Placing hubs in CO₂ pipelines: An application to industrial CO₂ emissions in the Iberian Peninsula

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HIGHLIGHTS

- Carbon capture and storage from industrial sources has great potential to mitigate GHG emissions.
 - CO₂ hubs is a strategy to optimize a carbon transportation network.
 - Kernel density analysis can be used to identify areas of high CO₂ emission density.
 - The Kernel analysis can be used to help to locate hubs in a pipeline network.
 - The methodology was applied to the Iberian Peninsula industrial emission sources.
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ABSTRACT

Carbon capture and geological storage (CCS) is a key technology for the World deep decarbonization. However, several challenges remain, such as the optimization of the carbon transportation infrastructures. This study proposes a methodology that applies the Kernel Density function in a geographic information system software and uses as input, CO₂ emission sources data to identify emission clusters and emission high-density hotspots. The main goal of the proposed methodology is to perform a preliminary screening to identify areas of interest to install hubs when designing an optimized CO₂ pipeline network. The methodology includes an estimation of capturable CO₂ emissions and a density analysis that was based on Kernel Density function from the ArcGIS Desktop 10. The methodology was applied to the Iberian Peninsula CO₂ industrial emission sources such as refineries, coal and natural gas power plants and cement factories (case study) and the results showed that in Portugal, CO₂ industrial emissions reduction can reach up to 68% and, in Spain, up to 74% of CO₂ industrial emissions, could be avoided. These are called capturable CO₂ emissions which means that they are the portion of the total emissions that can be captured from industrial processes before they reach the atmosphere. Moreover, hubs were shown to be more viable when Portugal and Spain are considered together, therefore, carbon routes (pipeline network) in the future may consider an integrated route for the Iberian Peninsula.

1. Introduction

Carbon capture and geological storage (CCS) is an option for mitigating carbon dioxide (CO₂) emissions from fuel combustion and other chemical reactions in industrial processes, preventing the CO₂ from

entering the atmosphere. The CCS chain consists of three parts: (i) capturing CO₂, (ii) transporting it, (iii) and securely storing these emissions, usually underground in geological formations [1,2], but also as a chemical product [3].

CCS is recognized worldwide as a technology capable of reducing

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large-scale CO₂ emissions. It is an important part of the portfolio of alternatives to achieve significant reductions in the greenhouse gases (GHG) global [1,2,4–9].

The potential for implementing CCS in energy intensive industrial sectors is significant, particularly in cement, oil and gas, iron and steel, and for ammonia production, as shown in Hendriks et al. [10], Onarheim et al. [6], Quader et al. [11], Rochedo et al. [12] and Volkart et al. [13].

Combined strategies relying on energy efficiency (Renewable Energy Sources - RES), demand side management and CCS can, then, pave the way for low carbon economies in different markets and regions. Initially, the electric power and oil sectors would be the main candidates to implement these CO₂ mitigation techniques. However, other sectors like steel industry and cement should not be discarded [14]. Also, Seixas et al. [15] indicate the cement industry as a potential sector for applying CCS in Portugal.

However, while carbon capture may impose significant costs on energy and industrial facilities, a major systemic challenge is to design and regulate optimal carbon transportation networks, which, in the case of Europe, can include different countries (CO₂ emission sources, transit sites and storage sites), with different perspectives on climate change policies.

Indeed, the urgency for developing a CCS industry around the world poses some challenges related to technological development, institutional arrangement and the need for a better planning of the CO₂ transportation network. In this paper, the focus is to make a CCS assessment for the countries in the Iberian Peninsula: Portugal and Spain. This includes the estimation of the CO₂ capture potential from the main emission sources, the establishment of a methodology for determining hotspots for emission sources and the analysis of the CO₂ transportation regulatory framework, associated with CCS in the Iberian Peninsula.

The CO₂ emission clusters are defined by the areas with the highest emission density. These areas compose the hotspots that should be analyzed as possible locations for hubs. According to The Global CCS Institute (2010), a CCS hub connects multiple CO₂ emitters and storage sites, using shared pipelines and transportation infrastructure. The hub and cluster approach aim to optimize pipeline networks and can reduce costs and risks for projects.

The concept of hubs also emerged from the concept of CCSR (Carbon Capture and Storage Ready). CCSR proposes that an energy or industrial installation or large CO₂ supply facility could be built and/or prepared to be equipped (retrofitted) with CCS technology. The goal of building new or modify existing CCSR facilities 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 CO₂ emissions mitigation, but a way to facilitate the mitigation of CO₂ in the future [1,16].

While planning the installation of new sites such as power plants or industrial facilities from the perspective of capture ready, it is not necessary to have the plant located near the storage site. However, it could be in a similar radial distance from the emission density area, making possible for the CO₂ to be collected, stored temporarily in the hub (when required) and transported to its final destination using shared pipelines [17,18].

Therefore, the methodology presented in this study to identify clusters was developed using the concept of hubs. A Georeferenced Information System (GIS) tool is applied to determine the optimal location of these CCS hubs. As mentioned before, these locations must be considered as hotspots when planning a pipeline grid.

This study develops the hubs placement methodology which is applied to the Iberian Peninsula's major CO₂ emission sources. This analysis includes identification of CO₂ emission clusters (hotspots to place hubs) and a comparison among possible arrangements for CO₂ pipeline networks, considering independent routes in Portugal and Spain and an integrated route for the Iberian Peninsula. Moreover, it also presents a discussion on CO₂ transportation regulatory frameworks and a carbon sink qualitative analysis. Section 2 presents a brief background

regarding CCS technologies implementation in the world. Section 3 presents the methodology for hubs placement developed by this study based on Kernel density estimation, and Section 4 shows the implementation of it in the case of the Iberian Peninsula. Section 5 focuses on the main results of the study and its regulatory implications. Finally, Section 6 summarizes the main conclusions of the study.

2. Background

CCS technologies have been studied all over the world, especially by energy-intensive sectors. China, for example, has been considering CCS, especially for coal-fired power plants for the next few decades in order to reduce CO₂ emissions. CCS is an option to help to reduce CO₂ emissions to a level that would be consistent with the climate agreement signed by the international community, which China has been increasingly committing to [8].

The United States of America (USA) and Canada have been capturing and injecting CO₂ for decades and they have implemented many demonstration projects in order to develop these technologies [19,20]. The USA has the oldest carbon pipeline, which is the Canyon Reef Carriers. It consists of a 225 km pipeline built in 1972 for EOR in Texas (USA). The longest is the 800 km Cortez pipeline, which carries 20 million tonnes/year of CO₂ from a natural source in Colorado to the oil fields in Denver City, Texas since 1983 [21]. USA use pipelines to transport CO₂ both from production/burning fossil fuels and from ethanol production [22,23].

Other countries in America have also applied carbon capture for removing CO₂ from natural gas associated with crude oil production. For instance, in Brazil, these practices have been applied to mitigate CO₂ emissions from the associated gas found in the country's petroleum pre-salt fields. It is estimated that there is a presence of large CO₂ content in these fields, ranging from 10 mol% to 45 mol% [12,24–26], which may be stored in the same underground fields.

Moreover, other studies for Brazil point out to the possibility of implementing carbon capture facilities in the power sector [14,27–28]), in sugar cane based bio refineries [29], in petroleum offshore platforms [30], in oil refineries [31], and industrial facilities [14]; and tried to evaluate the challenges for designing CO₂ pipelines [12,32].

As for Europe, CCS is also seen as an important option to contribute to mitigating climate change. In 2009, Directive 2009/31/EC [33] established the legal framework for the environmentally safe geological storage of carbon dioxide (also known as the CCS Directive). The European Commission [34] report on this Directive, concluded that confirm CCS as a fundamental option to reduce direct emission from large-scale industrial processes [34]. The report shows however that despite the urgency of deploying CCS, the number of large CCS plants is still very much limited and far from reaching the proposed demonstration targets.

The literature is vast in 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. [23] presenting a review of carbon dioxide capture and storage technologies, de Coninck and Benson [35] 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 [36] 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 points out the importance of further research on this theme.

Jägemann et al. [37] analyzed different pathways for the low carbon economy in Europe, pointing out the importance of the decarbonization of European electric power sector. The combination of CCS with Renewable Energy Sources - RES emerges then as a relevant option to be considered where RES already represents a high share of

the power system.

That is the case of Portugal, which is characterized by a high reliance on the hydropower sector and increasing importance of wind power [38]. However, fossil fuels still have an important role in the Portuguese electricity system, especially gas and coal. Power plants fueled by coal and gas supply electricity in Portugal, with a strong impact on the country's CO₂ emissions. Actually, emissions related to the energy sector in Portugal corresponded to 68% of the total CO₂ emissions in 2014 (without land use, land-use change, and forestry) [39].

Moreover, after 2012, Portugal released a National Program related to Climate Changes for 2020–2030, which indicates strategic orientations towards a Low Carbon Economy [39]. The Portuguese Environment Agency [39] developed a Green Growth Commitment, which determined specific goals for the Energy Sector by 2030: (i) CO₂ emission reduction up to 40% by 2030; (ii) up to 40% of RES participation in final energy use; (iii) increase energy efficiency by 30%. Therefore, considering the already existing restrictive scenario regarding greenhouse gases (GHG) in Portugal, the necessity of a CO₂ reduction in short term arises and the perspective of integration of CCS systems should not be overlooked.

Currently, Spain is involved in a few programs, which assess impacts, vulnerability and adaptation measures towards climate changes [40,41]. For example, it is part of the ADAPT Program and participates in the European Climate Adaptation Platform [40]. The Spanish research in this field is developed under energy research or climate change abatement Programmes and in several departments of Spanish universities.

In the Iberian Peninsula, the possibility of CCS has already been assessed in the scientific literature. Ioakimidis et al. [42] and Boavida et al. [43] concluded on the suitability of using pipelines to transport CO₂ emissions from the thermal power plants to saline aquifers for geological storage. Seixas et al. [15] analyzed the role of CCS for different energy scenarios, showing that under highly CO₂ constrained assumptions, CCS can be cost-effective.

The issue of CCS in the Iberian Peninsula has been gaining increasing attention with the academic research being strongly supported by PETROGAS and GALP [41,44–46]. However, there is a lack of analysis in the scientific literature related to the CO₂ capture potential and the regulatory framework for CCS in the Iberian Peninsula, which are covered by this paper. Section 3 presents the methodology for hubs placement developed by this study.

3. Methods

The main goal of the methodology is to create a preliminary screening on the territory to identify areas of interest when designing a CO₂ pipeline network. These areas, according to the proposed methodology, would have high density in terms of CO₂ emissions and would be considered hotspots to install CO₂ hubs. The steps of the methodology are shown below:

1. Identify the geographic location (coordinates) of each emission source;
2. Identify storage sites (sedimentary basins that could be available for CO₂ storage);
3. For each source, there should be accounted an annual CO₂ emission data to be captured, and the year of study should also be defined¹.
4. The collected data should be inserted into a geographic information system software of choice.

¹ When choosing the year of interest for the analysis, if there is a record for more than one year, the highest annual emission values should be considered. This data can be used latter on to size the carbon transportation infrastructure when designing the final pipeline grid.

At first, stationary emission sources that will be considered in CCS projects should be defined. For each of those, the amount of carbon dioxide emissions that could be captured (capturable CO₂ emissions) should be estimated by each source based on the processes that occur in each selected facility. The capturable emissions are usually related to energy consumption and industrial processes. The estimates of CO₂ captured are based on Rochedo et al. [12]. In the case of oil refineries, the estimates should focus on FCC and Hydrogen Generation units. For the former, oxyfuel combustion plus dehydration should be adopted, leading to 90% of capture. For the latter, physical absorption is applied, leading to 90% of capture. In the case of power plants, the estimates for coal fired and natural gas power plants, followed also Rochedo et al. [12], leading to 90% capture. For the cement industry, the estimates of CO₂ captured focus in Post-combustion technology route, leading to 90% of capture and considered the process emission factor according to IPCC [47] and Rochedo et al. [12].

In the proposed methodology, the commercial georeferenced software can be used, such as ArcGIS. This geographic information system software contains density calculation tools, which uses collected information as entry data and provide maps with the possible location of areas of interest. For this study, a density analysis was applied to CO₂ emissions sources based on Kernel Density from the ArcGIS Desktop 10.

Kernel Density is an analysis tool that calculates the spatial density of features in a neighborhood. Hence, it spatially distributes a property in a parametric way. Kernel density estimation (KDE) is a spatial data analysis technique, which the most common form 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, CO₂ emissions) within a user-specified search bandwidth (the search radius). The analysis results are a continuous surface that shows areas of high and low CO₂ emission density [48,49]. Eqs. (1) and (2) represent calculations performed in “Kernel Density” tool. ($x_1, x_2, \dots, x_n$) is a sample i taken from any distribution with an unknown density f . The aim is to estimate the shape of this function f . The Kernel density estimator is given by Eq. (1) [50,51].

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

where K is kernel – symmetric function, being $h > 0$ a smoothing parameter called the bandwidth. Kernel index h is called scaled kernel and is defined by Eq. (2).

$$K_h(x) = \frac{1}{h} K(x/h) \quad (2)$$

The Kernel analysis has been widely used for different purposes such as retail site location decision process, occurrence of car crashes and crimes in a specific area, even occurrence of cases of a certain disease; for establishing sites for biogas plants, among other examples [49,50,52–54]. In all these examples hotspots based on high-density areas could be calculated.

Thus, the Kernel Density function is proved to be a useful and practical approach for the identification of higher concentration areas of specific parameters and supporting decision making towards the location of related units. However, to the best of the authors' knowledge, the use of Kernel density for the location of CO₂ hubs has not yet been explored in the literature.

In fact, there are other methodologies to design carbon transportation networks, in the scientific literature. These methodologies include using optimization models to minimize costs of infrastructures, and cluster analyses considering qualitative information. This last analysis aims to aggregate emissions sources based on technical information similarities from each source. Information such as distance among sources and carbon sinks; use of the same carbon sink for different sources, sources' location, and CO₂ costs are needed.

Therefore, the proposed methodology in this paper is not a full methodology for designing a pipeline network, but a simple tool for locating hubs and proposing a preliminary analysis focused on CO₂ emissions, hubs and sedimentary basins (available storage sites). This present analysis does not propose a pipeline network design. It does a first screening of the possible areas to install hubs based on CO₂ emissions density. So, the areas that show higher density are the areas that most likely will need a hub. Moreover, the focus of the paper is the emission density analysis, that indicates visually where the most part of the emissions are and its distance to possible storage sites. It is clear that often the emission sources that have higher density emissions are located far from the storage sites and in different countries (different jurisdictions), so that explains the focus of the paper on regulatory implications.

Methodologies for designing pipeline networks are well known for decades and are widely used for natural gas, oil and water transportation and should be used to complement the present analysis. So, the proposed methodology can be used to suggest optimal locations for hubs and, other standard pipeline network design tool may be used to

connect the sources, suggested hubs and storage sites.

It is important to clarify that this analysis (Kernel Density analysis) is a first assessment that can indicate the regions that should be studied to install hubs based on a mathematical approach. Besides, it is easy to use, it requires few data and it is a low-cost analysis. It can also be associated with a cost optimization analysis according to Tagomori et al. [55]. The application of the proposed methodology for the Iberian Peninsula is shown in Section 4.

4. Results

Following the proposed steps showed in Section 3 of this paper, the results for the Iberian Peninsula CO₂ emission sources are presented in Sections 4.1 and 4.2.

4.1. Iberian peninsula CO₂ emission sources

The selection of emission sources to be studied in Portugal was based on the list of main CO₂ stationary emission sources in Portugal

Fig. 1. Iberian Peninsula CO₂ emission sources.

Table 1
Summary for CO₂ emission data for Iberian Peninsula.

	Type of facility	Number of facilities ^a	Total emissions ^a (Mt CO ₂)	CO ₂ capturable ^b (Mt CO ₂)
Spain	Oil refinery	9	14.06	9.51
	Power plants	72	17.84	12.83
	Cement industry	35	21.83	17.38
Portugal	Oil refinery	2	5.10	1.23
	Power plants	6	4.52	2.72
	Cement industry	6	12.12	10.81

^a EDP [64]; Seixas et al. [15], REN [56], MAGRAMA [65] and MAPAMA [66,67].

^b Based on Rochedo et al. [12], please refer to the methodology presented in Section 3.

obtained from Seixas et al. [15] and includes fossil fuel power plants, oil refineries and cement industrial facilities. The values of capturable² CO₂ emissions were estimated considering CO₂ emissions reported for the year 2014 for each sector [56].

In Spain, the emission sources were selected from the same energy-intensive sectors and the same year as Portugal. These sectors are known for having the highest potential for CO₂ capture [12,14–15,57]. Fig. 1 shows the locations of all the emission sources considered for the case study.

In total, 130 emission sources were analyzed in this study. The emission sources and their respective capturable CO₂ emissions are shown in the tables in the Supplementary Material (SM). Table 1 summarizes the data according to each sector and country.

4.2. Geographic information system software output

The methodology described in Section 3 was applied to the estimated CO₂ emissions from the power, cement, and oil refining sectors in the Iberian Peninsula. Then, all the data was inserted in the ArcGIS Desktop 10 software and the output maps³ presented in this section are based on two different cases: (i) Portugal and Spain would have isolated CO₂ pipeline grids (Figs. 2 and 3) and (ii) the Iberian Peninsula would have an integrated CO₂ pipeline grid (Fig. 4).

The Kernel map for Portugal, Fig. 2, has resulted in six hot spots. These spots can be identified on the map by the darker red color. The

first hotspot is located in the north region of Portugal (next to the city of Porto) and includes two Power Plants and the Matosinhos oil refinery. There are four hotspots located in the middle region of Portugal and they include power plants and cement facilities.

Lastly, there is an important hotspot located in the South that includes the Sines oil refinery, a power plant, and a cement facility. These areas should be further analyzed for installing CO₂ hubs since they present high density of CO₂ emissions, i.e., multiple sources of emissions with relatively high collective annual emission. By presenting high density, it implies that these six spots concentrate CO₂ emission sources that have the most capturable emissions in Portugal. Since this first analysis considered the case where Portugal would develop an isolated CO₂ pipeline, all the captured CO₂ in Portugal should be either stored or used in the Portuguese territory.

The results for Spain shows seven hotspots in the map in Fig. 3. The high density implies that these spots concentrate the emission sources that have the most capturable emissions in Spain. This map considered a situation that Spain, such as Portugal, would develop an isolated CO₂ pipeline and that the CO₂ emissions collected in Spain would also be either stored or used in the Spanish territory.

Finally, Fig. 4 presents Case 2, in which the Iberian Peninsula would have an integrated network and all the selected emission sources would be analyzed together. This map shows that the hotspots would be re-organized, especially in Portugal due to the lower emission of the Portuguese facilities. When analyzing the overall Iberian Peninsula,

Fig. 2. Result map for Portugal (Case 1). Results are reported in % of total capturable emissions.

² Capturable CO₂ is defined as the fraction of CO₂ emitted that can be directly removed from the flue gas, given a capture technological option. It does not consider, then, CO₂ emissions from life-cycle.

³ It is worth mentioning that this study focused on the Iberian Peninsula. Therefore, it does not consider possible connections with existing or to be constructed CO₂ pipelines in other countries in Europe or North Africa.

most of the hotspots would be located in Spain, with seven hotspots. It is interesting to note that a pattern appears in the Iberian Peninsula map: most of the emission sources are located within the boundary limits of both continental territories of Portugal and Spain. This probably occurs because these energy-intensive facilities are located next to seaports and/or energy resources delivery points.

Comparing both cases, it is possible to infer that Case 2 could be a

Fig. 3. Result Map for Spain (Case 1). Results are reported in % of total capturable emissions.

Fig. 4. Result map for Iberian Peninsula (Case 2). Results are reported in % of total capturable emissions.

Fig. 5. CO₂ emission sources and possible storage sites for the Iberian Peninsula. Source: Adapted from Global CCS Institute, 2005.

Fig. 6. Kernel results and storage sites for the Iberian Peninsula.

better solution for the Iberian Peninsula because Spain shows more geological storage potential than Portugal. The literature shows that the Spanish territory has storage sites available such as oil and gas reservoirs, deep saline aquifers and coal basins. There are storage possibilities in main sedimentary basins (Duero, Ebro, Madrid, Mula, Campo de Cartagena, Tajo, Gulf of Valencia and Guadalquivir) and in their associated mountain ranges (Cantabrian, Pyrenees, Iberian, and Betic). These are mainly located in the Mediterranean and the Gulf of Cádiz, can be observed in Fig. 5, and the total capacity has been estimated to reach up to 22 Gt of CO₂ [41,45].

In the case of Portugal, it shows some possible reservoirs such as saline aquifers, and the total storage capacity can reach up to 7.5 Gt of CO₂ [15]. It is worth mentioning that almost 95% of the storage capacity estimated for Portugal is located along the coast [15,41]. This leads to discussions about their public acceptance since they may cause environmental damages and may affect Portugal's tourism activities.

Moreover, the integrated map shows fewer hotspots because the emission density distribution is different, and they concentrate more emission sources per hotspot. In this case, fewer hubs would be required, as well as less pipeline infrastructure and equipment. The pipeline network would, probably, be smaller and, consequently, it would reduce costs for construction and installation. Moreover, Portugal and Spain have already a natural gas pipeline network that connects both countries and these pathways could be used as a proxy when installing future CO₂ pipelines. So, designing an integrated grid would not be a critical challenge.

Thus, since the majority of the possible hubs and most of the storage sites are located in Spain, there is a significant reason to set up a strategic plan and a regulatory framework that would allow the implementations of CCS projects not only in the country but in the region. Fig. 6 shows the results of the Kernel density analysis for the Iberian Peninsula and the locations of possible storage sites that are mostly in the Spanish territory.

Moreover, if Portugal does participate in an Iberian pipeline network, it would benefit from gaining access to the Spanish storage sites.

4.3. Discussion and regulatory implications

According to Carneiro et al. [58], Roddy [59], and Boavida et al. [43], 27 sources mapped sites were grouped into three clusters of CO₂ emissions in Portugal. These clusters were determined only by a qualitative analysis.

Similar studies in other countries such as Scotland, Italy, and Norway, also used this type of qualitative analysis to determine important areas for a preliminary screening of the territories [59,60]. In France, Bielicki et al. [61] applied a model that identified potential routes for CO₂ pipelines considering aspects to produce a 'cost surface' that indicates the degree to which pipelines should avoid some location.

Nevertheless, these methodologies differ from the one proposed here. First, the cluster analysis is not very accurate as it is based on a qualitative assessment of aggregate sources according to distances to possible carbon sinks. In turn, the optimization model analysis is based on CO₂ costs, which depends on a carbon market [55,61].

Hence, the proposed methodology of this study based on Kernel density function could be considered more accurate when compared to a qualitative emission source analysis. Also, is it not necessary to identify carbon sink locations and CO₂ costs to perform the analysis because the only data required as input are the sources' location and annual CO₂ capturable emissions amount from each source.

So, as mentioned before, the proposed methodology aims to analyze mostly the emission sources, requiring fewer data inputs and resulting in a faster, less complex and more accurate process. Moreover, the proposed methodology's main objective is to determine hotspots in terms of CO₂ emissions and then analyze these spots to evaluate potential installation of hubs. This is a necessary step towards designing an optimized carbon pipeline network since these spots represent

collecting points for the CO₂ captured in the emission sources.

The design of the network should focus first on connecting these points and then, connect these to the final destination of captured CO₂. The project design may consider the possibility to implement CCS technologies in the studied territory and to reduce CO₂ transportation investments and operational costs. Also, according to Tagomori et al. [55], it is possible to say that considering the advantage of the economies of scale, the carbon network proposed with the hubs, would probably lead to the same design as an alternative of optimization of pipelines.

However, for placing hubs and implementing carbon capture projects, a CO₂ pipeline network would require not only a methodology for identifying these hubs, but also a regulation framework for Spain and Portugal, as the existing legislation addresses only the storage of CO₂ and applies to the European level [40,62]. Actually, the European Union (EU) has already Directives⁴ regarding CO₂ management and CO₂ geological storage in the European territory. However, the existing legislation presents few provisions regarding CO₂ transportation [62].

Considering that CO₂ sources and storage sites can be located in different jurisdictions (countries), CO₂ transportation is a crucial and controversial step of the process. The most relevant points in these Directives, related to CO₂ transportation, focus on the composition of the CO₂ stream and on pipeline access. Due to the lack of information on the EU level, CO₂ transportation issues should be addressed under a national level and may, therefore, lead to a variety of national solutions [62]. In the case of creating a pipeline grid for the Iberian Peninsula, Spain and Portugal should follow their specific regulatory framework, as well. For example, when crossing the border between the two countries, responsibility for the transported, injected and stored CO₂ should be defined in the regulatory framework of each country.

In this case, each carbon capture project in a specific facility should be viewed as a component of an optimized carbon transportation network. The steps of this project include CO₂ capture, collection, transportation, injection, and storage. Each of these steps should be regulated according to the market structures related to them. The need for regulation is justified, mainly by the presence of segments in the chain of a CCS project that is characterized as natural monopolies. This paper is focused on the stages of CO₂ collection and transportation which consists in taking the CO₂ from the emission source to its final destination.

At these stages, for large volumes of CO₂, pipelines should be used. For smaller volumes and emission sources that do not have adequate infrastructure for transportation by pipelines, trucks can be used to collect the CO₂ from the emission source to the hub. These routes taken by trucks are called virtual pipelines. For transportation by pipelines, there should be a stream of CO₂ that must be compressed to a pressure of 150–180 bar [27,63]. Compressors are used to accomplish these pressure rates and they require large amounts of energy (electricity or natural gas when available on site). The maximum pressure drop in a pipeline should be 3 MPa. Assuming that pressure decreases at a rate of 20 Pa per meter [32], compressors should be installed every 150 km.

Moreover, the implementation of CCS to mitigate CO₂ emissions in the Iberian Peninsula requires a public policy. The carbon emitted by industrial and energy facilities should have a value, either indirectly through CO₂ emissions limit (cap) or directly through taxation. In these steps, the agents that would offer the lowest rates would operate the pipeline network. The Regulator would have an important role in these steps. First, it should act to ensure the existence of the monopoly itself. Second, it should act by setting a maximum rate for the auction of the rates to be charged by the operators, thus avoiding abuse by

⁴ [13]/31/EC of European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide, and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006.

monopolists. Moreover, future regulations should ensure the quality of service and ensure that the right of ownership of CO₂ would be transferred from the capture agent to the agents to collect and transport, upon payment of the service (CO₂ carrier).

Also, in the stages of CO₂ collection and transportation, regarding information asymmetry issues, the regulatory agency could minimize its effects by requesting periodic newsletters of operations, information on investments in its pipeline network and request reports every transfer of responsibility containing information on the achievements and the difficulties faced during the project.

Besides economic issues that justify the presence of a regulatory framework for CO₂ transportation, there are a few important items that should be included in the legislation and discussed, as well, such as public acceptance, preservation of historical centers and monuments in Europe. Both Portugal and Spain do not present too much information about CCS technologies and studies to the society, in general. In Spain, for instance, public awareness is not high. In several surveys conducted by Spanish research groups, it was stated that more than 75% of the population is not aware of CCS as a Climate Change mitigation option [41]. On the other hand, in areas where pilot and demonstration projects are planned, Ciuden and Endesa have carried out public awareness campaigns and the result shows that public opinion is mostly positive towards the application of these technologies [41,45].

5. Final remarks

The methodology presented for hubs placement analysis is easily applicable and provide relevant insights for a conceptual project of carbon pipelines networks intra and inter-countries. It helps to optimize the carbon transportation network, which should be planned and regulated particularly for the segments under natural monopoly. It also helps to understand the role of each carbon emitter source into the carbon transportation network. 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.

Therefore, this methodology aims to assist a Planning Agency to develop the pipeline network projects which will be used to transport CO₂ in CCGS projects. In addition, it was concluded that it could be applied to any domestic and international territory, by only having access to 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 a necessary step towards designing a carbon pipeline network to collect CO₂ emissions in the Iberian Peninsula. So, this is also a step towards considering CCS technologies for Portugal and Spain resulting in CO₂ emissions reduction. Moreover, collecting CO₂ besides reducing emissions could be a way of delivering CO₂ to industries that use it as feedstock, such as the food industry. This would result in a sustainable way of dealing with CO₂ emissions. Also, it could create a new market for selling and buying CO₂ in Europe. In sum, this methodology would be a beginning of a strategy that would bring environmental and economic benefits to Portugal and Spain.

CO₂ capture estimation showed that in Portugal CO₂ emissions reduction can reach up to 68% in the industrial sources analyzed here. In the case of Spain, up to 74% of CO₂ emissions from the emission sources analyzed here, could be avoided. These avoided emissions are called capturable CO₂ emissions which means that they are the portion of the total emissions that can captured from industrial processes before they reach the atmosphere.

From the contributions of this work, other relevant studies can be developed. Such as locating new energy-intensive installations already considering CCS technologies and CO₂ transportation networks and geological reservoirs that could store CO₂ from the new sources. Moreover, a study to analyze a possible integrated pipeline network at a European scale should also be considered.

It is worth to remember that this methodology does not define the exact location for hubs, other variables such as proximity to existing pipeline networks, costs and area occupation, and distances between emission sources and final reservoirs can be included in a further analysis. However, the proposed methodology is a necessary step towards implementing CCS in any place.

Future studies considering CO₂ pipelines for Europe may focus on transportation costs, including costs related to the installation of the network itself, using hubs. Further research is also necessary to assess the public perception and acceptance of such systems when compared to other mitigation options, such as renewable energy generation like wind turbines and photovoltaic panels.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apenergy.2018.11.050>.

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