LARGE SCALE CARBON CAPTURE AND STORAGE IN BRAZIL: A PRELIMINARY COST MODELLING FOR CAMPOS BASIN'S OIL FIELDS

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ABSTRACT - This study provides a preliminary cost assessment for large scale deployment of carbon capture and storage (CCS) in Brazil. A study case for CO_2 geological storage in the Campos Basin, one of the sedimentary basins with very large oil reserves in Brazil, was performed. The results showed that about 76% of this basin's CO_2 storage capacity (considering the 17 studied oil fields) can be used at storage costs lower than 4 €/t CO_2. The findings of the research indicate that about 10 $MtCO_2$ can be captured from neighbouring sources at costs lower than 28 €/tonne CO_2. An assessment of CCS chains under four different scenarios showed average costs for complete CCS chains in the range of 47 €/t by 2025 in a scenario with 10 $MtCO_2$ stored/yr to 82 €/t in a scenario with 35 $MtCO_2$ stored/yr. In the latter scenario, the estimated storage capacity of Campos basin's oil fields is filled in about 27 years. In all scenarios, CO_2 capture contributed the most to the total costs. The source-sink matching performed in this study is very important to support CCS planning in Brazil.
Keywords: CO_2 Capture Transport and Storage (CCS), Geographic Information System (GIS), Cost Modelling, Source-Sink Matching, Campos Basin

RESUMO - Este estudo apresenta uma avaliação preliminar dos custos para implantação em grande escala da tecnologia de captura e armazenamento geológico de CO_2 (CCS, do inglês *Carbon Capture and Storage*) no Brasil. Foi realizado um estudo de caso para armazenamento geológico de CO_2 na Bacia de Campos, uma das bacias sedimentares com maiores reservas de petróleo no Brasil. Os resultados mostraram que cerca de 76% da capacidade dessa bacia para armazenamento de CO_2 (considerando os 15 campos de petróleo estudados) pode ser usada com custo de armazenamento inferior a 4 €/tCO_2. Os resultados da pesquisa indicam que cerca de 10 $MtCO_2$ podem ser capturados a partir de fontes emissoras próximas da bacia a custo

inferior à 28 €/tCO_2. Uma avaliação de cadeias de CCS em quatro cenários diferentes mostrou os custos médios para as cadeias completa CCS na faixa de 47 € / t em 2025 em um cenário de armazenamento de 10 MtCO_2/ano a 82 € / t em um cenário de 35 MtCO_2 armazenados por ano. No último cenário, a capacidade de armazenamento estimada em campos de petróleo da Bacia de Campos é preenchido em cerca de 27 anos. Em todos os cenários, a etapa de captura de CO_2 configurou a maior parcela dos custos totais para a implementação da atividade. O estudo de associação entre fontes e reservatórios geológicos realizado é muito importante para apoiar o planejamento CCS no Brasil.
Palavras-chave: Captura e Armazenamento Geológico de CO_2 (CCS), Sistema de Informações Geográficas (SIG), Modelagem de Custos, Associação Fontes-Reservatórios, Bacia de Campos

INTRODUCTION

Carbon Dioxide Capture and Storage (CCS) is one of the most promising technologies to mitigate climate change (IPCC, 2007). CO_2 geological sequestration activity involves three distinct components: CO_2 capture (which consists of CO_2 capture from a CO_2 emitting source, compression, and dehydration), CO_2 transportation to the storage site, and its injection in a geological reservoir (Illustration 1). For the purpose of CO_2 storage, suitable geological reservoirs are expected to be at depth over 800 meters, in which the pressure could keep CO_2 in a supercritical state (IPCC, 2005).

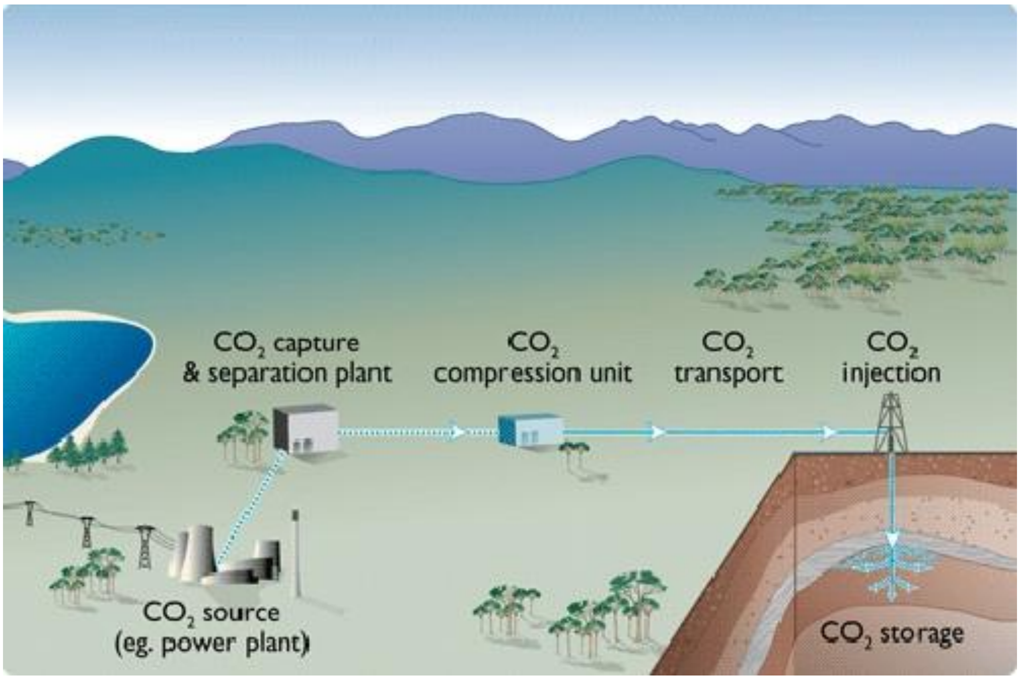


Illustration 1. Carbon Capture and Storage Scheme (CleanTechnica, 2011 - http://cleantechnica.com/)

According to the International Energy Agency (IEA), CCS can contribute up to 20% of global CO_2 emission reduction by 2030 and 40% by the end of this century. At world level, emissions from fossil fuel combustion are responsible for about 70% of the CO_2 in the atmosphere emissions from anthropogenic sources, while 30% of the CO_2 comes from deforestation and land-use change. In Brazil 77% of the CO_2 emissions come from deforestation/land-use change, 18% are from fossil fuel combustion (from stationary and mobile sources) and the remaining emissions (5%) are from industrial processes and others (Ministry of Science and Technology – MCT, 2010). Even with Brazil's clean energy portfolio – 46% of the produced energy comes from renewable energy sources (EPE, 2008) - consumption of fossil fuels is expected to increase in the coming years, due to the recent discovery of major oil fields (the pre-salt layers reserves with an estimated volume of 8 billion barrels of oil equivalent - PETROBRAS, 2011). This discovery also implies that fossil fuels usage with CCS may need to play an important role to CO_2 emission reduction in Brazil's future (IEA, 2008). Brazil already recognizes CCS as an important alternative to reduce CO_2 emissions, especially in the oil and gas sector and industry (National Plan on Climate Change - Brazil, 2008). Brazil is voluntary aiming to reduce CO_2 emissions from 36% to 39% of the emissions projected for 2020 according to a recently enacted law, which established the National Policy on Climate Change (Brasil, 2009). CCS represents an opportunity to mitigate CO_2 emissions, to move towards a more sustainable energy future, and to address local development needs (Cunha et al., 2007).

In Brazil, some studies on storage potential and source-sink matching - The CARBMAP Project - were conducted (Ketzer et al, 2007a; Ketzer et al, 2007b; Machado et al, 2009; 2013; Rockett et al, 2011a; 2011b; 2013) as well as economic feasibility studies for specific CO_2 storage sites (Hoppe, 2009; Ravagnani & Suslick, 2007). However, until now there are no integrated studies that assess large-scale implementation of CCS in Brazil. This study aims to identify cost-effective combinations of CO_2 emission sources and geological storage sites (sinks) by minimizing total chain costs for CO_2 capture, transport, and storage for the year 2025 in Campos Basin.

Study area: Campos basin

The Campos Basin is an offshore basin located in southeastern Brazil (Illustration 2), and contains 80% of the Brazilian petroleum reserves. The production from this basin nowadays is more than 1.5 million barrels of oil/day, being 84% of national oil production (PETROBRAS, 2010). The largest oil accumulation is in Marlim field (Milani e Araújo, 2003; Cândido, 1990). As all the Brazilian continental margin's basins, Campos is a passive margin basin. All of the basins located in Brazilian continental margin had been developed during the Gondwana paleocontinent rupture and subsequent opening of the Altantic ocean, in the Cretaceous age – around 140 million years ago (Guardado et al., 1989).

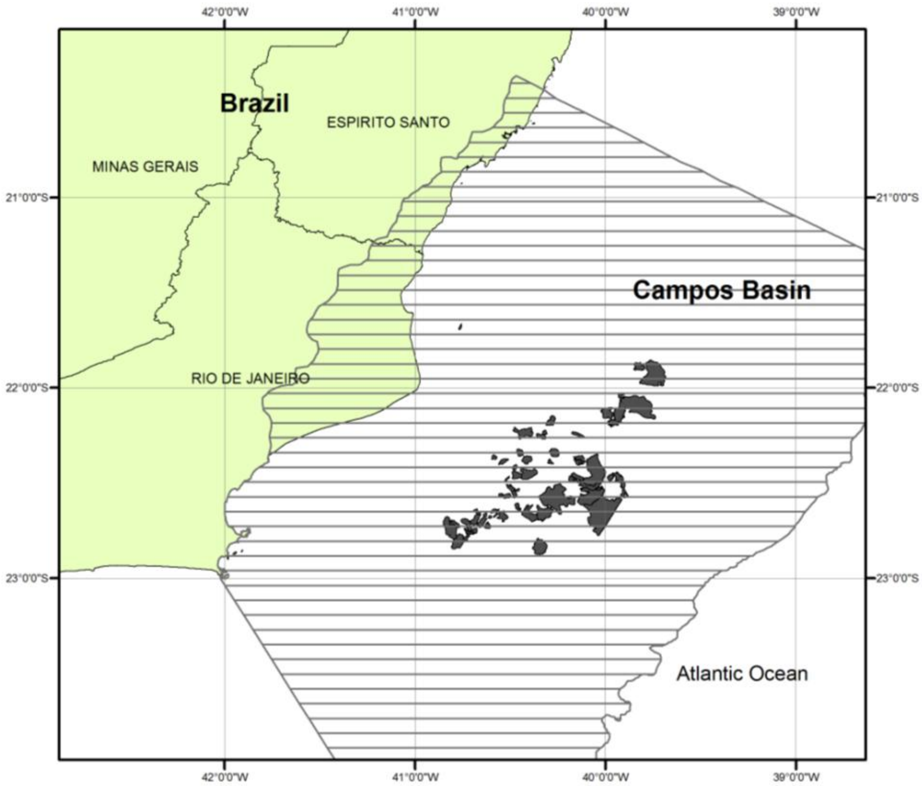


Illustration 2. Location of the Campos Basin, southeast of Brazil.

According to PETROBRAS (2010), there are 36 petroleum fields in Campos Basin which have already reached peak production and will be mature fields soon. Depleted oil fields are economically interesting sites for CO_2 storage, because the Enhanced Oil Recovery technique (in which CO_2 is injected to recover the field's residual oil) can increase the field exploration and economic benefits can be obtained. Because of this, and its estimated CO_2 emission storage capacity and its proximity to stationary large scale CO_2 emission sources, that Campos Basin is considered one of the most promising Brazilian basins for CO_2 storage development (Ketzer et al., 2007a, b).

METHODOLOGY

Data collection and assumptions

CO_2 Stationary Sources Data

In this study, data on CO_2 emission stationary sources is taken primarily from the International Energy Agency Greenhouse Gas R&D Programme's (IEA GHG) CO_2 Emissions database (IEA GHG, 2006). The database lists 361 stationary sources in Brazil which emit a total amount of about 214 Mt of CO_2 per year. Illustration 3 shows the total CO_2 stationary emissions per sector in Brazil. Biomass production plants are responsible for 33% of Brazilian stationary sources annual emissions, followed by the power sector with 25%.

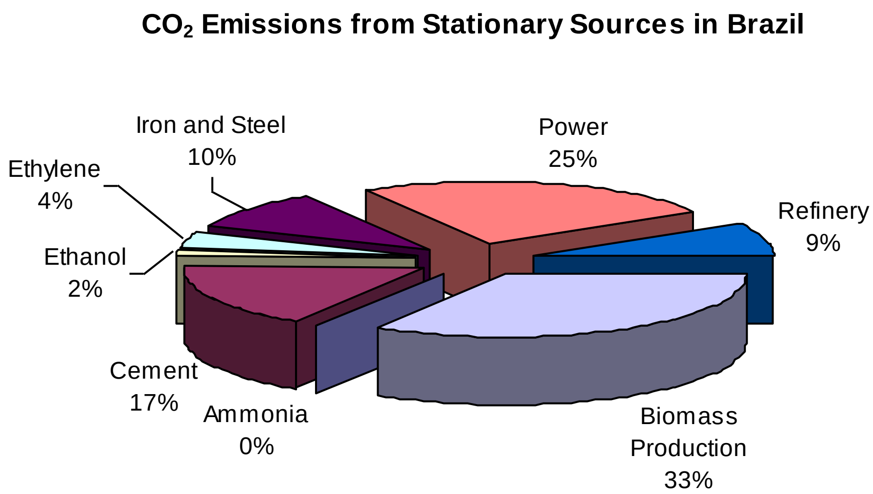


Illustration 3. CO_2 Emissions from stationary sources in Brazil (from IEA GHG, 2006)

Each point source from the IEA GHG database, including geographic coordinates, was validated by searching all the points by name of the plant, city and state with a Brazilian coordinate database and using visual inspection with Google Earth, similar to the Dahowski et al's (2009) methodology. All the data were then imported to a Geographic Information System (GIS).

CO_2 Transport Data

According to Hendriks et al. (2007) and Broek et al. (2010a), knowledge on the location of existing pipeline corridors is important considering legal and engineering advantages as well as land use legal issues advantages on choosing existing pipeline routes for CO_2 pipelines deployment. Data on existing pipelines was taken from four sources, the National Petroleum Agency (ANP, 2009a), the PETROBRAS (2003), the Ministry of Transports (2007), and the National Agency of Electrical Energy (ANEEL, 2005).

CO_2 Storage data

The geological reservoirs selected for this study are petroleum fields in the Campos Basin, because of the well-known structure and proven traps. As these petroleum fields are of strategic importance for the country, availability of specific data in publications is very limited. For this reason, only those fields for which specific data could be obtained were included in this analysis. The total number of fields is 15, representing ca. 60% of the Campos Basin's oil reserves. The oil fields considered are: Carapeba, Linguado, Marimbá, Marlim, Vermelho, Barracuda, Roncador, Caratinga, Jubarte, Namorado, Pampo, Enchova/Bonito, Garoupa, Albacora and Corvina, all of them are in production phase (ANP, 2009a). The reservoirs in these fields are mainly Cretaceous and Tertiary sandstones, and some Cretaceous limestones.

It should be noted that the analysis in this study is at the field level. In this context, average data were assumed for the field. Key parameters and collected data are:

Location: all geographical positions were obtained from the Brazilian Geological Survey georeferenced file (CPRM, 2003). The location of the Jubarte oil field was obtained from published articles.

Depth and thickness: The depths and thickness of fields were obtained from an extensive survey in scientific articles. When depth data was not available at the field level, it was estimated (for each field) by one of the following four indicators: (i) average depth of specific reservoirs in an oil field; (ii) average depth in a basin's depth range; (iii) average field depth extracted from geological sections (iv) oil-water contact depth. It is important to note that all the 15 reservoirs are deeper than 800 meters, which is required for CO_2 geological storage (IPCC, 2005).

Porosity and permeability: Data were obtained for 5 of the 17 oil fields. When data were not available at field level, it was estimated by one of the following approaches: (i) the average porosity/permeability from specific reservoirs in the oil field was used; (ii) the porosity/permeability data of a specific reservoir for which the data were available, was used; (iii) the porosity/permeability data of other oil fields in the same geological formation/ stratigraphic unit (with the same rock type and age) was taken.

Injection rate: Injection rate is defined as the average amount of CO_2 that can be injected in the reservoir per well per year. Since it is a site specific parameter, some assumptions were made to obtain data at the field level. Taking into account the data from existing CCS projects (field data and prospective analysis), the injection rate was defined for each Campos Basin's oil fields, based on the permeability of each site. For average permeabilities > 1,000mD, the injectivity was set to be 1Mt/year per well; for permeability ~400-500mD, the injectivity was set to be 0,5Mt/year per well; finally, for average permeability < 100mD, the injectivity was set to be 0,33Mt/year per well.

Drilled wells: inventory of wells were taken from the Exploration and Production database (ANP, 2009b), which was imported to the GIS. By means of the *Clipping tool*, it was possible to verify the location of the wells in each petroleum field. All drilled wells of the inventory were included with exception of those defined as 'abandoned'. The total number of wells is over 1,000 in the 15 oil fields.

CO_2 Storage Capacity: Theoretical CO_2 storage capacities for 17 Campos Basin's oil fields were estimated by Rockett (2010; 2013), based on the methodology proposed by Bachu et al. (2007). The storage capacities' from Rockett (2010; 2013) were used in this study.

Modelling approach

An schematic diagram of the core methodology applied in this research is shown in Illustration 4. The modelling is for the year 2025.

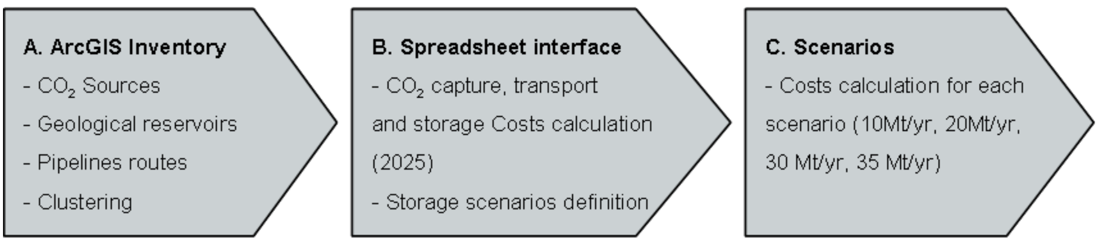


Illustration 4. Schematic representation of the methodological approach

The GIS inventory (step A) consists of georeferenced data regarding potential capture sites, storage sites and possible pipelines routes. A clustering methodology was used in this study, which enable the optimization of costs estimation for CO_2 transport in step B, which also includes storage costs estimation for the Campos Basin reservoirs, as well as capture costs for the specific sources. Based on the estimated costs, reduction emissions scenarios were also assessed in this study (step C).

CO_2 Sources and Capture

This study only took into account CO_2 stationary sources that emit more than 100 kt CO_2 per year (e.g. Broek et al., 2009; IEA GHG, 2005b; Dahowski et al., 2009). Distance was the criterion used to select those sources which could make use of the basin. The limit distance from the sinks' mean center was set to be 800 km –taking into account that Enhanced Oil Recovery (EOR) can be applied in the petroleum fields together with CCS activity, and that the largest pipeline used currently for CCS-EOR is 808 km length (CO_2 pipeline from Cortez to Denver in the United States - Svensson et al., 2004). Plants defined as "Biomass production" originally in the IEA GHG Emissions database (2006) were excluded from the analysis due to the heterogeneity of the industry activities in this section, further the heterogeneity of burned fuel (in case of biomass fired power plants). Status information of the selected power plants were checked, and only plants operating in 2010 were taken into account.

Following the work done by the IEA GHG (2005b), which used the 2000 base emission inventory for CO_2 transport and storage cost curves development, in this article we assume that emissions from industrial plants will stay at the levels of 2006, which is the inventory's base year. To calculate the power plants' CO2 emissions in 2025, the following assumptions were made:

1) All gas and oil fired power plants will have been replaced by natural gas combined cycle plants (NGCC) by 2025. This is based on reports indicating that the Brazilian government plans to replace diesel and oil fuelled power plants by gas fuelled ones in a near future (Villela and Silveira, 2007).

2) CO_2 emissions were re-calculated, based on emission factors, capacities and load hours. An emission factor of 400 gr CO_2/kWh was taken for natural gas (IEA GHG, 2006).

3) It was assumed that power production from thermal power plants will be remain at current levels and that power generation from renewables will grow (Ministry of Mines and Energy/EPE, 2011).

CO_2 capture costs were derived from Broek et al. (2010a) - assuming a discount rate of 7% for new power plants, capacity factor of 85% and NGCC lifetime of 40 years. Capture costs for industrial processes are derived from Damen (2009), assuming that in the year 2025 all heat is generated from biomass firing, 10% discount rate and a price of 13 €/GJ for heat. In all cases, the capture technology type is assumed to be post-combustion with chemical absorption (MEA). Table 1 shows the capture rates per industrial sector and the capture costs used in this study.

Table 1. CO_2 capture parameters used in this study (data source: Broek et al., 2010a; Damen et al., 2009)

Sector	Share of CO_2 that can be captured	Capture costs in 2025[a] (€/tCO2)
Ammonia	100%	15
Cement	85%	96
Ethanol	100%	15
Etihylene	90%	75
Refineries	90%	88
Iron and Steel	50%	28
Power plants (NGCC)	85%	49

[a] Compression cost included (110 bar)

Geological Reservoirs

Fifteen offshore oil fields were considered in the cost analysis. The storage cost parameters for offshore petroleum fields were adopted from Broek et al. (2010a). Table 2 shows these storage cost parameters.

Table 2. Storage cost data used in this study (source: Broek et al., 2010a)

Parameter	Reservoir type (Offshore petroleum fields)
Site development costs [a] (million €)	3.3
Surface facilities costs [b] – NEW (million €)	61.2
Surface facilities costs – RE-USE [c] (million €)	15.3
Drilling cost (€/m)	5314
Well fixed cost (million €/well)	8.2
Well workover [d] (million €)	2
Operating and maintenance cost (% of investment	5

[a] Includes site investigations costs, costs for preparation of the drilling site and costs for environmental impact assessment study, monitoring investment costs in pre-operational phase.

[b] Final facilities on the CO_2 injection site. Re-use of platforms can reduce costs considerably.

[c] Re-use of platforms

[d] Estimated cost to convert a production well into a CO_2 injection well.

[e] In the case of re-use, the investments of the old equipment is taken into account as well, because these need to be operated, maintained, and monitored as well.

Considering that all studied oil fields are currently in production phase, we assumed that all platforms could be re-used from 2025 on for CO_2 injection. For each sink, investment, monitoring and operating and maintenance (O&M) costs are calculated based on depth, thickness, CO_2 storage capacity, and injection rate per well. Because all these fields have already reached peak production, and, thus, are mature fields (PETROBRAS, 2010), it was assumed that all the oil fields will be available for CO_2 storage by 2025. The investment costs to prepare a specific reservoir for CO_2 storage was calculated using Equation 1.

$I_{re\text{-}use} = (Cd + Csf_{re\text{-}use} + Cm) + (W \times Cww)$ (Eq. 1)

Where $I_{re\text{-}use}$ is the total investment cost when re-using of platforms and wells (€); Cd is the site development costs (€); $Csf_{re\text{-}use}$ is the surface facilities costs in the injection site with re-use of platforms and Wells (€); Cm is the monitoring costs (€); W is the number of wells per sink, which depends on the storage potential of the sink and the injection rate per well for the sink. This was estimated for each individual storage site based on permeability data; Cww is the well workover costs (€). In this study it was assumed that the sinks will be filled at a maximum rate.

Investment costs using new platforms and wells are calculated using Equation 3. Operating and maintenance (O&M) costs of a sink can be estimated based on a fixed percentage of the investment costs for the development of a sink from scratch, because existing equipment also needs to be operated and maintained in case of re-use. Thus, for O&M costs calculation we had to calculate the investment costs for each site from the beginning (Equation 2).

$I = \Sigma(Cd + Csf_{new} + Cm) + \Sigma [W \times Cdw \times (H + TH)] + (W \times Cw)$ (Eq. 2)

Where I is the total investment cost per sink; Cd is the site development costs (€); Csf_{new} is the surface facilities costs in the injection site (€); Cm is the monitoring costs (€); W is the number of wells per sink (sink's storage potential and injectivity's dependant); Cdw is the drilling costs (€/meter); H is the reservoir depth (meter); TH is the reservoir thickness. The depth and thickness of the reservoir are required for the calculation of the drilling costs; and Cw is the fixed well costs (€ per well).

For each sink the lifetime was defined based on storage capacity and annual injection rate, with the maximum injection period set to 25 years. In case the sink is filled before the 25th year, the CO_2 storage facilities and injection wells will be dismantled and no O&M costs will be charged afterwards. Important to note that some average/estimated figures were taken into account in this estimative (see section 2.1.3).

CO_2 Transport

For calculating CO_2 transport costs, a clustering approach was applied in the analysis (Illustration 5). In this approach, CO_2 is captured at the plants and transported through satellite pipelines to the center of the source region in a CO_2 collector hub. CO_2 is then transported through a trunkline to the center of a sink region, and then it could be distributed to individual sinks/wells by satellite pipelines.

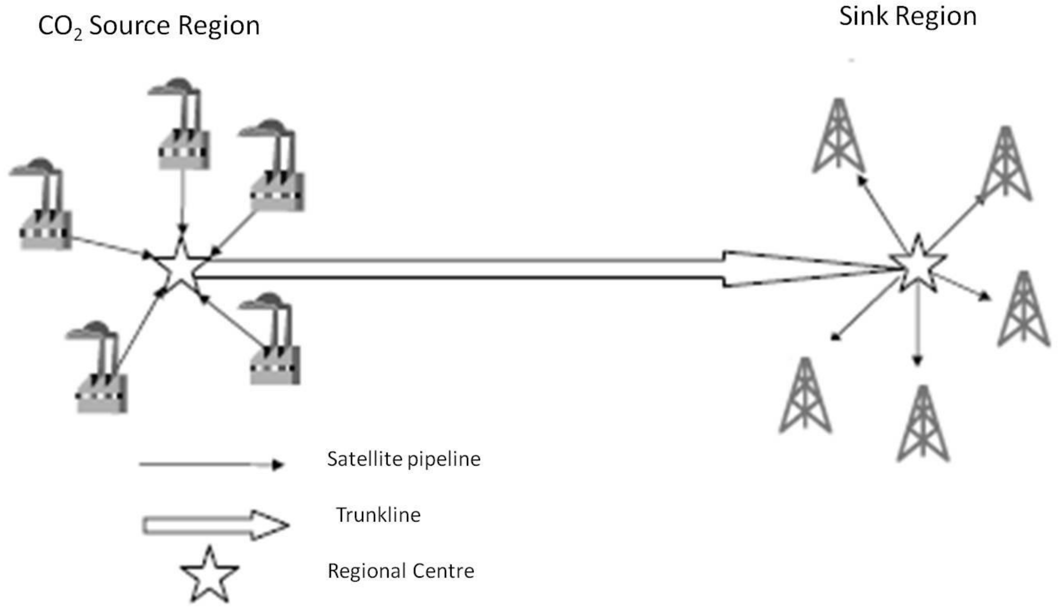


Illustration 5. Clustering methodology: CO_2 transport optimization (source: Broek, 2010b)

This clustering approach is used in order to minimize transport costs, as demonstrated in some studies (e.g. Broek et al., 2009; Haszeldine, 2009; Wildenborg et al., 2009).

Using the Geographic Information System, the central point of each cluster (or hubs) are determined. This tool identifies the geographic center for a set of features (in this case CO_2 sources and geological reservoirs), allowing the creation of a weighted mean center. As weight the estimated CO_2 emissions for 2025 of the sources or the storage capacity of the sinks in a region are used to take care that the large ones are closer to the hub. Thus, the thicker and more expensive satellite pipelines needed for the larger CO_2 flows can be shorter. Spatial analysis within a GIS allows the determination of the satellite pipelines distances as well as the trunklines distances, taking into account each before defined hub. The oil and gas pipelines' routes collected in the GIS inventory were considered for choosing preferential routes for the trunklines.

Total costs for CO_2 transport implementation include investment costs in the pipelines deployment and booster stations, which are need in case of long distances to compensate CO_2 pressure losses and keep supercritical conditions. In the literature, Heddle et al. (2003) indicated that recompression is needed for distances over 150 km, but it could not be necessary if pipeline diameters are sufficient, e.g. the Weyburn CO_2 pipeline with more than 300 km in length has no booster station. The IEA GHG (2005a) has assumed an average distance between booster stations of about 200 km. In this study the distance between booster stations was set at 250 km.

For each pipeline (satellite lines and trunklines) the investment costs for CO_2 transport were estimated based on Equation 3.

$I_T = L \times D \times cf_T$ (Eq. 3)

Where I_T is the pipeline transport investment costs; L is the pipeline length (m); D is the pipeline diameter, calculated based on pipeline length and CO_2 flow rate (m); and cf_T is a pipeline cost constant factor (1,600 €/m per meter). Total costs are estimated by summing investiment costs and booster stations costs.

Satellite pipelines' investment costs depends on the amount of CO_2 captured from each stationary sources (in case of satellite lines connecting sources to the cluster hub) or in injectivity rate (in case of satellite lines connecting the sinks hub to an individual sink). Trunklines' investment costs depend on the total amount of CO_2 captured from all the sources in each region (cluster). Table 3 shows the transport cost data used in this study.

Table 3. Transport cost parameters (sources: Brederode, 2008; IEA GHG, 2005a)

Parameter	Value
Cost Constant factor - pipelines (€/m²)	1.600[a]
O&M costs (% of investment costs)	3[a]
Booster station (€ / unit)	11.000.000[b]

[a] Source: Brederode (2008)

[b] Energy costs required for recompression are not included. Source: IEA GHG (2005a)

It is important to note that all the cost figures used in this study are from international literature (European figures).

Emission Reduction Scenarios

To assess possible shares of CCS implementation in Brazil, four emission reduction scenarios are assessed: 35, 30, 20 and 10 Mt of CO2 avoided per year, to be injected in Campos Basin's oil fields. The maximum scenario of 35 Mt/yr was set according to the capture potential of the analyzed sources within 800 km from the sink's mean center.

Considering that CO_2 capture is the most expensive step in the CCS chain (IEA GHG, 2002; IPCC, 2005; Damen et al., 2005), the optimization will take into account for instance the lower capture costs from CO_2 sources and the lower storage costs, in order to obtain the most cost-effective options for CCS deployment in Brazil.

Average costs for each CCS component were estimated for all the 4 scenarios, allowing the assessment of large scale CCS deployment costs - including costs for the three CCS components: capture, transport and storage. Although economic benefits can be obtained by EOR, this cost was not yet estimated in these oil fields and are not included in the cost modelling performed in this study.

RESULTS AND DISCUSSIONS

Stationary sources in Campos Basin vicinity, reservoirs and modeled thunklines

There are 48 CO_2 stationary sources in Campos basin vicinity: 17 cement plants, 11 power plants, 10 iron and steel plants, 5 refineries, 3 ethanol plants, 1 ethylene plant and 1 ammonia plant. Illustration 6 shows the number of plants and the total CO_2 emission per sector used for the cost modelling for the year 2025.

CO_2 emissions in Campos Basin's Vicinity (800 km radius) assuming all power plants will be replaced by NGCC plants by 2025 is ca. 50 $MtCO_2$ per year. Of this total emissions, 40% comes from Iron and steel plants, 27,34% from cement plants and 20% from refineries.

Iron and steel sector appears as the larger contributor of CO_2 emissions (20 Mt/yr), followed by the cement sector (14 Mt/yr). Power plants in Brazil are not the main contributor for CO_2 emissions, because they mainly operate in case of energy demand increases.

Clustering of Sinks and Sources

In this study CO_2 sources were clustered into 5 regions while the Campos basin's oil fields were clustered into 1 region. The cluster of sources number 1 consists of 16 CO_2 sources, including 1 iron and steel plant with CO_2 annual emission larger than 2.7 Mt., and 4 emission sources which each emit more than 1,3 Mt per year. In the cluster of sources number 2 there are 19 sources, with 2 sources emitting more than 2 Mt/year (1 refinery and 1 iron and steel plant); this includes the only ammonia plant in Brazil. Eight CO_2 sources make up the cluster of sources number 3, including the larger CO_2 source considered in this study: one iron and steel plant with annual emission of about 5.6 Mt per year. The second largest CO_2 source is located in Cluster number 4 with 1 other source of 0.7 Mt per year. Cluster number 5 consists of 3 sources, with a total emission of 1,6 Mt per year. The sinks' cluster consist of 15 oil fields. Illustration 6 depicts the clusters of CO_2 sources and sinks as well as their hubs.

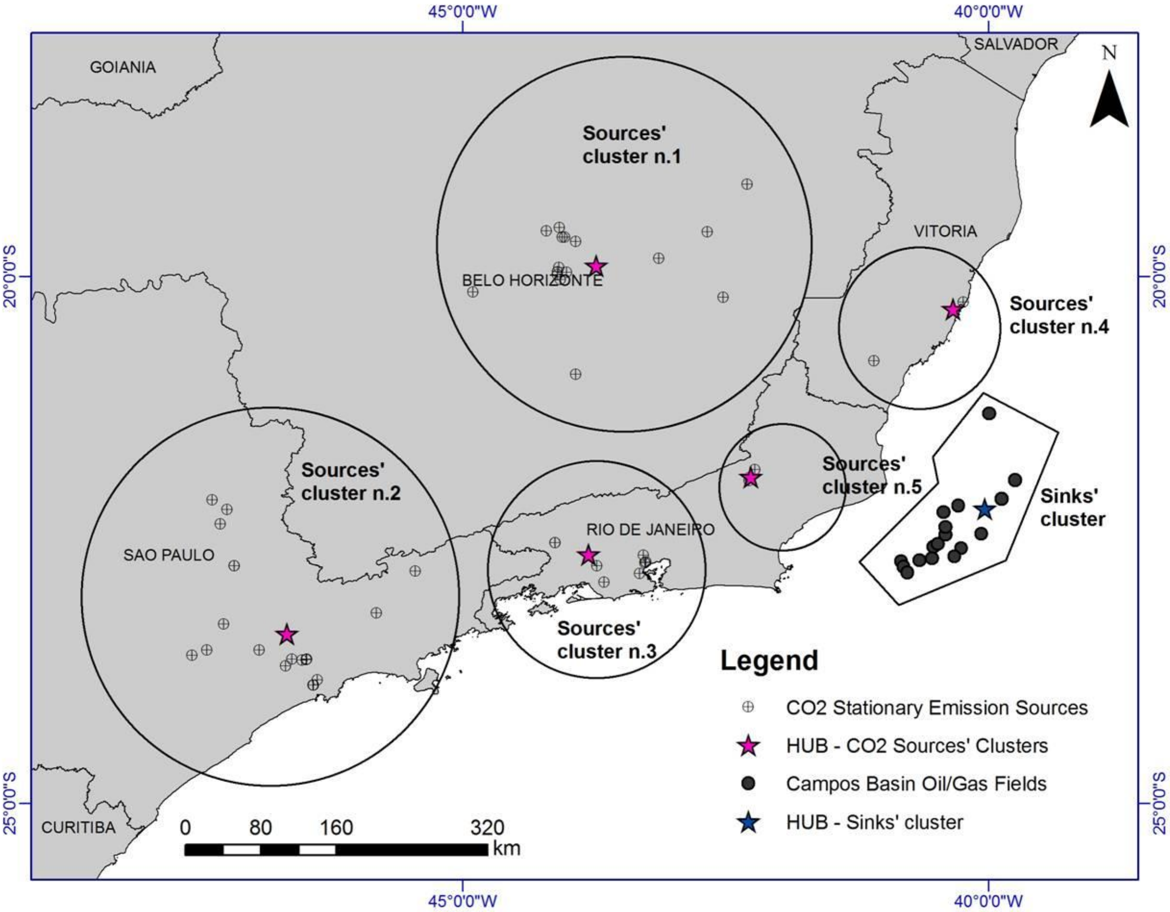


Illustration 6. Clusters of CO_2 sources and sinks (reservoirs) and their hubs

CO_2 Transport Network

The transport network was modelled considering existing pipeline routes and the short distanced between each source and the regional hub. The longer modelled trunklines are those that connect clusters 1 and 2 to the sinks, with lengths of ca. 700 km and 750 km, respectively. Booster stations are needed in all the 5 trunklines considered in this study.

Costs for large scale CCS implementation in Brazil

The findings of this research indicate that about 36 Mt of CO_2 can be captured per year from the 48 sources by 2025 (11 Mt in Cluster 1; 13 Mt in Cluster 2; 7 Mt in Cluster 3; 3 in Cluster 4 and 1 Mt in cluster 5). Note that only 50% of iron and steel emissions can be captured in the plants, therefore, besides being the larger CO_2 emitter among all the sources in Campos Basin's vicinity (40,4% of the total CO_2 emissions), the larger amount of CO_2 that can be captured for CCS comes from the cement plants (31% of the total captured CO_2). Iron and steel plants are the second larger CO_2 contributors for CCS implementation in Campos basin (28% of the total captured CO_2), in terms of CO_2 quantity, followed by refineries (25% of the total captured CO_2). Illustration 7 show the CO_2 capture potential per type of source in the 5 clusters in Campos basin's neighborhood.

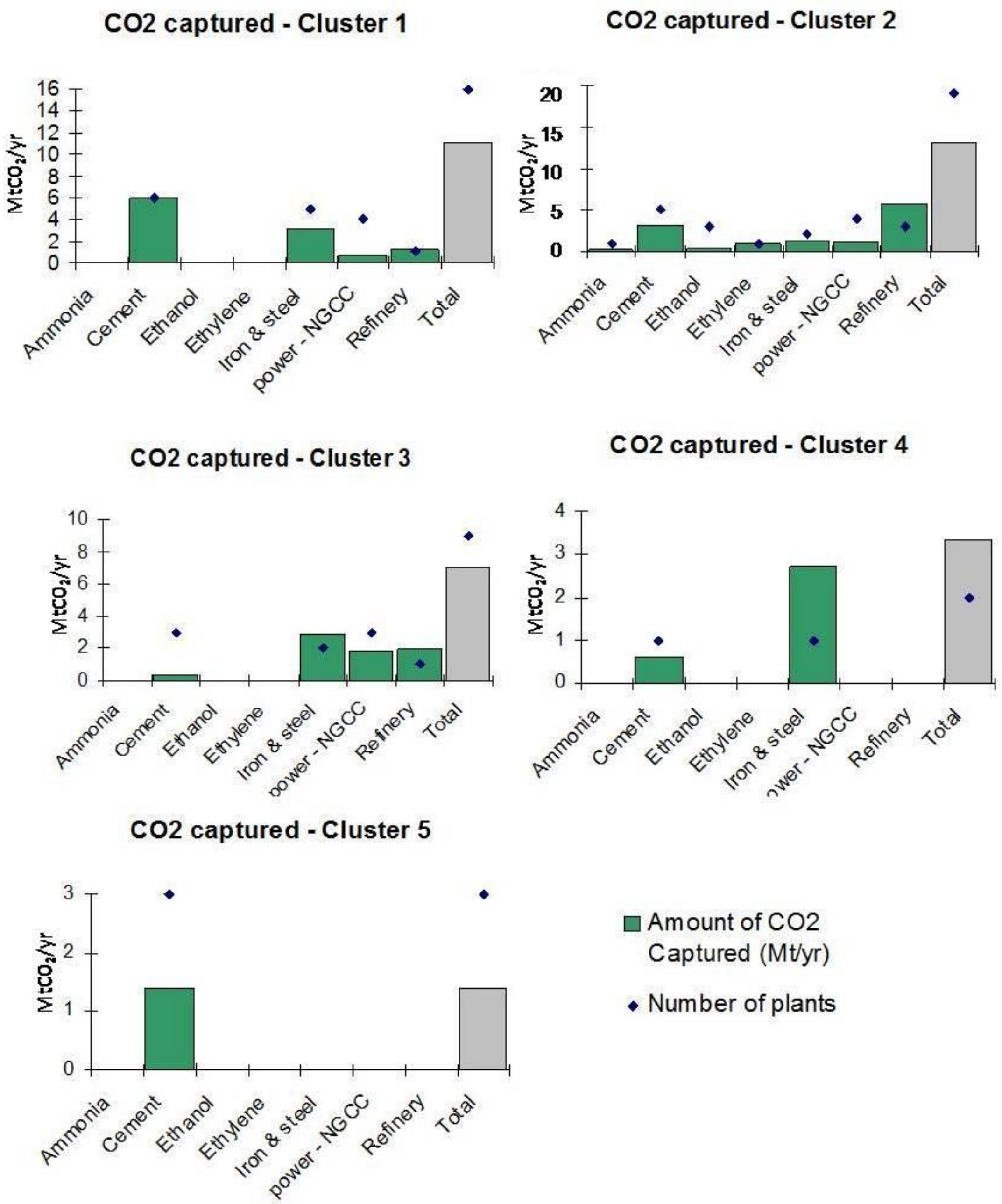


Illustration 7. Clusters of CO_2 sources in Campos Basin's neighborhood: CO_2 capture potential per sector by 2025.

For capture costs modelling for the year 2025 (Illustration 8), our results indicated that 0,5 Mt of CO_2 can be captured from the analyzed sources at costs lower than 20 €/t (in ammonia and ethanol plants). An additional amount of 9,8 Mt of CO_2 can be captured from iron and steel plants at 28 € per tonne. From power plants, a total amount of 3,8 Mt of CO_2 can be captured at costs around 49 €/t. Capture costs increases considerably when an amount >15Mt of CO_2 are considered for injection, due to the need for CO_2 capture from expensive sources, such as cement plants and refineries.

In this case study, which aims to store CO_2 in Campos basin's oil fields, the capture cost modelling show that the larger amount of CO_2 that can be captured from the considered sources (about 21,5 $MtCO_2$) implies in capturing CO_2 from sources with higher capture cost (>60 €/t). It means that there are many expensive sources in Campos Basin's vicinity.

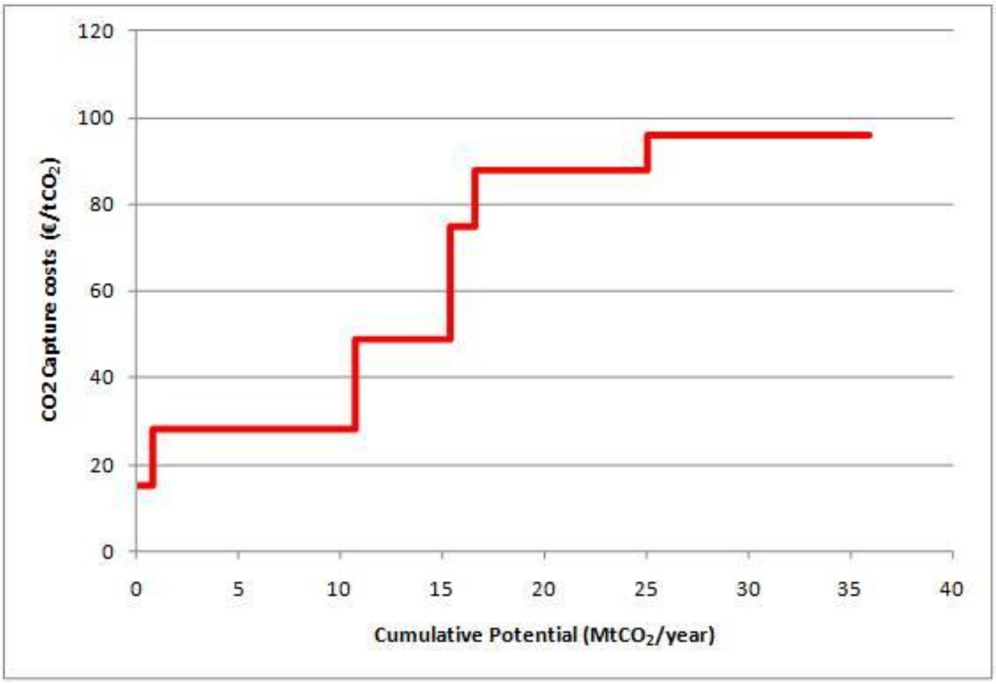


Illustration 8. CO_2 Capture in Campos Basin vicinity (800km distance): cost supply curve

Annual injection potential in the 15 studied oil fields is estimated at 40 Mt CO_2, based in the number of wells, well injectivity and injection lifetime for each sink. Figure 10 show the estimated storage costs and cumulative storage potential per year in Campos Basin. The results indicate that 30 Mt of CO_2 can be stored at costs lower than 4 €/t per year. The lower storage costs are related to mainly 4 oil sinks: Marlim, Barracuda, Albacora and Roncador.

The most economically viable oil field for CO_2 storage in Campos Basin is the Marlim field with estimated storage costs lower than 2 €/t in 2025, considering an injection period of 19 years and a total annual injection rate of 9 Mt. Barracuda's storage cost is estimated to be about 3 €/t CO_2, considering a total injection period of 22 years. Albacora and Roncador oil fields, although being the large CO_2 storage sinks in Campos basin, are slightly more expensive (3–3.6 €/t of CO_2) due to lower injectivities (compared to Marlim and Barracuda) and therefore a need for additional number of wells.

At costs ranging from 4.5 to 6.5 €/t, CO_2 can be stored in Jubarte, Caratinga and Enchova/Bonito oil fields. These 3 sinks together can store about 5.5 Mt of CO_2 per year. A cost supply curve (Illustration 9) shows that storage cost increases exponentially when a cumulative CO_2 storage potential of 35 Mt per year is reached. This very high costs refers to CO2 storage in the small storage capacities' sinks (< 30 Mt). Nevertheless, the costs remain relatively cheap. Cost for CO_2 storage at Marimbá, Pampo, Namorado, Carapeba and Vermelho oil fields are estimated in the range of 7 to 13 €/t CO_2 (with total storage capacity of 4 Mt CO_2 per year).

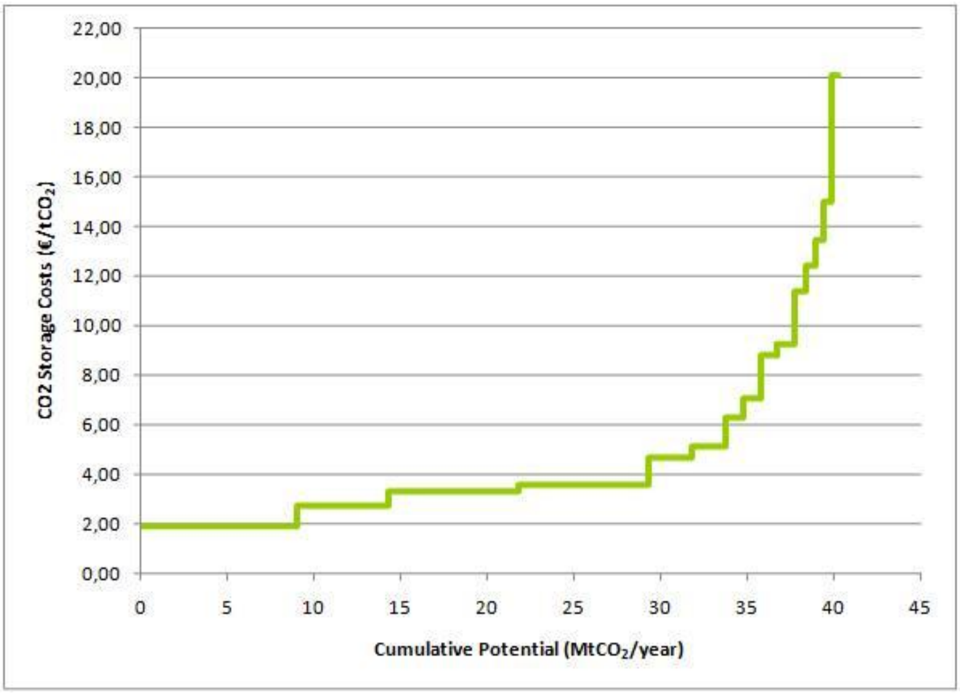


Illustration 9. CO_2 Storage in Campos Basin oil fields: cost supply curve (only storage cost)

It is important to note that the storage cost modelling took into account re-use of some wells and platforms currently installed in Campos Basin's oil fields, which allows for lower costs for the storage step (see Table 4).

With regard to the transport of CO_2, our findings indicate a transport cost for CO_2 in the range of 6 to 9 €/t of CO_2, considering that by 2025 the maximum flow rate from all the 48 stationary sources would be available (Illustration 10). Trunkline transport costs are the lower in cluster 3 with a value of 6 € per tonne. Trunklines of clusters 2 and 4 show costs of about 7 €/t CO_2. Although cluster 2 trunkline is two times longer than cluster 4, and need larger capital investment because of the installation of 2 booster stations, CO_2 annual flow in cluster 2 trunkline is 4 times higher, which compensates the final cost per tonne CO2 transported. The transport cost for cluster 1 and 5 are 8 and 9 €/tCO_2 respectively.

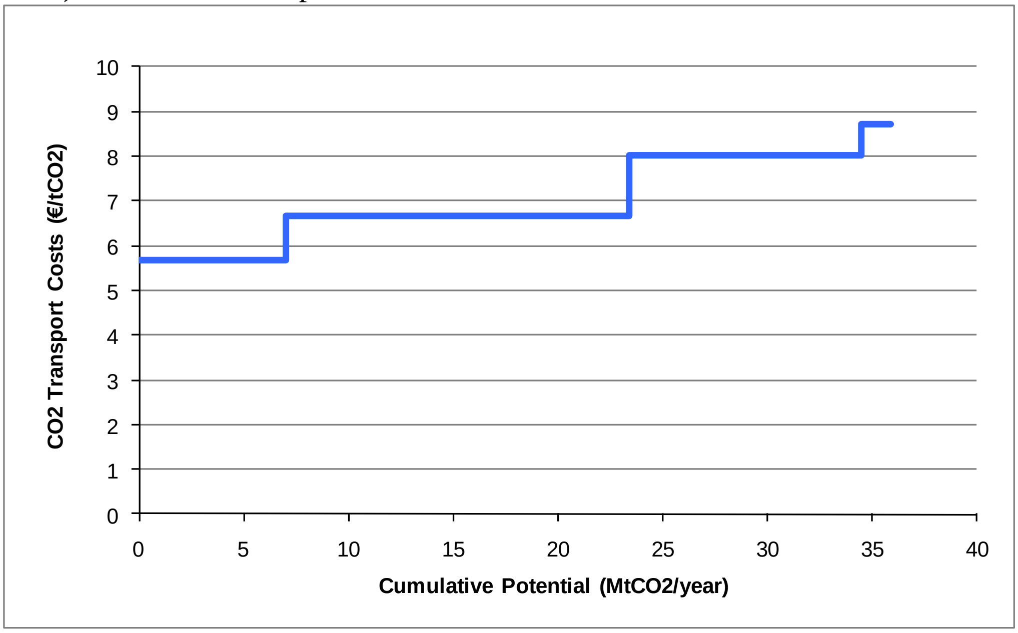


Illustration 10. CO_2 transport to Campos Basin oil fields: cost supply curve

Cost analysis results also show the most cost-effective options of sources, in which CO_2 capture and transport (satellite and trunkline) costs do not exceed 38 €/tCO_2. For only 8 of the 48 sources, CO_2 capture and transport costs would be low than 38 € per tonne, including 3 iron and steel plants in cluster 1, 1 ammonia plant and 2 iron and steel plants in cluster 2, 1 iron and steel plants in cluster 3 and 1 iron and steel plant in cluster 4.

Assessment of CCS chains

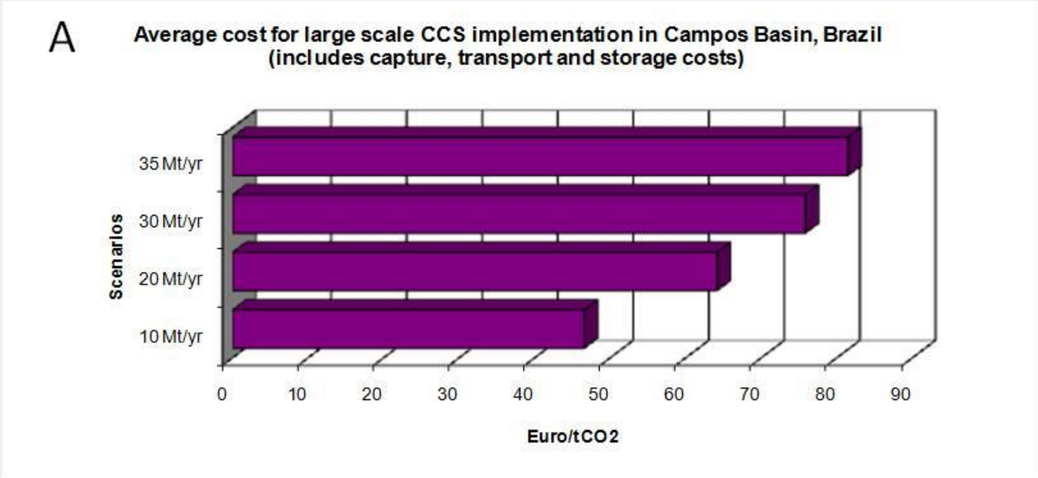
Cost for the whole CCS chain is composed of CO_2 capture, transport and storage costs which have been individually analyzed before. An assessment of the integration of three components provide insights into the optimal development of CCS chains under different conditions. For this assessment four cases have been considered: storing 10, 20, 30 and 35 Mt CO_2 per year in 2025.

In the first case (storing 10 MtCO_2 per year by 2025) 14 CO_2 sources from clusters 1, 2, 3 and 4 were taken into account. In the capture side, all iron and steel plants of the inventory of sources are considered, besides 3 ethanol plants and the ammonia plant. In the storage side the 10Mt of CO_2 are stored at Marlim and Barracuda's oil fields, which can meet the required annual injection of this scenario. The combination of capture, transport and storage in this case is possible at an average cost of 46,5 €/tCO_2.

For the 20 Mt CO_2 reduction per year scenario, average cost will be about 64 €/tCO_2 by 2025. For this emission reduction scenario 29 CO_2 sources from clusters 1, 2, 3 and 4 were considered in order to supply the required amount of CO_2. All iron and steel plants, ethanol plants, power plants and the ammonia plant were considered in the modelling, as well as 3 refineries and 1 ethilene plant. The storage sinks are set to be Marlim, Barracuda and Albacora oil fields.

In order to reduce 30 Mt of CO_2 per year, CO_2 capture from 37 sources will be needed. For this case, the cost modelling assessment shows an average cost of 76 €/tCO_2. For this scenario it was considered all the CO_2 from iron and steel, ethanol, ethylene, power, ammonia, refinery sector's plants, and 6 cement plants. Storage sinks are Marlim, Barracuda, Albacora and Roncador oil fields.

Finally, in the 35 Mt/yr case, the average cost per tonne of CO_2 is 82 €. CO_2 will need to be captured from 47 of the 48 total plants assessed in this study. 7 different sinks were set for 35 MtCO_2 injection: Marlim, Barracuda, Albacora, Roncador, Jubarte, Caratinga and Enchova/Bonito oil fields. Illustration 11 shows the average costs and the CO_2 origin for each scenario.



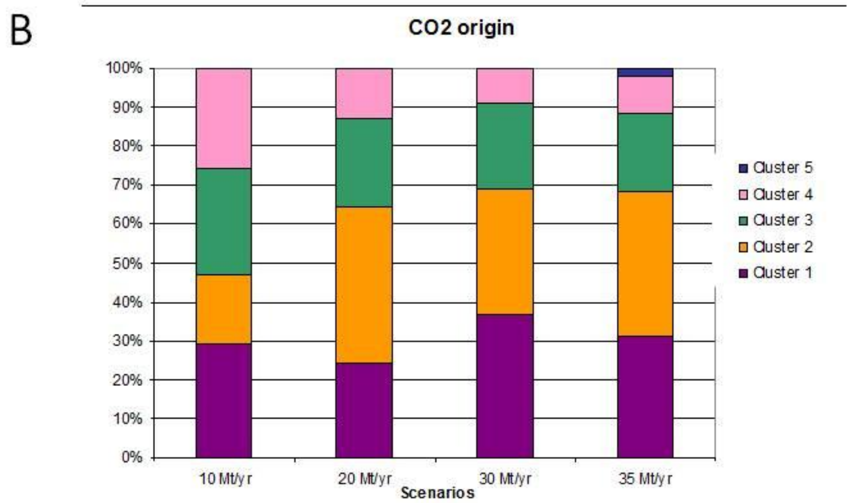


Illustration 11. Cost of CCS chains under four scenarios. A - average costs for CO_2 capture, transport and storage in Campos Basin; B - the origin of the CO_2 cluster in each scenario.

The increasing in average costs are mainly related to capture costs from the selected sources. In the 10Mt/yr scenario, capture costs represents 60% of the total average cost, while in the 35 Mt/yr scenario CO_2 capture account for 80% of the cost. Transport costs reflect economies of scale, with average costs decreasing with the CO_2 supply growth. In the 10Mt/yr scenario it accounts for 32% of the total costs while in the 35Mt/yr scenario it is only 10%. Storage costs shows only a minor increase between the cases studied (4,5% in the 10Mt/yr to 4% in the 35Mt/yr scenario), this increase is due to the use of the more expensive sinks with the increase in annual CO_2 injection demand.

CONCLUSIONS

In this research a first assessment on the costs for CO_2 storage at Campos Basin was conducted. The assessment includes not only the storage of CO_2 but also its capture and transport. Large scale CCS implementation's cost modelling in Brazil by 2025 shows that about 36 Mt of CO_2 can be captured per year from the 48 sources by 2025. Of this amount less than 10Mt can be captured at prices up to 28 €/tCO_2, which is due to the availability of CO_2 from industrial sources with relatively pure CO_2 streams (ammonia and iron and steel sources) close to the study area. An additional amount of 9,8 Mt of CO_2 can be captured from iron and steel plants at 28 € per tonne while about 4 Mt of CO_2 could be captured at a cost of 49 €/t from the NGCC power plants. This amount however reflect only a maximum technical potential. Further research at the industry and plant level will be needed to access the economic feasibility as well as operational and logistic implications of applying CO_2 capture. Such studies could result in a lower capture potential than the one provided in this study.

The findings also indicate that an amount of 9Mt of CO_2 could be injected per year at cost up to 2 €/t in Campos basin and that an additional 20 Mt per year could be stored at cost lower than 4 €/t. As a mature petroleum producer basin, there are many advantages for CCS implementation in Campos Basin, such as installed platforms and many drilled wells, which were taken into account in storage cost modelling. This combination of factors contributed to a reduced cost of storage in Campos Basin's oil fields. Transport costs modelling shows that pipelines transport costs are higher than storage costs (vary from 6 to 9 €/tCO_2), since they are very extent and investment cost in booster stations will be needed.

An assessment of the CCS chains under four different scenarios shows average costs for CCS in the range of 47 €/t by 2025 (10Mt of CO_2 case) to 82 €/t (for a 35 Mt/yr scenario). In the later case, the estimated storage lifetime of Campos basin's oil fields is about 27 years. In all cases studies, CO_2 capture had the main share of the total costs. This indicates that the key point for cost reduction is still capture costs, for which research are mostly needed in order to develop most cost-effective capture processes in a near future. It is important to point out that cost parameter used in this study are international, mostly European based parameters. Further research is required to calibrate such parameters to the Brazilian situation.

Finally, it can be concluded that CCS appears as an expensive but efficient alternative for CO_2 emissions reduction, so a large investment by the government will be needed in order to implement large scale CCS in Brazil. CCS with Enhanced Oil Recovery (EOR) activity may reduce costs due to the economic increasing with additional oil production, but this case was not modelled in our cost analysis.

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