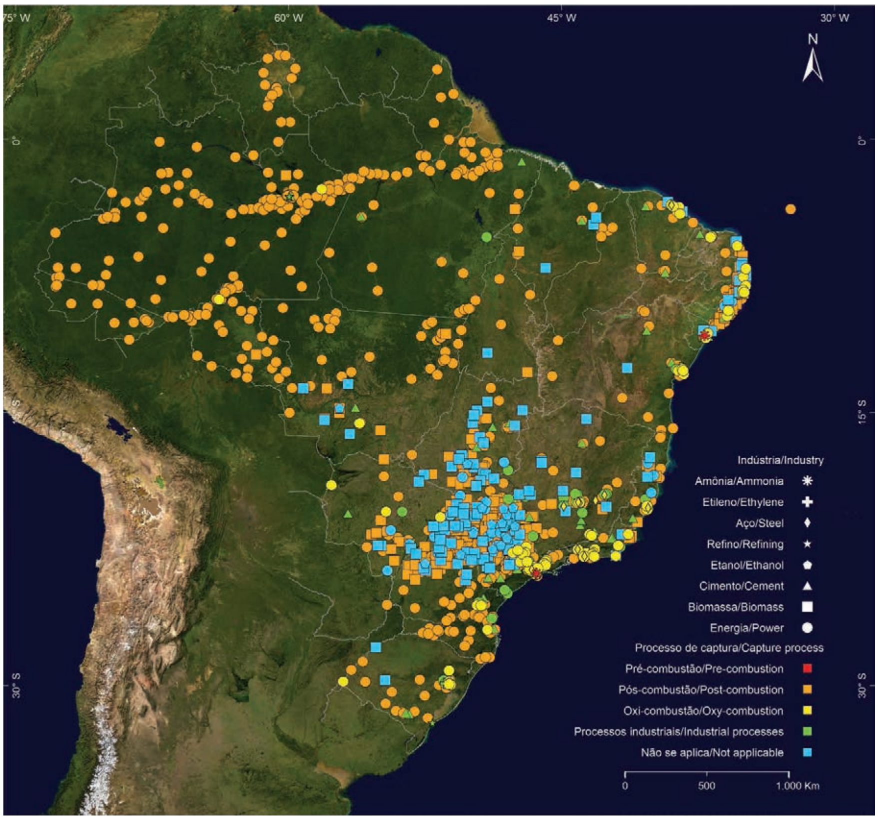

Figure 28: Potential CO_2 capture processes for emitting sources in Brazil.

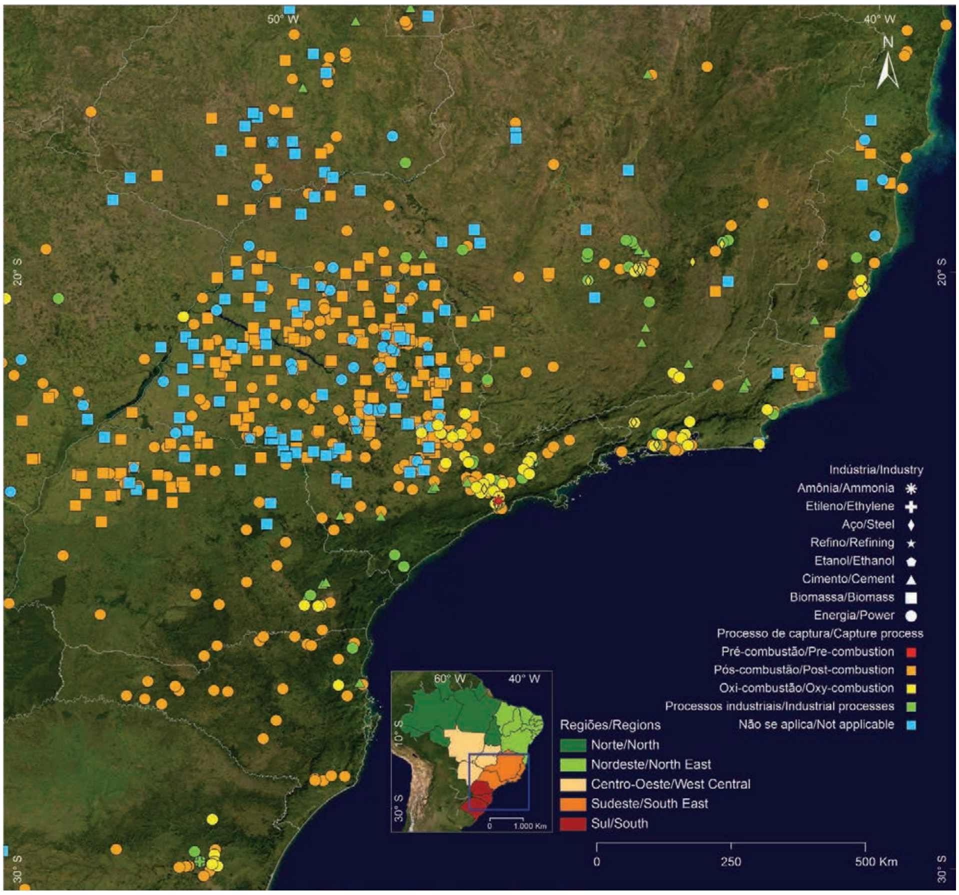

Figure 29: Potential CO_2 capture processes: Southeast region

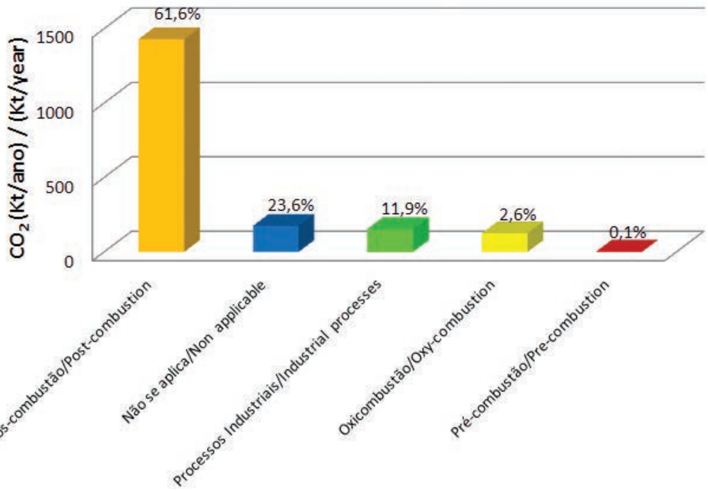

Figure 30: Potential amount of CO_2 captured by capture process.

CASE STUDY: CO_2 CAPTURE TEST FACILITY IN BRAZIL

In São Mateus do Sul, in the Paraná State, a series of tests were carried out between 2011 and 2012 to evaluate oxy-combustion technology in a fluid catalytic cracking (FCC) unit, as part of the international CO_2 Capture Project (CCP)*.
FCC units convert low-value, heavy hydrocarbons into a lighter, more valuable product. A catalyst, which decomposes over time, is necessary for this conversion, and a recovery process using air is used to regenerate the catalyst. Using oxy-combustion technology, where air is replaced by pure oxygen, a high-purity CO_2 stream is obtained as the combustion product. Results of the investigation confirmed the technical and economical viability of upgrading an FCC unit focusing on CO_2 capture through oxy-combustion (Figure 31).

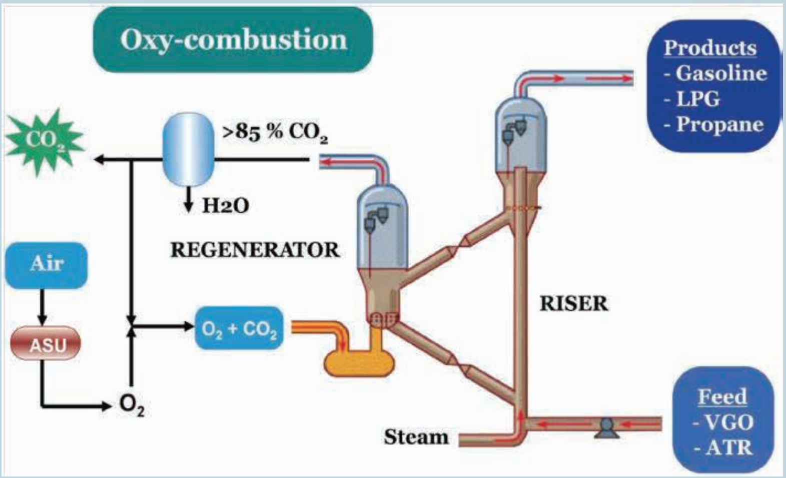

Figure 31: Oxy-combustion.
More information at:

Leonardo F. de Mello, Rodrigo Gobbo, Gustavo T. Moure, Ivano Miracca, Oxycombustion Technology Development for Fluid Catalytic Crackers (FCC) – Large Pilot Scale Demonstration, Energy Procedia, Volume 37, 2013, Pages 7815-7824.

* The CO_2 Capture Project is a partnership, signed in 2000, between the energy companies BP, Chevron, Eni, PETROBRAS, Shell and Suncor, with the involvement of government entities from the U.S., European Union and Norway.

Transport of CO_2

In Brazil, transport of fluids in the petroleum industry is done mostly using pipelines and tankers. Pipelines have several advantages over other transportation options, such as the capacity to move substances in high volumes, across difficult terrains, often with low unit costs.

However, the pipeline share of the Brazilian transport matrix is low - approximately 4.2%. Highways and railroads are the main transport options used in Brazil nowadays (Figure 32).

The Brazilian pipeline infrastructure is concentrated mostly in the southeast and coastal regions of the country, as most of the oilfields exploited are located in offshore basins (Figure 33).

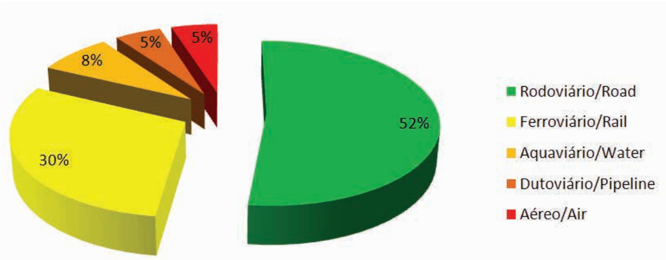

Figure 32: Cargo transportation matrix.
Source: Ministério dos Transportes, 2011.

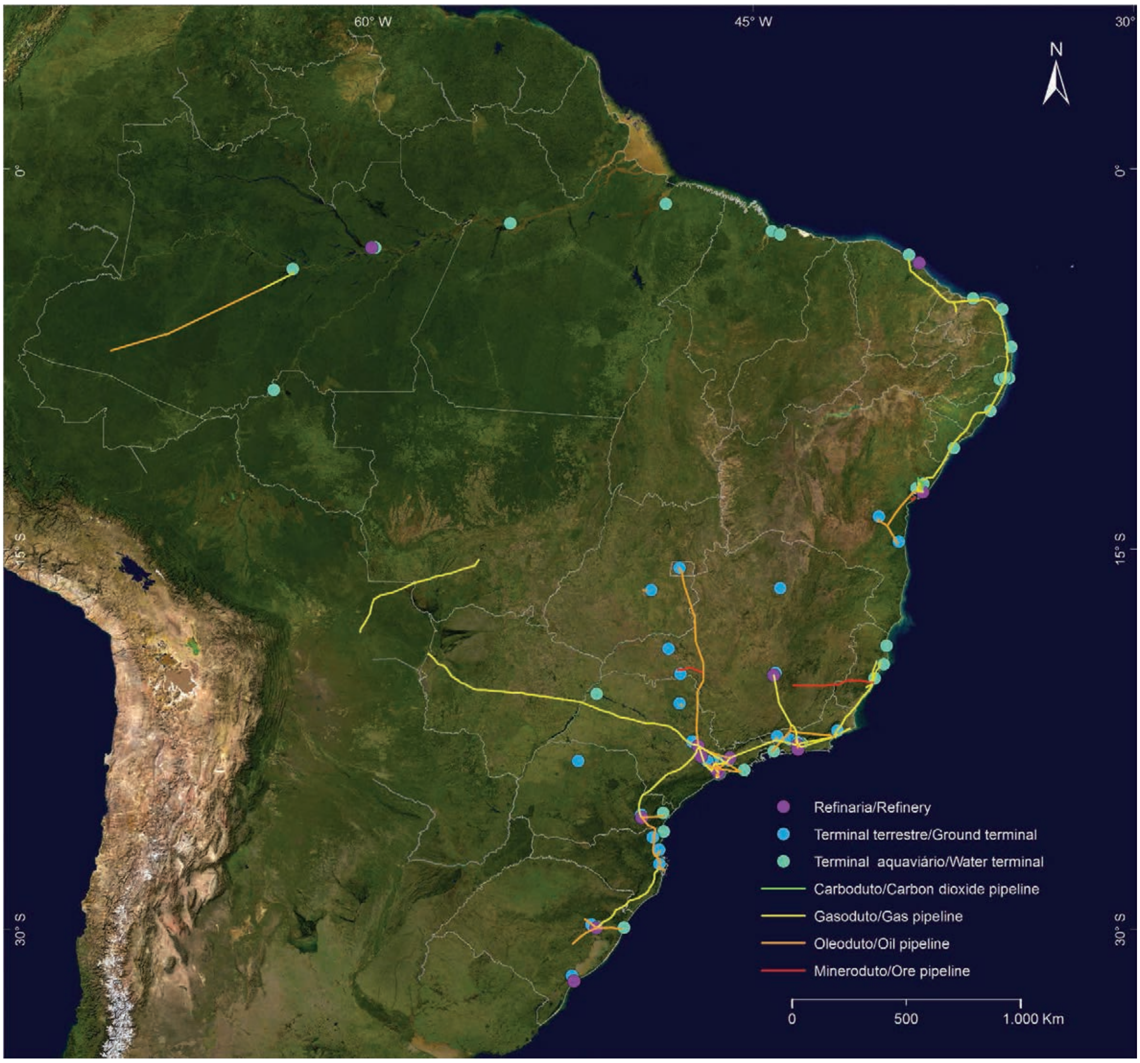

Figure 33: Pipeline network and terminals.

Source: PETROBRAS

Brazil currently has an infrastructure of nearly 15,400 kilometers (km) of pipelines, part of which could potentially be used for CO_2 transport. The same route could be used for CO_2 pipelines, thereby minimizing land-use and ownership issues. Currently, approximately 9600 km of pipelines are under construction or planned (Figure 34; Figure 35).

Terminals are stations located at the endpoint of pipeline sections. Terminal tanks store the product that has been transported. In Brazil, 103 terminals are authorized for operation in 2013, among aquatic, terrestrial and ethanol collecting points.

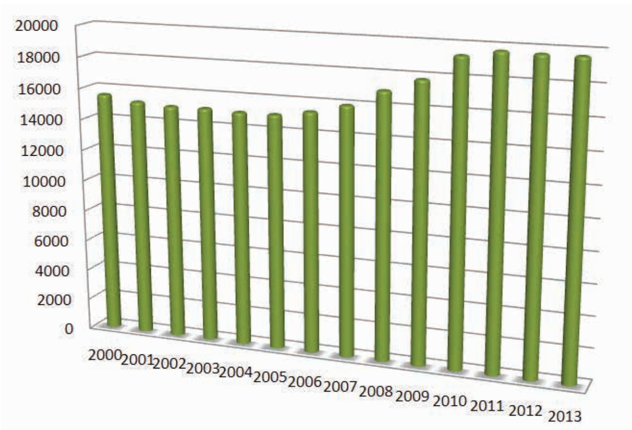

Figure 34: Total length of pipelines in operation from 2000 to 2013.
Source: ANP, Anuários Estatísticos.

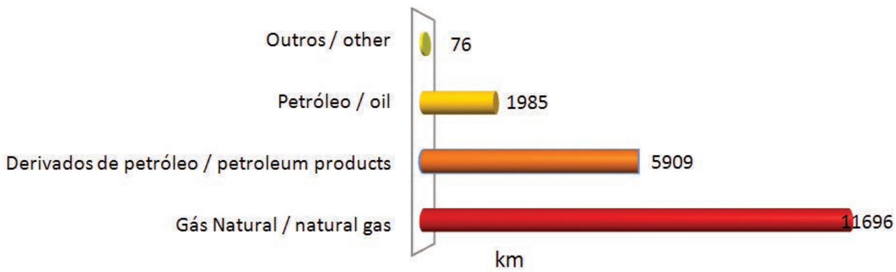

Figure 35: Length of pipeline per product type from 2000 to 2013.
Source: ANP, Anuários Estatísticos.

Pipeline routes studied, proposed or under construction in Brazil demonstrate the intended construction of a pipeline network crossing the inner territory of Brazil from north to south (Figure 36). Pipeline network planning is important to assist in the implementation of activities that might need them in the future (such as CO_2 transport).

Figure 36: Current and planned pipeline network.
Source: ANP, Anuários Estatísticos.

CO_2 PIPELINES IN BRAZIL

Brazil has one pipeline built for CO_2 transport in the Bahia state, northeast region of the country. Anthropogenic CO_2 is purchased from the Fertilizing Factory (FAFEN) and a petrochemical company (OXITENO) in Camaçari County (Bahia). This anthropogenic CO_2 is being transported through a pipeline for 70 km, where it is injected in the Buracica Field, to enhance oil recovery. One hundred tons of CO_2 per day is injected in this reservoir (Figure 37).

PETROBRAS has created the 'Recovery Program of Fields with High Exploitation Potential' (Recage) which focuses on increasing oil or gas recovery from mature fields, including recovery through the injection of carbon dioxide. Through a joint initiative between the Product & Exploration and Supply areas within PETROBRAS, a CO_2 pipeline will be laid out to carry the gas produced at the Landulfo Alves Refinery (RLAM), in Mataripe (Bahia) up to the Miranga field, where after an initial water injection (in order to increase the reservoir pressure and improve oil recovery), the gas will be injected in the Miranga field wells. This represents another dedicated CO_2 pipeline project in Brazil.

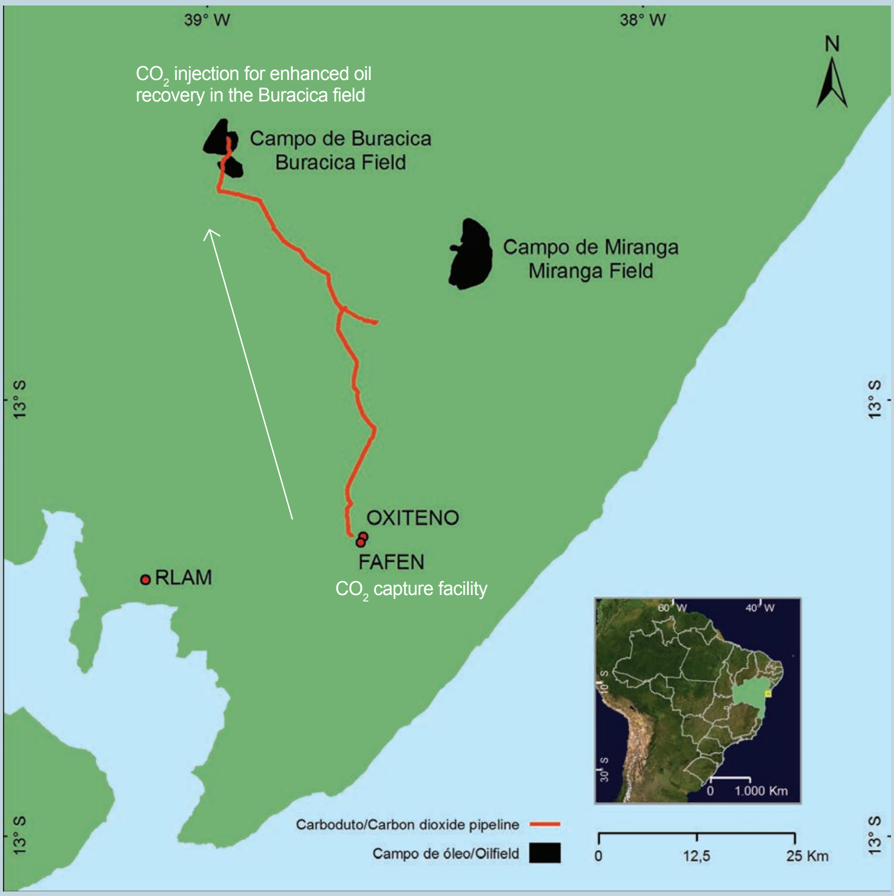

Figure 37: CO_2 pipelines in Brazil.

CO_2 Storage

Geology of Brazil

Brazil forms a major part of the South American Platform, a section of continental crust which in turn is the most stable part of the South American tectonic plate that extends into the Atlantic Ocean. Ancient igneous and metamorphic rocks formed during the Pre-Cambrian period (more than 590 million years ago) form a basement complex that underlies the entire platform, including Brazil.

Subsequent, complex movements of the earth's crust since Pre-Cambrian times have created a series of depressions or basins across various parts of Brazil. These basins allowed the accumulation of thick sequences of sedimentary rocks, which include significant oil, gas and coal deposits. In total, 31 sedimentary basins occur within Brazilian territory covering an area of approximately 6.4 million km^2, 75% of which is located onshore (Figure 38).

Figure 38: Sedimentary basins.

Oil and gas fields

From an economic viewpoint, the continental margin basins stand out as the main producers of hydrocarbons (Figure 40; Figure 41). Among these basins, the Campos Basin is notably the main oil producer, responsible for approximately 80% of the national oil production (Figure 42).

The Santos Basin will possibly be the main area of hydrocarbon production in Brazil from 2025 when exploitation of pre-salt reservoirs will increase substantially.

Figure 39: Hydrocarbon producing basins.

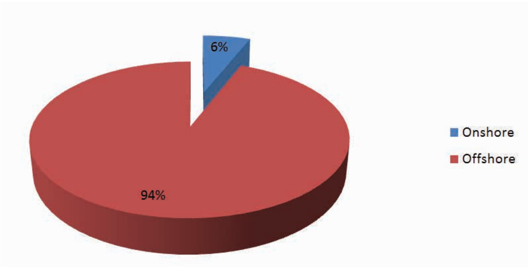

Figure 40: Proven oil reserves.

Source: ANP. Boletim Anual de Reservas: Reservas Nacionais de Petróleo e Gás Natural (dez/2013).

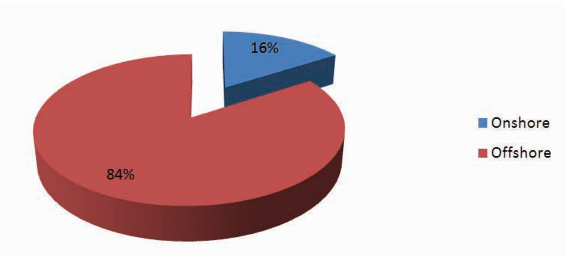

Figure 41: Proven natural gas reserves (m^3).

Source: ANP. Boletim Anual de Reservas: Reservas Nacionais de Petróleo e Gás Natural (dez/2013).

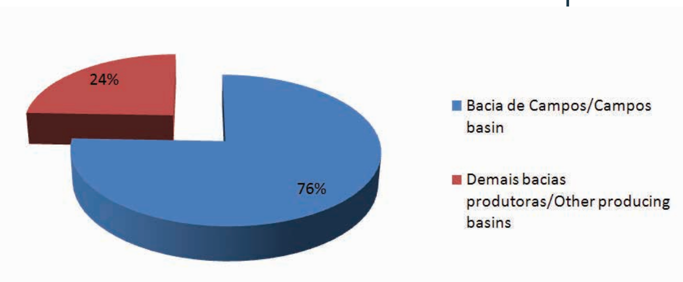

Figure 42: Oil production share in 2014.

Source: PETROBRAS

CASE STUDY: EOR IN BRAZIL

The Recôncavo Basin, located onshore in the Northeast region of Brazil, has 80 oilfields with active production. It has been exploited for more than 70 years and many of its oilfields are mature, i.e. in their final stages of exploitation. Among these, the Buracica field – located 120 km from Salvador, capital of the Bahia state – was used for CO_2 enhanced oil recovery, with ongoing injection since 1987. Injection of CO_2 (obtained from a nearby fertilizer plant) was alternated with water in seven wells to get a higher recovery from the reservoir.

Storage began in 1991, and by 2005 the reservoir had already stored 600,000 tonnes of CO_2. Monitoring of possible CO_2 leakages in the surface using geochemical techniques was also carried out. The project was highly successful, resulting in a partially sustained oil production from the field for approximately 20 years.

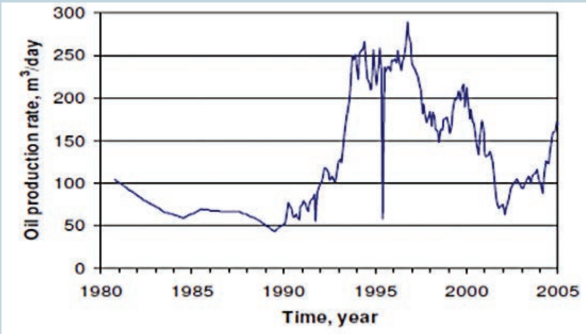

Figure 43: Oil production rate.

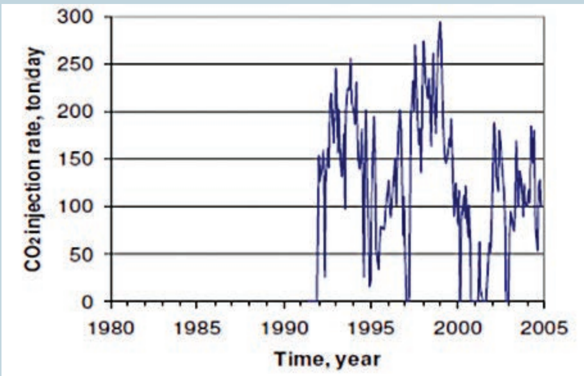

Figure 44: CO_2 injection rate.

More information at:

DINO, R.; GALLO, Y. LE. CCS project in Recôncavo Basin. Energy Procedia, v. 1, n. 1, p. 2005–2011, fev. 2009.

CASE STUDY: CO_2 STORAGE CAPACITY IN THE CAMPOS BASIN OILFIELDS

Theoretical capacity for CO_2 storage in oil and gas fields in the Campos Basin was estimated using the assumption that the volume previously occupied by produced hydrocarbons is (or will be) available to store CO_2.

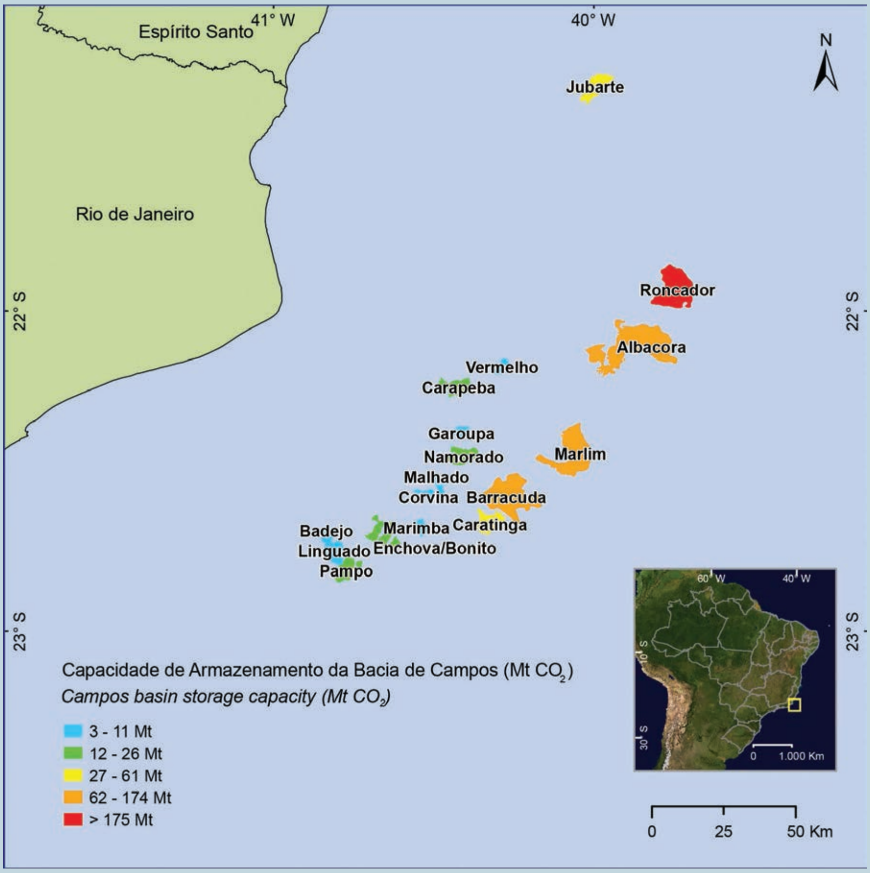

Figure 45: Campos basin storage capacity (Mt CO_2).

Since these fields are strategic for the country, most of the information is confidential and the availability of specific data is quite restricted. The reservoirs considered in this study correspond to the 17 oilfields in the Campos Basin for which specific data were available for the analysis. These oilfields amount to 59% of the total Campos Basin's reserves.

Some of the elements considered in estimating theoretical storage capacity included: identification of appropriate formations and representative or mean values for porosity, permeability, formation thickness, depth, oil density, original oil volume in place, and total remaining reserves. Results have shown that the Campos Basin has significant potential for CO_2 storage in the 17 oilfields analyzed, with a theoretical capacity estimated to be 950 MtCO_2, with ca. 75% of this capacity to be found in the Roncador (28%), Marlim (18%), Albacora (17%) and Barracuda (12%) fields. This estimated capacity would be sufficient to store the equivalent of 3.5 years of the total emissions from Brazilian stationary sources.

More information at:

ROCKETT, G. C. et al. CO2 Storage Capacity of Campos Basin's Oil Fields, Brazil. Energy Procedia, v. 00, p. 1–10, 2013.

The Pre-Salt

In November 2007, the discovery of giant hydrocarbon reservoirs was announced in ultra-deep waters in the offshore area of Brazil's southeastern coast (Santos Basin). The reserves are estimated to be up to 100 thousand million barrels, a landmark in the global oil industry.

These reservoirs are mainly composed of carbonate rocks with subordinate sandstones deposited in an interval called Pre-Salt, with an average thickness of 2 km. These reservoirs are located under a thick layer of salt (around 2 km of evaporitic rocks), deposited during the process of separation of Africa and South America plates in the Late Jurassic-Early Cretaceous (150 million years ago), resulting in the opening of the South Atlantic Ocean. In addition to the salt layer, the Pre-Salt reservoirs are overlain by 3 km of clastic reservoirs and 2 km of water column. Thus, these giant reservoirs are located in depths up to 7 km. With 149,000 km^2 of area, the Pre-Salt province spreads over 800 km, with ca. 200 km wide, along the eastern continental margin of Brazil (around 300 km from the coast), between the Santa Catarina and Espírito Santo States (Figure 46).

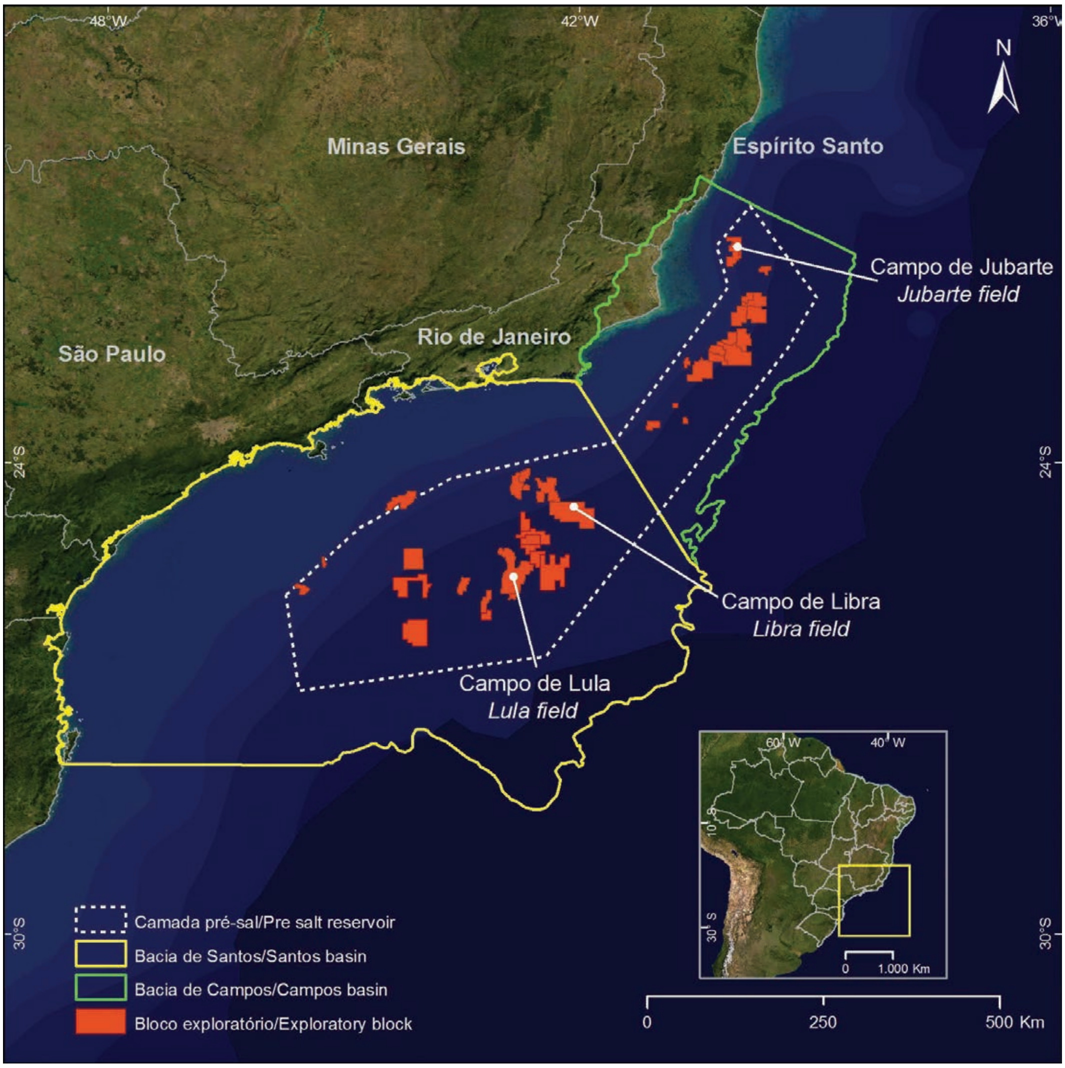

Figure 46: Area of occurrence of Pre-Salt petroleum reservoirs in the Campos and Santos basins.

The levels of exploration success are high in the pre-salt area and the oil found is considered light (29º API), not requiring complex refining processes. In 2014, production is approximately 480,000 barrels/day of oil and 16.2 million cubic meters/day of natural gas, coming from 34 producing wells in 9 fields in the Campos and Santos Basins. Projected oil production estimates are of 1 million barrels/day in 2017.

Several fields and oil wells have already been identified as having good exploitation potential in the Pre-Salt system. Among the most promising is the Lula field in Libra, with reserves estimated by PETROBRAS (2007) of between 5-8 billion barrels of oil. A few months later, the discovery of the Libra oilfield, also in the Campos Basin Pre-Salt interval, was announced. This field, possibly one of the largest in the world, has estimated reserves between 8 and 12 billion barrels of oil. For comparison, in 2007, the proven oil and gas reserves of PETROBRAS in Brazil were estimated to be 13.92 billion barrels-equivalent.

According to preliminary estimations, CO_2 emissions will be quadrupled when exploitation of these fields starts, as the Pre-Salt reservoir gases have from 3-4 times more CO_2 than those of the post-salt fields (CO_2 content in the producing field may reach up to 20%). This means that emissions of CO_2 will rise from 51 million tonnes to approximately 200 million tonnes/year. However, existing actions are in place to reduce emissions to up to 4.5 million tonnes by reinjecting the CO_2 into the reservoir, in either deep saline aquifers or caves in salt layer.

CASE STUDY: GAS HYDRATES

Gas hydrates are structures known as “clathrates” (from the Latin clathratus, which means “trapped behind bars”), in which molecules are completely trapped in cages formed by the host compound. In the case of gas hydrates, the host is water, and the guest gas is usually methane (CH_4) or other light hydrocarbons (ethane, propane, butane, CO_2 or H_2S). The clathrate capacity to entrap gases is determined by its geometry. In the case of methane, at standard temperature and pressure conditions, hydrates can hold up to 164 m^3 of gas in just 1 m^3 of water.

Gas hydrates are popularly known as “burning ice”, as they present a physical aspect similar to ice, yet are capable of burning when ignited due to the presence of hydrocarbons.

In Brazil, there is geophysical evidence indicating that these hydrates can be found in the Foz do Amazonas and the Pelotas basins . Furthermore, possible occurrences were inferred in the Campos, Espírito Santo and Cumuruxatiba Basins.

One method that has been investigated for the exploitation of gas from hydrates is the injection of CO_2, in gas, liquid or emulsion forms. This way, the recovery of methane would be combined with CO_2 storage. When CO_2 is injected in the hydrate reservoir, it will replace the existing gas in the structure of the hydrate, releasing it to the rock pores, and making it accessible for production. This exchange is possible since CO_2 hydrates are thermodynamically more stable than natural gas hydrates at the same pressure and temperature conditions in a reservoir. For each methane molecule withdrawn from the hydrate, up to 5 molecules of CO_2 can be entrapped, which makes it an efficient sink for carbon dioxide.

It should be noted however, that at this stage significant engineering and environmental challenges would need to be overcome for both large scale gas production and CO_2 storage in hydrates.

More information at:

Suess, E., Bohrman, G., Greinert, J., Lausch, E. 1999. **Flammable Ice**. Scientific American, 281 (5):76l-83

CASE STUDY: WELLBORE INTEGRITY FOR CARBON STORAGE

To inject and store CO_2 in geological reservoirs, it is necessary to construct a well structure connecting the target formation (i.e. the reservoir) with the surface.
While these wells are essential to inject and monitor the CO_2, they also represent a possible leakage pathway for the CO_2. Therefore, it is important to investigate the effects of CO_2 on the integrity of materials used in wells during injection and at completion of a geological storage project (Figure 47).

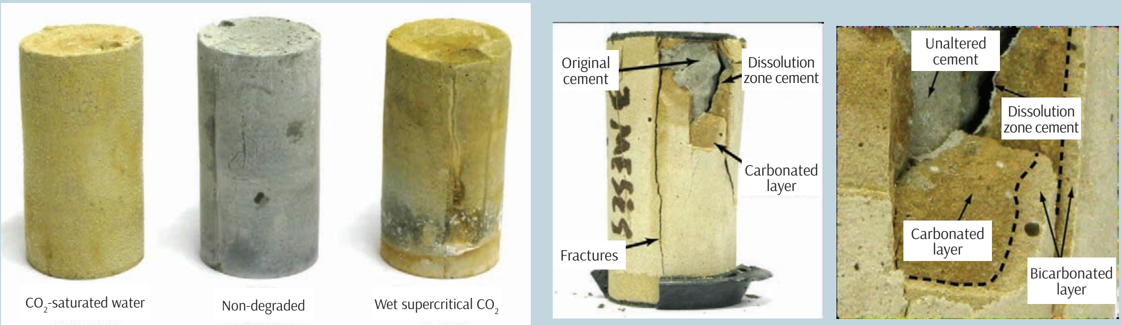

Figure 47: Studies of cement degradation from interaction with CO_2

According to the American Petroleum Institute (API), there are eight classes of cement (A to H) that can be employed in the wellbore completion. The most appropriate must be selected according to working depth, temperature and pressure. Cement classes G and H are the most employed in petroleum wells.
Resistance to degradation of materials by CO_2 is very important. The cement used in the well, positioned between the steel casing and the rock from the reservoir, must ensure the structural integrity of the well and formations during hydrocarbon exploitation, CO_2 injection and long-term storage. Cement is also used during the well abandonment operation, when the well is filled with cement paste. This procedure is known as well plugging.
Concerns related to the integrity of cement used in wells are due to the reaction of the cement paste - calcium hydroxide - with carbonic acid (which is formed by dissolution of CO_2 in the formation water). This reaction can alter cement composition, although recent research indicates that chemical reactions can serve to reduce cement permeability through precipitation of mineral phases, especially along flow pathways such as cracks or micro-annuli. Field experience from EOR projects also indicate that the quality of well engineering can be an important factor governing potential leakage in wellbores.

More information at:

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Krusciel de Moraes, M. Influência da temperatura no processo de degradação da pasta de cimento Classe G quando submetida às condições de armazenamento geológico de carbono. Mestrado em Engenharia e Tecnologia de Materiais. Porto Alegre, 2012.

Brazilian Coal Fields

Coal reserves in Brazil are estimated to be approximatelly 32 billion tonnes, of which approxminately 87% are found in the Rio Grande do Sul (RS) state, and 12% in the Santa Catarina (SC) state. Candiota (RS) is the largest coal deposit in the country, and accounts for approximately 38% of Brazilian coal reserves (Figure 48). These coal deposits, at appropriate depths and geological conditions, could potentially be used to store CO_2.

Source: CEPAC

Part of the coal deposits are found along the Jacuí River plains, which have been mined in open-pits and underground. These are the carboniferous basins of Capané, Iruí, Leão-Butiá, Charqueadas-Santa Rita and Faxinal.

Three still unmined deposits are found in the northeast region of Rio Grande do Sul at depths greater than 300 m: Morungava, Chico Lomã and Santa Terezinha. The Santa Terezinha limit to the eastern coast is still unknown as it extends down to the Pelotas Basin in the Atlantic Ocean.

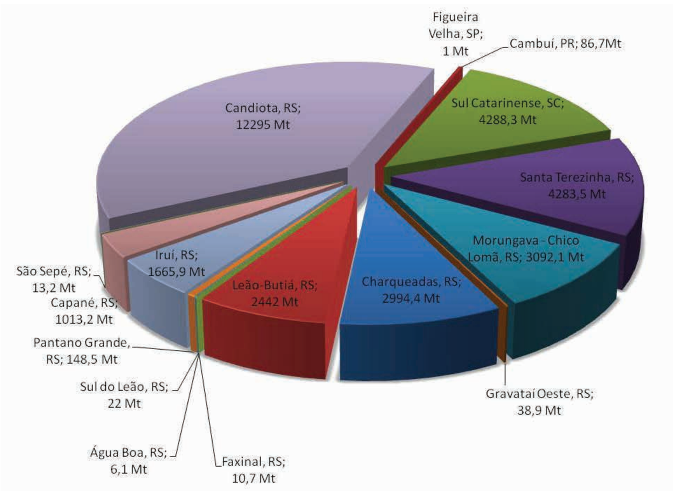

Figure 48: Coal reserves

The Sul-Catarinense deposit is the only coal deposit in the Santa Catarina state. Twelve coal beds are found in it, irregularly distributed along the basin. The most important and extensively mined is the Barro Branco, followed by Bonito.

In the Paraná state, coal is only found in isolated basins around the Ponta Grossa Arch. The most important coal deposit in Paraná is found in the northeast portion of the arch, in Curiúva, Figueira, Cambuí and Sapopema fields (Figure 49).

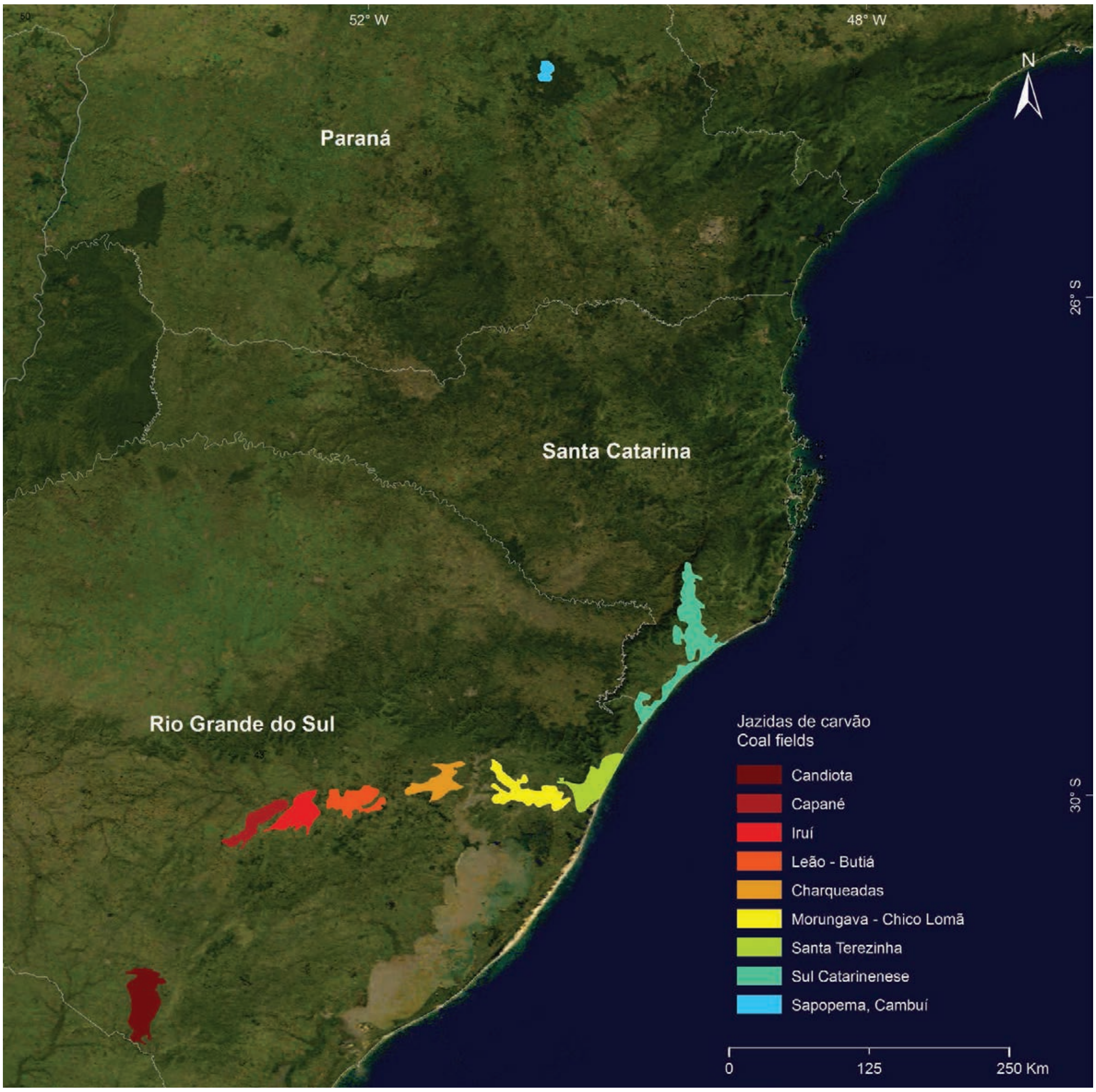

Figure 49: Coal deposits in Brazil.

Deep Saline Formations

As mentioned in the previous sections, deep saline formations offer the largest potential for CO_2 geological storage globally. As with storage of CO_2 in depleted oil and gas wells (associated with or without EOR), the CO_2 needs to be injected more than 800m underground to keep it in the supercritical (or dense phase) state.

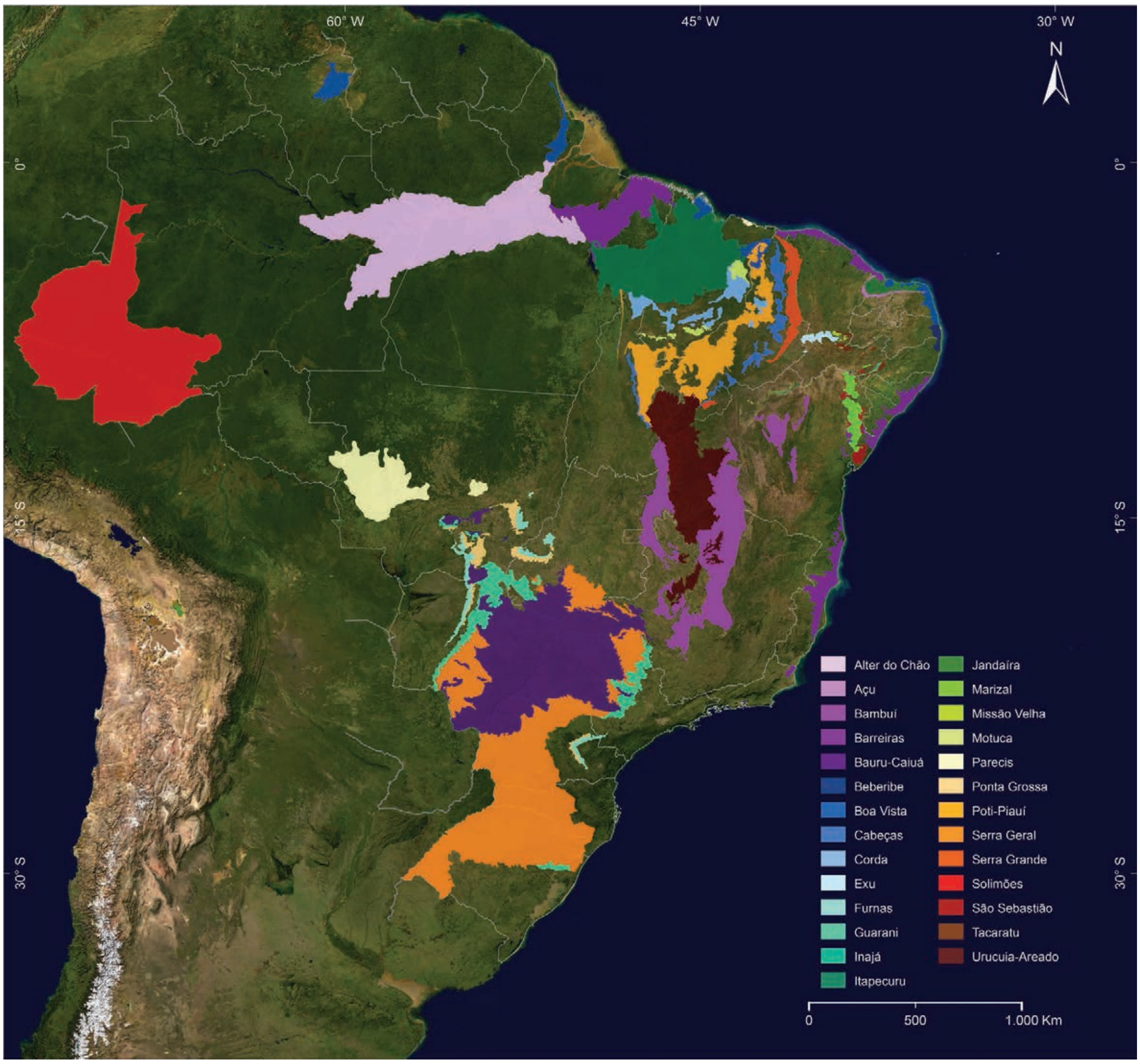

Figure 50: Hydrological basins and freshwater aquifers.

Currently, there is not much available data on saline formations in Brazil, as is usually the case elsewhere for these type of reservoirs. Most of the existing information is related to freshwater aquifers, which are unsuitable for storage (Figure 50). Deep saline formations can be found in most of the onshore basins, specially in the Parnaíba, São Francisco, Amazonas and Paraná Basins, and also offshore (Campos e Santos Basins). One of the most promising formations for geological storage in Brazil is the sandstones of the Rio Bonito Formation (Guatá Group, from the Paraná Basin), due to favorable characteristics such as porosity and permeability, and above all the proximity of CO_2 stationary sources in the south and southeast regions. Other formations in the Paraná Basin that have been studied and considered for CO_2 storage are the Furnas Formation (Paraná Group) and the Campo Mourão, Lagoa Azul and Taciba formations (Itararé Group). The upper sections of the Pirambóia and Botucatu formations (São Bento Group) hold the Guarani Aquifer, one of the largest freshwater aquifers in the world, which is not suitable for storage (Figure 51).

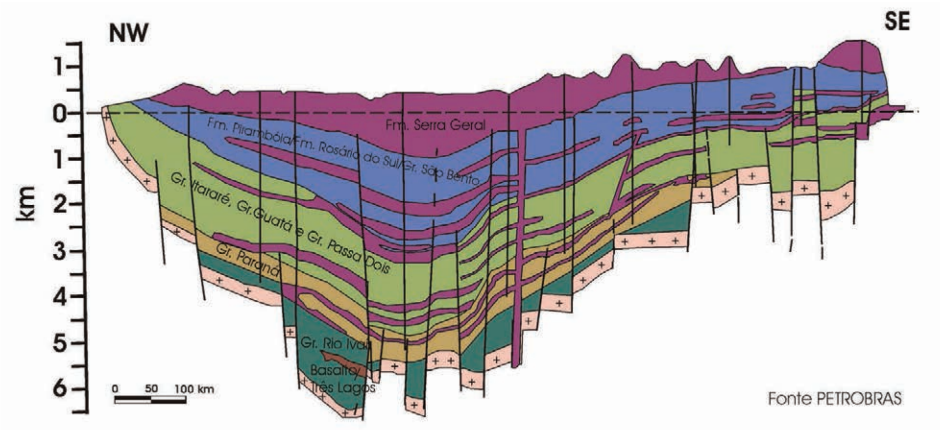

Figure 51: Paraná Basin geological section.
Source: PETROBRAS.

CO_2 STORAGE IN PARANÁ BASIN LAVA FLOWS

There may be potential for CO_2 storage in Brazil's giant lava flow deposits found in the Paraná Basin, (Serra Geral Formation, Cretaceous). These flood basalts cover extensive areas in the south-southeast region of Brazil, where most emitting sources of CO_2 are concentrated. The potential for CO_2 storage in these reservoir is approximately 270 Mt/year (Figure 52). However, CO_2 storage in volcanic rocks at an industrial scale is yet to be demonstrated.

More information at:

Carneiro, P.; Dullius, J.; Ligabue, R.; Machado, C. X.,; Ketzer, J. M.; Einloft, S. Carbonatação do basalto e seu potencial uso no armazenamento de CO_2. Tecnol. Metal. Mater. Miner., São Paulo, v. 10, n. 1, p. 43-49, jan.-mar. 2013

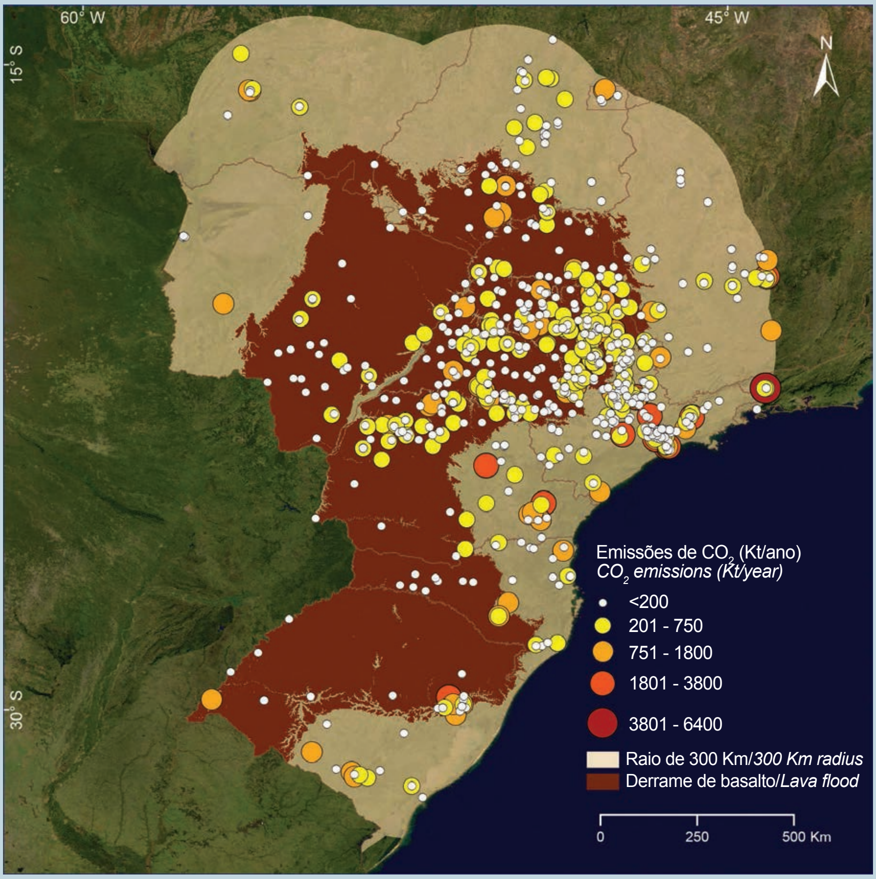

Figure 52: Paraná Basin lava flows and matching CO_2 sources.

Bio-energy with Carbon Capture and Storage

CCS associated with renewable energy sources (BECCS, short for bio-energy CCS), represents a promising alternative for greenhouse gas emission reductions. Unlike conventional CCS, where CO_2 emissions are captured from industry and power sectors, BECCS focuses specifically on capturing CO_2 from renewable carbon sources such as sugar and ethanol production plants. The advantage of applying the CCS component to these plants, as opposed to other emitting sources, is the fact that their emissions come from a renewable carbon source (biomass). This biomass removes CO_2 from the atmosphere during growth, and geological storage of CO_2 from renewable sources will result in negative emissions. Therefore, a BECCS project results in a direct removal of CO_2 and reduction of greenhouse gas concentrations in the atmosphere.

As the flue gases generated from these plants consist of nearly pure CO_2, capturing CO_2 from these plants is less costly compared to other processes with lower CO_2 concentrations (typical in most emitting sources). This high purity of CO_2 reduces the relative costs of BECCS endeavors compared to CCS projects associated with the power industry, for instance (Figure 53).

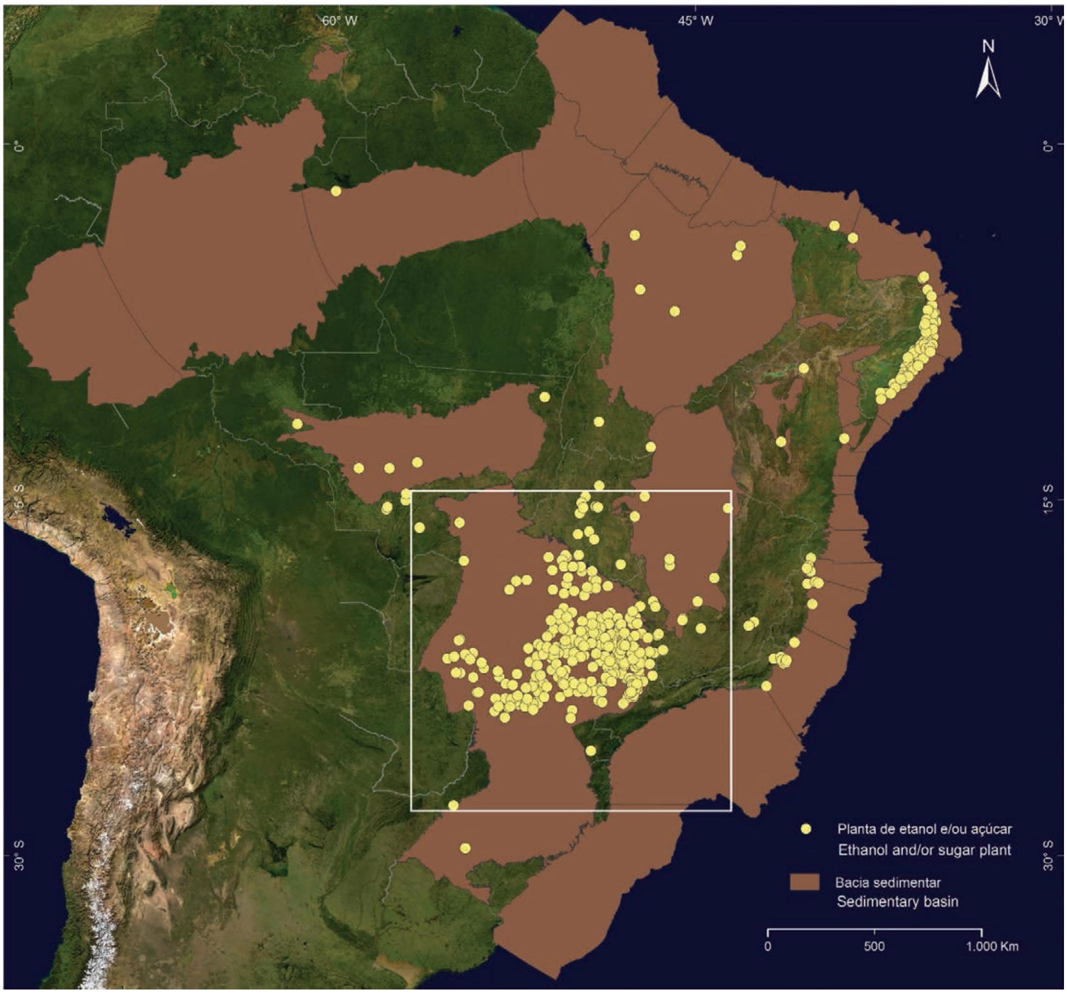

Figure 53: Occurrence of ethanol and/or sugar plants and sedimentary basins.

Brazil has 476 ethanol and sugar plants, whose emissions reach ca.89 Mt CO_2 per year. The majority of these plants (287 units) are concentrated within the Paraná Basin limits, and emit up to 54 Mt of CO_2/yr (Figure 54).

Among Brazilian States, São Paulo has the best potential for BECCS, with 46% of ethanol and sugar plants and highest emission amount (41 Mt of CO_2/yr) (Figure 53). Overall, bio-energy emissions represent 22% of the annual emissions in Brazil, which makes BECCS – and the potential negative emissions – a significant option for the country.

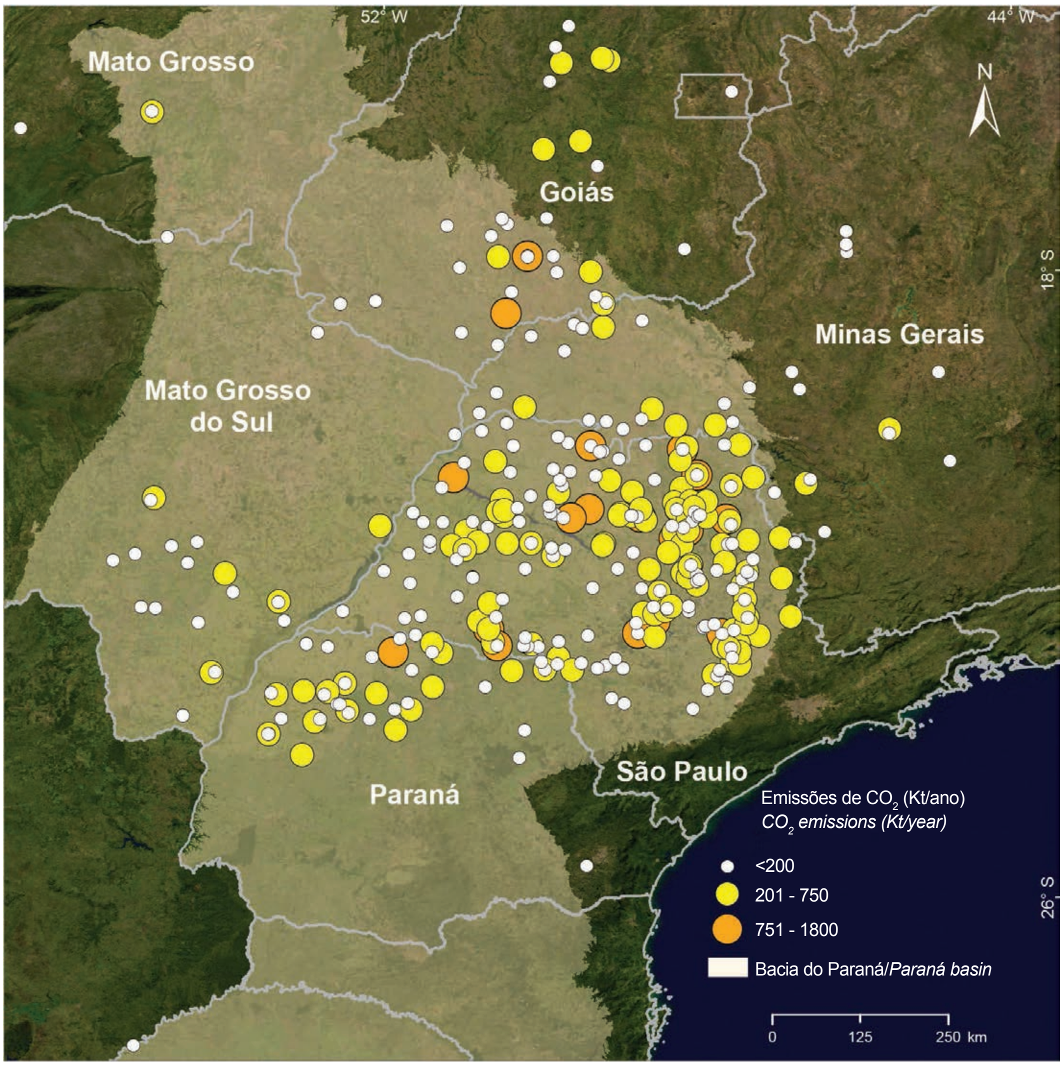

Figure 54: CO_2 emissions from ethanol and/or sugar plants in the Southeast region.

REGULATORY AND LEGAL ASPECTS OF CCS

Reducing costs, designing legal and regulatory frameworks as well as enhancing public acceptance have been some of the key issues in the deployment of large-scale carbon capture and storage (CCS) projects worldwide. According to the International Energy Agency, "legal and regulatory frameworks are critical to ensuring that geological storage of CO_2 is both safe and effective and that storage sites and the accompanying risks are appropriately managed after sites are closed". The long-term liability for potential leakage of stored carbon dioxide or any other potential damage has been considered as one of the most multifaceted subjects related to CCS regulation, especially if the project can be considered as a part of a project based emissions trading scheme (Figure 55).

COUNTRY	LSIPS	CCS LEGAL AND REGULATORY FRAMEWORK
United States	19	United States EPA's Class VI Regulations
China	12	Not available
Canada	7	Canadian Standard CSA-Z741/ Alberta's RFA
United Kingdom	5	United Kingdom Energy Act
Australia	3	Australia Offshore Petroleum and GHG Storage Act
Norway	2	European Union Directive 31/EC **
South Korea	2	Not available
Algeria	1	Not available
The Netherlands	1	European Union Directive 31/EC
Brazil	1	Not available
Saudi Arabia	1	Not available
United Arab Emirates	1	Not available

Figure 55: CCS legal and regulatory framework in countries with LSIPs. (55 active and planned large-scale integrated CCS projects - LSIPs)

Source: Romeiro, 2014 (Based on information from the Global CCS Institute, 2014).

In 2010, the United Nations Framework Convention on Climate (UNFCCC) recognized during the 16th Conference of the Parties (COP-16) that CCS represents a relevant technology strategy for climate change mitigation. The convention decided to include CCS technology as a project activity under the Clean Development Mechanism, a system defined in the Kyoto Protocol that provides for emissions reduction projects that generate carbon credits that can be negotiated in trading schemes. In 2011, the modalities and procedures for CCS as a Clean Development Mechanism (CDM) project were approved and liability was defined as "the legal responsibility arising from a CCS project to compensate for or remedy any significant damages, including damage to the environment, such as ecosystem damage, other material damages or personal injury". Nevertheless, determining the circumstances in which a host country would be able to act on behalf of a CCS-CDM project to implement corrective actions and measures still remains uncertain.

Although approximately two thirds of the large-scale integrated CCS projects (LSIPs) are currently placed in developed countries, the share of CCS deployment in developing countries is expected to increase by 2025, and these countries should focus their capacity building on identifying the challenges and solutions to address the main barriers to store CO_2. Specifically in the case of Brazil,

CO_2 is currently utilized at commercial scale by the oil and gas industry for enhanced oil recovery (EOR), and the country has already one large-scale and integrated CCS project in the Pre-Salt oil fields. As of 2014, no legal and regulatory framework for CCS is available in Brazil, and supportive policies and regulations are needed to support the development and deployment of CCS in Brazil. At the international level, Brazil has ratified a number of international environmental agreements that have some implications for CCS. The country is a member of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972), as well as the London Protocol (established in 1996 and amended in 2006 to allow CO_2 streams from CO_2 capture processes for sub-seabed CO_2 storage). Brazil has also ratified the United Nations Convention on the Law of the Sea (UNCLOS) in 1982, the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal (1989) and both UNFCCC (1992) and Kyoto Protocol (1997). As a Non Annex I party, the country has no binding targets until 2020.

At the national level, the National Plan on Climate Change (2008) refers to CCS as a relevant mitigation option for the energy sector and for industry. Conversely, the National Policy on Climate Change (2009) does not make any reference to CCS. Establishing a comprehensive policy to regulate CCS projects in Brazil can lead to a stronger market, but various aspects of the technology need to be clarified by a specific CCS regulatory framework, including the definition of access rights and long-liability issues related to use of the underground space. Article 20 of the Brazilian Federal Constitution of 1988 establishes that all mineral resources (including those on the subsurface) are owned by the federal government, which means that there is no private ownership of such resources before public concessions are granted for their exploitation. A specific CCS regulatory framework in Brazil is likely to include a range of existing regulations that will require joint coordination among the many ministries and stakeholders.

More information at:

Romeiro, Viviane. Carbon capture and storage legal and regulatory framework in developing countries: Proposals for Brazil. Ph.D. dissertation. University of Sao Paulo. Sao Paulo, 2014

Prospectivity for CO_2 Geological Storage in Brazil

Sedimentary basins have distinct characteristics which determine the potential for geological storage. Therefore, an evaluation of the degree of prospectivity of Brazilian sedimentary basins represents an important step in the selection of CO_2 storage sites. This evaluation assessed all sedimentary basins according to seven criteria, related to the stages of a CCS project. The following criteria were considered:

1. Occurrence of coal deposits;
2. Active production of hydrocarbons;
3. Existence of saline formations data;
4. Theoretical capacity for storing CO_2;
5. Existence of mature oil/gas fields;
6. Matching emitting sources;
7. Existence of transport infrastructure (pipelines and terminals)

Storage capacities were estimated at basin scale using a semi-quantitative approach following the methodology proposed by the Carbon Sequestration Leadership Forum.

A 300 km radius from the basin limits was considered for source-sink matching analyses, based on the IPCC estimated maximum economically viable distance from the emitting source.

Based on the above criteria, a prospectivity map was generated through a basin-by-basin analysis, ranking the basins by into three main groups: low, medium or high prospectivity for storage (Figure 56).

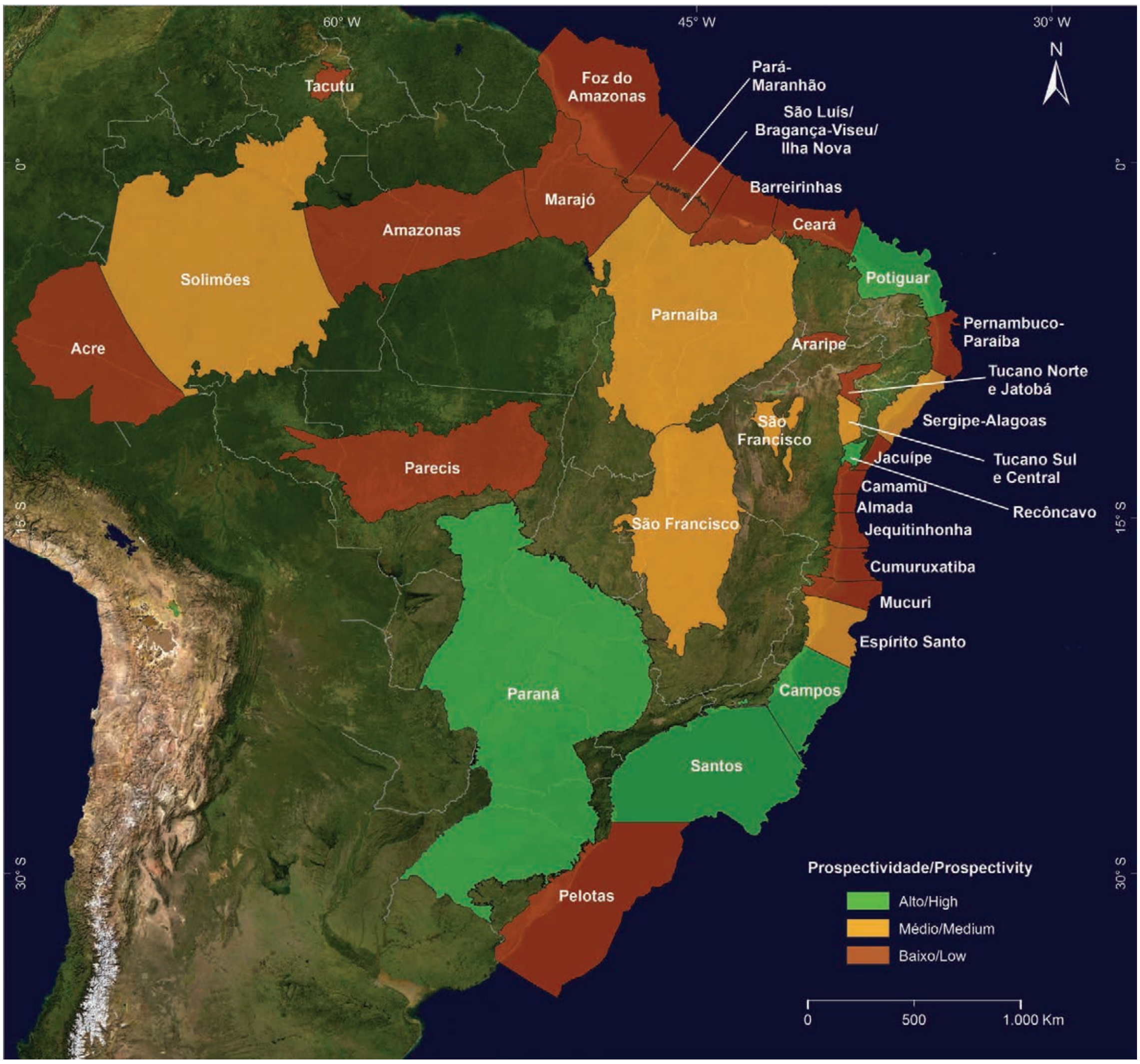

Figure 56: Prospectivity mapping for CCS

Low prospectivity

Due to absence of hydrocarbon production and the low mass of CO_2 emissions within its limits, most of the North and Northeast basins, as well as the Pelotas basin in the South region, have been ranked as having 'low prospectivity' for carbon storage (Figure 57).

Figure 57: Low prospectivity basins

Regarding storage capacity within this group, the Amazonas Basin stands out among the others, followed by Foz do Amazonas Basin, due their higher porosity volumes. Ceará is the only low prospectivity basin with hydrocarbon production. Mucuri, Pelotas and Tucano Norte and Jatobá basins are the only ones with a significant number of matching sources.

Medium prospectivity

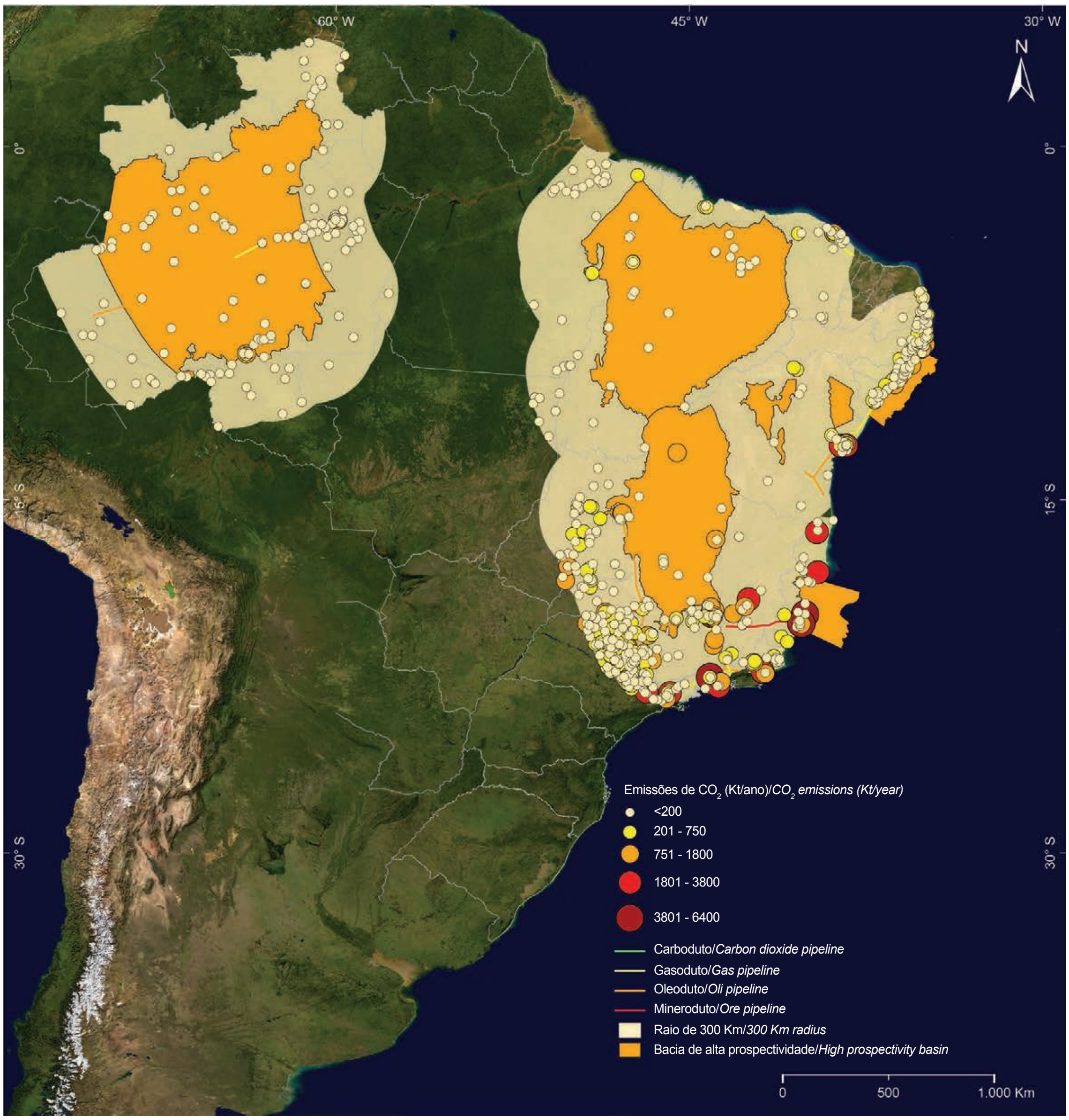

Figure 58: Medium prospectivity basins.

The Sergipe-Alagoas, Parnaíba, Espírito Santo, São Francisco, Solimões and Tucano Sul and Central basins have been ranked 'medium' in terms of prospectivity for CO_2 storage projects, as the evaluated criteria are only partially met, or stand out with respect to just one or two criteria. In this case, the basins have a high storage capacity; active production of hydrocarbons and/or presence of mature oil fields; and significant proximity to large emitting sources within the basin limits.

Within this group, the Sergipe-Alagoas basin was ranked as having the highest potential, despite not having the largest storage capacity. This rank is mostly due to hydrocarbons production and existing mature fields in this basin, and also to an existing pipeline structure and a reasonable matched point-sources of emissions (of 38 $MtCO_2$/y) in the vicinity

High Prospectivity

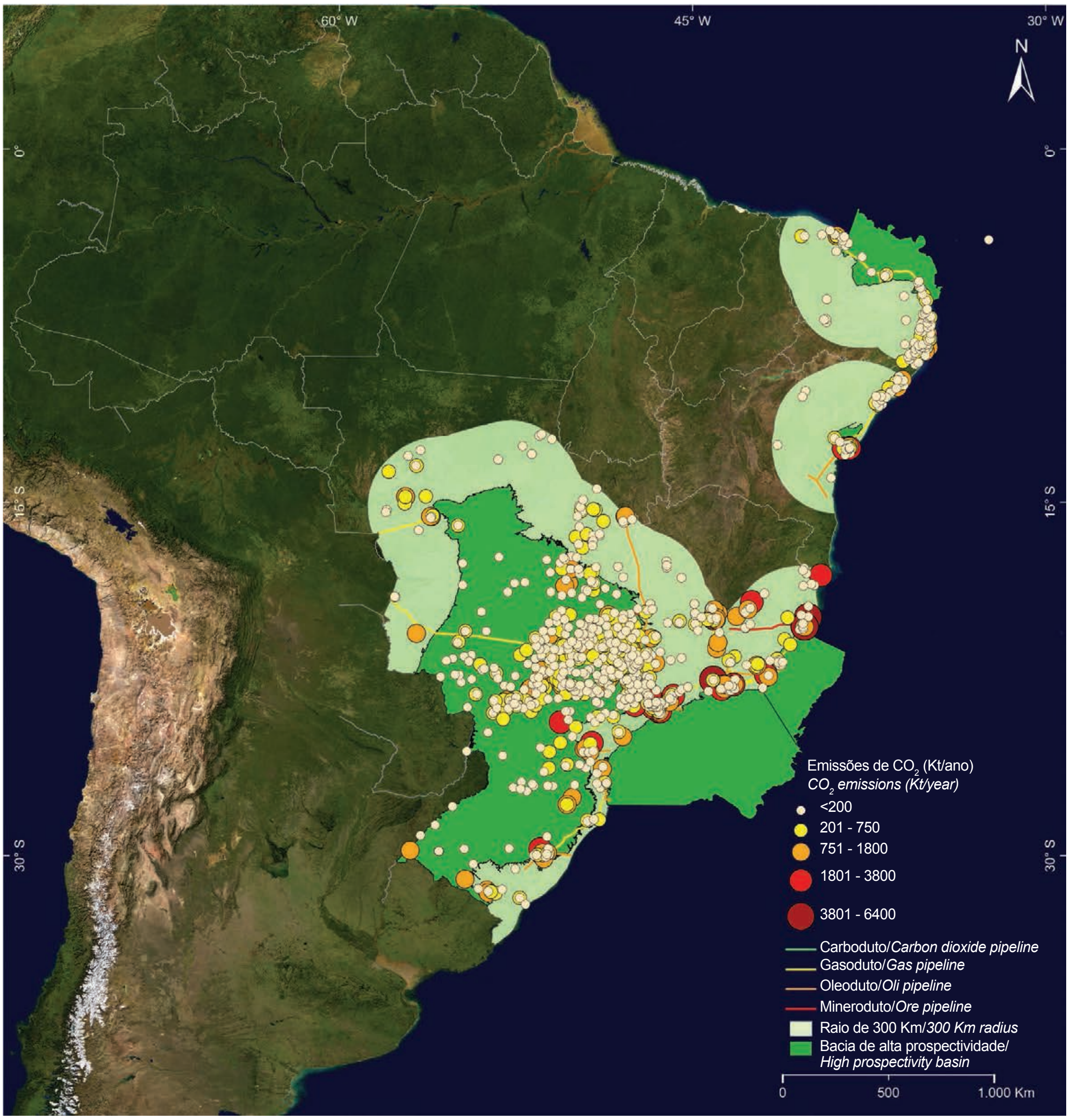

Figure 59: High prospectivity basins.

The Paraná, Campos, Santos, Potiguar and Recôncavo sedimentary basins are ranked as those with highest prospectivity for CO_2 storage in Brazil, mostly due to the outstanding production of hydrocarbons and presence of mature fields, and in the case of the Paraná Basin, to the occurrence of coal deposits. The Campos Basin is the largest oil-producing basin in the country, with production of approximately 1.8 billion barrels/day (as of July 2014) (Figure 59).

Additionally, these basins present a good source-sink matching and pipeline network for CO_2 transportation, which increases their suitability. The emissions from sources within these basins (up to the 300 km zone) amount to approximately 368 Mt/year. If only the 1115 industrial plants associated to the Paraná Basin are considered, CO_2 emissions in this region amount to 268 Mt/year, with the energy sector being responsible for 49% of this value, followed by the biomass sector (44%).

In terms of transport infrastructure, the basins in this group are served by approximately 14,300 km of pipelines, transporting oil, gas, minerals and CO_2.

Preliminary assessments indicate that the Campos Basin has the largest theoretical capacity for storage of CO_2 in petroleum fields. The other basins in the group present a large capacity associated with hydrocarbons production such as Santos Basin (including the Pre-Salt reservoirs). In the Paraná Basin, despite having occurrences of coal deposits, the high basin capacity is due to the occurrence of deep saline formations.

Final Remarks

The Brazilian Atlas of CO_2 Capture and Geological Storage represents the consolidation of nearly a decade of research and data gathering and compilation, carried out by a large number of professionals working in the CCS field in the country since 2007. This effort was led by the Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC), with help and support from PETROBRAS and the Global CCS Institute. Members of CEPAC who participated in this task included geologists, geographers, chemists, engineers, among others, reflecting the interdisciplinar essence of this endeavor.

This first edition of the Atlas has identified significant potential for CCS projects in Brazil, through a basin scale analysis of existing data. This resulted in a preliminary assessment of the most suitable areas for geological storage of CO_2 in the country.

Considering the innovative character of this technology and its recent period of development, this edition identifies some of the still existing information gaps inherent to such large-scale data mining and integration processes. Some important information is yet unaccounted in this first survey, such as CO_2 emissions from offshore sources. Future editions of this atlas will certainly minimize these limitations.

It is expected that this publication and the information shared here will broaden the knowledge of this technology, hopefully bringing attention to CCS stakeholders and increasing public awareness of CCS.

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