METHODOLOGY FOR HUBS PLACEMENT ANALYSIS: AN APPLICATION TO PORTUGUESE INDUSTRIAL CO_2 EMISSIONS

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ABSTRACT

Carbon capture and Geological storage (CCGS) is recognised as a technology capable of reducing large-scale emissions of carbon dioxide (CO_2), which is an important part of the portfolio of alternatives necessary to achieve significant reductions in the global emissions of greenhouse gases (GHG). As of this context where greenhouses gases constrains in Europe would come, and CCGS would be a mitigation option for GHG, it becomes necessary to develop a CO_2 transport network to collect and inject it in a proper geological reservoir. Therefore, the following methodology can help to implement a pipeline network in any region in the world by doing a preliminary analysis about the best places to locate a HUB (temporary CO_2 reservoir). In this paper, the demonstration of the methodology refers to Portugal's industrial emission sources in which CCS could be implemented.

INTRODUCTION

Carbon capture and storage (CCS) is a technology that captures carbon dioxide (CO_2) emissions from burning fossil fuels in electricity generation and from industrial processes, preventing the carbon dioxide from entering the atmosphere. The CCGS chain consists of three parts: capturing CO_2, transporting it, and securely store these emissions underground in geological formations (IPCC, 2007; IEA, 2010; IPCC, 2014).

CCGS is recognized worldwide as a technology capable of reducing large-scale CO_2 emissions. It is an important part of the portfolio of alternatives necessary to achieve significant reductions in the greenhouse gases (GHG) global emissions (IEA, 2010; Borba et al., 2012; IPCC, 2014; Onarheim et al., 2015; Viebahn et al., 2015; Valentic et al., 2016; Wang et al., 2016; Macdowell et al., 2016).

As for Europe, CCS is also seen as an important option to contribute to mitigate climate change and Directive 2009/31/EC established already the legal framework for the environmentally safe geological storage of carbon dioxide (CCS Directive). European Commission (2015) report on this Directive concluded that a number of official European publications confirm CCS as a fundamental option to reduce direct emission from large scale industrial processes. The report shows however that in spite of the urgency on deploying CCS, the number of large CCS plants is still very much limited and far from the reaching the demonstration targets proposed in European Council (2008). The literature is vast on the analysis of different scenarios including CCS, on the technological development, on impact assessment and on the modeling of CO2 capture, transport and storage infrastructures. Some recent examples discussing these issues include Leung et al. (2015) presenting a review of carbon dioxide capture and storage technologies, Coninck and Benson (2014) discussing the critical market and policy conditions for CCS to emerge as a viable option. The technical and political uncertainty surrounding CCS is still evident as Grafakos and Flamos (2015) demonstrated. Their work addressed low-carbon energy technologies in Europe, and showed major disagreements among European experts on critical issues related to future CCS deployment. As the authors concluded, this uncertainty point out the importance of further research on this theme.

Jägemann et al. (2013) analyzed different pathways for the low carbon economy in Europe, pointing out the importance of the decarbonization of Europe's power sector. The combination of CCS with Renewable Energy Sources (RES) emerges then as a relevant option to be considered in particular in systems where RES already represents high share of the power system. That is the case of Portugal. However, fossil fuels still have an important role on the Portuguese electricity system. Therefore, gas and coal power plants are considered to assure power electricity in Portugal, with strong impact on the CO_2 emissions of the countries. Considering an already existing restrictive scenario regarding greenhouse gases (GHG) in Portugal, arises the necessity of CO_2 reduction in short term and the perspective of integration of CCS systems should not be overlooked.

The potential for implementing CCS in energy intensive industrial sectors is also significant, in particular in cement, oil and gas or iron and steel, as shown in works such as Volkart et al. (2015), Onarheim et al (2015) or Quader et al. (2015). Combined strategies relying on energy efficiency, RES, demand side management and CCS can then open way for low carbon economies in different markets and regions. Initially, electric and oil sectors would be the main candidates to implementation of these CO_2 mitigation techniques. However, other sectors like steel industry and cement should not be discarded (Nogueira et al., 2013). Also, Seixas et al. (2015) indicate the cement industry as a potential target for CCS with the potential of resulting in significant reductions of CO_2 in the sector in Portugal.

The urgency for developing a CCS industry in Portugal also poses some challenges related to technological development, institutional arrangement and the need for a better planning of the CO_2 transportation.

This study proposes to apply a methodology for design hubs and the related CO_2 transportation grids in Portugal. Indeed, assuming that greenhouses gases constrains will be imposed in Portugal, and CCS may become a mitigation option, it is worthwhile planning and optimizing the CO_2 transport network, to collect and inject CO_2 in proper geological reservoirs. Related to this, the concept of intermediaries CO_2 reservoirs (HUBS) emerged from the concept of CCSR (Carbon Capture and Storage Ready) . CCSR proposes that an energy / industrial installation or large CO_2 supply facility could be built and / or prepared to be adapted (retrofit) with CCS technology. The goal of building new or modify existing facilities CCSR is to reduce the risk of carbon block -in or the inability to use them fully without CCS. The CCSR is not an option for CO_2 emissions mitigation, but a way to facilitate the mitigation of CO_2 in the future (GCCSI, 2010; IEA, 2010). In planning new sites of power plants and / or industrial facilities from the perspective of capture ready, it is not necessary that the plant is located near the storage site, but in a similar radial distance from the emission density area, making possible the CO_2 to be collected , stored temporarily in HUBS (when required) and transported to its final destination (Li et al, 2011; Costa, 2014).

In this work the possibility of Georeferenced Information System (GIS) tools are proposed to determine the optimal location of HUBS, corresponding to a scenario that would result in near decarbonization of the main stationary sources. It is not possible to capture the total CO_2 emitted by all industrial facilities mentioned. Therefore, it was used the concept of "capturable CO_2", defined as the part of CO_2 emitted – mostly, from heat generation and/or fossil fuel burn in industrial sector, and fossil fuels utilization in power generation –, that is viable to be separated through at least one of the capture routes (Costa, 2014). Capture routes are: post-combustion, oxy-combustion, pre-combustion. Furthermore, it is important to highlight that from the capturable CO_2, only about 85 a 90% of CO_2 is really captured, due to technical limitations from existing gases separation methods (IEA, 2012; Roddy, 2012; Rochedo, 2011; Kuramochi, 2012).

The paper is organized as follows. Next section will describe the proposed methodology for hubs placement. Following this, the application of the methodology to Portugal is shown, including the main stationary CO_2 sources and the main assumptions of the model. The results are then analyzed for the region showing the areas that have the greatest potential for placing hubs. Conclusions and directions for future research are pointed out in the last section.

METHODOLOGY FOR CO_2 HUBS PLACEMENT ANALYSIS

This methodology is a preliminary screening on a territory to identify areas of interest when designing a CO_2 pipeline network. These areas would have high density in terms of CO_2 emissions and would be considered hotspots to install CO_2 HUBS. By starting the analysis, stationary emission sources that will be considered in CCS projects should be selected. As of the definition of these sources and respective locations, steps should be followed in order to complete the analysis. It is important to mention that the amount of carbon dioxide emissions that could be captured should be estimated by each source, based on the processes that occur in each facility selected. The steps of the methodology are shown bellow:

1. Keep record of the geographic location (coordinates) of each emission source where carbon capture is technically feasible
2. For each source (industry/facility), it should be accounted the annual CO_2 emission data. If there is a record of more than one year, the highest annual values should be used.
3. Based on the values accounted previously, a capture factor is used. The factor can be up to 90% due to technical limitations from existing gases separation methods (IEA, 2012; Roddy, 2012; Rochedo et al., Hoffman et al., 2013; Kuramochi, 2012). The CO_2 emission data is finally calculated, and all the available data (coordinates and CO_2 emissions) will be used as inputs to the georeferrenced software chosen.

Commercial georeferenced softwares can be used, such as ArcGis, for instance. Georeferenced softwares contain density calculation tools, which would use collected information as entry data, and the tool's result would be maps with possible location of areas of interest. For this study, density analysis can be applied to CO_2 emissions sources, and Kernel Density from ArcGis Desktop 10 was used. Kernel Density is an analysis tool that spatially distributes density per calculated area unit for certain points (center).

Kernel density estimation (KDE) is a spatial data analysis technique. The most common form of KDE is the two-dimensional planar approach. With planar KDE, the study area is divided into a grid with a user-specified cell size. A kernel function is then used to calculate the density of discrete events (in this case, CO_2 emissions) within a user-specified search bandwidth (the search radius). The analysis results are a continuous surface that shows areas of high and low CO_2 emission density (Yamada and Thill, 2004; Young and Park, 2014). Equations 1, 2 and 3 represent calculations performed in "Kernel Density" tool. (x_1, x_2, ..., x_n) is a sample *i* taken from any distribution with an unknown density *f*. The interest is to estimate the shape of this function *f*. Kernel density estimator is (Okabe et al., 2009; Sreevani and Murthy, 2016):

$$\hat{f}_h(x) = \frac{1}{n}\sum_{i=1}^{n} K_h(x - x_i) \quad = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right),$$

(1)

Where $K(\bullet)$ is kernel – symmetric function, $h > 0$ is a smoothing parameter called the bandwidth.

Kernel index *h* is called scaled kernel and defined as:

$$\mathbf{Kh(x) = 1 / h\, K(x / h)} \qquad \mathbf{(2)}$$

If Gaussian basis functions are used to approximate univariate data, and density to be estimated is from Gaussian basis, then the ideal choice for *h* is:

$$h = \left(\frac{4\hat{\sigma}^5}{3n}\right)^{\frac{1}{5}} \approx 1.06\hat{\sigma}n^{-1/5},$$

(3)

Where $\hat{\sigma}$ is samples standard deviation. This approximation is called normal approximation distribution or Gauss approximation.

The Kernel analysis has been widely used for different purposes such as retail site location decision process, occurrence of car crashes and crimes in an specific area, even occurrence of cases of a certain disease; for determination of potential biomasses and sites for biogas plants, among other examples (Okabe et al., 2009; Young and Park, 2014; Roig-Tierno et al., 2013; Hohn et al., 2014; Yu et al., 2015). In all these examples hotspots based on high density areas could be calculated.

"Kernel Density" tool is, then, proved to be an useful and practical approach for the identification of higher concentration areas of specific parameters and supporting decision making towards location of related units. However, to the best of the authors knowledge, the use Kernel density for the location of CO_2 hubs has not yet been explored in the literature.

RESULTS AND DISCUSSION

The selection of emission sources conducted for this case study was based on the list of main CO_2 stationary emission sources from Seixas et al. (2015) and incudes fossil fuel power plants, oil refineries and cement industrial units. The values of CO_2 emissions were assumed to correspond to the values reported in 2014. The emission sources are shown in the table 1.

Table 1– Emission sources selected for Portugal

EMISSION SOURCES	EMISSIONS (tCO_2e)	CAPTURABLE EMISSIONS (tCO_2)[1]	SECTOR
Sines Coal Power Plant	7.40	6.58	Electric
Pego Coal Power Plant	4.29	3.85	Electric
Tapada do Outeiro CCGT	0.11	0.10	Electric
Ribatejo CCGT	0.10	0.09	Electric
Lares CCGT	0.12	0.11	Electric
Pego CCGT	0.09	0.08	Electric
Cimpor –Cement Production Alhandra	1.47	0.83	Cement
Souselas	1.13	0.62	Cement
SECIL – Outão	1.05	0.71	Cement
Maceira – Liz	0.31	0.23	Cement
Cement Production Loulé	0.32	0.17	Cement
Cibra - Pataias	0.25	0.16	Cement
Matosinhos	1.03	0.32	Oil Refining
Sines	4.07	0.91	Oil Refining

Source: Estimated based on EDP, 2014; REN, 2014; REE, 2014 and IPCC, 2001.

The map in Figure 1 is the tool output and it shows the areas (darkest blue) that have the greatest potential for placing hubs.

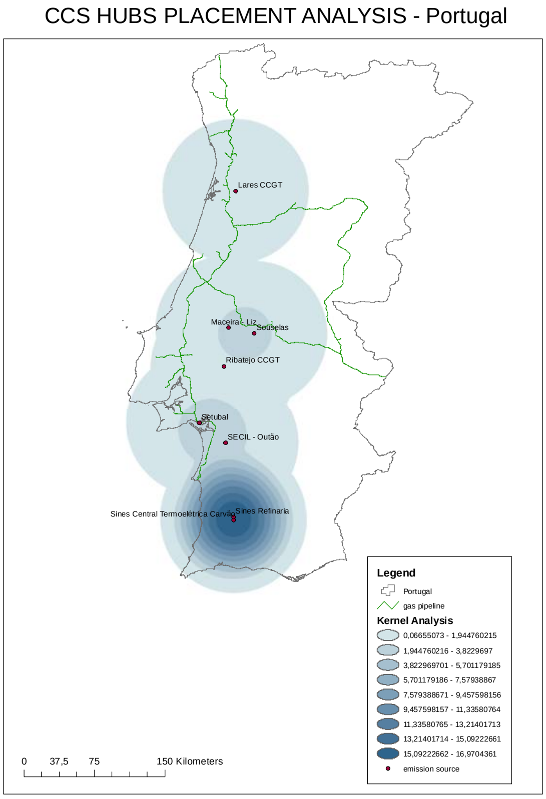

Figure 11 – "Kernel" Analysis

The darker areas, which are the intersections of the areas covered by the kernel densities calculated, represent the areas of highest emissions in Portugal. These numbers (densities) are shown in the Figure 1. These areas are, then, the hotspots that should be analyzed for placing the CO_2 HUBS.

Three points were selected as possible locations to install CO_2 HUBS. The first one is next to the greatest CO_2 stationary emitter in Portugal, which is Sines Coal Power Plant. This CO_2 hub would collect emissions from Sines Coal Power Plant, Sines Refinery, SECIL-Outão cement factory and Setubal Power Plant[1]. The second point would be located next to Maceira-Liz cement factory and would collect CO_2 from it and from Souselas Cement factory and Ribatejo Power Plant as well. The third point would be located next to Lares Power Plant and to Spain. This last CO_2 HUB would collect CO_2 from Lares power plant and could be the point of connection with a possible CO_2 pipeline in Spain.

Note that much of the darker areas are located close to existing gas pipelines, as can be seen on the map. This occurs because the most energy-intensive areas are also the areas with the highest GHG emissions rates. So, one possibility is to use existing gas pipelines routes to install HUBS and CO_2 pipelines. This action would reduce costs of implementing a pipeline network because there would be economies of scale in the pipeline's dimensions and use of more efficient compressors. Moreover, it would simplify the pipeline network and allows to control, in a better way, the pressure decrease along the pipelines.

It is important to mention that there are few technical differences among CO_2 and gas pipelines, and also the existing gas pipelines deliver natural gas to some of the emission sources that would have it's CO_2 captured. So, retroffiting these pipelines should not be an option.

CONCLUSIONS AND FURTHER RESEARCH

The methodology presented for HUBS placement analysis is unprecedented. It used the Kernel density analysis and it was possible to distribute spatially the emission densities from each selected emission source. The areas that presented higher densities, should be considered for placing a HUB. This methodology aims to assist a Planning Agency to develop the pipeline network projects which will be used to transport CO_2 in CCGS projects. In addition, it was concluded that it could be applied to any domestic and international territory, by only having access emission source locations and its annual carbon dioxide emissions. Qualitative analyzes showed the complexity of implementing such projects and that an accurate planning is required.

This methodology represents the first step towards designing a carbon pipeline network to collect CO_2 emissions in Portugal. So this is also a step towards considering CCS technologies for Portugal resulting in CO_2 emissions reduction. Moreover, collecting CO_2 besides reducing emissions could be a way of delivering CO_2 to industries that uses it as feedstock, such as the Food Industry. This would result in a sustainable way of dealing with CO_2 emissions. Also, could create a new market for selling and buying CO_2 in Portugal and in Europe. In sum, this methodology would be a beginning of a strategy that would bring environmental and economic benefits to Portugal.

From the contributions of this work other relevant studies can be developed. It is worth to remember that this methodology does not define the exact location for HUBS . Hence the need to include other variables such as proximity to existing pipeline networks, costs and area occupation and distances between emission sources and final reservoirs.

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[1] It is important to mention that Setubal Power Plant was closed on September, 2012 but is still showed in the map even though wasn't included in the Kernel analysis. Also all the emission sources presented in Table 1 were included in the analysis, but because of the calculation of the Kernel densities, some of the emission sources are overlapping.

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